

Flaxino dark matter and stau decay

To cite this article: Eung Jin Chun *et al*/JHEP03(2008)061

View the [article online](#) for updates and enhancements.

You may also like

- [R-parity violating anomaly mediated supersymmetry breaking](#)
Ben C. Allanach and Athanasios Dedes
- [Supersymmetric Boost on Intersecting D-branes](#)
Jin-Ho Cho and Phillial Oh
- [Closed string tachyons in non-supersymmetric heterotic theories](#)
Takao Suyama

Flaxino dark matter and stau decay

Eung Jin Chun

*Korea Institute for Advanced Study,
Seoul 130-722, Korea
E-mail: ejchun@kias.re.kr*

Hang Bae Kim

*BK21 Division of Advanced Research & Education in Physics,
Hanyang University,
Seoul 133-791, Korea
E-mail: hbkim@hanyang.ac.kr*

Kazunori Kohri and David H. Lyth

*Physics Department, Lancaster University,
Lancaster, Lancashire, LA1 4YB, U.K.
E-mail: k.kohri@lancaster.ac.uk, d.lyth@lancaster.ac.uk*

ABSTRACT: If the spontaneous breaking of Peccei-Quinn symmetry comes from soft supersymmetry breaking, the fermionic partners of the symmetry-breaking fields have mass of order the gravitino mass, and are called flatinos. The lightest flatino, called here the flaxino, is a CDM candidate if it is the lightest supersymmetric particle. We here explore flaxino dark matter assuming that the lightest ordinary supersymmetric particle is the stau, with gravity-mediated supersymmetry breaking. The decay of the stau to the flaxino is fast enough not to spoil the standard predictions of Big Bang Nucleosynthesis, and its track and decay can be seen in future colliders.

KEYWORDS: Supersymmetry Phenomenology, Cosmology of Theories beyond the SM.

Contents

1. Introduction	1
2. LSP from flat-direction axion sector	2
3. Stau lifetime	4
4. Abundance of the flaxino DM	5
5. The flaton and flatino mass spectrum	6
6. Results	6
7. Conclusions	8

1. Introduction

By observing the temperature anisotropy of Cosmic Microwave Background (CMB), the WMAP Collaboration reported that the density parameter of dark matter (DM) or cold dark matter (CDM) $\Omega_{\text{DM,obs}}$ is

$$\Omega_{\text{DM,obs}} h^2 = 0.104^{+0.007}_{-0.010}, \quad (1.1)$$

at 68 % C.L. [1] where h is the normalized Hubble constant. One of the most popular candidates for DM is the lightest supersymmetric particle (LSP) in supersymmetric theories with R-parity. Recent studies showed that Big Bang Nucleosynthesis (BBN) puts interesting limitations on the candidates of LSP DM.

A long-lived next LSP (NLSP) whose lifetime is longer than 0.1 sec is dangerous for the successful BBN because the decaying NLSP produces a lot of (high-energy) daughter particles such as photons and hadrons during/after BBN, which can destroy ^4He (and D) and non-thermally produce another light elements copiously [2–4]. In particular, a non-thermal hadron emission due to the decaying NLSP is severely constrained by the observational light-element abundances of D, ^4He , ^6Li , and ^7Li [3, 4].

In the popular case of the neutralino (gaugino or higgsino) LSP, as is well-known, the unstable gravitino decay puts stringent upper bound on the reheat temperature after primordial inflation, which could be problematic for various cosmological considerations, e.g., of the inflation models. This problem can be avoided if the gravitino is the LSP. (See also [5] for constraints on the reheat temperature in the gravitino LSP scenario). However, the decays of ordinary supersymmetric particles to the gravitino turn out to be dangerous as well.

The case of neutralino NLSP, because the branching ratio into hadrons is close to the order of $\mathcal{O}(1)$, is almost excluded [6, 7] by considering BBN constraints [3, 4]. Slepton NLSP scenarios appear much more favorable than neutralino NLSP scenarios in cosmology. Although the sneutrino NLSP scenario should be possible because of the smaller hadronic and radiative decaying modes, the primordial abundance of the sneutrino is too small to satisfy the dark matter density for its daughter LSP particle [8, 9]. Therefore, we would need another production mechanism of the LSP in cosmology, which usually requires a fine tuning.

Recently, the stau NLSP scenario has been discussed a lot as there are specifically severer/more interesting problems in BBN related to the long-lived negatively charged particle [10–13]. See also long-term problems discussed in literature [14] and topics in doubly-charged particles [15]. If the lifetime of the negatively charged particle C^- such as $\tilde{\tau}^-$ is longer than 10^2 sec, bound states with ambient light elements can be produced. In particular, the bound state with ${}^4\text{He}$ denoted by $({}^4\text{He}, C^-)$, which is produced after 10^3 sec, significantly enhances the reaction rate $D + ({}^4\text{He}, C^-) \rightarrow {}^6\text{Li} + C^- + \gamma$ [10] by a factor of $\sim \mathcal{O}(10^7)$ [16]. Then ${}^6\text{Li}$ is over-produced by the catalyzed BBN, and this scenario is severely constrained by observations [17].

Various attempts [18–21] have been made to tackle this problem and realize a successful dark matter production mechanism. In this paper, we suggest the “flaxino” DM as a viable option to avoid the above-mentioned difficulties for the neutralino or slepton NLSP. The flaxino is an axino-like fermion appearing in flat-direction axion models where the spontaneous breaking of Peccei-Quinn symmetry comes from soft supersymmetry breaking and thus all of the fermionic partners of the symmetry-breaking fields have mass of order the gravitino mass. The flaxino has a coupling to the ordinary superparticles suppressed by the axion scale F_a and thus attractively leads to a fast decay of NLSP, which should be compared with the gravitino coupling suppressed by the Planck scale.

