Physics Letters B 733 (2014) 25–31

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The 7 keV axion dark matter and the X-ray line signal

Tetsutaro Higaki [a], Kwang Sik Jeong [b], Fuminobu Takahashi [c,d,*]

[a] Theory Center, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[b] Deutsches Elektronen Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany
[c] Department of Physics, Tohoku University, Sendai 980-8578, Japan
[d] Kavli IPMU, TODIAS, University of Tokyo, Kashiwa 277-8583, Japan

ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form 29 March 2014
Accepted 2 April 2014
Available online 12 April 2014
Editor: J. Hisano

ABSTRACT

We propose a scenario where the saxion dominates the energy density of the Universe and reheats the standard model sector via the dilatonic coupling, while its axionic partner contributes to dark matter decaying into photons via the same operator in supersymmetry. Interestingly, for the axion mass $m_a \simeq$ 7 keV and the decay constant $f_a \simeq 10^{14-15}$ GeV, the recently discovered X-ray line at 3.5 keV in the XMM Newton X-ray observatory data can be explained. We discuss various cosmological aspects of the 7 keV axion dark matter such as the production of axion dark matter, the saxion decay process, hot dark matter and isocurvature constraints on the axion dark matter, and the possible baryogenesis scenarios.

1. Introduction

In supergravity and superstring theories there appear many moduli fields at low energy scale through compactifications of extra dimensions [1]. Moduli fields must be stabilized to obtain a sensible low-energy theory, and it is known that many of them are fixed by flux compactifications and acquire a heavy mass [2]. The remaining light moduli not fixed by the fluxes can be stabilized either by instantons/gaugino condensations *a la* KKLT [3] or by supersymmetry (SUSY) breaking effects [4–7].[1] Such light moduli fields may play an important role in cosmology; some of them may dominate the Universe and decay into the standard model (SM) sector, or others could contribute to dark matter or dark energy if their masses are sufficiently light.

Recently an unidentified X-ray line at about 3.5 keV in the XMM-Newton X-ray observatory data of various galaxy clusters and the Andromeda galaxy was reported independently by two groups [8,9]. While there are a variety of systematic uncertainties that can affect the observed line energy and flux, it is intriguing that the X-ray line can be explained by decaying dark matter such as sterile neutrinos[2] [11] or moduli fields [12–15].

The observations suggest the mass and the lifetime of the dark matter as [8,9]:

$$m_{\rm DM} \simeq 7\ {\rm keV}, \tag{1}$$

$$\tau_{\rm DM} \simeq 2 \times 10^{27}\text{–}2 \times 10^{28}\ {\rm s}, \tag{2}$$

where we have used the values obtained by the M31 data [9], and we adopt them as reference values in the following analysis assuming that decaying dark matter is the origin of the 3.5 keV X-ray line. Note that one needs to multiply a factor of 2 with the lifetime if the dark matter decays into two photons as we shall consider below.

The light dark matter mass about 7 keV may be due to some approximate symmetry forbidding the mass. We focus on the axion component of a modulus field $\Phi = (\sigma + ia)/\sqrt{2}$ stabilized by SUSY breaking effects, where σ and a are the saxion and the axion components, respectively. The axion a can remain extremely light as a result of the axionic shift symmetry,

$$\Phi \to \Phi + iC, \tag{3}$$

where C is a real transformation parameter. The axion can acquire a small but non-zero mass of 7 keV from some non-perturbative effects which explicitly break the above shift symmetry. We shall see that, if the modulus field Φ is coupled to the SM gauge fields with a decay constant of order 10^{14-15} GeV, the lifetime of the

* Corresponding author.
E-mail addresses: thigaki@post.kek.jp (T. Higaki), kwangsik.jeong@desy.de (K.S. Jeong), fumi@tuhep.phys.tohoku.ac.jp (F. Takahashi).

[1] For instance the QCD axion could be the axion component of such a modulus field mainly stabilized by the SUSY breaking effects.

[2] Recently, Ishida and two of the present authors (KSJ and FT) showed that the small mass and mixing of sterile neutrino dark matter suggested by the X-ray line can be easily realized by the split flavor mechanism where the breaking of flavor symmetry is tied to the breaking of the $B-L$ symmetry [10].

http://dx.doi.org/10.1016/j.physletb.2014.04.007

axion falls in the range of (2), explaining the observed X-ray line. On the other hand, the saxion σ generically acquires a mass of order of the gravitino mass from SUSY breaking effects. The gravitino mass is not known, but it must be heavier than the electroweak scale in the gravity or anomaly mediation. We assume this is the case throughout this letter.

