DESY 14-114
July, 2014

Axino Dark Matter in Moduli-induced Baryogenesis

Koji Ishiwata

Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany

Abstract

We consider axino dark matter in large R-parity violation (RPV). In moduli-dominated universe, axino is produced thermally or non-thermally via saxion decay, then late-decaying moduli dilute axino density, which results in the right abundance to explain the present dark matter. At the same time baryon asymmetry is generated due to moduli-induced baryogenesis via the large RPV. Axino is cosmologically stable in spite of the large RPV since its decay rate is suppressed by the axion decay constant, heavy squark mass or kinematics.

1 Introduction

The discovery of the Higgs boson at the LHC confirmed the standard model of particle physics [1, 2]. So far no phenomenon, which shows severe inconsistency with the standard model (SM), has been reported on the ground-based experiments (except for neutrino oscillation). In cosmology, however, it is clear that we need new physics beyond the standard model. First of all, the standard cosmology can not explain the existence of dark matter (DM). In addition, the baryon density predicted in the standard model is too small to account for the observed value. Supersymmetry (SUSY) is a promising solution to the issues. On top of that, string theory, which requires supersymmetry for the consistency, is a viable candidate for the theory of everything.

However, such an extension may cause another problem especially in cosmology. Moduli fields, which must be stabilized to compactify the extra dimensions in string theory, may be destabilized during inflation if the inflation scale is very high, which is indicated by the recent BICEP2 observation [3]. Even if the destabilization is avoided in some ways [4, 5], it is likely that moduli are displaced far from their true minima at the end of inflation. Then moduli start to oscillate, and soon dominate the energy density of the universe. The moduli-dominated universe ends when moduli decay, accompanying a huge entropy injection. This is potentially problematic because such substantial an entropy production dilutes pre-existing matter density, then it is difficult to lead to big bang nucleosynthesis (BBN) and the structure formation of the universe. Possible way out are following: production of a large amount of the matter density before moduli decay or generation of the matter density after moduli decay. As for baryonic matter, Affleck-Dine mechanism [6, 7] is a typical example of the former one. On the other hand, late-decaying gravitino [8] or saxion [9] can also produce baryon asymmetry, which corresponds to the latter. Recently another mechanism, moduli-induced baryogenesis, was proposed [10]. It was shown that Kachru-Kallosh-Linde-Trivedi scenario [11] has built-in features for baryogenesis, such as large enough CP phase and suitable mass spectrum for superparticles. Then subsequent decays of gluino and squarks from moduli produce sufficient baryon asymmetry. In those baryogenesis due to late-decaying particle, however, a large R-parity violation (RPV) is assumed, which makes lightest superparticle (LSP) unstable. This is a downside to accounting for dark matter.

In this paper we consider axino LSP in large R-parity violation. Introducing the axion supermultiplet is motivated by Peccei-Quinn (PQ) mechanism [12], which solves the strong CP problem. Assuming that the fermionic component of the axion multiplet, axino, is the LSP, axino is copiously produced by its radial component, saxion, decay and the scattering from thermal plasma. Axino can be cosmologically stable even if the RPV is $O(1)$ because its decay rate is suppressed by the axion decay constant, squark mass or kinematics. After saxion decay, moduli decay follows to dilute axino abundance, which results in the observed relic of dark matter. At the same time, baryon asymmetry of the universe is generated in moduli-induced baryogenesis with the RPV.

2 Cosmological scenario

In this section we describe the basic picture of our scenario. In the scenario moduli dominate the total energy of the universe after inflation. Axino is produced thermally or by non-thermal saxion decay in the epoch of moduli domination. Eventually moduli decay and dilute the axino abundance, which gives the right value to explain DM. Here baryon asymmetry is generated from moduli decay as well due to R-parity violated interaction. The saxion decay also generates axion. Although it is diluted by moduli decay, the produced axion may give a sizable contribution to radiation as dark radiation. Finally the stability of axino under the RPV is discussed.

2.1 Moduli-dominated universe

Let us begin with the thermal history after inflation. As we mentioned in the Introduction, the modulus field tends to be displaced from its true minimum due to the deformed potential during inflation or due to the initial condition. Then after inflation, it starts to oscillate around the true minimum when the Hubble parameter H reduces to moduli mass m_X. Assuming T_R, the reheating temperature after inflation, is comparable to $T_{X,\rm osc}$, the temperature when modulus begins to oscillate, the energy density of modulus field X per entropy density freezes after the oscillation starts at a value of

$$\frac{\rho_X(T)}{s(T)} = \frac{1}{8}T_{X,\rm osc}\left(\frac{\delta X_{\rm ini}}{M_{\rm Pl}}\right)^2 \equiv \left[\frac{\rho_X}{s}\right]_{\rm osc}. \tag{2.1}$$

Here T is the cosmic temperature, ρ_X is the energy density of modulus, $s(T)$ is the entropy density and $\delta X_{\rm ini}$ is the initial amplitude of X measured from its true minimum. Typically we expect $\delta X_{\rm ini} \sim M_{\rm Pl}$ where $M_{\rm Pl} \simeq 2.4 \times 10^{18}\,{\rm GeV}$ is the reduced Planck mass. $T_{X,{\rm osc}}$ is estimated from the equation $H \simeq m_X$ as

$$\begin{aligned} T_{X,{\rm osc}} &= \left[\frac{90}{\pi^2 g_*(T_{X,{\rm osc}})}\right]^{1/4} \sqrt{M_{\rm Pl} m_X} \\ &\simeq 6.9 \times 10^{13}\,{\rm GeV} \left(\frac{m_X}{10^{10}\,{\rm GeV}}\right)^{1/2}. \end{aligned} \tag{2.2}$$

Here $g_*(T)$ counts degree of freedom of relativistic particles in the thermal bath. Due to their huge energy density, moduli soon dominate the energy density of the universe. The temperature when moduli begin to dominate the universe is estimated from the relation $\rho_X \simeq \rho_R$ as

$$T_{\rm dom} \simeq \frac{1}{6} T_{X,{\rm osc}} \left(\frac{\delta X_{\rm ini}}{M_{\rm Pl}}\right)^2, \tag{2.3}$$

where we have used Eq. (2.1). It is seen moduli dominate the total energy density soon after starting to oscillate.

Since the energy density of moduli redshift as $\rho_X \propto a^{-3}$, it is given by

$$\rho_X(T) = \left[\frac{\rho_X}{s}\right]_{\rm osc} s(T), \tag{2.4}$$

until moduli decay. As $\rho_{\rm tot}$, the total energy density of the universe, is equal to ρ_X during moduli domination, the Hubble parameter in moduli-dominated universe is given by

$$H \simeq \sqrt{\frac{\rho_{\rm tot}}{3M_{\rm Pl}^2}} \simeq \frac{\sqrt{T_{\rm dom} s(T)}}{2M_{\rm Pl}}. \tag{2.5}$$

The epoch of moduli domination terminates when moduli decay to particles in minimal supersymmetric standard model (MSSM), and it turns into radiation domination. The temperature at the beginning of this radiation-dominated universe is determined by $H \simeq \Gamma_X$ as

$$\begin{aligned} T_X &= \left[\frac{90}{\pi^2 g_*(T_X)}\right]^{1/4} \sqrt{M_{\rm Pl} \Gamma_X} \\ &\simeq 9.8 \times 10^{4}\,{\rm GeV} \left(\frac{m_X}{10^{10}\,{\rm GeV}}\right)^{3/2}. \end{aligned} \tag{2.6}$$

Here we have used the decay rate of moduli, which is given by [13]

$$\Gamma_X \simeq \frac{c_X}{4\pi} \frac{m_X^3}{M_{\rm Pl}^2}, \tag{2.7}$$

where c_X is $O(1)$ constant and here and hereafter we take it as unity.[#1] The moduli masses have to be larger than around 100 TeV in order not to destroy BBN. Even if $m_X \gtrsim 100$ TeV is satisfied, however, a huge entropy production due to moduli decay may strongly dilute primordial relics, such as baryon and DM. The effect is described by a dilution factor, which is given by a ratio of entropy density before and after the moduli decay,

$$\begin{aligned} d_X &= \frac{3}{4} T_X \left[\frac{\rho_X}{s}\right]_{\rm osc}^{-1} = 6 \, \frac{T_X}{T_{X,\rm osc}} \left(\frac{M_{\rm Pl}}{\delta X_{\rm ini}}\right)^2 \\ &\simeq 8.5 \times 10^{-9} \left(\frac{m_X}{10^{10}\,\rm GeV}\right) \left(\frac{M_{\rm Pl}}{\delta X_{\rm ini}}\right)^2 . \end{aligned} \tag{2.8}$$

The dilution is important to reduce over-produced axino (and axion), which is discussed below.

