Axion-Photon Conversion and Effects on 21cm Observation

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Abstract

Recently the EDGES experiment reported an enhanced 21cm absorption signal in the radio wave observation, which may be interpreted as either anomalous cooling of baryons or heating of cosmic microwave background photons. In this paper, we pursue the latter possibility. We point out that dark radiation consisting of axion-like particles can resonantly convert into photons under the intergalactic magnetic field, which can effectively heat up the radiation in the frequency range relevant for the EDGES experiment. This may explain the EDGES anomaly.
1 Introduction

Recently the EDGES experiment announced a measurement of the cosmic radio background flux at the frequency range 50 MHz–100 MHz to search for the 21 cm absorption signal at the epoch of redshift $z \sim 20$, and found anomalously large absorption than that expected in the standard reionization models [1]. They measured the 21 cm brightness temperature relative to that of the cosmic microwave background (CMB), which is given by [2, 3]

$$T_{21}(z) \simeq 23 \text{ mK} \times x_{\text{HI}}(z) \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_m h^2} \right)^{1/2} \left( 1 - \frac{T_\gamma(z)}{T_S(z)} \right),$$

where $x_{\text{HI}}$ is the neutral fraction of the hydrogen atom, $T_\gamma$ is the brightness temperature of the CMB, $T_S$ is the spin temperature, $\Omega_b$ and $\Omega_m$ are the density parameters of the baryon and matter and $h$ is the present Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. It was realized [1] that the result may indicate that either the baryon gas temperature is lower than the standard scenario by a factor $\sim 2$ to reduce the spin temperature by a factor $\sim 2$ #1 or the CMB brightness temperature at that frequency range is higher by a factor $\sim 2$. The former interpretation was achieved by introducing relatively large scattering of baryon with dark matter so that the kinetic energy of baryon is transferred to dark matter [6]. However, this explanation was soon challenged and actually highly constrained by cosmological observations and laboratory experiments [7–9]. Since then various new constraints on dark matter from this measurement has also been studied [10–16].

As for the latter possibility, one may introduce light particles decaying into photons with CMB Rayleigh-Jeans tail frequency range, but it is found that the required decay rate to explain the anomaly is so large that it requires some additional mechanism to enhance the energy injection rate such as minicluster [10].

A simple alternative scenario along the latter possibility was considered in Ref. [17], where it is proposed that the hidden photon background, existing as dark radiation, are resonantly converted into photons through the kinetic mixing at the redshift $20 < z < 1700$. Since the number of hidden photons can be many orders of magnitude larger than the CMB photon number density at the Rayleigh-Jeans tail frequency range, even a small conversion rate can lead to a factor 2 enhancement of the CMB brightness temperature.

In this paper, motivated by the EDGES result, we consider axion-like particle (ALP) dark radiation, which are resonantly converted into photons. The existence of ALPs may be ubiquitous in string-theoretic framework and their masses and decay constants can take wide range of values [18]. Moreover, there is evidence of the existence of the primordial magnetic field $B_0 \gtrsim 10^{-17} \text{ G}$ on Mpc scales [19]. On these grounds, we examine the possibility that the ALP conversion into photon under the primordial magnetic fields explains the EDGES anomaly #2. Cosmological effects of (resonant) axion conversion into the photon have been

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#1 Around the epoch of $z \sim 17$, Lyman $\alpha$ photons are produced by stars and they couple the gas temperature to the spin temperature [45].

#2 See also Refs. [20, 21] for some other relations between the axion and 21cm signal, and Ref. [22] for modification of recombination history.
considered in Refs. [23–25], but the case of axion dark radiation with energy much lower than the CMB photon was not considered so far. We will show that actually the axion dark radiation with such low energy can modify the CMB spectrum of its Rayleigh-Jeans tail and hence it can affect the 21cm observation.

