PHYSICAL REVIEW D **90,** 023540 (2014)

3.55 keV photon line and its morphology from a 3.55 keV axionlike particle line

Michele Cicoli[*]
Dipartimento di Fisica ed Astronomia, Università di Bologna, via Irnerio 46, 40126 Bologna, Italy;
INFN, Sezione di Bologna, 40126 Bologna, Italy; and Abdus Salam ICTP,
Strada Costiera 11, Trieste 34014, Italy

Joseph P. Conlon,[†] M. C. David Marsh,[‡] and Markus Rummel[§]
Rudolph Peierls Centre for Theoretical Physics, University of Oxford,
1 Keble Road, Oxford OX1 3NP, United Kingdom
(Received 26 March 2014; published 25 July 2014)

Galaxy clusters can efficiently convert axionlike particles (ALPs) to photons. We propose that the recently claimed detection of a 3.55–3.57 keV line in the stacked spectra of a large number of galaxy clusters and the Andromeda galaxy may originate from the decay of either a scalar or fermionic 7.1 keV dark matter species into an ALP of mass $m_a \lesssim 6 \times 10^{-11}$ eV, which subsequently converts to a photon in the cluster magnetic field. In contrast to models in which the photon line arises directly from dark matter decay or annihilation, this can explain the anomalous line strength in the Perseus cluster. As cool-core clusters have high central magnetic fields and axion-photon conversion scales as B^2, this model can also explain the observed peaking of the line emission in the cool cores of the Perseus, Ophiuchus, and Centaurus clusters, as opposed to the much larger dark matter halos. We describe distinctive predictions of this scenario for future observations.

DOI: 10.1103/PhysRevD.90.023540 PACS numbers: 98.80.Cq, 95.35.+d, 14.80.Va, 98.65.Cw

Recently two analyses have appeared which claim the possible existence of a photon line at $E \sim 3.55$ keV, based on stacked data from galaxy clusters and also from the Andromeda galaxy [1,2]. In [1], the line was found in the stacked spectrum of 73 galaxy clusters independently in observations with the XMM-Newton PN and MOS instruments to a high (4–5σ) statistical significance. After dividing the full sample into the three subsamples (Perseus, Coma + Ophiuchus + Centaurus, and all others), the signal was found in all three subsamples by the MOS instrument, by PN in the "all others" subsample, and also with Chandra observations of the Perseus cluster. In Ref. [2], a similar line was found at 3.5 keV using XMM-Newton data for the Andromeda galaxy and the Perseus cluster (the Perseus signal being found in both MOS and PN data).

Perhaps the most exciting interpretation of this line is as originating from dark matter decay to produce photons. This has been discussed in the context of sterile neutrinos, axionlike dark matter, axinos, and excited states of dark matter [3–16].

However, there are aspects of this potential signal that are inconsistent with the interpretation as dark matter decaying directly to photons.

(1) The signal found from the Perseus cluster is much stronger than the signal found from other galaxy clusters. A line arising from dark matter decay to photons can only trace the quantity of dark matter in each cluster. This makes a clear prediction for the relative magnitude of signal from each cluster. However, the effective inferred dark matter decay rate from Perseus is a factor four to eight greater than for the stacked sample of clusters (depending on whether the central $1'$ is included or not, and depending on whether XMM or Chandra data is used).

(2) The effective inferred decay rate for the nearby bright clusters Coma, Ophiuchus, and Centaurus is also at mild tension (1.8σ) with the effective inferred decay rate for the stacked sample of more distant clusters.

(3) Perseus is the archetypal cool-core cluster, and in Perseus both XMM and Chandra observations show a large fraction of the signal arising from the cool core at the very center of the cluster. In the analysis of [1], excising the central arcminute—a radius of approximately 20 kpc—removed around half the inferred signal for the XMM MOS detector. The cool core arises from the collisional cooling of the central dense ICM gas and is on far smaller scales than that of the dark matter halo. As the physics that leads to the formation of the cool core is entirely astrophysical, any signal from direct dark matter decay to photons should not peak on these scales.

---

[*] mcicoli@ictp.it
[†] j.conlon1@physics.ox.ac.uk
[‡] david.marsh1@physics.ox.ac.uk
[§] markus.rummel@physics.ox.ac.uk

(4) The line signal from a stacked sample of three nearby bright clusters (Coma, Ophiuchus, and Centaurus) is also dominated by emission from the cool cores of Ophiuchus and Centaurus (note that Coma is not a relaxed cluster and does not have a cool core). As above, the extent of the cool core is set by astrophysical processes and will not trace the dark matter distribution.