2.2 Saxion decay

Saxion is the radial component field in the axion supermultiplet. The axion supermultiplet is determined as a flat direction of the scalar potential given by the PQ fields. Here the PQ fields have non-zero PQ charges and break PQ symmetry spontaneously. We define the axion supermultiplet as

$$A = \frac{1}{\sqrt{2}}(\sigma + i\,a) + \sqrt{2}\theta\tilde{a} + F\text{-term}. \tag{2.9}$$

Here σ, a and $\tilde{a}$ are saxion, axion and axino, respectively. For later calculation we define the axion decay constant as $f_a = \sqrt{2\sum_i q_i^2 v_i^2}$ where q_i and $v_i = \langle \Phi_i \rangle$ are the PQ charge and the vacuum expectation value (VEV) of a PQ field Φ_i, respectively. If the domain wall number $N_{\rm DW}$ is not unity, then f_a should be $\sqrt{2\sum_i q_i^2 v_i^2}/N_{\rm DW}$.

Similar to moduli, saxion tends to have initial amplitude around its true minimum after inflation then it starts oscillation when $H \simeq m_\sigma$ (m_σ is saxion mass). Around this period, moduli begin to dominate the total energy. If saxion starts to oscillate before moduli domination, the temperature at the beginning of the oscillation is given by

$$T_{\sigma,\rm osc} \simeq \left[\frac{90}{\pi^2 g_*(T_{\sigma,\rm osc})}\right]^{1/4} \sqrt{M_{\rm Pl} m_\sigma}, \tag{2.10}$$

and its energy density to entropy ratio is fixed at

$$\left[\frac{\rho_\sigma}{s}\right]_{\rm osc} = \frac{1}{8} T_{\sigma,\rm osc} \left(\frac{\delta\sigma_{\rm ini}}{M_{\rm Pl}}\right)^2 . \tag{2.11}$$

[#1] In the numerical analysis, we use the results given in Ref. [10].

Here $\delta\sigma_{\rm ini}$ is the saxion initial amplitude, which is expected to be order of f_a to $M_{\rm Pl}$. The value depends on the saxion potential (see, *e.g.*, Refs. [14, 15, 16]). On the other hand, saxion starts to oscillate after the universe is dominated by moduli when $T_{\sigma,\rm osc} < T_{\rm dom}$. In such a case, saxion energy density per entropy density has a fixed value

$$\left[\frac{\rho_\sigma}{s}\right]_{\rm osc} = \frac{1}{8} T_{\rm dom} \left(\frac{\delta\sigma_{\rm ini}}{M_{\rm Pl}}\right)^2. \tag{2.12}$$

In our scenario we consider m_X is relatively larger than m_σ. Then the energy density of moduli is much larger than that of saxion during the period of moduli domination in either case.

After the coherent oscillation, saxion decays to lighter particles. The decay rate depends on axion model, *i.e.*, Kim-Shifman-Vainshtein-Zakharov (KSVZ) (or hadronic axion) model [17] or Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) model [18]. In both KSVZ and DFSZ models saxion couples to axino and axion via the kinetic term, which is given as [19]

$$\mathcal{L}_\sigma = \left(1 + \frac{2\xi}{f_a}\sigma\right) \left[\frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu a)^2 + \frac{1}{2}\bar{\tilde{a}} i \partial\!\!\!/ \tilde{a}\right], \tag{2.13}$$

where $\xi = 2\sum_i q_i^3 v_i^2 / f_a^2$. Here we have used $\tilde{a}$ as a four component axino spinor. From this interaction, the partial decay widths for $\sigma \to aa$ and $\sigma \to \tilde{a}\tilde{a}$ are computed as

$$\Gamma(\sigma \to aa) = \frac{\xi^2}{32\pi} \frac{m_\sigma^3}{f_a^2}, \tag{2.14}$$

$$\Gamma(\sigma \to \tilde{a}\tilde{a}) = \frac{\xi^2}{4\pi} \frac{m_\sigma m_{\tilde{a}}^2}{f_a^2} \left(1 - 4\frac{m_{\tilde{a}}^2}{m_\sigma^2}\right)^{3/2}, \tag{2.15}$$

where $m_{\tilde{a}}$ is axino mass. In KSVZ model, the process $\sigma \to aa$ overwhelms the other decay modes if $\xi \sim O(1)$. We take $\xi = 1$ unless otherwise noted. Then the total decay rate is given by $\Gamma_\sigma \simeq \Gamma(\sigma \to aa)$.[#2] On the other hand, in DFSZ model, saxion interacts with Higgs doublets in F-term potential. Then saxion can decay to the SM-like Higgs pair, whose partial decay width is

$$\Gamma(\sigma \to hh) = \frac{k_\sigma}{4\pi} \frac{\mu^4}{f_a^2 m_\sigma} \left(1 - 4\frac{m_h^2}{m_\sigma^2}\right)^{1/2}, \tag{2.16}$$

[#2]There exist the decay modes to gauge bosons. However, they are sub-dominant since they are suppressed by gauge coupling constant and the loop factor.

where k_σ is $O(1)$ constant, which is taken to be unity in the later numerical evaluation, and μ is the μ parameter in the MSSM superpotential.[#3] This decay mode dominates the total decay rate if $\mu \gtrsim m_\sigma$. Saxion can also decays to sfermion pairs if kinematically allowed. The decay rate for the process, however, is suppressed by $\langle H_{u(d)} \rangle^2/\mu^2$ times Yukawa coupling constant squared. ($\langle H_{u(d)} \rangle$ is the VEV of up (down)-type Higgs.) Thus we ignore it. For later calculation, we define the branching fraction for axino pair production as

$$\mathrm{Br}(\sigma \to \tilde{a}\tilde{a}) = \frac{\Gamma(\sigma \to \tilde{a}\tilde{a})}{\Gamma_\sigma}. \tag{2.17}$$

In KSVZ model, the branching ratio is simply given by $\mathrm{Br}(\sigma \to \tilde{a}\tilde{a}) \simeq 8m_{\tilde{a}}^2/m_\sigma^2$ in the limit $m_\sigma \gg m_{\tilde{a}}$. This is also true in DFSZ model when $\mu \lesssim m_\sigma$.

2.3 Axino production

Axino is the fermionic component in the axion supermultiplet. Axino can be produced in several ways; thermal production, non-thermal saxion decay or the next-LSP (NLSP) decay. The production due to the NLSP decay is negligible because the NLSP mainly decays to the SM particles via RPV. The other two, *i.e.*, saxion decay and thermal production, are potentially important. In terms of yield variable $Y_{\tilde{a}} \equiv n_{\tilde{a}}/s$ ($n_{\tilde{a}}$ is the number density of axino), the resultant abundance of axino is expressed as,

$$Y_{\tilde{a}} = Y_{\tilde{a}}^{\mathrm{DEC}} + Y_{\tilde{a}}^{\mathrm{TH}}, \tag{2.18}$$

where $Y_{\tilde{a}}^{\mathrm{DEC}}$ and $Y_{\tilde{a}}^{\mathrm{TH}}$ are contributions from saxion decay and thermal production, respectively.

