XENON1T anomaly from anomaly-free ALP dark matter and its implications for stellar cooling anomaly

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Introduction.— An excess of electron recoil events over the background has been recently reported by the XENON1T experiment. The excess may be explained by an axion-like particle (ALP) with mass of a few keV and a coupling to electron of \(g_{ae} \sim 10^{-13}\), if the ALP constitutes all or some fraction of local dark matter (DM). In order to satisfy the X-ray constraint, the ALP coupling to photons must be significantly suppressed compared to that to electrons. This strongly suggests that the ALP has no anomalous couplings to photons, i.e., there is no U(1)\(_{PQ}\)-U(1)\(_{em}\) anomaly. We show that such anomaly-free ALP DM predicts an X-ray line signal with a definite strength through the operator arising from threshold corrections. The strength of the signal, however, falls slightly short of the projected sensitivity of the ATHENA X-ray observatory unless the ALP mass is heavier than about \((4 - 5)\) keV. The abundance of ALP DM can be explained by the misalignment mechanism, or by thermal production if it constitutes a part of DM. In particular, we find that the anomalous excess reported by the XENON1T experiment as well as the stellar cooling anomalies from white dwarfs and red giants can be explained simultaneously better when the ALP constitutes about 10% of DM. As concrete models, we revisit the leptophilic anomaly-free ALP DM considered in Ref.\(^1\) as well as an ALP model based on 2HDM.

The ALP is a pseudo-Nambu-Goldstone boson that appears when a continuous global symmetry is spontaneously broken. Hereafter we call the symmetry the Pecei-Quinn (PQ) symmetry \(^9\)\(^10\), although the ALP considered in this letter is not the QCD axion. See Refs.\(^11\)\(^14\)\(^17\) for reviews. There are two relevant parameters that characterize the ALP: one is the mass, \(m_a\), and the other is the decay constant, \(f_a\). The decay constant is of order the symmetry breaking scale unless the sector responsible for the spontaneous symmetry breaking is rather contrived as in the clockwork/aligned axion model \(^15\)\(^23\). Since the mass is suppressed thanks to the PQ symmetry, the ALP can be naturally light. If the lifetime of the ALP is much longer than the age of the Universe, it can be all or a part of DM.

The ALP is considered to have various couplings to the standard model (SM) particles, and among them, we focus on the couplings to photons and electrons, but we will give a comment on a coupling to nucleons later. Throughout this letter we assume the ALP mass and coupling to electron suggested by the XENON1T excess. Then, the preferred range of \(g_{ae}\) implies that the typical value of the decay constant is \(f_a \sim 10^{9-10}\) GeV.

Let us first assume that the ALP has an anomaly of U(1)\(_{PQ}\)-U(1)\(_{em}\)-U(1)\(_{em}\), where U(1)\(_{em}\) is the electromagnetic gauge symmetry. Then the ALP also couples to photons with a coupling of \(g_{a\gamma\gamma} \sim \alpha_{em}/2\pi f_a\), where \(\alpha_{em}\) is a fine-structure constant of the electromagnetic interaction. Here we omit a model-dependent constant which is of order unity in most cases. This leads to the decay of ALP into two photons in the late universe, which may leave a detectable X-ray line signal. In fact, such ALP DM with an anomalous coupling to photons is excluded by the X-ray constraint on the coupling \(g_{a\gamma\gamma}\) for \(m_a \gtrsim 0.1\) keV (see e.g. Ref.\(^16\) and references therein)\(^1\)\(^4\). Therefore, we are led to consider an ALP DM whose coupling to electrons is significantly suppressed compared to that to electron, if it is responsible for the XENON1T excess.

Another interesting observation is that the axion-electron coupling \(g_{ae} \sim 10^{-13}\) suggested by the XENON1T excess has an overlap with that hinted by various cooling excesses found in e.g. white dwarfs (WD) and red-giants (RG) \(^8\). Considering that the stellar scientific community
cooling argument does not depend on the cosmological abundance of the ALP DM, and that the ALP mass is usually set to be much lighter than the typical energy scale in the stellar environment, we will see how the overlap becomes (even) better by varying the fraction of ALP DM and the ALP mass. In particular, the ALP mass of keV is close to the typical temperature of the stellar systems, and the mass dependence of the stellar cooling bound was recently studied in Ref. [24], which we will use in our calculation.