Such features, if persisting in a fuller subsequent analysis, would be inconsistent with an interpretation of the line in terms of dark matter decaying to photons.

In this paper we propose a model which can reconcile these features with a dark matter origin of the 3.55 keV line. Our proposal is that the dark matter decay generates a monochromatic 3.55 keV line for an axionlike particle (ALP), which then converts into a 3.55 keV photon in the magnetic field of the galaxy cluster.

The existence of axionlike particles is theoretically well motivated. The QCD axion is by far the most plausible solution to the strong *CP* problem of the Standard Model. Axionlike particles frequently arise in compactifications of string theory [17–19] and there is an active experimental program searching for their existence [20–22]. The observability of axionlike particles is set by their coupling to photons,

$$\frac{a}{M}\mathbf{E}\cdot\mathbf{B},$$

which implies that ALPs convert to photons in background magnetic fields. For massless ALPs, M is bounded by $M \gtrsim 10^{11}$ GeV [23].

The intracluster medium of galaxy clusters is pervaded by large-scale turbulent magnetic fields. The existence of these magnetic fields is established from observation of synchrotron emission from clusters in the form of radio halos, minihalos, or relics, and from Faraday rotation measures of background radio sources with the cluster as a Faraday screen. These measurements imply that cluster magnetic fields are generally $B \sim O(\mu G)$, with larger values of $B \sim O(10\ \mu G)$ found near the center of cool-core clusters. The magnetic field is multiscale, with typical coherence lengths $L \sim 1$–10 kpc which can extend to $L \sim 100$ kpc.

This intracluster medium can in fact be an efficient convertor of ALPs to photons (e.g., see [24–26]). For $M \sim 10^{11}$ GeV, a massless ALP with x-ray energies will have a conversion probability that is at or close to the saturation level of $\langle P_{a\to\gamma}\rangle = 1/3$, although with stochastic variations that depend on the line-of-sight realization of the magnetic field. Any significant source of x-ray ALPs in a cluster can then generate an appreciable source of x-ray photons.

The conversion of x-ray ALPs to photons in the Coma cluster has been studied in detail in [26]. Many string theory scenarios of the early Universe predict a dark radiation cosmic axion (or ALP) background in the 0.1–1 keV waveband, originating from moduli decays in the early Universe. Such ALPs can convert to photons in the cluster magnetic field, generating a broad excess x-ray flux which may explain the long-standing excess in soft x-rays from many galaxy clusters [27–29], which is particularly well established for the case of Coma [28,30–32].

In [26], ALPs were propagated through a full 2000^3 simulation of the magnetic field of the Coma cluster using the magnetic field parameters determined in [33] as a best fit to Faraday rotation measures. For this case of the Coma cluster, it was found that for an ALP-photon coupling $M \sim 10^{13}$ GeV, the central conversion probability of a 3.55 keV ALP was $P_{a\to\gamma} \sim 10^{-3}$, this conversion probability scaling as $(\frac{10^{13}\ \mathrm{GeV}}{M})^2$.

As described in the original papers [1,2], if the 3.55 keV line is produced by dark matter decaying directly to photons, the dark matter lifetime is $\tau \sim 10^{28}$ s. As the age of the Universe is $\tau \sim 4 \times 10^{17}$ s, it is clear that there is significant room for a shorter lifetime for decay to ALPs $\tau \ll 10^{28}$ s balanced by a conversion probability $P_{a\to\gamma} \ll 1$. We impose a conservative value $\tau > 2 \times 10^{19}$ s for the dark matter lifetime [34].