$Y_{\tilde{a}}^{\mathrm{DEC}}$ is easily obtained. Using Eqs. (2.11) and (2.12), the present axino density due to saxion decay is given by

$$Y_{\tilde{a}}^{\mathrm{DEC}} = \frac{1}{4} d_X \frac{\max\{T_{\sigma,\mathrm{osc}}, T_{\mathrm{dom}}\}}{m_\sigma} \left(\frac{\delta\sigma_{\mathrm{ini}}}{M_{\mathrm{Pl}}}\right)^2 \mathrm{Br}(\sigma \to \tilde{a}\tilde{a}). \tag{2.19}$$

Here we note that the produced axino is diluted due to the late-decaying moduli, which is taken into account by the dilution factor d_X. There is an entropy production due to saxion decay. However, it is much smaller than the entropy production from

[#3] Suppose there are two PQ fields, Φ_1 and Φ_2, and both of them get VEVs as $\langle \Phi_1 \rangle = \langle \Phi_2 \rangle$. If Φ_1 couples to up- and down-type Higgses (denoted as H_u and H_d, respectively) in superpotential, $\lambda \Phi_1 H_u H_d$ ($\lambda(\Phi_1^2/M_{\mathrm{Pl}}) H_u H_d$), then $\mu = \lambda \langle \Phi_1 \rangle$ ($\lambda \langle \Phi_1 \rangle^2/M_{\mathrm{Pl}}$) and $k_\sigma = 1$ (2).

moduli. This is because saxion decays before moduli, the energy density of saxion is smaller than that of moduli and that the branching fraction to the MSSM-sector particles in saxion decay is typically suppressed. Therefore, the dilution due to saxion decay is negligible compared to moduli decay.

The thermal production, on the other hand, is highly model-dependent. It is described by Boltzmann equation,

$$\dot{n}_{\tilde{a}} + 3Hn_{\tilde{a}} = C_{\rm prd}. \tag{2.20}$$

Here a dot means derivative with respect to the cosmic time and $C_{\rm prd}$ is axino production rate per unit volume, which depends on the axion model. The solution of the Boltzmann equation in radiation domination is given by (using $\dot{T} = -HT$)

$$Y_{\tilde{a}}^{\rm TH} = \int dT \frac{C_{\rm prd}}{s(T)HT}. \tag{2.21}$$

In KSVZ model, axino is mainly produced by thermal scattering or decay of the particles in thermal plasma via strong interaction. For example, the production rate due to scattering processes, such as $\tilde{q}g \to \tilde{a}q$, $\tilde{g}g \to \tilde{a}g$, is roughly estimated as $C_{\rm prd} \sim \frac{\alpha_s^3}{f_a^2} n_{\rm MSSM}^2$ at high temperature. (α_s is strong coupling constant and $n_{\rm MSSM}$ is the number density of the MSSM particle.) Then from Eq. (2.21) the yield variable of axino is estimated as

$$Y_{\tilde{a},{\rm KSVZ}}^{\rm th} \sim O(10^{-3}) \times \frac{\alpha_s^3 M_{\rm Pl} T_R}{f_a^2}. \tag{2.22}$$

It is seen that the axino production is the most active at the highest temperature of the universe, *i.e.*, T_R.[#4] Thus the axino abundance is almost determined by the production from thermal plasma before moduli dominates the total energy, which guarantees that we have used Eq. (2.21). More precise computation of the axino production in radiation domination is done by Refs. [20, 21, 22, 23, 24]. In our later numerical calculation we adopt the result given in Ref. [22] and fit their result as

$$Y_{\tilde{a},{\rm KSVZ}}^{\rm th} \simeq \min\left\{ Y_{\tilde{a}}^{\rm eq},\ 4 \times 10^{-3} \alpha_s^3 \log(0.1/\alpha_s) \left(\frac{T_R}{10^4\ {\rm GeV}}\right) \left(\frac{10^{11}\ {\rm GeV}}{f_a}\right)^2 \right\}, \tag{2.23}$$

where only QCD interaction is considered.[#5] It is seen that the estimate given in Eq. (2.22) roughly agrees with the expression. $Y_{\tilde{a}}^{\rm eq}$ is the value when axion is

[#4] Saxion decay reheats radiation during moduli domination. If the reheating temperature exceeds squark or gluino mass, then axino is also produced at the time of saxion decay. The production is, however, negligible since the reheating temperature is much smaller than T_R and that the production is suppressed by $T_{\rm dom}$ (see also later discussion).

[#5] The fitting formula is applicable where $T_R \gtrsim 10^4$ GeV and gluino or squarks are thermalized.

thermalized, and typically $Y_{\tilde{a}}^{\rm eq} \simeq 1.8 \times 10^{-3}$ using $g_* = 228.75$. The decoupling temperature T_D can be estimated by equating the scattering rate for the production process with the Hubble parameter and it is obtained as

$$T_D^{\rm KSVZ} \sim 10^8 {\rm GeV} \left(\frac{f_a}{10^{11}\,{\rm GeV}}\right)^2 \left(\frac{0.04}{\alpha_s}\right)^3, \tag{2.24}$$

which is consistent with Ref. [25]. Then axino is thermalized when $T_R \gtrsim T_D^{\rm KSVZ}$. Since we assume $T_R \sim T_{X,{\rm osc}}$, axino is thermalized in a wide range of the parameter space.

Thermal production of axino in DFSZ model is different from the one in KSVZ model. As it is mentioned in Refs. [26, 27, 28, 22], the scattering process via strong interaction is suppressed at high temperature. Instead, the production due to axino interaction with Higgs and Higgsino or stop and top is effective. For example, the production rate for the processes, such as $\tilde{H}t \to \tilde{a}t$, $\tilde{t}\bar{t} \to \tilde{a}h$, is roughly $C_{\rm prd} \sim \frac{\mu^2}{\pi f_a^2 T^2} n_{\rm MSSM}^2$. Thus axino production occurs mainly in a lower temperature regime. From this fact axino is produced after moduli dominates the total energy. The solution given in Eq. (2.21) can be used for the axino production, except for using Eq. (2.5) for the Hubble parameter. As a result, the yield variable of axino during the epoch of moduli domination is roughly obtained as

$$Y_{\tilde{a},{\rm DFSZ}}^{\rm th}\Big|_{\rm XD} \sim O(10^{-4}) \times \frac{\mu^2}{f_a^2} \frac{M_{\rm Pl}}{\sqrt{T_{\rm dom}\mu}}. \tag{2.25}$$

The contribution from decay gives the same order. Here we have assumed that $T_R > \mu$. It is seen that the resultant abundance is highly suppressed by $T_{\rm dom}$. In addition, it is diluted by the late moduli decay. Thus the contribution of the thermal production to axino abundance before moduli decay is negligible in a wide parameter range.[#6]

Axino is also produced in the era of radiation domination after moduli decay. Here T_X plays the role of T_R in the above discussion. In KSVZ model, however, the axino production is negligible because T_X is smaller than gluino or squark mass in a wide parameter region, *i.e.*, processes, such as $gg \to \tilde{a}\tilde{g}$, $qg \to \tilde{a}\tilde{q}$, are kinematically suppressed and gluino and squarks are not thermalized.[#7] On the other hand, in

[#6] Axino thermal production occurs after saxion decay if the decay reheats radiation to a temperature larger than μ. The production results in the same order of yield variable given in Eq. (2.25). Therefore it is negligible for the same reason.