In this letter, we study the ALP DM as a potential source for the XENON1T excess, and discuss its implications for the stellar cooling anomaly. To satisfy the observational constraint, the ALP coupling to photons is significantly suppressed compared to that to electrons. This is indeed realized if the PQ symmetry is free from the U(1)$_{\text{PQ}}$-U(1)$_{\text{em}}$-$U(1)$_{\text{em}}$ anomaly [25]. As we will see, even in the anomaly-free ALP models, the ALP does have a nonzero coupling to photons, which arises from threshold corrections. The corresponding operator is suppressed by the mass ratio between the ALP and the charged fermions to which the ALP is coupled, and thus, it is dominated by the contribution of electron. Therefore, the decay rate for the ALP into two photons is rather robust and universal for a generic anomaly-free ALP model. We will show that the flux of the X-ray from the ALP decay is within the reach of the future ATHENA X-ray observatory [25] for the ALP mass heavier than $\sim (4-5)$ keV, but it is slightly below the sensitivity if the mass is in the range of $(2-3)$ keV.

The anomaly-free ALP DM was studied by Nakayama, Yanagida and one of the present authors (FT), where the PQ symmetry is identified as a certain flavour symmetry [1]. The central idea of the work was to pursue a possibility that an ALP is lurking at a intermediate scale avoiding tight constraints on the axion-photon coupling, partly motivated by the 3.5 keV X-ray anomaly. As we will see, even if, e.g., $r=0.1$, we have $f_a/q_e \simeq 3 \times 10^8$ GeV.

ALP couplings to SM particles. Following Ref. [1], we consider the case in which there is no U(1)$_{\text{PQ}}$-U(1)$_{\text{em}}$-$U(1)$_{\text{em}}$ anomaly. An explicit construction of this kind of models will be discussed shortly.

We start from the following interactions,

$$-\mathcal{L}_L = \sum_f m_f \bar{f}_R f_L e^{i q_f \frac{a}{f_e}} ,$$

where $a$ is the ALP, and $q_f$ ($f = e, \mu, \tau, u, d, c, s, t, b$) are the PQ charges of the SM particle $f$.

We choose the PQ charges so that there is no U(1)$_{\text{PQ}}$-U(1)$_{\text{em}}$-$U(1)$_{\text{em}}$ anomaly [2]. The coupling between the ALP and electron is given by $g_{ae} = q_e m_e / f_a$, in other words,

$$\frac{f_a}{q_e} \simeq 10^{10} \text{ GeV} \left( \frac{g_{ae}}{5 \times 10^{-14}} \right) .$$

If the ALP constitutes all DM, the excess reported by the XENON1T experiment implies $f_a / q_e \simeq 10^{10}$ GeV. However, it is possible (and might be rather natural as we will discuss later) that the ALP constitute some fraction of DM. We denote the fraction by

$$r = \frac{\Omega_{\text{ALP}}}{\Omega_{\text{DM}}},$$

with $\Omega_{\text{ALP}}$ being the density parameter of ALP and $\Omega_{\text{DM}}^{\text{obs}}$ ($\simeq 0.24$) the observed DM abundance. Since the XENON1T experiment is sensitive to the combination of $g_{ae} / \sqrt{r}$, its excess implies $f_a / q_e \simeq \sqrt{r} 10^{10}$ GeV. In particular, if, e.g., $r=0.1$, we have $f_a / q_e \simeq 3 \times 10^8$ GeV.

We are interested in the case in which the ALP mass is of order keV, which is much smaller than the electron mass. Thus we can integrate out all the quarks and leptons to investigate the axion coupling to photons in the low energy. For the on-shell ALP and photons, the relevant term in the effective Lagrangian is given by

$$\frac{\alpha_{ae} m_a^2 q_e}{48\pi f_a} \bar{e} \gamma \mu \tilde{F}^{\mu \nu} .$$

We can neglect contributions from fermions heavier than electron because the dominant contribution comes from the lightest one.