I. MODELS FOR AXION PRODUCTION

A monochromatic ALP can be produced by the decay of either scalar or fermionic dark matter. For the scalar case, an example is moduli dark matter, which can decay to ALPs via the kinetic coupling

$$\frac{\Phi}{\Lambda}\partial_\mu a \partial^\mu a.$$

This coupling has been considered in the context of dark radiation in [35–38]. This induces decays of moduli to ALPs with a decay rate of

$$\Gamma_\Phi = \frac{1}{32\pi}\frac{m_\Phi^3}{\Lambda^2}. \tag{1}$$

The corresponding lifetime is then

$$\tau_\Phi = \left(\frac{7.1\ \mathrm{keV}}{m_\Phi}\right)^3\left(\frac{\Lambda}{10^{17}\ \mathrm{GeV}}\right)^2 1.85\times 10^{27}\ \mathrm{s}. \tag{2}$$

An explicit string model with stabilized moduli which features a very light modulus with these properties has been derived in [39] in the context of type IIB LARGE Volume Scenarios. The model described in [39] is characterized by the presence of two very light moduli ϕ_1 and ϕ_2 with masses:

$$m_{\phi_2} \simeq M_P \epsilon^{5/3} \ll m_{\phi_1} \simeq M_P \epsilon^{3/2}, \tag{3}$$

with $\epsilon = \frac{m_{3/2}}{M_P} \ll 1$. For soft supersymmetry breaking terms at the TeV scale, this model requires $\epsilon \simeq 10^{-14}$, leading to the moduli masses: $m_{\phi_1} \simeq \mathcal{O}(1)$ MeV and $m_{\phi_2} \simeq \mathcal{O}(10)$ keV. While such light moduli generically lead to severe cosmological problems, the model may be viable with the inclusion of some additional mechanism which suppresses their misalignment during inflation [40] (see also [15]). In this case, ϕ_2 would have a lifetime of order $\tau \sim 10^{27}$ s and could account for most of the dark matter density without overclosing our Universe.

In general, moduli may also have a coupling to photons and for this scenario it is important that decay modes to photons do not dominate. While this is model dependent, we note that in string scenarios where the Standard Model is sequestered, direct couplings of moduli to photons may be highly suppressed.

For the fermionic case, a massive fermionic dark matter particle ψ can decay to a fermion χ and an ALP as $\psi \to \chi a$ via the coupling

$$\frac{\partial_\mu a}{\Lambda} \bar{\psi}\gamma^\mu\gamma^5\chi. \tag{4}$$

This generates a tree-level decay $\psi \to \chi a$, with a rate of

$$\Gamma_{\psi\to\chi a} = \frac{1}{16\pi}\frac{(m_\psi^2 - m_\chi^2)^3}{m_\psi^3\Lambda^2}, \tag{5}$$

which for $m_\chi \ll m_\psi$ corresponds to a lifetime of

$$\tau_\psi = \left(\frac{7.1\ \text{keV}}{m_\psi}\right)^3 \left(\frac{\Lambda}{10^{17}\ \text{GeV}}\right)^2 0.92 \times 10^{27}\ \text{s}. \tag{6}$$

While this has been written for general fermionic dark matter ψ, we see no reason this may not also exist for the particular case of a massive sterile neutrino (as an additional decay channel to $\nu\gamma$).

Although axionlike particles are generally weakly coupled to matter, when dealing with lifetimes $\tau > 10^{20}$ s, there is no good reason to neglect ALP decay channels. Given the often-considered range for the QCD axion of $f_a \sim 10^9$–10^{12} GeV, we see that the axionic coupling constants considered above are entirely reasonable from a particle physics perspective.

II. ALP-PHOTON CONVERSION

Once an ALP is produced, ALP to photon conversion occurs via the operator

$$\frac{a}{M}\mathbf{E}\cdot\mathbf{B}. \tag{7}$$

It follows that the morphology and strength of an observed photon line signal is set by the magnetic field environment. At the simplest level, the signal scales as the square of the magnetic field, although as we discuss below the magnetic field coherence length and the electron density also play significant roles. It is this that both distinguishes the predictions of our model from the many variants of dark matter decaying directly to photons and allows it to explain aspects of the data that are inconsistent with conventional explanations.

After including the operator (7), the linearized equations of motion for ALP-photon modes of energy ω is given by

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & \Delta_F & \Delta_{\gamma ax} \\ \Delta_F & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} |\gamma_x\rangle \\ |\gamma_y\rangle \\ |a\rangle \end{pmatrix} = 0. \tag{8}$$

Here, $\Delta_\gamma = -\omega_{pl}^2/2\omega$, where

$$\omega_{pl} = \left(4\pi\alpha\frac{n_e}{m_e}\right)^{1/2} = 1.2\times 10^{-12}\sqrt{\frac{n_e}{10^{-3}\ \text{cm}^{-3}}}\ \text{eV}$$

denotes the plasma frequency of the ICM. Furthermore, $\Delta_a = -m_a^2/\omega$, $\Delta_{\gamma ai} = B_i/2M$, and Δ_F, which will be unimportant for the subsequent discussion, denote the Faraday rotation of photon polarization states caused by the cluster magnetic field.

