Excess Astrophysical Photons from a 0.1–1 keV Cosmic Axion Background

Joseph P. Conlon* and M. C. David Marsh†

Rudolph Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, OX1 3NP Oxford, United Kingdom
(Received 23 May 2013; published 11 October 2013)

Primordial decays of string theory moduli at $z \sim 10^{12}$ naturally generate a dark radiation cosmic axion background with 0.1–1 keV energies. This cosmic axion background can be detected through axion-photon conversion in astrophysical magnetic fields to give quasithermal excesses in the extreme ultraviolet and soft x-ray bands. Substantial and observable luminosities may be generated even for axion-photon couplings $\ll 10^{-11}$ GeV^{-1}. We propose that axion-photon conversion may explain the observed excess emission of soft x rays from galaxy clusters, and may also contribute to the diffuse unresolved cosmic x-ray background. We list a number of correlated predictions of the scenario.

DOI: 10.1103/PhysRevLett.111.151301 PACS numbers: 95.35.+d, 14.80.Va, 98.65.Cw, 98.70.Qy

The success of the simple ΛCDM model cannot obscure the fact that it will not be the last word in cosmology. One natural extension of ΛCDM is to include an extra, relativistic contribution to the energy density of the Universe. Such dark radiation is conventionally parametrized as an excess number of neutrino species, $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$. There are indeed observational hints for such a contribution including the Hubble Space Telescope (HST) measurement of the Hubble constant [1], the current observational values from WMAP (Wilkinson microwave anisotropy Probe), ACT (Atacama Cosmology Telescope), SPT (South Pole Telescope), and Planck are $N_{\rm eff} = 3.84 \pm 0.40$ (WMAP9, [2]), 3.71 ± 0.35 (SPT, [3]), 3.50 ± 0.42 (ACT, [4]), and 3.62 ± 0.25 (Planck, [5]). Without combining with H_0, the values for $N_{\rm eff}$ are $N_{\rm eff} = 3.55 \pm 0.60$ (WMAP9), 2.87 ± 0.60 (ACT), 3.50 ± 0.47 (SPT), and 3.30 ± 0.27 (Planck).

Dark radiation is a theoretically intriguing extension to ΛCDM as it is a natural consequence of simple and appealing models of the early Universe. The standard postinflationary picture of the early Universe involves the reheating of the standard model (SM) from the decays of a scalar field. In addition to its decay modes to visible sector SM particles, this field may also decay to (effectively) massless weakly coupled hidden sectors, such as axions or hidden photons. If these particles are sufficiently weakly coupled to SM matter, they will not thermalize and will remain as relativistic dark radiation, redshifting with the expansion of the Universe.

This picture is particularly well motivated within string theory models of the early Universe. As radiation redshifts as a^{-4} and matter redshifts as a^{-3}, we expect reheating to be driven by the last scalar field to decay. String theory contains many light scalar fields, called moduli, with gravitational strength couplings. Such moduli are very long lived, with lifetimes

$$\tau \sim 8\pi \frac{M_{\rm Pl}^2}{m_\Phi^3}, \qquad (1)$$

where $M_{Pl} = 2.4 \times 10^{18}$ GeV. Moduli generically couple both to visible SM matter and any hidden axions that are present [6–8].

As the energy density at decay is $V = 3H_{\rm decay}^2 M_{\rm Pl}^2$ with $H_{\rm decay} \sim \tau^{-1}$, the SM reheat temperature is

$$T_{\rm reheat} \sim \frac{m_\Phi^{3/2}}{M_{\rm Pl}^{1/2}} \sim 0.6\ {\rm GeV}\left(\frac{m_\Phi}{10^6\ {\rm GeV}}\right)^{3/2}. \qquad (2)$$

Hidden sector decays $\Phi \to aa$ generate a cosmic axion background (CAB). As these decays are 2-body with $E_a = m_\Phi/2$, the CAB energies are substantially greater than the SM reheat temperature, by a factor $(M_{\rm Pl}/m_\Phi)^{1/2}$.