2 Resonant conversion of axion into photon

The ALP, represented by $a$, is assumed to have a coupling to photon as

$$\mathcal{L} = -\frac{1}{4} g_a a F_{\mu\nu} \tilde{F}^{\mu\nu},$$

(2)

where $F_{\mu\nu}$ is the electromagnetic field strength tensor, $\tilde{F}^{\mu\nu}$ is its dual, and $g_a$ represents the strength of the ALP-photon coupling. Under the background magnetic field $\vec{B}$, it gives an effective mixing between the ALP and photon [26]. Let us consider ALP/photon with energy $E$ which passes through the region with non-vanishing magnetic field. The effective mass matrix of the ALP and photon looks like

$$\mathcal{M}^2 = \begin{pmatrix} m_a^2 & Eg_a B_\perp \\ Eg_a B_\perp & \omega_p^2 \end{pmatrix},$$

(3)

where $B_\perp$ denotes the strength of the magnetic field perpendicular to the ALP/photon momentum direction and we have included the effective photon mass, the so-called plasma frequency,

$$\omega_p(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}} \simeq 1.9 \times 10^{-14} \text{eV} \ (1+z)^{3/2} X_e^{1/2}.$$  

(4)

Here $\alpha$ is the electromagnetic fine structure constant, $m_e$ is the electron mass, $z$ is the redshift, and $X_e$ denotes the ionization fraction of the hydrogen atom. The mixing angle between photon and ALP is found to be

$$\sin^2(2\theta) = \frac{(2Eg_a B_\perp)^2}{(2Eg_a B_\perp)^2 + (\omega_p^2 - m_a^2)^2}.$$  

(5)

Since $\omega_p(z)$ changes with Hubble expansion, there is an epoch, denoted by $z = z_{\text{res}}$, at which $\omega_p^2$ becomes equal to $m_a^2$ for a certain range of ALP mass. For the resonant conversion to happen after the matter-radiation equality, for example, the ALP mass should be in the following range: $m_a \sim 10^{-14} \text{eV} - 10^{-9} \text{eV}$. Then the mixing angle becomes maximum and the resonant conversion of the ALP into photon (or the opposite process) happens [23,27]. The conversion probability of the ALP into photon after the resonance is [27]

$$P_{a\rightarrow\gamma} = \frac{1}{2} \left[ 1 - \exp \left( -\frac{2\pi r g_a^2 B_\perp^2 E}{m_a^2} \right) \right] \simeq \frac{\pi r g_a^2 B_\perp^2 E}{m_a^2},$$

(6)
Figure 1: The conversion probability $P_{a \rightarrow \gamma}$ as a function of the redshift at the resonance $z_{\text{res}}$. We have used $g_a B_0 = 10^{-12} \text{GeV}^{-1} \text{nG}$ and $E_0 = 0.3 \mu \text{eV}$ for illustration.

where, denoting the expansion rate of the Hubble parameter as $H$,

$$r^{-1} \equiv \frac{d \ln \omega_p}{dt} = 3H + \frac{d \ln X_e}{dt},$$

(7)

with all quantities being evaluated at $z = z_{\text{res}}$. Here, we have assumed the probability is much smaller than unity in the last similarity of (6). As we will see below, such a condition holds for the case of our interest. Note that in a cosmological setup, the relative direction of $\vec{B}$ is random against the ALP/photon momentum direction, and hence $B_\perp^2$ in (6) should be regarded as $\langle B_\perp^2 \rangle = B^2/3$. We assume $B(z) = B_0(1 + z)^2$\textsuperscript{19}.

In Fig. 1 we show the conversion probability $P_{a \rightarrow \gamma}$ as a function of redshift at the resonance, $z_{\text{res}}$. We have taken $g_a B_0 = 10^{-12} \text{GeV}^{-1} \text{nG}$ and $E_0 = 0.3 \mu \text{eV}$ for illustration (with $E_0$ being the present energy of ALP/photon); the EDGES frequency range 50 MHz–100 MHz corresponds to $E_0 \simeq (0.2 - 0.4) \mu \text{eV}$\textsuperscript{3}. We have used HyRec code for the calculation of $X_e$\textsuperscript{29}. The sudden jump around redshift $z \simeq 1000$ is due to the recombination effect. At the recombination epoch the ionization fraction $X_e$ decreases dramatically, which leads to a much smaller plasma mass. Therefore, the probability of the resonant conversion is greatly enhanced for $z_{\text{res}} \lesssim 1000$. We also give an approximate formula of the conversion probability as

\textsuperscript{#3} The relation between energy $E$ and frequency $f$ is given as $E = 2\pi f \simeq 4.14 \mu \text{eV}(f/1 \text{GHz})$.  