The mass hierarchy between the saxion and the axion leads to a unified picture of the cosmological role of light moduli fields: the saxion dominates the Universe and reheats the SM sector via the dilatonic coupling, while the axion contributes to dark matter decaying into photons via the same operator in SUSY. As we shall see shortly, the right abundance of axion dark matter can be produced by coherent oscillations for the saxion mass about 10^6 GeV and the decay constant $f_a \simeq 10^{14-15}$ GeV without fine-tuning of the initial misalignment angle.[3] We shall also see that the axions are generically produced by the saxion decay, which may contribute to hot dark matter (HDM) component in agreement with the recent observations [17–19]. Therefore, the detailed study of the decaying axion dark matter via the X-ray observation and the observations of large-scale structure can be a probe of not only the nature of dark matter but also the reheating of the Universe as well as the high-energy physics close to the GUT scale.

In this letter we propose a scenario in which the 7 keV axion dark matter decaying into photons explains the origin of the 3.5 keV X-ray line, while the saxion dominates the Universe and reheats the SM sector via the same dilatonic coupling in SUSY. We will study various aspects of this scenario, focusing on the saxion cosmology, the production mechanism of the axion dark matter, the isocurvature and HDM constraints, and possible baryogenesis scenarios in turn.

Lastly let us briefly mention the differences of our work from Ref. [15] (and other works [12–14]). One of the main differences is the SUSY breaking scale, i.e., the gravitino mass. They focused on the light gravitino mass between keV and MeV, and consider moduli dark matter with a similar mass, which corresponds to the real component of the moduli, i.e. the saxion, in our scenario. On the other hand, it is its axionic partner that becomes dark matter in our scenario. As long as the implications for the observation of the X-ray line are concerned, there is no significant difference between these two models. The crucial difference is that the heavy gravitino we consider enables a scenario in which the saxion dominates and reheats the Universe via the same dilatonic coupling in SUSY. Then we can unambiguously discuss the saxion and axion cosmology.

2. Moduli stabilization and light axion

We consider KKLT-type flux compactifications on a Calabi–Yau space [3] where the dilaton and complex structure moduli are stabilized by closed string fluxes. The low energy effective theory of complexified Kähler moduli X_I possesses perturbative shift symmetries, and is described by the Kähler potential of no-scale form at the leading order of string coupling and α'-corrections:

$$K = -2\ln \mathcal{V}_{\rm CY}\big(X_I + X_I^*\big), \tag{4}$$

where the Calabi–Yau volume $\mathcal{V}_{\rm CY}$ is a homogeneous function of degree $3/2$ in $X_I + X_I^*$. The shift symmetry makes ${\rm Im}(X_I)$ massless until non-perturbative effects are added. To have a light string axion, we clearly need some mechanism to stabilize its scalar partner, the saxion, while preserving the associated shift symmetry.

An interesting possibility is to stabilize the saxion by Kähler potential in the presence of sequestered uplifting sector [6,7]. This works when the superpotential includes non-perturbative terms to stabilize Kähler moduli as in the original KKLT, but with smaller number of terms than the number of Kähler moduli. Let us consider the case where there are $n-1$ non-perturbative superpotential terms for n Kähler moduli. Then appropriate field redefinition leads to

$$K = K\big(\Phi + \Phi^*, X_i + X_i^*\big),$$
$$W = \omega_0 + \sum_i A_i e^{-a_i X_i}, \tag{5}$$

for $X_I = (\Phi, X_i)$, where we have included a constant superpotential, ω_0, which is originated from background fluxes. For string compactification allowing

$$\partial_\Phi K = 0, \tag{6}$$
$$\partial_{X_i} W + (\partial_{X_i} K) W = 0, \tag{7}$$

there exists a supersymmetric field configuration, and consequently all the Kähler moduli are stabilized at a dS vacuum with a vanishingly small cosmological constant after adding sequestered uplifting potential,

$$V_{\rm up} = \epsilon e^{2K/3}, \tag{8}$$

where $\epsilon = \mathcal{O}(\omega_0^2)$ is chosen to cancel the cosmological constant. The Kähler moduli X_i acquire large supersymmetric masses around $\ln(M_p/m_{3/2}) \times m_{3/2}$ from the non-perturbative superpotential terms, where $m_{3/2} = \langle e^{K/2} W\rangle$ is the gravitino mass and M_p denotes the reduced Planck scale.[4] On the other hand, Φ is fixed by the condition $\partial_\Phi K = 0$. The saxion is relatively light compared to X_i, and the axion remains massless due to the shift symmetry:

$$m_\sigma \simeq \sqrt{2} m_{3/2}, \qquad m_a = 0, \tag{9}$$

for $\Phi = \langle\Phi\rangle + (\sigma + ia)/\sqrt{2}$. The fermionic component has mass approximately equal to $m_{3/2}$. It is important to note that these results follow from the no-scale structure, and are insensitive to the precise form of the Kähler potential [7]. One may consider more general Kähler potential, for which the saxion is stabilized in a similar way, and its mass is of order of the gravitino mass [20].