[#7] This fact is crucial for moduli-induced baryogenesis. Otherwise produced baryon would be washed out. Axino can be produced via RPV interaction, such as $qq \to \tilde{a}q$. We have checked that this production is negligible in the parameter region that we are interested in.

DFSZ model, axino production may be substantial since the production is effective at low temperature. The processes without external stop, such as $\tilde{H}t \to \tilde{a}t$ or $\tilde{H} \to \tilde{a}h$, contribute to the production because the number density of stop is Boltzmann-suppressed. Here we assume $T_X > \mu$. Then the production due to the scattering leads to axino yield variable after moduli decay

$$Y^{\rm th}_{\tilde{a},{\rm DFSZ}}\Big|_{\rm RD} \sim O(10^{-4}) \times \frac{M_{\rm Pl}\mu}{f_a^2}. \tag{2.26}$$

The contribution of Higgsino decay has the same order as one from the scattering. The above result roughly agrees with more accurate numerical calculation in the literature. Using the recent result given in Ref. [28], the yield variable of axino is read as[#8]

$$Y^{\rm th}_{\tilde{a},{\rm DFSZ}} \simeq \min\left\{ Y^{\rm eq}_{\tilde{a}},\ 10^{-5}\left(\frac{\mu}{1\ {\rm TeV}}\right)\left(\frac{10^{11}\ {\rm GeV}}{f_a}\right)^2 \right\}. \tag{2.27}$$

Here axino is thermalized when $T_D^{\rm DFSZ} \gtrsim \mu$, where decoupling temperature $T_D^{\rm DFSZ}$ is given by

$$T_D^{\rm DFSZ} \sim M_{\rm Pl}\frac{\mu^2}{f_a^2}. \tag{2.28}$$

Then the condition for axino thermalization becomes $\mu \gtrsim 10^4\,{\rm GeV}\,(f_a/10^{11}\,{\rm GeV})^2$. This estimate is roughly consistent with Eq. (2.27).

In summary, axino yield variable due to the thermal production is given by

$$Y^{\rm TH}_{\tilde{a}} = \begin{cases} d_X Y^{\rm th}_{\tilde{a},{\rm KSVZ}} & ({\rm KSVZ}) \\ Y^{\rm th}_{\tilde{a},{\rm DFSZ}} & ({\rm DFSZ}) \end{cases}. \tag{2.29}$$

Then the density parameter of axino at present time is obtained by

$$\Omega_{\tilde{a}} = m_{\tilde{a}} Y_{\tilde{a}}\,(\rho_c/s)_0^{-1} = \Omega^{\rm DEC}_{\tilde{a}} + \Omega^{\rm TH}_{\tilde{a}}, \tag{2.30}$$

where $(\rho_c/s)_0 \simeq 3.6\,h^2 \times 10^{-9}\,{\rm GeV}$ for $h \simeq 0.67$ [29]. Here we have split two contributions for later convenience. For example, in KSVZ model, they are typically

$$\begin{aligned} \Omega^{\rm DEC}_{\tilde{a}}h^2 &\simeq 0.43 \times \left(\frac{m_{\tilde{a}}}{20\ {\rm GeV}}\right)^3 \left(\frac{10^6\ {\rm GeV}}{m_\sigma}\right)^3 \left(\frac{m_X}{10^{10}\ {\rm GeV}}\right)^{3/2} \left(\frac{\delta\sigma_{\rm ini}}{M_{\rm Pl}}\right)^2, && (2.31) \\ \Omega^{\rm TH}_{\tilde{a}}h^2 &\simeq 0.084 \times \left(\frac{m_{\tilde{a}}}{20\ {\rm GeV}}\right)\left(\frac{m_X}{10^{10}\ {\rm GeV}}\right)\left(\frac{M_{\rm Pl}}{\delta X_{\rm ini}}\right)^2. && (2.32) \end{aligned}$$

Here we have used $T_{\rm dom}$ and $Y^{\rm eq}_{\tilde{a}}$ in the estimation of $\Omega^{\rm DEC}_{\tilde{a}}$ and $\Omega^{\rm TH}_{\tilde{a}}$, respectively. The expression of $\Omega^{\rm DEC}_{\tilde{a}}$ can be applied in DFSZ model when $\mu \lesssim m_\sigma$.

[#8] In Ref. [28], the result is given for the case relativistic stop is in thermal bath and its mass is larger than μ. In such a case the yield variable is proportional to $\frac{M_{\rm Pl}\mu^2}{f_a^2 m_{\tilde{t}}}$.

2.4 Axion production

We have seen that saxion mainly decays to axion pair. The produced axion is relativistic thus behaves as radiation, which is so-called dark radiation. The additional degree of freedom in radiation is described in terms of the effective number of neutrinos $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$. Here $N_{\rm eff}^{\rm SM} = 3.046$ [30] is the prediction in the standard model. The result by Planck satellite [29], combined with the measurements of the present Hubble parameter by Hubble Space Telescope [31], gives $N_{\rm eff} = 3.83 \pm 0.54$ at 95% C.L.. When the data from WMAP9 [32], the Atacama Cosmology Telescope [33] and the South Pole Telescope [34, 35] are included, the analysis gives $N_{\rm eff} = 3.62^{+0.50}_{-0.48}$ at 95% C.L. [29]. Though the current observations are consistent with the SM value, the central values are slightly deviated from the SM prediction. We will see below that $\Delta N_{\rm eff}$ can be $O(1)$ in our scenario.

Referring to Refs. [36, 37], $\Delta N_{\rm eff}$ in our scenario is given by

$$\Delta N_{\rm eff} = 3 \left[\frac{\rho_a}{\rho_\nu}\right]_{\nu\,{\rm decp}} = \frac{43}{7}\left(\frac{10.75}{g_*(T_X)}\right)^{1/3}\left[\frac{\rho_a}{\rho_R}\right]_{X\,{\rm dec}}. \tag{2.33}$$

Here ρ_ν and ρ_a are the energy density of neutrinos and axion, respectively, and "ν decp" means the values at neutrino decoupling. $[\rho_a/\rho_R]_{X\,{\rm dec}}$ is the ratio of the energy density of axion produced by saxion and radiation at the time of moduli decay. Using $\rho_\sigma \simeq \rho_a$ at the time of saxion decay, it is straightforward to get

$$\left[\frac{\rho_a}{\rho_R}\right]_{X\,{\rm dec}} = \frac{4}{3} d_X \frac{[\rho_\sigma/s]_{\rm osc}}{T_X}\left(\frac{\Gamma_X}{\Gamma_\sigma}\right)^{2/3} \tag{2.34}$$

Assuming $\Gamma_\sigma \simeq \Gamma(\sigma \to aa)$ and using Eq. (2.12), $\Delta N_{\rm eff}$ is estimates as

$$\Delta N_{\rm eff} \simeq 0.028 \left(\frac{10^{10}\,{\rm GeV}}{m_X}\right)^2 \left(\frac{m_\sigma}{10^6\,{\rm GeV}}\right)^2 \left(\frac{f_a/\xi}{10^{11}\,{\rm GeV}}\right)^{4/3} \left(\frac{\delta\sigma_{\rm ini}}{M_{\rm Pl}}\right)^2. \tag{2.35}$$

In this paper we impose a conservative bound $\Delta N_{\rm eff} \lesssim 1$ on our scenario.

