Cluster X-ray line at 3.5\,keV from axion-like dark matter

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Abstract

The recently reported X-ray line signal at $E_{\gamma} \simeq 3.5\,\text{keV}$ from a stacked spectrum of various galaxy clusters and Andromeda galaxy may be originated from a decaying dark matter particle of the mass $2E_{\gamma}$. A light axion-like scalar is suggested as a natural candidate for dark matter and its production mechanisms are closely examined. We show that the right amount of axion relic density with the preferred parameters, $m_a \simeq 7\,\text{keV}$ and $f_a \simeq 4 \times 10^{14}\,\text{GeV}$, is naturally obtainable from the decay of inflaton or saxion decay. The small misalignment angles of the axion, $\theta_a \sim 10^{-4} - 10^{-1}$, depending on the reheating temperature, can be also the source of axion production. The model satisfies the constraints required for structure formation and iso-curvature perturbation.

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1 Introduction

It has been recently reported by two groups [1, 2] that there exists an unidentified line in a stacked X-ray spectrum of galaxy clusters and Andromeda galaxy at an energy, \( E_\gamma \approx 3.5 \text{ keV} \), after the EPIC data of XMM-Newton observations [3] were analyzed. As a result, the measured line energy and flux are consistent with monochromatic photon(s) due to a decaying dark matter (DM), having the mass of \( m_{\text{DM}} \sim 7 \text{ keV} \) and the lifetime of \( \tau_{\text{DM}} \sim 10^{28} \text{ sec} \). It is intriguing that the X-ray spectrum of galaxy clusters at different redshifts shows a consistent line signal for dark matter. For a further confirmation of the observed X-ray line, however, we need more objects and a better spectral resolution as in Astro-H mission [4]. It has been shown that the observed X-ray line signal can be explained well by the decay of sterile neutrino that appears in a minimal extension of the Standard Model explaining observed small neutrino masses [1, 2, 5]. Nonetheless, it would be worthwhile to investigate alternative dark matter models for the X-ray line [6].

We consider an axion-like dark matter for explaining the 3.5 keV X-ray line \(^\dagger\). Axion-like particles are ubiquitous in string compactifications and QCD axion models, etc, as they appear as pseudo-Goldstone bosons at low energies after the breakdown of accidental global symmetries [7]. When the axion-like scalar with 7 keV decays into a pair of photons due to anomaly interactions, it can accommodate the observed X-ray line consistently with the axion decay constant, \( f_a \approx 4 \times 10^{14} \text{ GeV} \). Furthermore, we discuss the mechanisms for producing the correct relic density of axion-like dark matter by either the axion misalignment or the non-thermal production from the decay of the inflaton or the scalar partner of axion, so called saxion. Depending on the temperature at which axion or saxion starts to oscillate coherently and on whether saxion decays after or before reheating after inflation, we divide our discussion into different scenarios of the axion production and impose on each case the bounds coming from structure formation and iso-curvature perturbations.

The paper is organized as follows. We begin with a description of the model for axion-like dark matter explaining the X-ray line and discuss the cosmological bounds involved with the non-thermal production of axions and the axion misalignment angle. Then, various scenarios of axion production will be discussed in the cases of inflaton/saxion decays and axion misalignment. Then, conclusions will be drawn.

2 A keV scale axion for the X-ray line

The recently reported X-ray line at about 3.5 keV may be explained by a 7-keV dark matter decaying two photons. Axion-like scalar is a very good candidate for such a light dark matter. In this section, assuming that the X-ray line spectrum stems from a 7-

\(^\dagger\)We note that there appeared a related paper on keV axion dark matter [8, 9] while we were finalizing our work.
keV axion dark matter, we discuss the necessary properties of the axion and possible cosmological constraints on that.