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In the above expression, we have assumed that the resonance happens in the matter-dominated era and approximated $r \sim (3H)^{-1}$. Note that $m_a^2 \propto (1 + z_{\text{res}})^3$ and hence Eq. (8) is weakly dependent on $z_{\text{res}}$ as $P_{a\rightarrow\gamma} \propto \sqrt{1 + z_{\text{res}}}$. Note also that such low-energy photons may experience bremsstrahlung absorption above the redshift $z \gtrsim 1700$ [28], and hence the resonant redshift may be constrained as $z_{\text{res}} \lesssim 1700$.

We have made several assumptions for deriving the conversion probability. One is that the oscillation length is shorter than the typical coherent length of the magnetic field. The oscillation length is given by

$$\ell_{\text{osc}} \sim \frac{4E_{0}}{|\omega_{p}^{2} - m_{a}^{2}|} \bigg|_{z = z_{\text{res}}} \sim \frac{4\sqrt{Er}}{m_{a}} \bigg|_{z = z_{\text{res}}} \sim 1.1 \times 10^{28} \text{eV}^{-1} \left( \frac{10^{-14} \text{eV}}{m_{a}} \right) \left( \frac{E_{0}}{1 \mu\text{eV}} \right)^{1/2} (1 + z_{\text{res}})^{-1/4},$$

where we have assumed that the resonance happens in the matter-dominated era and approximated $r \sim (3H)^{-1}$ in the last line. The coherent length of the magnetic field is assumed to be [19]

$$\ell_{B} \sim 1 \text{Mpc} (1 + z)^{-1} \simeq 1.6 \times 10^{29} \text{eV}^{-1} (1 + z)^{-1}.$$

The other condition is that the oscillation length is shorter than the mean free path of the photon,

$$\ell_{\gamma} = (\sigma_{T} n_{e})^{-1} = \frac{3m_{a}^{2}}{8\pi\alpha^{2}n_{e}} \simeq 3.0 \times 10^{35} \text{eV}^{-1} (1 + z)^{3} X_{e}^{-1},$$

where $\sigma_{T}$ denotes the cross section of Thomson scattering. For the parameters of our interest $20 \lesssim z_{\text{res}} \lesssim 1700$, $\ell_{\text{osc}}$ is typically smaller than $\ell_{B}$ and $\ell_{\gamma}$ and hence we can use (6) as a conversion probability.

### 3 Effect of ALP-photon conversion on the CMB

Let us consider a process that a moduli-like scalar field $\phi$ decays into the ALP pair, $\phi \rightarrow aa$ and assume that the interaction of ALP is weak enough so that ALPs are regarded as free particles. The ALP number density spectrum at the redshift $z$ is given as

$$E \frac{dn_{a}}{dE}(z) = \frac{2n_{\phi}(z_{i})a^{3}(z_{i})}{\tau_{\phi} H(z_{i})a^{3}(z)},$$

where $n_{\phi}(z_{i})$ and $a^{3}(z_{i})$ are the number density and scale factor at the time of the decay, respectively, and $\tau_{\phi}$ is the lifetime of the scalar field. The conversion probability $P_{a\rightarrow\gamma}$ is given by

$$P_{a\rightarrow\gamma} = 1.7 \times 10^{-7} \left( \frac{E_{0}}{1 \mu\text{eV}} \right) \left( \frac{g_{a}}{10^{-11} \text{GeV}^{-1}} \right)^{2} \left( \frac{B_{0}}{1 \text{nG}} \right)^{2} \left( \frac{10^{-14} \text{eV}}{m_{a}} \right)^{2} (1 + z_{\text{res}})^{7/2}.$$
where \( m_\phi \) and \( \tau_\phi \) are the mass and lifetime of \( \phi \) respectively, \( E' = E(1 + z')/(1 + z) \) and \( z_i \) is the redshift at the production of the ALP with energy \( E \) at \( z \), which is given by \( 1 + z_i = m_\phi(1 + z)/(2E) \). The number density of \( \phi \) is given by

\[
n_\phi(z) = Y_\phi s(z) \exp\left(-\frac{t(z)}{\tau_\phi}\right),
\]

where \( Y_\phi \) parametrizes the number density of \( \phi \). The total ALP energy density is given by

\[
\rho_a(z) = \int dE E \frac{dn_a}{dE}(z).
\]