Axion is also produced by coherent oscillation when the Hubble parameter becomes comparable to axion mass. If moduli decays before the axion coherent oscillation, the abundance of the axion due to the oscillation is the conventional value given in Ref. [38], *i.e.*, $\Omega_a^{\rm c.o.} h^2 \simeq 0.2\theta_a^2 (f_a/10^{12}\,{\rm GeV})^{1.19}$. Here θ_a is the initial misalignment angle of axion and it should be small in order for axion not to overclose the universe if $f_a \gtrsim 10^{12}$ GeV. The tuning of θ_a is possible when PQ symmetry is broken during or before inflation. Meanwhile, if PQ symmetry is broken after inflation, the misalignment angle should be replaced by $\pi/\sqrt{3}$. Then the tuning is impossible and f_a is severely constrained.[#9] In the case where moduli decay after the coherent oscillation begins, the axion abundance is diluted by moduli decay. Similar case is discussed in Ref. [14]. Since the axion abundance is model-dependent and that we are interested in the axino DM scenario, we simply assume that the axion energy density due to the coherent oscillation is sub-dominant. It is straightforward to take into account the axion abundance from the coherent oscillation and consider mixed axion and axino DM.

2.5 Axino stability

In our model we consider RPV for moduli-induced baryogenesis. Through RPV interaction, axino decays to SM particles even if it is the LSP. The renormalizable RPV interaction in superpotential is

$$W_{\not{R}_p} = \mu_i L_i H_u + \lambda_{ijk} Q_i L_j D_k^c + \lambda'_{ijk} L_i L_j E_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c, \tag{2.36}$$

where L_i, E_i^c, Q_i, U_i^c, D_i^c are chiral superfields of left-handed lepton doublet, right-handed charged lepton, left-handed quark doublet, right-handed up-type quark, right-handed down-type quark, respectively. i, j, k are generation indices. In the present paper, we will take phenomenological approach to determine the order of each RPV couplings as follows. In our model baryon asymmetry is generated through the RPV interaction. Among the four types of interactions, $U^c D^c D^c$ type is the most effective for moduli-induced baryogenesis.[#10] For example, λ''_{332} can be order of unity evading from the severe constraint from proton decay, and generate the observed baryon asymmetry [10]. The other couplings are partly constrained phenomenologically (see, *e.g.*, Ref. [42]). Based on the facts, we simply consider a case where at least one of λ''_{ijk} is $O(1)$ and the others are irrelevant.[#11]

Axino lifetime is determined by the process $\tilde{a} \to u_i d_j d_k$. Relevant interaction for this process is dimension four axino-quark-squark coupling:

$$\mathcal{L}_{\tilde{a}\text{-}q\text{-}\tilde{q}} = g_{\text{eff}}^{(L/R)} \tilde{q}_{L_i/R_i} \bar{q}_i P_{R/L} \gamma_5 \tilde{a}, \tag{2.37}$$

[#9] In this case, the domain wall number should be unity. Even if $N_{\rm DW} = 1$, axion is also produced from axionic string and axionic domain wall, which gives stringent constraint for the the decay constant, *i.e.*, $f_a \lesssim (2.0\text{-}3.8) \times 10^{10}\,\text{GeV}$ [39]. When the PQ symmetry is broken in during inflation, on the contrary, there is constraint from the isocurvature perturbation (see, *e.g.*, Ref. [40]).

[#10] In Ref. [41] a simple baryogenesis is suggested in a minimal extension of the standard model by using *udd* type higher dimension operator, which also contains a DM candidate.

[#11] Axino DM with different RPV operators is studied in, *e.g.*, Refs. [43, 44, 45, 46].

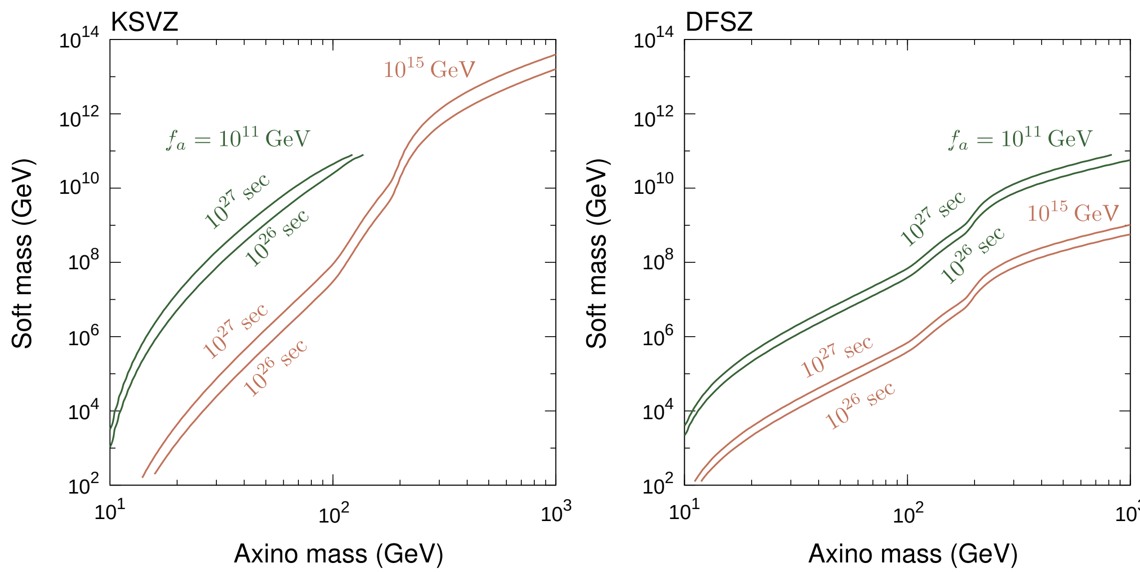

Figure 1: Contour of axino lifetime. Left and right panels correspond to KSVZ and DFSZ model, respectively. The contours of $\tau_{\tilde{a}} = 10^{26}$, 10^{27} sec are depicted by taking $f_a = 10^{11}$ (green), 10^{15} GeV (red) in each panel. The plots are given in the region where the soft mass is less than f_a. Here we take $m_{\rm soft} = m_{\tilde{g}} = m_{\tilde{t}}$, $\lambda''_{332} = 1$ and the others are zero.

where $P_{R/L} = (1 \pm \gamma_5)/2$ and $\tilde{q}_{L_i/R_i}$ is left-/right-handed squark. Here quark and squarks are in the MSSM sector. In KSVZ model, although axino has no interaction with quark and squark in the MSSM sector at tree level, the effective interaction is induced at loop level. The effective coupling is given by [21]

$$g_{\rm eff}^{(L/R)} \simeq \mp \frac{\alpha_s^2}{\sqrt{2}\pi^2} \frac{m_{\tilde{g}}}{f_a} \log\left(\frac{f_a}{m_{\tilde{g}}}\right), \tag{2.38}$$

where $m_{\tilde{g}}$ is gluino mass. On the other hand, in DFSZ model, tree-level interaction exists in F-term potential, given by [26]

$$g_{\rm eff}^{(L/R)} \simeq \mp i \frac{m_q}{f_a} \begin{cases} \cos^2\beta & \text{(for up-type quark)} \\ \sin^2\beta & \text{(for down-type quark)} \end{cases}. \tag{2.39}$$

Here m_q is quark mass and $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$. In our model the soft SUSY breaking scale tends to be large. To get the observed Higgs mass of around 126 GeV [1, 2], $\tan\beta \simeq 1$ is required in the MSSM. Therefore we consider $\tan\beta = 1$, which means that the axino decay is induced mainly by axino-top-stop interaction.

In the following discussion we assume that all superparticle (except Higgsino) in the MSSM sector have the same mass scale, which is characterized by the soft mass

$m_{\rm soft}$, *i.e.*,

$$m_{\rm soft} \sim m_{\tilde{f}},\ m_{\tilde{g}}, \text{ etc.} \tag{2.40}$$

where $m_{\tilde{f}}$ represents sfermion mass. In the calculation of axino lifetime, we use HELAS package [47].