This ratio is effectively maintained throughout cosmic history, up to small $g_*^{1/3}$ boosts in the photon temperature, and therefore also sets the present day axion energies relative to the Cosmic Microwave Background (CMB). In these expressions the moduli mass m_Φ is unspecified, although the requirement that reheating occurs before Big Bang nucleosynthesis implies $m_\Phi \gtrsim 30$ TeV. The moduli masses are normally comparable to or slightly larger than the scale of supersymmetry breaking. If supersymmetry is relevant to the hierarchy between the Planck scale and the weak scale, the lightest modulus is expected to have $m_\Phi \lesssim 10^7$ GeV and in many models has $m_\Phi \sim 10^6$ GeV (cf. [9] for the LARGE volume scenario, and [10,11] for other work). In [12], we pointed out that this gives rise to a prediction of a CAB with $\mathcal{O}(E) \sim 200$ eV and a homogeneous and isotropic flux of $10^6\ {\rm cm}^{-2}\,{\rm s}^{-1}$. The (nonthermal) spectral shape of the CAB arises from modulus decays and—as is shown in Fig. 1—has a "quasithermal" shape [12].

This CAB would have freely propagated since $z \sim 10^{12}$ ($t \sim 10^{-6}$ s), which is a factor of 10^{19} earlier in time than the CMB. This would provide a spectacular probe of the early Universe. In this Letter, we search for signatures of this CAB through $a \to \gamma$ conversion in astrophysical and cosmological magnetic fields.

Although subdominant in energy density to either baryonic matter or the CMB, the energy density associated to the CAB is still substantial,

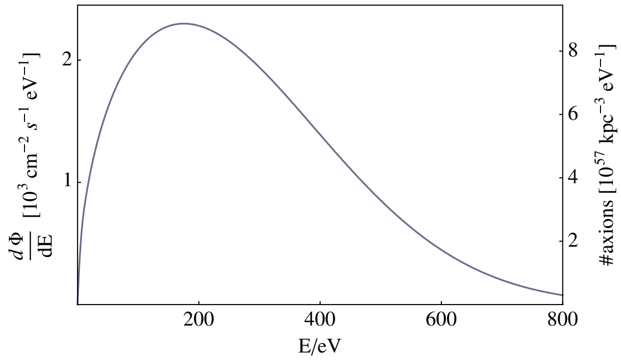

FIG. 1 (color online). The present day axion spectrum resulting from the decay of a modulus of mass $m_\Phi \sim 10^6$ GeV.

$$\rho_{\rm CAB} = 1.6 \times 10^{60}\ {\rm erg\,Mpc^{-3}}\left(\frac{\Delta N_{\rm eff}}{0.57}\right), \tag{3}$$

and entirely located in the extreme ultraviolet (EUV) and soft x-ray bands. A galaxy cluster occupies an approximate volume of 1 Mpc^3 and has a typical x-ray luminosity of $\mathcal{L}_{\rm cluster} \sim 10^{44}$ erg s^{-1}. This makes it clear that even a very small $a \to \gamma$ conversion rate will generate a large signal.

Axion-photon conversion is well known to occur in the presence of coherent magnetic fields [13,14]. The axion-photon Lagrangian is given by

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4M}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2, \tag{4}$$

where the coupling M^{-1} has dimension -1 and gives rise to oscillations between axions and photons. Here, the axion field a is a general pseudo Nambu-Goldstone boson of a broken shift symmetry which need not correspond to the QCD axion [15].

For this case M and m_a are uncorrelated and a is sometimes called an axionlike particle. We will mostly be interested in $m_a \lesssim 10^{-9}$ eV, where direct bounds are $M \gtrsim 10^{11}$ GeV.

The $a \to \gamma$ conversion probability for an axion in a coherent magnetic field domain of length L and with transverse component $B_\perp$ can be computed by elementary methods [16], and is given by

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right), \tag{5}$$

where $\tan 2\theta = 2B_\perp\omega/Mm_{\rm eff}^2$, $\Delta = m_{\rm eff}^2 L/4\omega$, $m_{\rm eff}^2 = m_a^2 - \omega_{\rm pl}^2$, $\omega_{\rm pl}$ is the plasma frequency,

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

and ω denotes the photon energy. Though not crucial for our analysis, we note that in the small-angle approximation $\theta \ll 1$ and $\Delta \ll 1$, the conversion probability is simply given by

$$P(a \to \gamma) = \frac{1}{4}\left(\frac{B_\perp L}{M}\right)^2. \tag{6}$$

We will apply Eqs. (5) and (6) to obtain signatures of the CAB. To allow an easy estimation of magnitudes, we will generally quote results within the small angle approximation, but for plots we shall use the full expression in Eq. (5).