The present CMB spectrum arising from the conversion of ALP is given by

\[
E_0 \frac{dn_\gamma}{dE_0} = \left( E \frac{dn_a}{dE}\right)_{z=z_{\text{res}}} P_{a\to\gamma}(z_{\text{res}}) \left(\frac{1}{1 + z_{\text{res}}}\right)^3 = \left( E \frac{dn_a}{dE}\right)_{z=0} P_{a\to\gamma}(z_{\text{res}}).
\]

An example of the present ALP dark radiation spectrum compared with the CMB (without any absorption and emission by the 21cm line) as a function of the ALP/photon frequency is shown in Fig. 2. The vertical axis corresponds to the energy spectrum \( E d\rho_a/dE \) or \( E d\rho_\gamma/dE \) normalized by the total CMB energy density. Two vertical lines show the EDGES frequency range. We have taken \( m_\phi = 20 \mu\text{eV}, \tau_\phi = 10^{15} \text{sec} \) and \( Y_\phi = 22 \). We have \( \Delta N_{\text{eff}} \simeq 0.26 \) (see below) in this parameter set.

Now let us estimate the required conversion probability for explaining the EDGES anomaly. The energy fraction of the CMB in the EDGES frequency range is

\[
f_\gamma^{\text{(EDGES)}} = \frac{\pi^{-2} \int T_0 E^2 dE}{\pi^2 T_0^4/15} \simeq 2.5 \times 10^{-10},
\]

where \( T_0 \) is the present CMB temperature and the integration range is \( E = (0.2 - 0.4) \mu\text{eV} \). On the other hand, the energy fraction of the ALP dark radiation in the EDGES frequency range is

\[
f_a^{\text{(EDGES)}} = \frac{\int dE E d\rho_a/dE}{\rho_a},
\]

where the integration range in the numerator is again \( E = (0.2 - 0.4) \mu\text{eV} \). Of course \( f_a^{\text{(EDGES)}} \) depends on the position of the peak ALP energy. Numerically we find that it takes a maximum value \( f_a^{\text{(EDGES)}} \sim 0.4 \) when the peak energy is \( \sim 0.7 \mu\text{eV} \). Therefore, in order to increase the photon energy density in the EDGES range by an amount of \( \mathcal{O}(1) \) due to the ALP-photon conversion, we need

\[
\rho_a f_a^{\text{(EDGES)}} P_{a\to\gamma}(E_0) \sim \rho_\gamma f_\gamma^{\text{(EDGES)}},
\]
Figure 2: An example of the present ALP dark radiation spectrum compared with the CMB as a function of the ALP/photon frequency. The vertical axis corresponds to the energy spectrum $E d \rho_a / dE$ or $E d \rho_\gamma / dE$ normalized by the total CMB energy density. Two vertical lines show the EDGES frequency range. We have taken $m_\phi = 20 \mu eV$, $\tau_\phi = 10^{15} \text{sec}$ and $Y_\phi = 22$ for illustration.

with $E_0$ being the EDGES energy range. Thus the required conversion probability is given by

$$P_{a \rightarrow \gamma}(E_0) \sim 1.1 \times 10^{-9} \left( f_a^{\text{(EDGES)}} \Delta N_{\text{eff}} \right)^{-1},$$

where we have parameterized the ALP energy density by the extra effective number of neutrino species $\Delta N_{\text{eff}}$, which is given by

$$\Delta N_{\text{eff}} \simeq \frac{\rho_a}{0.23 \rho_\gamma},$$

with 0.23$\rho_\gamma$ corresponding to the neutrino energy density of one species. The Planck constraint is $\Delta N_{\text{eff}} \lesssim 0.33$ \cite{30} \footnote{If ALP dark radiation is produced well after the recombination, larger dark radiation energy density may be allowed. Also, the upper limit on $\Delta N_{\text{eff}}$ depends on the cosmological models and some scenarios still allow $\Delta N_{\text{eff}} \lesssim 0.7$ \cite{30}.}. Therefore we need at least $P_{a \rightarrow \gamma}(E_0) \gtrsim 8 \times 10^{-9}$ at the EDGES frequency range.