Equation (8) is easily solved for a single domain of length L with a constant magnetic field. Denoting the component of the magnetic field transverse to the motion by $B_\perp$, the resulting conversion probability is given by [41,42],

$$P_{a\to\gamma}^{\text{single domain}} = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right), \tag{9}$$

where $\tan 2\theta = \frac{2B_\perp\omega}{Mm_{\text{eff}}^2}$, $\Delta = \frac{m_{\text{eff}}^2 L}{4\omega}$, $m_{\text{eff}}^2 = m_a^2 - \omega_{pl}^2$.

For ALP masses smaller than the plasma frequency in the cluster, we can write $m_{\text{eff}}^2 = -\omega_{pl}^2$, and the angles θ and Δ evaluate to

$$|\theta| \approx \frac{B_\perp\omega}{Mm_{\text{eff}}^2} = 5.0\times 10^{-4}\times\left(\frac{10^{-3}\ \text{cm}^{-3}}{n_e}\right)\left(\frac{B_\perp}{1\ \mu\text{G}}\right) \times\left(\frac{\omega}{3.55\ \text{keV}}\right)\left(\frac{10^{14}\ \text{GeV}}{M}\right), \tag{10}$$

$$\Delta = 0.015\times\left(\frac{n_e}{10^{-3}\ \text{cm}^{-3}}\right)\left(\frac{3.55\ \text{keV}}{\omega}\right)\left(\frac{L}{1\ \text{kpc}}\right). \tag{11}$$

In the small-angle approximation $|\theta| \ll 1$ and $\Delta \ll 1$, the single domain conversion probability is simply given by

$$P_{a\to\gamma}^{\text{single domain}} = \frac{1}{4}\left(\frac{B_\perp L}{M}\right)^2 = 2.3\times 10^{-10}\times\left(\frac{B_\perp}{1\ \mu\text{G}}\frac{L}{1\ \text{kpc}}\frac{10^{14}\ \text{GeV}}{M}\right)^2. \tag{12}$$

Given a model of the turbulent, multiscale magnetic field in galaxy clusters, Eq. (8) can be solved numerically as was done in [26] for the particular case of the Coma cluster. However, as noted in [26], many of the features of the resulting conversion probabilities can be already understood from the single-domain formula, Eq. (9). Thus, we expect that for the purpose of order-of-magnitude estimates and scalings, the conversion probability in a cluster is sufficiently well approximated by

$$\begin{aligned} P_{a\to\gamma}^{\text{cluster}}(\bar{B},\bar{L}) &\approx \sum_i P_{i,a\to\gamma}^{\text{single domain}} \\ &= \frac{R_{\text{cluster}}}{\bar{L}} P_{a\to\gamma}^{\text{single domain}}(\bar{B},\bar{L}) \\ &\to \frac{\bar{B}^2 L R_{\text{cluster}}}{4M^2}, \end{aligned} \tag{13}$$

where R_{cluster} is a measure of the size of the cluster and where, in the last line, we have imposed the small θ and small Δ approximation.

For ALP masses $m_a \gg \omega_{pl}$, the ALP to photon conversion probability scale like $P_{a\to\gamma} \sim m_a^{-4}$, thus rapidly making the conversion process inefficient. For $\tau_{\text{DM}} \gtrsim 2\times 10^{19}$ s, this constrains the ALP mass to $m_a \lesssim 6\times 10^{-11}$ eV.

III. AN X-RAY LINE FROM AN ALP LINE

In our model, the observed photon flux of the 3.55 keV photon line from a source at redshift z and luminosity distance $d(z)$ is given by

$$F = \frac{\Gamma_{\text{DM}\to a}}{4\pi d(z)^2}(1+z)\int_V \frac{\rho_{\text{DM}}}{m_{\text{DM}}} P_{a\to\gamma} dV. \tag{14}$$

Let us work out the coupling parameters required for our model. An exact calculation requires the detailed magnetic field profile of the clusters that contribute to the signal, to determine ALP conversion probabilities when propagated through the cluster. However, as an approximate guide to parameters, we take those computed for the central region of Coma, for which a massless ALP with energy $E_a = 3.55$ keV will convert to a photon with $P_{a\to\gamma}^{\text{Coma}} \sim 10^{-3}$ for $M \sim 10^{13}$ GeV.