2. LSP from flat-direction axion sector

The strong CP problem can be naturally resolved by assuming the Peccei-Quinn $U(1)$ symmetry spontaneously broken at the usual high scale, $F_a = 10^{10-12}$ GeV, and thus leads to an axion of the KSVZ [22] or DFSZ type [23]. In the supersymmetric standard model, the realization of the DFSZ axion model nicely leads to the origin of the μ term [24]. Furthermore, the axion scale F_a appears as the geometric mean of the Planck scale and soft supersymmetry breaking scale by invoking an almost flat potential for the Peccei-Quinn symmetry breaking fields [25, 26]. For instance, let us introduce two singlet fields P, Q with appropriate Peccei-Quinn charges to allow [27, 28]

$$W = h \frac{PQ}{M_P} H_1 H_2 + f \frac{P^3 Q}{M_P} \quad (2.1)$$

where M_P is the reduced Planck scale. Then, the μ term and axion scale can be related by $\mu = h \langle P \rangle \langle Q \rangle / M_P$ and $F_a \sim \langle P \rangle, \langle Q \rangle \sim \sqrt{\tilde{m} M_P} \sim 10^{10}$ where $\tilde{m} \sim 10^{2-3}$ GeV is the typical soft mass scale (correctly $F_a = \sqrt{\langle P \rangle^2 + 9 \langle Q \rangle^2}$ in this model). This is below the scale $F_a \gtrsim 10^{12}$ GeV required to make the axion the CDM. This model contains two scalar

flatons $F_{1,2}$, one pseudoscalar flaton F' , and two flatinos $\tilde{F}_{1,2}$. This kind of flat DFSZ axion models lead to thermal inflation [29] and the model parameters are rather severely constrained in order to avoid the over-production of unwanted relics like axions or the LSP after thermal inflation [26]. An interesting collider implication of such models has been pointed out in ref. [30]. The LSP can be some linear combination of the fermionic parts of P and Q , which we now call “flaxino” (denoted by \tilde{F}_1), and then the usual neutralino or stau NLSP decays to the flaxino mainly through its mixing with higgsinos driven by the μ term. Although the corresponding decay lengths can be larger than the size of detectors, the copious production of the NLSPs in future colliders may enable us to observe their decays for the low axion scale $F_a \sim 10^{10}$ GeV [30]. The general idea of the axino DM has been put forward in ref. [31] (see also a recent related paper [32]).

Some of the current authors have investigated the scenario of the “flaxino” LSP and the neutralino NLSP in the flat DFSZ axion models using gravity-mediated SUSY breaking [27, 28]. The axino LSP in KSVZ type models has been considered in ref. [33]. The KSVZ type models (hadronic axion models) do not agree with the framework of the flat-direction models because of the overproduction of the flaxino abundance, which is excluded by BBN [27]. Extending the analysis of ref. [28] where the neutralino NLSP is assumed, we will consider the possibility of the stau NLSP which is also allowed in a large parameter space of the MSSM with the minimal supergravity scheme.

Let us first note that the DFSZ models predict a shorter lifetime of the stau NLSP compared to the KSVZ models since the stau-axino/flaxino coupling arises at tree level in the former case and at one-loop level in the latter. As we will see later, even in the case of $F_a \lesssim 10^{14}$ GeV, the stau lifetime does not exceed 10^3 sec for typical mass scales of SUSY particles in the DFSZ axion models and does not induce the ${}^6\text{Li}$ over-production problem. This is a distinct feature of the DFSZ axion models. Recall that the usual upper bound, $F_a \lesssim 10^{12}$ GeV, can be relaxed in late-time entropy production scenarios such as thermal inflation models which we are considering at present.

From the viewpoint of detectabilities of a superparticle at Large Hadron Collider (LHC), such a long-lived charged particle is promising as it can be easily traced within the detector. Moreover, quite recently refs. [34–36] have discussed aggressive future plans to place new stopper, e.g., 5 - 10 meter wall made of iron, water tanks, rocks and so on, outside regular detectors in LHC such as ATLAS or CMS to electromagnetically stop the produced staus. If these plans are realized, we will be able to measure the stau’s lifetime even if its decay length is longer than the size of the detectors ($\lesssim \mathcal{O}(10)$ m), and reconstruct the track of the neutral LSP by catching other daughter particles. Then, according to a similar discussion in Brandenburg et al’s analysis [33], observing three-body decay of the staus will enable us to distinguish between signals of the axino/flaxino LSP and the gravitino LSP.

We refer to [37] for another topics of axino DM and gauge-mediation supersymmetry breaking models, and ref. [38] for general cosmological constraints on a decaying saxion or flaton. See also [39] for an inverted mass case such as the axino NLSP and the neutralino LSP, and [40] for the gravitino NLSP and the axino LSP in gauge-mediated supersymmetry breaking models.

3. Stau lifetime

Following ref. [30], we calculate the lifetime of the stau NLSP which decays into the flaxino LSP \tilde{F}_1 in the DFSZ axion models. For the sake of simplicity we show only mixing between \tilde{F}_1 and the usual four neutralino components; bino, wino, and two higgsinos. This case is sufficient if we are not interested in the heavier flaxino \tilde{F}_2 whose mass is larger than $m_{\tilde{N}_1^0}$. Then, we get

$$\Gamma(\tilde{\tau}_1 \rightarrow \tau \tilde{F}_1) = \frac{m_{\tilde{\tau}_1}}{16\pi} \sqrt{\lambda(1, r_0^2, r_\tau^2)} \left[\left(|a_0^{\tilde{\tau}_1}|^2 + |b_0^{\tilde{\tau}_1}|^2 \right) (1 - r_0^2 - r_\tau^2) - 4r_0 r_\tau \text{Re} \left(a_0^{\tilde{\tau}_1} b_0^{\tilde{\tau}_1*} \right) \right] \quad (3.1)$$

where $m_{\tilde{\tau}_1}$ is the lightest stau mass ($\equiv m_{\tilde{\tau}}$ in this paper), $r_0 = m_{\tilde{N}_1}/m_{\tilde{\tau}_1}$, $r_\tau = m_\tau/m_{\tilde{\tau}_1}$ with

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx, \quad (3.2)$$

and

$$a_0^{\tilde{\tau}_1} = \sqrt{2} s_{\tilde{f}} [g g T_{3f} N_{02}^* + g' (q_f - T_{3f} N_{01}^*)] - c_{\tilde{f}}^* g N_{03}^* m_\tau / \sqrt{2} c_\beta m_W, \quad (3.3)$$

$$b_0^{\tilde{\tau}_1} = \sqrt{2} c_{\tilde{f}} g' q_f N_{01} + s_{\tilde{f}} g N_{03} m_\tau / \sqrt{2} c_\beta m_W. \quad (3.4)$$