Fig. 1 shows contours of axino lifetime $\tau_{\tilde{a}}$. Here we take $m_{\rm soft} = m_{\tilde{g}} = m_{\tilde{t}}$ ($m_{\tilde{t}}$ is stop mass), $\lambda''_{332} = 1$ and the other λ''_{ijk} are zero.[#12] Via λ''_{332} axino decays to tbs if kinematically allowed. If axino is lighter than top but heavier than W boson, the final state is $Wbbs$. The final state becomes five body in which off-shell W boson decays when $m_{\tilde{a}} \lesssim m_W$. (In the five-body final state, we ignored fermion masses except for bottom quark.) Those behavior can be seen in the plot. When axino mass is around W boson mass and top mass, the lifetime is enhanced. Then large soft mass is required to suppress the lifetime. In KSVZ model the lifetime is not strongly suppressed by the soft mass compared to in DFSZ model. This is due to a factor of gluino mass in the effective $\tilde{a}$-$\tilde{q}$-q coupling. Then the lifetime should be suppressed by even larger soft mass.

3 Results

Now we are ready to give numerical results. Before showing the results, we summarize the conditions which need to be satisfied for our scenario:

$$i) \quad T_X \gtrsim 10 \text{ MeV}, \tag{3.1}$$

$$ii) \quad \tau_{\tilde{a}} \gtrsim 10^{26} \text{ sec}, \tag{3.2}$$

$$iii) \quad \Gamma_\sigma > \Gamma_X. \tag{3.3}$$

i) and *ii)* are the phenomenological constraints, *i.e.*, moduli decays before BBN and axino should not produce any exotic cosmic rays. The last one is the condition in order for our scenario to work, *i.e.*, saxion decays before moduli. In KSVZ model, it is simply given by $m_X/m_\sigma \le 4.2 \times 10^4 \left(\frac{10^{11}\text{ GeV}}{f_a/\xi}\right)^{2/3}$ in $m_\sigma \gg m_{\tilde{a}}$ limit. It should be also reminded that we are interested in the mass spectrum, such as

$$m_{\tilde{a}} < (\mu,\, m_\sigma,\, m_{\rm soft}) < m_X. \tag{3.4}$$

[#12] In the computation we ignored left-right mixing in squark sector for simplicity. (Taking into account it is straightforward.) Here sbottom mediated diagram is neglected for simplicity by assuming stop is the lightest squark.

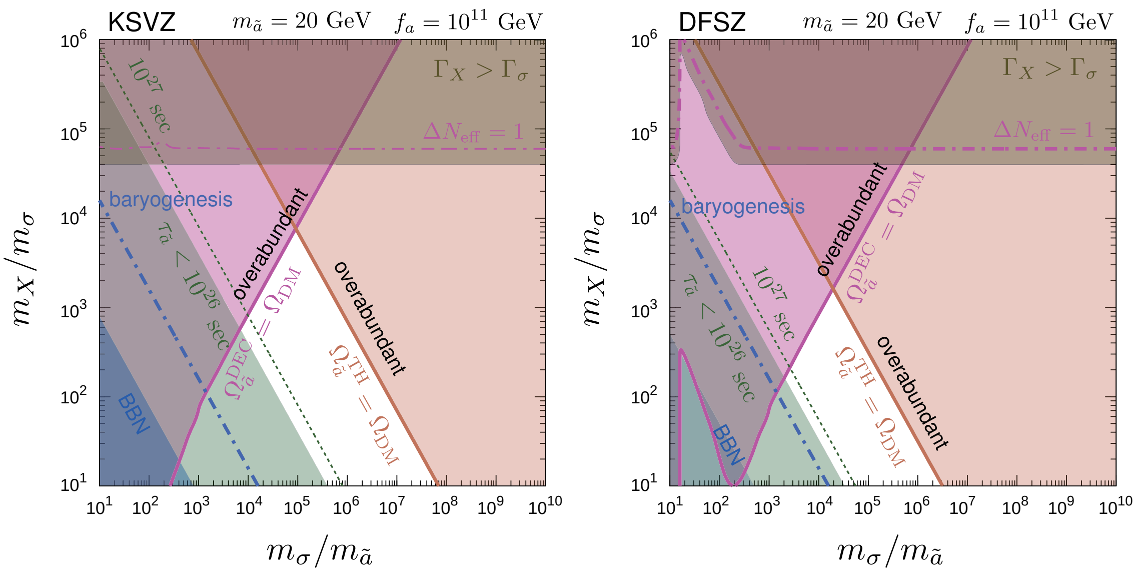

Figure 2: Contours of $\Omega_{\tilde{a}}^{\rm DEC} = \Omega_{\rm DM}$ and $\Omega_{\tilde{a}}^{\rm TH} = \Omega_{\rm DM}$ on $(m_\sigma/m_{\tilde{a}},\, m_X/m_\sigma)$ plane. Left (right) panel corresponds to KSVZ (DFSZ) model. We take $m_{\tilde{a}} = 20$ GeV, $f_a = 10^{11}$ GeV, $\lambda''_{332} = (3 \times 10^6\,{\rm GeV}/m_X)^{1/4}/2$ and $\delta X_{\rm ini} = \delta\sigma_{\rm ini} = M_{\rm Pl}$ for both models, and $\mu = 10^2\, m_{\tilde{a}}$ for DFSZ model. In the plot shaded regions are excluded. "BBN" region is excluded due to $T_X < 10$ MeV and "overabundant" means the region where $\Omega_{\tilde{a}} > \Omega_{\rm DM}$. The others are described in the figure. $m_X = 3 \times 10^6$ GeV is drawn in (blue) dash-dotted line (also indicated as "baryogenesis") to show that successful baryogenesis is realized in region above the line. $\Delta N_{\rm eff} < 1$ is satisfied in the region below the line $\Delta N_{\rm eff} = 1$. For reference, contour of $\tau_{\tilde{a}} = 10^{27}$ sec is also plotted in (green) dotted line.

In Fig. 2, contours of $\Omega_{\tilde{a}}^{\rm DEC} = \Omega_{\rm DM}$ and $\Omega_{\tilde{a}}^{\rm TH} = \Omega_{\rm DM}$ ($\Omega_{\rm DM} h^2 = 0.1196 \pm 0.0031$ at 68% C.L. [29]) are plotted on $(m_\sigma/m_{\tilde{a}},\, m_X/m_\sigma)$ plane. Here we take $m_{\tilde{a}} = 20$ GeV, $m_{\rm soft} = m_X/50$, $f_a = 10^{11}$ GeV, $\delta X_{\rm ini} = \delta\sigma_{\rm ini} = M_{\rm Pl}$. Left (right) panel shows the result in KSVZ (DFSZ) model. In the plot of DFSZ model, we take $\mu = 10^2\, m_{\tilde{a}}$. For the determination of the axino lifetime we take $\lambda''_{332} = (3 \times 10^6\,{\rm GeV}/m_X)^{1/4}/2$ to explain the present baryon density [10] and the others are taken to be zero. $m_X \gtrsim 3 \times 10^6$ GeV should be satisfied for the baryogenesis, which is also shown in dot-dashed line. In the figure shaded regions are excluded. Since axino mass is lighter than W boson mass, the axino decay is five body. We found that the constraint $\tau_{\tilde{a}} \gtrsim 10^{26}$ sec is much more stringent than the BBN constraint, which excludes the lower mass range. The bound is stronger in KSVZ model due to the enhancement of the effective $\tilde{a}$-$\tilde{q}$-q coupling. However, it turns out that the region $\Omega_{\tilde{a}} \simeq \Omega_{\rm DM}$ exists in the valid parameter region for both models. Two contributions, $\Omega_{\tilde{a}}^{\rm DEC}$ and

$\Omega_{\tilde{a}}^{\rm TH}$, have different dependence on the mass parameters. In both models $\Omega_{\tilde{a}}^{\rm DEC}$ is the same and well agree with Eq. (2.31).[#13] As for the thermal production, on the other hand, axino is thermalized in the region near $\Omega_{\tilde{a}}^{\rm TH} \simeq \Omega_{\rm DM}$ but diluted effectively to give the right amount in KSVZ model, which is consistent with Eq. (2.32). In DFSZ model, axino is copiously produced when T_X become larger than μ, which soon becomes overabundant. Therefore, the line $\Omega_{\tilde{a}}^{\rm TH} = \Omega_{\rm DM}$ locates near $T_X \sim \mu$. Regarding to axion dark radiation, we have found that $\Delta N_{\rm eff}$ is less than unity in the valid parameter region. To be concrete, the constraint $\Delta N_{\rm eff} < 1$ is always satisfied in the region $\Gamma_\sigma > \Gamma_X$, independent of the parameters. (See Eq. (2.35).)