Reproducing the 3.55 keV line by direct decays to photons requires a lifetime of $\tau \sim 5\times 10^{27}$ s. We therefore see that for decays to ALPs, we require

$$\tau_{\text{DM}\to a} \sim 5\times 10^{24}\ \text{s}\left(\frac{10^{13}\ \text{GeV}}{M}\right)^2. \tag{15}$$

Applying a conservative restriction $\tau_{\text{DM}} \geq 2\times 10^{19}$ s, we see that the line signal can be reproduced for M as large as $M \sim 5\times 10^{15}$ GeV. Note that even though our model has in principle two free parameters, $\tau_{\text{DM}\to a}$ and M, observations in terms of photon fluxes only depend on $\tau_{\text{DM}\to a}/M^2$. Hence, as far as Occam's razor is concerned, there is effectively only one free parameter in our model, as there is in dark matter decaying to photons.

Combining the two processes (dark matter decay to ALPs and ALP conversion to photons), we see that reproducing the observed signal requires

$$\left(\frac{\Lambda}{2.7\times 10^{14}\ \text{GeV}}\right) = \left(\frac{2.7\times 10^{14}\ \text{GeV}}{M}\right). \tag{16}$$

This holds for $\Lambda \gtrsim 5\times 10^{12}$ GeV (to ensure the dark matter lifetime is $\tau_{\text{DM}} > 10^{19}$ s) and $M \gtrsim 10^{11}$ GeV (at which point the $a\to\gamma$ conversion probability in clusters saturates at $\langle P_{a\to\gamma}\rangle = 1/3$. This equation must be read as an approximate relation. The actual values of the ALP-photon conversion probabilities will vary from cluster to cluster depending on the cluster electron density and the magnitude and coherence lengths of the magnetic field in each cluster.

We also note from Eq. (16) that the ALP properties required for this signal are consistent with those required for the explanation of the cluster soft excess as originating from a cosmic ALP background converting to photons in the cluster magnetic field. This scenario required $M \sim 10^{13}$ GeV [26], and so it is possible that the same ALP could be responsible for both—in one case produced primordially, and in another case produced by dark matter decays.

The central magnetic field in the cool core of the Perseus cluster has been estimated at the relatively large $B \sim 25$ μG [43]. Centaurus is also a cool-core cluster, with a magnetic field estimated as $B \sim 11$–25 μG [44]. We were unable to find an observational estimate for the central magnetic field for Ophiuchus (another cool-core cluster), although generally Faraday rotation measures indicate $\sim O(10)$ μG magnetic fields in the center of cool-core clusters, e.g., for A2199 see [45]. A theoretical estimate for Ophiuchus drawn from [46] is 9.5 μG. In contrast estimates of central field strengths for non-cool-core clusters give lower values: for example $B \sim 4.7$ μG for Coma [33], $B \sim 2$–2.5 μG for A2255 [47], or $B \sim 1$ μG for A665 [48].

The central electron density of the Perseus cluster at a radius of $r \sim 10$ kpc has been measured as $n_e \sim 4\times 10^{-2}$ cm^{-3} [49,50]. It follows that one expects the small angle approximation to be a relatively good approximation throughout the cluster.

IV. PERSEUS

In this section, we provide a more detailed estimate of the morphology of the 3.5 keV line as arising from ALP-photon conversion of a 3.5 keV ALP line and compare this estimate to the morphology of a line from decaying dark matter. To this end, we will use a simplistic model of the Perseus cluster magnetic field which we expect to correctly capture our main point: the photon flux from ALP-photon conversion decays much faster with radial distance from the center of the cluster than for the case of dark matter decaying directly to photons.

The flux from dark matter decaying directly into photons is given by

$$F_{\mathrm{DM}\to\gamma} = \frac{\Gamma_{\mathrm{DM}\to a}}{4\pi d^2(z)}(1+z)\int_V \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}dV. \tag{17}$$

For the dark matter density in the Perseus cluster we take a Navarro-Frenk-White profile

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_0}{r/R_s(1+r/R_s)^2}, \tag{18}$$

with $R_s = 360\,\mathrm{kpc}$ [51]. This completely specifies the expected flux from dark matter decaying directly into photons.