Here m_τ and m_W are the masses of the tau lepton and the weak boson, g and g' are the weak and electromagnetic coupling constants, respectively, and the Z-boson couplings to quarks and leptons for the tau lepton are give by $(T_{3\tau}, q_\tau) = (-1/2, -1)$. The matrix elements N_{0i} ($i=1,2,3,4$) are flaxino-neutralino components of a unitary matrix N_{ij} which is the 5×5 mass matrix of four neutralinos plus one flaxino, $M_{kl}^{(5)}$ ($k, l=0,1,2,3,4$) in the $(\tilde{F}_1, \tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$ basis. It can be diagonalized as

$$N_{jk}^* M_{kl}^{(5)} N_{lj} = \delta_{ij} m_{\tilde{N}_i}, \quad (3.5)$$

where

$$M^{(5)} = \begin{pmatrix} m_{\tilde{F}_1} & 0 & 0 & -\delta_1 s_\beta \mu & -\delta_1 c_\beta \mu \\ 0 & M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -\delta_1 s_\beta \mu & -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ -\delta_1 c_\beta \mu & s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \quad (3.6)$$

Here $s_\beta = \sin \beta$, $c_\beta = \cos \beta$, $s_W = \sin \theta_W$, and $c_W = \cos \theta_W$ with the Weinberg angle θ_W , and

$$\delta_1 \equiv \frac{v}{F_a} \frac{\sqrt{x^2 + 1}}{x} \left(\cos \tilde{\phi} + x \sin \tilde{\phi} \right), \quad (3.7)$$

with the electroweak scale $v = 264 \text{ GeV}$, $x \equiv \langle P \rangle / \langle Q \rangle$, the mixing angle $\tilde{\phi}$ between \tilde{F}_1 and \tilde{F}_2 which is expressed by using x to be $\cos 2\tilde{\phi} = -1/\sqrt{x^2 + 1}$ and $\sin 2\tilde{\phi} = -x/\sqrt{x^2 + 1}$ [28]. The mass eigenstate labels follow the convention: $m_{\tilde{F}_1} \simeq m_{\tilde{N}_0} < m_{\tilde{N}_1} < m_{\tilde{N}_2} < m_{\tilde{N}_3} <$

$m_{\tilde{N}_4}$ (Note that $m_{\tilde{F}_2}$ can be larger than $m_{\tilde{N}_1}$ although we did not write it down explicitly in (3.6)). In the stau sector, the diagonalization is taken as follows;

$$\begin{pmatrix} \tilde{\tau}_R \\ \tilde{\tau}_L \end{pmatrix} = \begin{pmatrix} c_{\tilde{\tau}} & s_{\tilde{\tau}} \\ -s_{\tilde{\tau}}^* & s_{\tilde{\tau}}^* \end{pmatrix} \begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix}. \quad (3.8)$$

Because the mixing angle in $s_{\tilde{\tau}}$ and $c_{\tilde{\tau}}$ is an unknown parameter, we will study the $s_{\tilde{\tau}}$ dependence by changing it from zero to unity.

Note that the stau decay rate is approximately represented by

$$\begin{aligned} \Gamma(\tilde{\tau}_1 \rightarrow \tau \tilde{F}_1) &\sim \frac{m_{\tilde{\tau}}}{16\pi} \left| \delta_1 \frac{\mu}{v} \right|^2 \times \frac{1}{\Delta} \\ &\sim (1\text{m} \times \Delta)^{-1}, \end{aligned} \quad (3.9)$$

for $F_a \sim 10^{10}$ GeV and $m_{\tilde{\tau}} \sim \mu \sim \mathcal{O}(10^2)$ GeV with a suppression factor $\Delta \sim \mathcal{O}(10)$ caused by electroweak couplings, mixing angles, kinematic suppressions and so on. Thus, we can expect the decay signals of staus within the meter-size detectors in LHC.

4. Abundance of the flaxino DM

The flaxino LSP abundance is determined by the thermal generation and the non-thermal generation from the stau NLSP decay:

$$\Omega_{\tilde{F}_1} h^2 = \Omega_{\tilde{F}_1, \text{th}} h^2 + \Omega_{\tilde{F}_1, \text{nonth}} h^2. \quad (4.1)$$

First, the freeze-out density of the relic stau can be calculated by taking the leading s -wave stau annihilation to photons whose thermal-averaged cross section is given by $\sigma \approx 2\pi\alpha^2/m_{\tilde{\tau}}^2$ with the fine structure constant α . Then, following the standard procedure presented in [41], the non-thermal density of \tilde{F}_1 can be estimated as

$$\Omega_{\tilde{F}_1, \text{nonth}} h^2 = 0.1 \left(\frac{m_{\tilde{F}_1}}{400\text{GeV}} \right) \left(\frac{m_{\tilde{\tau}}}{400\text{GeV}} \right). \quad (4.2)$$

By using the analytical calculation in ref. [28], the density parameter of the thermal component of \tilde{F}_1 is estimated to be

$$\Omega_{\tilde{F}_1, \text{th}} h^2 = 0.1 \left(\frac{m_{\tilde{F}_1}}{m_{\tilde{q}}} \right) \left(\frac{\epsilon_{\tilde{q}\tilde{q}\tilde{F}_1}}{10^{-8}} \right)^2 \left(\frac{x_{\tilde{q}}}{19.45} \right)^2 \exp[-0.98(x_{\tilde{q}} - 19.45)]. \quad (4.3)$$

Here $x_{\tilde{q}} \equiv m_{\tilde{q}}/T_{\text{RH}}$, with $m_{\tilde{q}}$ the squark mass and T_{RH} the reheat temperature after the lightest flaton F_1 decay,

$$T_{\text{RH}} = 19\text{GeV} \left(\frac{m_{F_1}}{10^2\text{GeV}} \right)^{3/2} \left(\frac{F_a}{10^{10}\text{GeV}} \right)^{-1} \left(\frac{B_a}{0.1} \right)^{-1}, \quad (4.4)$$

with B_a the branching ratio of F_1 decaying into axions. T_{RH} should be sufficiently high for daughter axions produced by the decay of F_1 not to induce ${}^4\text{He}$ overproduction ($B_a < 0.1$ [28]) and must be also larger than $m_{\tilde{\tau}}/25$ to thermally produce the NLSP staus. The quantity $\epsilon_{\tilde{q}\tilde{q}\tilde{F}_1}$ denotes the squark-quark-flaxino mixing which becomes the largest for the stop having an order-one top Yukawa coupling h_t : $\epsilon_{\tilde{q}\tilde{q}\tilde{F}_1} = h_t N_{04}$ with $N_{04} \simeq \delta_1 c_\beta \sim \mathcal{O}(v/F_a)$.