ALP decay to photons and X-ray prediction. The interaction Eq. (4) leads to the decay of the ALP into two photons. The decay rate is calculated as [1]

$$\Gamma_{a \rightarrow \gamma \gamma} \simeq \frac{\alpha_{ae}^2 m_a^2 q_e^2}{9216 \pi^3 m_e^2 f_a^4} ,$$

$$\simeq 3.5 \times 10^{-57} \text{ GeV} \left( \frac{m_a}{2 \text{ keV}} \right)^7 \left( \frac{f_a / q_e}{10^{10} \text{ GeV}} \right)^{-2} .$$

There is a constraint on the flux of the X-ray photons produced by the ALP decay. It is shown as the blue shaded region in Fig. [1]. Here, we converted the X-ray constraint on the mixing angle, $\theta^2$, for sterile neutrino DM in [28] to $g_{ae}$ by using the condition, $\tau \Gamma_{a \rightarrow \gamma \gamma} = \frac{1}{2} \Gamma_{\nu_{\mu} \rightarrow \gamma \mu} \approx$}

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2 Here we focus on the ALP coupling to charged SM fermions. If the ALP has a similar coupling to neutrinos, the ALP will mainly decay into neutrinos.

3 If the axion is coupled to quarks, the color anomaly should also vanish (or should be suppressed by several orders of magnitude), since otherwise the mixing with $\pi^0$ would induce the axion-photon coupling. In this sense, the ALP considered in our scenario is complementary to the QCD axion.

4 It may also possible that the abundance of the DM is suppressed locally around Earth. In this case, we have rather stronger X-ray production far from Earth than the case with $r \lessgtr 0.1$. 

\[ \frac{1}{2} g_a^2 \frac{3 \alpha_n e G_F^2 M^5}{32\pi a^2}, \]
where the factor 1/2 is from the number difference of daughter photons. Also shown as the blue dashed line is the combined sensitivity reaches of the Athena X-ray telescope \cite{25} and that obtained by taking cross correlation of the X-ray line emission with galaxy catalogs \cite{28}. The green and yellow bands represent the expected sensitivity of the XENON1T experiment and the solid black line is the actually obtained limit. The weaker-than-expected limit around \((2 - 3)\) keV is the region of interest. Thus, one can see that the ALP DM hint from the XENON1T excess is consistent from the current X-ray bound. For \(m_a = 2 - 3\) keV, the suggested value of the electron coupling \(g_{ae} \approx 10^{-13}\) cannot be reached in the future observation. If the excess shifts to slightly higher energy in the future experiments (say, \(m_a > (4 - 5)\) keV) with a similar value of \(g_{ae}\), the anomaly-free ALP DM scenario may be confirmed by observing the X-ray line emission.

**Stellar cooling anomaly.**—The gray region in Fig. 1 is excluded by the stellar cooling arguments \cite{24}. The XENON1T excess is well below the gray region if \(r = 1\). Slightly below the excluded region, there are regions known as the stellar cooling anomalies, where various measurement/observations of WD, RG, and other type of stellar objects can be better fitted in the presence of excessive cooling. One of the WD cooling anomaly based on the analysis of the luminosity function \cite{1} favors the red-shaded region in Fig. 1 while the RG cooling anomaly \cite{3} favors the parameter centered by the red dashed line. Note that we show only the central value for the RG cooling anomaly. Roughly speaking, the region around and below the red dashed line in this figure is favored. These regions hinted by the stellar cooling argument are intriguingly close to the excess found in the XENON1T data. In fact, the overlap becomes even better if the fraction of ALP constitutes about 10\% of DM, namely \(r \approx 0.1\). This is because the X-ray bound as well as the XENON1T data scales as \(1/\sqrt{r}\) in Fig. 1. This can be seen in the lower panel in Fig. 1 where we take \(r = 0.07\). The red-shaded region, red dashed line, and the black line nicely overlap around \(m_a = (2 - 3)\) keV and \(g_{ae} = 2 \times 10^{-13}\). Here note that the cooling anomalies require a stronger interaction if the ALP mass is larger than the typical temperature of the stellar system; the temperature of WD is about 1 keV while that of RG is about 10 keV \cite{21}.