To make the axion massive, one can introduce small non-perturbative effects involving Φ so that the associated shift symmetry is explicitly broken:

$$\Delta W = A e^{-\sum_i b_i X_i} e^{-b\Phi}, \tag{10}$$

for real constants b and b_i. If the dynamical scale is below the gravitino mass, we need to consider the non-perturbative dynamics in a non-SUSY framework. In the following we will simply assume that the axion acquires a small mass, $m_a \simeq 7$ keV, as a result of some non-perturbative dynamics. For instance, it can be induced by hidden gauge interactions to which Φ is coupled. Note that the axion cannot be the QCD axion because of its mass. The large mass hierarchy between the saxion and axion is achieved when ΔW is much smaller than $m_{3/2}$ at the vacuum.

The axion dark matter of mass 7 keV should couple to photons in order to account for the observed X-ray line. The axion coupling to photons arises from the interaction

$$\mathcal{L} = \frac{1}{4}\int d^2\theta\, F(X_I)\mathcal{W}^\alpha \mathcal{W}_\alpha + \text{h.c.}, \tag{11}$$

where the gauge kinetic function linearly depends on the Kähler moduli:

[3] Axion-like particles are a good candidate for cold dark matter. See e.g. Ref. [16].

[4] We take the Planck scale to be unity unless otherwise stated.

$$F = k\Phi + \sum_i k_i X_i + \text{constant}, \tag{12}$$

as indicated by the perturbative shift symmetry. Here k and k_i are real constants, and $\mathcal{W}_\alpha$ denotes the supersymmetric field strength of the SM gauge fields. The gauge kinetic functions for the SM gauge groups have been assumed to have the same dependence on the Kähler moduli, as would be required for the gauge coupling unification.[5] From the above interaction, one obtains the axion coupling to photons in the canonical basis,

$$\mathcal{L}_{\text{axion}} = \frac{\alpha_{\text{EM}}}{4\pi}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{13}$$

where the axion decay constant is determined by

$$f_a = \frac{M_p}{4\sqrt{2}\pi^2}\frac{1}{k}\langle \partial_\Phi \partial_{\Phi^*} K\rangle^{1/2}, \tag{14}$$

where $F_{\mu\nu}$ is the electromagnetic field strength, and α_{EM} is its gauge coupling. The value of $\partial_\Phi \partial_{\Phi^*} K$ depends on the details of the moduli stabilization, especially on the volume of the Calabi–Yau space. In the current set-up, if there is a hidden gauge group with the rank of $\mathcal{O}(10)$ on the D-brane wrapping on the bulk cycle, it can be one order of magnitude smaller. Also k can easily take a value larger or smaller than unity by a factor of 10, if we allow some mild tuning of the moduli fields X_I, as we have taken the field basis such that X_i is the exponent of a non-perturbative superpotential term. Therefore, the plausible range of f_a is between 10^{14} GeV and 10^{16} GeV.

The decay rate of the axion into photons is given by

$$\Gamma_{a\to\gamma\gamma} = \frac{\alpha_{\text{EM}}^2}{64\pi^3}\frac{m_a^3}{f_a^2}, \tag{15}$$

and therefore its lifetime is estimated to be

$$\tau_a \simeq 2\times 10^{28}\ \text{s} \times \left(\frac{\alpha_{\text{EM}}}{1/137}\right)^{-2}\left(\frac{m_a}{7\ \text{keV}}\right)^{-3}\left(\frac{f_a}{5\times 10^{14}\ \text{GeV}}\right)^2, \tag{16}$$

assuming that the axion mainly decays into photons via the above coupling. Hence, the observed 3.5 keV X-ray line can be explained for $m_a \simeq 7$ keV and $f_a \simeq (2\text{–}7)\times 10^{14}$ GeV which is within the expected range of (14).

3. Cosmology of 7 keV axion dark matter

3.1. Abundance of axion dark matter

Let us discuss the production of the 7 keV axion dark matter. First let us estimate thermal production of axions. Applying the result for the QCD axion [21–25] to the 7 keV axion, the axion abundance is

$$\Omega_a^{(th)} h^2 \simeq 0.2\left(\frac{\gamma_a}{10^{-2}}\right)\left(\frac{106.75}{g_*}\right)\left(\frac{m_a}{7\ \text{keV}}\right) \times \left(\frac{2\times 10^{14}\ \text{GeV}}{f_a}\right)^2\left(\frac{T_R}{10^{12}\ \text{GeV}}\right), \tag{17}$$

where γ_a is a numerical factor that parametrizes contributions from various sources, and its typical value is between 0.01 and 0.1 for 10^4 GeV $< T_R < 10^{12}$ GeV [25]. g_* counts the relativistic degrees of freedom at the reheating. As we shall see later, as long as the saxion dominates the Universe, the decay temperature cannot be as high as 10^{12} GeV. Therefore the thermal production is not efficient in the saxion-dominated Universe. Although not pursued here, if the saxion does not dominate the Universe, the thermally produced axions can explain the observed dark matter abundance if $T_R \sim 10^{12\text{–}13}$ GeV, and also, they will contribute to warm dark matter. For lower T_R, the thermally produced axions contribute only a small fraction of the total dark matter density.