5. The flaton and flatino mass spectrum

By assuming the superpotential given in (2.1), we have a scalar potential including soft supersymmetry breaking terms,

$$V_{\text{soft}} = f \frac{A_f}{M_p} P^3 Q + h.c. \quad (5.1)$$

Then the flaton masses are given by

$$m_{F_{1,2}} = \frac{\tilde{\mu}}{\sqrt{2}} \sqrt{3(12 - \xi) + x^2(12 + \xi) \pm |12 - \xi| \sqrt{x^4 + 42x^2 + 9}}, \quad (5.2)$$

$$m_{F'} = \tilde{\mu} \sqrt{\xi(x^2 + 9)}, \quad (5.3)$$

where $\tilde{\mu} \equiv \mu f/h$ and $\xi \equiv -A_f/(f\mu_0)$ with $\mu_0 = \langle P \rangle \langle Q \rangle / 2M_p$. Then, the flatino masses are represented by

$$m_{\tilde{F}_{1,2}} = 3\tilde{\mu} \left(\sqrt{x^2 + 1} \pm 1 \right). \quad (5.4)$$

Allowed parameter regions for x and ξ of our interest (i.e, parameters where the flatons cannot decay into flatinos, $m_{F_{1,2},F'} < 2m_{\tilde{F}_{1,2}}$) are given in (28) in ref. [28].

6. Results

We present our results on the DM abundance and the stau lifetime by taking some typical parameter sets of the flat DFSZ model. Following the notations and the parameters presented in the previous sections and ref. [28], we take a set of $x = 4$, $\xi = 13$, $f/h = 1/24$, $A_h/\mu = -1$, $A_f/\mu = 13/24$, $\tan \beta = 3$, and $M_2 = 2M_1$. In this paper we show two cases of the mass parameters 1) $\mu = 287 \text{ GeV}$ ($\tilde{\mu} = 12$) and $M_1 = 130 \text{ GeV}$, and 2) $\mu = 813 \text{ GeV}$ ($\tilde{\mu} = 34$) and $M_1 = 530 \text{ GeV}$.

We can calculate the mass spectrum in GeV unit of the flatons $F_{1,2}$, the pseudoscalar flaton F' , and the flatinos $\tilde{F}_{1,2}$ which is given as

$$\left[m_{F'}, m_{F_2}, m_{F_1}, m_{\tilde{F}_2}, m_{\tilde{F}_1} \right] = \begin{cases} [216, 175, 162, 184, 112] & (\tilde{\mu} = 12), \\ [616, 500, 462, 525, 320] & (\tilde{\mu} = 34). \end{cases} \quad (6.1)$$

In each case, by using eq. (4.4) the reheat temperature after the thermal inflation (from the decay of the lightest flaton F_1) is given by $T_{\text{RH}} = 39$ ($T_{\text{RH}} = 189 \text{ GeV}$) for $\tilde{\mu} = 12$ ($\tilde{\mu} = 34$).

In addition, we can diagonalize the 6×6 mass matrix by using the approximated 5×5 method discussed in section 3 and get the mass spectrum of four neutralinos plus two flatinos. Then we can calculate the mass of the lightest neutralino $\tilde{\chi}_0$ (or \tilde{N}_1) and get 1) $m_{\tilde{\chi}_0} = 120 \text{ GeV}$ and 2) 525 GeV , respectively.

In figures 1 and 2 we plot the observationally-allowed region which is enclosed by two solid lines in $(m_{\tilde{\tau}}, m_{\tilde{q}})$ plane for $\tilde{\mu} = 12$ and 34 , respectively. Here we have $F_a = 10^{10} \text{ GeV}$. In both figures, the vertical area enclosed by solid lines comes from the non-thermal contribution and the narrow horizontal area from the thermal contribution which is very sensitive

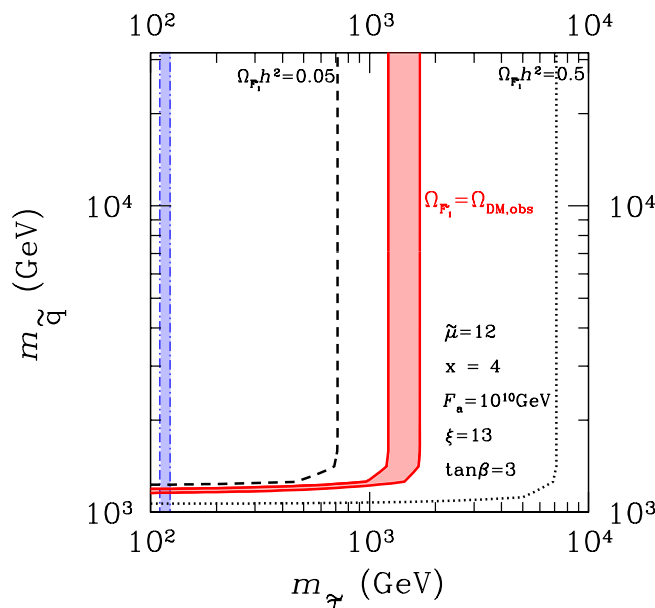


Figure 1: Allowed regions of flaxino dark matter. The axes correspond to the masses of the stau and the squark (stop). The other parameters are as described in the text, with the choices $\tilde{\mu}=12$, $x=4$, $\xi=13$, $\tan\beta=3$, and $F_a = 10^{10}$ GeV. The region between the two solid lines satisfies the WMAP constraints on Ω_{LSP} given in eq. (1.1). The lightest flatino LSP and the stau NLSP can be realized in the region between the two dot-dashed lines. The intersection of these regions is allowed.

function of $x_{\tilde{q}}$. The vertical band between two dot-dashed lines denotes a region where the lightest flatino (flaxino) LSP and the stau NLSP are realized. In figure 2, we see that the flaxino dark matter naturally agrees with observations in broad parameter spaces of $m_{\tilde{q}}$ at the weak scale.