There are several constraints on the parameters. The CAST experiment is searching for axions from the Sun and the current constraint is $g_a \lesssim 6.6 \times 10^{-11} \text{GeV}^{-1}$ \cite{31}. Constraint
from the cooling of horizontal branch star is comparable. The CMB observation constrains on the magnetic field on the Mpc scale as $B_0 \lesssim \text{a few nG}$ [19,32]. The most important constraint in our scenario comes from the inverse conversion process: CMB photon conversion into the ALP. Since the conversion rate is proportional to $E$, it can be important at the CMB peak frequency range. Ref. [27] derived constraint on the combination $g_a B_0$ from the distortion of the CMB due to the conversion of CMB photon into the ALP. The constraint reads $g_a B_0 \lesssim 10^{-13} - 10^{-11} \text{GeV}^{-1} \text{nG}$ for $m_a \sim 10^{-14} \text{eV} - 10^{-9} \text{eV}$ from the measurement by the COBE FIRAS experiment [33]. The ARCADE2 experiment also measured the CMB flux above the frequency 3 GHz, although it does not give a stringent bound compared with the above [34].

In Fig. 3 on the $(m_a, g_a B_0)$ plane, we show the contours of constant conversion probability $P_{a\rightarrow\gamma}$ for $E_0 \simeq 0.3 \mu \text{eV}$ as well as the constraint from distortion of the CMB spectrum. The long-dashed orange line gives the conversion probability $P_{a\rightarrow\gamma} \gtrsim 8 \times 10^{-9}$, while the purple dot-dashed and blue dotted ones give $P_{a\rightarrow\gamma} = 2 \times 10^{-8}$ and $1 \times 10^{-7}$, respectively. The red solid line is the upper bound on the product $g_a B_0$ from the CMB spectral distortion given in Ref. [27]. We also indicate the redshifts at the resonant conversion $z_{\text{res}} = 20$, 1700 and $2 \times 10^4$ with vertical dashed lines. To avoid the efficient absorption of the converted photons, we may need $z_{\text{res}} \lesssim 1700$ [28] as mentioned earlier. It is seen that there are parameter regions in which $P_{a\rightarrow\gamma} \gtrsim 10^{-8}$, which is required for explaining the EDGES anomaly. Interestingly, the future axion helioscope experiment IAXO [35] can reach the sensitivity of $g_a \sim (\text{a few}) \times 10^{-12} \text{GeV}^{-1}$ and the preferred region may be covered if the strength of the intergalactic magnetic field is close to the observational upper bound $B_0 \sim 1 \text{nG}$. Future CMB experiments such as PIXIE [36] or PRISM [37] will also significantly improve the constraint from CMB spectral distortion, which may confirm or rule out this scenario.

So far we have not specified the origin of $\phi$. A general discussion about the possibility of $\phi$ is beyond the scope of this paper. Here, we propose one viable scenario, a simple one based on a supersymmetric model; we consider a scenario in which the ALP, a pseudo Nambu-Goldstone boson, is embedded into a complex scalar field and the radial component of the complex scalar field plays the role of $\phi$. (Thus, $\phi$ is also called as “saxion” hereafter.) For simplicity, we assume that the potential of $\phi$ is well approximated by a parabolic one, which is the case in a large class of supersymmetric model. The decay rate of $\phi$ into the ALP pair may be given by [39]

$$\tau^{-1}_\phi = \frac{1}{\Gamma_{\phi \rightarrow 2a}} = \frac{m_\phi^3}{64 \pi f^2},$$

(21)

where $f$ is the associated symmetry breaking scale, which is expected to be related to $g_a$ as $g_a \sim \alpha/16\pi f$. The parent particle $\phi$ mostly decays at the epoch at $H \sim \Gamma_{\phi \rightarrow 2a}$. The ALP has a energy of $m_\phi/2$ at the production and it is red-shifted to the EDGES frequency. We