Although still under debate \cite{30}, an excessive cooling was reported in the measurement of neutron star in Cassiopeia A \cite{31,32}. This favors an ALP-nucleon coupling constant of \(g_{N} \approx 4 \times 10^{-10}\) \cite{33}. In our model, there is a nonzero ALP-nucleon coupling if the ALP is coupled to quarks (see, e.g., Ref. \cite{34}). Depending on the PQ charge of quarks, the coupling can be as large as \(m_N/f_a\), where \(m_N\) is the neutron mass. Thus we may be able to simultaneously explain the cooling rate of the neutron star as well as the other cooling anomalies, and the XENON1T result.

**Production processes.**—The ALPs can be produced via thermal and non-thermal production processes in the early Universe.

Relativistic ALPs are produced from the scatterings between fermions (quarks and/or leptons) and the Higgs bosons in the thermal bath. The resulting ALP abun-
The resulting relic abundance depends on $q_e$ once we choose $f_a/q_e$ to be the value favored by the XENON1T result. We find with the PQ charge, $q_e$, the initial misalignment angle, $\theta_*$, (slightly larger than) order unity, the ALP abundance can be consistent with the observed amount of DM, namely $r = 1$, with $T_R > T_{\text{osc}}$. However, depending on the coupling of ALP to other SM particles, the reheating temperature may not be high enough to have $T_R \gtrsim T_{\text{osc}}$. In this case, it is possible to make $q_e$ much larger than unity by using, e.g., the clockwork mechanism \cite{1811.01115,1901.06894,2203.06955}, while $f_a/q_e$ is fixed.

We note that $r \approx 0.1$ is interesting in light of cooling anomaly. In this case, we do not need to produce ALPs by the misalignment mechanism because $r^{(th)} = r \approx 0.1$ satisfies the Lyman-$\alpha$ constraint of $r^{(th)} \lesssim 0.13 - 0.2$.

\section*{Isocurvature constraint.} Now we comment on the isocurvature constraint on this scenario. We implicitly assume that the PQ symmetry is spontaneously broken before inflation. In this case, the ALP predicts an isocurvature perturbation due to quantum fluctuations during inflation. The fluctuation is proportional to the Hubble parameter of inflation, $H_{\text{inf}}$, so that the constraint on the isocurvature perturbation can be rewritten as that on $H_{\text{inf}}$. The result is given by \cite{1101.3090}

\begin{equation}
    H_{\text{inf}} \lesssim 3 \times 10^6 \theta_* r^{-1} \left( \frac{f_a}{10^{10} \text{GeV}} \right) \text{GeV}.
\end{equation}

Note that the Universe must be reheated after inflation and the energy of the thermal bath cannot exceed the energy scale of inflation. Thus the upper bound on $H_{\text{inf}}$ implies that the reheating temperature must satisfy

\begin{equation}
    T_R \lesssim 8 \times 10^{11} \text{GeV} \sqrt{\frac{H_{\text{inf}}}{10^9 \text{GeV}}}.
\end{equation}

in the case of the instantaneous reheating. This is consistent with the scenario of ALP production explained above. A relatively low reheating temperature ($T_R \ll f_a$) is also consistent with the assumption that the PQ symmetry is spontaneously broken before inflation and is never restored after inflation.

\section*{Models of anomaly-free ALP.} The idea and some explicit examples of the anomaly-free ALP were proposed in Ref. \cite{1707.00011}. Here we briefly review a model where the ALP is coupled only to electron and muon, on the other hand, the reheating temperature can be as high as of order $10^3$ GeV. Such high reheating temperature is favored in light of the generation of baryon asymmetry via thermal leptogenesis \cite{1501.02781,1602.02824} or (mild) resonant leptogenesis \cite{1606.01713,1606.07246}.