In figures 3 and 4 we plot the lifetime of stau as a function of stau mass in case of $\tilde{\mu} = 12$, and 34, respectively. The thick (thin) solid line denotes the case of the mixing angle $s_{\tilde{\tau}} = 1(0)$. Here we have taken $F_a = 10^{10}$ GeV to minimize the decay length. In case of $\tilde{\mu} = 12$, the decay length is shown to be around 1 m and thus the stau NLSP decay to the flaxino LSP will be possibly searched for at LHC. Note that the lifetime scales $\propto F_a^2$. From these figures we see that the lifetime is sufficiently shorter than 10^3 sec excluding the special case of degenerate masses $m_{\tilde{\tau}} - m_{\tilde{F}_1} \sim m_{\tau}$ (~ 1.8 GeV). Hence this scenario is not constrained by the ${}^6\text{Li}$ overproduction through BBN if we adopt the standard range of $F_a = 10^{10}$ GeV — 10^{12} GeV. In other words, even larger value $F_a \sim 10^{14}$ GeV can be allowed from the viewpoint of BBN. Such a high value might not lead to the overclosure of the universe by the axions because of a sufficiently low reheating temperature and large entropy productions after the thermal inflation [26]. See also ref. [42] for recent detailed analyses of the thermally-produced axions for a relatively low reheating temperature.

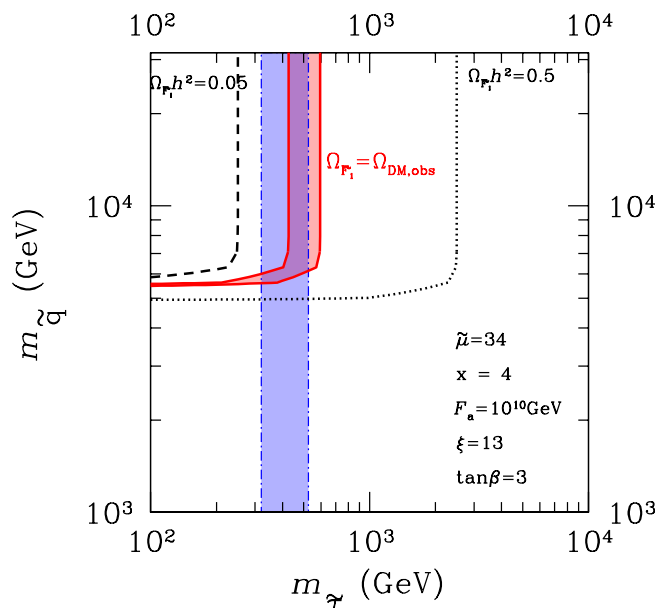


Figure 2: Same as figure 1 but for $\tilde{\mu}=34$.

7. Conclusions

The lightest supersymmetric particle (LSP) is a dark matter candidate. It is usually said that the LSP will be either the lightest superpartner of a Standard Model particle (so called LOSP), the gravitino or the axino. For cosmological constraints and collider signals of the LSP, it matters what is the NLSP. In this paper we revisited the axino-like LSP arising in the flat DFSZ axion models for the case of the stau NLSP.

Following [28], we assumed that the spontaneous breaking of Peccei-Quinn symmetry comes only from supersymmetry breaking. Then all of the PQ particles except the axion will have masses of order the gravitino mass. The scalar particles are called flatons and their superpartners are called flatinos.

In this scenario the saxion is a linear combination of flatons and the axino a linear combination of flatinos, but they are not mass eigenstates and have no special status. So the LSP candidate from the PQ sector is not the axino, but the lightest flatino which we have dubbed the flaxino. We have explored the simplest version of this scenario, which has two flatinos and assumes gravity mediated supersymmetry breaking.

We have found that the stau NLSP decay to the flaxino LSP is fast enough to maintain the standard predictions of Big Bang Nucleosynthesis. The big difference from the gravitino dark matter scenario is that the flaxino/axino coupling ($\sim 1/F_a$) is much larger than the gravitino coupling ($\sim 1/M_P$), which makes the stau NLSP decay much faster. In the DFSZ axion model, the stau-flaxino/axino coupling appears at tree level as a consequence of the μ term mixing between the higgsino and flaxino/axino. This makes the NLSP decay more efficient compared with the KSVZ axion models.

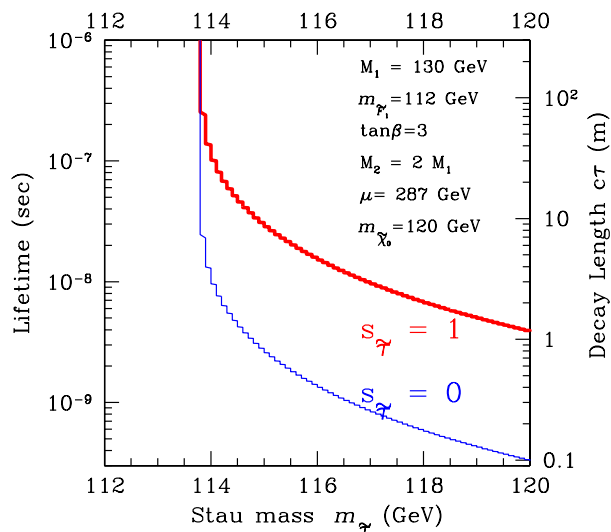


Figure 3: Stau lifetime decaying into the lightest flatino. The thick (thin) solid line denotes the case of the mixing angle $s_{\tilde{\tau}} = 1$ ($s_{\tilde{\tau}} = 0$). Here we have adopted $F_a = 10^{10}\text{GeV}$ and the electroweak scale $v = 264\text{GeV}$. Note that $m_{\tilde{F}_1} = 112\text{GeV}$, and the mass of the lightest neutralino \tilde{N}_1 ($m_{\tilde{\chi}_0} = m_{\tilde{N}_1} = 120\text{GeV}$) is smaller than that of \tilde{F}_2 ($m_{\tilde{F}_2} = 184\text{GeV}$) in this case.