While thermal production is negligibly small in our scenario, the axions can be copiously produced by coherent oscillations. Neglecting the anharmonic effects [26–29], the axion abundance can be estimated as

$$\frac{\rho_a}{s} \simeq \frac{1}{8} T_R \left(\frac{a_*}{M_p}\right)^2, \tag{18}$$

for the reheating temperature $T_R \lesssim \sqrt{m_a M_p} \sim 4\times 10^6$ GeV, where a_* denotes the initial oscillation amplitude. In this case the axion starts to oscillate before reheating. The cosmic density is given by

$$\Omega_a h^2 \simeq 0.2\left(\frac{T_R}{4\ \text{GeV}}\right)\left(\frac{f_a}{5\times 10^{14}\ \text{GeV}}\right)^2\left(\frac{a_*/f_a}{0.2}\right)^2, \tag{19}$$

independent of the axion mass, where we have used the critical density to entropy ratio, $\rho_c/s \simeq 3.6\times 10^{-9} h^{-2}$ GeV. For relatively low reheating temperature about GeV, the axion abundance falls in the right range without fine-tuning of the initial misalignment angle $\theta_* \equiv a_*/f_a$.[6] The amount of fine-tuning increases in proportion to $1/\sqrt{T_R}$. On the other hand, for $T_R \gtrsim \sqrt{m_a M_p}$, the axion starts to oscillate after reheating, and the abundance is approximately given by (18) and (19) with T_R replaced with $\sqrt{m_a M_p}$. For $T_R \gtrsim 10^6$ GeV, the initial misalignment angle must be of order 10^{-4} for the right dark matter abundance.

As we shall see below, if the saxion dominates the Universe and decays into the SM sector, the reheating temperature is determined by the saxion mass m_σ and the decay constant f_a. For instance, $T_R \simeq 4$ GeV is realized for $m_\sigma \simeq 10^6$ GeV and $f_a \simeq 5\times 10^{14}$ GeV.

The axions produced by the initial misalignment mechanism are non-relativistic and therefore contribute to cold dark matter (CDM). This should be contrasted to the sterile neutrinos with the same mass, which contribute to warm dark matter. Interestingly, as we shall see later in this section, the axions can be also produced by the saxion decay, which may contribute to the HDM component. Therefore a mixed CDM + HDM model is possible in our scenario.

3.2. Saxion decay

The saxion is stabilized by SUSY breaking effects, and its mass is of order the gravitino mass. If the inflation scale is larger than or comparable to the gravitino mass, the position of the saxion during inflation is likely deviated from the low-energy minimum. Then the saxion will start to oscillate with a large initial amplitude when the Hubble parameter becomes comparable to m_σ, and may eventually dominate the Universe after the inflaton decays. For simplicity we assume that the Universe is dominated by the saxion before the axion commences its oscillations.[7]

[5] In general the gauge kinetic function can be different for each gauge group, which however slightly weakens the relation between the axion dark matter decay and the saxion decay as there are more degrees of freedom.

[6] Strictly speaking, the decay constant for the axion potential could be slightly different from f_a, which is defined by the coupling to the SM gauge sector (14). This however slightly modifies the required fine-tuning for obtaining the right dark matter abundance, and our results are not changed.

[7] If the saxion receives a mass of order $\mathcal{O}(H)$, the coherent oscillations can be significantly suppressed [30–32]. In this case the saxion can be mainly produced by thermal scattering [23].

The saxion is coupled to the SM gauge sector through the interaction (11). The relevant interactions are

$$\mathcal{L}_{\rm saxion} = -\frac{g_a^2}{32\pi^2}\frac{\sigma}{f_a}F^a_{\mu\nu}F^{a\mu\nu} + \left(\kappa\frac{g_a^2}{32\pi^2}\frac{m_\sigma}{f_a}\sigma\lambda_a\lambda_a + \text{h.c.}\right), \tag{20}$$