Axion-photon conversion is maximized in regions of large coherent magnetic fields. Galaxy clusters and the intracluster medium (ICM) provide such regions. The existence of magnetic fields in the ICM has been established by a number of methods, with typical values of $\mathcal{O}(B) \sim \mu$G, and with larger values observed close to cluster cooling cores [17]. The coherence lengths of these fields are not known in detail, but are expected to be in the range $L \sim 1$–10 kpc.

The CAB axions will convert into photons with energies $\mathcal{O}(\omega) = 0.1$–1 keV, and for very small axion masses where $m_{\rm eff}^2 = \omega_{\rm pl}^2$ we find

$$\theta \approx \frac{B_\perp\omega}{Mm_{\rm eff}^2} = 2.8 \times 10^{-5}\left(\frac{10^{-3}\ {\rm cm}^{-3}}{n_e}\right) \times \left(\frac{B_\perp}{1\ \mu{\rm G}}\right)\left(\frac{\omega}{200\ {\rm eV}}\right)\left(\frac{10^{14}\ {\rm GeV}}{M}\right). \tag{7}$$

The small-θ approximation is then almost always justified. We also have

$$\Delta = 0.27\left(\frac{n_e}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{200\ {\rm eV}}{\omega}\right)\left(\frac{L}{1\ {\rm kpc}}\right). \tag{8}$$

The small-Δ approximation is then only valid for a limited parameter range.

For illustration, we first work in a parameter regime where (6) applies. Axions traveling through a 1 kpc ICM magnetic field convert to photons with probability

$$P(a \to \gamma) = 2.3 \times 10^{-10}\left(\frac{B_\perp}{1\ \mu{\rm G}}\frac{L}{1\ {\rm kpc}}\frac{10^{14}\ {\rm GeV}}{M}\right)^2. \tag{9}$$

The corresponding conversion rate per axion per second is $2.3 \times 10^{-21}\ {\rm s}^{-1}\ ((B_\perp/1\ \mu{\rm G})(10^{14}\ {\rm GeV}/M))^2(L/1\ {\rm kpc})$.

We now for simplicity assume that the dark radiation is dominated by a single axion species and compute the induced luminosity from $a \to \gamma$ conversion. As the axion flux is homogeneous and isotropic, we average over the alignment of the axion velocity to the magnetic field, giving $\langle B_\perp^2\rangle = \frac{1}{2}B^2$, where B denotes the magnitude of the magnetic field. Summing over magnetic domains, the luminosity from $a \to \gamma$ conversion is

$$\mathcal{L}_{\rm Mpc^3} = 3.6 \times 10^{39}\ {\rm erg\,Mpc^{-3}\,s^{-1}} \times \left(\frac{\Delta N_{\rm eff}}{0.57}\right)\left(\frac{B}{\sqrt{2}\ \mu{\rm G}}\frac{10^{14}\ {\rm GeV}}{M}\right)^2\left(\frac{L}{1\ {\rm kpc}}\right), \tag{10}$$

and lies dominantly in the EUV and soft x-ray bands. In the small angle approximation, the shape of the resulting photon spectrum is identical to the axion spectrum in

Fig. 1. Beyond this approximation the conversion probability is dependent on ω, and the resulting photon spectrum is obtained by weighting the axion spectrum with Eq. (5).

Since the launch of EUVE, excess EUV and soft x-ray cluster emission above the hot ($T \sim 5$–10 keV) intracluster medium has been observed by all major space telescopes with soft x-ray sensitivity in a large number of galaxy clusters. As is reviewed in [18], these include EUVE [19], ROSAT [20], BeppoSAX [21], XMM-Newton [22], Chandra [23,24], and Suzaku [25].

One particularly well studied cluster is Coma, which is large, luminous, and nearby. The soft x-ray excess has been well documented in Coma since the original discovery [19]. It has been established that the soft x-ray excess is diffuse and extends beyond the region containing the hot intracluster gas, up to 5 Mpc from the cluster center [26]. Based on data in [19], the excess luminosity in the 0.1–1 keV range within a central 18 arcminute radius (corresponding to $r \leq 0.50$ Mpc with $H_0 = 73\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$) of the cluster center is 1.6×10^{42} erg/s. Within radii of 1 Mpc, the magnetic field strength in the Coma cluster has been measured to be around 2–5 μG with coherence lengths ranging from 2 to 34 kpc [27].