In a specific DFSZ model whose parameters are constrained by various cosmological considerations, we identified the region of the stop and stau masses which is compatible with the required dark matter density. Within the conventional bound on the axion scale $F_a \lesssim 10^{12}\text{GeV}$, the stau decay to the flaxino LSP never becomes dangerous for BBN. Furthermore, with the chosen parameter sets in the first case ($\tilde{\mu} = 12$), the stau decay length turns out to be $\mathcal{O}(1)\text{m}$ so that a fair number of stau decays can be captured in colliders when the axion scale is close to its lower bound, $F_a \sim 10^{10}\text{GeV}$. In the second case ($\tilde{\mu} = 34$), the flaxino LSP is naturally realized in the broad parameter space of the squark mass. Although the decay length is longer than $\mathcal{O}(10)\text{m}$, the additional detectors proposed by [34–36] will catch the staus even in this case.

Let us finally remark that, in our scheme, the unstable gravitino decaying to ordinary superparticle or flaxino does not contradict with BBN as the primordial gravitino abundance will be diluted away by the entropy production after thermal inflation caused by the flat direction in the model. A gravitino even lighter than the flaxino is also allowed since the flaxino decay to the gravitino and the axion causes no trouble with BBN.

Acknowledgments

This work was supported by the Science Research Center Program of the Korea Science

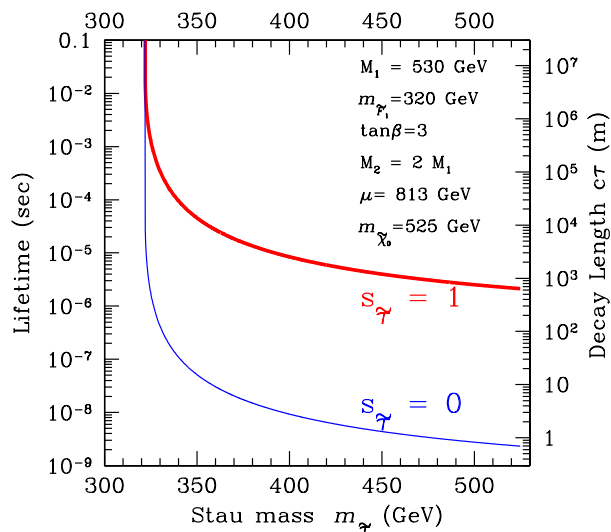


Figure 4: Same as figure 3 but for $\tilde{\mu}=34$ ($\mu = 813$ GeV) and $M_1 = 530$ GeV. Then, $m_{\tilde{F}_1} = 320$ GeV, and $m_{\tilde{N}_1} \simeq m_{\tilde{F}_2} = 525$ GeV.

and Engineering Foundation through the Center for Quantum Spacetime(CQeST) of Sogang University with grant number R11-2005-021 (H.B.K.). The research at Lancaster is supported by PPARC grant PP/D000394/1 and by EU grants MRTN-CT-2004-503369 and MRTN-CT-2006-035863, the European Union through the Marie Curie Research and Training Network "UniverseNet".

References

- [1] WMAP collaboration, D.N. Spergel et al., *Wilkinson Microwave Anisotropy Probe (WMAP) three year results: implications for cosmology*, *Astrophys. J. Suppl.* **170** (2007) 377.
- [2] S. Weinberg, *Cosmological constraints on the scale of supersymmetry breaking*, *Phys. Rev. Lett.* **48** (1982) 1303;
 J. Silk and A. Stebbins, *Decay of longlived particles in the early universe*, *Astrophys. J.* **269** (1983) 1;
 J.R. Ellis, J.E. Kim and D.V. Nanopoulos, *Cosmological gravitino regeneration and decay*, *Phys. Lett. B* **145** (1984) 181;
 D. Lindley, *Cosmological constraints on the lifetime of massive particles*, *Astrophys. J.* **294** (1985) 1;
 M.Y. Khlopov and A.D. Linde, *Is it easy to save the gravitino?*, *Phys. Lett. B* **138** (1984) 265;
 J.R. Ellis, D.V. Nanopoulos and S. Sarkar, *The cosmology of decaying gravitinos*, *Nucl. Phys. B* **259** (1985) 175;