In contrast, to evaluate the photon flux arising from Eq. (14), we need to estimate the conversion probability $P_{a\to\gamma}$ in the cluster. The electron density in Perseus is well approximated by the double β model [49]

$$n_e(r) = \frac{3.9\times10^{-2}\ \mathrm{cm}^{-3}}{(1+(r/80\ \mathrm{kpc})^2)^{1.8}} + \frac{4.05\times10^{-3}\ \mathrm{cm}^{-3}}{(1+(r/280\ \mathrm{kpc})^2)^{0.87}}, \tag{19}$$

from which we note that even in the central $r \lesssim 100$ kpc cool-core region of the cluster, the electron density is no larger than $n_e \approx 4\times10^{-2}\ \mathrm{cm}^{-3}$. In this region the magnetic field can be expected to be turbulent over $O(1)$ kpc scales. It then follows from Eq. (11) that while angle Δ is maximized in the central region of the cluster, it only leaves the small angle regime very close to the center. For a detailed discussion on the behavior of the ALP-photon conversion probability in close to $\Delta = 1$, we refer to [26]. Here, we simply note that the small Δ approximation should be sufficient for an estimate of the conversion probability in both the central and more remote regions of the cluster.

As a simple model for the magnetic field strength in the cluster we take

$$B(r) = B_0\sqrt{\frac{n_e(r)}{n_e(0)}}, \tag{20}$$

where $B_0 = 25\ \mu\mathrm{G}$, with coherence length 1 kpc and a cluster size of 1 Mpc. This is a deliberately simplistic model compared to the actual turbulent, multiscale cluster magnetic field. Our purpose in using it is to illustrate our key point: the photon flux in our scenario exhibits a clear peak in the central region in which the magnetic field is enhanced. This is illustrated in Fig. 1, where we plot the central enhancement of the signal compared to the case of direct dark matter decay to photons.

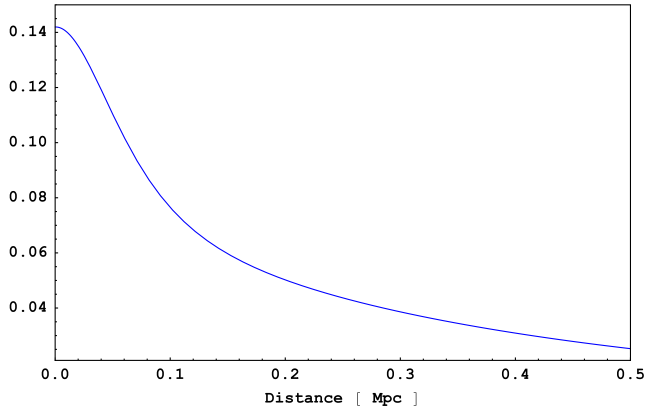

FIG. 1 (color online). Radial profile of the conversion probability $P^{\mathrm{cluster}}_{a\to\gamma}$ as a function of the distance R from the center of Perseus, showing a sharp central peaking behavior. The probability is given in arbitrary units since we do not specify M; see (13).

V. ANDROMEDA

An x-ray line signal has also been reported in [2] for the Andromeda galaxy. While generally one would expect galaxies to have suppressed signals compared to galaxy clusters, the actual calculation of the expected flux from the Andromeda galaxy requires both the dark matter profile and the magnetic field profile in Andromeda. As Andromeda is close to edge on, with an inclination angle of 77 degrees, ALPs emitted from the dark matter halo will have significant passage through the Andromeda disk, where they can convert to photons in the Andromeda magnetic field. Reference [52] estimates a central magnetic field in Andromeda of $B \sim 50\ \mu\mathrm{G}$, and [53] reports a coherent regular magnetic field of $B \sim 5\ \mu\mathrm{G}$ between 6 and 14 kpc from the center of Andromeda.

Currently, the combined uncertainties in signal strength and dark matter density in Andromeda are large. For Andromeda, the effective inferred dark matter lifetime in Ref. [2] is a factor 2–20 longer than that computed in [1] using MOS observations of the Perseus cluster. Detailed analysis of ALP-photon conversion in Andromeda is required to determine whether this ratio is consistent with the explanation of the cluster x-ray line as arising from dark matter decays to ALPs.

VI. PREDICTIONS AND CONCLUSIONS

The key feature of this scenario is that the observed photon signal is a convolution of the dark matter density with the magnetic field structure along the line sight.