2.1 Axion properties

We introduce an axion-like particle as a pseudo-Goldstone scalar associated with a broken anomalous $U(1)$ symmetry. After the symmetry-breaking, the model-independent effective Lagrangian for axion $a$ and saxion $s$ (the radial component of the symmetry breaking field) can be expressed as

\[ L = \frac{1}{2} (\partial_\mu s)^2 + \frac{1}{2} (\partial_\mu a)^2 - \frac{s}{2 f_a} (\partial_\mu a)^2 - \frac{1}{2} m_s^2 s^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
+ \frac{c_1 \alpha_{em}}{8\pi f_a} (a F_{\mu\nu} - s F_{\mu\nu}) + \frac{c_2}{f_a} (\partial_\mu a) f^\gamma_5 \gamma^5 f + i f \not\!D_{\mu} f + m_f f \bar{f} \\
- (m_f e^{c_3 (s+ia)/f_a} \bar{f}_L f_R + h.c.) + L_I \]  

where $\alpha_{em}$ is the fine structure constant of electromagnetic interaction, $f_a$ is the axion coupling constant, and $F_{\mu\nu}$ and $\tilde{F}_{\mu\nu}$ are the field-strength tensor and its dual for electromagnetic field, respectively. We note that $c_{1,2,3}$ are dimensionless parameters of order one and we have included an extra charged fermion $f$ that is responsible for the generation of anomalies. Here, the saxion interactions are motivated by a supersymmetric axion model [10] where the axion chiral multiplet $A$ with $A|_{\theta=0} = s + ia$ appears in the superspace interactions as $\int d^2\theta A W^\alpha W_\alpha$ and $\int d^2\theta m_f e^{c_3 A/f_a} \Phi_L \Phi_R$ where $W_\alpha$ is the field strength superfield and $\Phi_{L,R}$ are matter chiral multiplets containing the extra charged fermion. We can add the Lagrangian for inflation by $L_I$.

For a keV-scale axion, the first term of the second line in Eq. (1) provides the main decay channel with a rate given by

\[ \Gamma_{a \rightarrow \gamma \gamma} = \frac{\alpha_{em}^2 m_a^3}{64\pi^3 f_a^2}. \]  

where we set $c_1 = 1$ for simplicity. This axion decay can be a possible origin of the recently reported X-ray spectrum if the axion saturates the dark matter relic density and has the following properties [1,2]

\[ m_a = 7.1 \text{ keV}, \quad \tau_a = 1.14 \times 10^{28} \text{ sec} \rightarrow \Gamma_a = 5.73 \times 10^{-53} \text{ GeV} \]  

where $\tau_a$ is the life-time of axion. This implies that the axion coupling constant should be

\[ f_a \approx 4 \times 10^{14} \text{ GeV} \left( \frac{m_a}{7 \text{ keV}} \right)^{3/2}. \]  

2.2 Cosmological constraints

Our keV-scale axion can be constrained by astrophysics and cosmology, namely, structure formation or iso-curvature perturbation of dark matter, depending on how it is produced.
2.2.1 Structure formation

The keV axion may be a decay product of the inflaton and/or saxion. Suppose that the mother particle, denoted as $X$, decays to two axions, each of which carries the energy of

$$E_{a,i} = m_X/2$$  \hspace{1cm} (5)$$

when the axion mass is ignored. Then, in order not to destruct large scale structures, axion should be non-relativistic around the epoch when a Hubble patch contains mass energy corresponding to the galactic-sized halo (corresponding to $T \sim T_\ast \equiv 300$ eV) (see for example [11,12]). This implies that

$$p_a(t_\ast) = p_{a,i} \left( \frac{g_{*S}(T_\ast)}{g_{*S}(T_i)} \right)^{1/3} \left( \frac{T_\ast}{T_i} \right) < m_a \Rightarrow T_i > 5.8 \times 10^{-3} m_X \left( \frac{7 \text{keV}}{m_a} \right)$$  \hspace{1cm} (6)$$

where the initial momentum of axion is $p_{a,i} \simeq E_{a,i}$ for $E_{a,i} \gg m_a$, $g_{*S}(T)$ is the relativistic degrees of freedom at a temperature $T$, and $T_i$ is the background temperature when axion is produced from the decay of the mother particle $X$. Here, we used $g_{*S}(T_\ast) = 3.9$ and $g_{*S}(T_i) = 200$ for obtaining the lower bound of $T_i$.