The ALP can be produced also by a non-thermal process, called the misalignment mechanism. When the Hubble parameter becomes lower than the ALP mass, the ALP starts to oscillate around its potential minimum. We denote the temperature at the onset of the ALP oscillation as $T_{\text{osc}}$, which is given by

\begin{equation}
    T_{\text{osc}} \sim 10^6 \text{GeV} \left( \frac{m_a}{2 \text{ keV}} \right)^{1/2}.
\end{equation}

At a temperature above $T_{\text{osc}}$, the axion field stays at a field value which is generically different from the potential minimum. Denoting that the initial oscillation amplitude as $a_{\text{ini}} = \theta_0 f_a$, the oscillation energy of the ALP is given by

\begin{equation}
    \Omega_{\text{ALP}} h^2 \sim 0.1 \left( \frac{\theta_0}{2} \right)^2 \left( \frac{q_e}{4} \right)^2 \left( \frac{f_a/q_e}{10^{10} \text{ GeV}} \right)^2 \times \left\{ \begin{array}{ll}
        \left( \frac{T_R}{10^6 \text{ GeV}} \right)^2 & \text{for } T_R \lesssim T_{\text{osc}} \\
        \left( \frac{m_a}{2 \text{ keV}} \right)^{1/2} & \text{for } T_R \gtrsim T_{\text{osc}}
    \end{array} \right.
\end{equation}

7 If the reheating temperature is lower than the top mass, we have to take into account the entropy production due to the inflaton decay to correctly estimate the ALP abundance, and it will be smaller than the one given by Eq. (6). However, if the reheating temperature is comparable to the top mass, Eq. (6) is a good estimate.
symmetry is broken by the B-L Higgs fields whose vacuum expectation values are assumed to be of the order of \(10^{9–10}\) GeV. The ALP resides mainly in the phases of the B-L Higgs fields.

Here we comment on the possible origin of the mass of the ALP. The ALP mass arises from an explicit breaking of the PQ symmetry. Noting that the keV scale comes from two different energy scales of \(10^{10}\) GeV and the electroweak scale, we consider the following PQ-breaking term:

\[
m_H^2 H(-3)\dagger H(3) + \text{h.c.} \tag{12}\n\]

This leads to \(m_{\text{ALP}} = O(1)\) keV if the size of the expectation value of the above operator is of order [the weak scale]\(^4\) and \(f_a \sim 10^{10}\) GeV. This is realized for a certain choices of \(m_H\), \(\langle H(-3)\rangle\), and \(\langle H(3)\rangle\). It is interesting to note that the keV scale favored by the XENON1T anomaly comes from the PQ breaking scale and the electroweak scale without additional small parameters. We assume that the Higgs fields other than the lightest one are heavy enough to evade the collider constraints. However, some of them may be within the reach of future collider experiments because of the miraculous relation between the three energy scales.

One can also construct many models of anomaly free ALP that is coupled to other quarks and leptons. For example, one can simply assume that the fermions are universally charged under the PQ symmetry. The ALP mass is generated by introducing higher dimensional terms which explicitly break the PQ symmetry. This is the case in a two Higgs doublet model with Higgs \(H_u\) and \(H_d\) to be both charged under the PQ symmetry. The mixing term, \(L \supset H_u H_d\), is not invariant under the PQ symmetry and thus is obtained through the spontaneous breaking of the PQ symmetry. Their VEVs are given as \(\langle H_u\rangle = v \sin \beta\), and \(\langle H_d\rangle = v \cos \beta\) with \(v \approx 174\) GeV. In the low-energy effective theory after integrating out heavy Higgs and PQ breaking fields, one obtains

\[
H_u = \bar{H} \sin \beta \exp \left[ i Q[H_u] \frac{\phi}{f_a} \right], \tag{13}\n\]

\[
H_d = \bar{H} \cos \beta \exp \left[ i Q[H_d] \frac{\phi}{f_a} \right]. \tag{14}\n\]

where \(Q[H_d]/Q[H_u] = \tan^2 \beta\). Here \(H\) and \(\bar{H}\) both represent the SM Higgs doublet with \(\bar{H} = i \sigma_2 H^*\). If either \(H_u\) or \(H_d\) does not couple to the SM fermions, \(a la\) type I (fermiophobic) 2HDM, the PQ charges of the SM fermions are universal \[17]. Then one can easily check that the anomaly is automatically cancelled in this model.