Let us enumerate the distinctive predictions this implies:

(1) A signal strength, or inferred dark matter decay time, that varies from cluster to cluster. While the position of the line will be identical across clusters (up to the redshift correction), the strength will vary. Other

aspects being equal, clusters with larger magnetic fields will give larger signals.

(2) Within a cluster, the strength of the line will approximately trace the squared magnetic field strength. For cool-core clusters with high central magnetic fields within the core, the line signal should peak at the core (assuming the electron density does not significantly exceed 0.1 cm^{-3}).

(3) If a large stacked sample of clusters is divided into cool-core clusters and non-cool-core clusters, the central region of cool-core clusters should give a stronger signal (i.e., a shorter effective dark matter lifetime) than the central region of non-cool-core clusters.

(4) In environments with high dark matter densities but low magnetic fields, such as dwarf galaxies, the line should be suppressed, with the dominant contribution to ALP-to-photon conversion coming from the magnetic field of the Milky Way. For such local dwarf galaxies, the signal should be stronger for those closer to the plane of the Milky Way, and also stronger for those at low values of galactic longitude $|l|$ (so the ALPs pass through more of the Milky Way before reaching Earth).

(5) For observations of the line from local spiral galaxies, the signal should be stronger for spiral galaxies which are edge on to us compared to those which are face on. For edge on galaxies, the ALPs produced by dark matter decay propagate through the disk of their host galaxy, where the magnetic field is largest and with the largest coherence scales. For face on spiral galaxies, the ALPs reach us by propagating out of the plane of their host galaxy. This reduces their time spent in the magnetic field of their host galaxy, reducing the conversion probabilities.

These predictions will be made sharper by better knowledge of the intracluster magnetic fields, as will be provided by, for example, LOw Frequency ARray [54] and Square Kilometre Array.

ACKNOWLEDGMENTS

We thank E. Bulbul for clarifying a point in [1] and A. Payez, A. Ringwald, and M. Zahlen for helpful discussions. We thank the Isaac Newton Institute for hospitality while finishing the paper. We are supported by the Royal Society and the ERC grant "Supersymmetry Breaking in String Theory."

[1] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, and S. W. Randall, Astrophys. J. **789**, 13 (2014).
[2] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse, arXiv:1402.4119.
[3] H. Ishida, K. S. Jeong, and F. Takahashi, arXiv:1402.5837.
[4] D. P. Finkbeiner and N. Weiner, arXiv:1402.6671.
[5] T. Higaki, K. S. Jeong, and F. Takahashi, Phys. Lett. B **733**, 25 (2014).
[6] J. Jaeckel, J. Redondo, and A. Ringwald, Phys. Rev. D **89**, 103511 (2014).
[7] H. M. Lee, S. C. Park, and W.-I. Park, arXiv:1403.0865.
[8] K. N. Abazajian, Phys. Rev. Lett. **112**, 161303 (2014).
[9] R. Krall, M. Reece, and T. Roxlo, arXiv:1403.1240.
[10] C. E. Aisati, T. Hambye, and T. Scarna, arXiv:1403.1280.
[11] K. Kong, J.-C. Park, and S. C. Park, Phys. Lett. B **733**, 217 (2014).
[12] K. Hamaguchi, M. Ibe, T. T. Yanagida, and N. Yokozaki, arXiv:1403.1398.
[13] M. Frandsen, F. Sannino, I. M. Shoemaker, and O. Svendsen, J. Cosmol. Astropart. Phys. 05 (2014) 033.
[14] S. Baek and H. Okada, arXiv:1403.1710.
[15] K. Nakayama, F. Takahashi, and T. T. Yanagida, arXiv:1403.1733.
[16] K.-Y. Choi and O. Seto, Phys. Lett. B **735**, 92 (2014).
[17] J. P. Conlon, J. High Energy Phys. 05 (2006) 078.
[18] P. Svrcek and E. Witten, J. High Energy Phys. 06 (2006) 051.
[19] M. Cicoli, M. Goodsell, and A. Ringwald, J. High Energy Phys. 10 (2012) 146.
[20] A. Ringwald, Phys. Dark Univ. **1**, 116 (2012).
[21] R. Bähre *et al.*, JINST **8**, T09001 (2013).
[22] E. Armengaud *et al.*, JINST **9**, T05002 (2014).
[23] J. W. Brockway, E. D. Carlson, and G. G. Raffelt, Phys. Lett. B **383**, 439 (1996).
[24] C. Burrage, A.-C. Davis, and D. J. Shaw, Phys. Rev. Lett. **102**, 201101 (2009).
[25] J. P. Conlon and M. C. D. Marsh, Phys. Rev. Lett. **111**, 151301 (2013).
[26] S. Angus, J. P. Conlon, M. C. D. Marsh, A. Powell, and L. T. Witkowski, arXiv:1312.3947.
[27] R. Lieu, J. P. D. Mittaz, S. Bowyer, F. J. Lockman, C.-y. Hwang, and J. H. M. M. Schmitt, Astrophys. J. **458**, L5 (1996).
[28] M. Bonamente, R. Lieu, M. K. Joy, and J. H. Nevalainen, Astrophys. J. **576**, 688 (2002).
[29] F. Durret, J. S. Kaastra, J. Nevalainen, T. Ohashi, and N. Werner, Space Sci. Rev. **134**, 51 (2008).
[30] R. Lieu, J. P. D. Mittaz, S. Bowyer, J. O. Breen, F. J. Lockman, E. M. Murphy, and C.-y. Hwang, Science **274**, 1335 (1996).
[31] S. Bowyer, T. W. Berghöfer, and E. J. Korpela, Astrophys. J. **526**, 592 (1999).