2.2.2 Isocurvature perturbation

If axion dark matter is produced mainly from the coherent oscillation caused by axion misalignment, it is subject to the bound on dark matter iso-curvature perturbation. The recent Planck data combined with WMAP polarization data leads to a constraint on the fraction of iso-curvature perturbation by [13],

$$\frac{P_S}{P_R} < 0.041,$$  \hspace{1cm} (7)$$

at 95% CL, where $P_R \simeq 2.2 \times 10^{-9}$ and $P_S$ are the power spectrum of curvature and iso-curvature perturbations, respectively. The iso-curvature perturbation of axion dark matter can be expressed as [14]

$$P_S = \left( \frac{\partial \ln \Omega_a}{\partial a_{osc}} \frac{H_I}{2\pi} \right)^2$$  \hspace{1cm} (8)$$

where $a_{osc}$ is the initial oscillation amplitude of axion caused by misalignment, $H_I$ is the expansion rate during inflation, and we assumed axion dark matter from the misalignment saturates the observed relic density of dark matter. As described in the next section, for $a_{osc} \ll f_a$, $\Omega_a \propto a_{osc}^2$, hence one finds

$$H_I \lesssim 1.2 \times 10^6 \text{GeV} \left( \frac{a_{osc}/f_a}{10^{-4}} \right) \left( \frac{f_a}{4 \times 10^{14} \text{GeV}} \right)$$  \hspace{1cm} (9)$$
3 Scenarios of axion production

Axion-like scalars can be produced from decays of heavy particles or coherent oscillations. In this section, we discuss how we can obtain a right amount of keV-scale axion while satisfying various constraints given in the previous section. In particular, we consider the axion production from inflaton/saxion decay and axion misalignment in both cases of high and low reheating temperature after primordial inflation. In order to match the relic density of dark matter to the observed one, $\Omega_a = 0.268$ [13], we quote the necessary axion abundance at present as

$$Y_a \simeq 6.9 \times 10^{-5} \left( \frac{7 \text{ keV}}{m_a} \right).$$

(10)

3.1 Inflaton decay

In inflation scenarios where inflation is responsible for the density perturbation of the present universe, inflation should decay mainly to SM particles. It can also partially decay to axions we are considering now. In the sudden decay approximation, the axion abundance from such a partial decay of inflaton is given by

$$Y_a = \frac{3 T_R}{4 m_I} \frac{\text{Br}(I \to aa)}{\text{Br}(I \to \text{SM})} \simeq 7.5 \times 10^{-3} \frac{\text{Br}(I \to aa)}{T_R/m_I} \left( \frac{10^{-2}}{10^{-2}} \right)$$

(11)

where $\text{Br}(I \to aa)$ and $\text{Br}(I \to \text{SM})$ are respectively the branching fraction of inflaton ($I$) to axions and to SM particles, and $T_R$ and $m_I$ are the reheating temperature and mass of inflaton, respectively. We assumed $\text{Br}(I \to \text{SM}) \simeq 1$ in the far right side of Eq. (11). Compared to Eqs. (6) and (10), we find that a right amount of axion relic density can be obtained while satisfying the constraint from structure formation, provided that

$$\frac{T_R}{m_I} \gtrsim 5.8 \times 10^{-3}, \quad \text{Br}(I \to aa) \lesssim 1.6 \times 10^{-2}. \quad (12)$$

3.2 Saxion decay

The saxion, the radial component of the complex field containing axion, can play a crucial role in axion production, since it can decay into a pair of axions via the axion kinetic term,

$$L \supset \frac{1}{2} \frac{s}{f_a} (\partial a)^2.$$ 

(13)

In this case, the decay rate of saxion to a pair of axions is given by

$$\Gamma_{s \to aa} = \frac{1}{64\pi} \frac{m_s^3}{f_a^2}.$$ 

(14)
In the presence of an extra heavy charged fermion coupled with saxion via a Yukawa coupling in the following form,
\[ \mathcal{L} \supset -\lambda s \bar{f} f, \]  
(15)
there is an additional contribution to the saxion decay rate,
\[ \Gamma_{s \rightarrow \bar{f} f} = \frac{\lambda^2}{8\pi} m_s \left(1 - \frac{4m_f^2}{m_s^2}\right)^{3/2} \]
\[ = \frac{c_3^2 m_f^2 m_s}{8\pi f_a^2} \left(1 - \frac{4m_f^2}{m_s^2}\right)^{3/2} \]
(16)
where in the second line, use is made of the Yukawa interaction from the effective Lagrangian in Eq. (1). Then, for \( \Gamma_{s \rightarrow aa} \ll \Gamma_{s \rightarrow \bar{f} f} \), the branching fraction of saxion decaying to a pair of axions is given by
\[ \text{Br}(s \rightarrow aa) \simeq \frac{m_s^2}{8c_3^2 m_f^2} > \frac{1}{2c_3^2}. \]
(17)
Thus, for \( |c_3| \gtrsim 7 \), we can obtain a small branching fraction, \( \text{Br}(s \rightarrow aa) \sim 10^{-2} \), as required for structure formation in a later discussion.