with g_a being the gauge coupling. Here κ is generally of order unity, and its precise value depends on the saxion stabilization and the detailed structure of the Kähler potential.[8] The typical gaugino mass is loop-suppressed compared to the gravitino mass in KKLT-type compactifications with sequestered uplifting sector. This is because the moduli have F-terms around $m_{3/2}/\ln(M_p/m_{3/2})$, making moduli mediation comparable to anomaly mediation [41–43].[9] Therefore, the saxion decays into gauginos with a sizable branching fraction, and it is not helicity suppressed [33,44]. The partial decay rates of the saxion into the SM gauge bosons and gauginos via (20) are given by

$$\Gamma_{\sigma\to A_\mu A_\mu} = N_g\frac{\alpha^2}{256\pi^3}\frac{m_\sigma^3}{f_a^2}, \tag{21}$$

$$\Gamma_{\sigma\to\lambda_a\lambda_a} \simeq N_g|\kappa|^2\frac{\alpha^2}{256\pi^3}\frac{m_\sigma^3}{f_a^2}, \tag{22}$$

taking $g_a^2 = 4\pi\alpha$, where $N_g = 12$ counts the SM gauge degrees of freedom, and we have omitted the phase space factor in the second equation. In the following we will take $|\kappa| = 1$ as a reference value for simplicity. The lightest SUSY particle (LSP) is overproduced in this case [33], as long as the R-parity is conserved. To avoid the overclosure of the Universe, we assume that the R-parity is broken. Alternatively the LSP abundance can be suppressed in the presence of late-time entropy production, which is not pursued here.

The saxion also decays into a pair of axions with a rate

$$\Gamma_{\sigma\to aa} = \frac{1}{64\pi}\frac{\langle\partial_\Phi^3 K\rangle^2}{\langle\partial_\Phi^2 K\rangle^3}m_\sigma^3, \tag{23}$$

which can be comparable to the decay rate into the SM gauge sector. To see this let us calculate the ratio of the rates,

$$\frac{\Gamma_{\sigma\to aa}}{\Gamma_{\sigma\to A_\mu A_\mu}+\Gamma_{\sigma\to\lambda_a\lambda_a}} \simeq 0.33\left(\frac{2}{k^2(1+|\kappa|^2)}\right)\left(\frac{12}{N_g}\right)\left(\frac{1/25}{\alpha}\right)^2\left(\frac{\langle\partial_\Phi^3 K\rangle}{\langle\partial_\Phi^2 K\rangle}\right)^2. \tag{24}$$

Thus produced axions lead to cosmological problems, which is a general feature of such moduli fields stabilized by SUSY breaking effects: the so-called "the moduli-induced axion problem" [34].[10] Those axions are ultra-relativistic at the production. They get redshifted as the Universe expands, and eventually become non-relativistic as they have a non-zero mass about 7 keV. They are subject to the BBN constraint on the additional effective neutrino species $\Delta N_{\rm eff}$ [45] as well as the HDM constraint set by the large-scale structure observation [17–19]. The axion contribution to $\Delta N_{\rm eff}$ can be suppressed if there is an approximate Z_2 symmetry under which Φ changes the sign in the underlying theory. For the moment we set $\langle\partial_\Phi^3 K\rangle = 0$ for simplicity. We will return to the case of $\langle\partial_\Phi^3 K\rangle \neq 0$ when we discuss the HDM constraint on the axions produced by the saxion decay.

On the other hand, the saxion decay into a pair of gravitinos or axinos can be kinematically forbidden as these particles have a comparable mass. Therefore the notorious moduli-induced gravitino problem [44,46,47] can be avoided in our scenario. This is indeed the case in the moduli stabilization discussed in Section 2.

Assuming that the saxion mainly decays into the SM sector via the dilatonic coupling, the decay temperature is estimated as

$$T_R \simeq 4\ \text{GeV}\left(\frac{g_*(T_R)}{106.75}\right)^{-\frac{1}{4}}\left(\frac{m_\sigma}{10^6\ \text{GeV}}\right)^{\frac{3}{2}}\left(\frac{f_a}{5\times10^{14}\ \text{GeV}}\right)^{-1}, \tag{25}$$

where $g_*(T_R)$ counts the relativistic degrees of freedom in the plasma at the saxion decay. Combined with (19), one can see that the right amount of axion dark matter is produced for the saxion mass about 10^6 GeV, the decay constant $f_a \simeq 5\times10^{14}$ GeV and the initial misalignment angle $\theta_* \sim 0.2$. For a heavier mass of the saxion, θ_* should be suppressed in proportion to $m_\sigma^{-3/4}$.

3.3. Hot dark matter constraint

The axions produced by the saxion decay may contribute to the HDM component. This issue was discussed in detail in Ref. [48], motivated by the cosmological preference for an HDM component [17–19].