[32] M. Bonamente, R. Lieu, and E. Bulbul, Astrophys. J. **696**, 1886 (2009).

[33] A. Bonafede, L. Feretti, M. Murgia, F. Govoni, G. Giovannini, D. Dallacasa, K. Dolag, and G. B. Taylor, Astron. Astrophys. **513**, A30 (2010).

[34] Y. Gong and X. Chen, Phys. Rev. D **77**, 103511 (2008).

[35] M. Cicoli, J. P. Conlon, and F. Quevedo, Phys. Rev. D **87**, 043520 (2013).

[36] T. Higaki and F. Takahashi, J. High Energy Phys. 11 (2012) 125.

[37] T. Higaki, K. Nakayama, and F. Takahashi, J. High Energy Phys. 07 (2013) 005.

[38] S. Angus, J. P. Conlon, U. Haisch, and A. J. Powell, J. High Energy Phys. 12 (2013) 061.

[39] M. Cicoli, J. P. Conlon, and F. Quevedo, J. High Energy Phys. 10 (2008) 105.

[40] A. D. Linde, Phys. Rev. D **53**, R4129 (1996).

[41] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).

[42] G. Raffelt and L. Stodolsky, Phys. Rev. D **37**, 1237 (1988).

[43] G. B. Taylor, N. E. Gugliucci, A. C. Fabian, J. S. Sanders, G. Gentile, and S. W. Allen, Mon. Not. R. Astron. Soc. **368**, 1500 (2006).

[44] G. B. Taylor, A. C. Fabian, G. Gentile, S. W. Allen, C. Crawford, and J. S. Sanders, Mon. Not. R. Astron. Soc. **382**, 67 (2007).

[45] V. Vacca, M. Murgia, F. Govoni, L. Feretti, G. Giovannini, R. A. Perley, and G. B. Taylor, Astron. Astrophys. **540**, A38 (2012).

[46] M. W. Kunz, A. A. Schekochihin, S. C. Cowley, J. J. Binney, and J. S. Sanders, Mon. Not. R. Astron. Soc. **410**, 2446 (2011).

[47] F. Govoni, M. Murgia, L. Feretti, G. Giovannini, K. Dolag, and G. B. Taylor, Astron. Astrophys. **460**, 425 (2006).

[48] V. Vacca, M. Murgia, F. Govoni, L. Feretti, G. Giovannini, E. Orrù, and A. Bonafede, Astron. Astrophys. **514**, A71 (2010).

[49] E. Churazov, W. Forman, C. Jones, and H. Böhringer, Astrophys. J. **590**, 225 (2003).

[50] J. Graham, A. C. Fabian, and J. S. Sanders, Mon. Not. R. Astron. Soc. **386**, 278 (2008).

[51] A. Simionescu *et al.*, Science **331**, 1576 (2011).

[52] A. E. Egorov and E. Pierpaoli, Phys. Rev. D **88**, 023504 (2013).

[53] A. Fletcher, E. M. Berkhuijsen, R. Beck, and A. Shukurov, Astron. Astrophys. **414**, 53 (2004).

[54] M. P. van Haarlem *et al.*, Astron. Astrophys. **556**, A2 (2013).