In the early universe, saxion might be at the broken phase with \( H_I \gtrsim m_s \), but could undergo a coherent oscillation as \( H \lesssim m_s \). Then, the saxion decay might be the main source of axion production, although structure formation constrains the branching fraction to axions, similarly to the case of inflaton decay. In the following argument, for simplicity, we express the full decay width of saxion as
\[ \Gamma_s = \Gamma_{s \rightarrow aa}/\text{Br}(s \rightarrow aa) \]
(18)
and we will use the sudden decay approximation for saxion decay.

### 3.2.1 High \( T_R \)

If inflaton decays before saxion starts its oscillation, from Eq. (18) and
\[ T_i = \left(\frac{\pi^2}{90} g_*(T_i)\right)^{-1/4} \sqrt{\Gamma_{s \rightarrow aa} M_{Pl}/\text{Br}(s \rightarrow aa)}, \]
(19)
with \( g_*(T_i) = 200 \), we find that the constraint from structure formation (Eq. (6)) is translated to
\[ m_s > 2.1 \times 10^7 \text{GeV} \left(\frac{\text{Br}(s \rightarrow aa)}{10^{-2}}\right) \left(\frac{f_a}{4 \times 10^{14} \text{GeV}}\right)^2 \left(\frac{7 \text{keV}}{m_a}\right)^2. \]
(20)
Then, putting Eq. (20) back to Eq. (6), we find

\[ T_i \gtrsim 1.2 \times 10^5 \text{GeV} \left( \frac{\text{Br}(s \rightarrow aa)}{10^{-2}} \right) \left( \frac{f_a}{4 \times 10^{14} \text{GeV}} \right)^2 \left( \frac{7 \text{keV}}{m_a} \right)^3. \]  

(21)

In order to get a right relic density for axion from the saxion decay by

\[ Y_a = 2 \text{Br}(s \rightarrow aa) Y_s(t_i), \]  

(22)

and Eq. (10), the required saxion abundance should be

\[ Y_s(t_i) \simeq 3.5 \times 10^{-3} \left( \frac{10^{-2}}{\text{Br}(s \rightarrow aa)} \right) \left( \frac{7 \text{keV}}{m_a} \right). \]  

(23)

If saxion is produced via coherent oscillation while universe is dominated by radiation, we obtain

\[ Y_s(t_i) = Y_s(t_{s, \text{osc}}) \]  

where \( Y_s(t_{s, \text{osc}}) \) is the initial abundance of saxion in coherent oscillation, given by

\[ Y_s(t_{s, \text{osc}}) \sim \left( \frac{f_a}{M_{\text{Pl}}} \right)^2 \left( \frac{M_{\text{Pl}}}{m_s} \right)^{1/2} \simeq 4.3 \times 10^{-4} \left( \frac{f_a}{4 \times 10^{14} \text{GeV}} \right)^2 \left( \frac{10^{10} \text{GeV}}{m_s} \right)^{1/2}. \]  

(24)

Here, we assumed that the initial saxion misalignment is almost the same as the axion decay constant \( f_a \). As shown in the left plot of Fig. 1, a right amount of axion relic density can be obtained only for \( m_s \lesssim \mathcal{O}(10^6) \text{GeV} \) with \( \text{Br}(s \rightarrow aa) \lesssim \mathcal{O}(10^{-3}) \), due to the constraint from structure formation.

Note that, if the decay of saxion is delayed, saxion starts to dominate the universe when the expansion rate becomes

\[ H_{\text{SD}} \sim m_s \left( \frac{f_a}{M_{\text{Pl}}} \right)^4 = 64 \pi \left( \frac{M_{\text{Pl}}}{m_s} \right)^2 \left( \frac{f_a}{M_{\text{Pl}}} \right)^6 \Gamma_{s \rightarrow aa} \]  

\[ \simeq 25 \left( \frac{\text{Br}(s \rightarrow aa)}{10^{-3}} \right) \left( \frac{10^6 \text{GeV}}{m_s} \right)^2 \left( \frac{f_a}{4 \times 10^{14} \text{GeV}} \right)^6 \Gamma_s. \]  

(25)