#5 See Ref. [38] for the case of hidden photon.
can derive a consistency condition as

\[
m_\phi \sim \begin{cases} 
4 \times 10^4 \text{GeV} \left( \frac{f}{10^6 \text{ GeV}} \right)^2 \left( \frac{1 \mu \text{eV}}{E_{\text{peak}}} \right)^2 & \text{if } \Gamma_{\phi \to 2a} < H_{T=T_R}, \\
2 \times 10^4 \text{GeV} \left( \frac{f}{10^6 \text{ GeV}} \right)^{4/3} \left( \frac{1 \mu \text{eV}}{E_{\text{peak}}} \right) \left( \frac{T_R}{10^3 \text{ GeV}} \right) & \text{if } \Gamma_{\phi \to 2a} > H_{T=T_R},
\end{cases}
\]  

(22)

where \( T_R \) denotes the reheating temperature and \( E_{\text{peak}} \) denotes the peak energy of the present ALP spectrum. Here we simply assume \( m_\phi/2 = E_{\text{peak}}(1 + z_{\text{dec}}) \) with \( z_{\text{dec}} \) being the redshift at the cosmic time comparable to the lifetime of \( \phi \), i.e., \( H(z_{\text{dec}}) = \Gamma_{\phi \to 2a} \). For the case of low reheating temperature so that \( m_\phi > H_{T=T_R} \), for example, the abundance of \( \phi \) in the form of coherent oscillation is given by

\[
m_\phi Y_\phi = \frac{1}{8} T_R \left( \frac{\phi_i}{M_P} \right)^2 \simeq 1.3 \times 10^2 \text{GeV} \left( \frac{T_R}{10^3 \text{ GeV}} \right) \left( \frac{\phi_i}{M_P} \right)^2,
\]  

(23)

where \( \phi_i \) is the initial amplitude of \( \phi \) and \( M_P \) the reduced Planck scale. Choosing \( \phi_i \) appropriately (close to \( M_P \)), it is possible to yield ALP with \( \Delta N_{\text{eff}} \sim \mathcal{O}(0.1) \) by the decay of
In order for the momentum distribution of produced ALP not to be modified by the scattering with thermal photons, it is necessary to satisfy $\alpha g_a^2 T^3 \lesssim H$, which implies, in the radiation-dominated universe,

$$T \lesssim 10^4 \text{GeV} \times \left(\frac{g_a}{10^{-10} \text{GeV}^{-1}}\right)^{-2}. \quad (24)$$

Based on Eq. (22), we may adopt $f \sim 10^8 \text{GeV}$ (and $g_a \sim 10^{-12} \text{GeV}^{-1}$), $m_\phi \sim 10^3 \text{GeV}$, and $T_R \sim 10^3 \text{GeV}$, with which the constraint (24) is satisfied while $P \gtrsim 10^{-8}$ is possible taking $B_0 \gtrsim 0.1 - 1 \text{nG}$ to produce enough amount of radiation in the Rayleigh-Jeans tail.

## 4 Conclusions

Motivated by the recent anomalous enhanced absorption of 21cm radio signal reported by the EDGES experiment, we have explored a possible explanation by the ALP-photon resonant conversion. In this scenario, ALP has a mixing with photon and can convert to photon under intergalactic magnetic field, which effectively increases the brightness temperature at the radio band. As long as the resonant conversion occurs before the redshift $z \gtrsim 20$, the intensity of the observable 21cm signal can be enhanced relative to the purely astrophysical effects. Our scenario does not suffer from the difficulties faced by other proposals with dark matter scattering with baryons [6, 8, 9, 16]. Instead, the viable parameter region of ALP-photon coupling has a strength that can be tested in future axion experiment such as IAXO. Future CMB experiments such as PIXIE and PRISM will significantly improve the bound from CMB spectral distortion, which may confirm or rule out our scenario. This scenario may also leave characteristic signatures on the fluctuation of 21cm lines depending on the power spectrum of the primordial magnetic field. We leave it as a future work.

So far we have assumed a pseudo-scalar $a$ that has a coupling to the photon through $a F_{\mu\nu} F^{\mu\nu}$. Most discussion is parallel for the case of a light scalar field $\sigma$ that has a coupling through $\sigma F_{\mu\nu} F^{\mu\nu}$; dark radiation consisting of $\sigma$ may be converted into photons in a similar fashion under the intergalactic magnetic field.

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#6 The saxion can have amplitude much large than $f$ in a supersymmetric setup [40]. There is also a thermal contribution to the abundance of $\phi$ [41], but it is subdominant compared with coherent oscillation if $\phi_i$ is close to $M_P$. 

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