The properties of HDM can be characterized by the abundance and the effective mass. The abundance is often expressed in terms of the additional neutrino species, $\Delta N_{\rm eff}$, defined by the ratio of the HDM energy density to the energy density of single neutrino species in the relativistic limit. The contribution of axions to $\Delta N_{\rm eff}$ is given by [37,49]

$$\Delta N_{\rm eff} = \frac{43}{7}\left(\frac{g_{*\nu}}{g_*(T_R)}\right)^{\frac{1}{3}}\frac{B_a}{1-B_a}, \tag{26}$$

where B_a denotes the branching fraction into axions, and $g_{*\nu} = 10.75$. For instance, $\Delta N_{\rm eff} = 0.6$ is obtained for $B_a \simeq 0.17$ and $g_*(T_R) = 106.75$. Note that the abundance is fixed by $\langle\partial_\Phi^3 K\rangle^2/\langle\partial_\Phi^2 K\rangle^3$, independent of the saxion mass. In general, $\Delta N_{\rm eff} = \mathcal{O}(0.1-1)$ is expected [34].

The timing when the axions become non-relativistic can be estimated by the effective hot dark matter mass [48],

$$m_a^{(\rm eff)} = \frac{\pi^4}{30\zeta(3)}\Delta N_{\rm eff}\frac{T_R}{m_\sigma/2}\left(\frac{g_*(T_R)}{g_{*\nu}}\right)^{\frac{1}{3}}m_a, \tag{27}$$

which roughly coincides with a mass of thermally produced HDM with the abundance $\Delta N_{\rm eff}$. Namely, the axion HDM becomes non-relativistic when the cosmic temperature is comparable to $m_a^{(\rm eff)}$. As the axions are ultra-relativistic at the production, they behave like HDM with an effective mass much lighter than their actual mass. For the parameters of our interest, it is given by

$$m_a^{(\rm eff)} \simeq 0.2\ \text{eV}\left(\frac{\Delta N_{\rm eff}}{0.6}\right)\left(\frac{m_a}{7\ \text{keV}}\right) \times\left(\frac{m_\sigma}{10^6\ \text{GeV}}\right)^{\frac{1}{2}}\left(\frac{f_a}{5\times10^{14}\ \text{GeV}}\right)^{-1}, \tag{28}$$

where we have set $g_*(T_R) = 106.75$ and $\alpha = 1/25$.

It is interesting to compare the above values of $\Delta N_{\rm eff}$ and $m_a^{(\rm eff)}$ with the recent results of Refs. [17–19]. According to Ref. [18], a combination of Planck data, WMAP-9 polarization data, measurements of the BAO scale, the HST measurement of the H_0, Planck

[8] The expression for κ was given in Ref. [33], and for instance, $\kappa = \sqrt{2}$ in the framework of Ref. [34].

[9] It is possible to consider additional contributions to the gaugino masses so that the saxion decay into gauginos is kinematically forbidden.

[10] There is a similar problem in the case of the QCD axion. See e.g. Refs. [34–40].

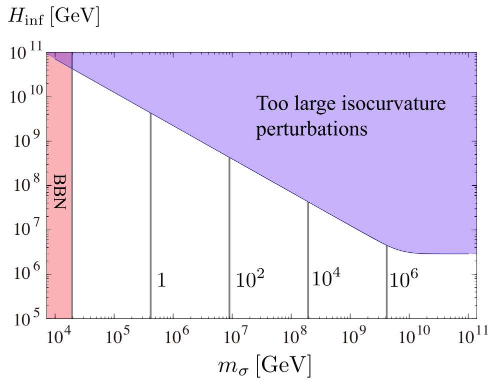

Fig. 1. The shaded regions are excluded by too large isocurvature perturbations of the axion dark matter (upper right triangle region) or by too low reheating temperature, $T_R \lesssim 10$ MeV, which would spoil the BBN (left rectangular region). Here we take $r = 1$, namely, the axion explains all the dark matter, and $f_a = 5 \times 10^{14}$ GeV. The contours for the reheating temperature, $T_R = 1, 10^2, 10^4, 10^6$ GeV, are also shown. The isocurvature constraint becomes insensitive to m_σ for $T_R \gtrsim \sqrt{m_\sigma M_P}$.

galaxy cluster counts and galaxy shear data from the CFHTLens survey yields

$$\Delta N_{\rm eff} = 0.61 \pm 0.30, \tag{29}$$

$$m_{\rm HDM} = (0.41 \pm 0.13)\ {\rm eV}, \tag{30}$$

at 1σ. Note however that, precisely speaking, we cannot directly apply the observational results (29) and (30) to the case of the axion HDM, due to the different momentum distribution as well as the numerical coefficient in the definition of the effective mass. Nevertheless it is intriguing that our set-up can naturally implement the HDM, which seems favored by the observations.