Therefore, the allowed region with \( \text{Br}(s \rightarrow aa) \lesssim \mathcal{O}(10^{-3}) \) in the left panel of Fig. 1 tends to be saxion-dominated. In such a case, the abundance of axion from the decay of saxion is given by

\[ Y_a \simeq \frac{3}{2} \text{Br}(s \rightarrow aa) \frac{T_{R,s}}{m_s}. \]  

(26)

where \( T_{R,s} \) is the late-time reheating temperature after the decay of saxion, and we assumed that saxion decays mainly to SM particles. Using Eq. (19) evaluated at \( T_{R,s} \), we obtain

\[ \frac{T_{R,s}}{m_s} \simeq 4.0 \times 10^{-4} \left( \frac{m_s}{\text{Br}(s \rightarrow aa)^{1/2}} \right) \left( \frac{10^6 \text{GeV}}{m_s} \right) \left( \frac{4 \times 10^{14} \text{GeV}}{f_a} \right). \]  

(27)
Figure 1: Bounds from the axion relic abundance produced after the saxion decay for $\Gamma_I > m_s$ with $f_a = 4 \times 10^{14}$ GeV and $m_a = 7$ keV. Left: The case of radiation domination at the time of saxion decay. In this case, Eqs. (23) and (24) were used. In the right side of dashed-red line, axion is relativistic. Right: The case of saxion domination at the time of saxion decay. In this case, Eq. (28) was used. In the region above the dashed-red line, axions are relativistic. In both plots, gray region is excluded due to too many axions.

As a consequence, in the case of saxion dominance, the axion abundance Eq. (26) becomes

$$Y_a \approx 7.6 \times 10^{-5} \times \left( \frac{\text{Br}(s \to aa)}{10^{-2}} \right)^{1/2} \left( \frac{m_s}{10^6 \text{ GeV}} \right)^{1/2} \left( \frac{4 \times 10^{14} \text{ GeV}}{f_a} \right).$$

Note that in the case of saxion domination, the constraint from structure formation still applies by $T_{R,s} \gtrsim 6 \times 10^{-3} m_s$. As shown in the right panel of Fig. 1 where $Y_a$ with Eq. (28) is depicted as a function of $m_s$ and $\text{Br}(s \to aa)$, the constraint from structure formation, shown in red-dashed line, limits the parameter space so that a right amount of axion dark matter can be obtained only for $\text{Br}(s \to aa) \lesssim 10^{-2}$.

3.2.2 Low $T_R$

Inflaton decay might be delayed to a time after axion production, i.e., $\Gamma_I < \Gamma_s$ which requires

$$m_s > \left[ \frac{\pi^2}{90} g_s(T_R) \times 64\pi \right]^{1/3} \left( \frac{f_a}{M_{Pl}} \right)^{2/3} \left( \frac{\text{Br}(s \to aa) T_R^2 M_{Pl}}{10^2} \right)^{1/3} \approx 6.6 \times 10^6 \text{ GeV} \left( \frac{f_a}{4 \times 10^{14} \text{ GeV}} \right)^{2/3} \left( \frac{\text{Br}(s \to aa)}{10^{-2}} \right)^{1/3} \left( \frac{T_R}{10^4 \text{ GeV}} \right)^{2/3}.$$ (29)
where we used
\[ \Gamma_I = \left( \frac{\pi^2}{90} g_*(T_R) \right)^{1/2} \frac{T_R^2}{M_{Pl}} \] (30)
with \( g_*(T_R) = 200 \). In this case, the constraint from structure formation reads
\[ p_a(t_*) = p_{a,i} \left( \frac{\Gamma_I}{\Gamma_s} \right)^{2/3} \left( \frac{g_{*S}(T_*)}{g_{*S}(T_R)} \right)^{1/3} \left( \frac{T_*}{T_R} \right) < m_a \] (31)
which results in
\[ m_s > \frac{1}{2} \left[ \frac{\pi^2}{90} g_*(T_R) \times 64\pi \text{Br}(s \to aa) \right]^{2/3} \left( \frac{g_{*S}(T_*)}{g_{*S}(T_R)} \right)^{1/3} \left( \frac{T_*}{m_a} \right) \left( \frac{f_a}{M_{Pl}} \right)^{4/3} \left( \frac{T_R M_{Pl}^2}{m_s} \right)^{1/3} \]
\[ \simeq 2.6 \times 10^7 \text{GeV} \left( \frac{7 \text{keV}}{m_a} \right) \left( \frac{f_a}{4 \times 10^{14} \text{GeV}} \right)^{4/3} \left( \frac{\text{Br}(s \to aa)}{10^{-2}} \right)^{2/3} \left( \frac{T_R}{10^4 \text{GeV}} \right)^{1/3} \] (32)
where \( g_{*S}(T_*) = 3.91 \) and \( g_{*S}(T_R) = 200 \) were used. If saxion starts its coherent oscillation as \( H \lesssim m_s \), the abundance of axion when inflaton decays is given as
\[ Y_a(T_R) \simeq \frac{1}{2} \text{Br}(s \to aa) \left( \frac{f_a}{M_{Pl}} \right)^2 \left( \frac{T_R}{m_s} \right) \]
\[ \simeq 1.4 \times 10^{-10} \left( \frac{\text{Br}(s \to aa)}{10^{-2}} \right) \left( \frac{f_a}{4 \times 10^{14} \text{GeV}} \right)^2 \left( \frac{T_R}{m_s} \right) \] (33)
Hence, we find that, once Eq. (32) is satisfied, axion abundance coming from the decay of saxion turns out to be too small if inflaton decays after axion production.