- R. Juskiewicz, J. Silk and A. Stebbins, *Constraints on cosmologically regenerated gravitinos*, *Phys. Lett. B* **158** (1985) 463;
- J.R. Ellis, G.B. Gelmini, J.L. Lopez, D.V. Nanopoulos and S. Sarkar, *Astrophysical constraints on massive unstable neutral relic particles*, *Nucl. Phys. B* **373** (1992) 399;
- 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](#)];
- E. Holtmann, M. Kawasaki, K. Kohri and T. Moroi, *Radiative decay of a longlived particle and big bang nucleosynthesis*, *Phys. Rev. D* **60** (1999) 023506 [[hep-ph/9805405](#)];
- K. Jedamzik, *⁶Lithium: a probe of the early universe*, *Phys. Rev. Lett.* **84** (2000) 3248 [[astro-ph/9909445](#)];
- M. Kawasaki, K. Kohri and T. Moroi, *Radiative decay of a massive particle and the nonthermal process in primordial nucleosynthesis*, *Phys. Rev. D* **63** (2001) 103502 [[hep-ph/0012279](#)];
- R.H. Cyburt, J.R. Ellis, B.D. Fields and K.A. Olive, *Updated nucleosynthesis constraints on unstable relic particles*, *Phys. Rev. D* **67** (2003) 103521 [[astro-ph/0211258](#)];
- J.R. Ellis, K.A. Olive and E. Vangioni, *Effects of unstable particles on light-element abundances: lithium versus deuterium and He₃*, *Phys. Lett. B* **619** (2005) 30 [[astro-ph/0503023](#)].
- [3] M.H. Reno and D. Seckel, *Primordial nucleosynthesis: the effects of injecting hadrons*, *Phys. Rev. D* **37** (1988) 3441;
- 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;
- K. Kohri, *Primordial nucleosynthesis and hadronic decay of a massive particle with a relatively short lifetime*, *Phys. Rev. D* **64** (2001) 043515 [[astro-ph/0103411](#)].
- [4] 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](#)];
- Big-bang nucleosynthesis and hadronic decay of long-lived massive particles*, *Phys. Rev. D* **71** (2005) 083502 [[astro-ph/0408426](#)];
- K. Kohri, T. Moroi and A. Yotsuyanagi, *Big-bang nucleosynthesis with unstable gravitino and upper bound on the reheating temperature*, *Phys. Rev. D* **73** (2006) 123511 [[hep-ph/0507245](#)];
- K. Jedamzik, *Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles*, *Phys. Rev. D* **74** (2006) 103509 [[hep-ph/0604251](#)].
- [5] T. Moroi, H. Murayama and M. Yamaguchi, *Cosmological constraints on the light stable gravitino*, *Phys. Lett. B* **303** (1993) 289.
- [6] J.L. Feng, S. Su and F. Takayama, *Supergravity with a gravitino LSP*, *Phys. Rev. D* **70** (2004) 075019 [[hep-ph/0404231](#)].
- [7] F.D. Steffen, *Gravitino dark matter and cosmological constraints*, *JCAP* **09** (2006) 001 [[hep-ph/0605306](#)].
- [8] J.L. Feng, S.f. Su and F. Takayama, *SuperWIMP gravitino dark matter from slepton and sneutrino decays*, *Phys. Rev. D* **70** (2004) 063514 [[hep-ph/0404198](#)].
- [9] T. Kanzaki, M. Kawasaki, K. Kohri and T. Moroi, *Cosmological constraints on gravitino LSP scenario with sneutrino NLSP*, *Phys. Rev. D* **75** (2007) 025011 [[hep-ph/0609246](#)].
- [10] M. Pospelov, *Particle physics catalysis of thermal big bang nucleosynthesis*, *Phys. Rev. Lett.* **98** (2007) 231301 [[hep-ph/0605215](#)].

- [11] K. Kohri and F. Takayama, *Big bang nucleosynthesis with long lived charged massive particles*, *Phys. Rev. D* **76** (2007) 063507 [[hep-ph/0605243](#)].
- [12] M. Kaplinghat and A. Rajaraman, *Big bang nucleosynthesis with bound states of long-lived charged particles*, *Phys. Rev. D* **74** (2006) 103004 [[astro-ph/0606209](#)].
- [13] R.H. Cyburt, J.R. Ellis, B.D. Fields, K.A. Olive and V.C. Spanos, *Bound-state effects on light-element abundances in gravitino dark matter scenarios*, *JCAP* **11** (2006) 014 [[astro-ph/0608562](#)].
- [14] R.N. Cahn and S.L. Glashow, *Chemical signatures for superheavy elementary particles*, *Science* **213** (1981) 607;
R.N. Boyd, R.J. Perry, T.A. Miller and K. Takahashi, *Optimum chemical sites and techniques for searches for negatively charged rare particles*, *Science* **244** (1989) 1450;
A. De Rujula, S.L. Glashow and U. Sarid, *Charged dark matter*, *Nucl. Phys. B* **333** (1990) 173;
S. Dimopoulos, D. Eichler, R. Esmailzadeh and G.D. Starkman, *Getting a charge out of dark matter*, *Phys. Rev. D* **41** (1990) 2388.
- [15] D. Fargion, M. Khlopov and C.A. Stephan, *Cold dark matter by heavy double charged leptons?*, *Class. and Quant. Grav.* **23** (2006) 7305 [[astro-ph/0511789](#)];
M.Y. Khlopov and C.A. Stephan, *Composite dark matter with invisible light from almost-commutative geometry*, [astro-ph/0603187](#);
M.Y. Khlopov and C. Kouvaris, *Strong interactive massive particles from a strong coupled theory*, [arXiv:0710.2189](#).
- [16] K. Hamaguchi, T. Hatsuda, M. Kamimura, Y. Kino and T.T. Yanagida, *Stau-catalyzed ${}^6\text{Li}$ production in big-bang nucleosynthesis*, *Phys. Lett. B* **650** (2007) 268 [[hep-ph/0702274](#)].
- [17] M. Kawasaki, K. Kohri and T. Moroi, *Big-bang nucleosynthesis with long-lived charged slepton*, *Phys. Lett. B* **649** (2007) 436 [[hep-ph/0703122](#)].
- [18] C. Bird, K. Koopmans and M. Pospelov, *Primordial lithium abundance in catalyzed big bang nucleosynthesis*, [hep-ph/0703096](#).
- [19] J. Pradler and F.D. Steffen, *Constraints on the reheating temperature in gravitino dark matter scenarios*, *Phys. Lett. B* **648** (2007) 224 [[hep-ph/0612291](#)];
T. Jittoh et al., *Possible solution to the ${}^7\text{Li}$ problem by the long lived stau*, *Phys. Rev. D* **76** (2007) 125023 [[arXiv:0704.2914](#)];
S. Kasuya and F. Takahashi, *Entropy production by Q-ball decay for diluting long-lived charged particles*, *JCAP* **11** (2007) 019 [[arXiv:0709.2634](#)];
F. Takayama, *Extremely long-lived charged massive particles as a probe for reheating of the universe*, [arXiv:0704.2785](#);
J. Pradler and F.D. Steffen, *Implications of catalyzed BBN in the CMSSM with gravitino dark matter*, [arXiv:0710.2213](#);
N. Okada and O. Seto, *Gravitino dark matter from increased thermal relic particles*, [arXiv:0710.0449](#);
J. Kersten and K. Schmidt-Hoberg, *The gravitino-stau scenario after catalyzed BBN*, *JCAP* **01** (2008) 011 [[arXiv:0710.4528](#)];
- [20] W. Buchmuller, L. Covi, K. Hamaguchi, A. Ibarra and T. Yanagida, *Gravitino dark matter in R-parity breaking vacua*, *JHEP* **03** (2007) 037 [[hep-ph/0702184](#)].