If the preference for a HDM component is simply an artifact of the systematic uncertainties of various observations, the axion HDM abundance must be sufficiently small. This can be realized by suppressing $\langle \partial_\Phi^3 K \rangle$ without severe fine-tuning. For instance, $\langle \partial_\Phi^3 K \rangle / \langle \partial_\Phi^2 K \rangle \sim 0.1$ would give $\Delta N_{\rm eff} \sim 0.01$, which has only negligible impact on the large-scale structure.

3.4. Isocurvature constraints

The axion acquires quantum fluctuations during inflation, giving rise to the CDM isocurvature perturbations, as in the case of the QCD axion. The mixture of the CDM isocurvature perturbations is tightly constrained by the CMB observations [50] as

$$\frac{\mathcal{P}_S}{\mathcal{P}_\mathcal{R} + \mathcal{P}_S} < 0.039\ (95\%\ {\rm CL},\ {\rm Planck} + {\rm WP}) \tag{31}$$

where $\mathcal{P}_S$ and $\mathcal{P}_\mathcal{R}$ are the power spectrum for the isocurvature and curvature perturbations, respectively. The Planck normalization reads $\mathcal{P}_\mathcal{R} \simeq 2.2 \times 10^{-9}$.

In our axion dark matter model, the power spectrum of the isocurvature perturbations is estimated by [29][11]

$$\mathcal{P}_S = \left(r \frac{\partial \ln \Omega_a}{\partial \theta_*} \frac{H_{\rm inf}}{2\pi f_a} \right)^2, \tag{32}$$

where r denotes the fraction of the axion density to the total dark matter density, $\theta_* \equiv a_*/f_a$ represents the initial misalignment angle, and $H_{\rm inf}$ is the Hubble parameter during inflation. Assuming the axion explains the total dark matter density, i.e., $r = 1$, and $\Omega_a \propto \theta_*^2$ as in Eq. (19), we obtain $\mathcal{P}_S \simeq (H_{\rm inf}/\pi a_*)^2$. Then the observational bound reads[12]

$$H_{\rm inf} \lesssim 3 \times 10^9\ {\rm GeV} \left(\frac{a_*/f_a}{0.2} \right) \left(\frac{f_a}{5 \times 10^{14}\ {\rm GeV}} \right). \tag{33}$$

In Fig. 1 we show the region excluded by the isocurvature constraints in the plane of the saxion mass and the Hubble parameter during inflation. Among the 5 parameters, $H_{\rm inf}$, m_σ, m_a, f_a, and θ_*, the dark matter abundance and the observed X-ray line fix 3 of them, the axion mass, the decay constant, and a combination of m_σ and θ_*. Then we can express the initial misalignment angle and the reheating temperature as a function of the saxion mass by using (19), as one can see the contours of $T_R = 1, 10^2, 10^4, 10^6$ GeV in the figure. We have set $f_a = 5 \times 10^{14}$ GeV. We also show the region excluded by the big bang nucleosynthesis where the reheating temperature is below 10 MeV [54].

The isocurvature perturbations can be suppressed if the axion acquires a large mass during inflation by some non-perturbative dynamics, which disappears after inflation. For instance, if the Higgs field has a large expectation value during inflation, the QCD interactions become strong at an intermediate or high energy scale, generating a heavy mass to the axion [55].

3.5. Baryogenesis

In our scenario the saxion dominates the Universe and reheats the SM sector. Because of a relatively large decay constant, the reheating temperature tends to be low, as one can see from Fig. 1. This could be an obstacle for creating the right amount of baryon asymmetry. Here we briefly mention a couple of possible ways to generate baryon asymmetry.

The saxion decays into the SUSY particles with an unsuppressed rate, and so, the LSPs would overclose the Universe unless the R-parity is broken. To avoid this problem we have assumed that the R-parity is explicitly broken. In fact, the right amount of baryon asymmetry can be generated through CP violating decay of gluino into quark and squark followed by baryon-number violating squark decay [56]. (See also Refs. [57,58].) For this saxion-induced baryogenesis to work, we introduce the R-parity and baryon-number violating operator,

$$W = \frac{1}{2} \lambda_{ijk} U_i^c D_j^c D_k^c, \tag{34}$$

where U_i^c and D_j^c are the $SU(2)_L$ singlet up-type and down-type quarks, respectively, and i, j, k are flavor indices. The required CP phase between the gaugino mass and the A-term of the above operator can be generated from the relative phase between the non-perturbative terms[13] through a mixed modulus-anomaly mediation of the heavy moduli X_i [56]. The resultant baryon asymmetry is given by

$$\frac{n_B}{s} \simeq 3 \times 10^{-10} \frac{|\kappa|^2}{\sqrt{1+|\kappa|^2}} \left(\frac{m_\sigma}{10^6\ {\rm GeV}} \right)^{1/2} \times \left(\frac{f_a}{5 \times 10^{14}\ {\rm GeV}} \right)^{-1} \left(\frac{\epsilon_B}{10^{-4}} \right), \tag{35}$$

[11] The saxion is considered to be deviated from the low-energy minimum during inflation, which may change the isocurvature perturbations by a factor of $\mathcal{O}(1)$.