### 3.3 Axion misalignment

The keV-scale mass of axion is far below the typical mass scale of inflation. In addition, the mass of axion is generated by the anomaly only after the associated symmetry is broken. Hence, if the symmetry were broken after inflation, a typical axion misalignment would be of order of the axion decay constant. On the other hand, if the symmetry were broken before or during inflation, the amount of misalignment can be much smaller than the axion decay constant. In the following argument, we assume the latter case to allow a wide range of misaligned axion field values.

#### 3.3.1 High \( T_R \)

The energy density of axion at the onset of oscillation can be expressed as
\[ \rho_{a,osc} = \frac{1}{2} m_a^2 a_{osc}^2 \] (34)

8
where $a_{\text{osc}}$ is the initial oscillation amplitude, and $a_{\text{osc}} \ll f_a$ was assumed. We assume that inflaton decays before axion starts its oscillation. Then, the present abundance of misalignment axion is

$$Y_a = \frac{\sqrt{3}}{8} \left( \frac{\pi^2}{90} g_*(T_{\text{osc}}) \right)^{-1/4} \left( \frac{a_{\text{osc}}}{M_{\text{Pl}}} \right)^2 \left( \frac{M_{\text{Pl}}}{m_a} \right)^{1/2}$$

(35)

This can be consistent with the observed relic density if

$$a_{\text{osc}} \lesssim 8.2 \times 10^{10} \text{ GeV} \left( \frac{7 \text{ keV}}{m_a} \right)^{1/2}$$

(36)

where we used $g_*(T_{\text{osc}}) = 200$, and the upper-bound saturates the relic density.

A remark is in order here. Considering primordial inflation, one notice that such an intermediate scale misalignment with the symmetry-breaking scale larger than $a_{\text{osc}}$ by several orders of magnitude requires that the modulus associated with the axion should be in the broken phase during inflation so as for a Hubble patch to be occupied by a particular value of $a_{\text{osc}}$. In addition, as already shown in Eq. (9), for $a_{\text{osc}} \lesssim 10^{10} \text{ GeV}$, the expansion rate of the primordial inflation should be less than of order of $O(10^6) \text{ GeV}$ in order not to produce too much iso-curvature perturbation caused by perturbations of $a_{\text{osc}}$.

If there is a coherent oscillation of saxion, and the saxion decay is delayed to a very late time, saxion may dominate the universe at some point. Comparing the Hubble scale evaluated at saxion domination to the axion mass as

$$H_{\text{SD}} \sim \left( \frac{m_s}{m_a} \right) \left( \frac{f_a}{M_{\text{Pl}}} \right)^4 \simeq 7.7 \times 10^{-16} \left( \frac{m_s}{m_a} \right) \left( \frac{f_a}{4 \times 10^{14} \text{ GeV}} \right)^4,$$

(37)

we find that saxion domination can take place after the onset of axion oscillation for $m_s \lesssim 10^{10} \text{ GeV}$. In this case, the axion abundance from the misalignment is given by

$$Y_a \simeq \frac{1}{8} \left( \frac{a_{\text{osc}}}{M_{\text{Pl}}} \right)^2 \left( \frac{H_{\text{SD}}}{m_a} \right)^{1/2} \left( \frac{T_{R,s}}{m_a} \right)$$