Since the ALP couples to all the SM fermions in this model, the thermal production is very efficient, and the Lyman-\(\alpha\) constraint of \(r^{(\text{th})} \lesssim 0.13 – 0.2\) cannot be satisfied unless \(T_R \lesssim 100\) GeV. With \(T_R < 100\) GeV, this can be evaded but the misalignment contribution is suppressed due to entropy production from the inflaton decay (i.e., \(T_R < T_{\text{isc}}\)). Therefore, the ALP cannot explain all the DM. Still, it is possible to explain the excess if the warm component fraction satisfies \(r^{(\text{th})} \lesssim 0.13 – 0.2\) to meet the Lyman-\(\alpha\) constraint. In such a low reheating temperature, the baryon asymmetry of the Universe may be generated by, e.g., the Affleck-Dine mechanism \[28, 29\] or the spontaneous baryogenesis around the electroweak phase transition \[50–54\].

Notice that the model has not only the ALP-electron coupling but also a related ALP-nucleon coupling

\[
g_{\text{AN}} \sim 0.5 \frac{m_{\text{N}}}{m_e} g_{\text{en}} \sim 2 \times 10^{-10} \left( \frac{g_{\text{en}}}{2 \times 10^{-13}} \right). \tag{15}\n\]

This is around the aforementioned value hinted by the possible cooling anomaly of the neutron star in Cassiopeia A \[33\].

**Discussion.**– We have pointed out that, if the XENON1T excess in the electron recoil data is due to the ALP DM, its coupling to photons must be significantly suppressed than naively expected from the suggested ALP-electron coupling. This is because of the tight bound coming from the X-ray observations. This argument led us to the anomaly-free ALP model, where the ALP-photon coupling arises only from threshold corrections.

Broadly speaking, there are two possibilities regarding the ALP abundance. If the ALP constitutes all DM, it should be mainly produced by the misalignment mechanism to satisfy the Lyman-\(\alpha\) bound. This sets the lower bound on the reheating temperature. Then it turns out that the ALP should not be coupled to heavy fermions (such as the top quark) in this case, since otherwise thermally produced ALP, which behaves as warm DM, is overproduced. If the ALP is coupled only to the electron and muon, the reheating temperature can be as high as \(10^8\) GeV and the right relic abundance of ALP is generated by the misalignment mechanism.

On the other hand, one can consider the case in which the ALP constitutes about 10% of DM. In this case, the reheating temperature does not need to be high enough to obtain a correct relic abundance from the misalignment mechanism and all ALPs can be thermally produced. Although it can evade the bound from the Lyman-\(\alpha\) forest data, we expect that there is still some effect on the small-scale structure formation that can be searched for by future astrophysical observations. The interesting feature of this scenario is that the XENON1T excess favors a larger value of \(g_{\text{en}} \approx 10^{-13}\) (it scales as \(1/\sqrt{f}\)). This makes the overlap with the coupling suggested by the stellar cooling anomaly found in WD and RG even better.

We note that it might be natural to consider the ALP as a subdominant component of DM in light of the anthropic principle \[55, 56\] and the string axiverse \[60, 61\]. According to the string axiverse, there are many ALPs with logarithmically distributed masses in the low-energy effective theory, one of which may be identified as the very ALP used in this letter. We expect that there are many other ALPs, some of which may be very light and contribute as dark radiation \[62\] while some others may
be heavy and contribute as DM. The relic abundance of the latter ALPs may depend on parameters that vary in the multiverse. According to the selection effect due to the anthropic condition, the abundance of these ALPs (and the other DM candidates) should not be much larger than the observed amount of DM to avoid the overproduction of cosmological structures in habitable universes (see, e.g., Ref. [62]). We thus expect multi-component DM, where there are several DM candidates with energy densities smaller than the observed one. In this respect, it is natural that our ALP, which is one of the DM components, constitutes $\mathcal{O}(10\%)$ fraction of DM. The reason that the ALP decay constant is close to the stellar cooling bound may also be explained by the anthropic principle.

Although we take $m_a = 2 - 3$ keV as a reference value in this letter, we note that a heavier ALP is well fitted by our model. It is still possible that improved data by XENONnT will favor a heavier ALP mass. If the ALP is as heavy as $(4 - 5)$ keV, we expect that the X-ray signals from the ALP decay will be observed by ATHENA [25].

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