We found the upper bound for axino mass. For large axino mass, the bound from the lifetime becomes stringent. In order to suppress the decay width of axino, large soft mass (*i.e.* moduli mass) is needed. In KSVZ model, however, large axino mass and soft mass enhance the thermal production of axino (see Eq. (2.32)). Then we found numerically

$$m_{\tilde{a}} \lesssim 1 \times 10^2\,\text{GeV}, \tag{3.5}$$

by taking $f_a = 10^{15}\,\text{GeV}$. This bound can be also read from Fig. 1. When axino mass is larger than $O(100\text{ GeV})$, axino decays to $Wbbs$ where W boson is on-shell, which leads to enhance the decay rate. As a consequence, the constraint from the lifetime and the overabundant bound destroy viable parameter region. In DFSZ model, the bound from the lifetime becomes stringent for large axino mass as well. In this case the thermal production after moduli decay can be avoided if large μ is taken. However, the production during moduli domination is enhanced instead for large μ, which leads to overabundant axino. Then we found numerically the upper bound for axino mass as

$$m_{\tilde{a}} \lesssim 10^5\,\text{GeV} \tag{3.6}$$

while taking $f_a = 10^{15}\,\text{GeV}$.

There is no lower bound for axino mass in this context. Then it is possible to consider very large moduli mass. Let us suppose that moduli mass is $O(10^{16}\,\text{GeV})$. ($m_X \gtrsim 10^{16}\,\text{GeV}$ is invalid since T_X may be as large as the soft mass scale, which may erase the baryon asymmetry.) With such a large m_X and small $m_{\tilde{a}}$, axino relic is mainly from thermal production. Then axino with a mass of $O(10\text{ keV})$ can be DM in KSVZ model. In DFSZ model, axino DM should have a mass of

[#13]Except for low m_σ range because σ decay to Higgs pair changes $\text{Br}(\sigma \to \tilde{a}\tilde{a})$.

$m_{\tilde{a}} \sim O(0.1\ \text{MeV})$ when $f_a = 10^{16}\,\text{GeV}$ and $\mu \sim 10^{14}$ GeV, for example. If the BICEP2 result is confirmed, moduli mass should be larger than around $10^{16}\,\text{GeV}$ in order for moduli to be stabilized.#14 Therefore our scenario is compatible with high-scale inflation while stabilizing moduli.

Finally we discuss the experimental signatures involved in the scenario. Near the region $\tau_{\tilde{a}} \sim 10^{26\text{-}27}\,\text{sec}$, the decay of axino produces hadrons and leptons, which may be observed as cosmic rays. Among them hadronic decay products are especially constrained by cosmic-ray anti-proton observation by PAMELA [49].#15 When axino mass is larger than order of a hundred GeV, a large amount of high energy cosmic-ray anti-protons are generated. Then the cosmic rays will be detected by AMS-02 experiment as an exotic signal, otherwise more stringent constraint will be given. If axino mass is smaller, the energy of the produced anti-proton gets smaller. In such a low energy range, the background cosmic ray increases. Thus it would be more difficult to see the signal, depending on the lifetime. If axino is lighter than 1 GeV, then axino becomes stable because it can not decay to the SM fermions. However, proton decays to axino via the RPV instead. As pointed out in Ref. [52], λ''_{332} induces $ud\tilde{s}$ type coupling, κ_{uds}, which is $O(10^{-7}) \times \lambda''_{332}$. Then proton decay to $K^+\tilde{a}$. The decay rate of proton is estimated as $\Gamma_{p\to K^+\tilde{a}} \sim \frac{m_p}{16\pi}\left(\frac{\tilde{\Lambda}_{\text{QCD}}}{m_{\text{soft}}}\right)^4 |\kappa_{uds}\, g_{\text{eff}}^{(L/R)}|^2$. Here $\tilde{\Lambda}_{\text{QCD}} \sim 250\,\text{MeV}$ is the QCD scale. Then the lifetime of proton is estimated as $\tau_{p\to K^+\tilde{a}} \sim 3\times 10^{32}\,\text{yr}\left(\frac{f_a}{10^{10}\,\text{GeV}}\right)^2\left(\frac{m_X}{10^{10}\,\text{GeV}}\right)^4\left(\frac{4}{\log(f_a/m_X)}\right)^2\left(\frac{250\,\text{MeV}}{\tilde{\Lambda}_{\text{QCD}}}\right)^4$ in KSVZ model, and $\tau_{p\to K^+\tilde{a}} \sim 5\times 10^{35}\,\text{yr}\left(\frac{f_a}{10^{10}\,\text{GeV}}\right)^2\left(\frac{m_X}{10^{8}\,\text{GeV}}\right)^4\left(\frac{250\ \text{MeV}}{\tilde{\Lambda}_{\text{QCD}}}\right)^4$ in DSVZ model. Here we have used $m_{\text{soft}} = m_X/50$ and $\lambda''_{332} \sim 0.07$ and 0.2 in KSVZ and DFSZ model, respectively. The current experimental bound is $\tau_{p\to K^+\nu} \geq 2.3\times 10^{33}\,\text{yr}$ [53]. Therefore, proton decay experiment in the future could be a test of this scenario even in high moduli mass (soft mass) region.

In our scenario, lighter neutral Higgsino may be the LSP in the MSSM sector and as light as $O(100\ \text{GeV-}1\ \text{TeV})$. If the Higgsino is produced at a collider, it would decay inside the detector via the $O(1)$ RPV. However, its decay width is suppressed by the soft mass, thus it would decay from the interaction point. Even if the decay width of Higgsino is so suppressed by the soft mass that the decay occurs far from the interaction point, the decay would be observed. Then counting the number of the decay events, the lifetime might be determined [54]. Then it may be possible to probe the validity of this scenario in the high soft mass region.

#14See, *e.g.*, a recent work [48], which takes into account the back-reaction effect.

#15See earlier works , *e.g.*, [50, 51], which study cosmic-ray anti-proton from decaying DM.

4 Conclusion

In this paper we consider axino dark matter in large R-parity violation. While moduli dominate the universe after inflation, saxion also oscillates coherently and eventually decays to produce large amount of LSP axino. Axino is also produced thermally at the reheating after inflation or lower temperature, depending on axion model. Such axinos are diluted by late moduli decay. We have found that the axino relic can give the correct amount to explain the present dark matter abundance in both KSVZ and DFSZ models. Though axino is metastable due to the large R-parity violation, its decay rate is suppressed the axion decay constant, soft SUSY breaking mass or kinematics. Then the lifetime can be longer in order axino not to produce exotic cosmic rays. With the large R-parity violation, baryon asymmetry is generated in moduli-induced baryogenesis as well. Therefore the scenario explains both dark matter and baryon existing in the present universe.

Acknowledgment

We are grateful to Wilfried Buchmüller for discussions and giving fruitful comments and suggestions during the research. We are also thankful to Kwang Sik Jeong, Fuminobu Takahashi and Martin Winkler for useful discussions.

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[3] P. A. R. Ade *et al.* [BICEP2 Collaboration], arXiv:1403.3985 [astro-ph.CO].

[4] R. Kallosh and A. D. Linde, JHEP **0412**, 004 (2004) [hep-th/0411011].