(38)

where $T_{R,s}$ is the late-time reheating temperature from the decay of saxion, and we assumed that saxion decays mainly to SM particles. Hence, using Eqs. (27) and (37), we find

$$Y_a \sim 6.6 \times 10^{-5} \left( \frac{0.1}{\text{Br}(s \to aa)} \right)^{1/2} \left( \frac{a_{\text{osc}}/f_a}{0.1} \right)^2 \left( \frac{f_a}{4 \times 10^{14} \text{ GeV}} \right)^3 \left( \frac{m_s}{10^6 \text{ GeV}} \right)^2 \left( \frac{7 \text{ keV}}{m_a} \right)^{3/2}$$

(39)

In the case of saxion domination, we show $Y_a$ as a function of $m_s$ and $\text{Br}(s \to aa)$ in Fig. 2. The right panel of Fig. 1 was overlapped in the figure. As shown in the figure, a right amount of axion relic density can be obtained only from axion misalignment for $m_s \lesssim O(10^5) \text{ GeV}$ with $\text{Br}(s \to aa) \lesssim O(10^{-3})$. 
Figure 2: Bounds from the axion relic abundance produced due to axion misalignment, for \( a_{\text{osc}}/f_a = 0.1 \) with \( f_a = 4 \times 10^{14} \text{ GeV} \) and \( m_a = 7 \text{ keV} \). Bluish regions are excluded due to too many misalignment axions estimated from Eq. (39) for \( a_{\text{osc}}/f_a = 10^{-1}, 10^{-2}, 10^{-3} \) from left to right. Gray region (upper-right side of dotted gray line) and dashed-red line is taken from the right panel of Fig. 1.

### 3.3.2 Low \( T_R \)

Inflaton might decay at a very late time, and axion might start its oscillation when the universe is still dominated by inflaton. In this case, the axion abundance is given by

\[
Y_a = \frac{1}{8} \frac{T_R}{m_a} \left( \frac{a_{\text{osc}}}{M_{\text{Pl}}} \right)^2
\]

where \( T_R \) is the reheating temperature of inflaton. Hence \( a_{\text{osc}} \) is upper-bounded as

\[
\frac{a_{\text{osc}}}{f_a} \lesssim 4.8 \times 10^{-2} \left( \frac{4 \times 10^{14} \text{ GeV}}{f_a} \right) \left( \frac{10 \text{ MeV}}{T_R} \right)^{1/2}
\]

Note that, since \( T_R \gtrsim 10 \text{ MeV} \), saxion had to be in the broken phase before or during inflation, otherwise cold axion would be over-produced.

### 4 Conclusion

We proposed a simple model for keV-scale axion dark matter whose decay product into monochromatic photons can be the source of the recently reported X-ray spectrum at
about 3.5 keV. Such a light axion can be produced in the decay of a heavy particle or from the coherent oscillation of axion caused by misalignment. Depending on the axion production mechanisms and the amount of dark matter relic density, we showed how the keV-scale axion model is constrained by structure formation and iso-curvature perturbation.

We found that axions produced from the inflaton decay can saturate the observed relic density of dark matter while satisfying the constraint from structure formation, provided that the reheating temperature is higher than the inflaton mass by two orders of magnitude and the branching fraction of the inflaton decay to axions is less than about 0.01. In the case of saxion decay, we considered the case that inflaton decays first, and saxion, which in the broken phase, then starts its coherent oscillation. In this case, saxion mass should be about $10^6$ GeV for the branching fraction of saxion into axions of about $10^{-3}$. The smaller the branching fraction is, the smaller the saxion mass is required. If the saxion of coherent oscillation dominates the universe at a later time, a wider range of parameter space is allowed. On the other hand, if inflaton decays at a late time after the decay of saxion, the axion relic density cannot saturate the observed dark matter relic density, without disturbing the structure formation due to relativistic axions.

In the case of axion misalignment, if inflaton decays before axion starts its oscillation, the misalignment angle $\theta_a$ should be about $10^{-4}$ to saturate the relic density. On the other hand, if the reheating temperature of primordial inflation is about 10 MeV, it is possible to have a natural value of $\theta_a \sim 0.1$. In saxion domination, the misalignment axion constrains the parameter space more such that some allowed region of axions produced in the case of saxion decay is removed, although the limitation depends on the misalignment angle.

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