[12] After submission of this letter, the BICEP2 experiments reported detection of the primordial B-mode polarization [51]. Although it needs confirmation by other experiments, the results suggest the inflation scale much higher than this bound. There are a couple of ways to resolve this tension. For instance, if the axion is so heavy during inflation, the isocurvature perturbations can be suppressed [52,53].

[13] In Eq. (5), we can add exponential terms of X_i without modifying the discussion so far. Then the relative phases among the non-perturbative terms source the CP phase.

where we have set $g_*(T_R) = 106.75$, and ϵ_B denotes the effective baryon number generated by a single gluino decay. Also we assumed that only λ_{332} is non-zero and of order unity, and in this case, the efficiency coefficient is given by $\epsilon_B \lesssim 10^{-2}$, where the upper bound is saturated for the maximal CP phase. Therefore, the right amount of baryon asymmetry can be generated for the saxion mass of our interest. For the saxion mass of $\mathcal{O}(10^{4-5})$ GeV, the typical soft mass for the SUSY SM particles is in the TeV range. Then, some of them may be within the reach of LHC, and also, a part of the parameter space can be probed by the dinucleon decay search experiment and the measurement of the electric dipole moments of neutron and electron [56].

For the saxion mass $m_\sigma \gtrsim 10^{10}$ GeV, the reheating temperature becomes high enough for non-thermal leptogenesis [59] to work, if the saxion mainly decays into the right-handed neutrinos [39]. Another possibility is to generate a large amount of the baryon asymmetry by the Affleck–Dine mechanism [60,61].

4. Discussion and conclusions

There appear many moduli fields in the low energy through compactifications of extra dimensions in superstring theories. Some of the moduli fields may remain light after the closed string flux is turned on. We have focused on a modulus field which is stabilized by the SUSY breaking effect and its axion component remains much lighter than the saxion component. As long as the strong CP problem is solved by the string-theoretic QCD axion, there must be at least one such modulus field, and in general, there might be more. As such moduli fields tend to be lighter than those stabilized by the non-perturbative effects *a la* KKLT, they likely play an important cosmological role.

We have proposed a scenario in which the saxion component of such modulus field dominates the energy density of the Universe and reheats the SM sector via its dilatonic couplings, while its axion partner contributes to dark matter decaying into photons via the same dilatonic coupling to photons in SUSY. The point is that both the reheating of the Universe and the decay of dark matter into photons are induced by the same supermultiplet (i.e. saxion and axion) through the same operator in SUSY. This observation partially explains why dark matter decays into photons at all. If there are light axions, one of them can easily explain the dark matter abundance as the axions are copiously generated by coherent oscillations. Then, there is no special reason why the axion dark matter should be coupled to photons. The situation changes if the bosonic partner, the saxion, dominates the Universe and reheats the SM sector through the same operator in SUSY. In this case, the axion dark matter must be coupled to the SM sector, in order for successful reheating. In other words, the decaying dark matter can be a probe of the reheating of the Universe.

We have also discussed the saxion decay process, the HDM constraint on the axions produced by the saxion decay, the isocurvature constraint on the axions produced by coherent oscillations, and the baryogenesis scenarios. Some of our results, especially those about the nature of axion dark matter (i.e. abundance, lifetime and isocurvature constraints), can be straightforwardly applied to the case in which the saxion does not dominate the Universe. This is likely the case e.g. if the Hubble parameter during inflation is smaller than the saxion mass.

Interestingly, for the axion mass $m_a \simeq 7$ keV and the decay constant $f_a \simeq 10^{14-15}$ GeV, the recently discovered X-ray line at 3.5 keV in the XMM Newton X-ray observatory data can be explained by the decay of the axion dark matter. The suggested value of the decay constant is within the expected range for the string-theoretic axion. It is of course possible to consider field-theoretic axions or pseudo Nambu–Goldstone bosons of mass 7 keV which have couplings to photons with a similar strength. The detailed X-ray line search in future may not only probe the nature of dark matter but also unravel the very early history of our Universe as well as physics close to the GUT scale.

Acknowledgements

This work was supported by Grant-in-Aid for Scientific Research on Innovative Areas (Nos. 24111702, 21111006, and 23104008) [FT], Scientific Research (A) (Nos. 22244030 and 21244033) [FT], and JSPS Grant-in-Aid for Young Scientists (B) (No. 24740135 [FT] and No. 25800169 [TH]), and Inoue Foundation for Science [FT]. This work was also supported by World Premier International Center Initiative (WPI Program), MEXT, Japan [FT].

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