[5] J. J. Blanco-Pillado, R. Kallosh and A. D. Linde, JHEP **0605**, 053 (2006) [hep-th/0511042].

[6] I. Affleck and M. Dine, Nucl. Phys. B **249**, 361 (1985).

[7] M. Dine, L. Randall and S. D. Thomas, Nucl. Phys. B **458**, 291 (1996) [hep-ph/9507453].

[8] J. M. Cline and S. Raby, Phys. Rev. D **43**, 1781 (1991).

[9] S. Mollerach and E. Roulet, Phys. Lett. B **281**, 303 (1992).

[10] K. Ishiwata, K. S. Jeong and F. Takahashi, JHEP **1402**, 062 (2014) [arXiv:1312.0954 [hep-ph]].

[11] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, Phys. Rev. D **68**, 046005 (2003) [hep-th/0301240].

[12] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977).

[13] M. Endo, K. Hamaguchi, F. Takahashi, Phys. Rev. Lett. **96**, 211301 (2006). [hep-ph/0602061]; Phys. Rev. **D74**, 023531 (2006). [hep-ph/0605091]; S. Nakamura, M. Yamaguchi, Phys. Lett. **B638**, 389-395 (2006). [hep-ph/0602081]; M. Dine, R. Kitano, A. Morisse, Y. Shirman, Phys. Rev. **D73**, 123518 (2006). [hep-ph/0604140].

[14] M. Kawasaki, N. Kitajima and K. Nakayama, Phys. Rev. D **83**, 123521 (2011) [arXiv:1104.1262 [hep-ph]].

[15] T. Moroi and M. Takimoto, Phys. Lett. B **718**, 105 (2012) [arXiv:1207.4858 [hep-ph]].

[16] T. Moroi, K. Mukaida, K. Nakayama and M. Takimoto, JHEP **1306**, 040 (2013) [arXiv:1304.6597 [hep-ph]].

[17] J. E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Nucl. Phys. B **166**, 493 (1980).

[18] M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B **104**, 199 (1981); A. R. Zhitnitsky, Sov. J. Nucl. Phys. **31**, 260 (1980) [Yad. Fiz. **31**, 497 (1980)].

[19] E. J. Chun and A. Lukas, Phys. Lett. B **357**, 43 (1995) [hep-ph/9503233].

[20] L. Covi, J. E. Kim and L. Roszkowski, Phys. Rev. Lett. **82**, 4180 (1999) [hep-ph/9905212].

[21] L. Covi, H. -B. Kim, J. E. Kim and L. Roszkowski, JHEP **0105**, 033 (2001) [hep-ph/0101009].

[22] K. -Y. Choi, L. Covi, J. E. Kim and L. Roszkowski, JHEP **1204**, 106 (2012) [arXiv:1108.2282 [hep-ph]].

[23] A. Brandenburg and F. D. Steffen, JCAP **0408**, 008 (2004) [hep-ph/0405158].

[24] A. Strumia, JHEP **1006**, 036 (2010) [arXiv:1003.5847 [hep-ph]].

[25] K. Rajagopal, M. S. Turner and F. Wilczek, Nucl. Phys. B **358**, 447 (1991).

[26] E. J. Chun, Phys. Rev. D **84**, 043509 (2011) [arXiv:1104.2219 [hep-ph]].

[27] K. J. Bae, K. Choi and S. H. Im, JHEP **1108**, 065 (2011) [arXiv:1106.2452 [hep-ph]].

[28] K. J. Bae, E. J. Chun and S. H. Im, JCAP **1203**, 013 (2012) [arXiv:1111.5962 [hep-ph]].

[29] P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO].

[30] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti and P. D. Serpico, Nucl. Phys. B **729**, 221 (2005) [hep-ph/0506164].

[31] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha and W. Li *et al.*, Astrophys. J. **730**, 119 (2011) [Erratum-ibid. **732**, 129 (2011)] [arXiv:1103.2976 [astro-ph.CO]].

[32] G. Hinshaw *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **208**, 19 (2013) [arXiv:1212.5226 [astro-ph.CO]].

[33] J. L. Sievers *et al.* [Atacama Cosmology Telescope Collaboration], JCAP **1310**, 060 (2013) [arXiv:1301.0824 [astro-ph.CO]].

[34] K. T. Story, C. L. Reichardt, Z. Hou, R. Keisler, K. A. Aird, B. A. Benson, L. E. Bleem and J. E. Carlstrom *et al.*, Astrophys. J. **779**, 86 (2013) [arXiv:1210.7231 [astro-ph.CO]].

[35] Z. Hou, C. L. Reichardt, K. T. Story, B. Follin, R. Keisler, K. A. Aird, B. A. Benson and L. E. Bleem *et al.*, Astrophys. J. **782**, 74 (2014) [arXiv:1212.6267 [astro-ph.CO]].

[36] K. S. Jeong and F. Takahashi, JHEP **1208**, 017 (2012) [arXiv:1201.4816 [hep-ph]].

[37] K. Choi, K. -Y. Choi and C. S. Shin, Phys. Rev. D **86**, 083529 (2012) [arXiv:1208.2496 [hep-ph]].

[38] M. S. Turner, Phys. Rev. D **33**, 889 (1986).

[39] T. Hiramatsu, M. Kawasaki, K. 'i. Saikawa and T. Sekiguchi, Phys. Rev. D **85**, 105020 (2012) [Erratum-ibid. D **86**, 089902 (2012)] [arXiv:1202.5851 [hep-ph]].

[40] M. PHertzberg, M. Tegmark and F. Wilczek, Phys. Rev. D **78**, 083507 (2008) [arXiv:0807.1726 [astro-ph]].

[41] C. Cheung and K. Ishiwata, Phys. Rev. D **88**, no. 1, 017901 (2013) [arXiv:1304.0468 [hep-ph]].

[42] R. Barbier, C. Berat, M. Besancon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet and S. Lavignac *et al.*, Phys. Rept. **420**, 1 (2005) [hep-ph/0406039].

[43] H. -B. Kim and J. E. Kim, Phys. Lett. B **527**, 18 (2002) [hep-ph/0108101].

[44] D. Hooper and L. -T. Wang, Phys. Rev. D **70**, 063506 (2004) [hep-ph/0402220].

[45] E. J. Chun and H. B. Kim, JHEP **0610**, 082 (2006) [hep-ph/0607076].

[46] M. Endo, K. Hamaguchi, S. P. Liew, K. Mukaida and K. Nakayama, Phys. Lett. B **721**, 111 (2013) [arXiv:1301.7536 [hep-ph]].

[47] H. Murayama, I. Watanabe and K. Hagiwara, KEK-91-11.

[48] W. Buchmuller, C. Wieck and M. W. Winkler, arXiv:1404.2275 [hep-th].

[49] O. Adriani *et al.* [PAMELA Collaboration], Phys. Rev. Lett. **105**, 121101 (2010) [arXiv:1007.0821 [astro-ph.HE]].

[50] A. Ibarra and D. Tran, JCAP **0807**, 002 (2008) [arXiv:0804.4596 [astro-ph]].

[51] K. Ishiwata, S. Matsumoto and T. Moroi, JHEP **0905**, 110 (2009) [arXiv:0903.0242 [hep-ph]]; K. Ishiwata, S. Matsumoto and T. Moroi, JHEP **1012**, 006 (2010) [arXiv:1008.3636 [hep-ph]].

[52] S. Dimopoulos and L. J. Hall, Phys. Lett. B **196**, 135 (1987).

[53] K. Kobayashi *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D **72**, 052007 (2005) [hep-ex/0502026].

[54] K. Ishiwata, T. Ito and T. Moroi, Phys. Lett. B **669**, 28 (2008) [arXiv:0807.0975 [hep-ph]].