- [21] K. Jedamzik, *The cosmic ${}^6\text{Li}$ and ${}^7\text{Li}$ problems and BBN with long-lived charged massive particles*, [arXiv:0707.2070](#); *Bounds on long-lived charged massive particles from big bang nucleosynthesis*, [arXiv:0710.5153](#);
M. Kusakabe, T. Kajino, R.N. Boyd, T. Yoshida and G.J. Mathews, *A simultaneous solution to the ${}^6\text{Li}$ and ${}^7\text{Li}$ big bang nucleosynthesis problems from a long-lived negatively-charged leptonic particle*, *Phys. Rev. D* **76** (2007) 121302 [[arXiv:0711.3854](#)].
- [22] J.E. Kim, *Weak interaction singlet and strong CP invariance*, *Phys. Rev. Lett.* **43** (1979) 103;
M.A. Shifman, V.I. Vainstein and V.I. Zakharov, *Can confinement ensure natural CP invariance of strong interactions?*, *Nucl. Phys. B* **166** (1980) 493.
- [23] M. Dine, W. Fischler and M. Srednicki, *A simple solution to the strong CP problem with a harmless axion*, *Phys. Lett. B* **104** (1981) 199;
A.R. Zhitnitsky, *On possible suppression of the axion hadron interactions*, *Sov. J. Nucl. Phys.* **31** (1980) 260 [*Yad. Fiz.* **31** (1980) 497].
- [24] J.E. Kim and H.P. Nilles, *The μ problem and the strong CP problem*, *Phys. Lett. B* **138** (1984) 150;
E.J. Chun, J.E. Kim and H.P. Nilles, *A natural solution of the μ problem with a composite axion in the hidden sector*, *Nucl. Phys. B* **370** (1992) 105.
- [25] H. Murayama, H. Suzuki and T. Yanagida, *Radiative breaking of Peccei-Quinn symmetry at the intermediate mass scale*, *Phys. Lett. B* **291** (1992) 418.
- [26] K. Choi, E.J. Chun and J.E. Kim, *Cosmological implications of radiatively generated axion scale*, *Phys. Lett. B* **403** (1997) 209 [[hep-ph/9608222](#)].
- [27] E.J. Chun, D. Comelli and D.H. Lyth, *The abundance of relativistic axions in a flaton model of Peccei-Quinn symmetry*, *Phys. Rev. D* **62** (2000) 095013 [[hep-ph/0008133](#)].
- [28] E.J. Chun, H.B. Kim and D.H. Lyth, *Cosmological constraints on a Peccei-Quinn flatino as the lightest supersymmetric particle*, *Phys. Rev. D* **62** (2000) 125001 [[hep-ph/0008139](#)].
- [29] D.H. Lyth and E.D. Stewart, *Cosmology with a TeV mass GUT Higgs*, *Phys. Rev. Lett.* **75** (1995) 201 [[hep-ph/9502417](#)];
Thermal inflation and the moduli problem, *Phys. Rev. D* **53** (1996) 1784 [[hep-ph/9510204](#)].
- [30] S.P. Martin, *Collider signals from slow decays in supersymmetric models with an intermediate-scale solution to the μ problem*, *Phys. Rev. D* **62** (2000) 095008 [[hep-ph/0005116](#)].
- [31] 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*, *JHEP* **05** (2001) 033.
- [32] A. Brandenburg and F.D. Steffen, *Axino dark matter from thermal production*, *JCAP* **08** (2004) 008 [[hep-ph/0405158](#)].
- [33] L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, *Axino dark matter and the CMSSM*, *JHEP* **06** (2004) 003 [[hep-ph/0402240](#)];
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](#)].
- [34] K. Hamaguchi, Y. Kuno, T. Nakaya and M.M. Nojiri, *A study of late decaying charged particles at future colliders*, *Phys. Rev. D* **70** (2004) 115007 [[hep-ph/0409248](#)].

- [35] J.L. Feng and B.T. Smith, *Slepton trapping at the large hadron and international linear colliders*, *Phys. Rev. D* **71** (2005) 015004 [*Erratum ibid.* **D 71** (2005) 0109904] [[hep-ph/0409278](#)].
- [36] A. De Roeck, J.R. Ellis, F. Gianotti, F. Moortgat, K.A. Olive and L. Pape, *Supersymmetric benchmarks with non-universal scalar masses or gravitino dark matter*, *Eur. Phys. J. C* **49** (2007) 1041 [[hep-ph/0508198](#)].
- [37] L. Roszkowski and O. Seto, *Axino dark matter from Q -balls in Affleck-Dine baryogenesis and the $\Omega_b - \Omega_{DM}$ coincidence problem*, *Phys. Rev. Lett.* **98** (2007) 161304 [[hep-ph/0608013](#)];
O. Seto and M. Yamaguchi, *Axino warm dark matter and $\Omega_b - \Omega_{DM}$ coincidence*, *Phys. Rev. D* **75** (2007) 123506 [[arXiv:0704.0510](#)].
- [38] M. Kawasaki, K. Nakayama and M. Senami, *Cosmological implications of supersymmetric axion models*, *JCAP* **03** (2008) 009 [[arXiv:0711.3083](#)].
- [39] K.-Y. Choi, J.E. Kim, H.M. Lee and O. Seto, *Neutralino dark matter from heavy axino decay*, [arXiv:0801.0491](#).
- [40] T. Asaka and T. Yanagida, *Solving the gravitino problem by axino*, *Phys. Lett. B* **494** (2000) 297 [[hep-ph/0006211](#)].
- [41] E.W. Kolb and M.S. Turner, *The early universe*, Addison-Wesley, Reading MA U.S.A. (1989).
- [42] D. Grin, T.L. Smith and M. Kamionkowski, *Axion constraints in non-standard thermal histories*, [arXiv:0711.1352](#).