Proposed astrophysical explanations of the soft excess include either thermal emission from a warm $T \sim 0.2$ keV gas or non-thermal inverse Compton scattering of relativistic electrons off CMB photons (IC-CMB, e.g., [28,29]). The former explanation is problematic for two reasons. First, a thermal gas should also generate emission lines (for example from O_{VII} at 560 eV), and no such lines have been observed. Second, such a gas would cool very rapidly as it requires a large density to maintain pressure against the intracluster medium.

The ostensible explanation of the soft excess by IC-CMB is also problematic. By construction, it requires a large population of relativistic electrons with $\gamma \sim 300$ that scatter off the CMB. As discussed in [30,31], this population is constrained by its synchrotron emission in radio frequencies and its bremsstrahlung emission in gamma rays.

Most proposed models of IC-CMB assume either a power-law shape of the electron number density from $\gamma \sim 300$ (where it is fixed by the observed soft excess) to $\gamma \sim 3000$ (where it emits radio-frequency synchrotron radiation), or a power law with a spectral break at some intermediate value of γ.

The limits on radio emission from the Coma radio halo together with improved determinations of the Coma magnetic field [27] place stringent constraints on the IC-CMB models: since the synchrotron emission scales as B^2, models which were plausible for magnetic field values of 0.2–0.5 μG are immediately excluded for 2–5 μG Coma magnetic fields. We note that these improved observations exclude the vast majority of all models of the soft excess as arising from IC-CMB.

Any viable IC-CMB model must therefore have a sharp spectral cutoff between $\gamma \sim 300$ and $\gamma \sim 3000$. This cutoff may potentially be generated from a single injection event at some point in the past, followed by subsequent radiative losses. However, independently of the spectral shape at large γ, the electrons with $\gamma \sim 300$ (whose number density, by assumption, is fixed by the magnitude of the soft excess) must still emit gamma rays through bremmstrahlung. In [30] this emission was calculated and found to be well in excess of the FERMI-LAT sensitivity. As Fermi has not observed any clusters in gamma rays [32,33], such IC-CMB models appear to be ruled out.

Thus, recent observations appear to have ruled out the proposed astrophysical models for the soft excess in Coma, either through the combination of the comparatively large magnetic field and the limits on radio emission, or through the failure of Fermi-LAT to observe clusters in gamma rays. While it would be premature to conclude that no astrophysical model can work, this motivates consideration of alternative explanations.

From Eq. (10), we note that in the small angle approximation, the luminosity from axion-photon conversion in a cylindrical volume with radius 0.5 Mpc and length 3 Mpc is given by

$$\mathcal{L} = 1.7 \times 10^{42}\ \mathrm{erg\,s^{-1}} \times \left(\frac{\Delta N_{\mathrm{eff}}}{0.57}\right)\left(\frac{B}{2\ \mu\mathrm{G}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2\left(\frac{L}{1\ \mathrm{kpc}}\right). \quad (11)$$

In Fig. 2, we show the total luminosity per Mpc^3, where we have also marginalized over L. This plot is evaluated using the full expression Eq. (5) and is not restricted to the small angle approximation.

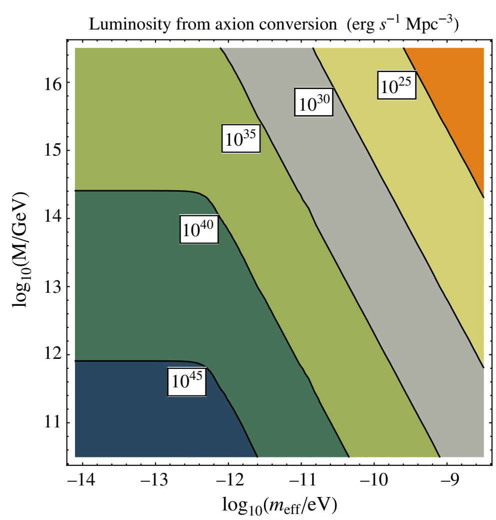

FIG. 2 (color online). The CAB luminosity from axion conversion with $\Delta N_{\mathrm{eff}} = 0.57$, $B_\perp = 1\ \mu$G, and $\omega = 200$ eV. The distribution of L is taken to be uniform in the range of 2–34 kpc and is marginalized over.

As the direct constraint on M for light axions is only $M \gtrsim 10^{11}$ GeV we conclude that axion-photon conversion in the Coma ICM may easily give rise to a soft x-ray excess of the observed order of magnitude.

In addition to reproducing the soft x-ray excess, our model makes several additional predictions. As the CAB is uniformly distributed, the produced luminosity is determined only by the magnetic field and the electron density, and is independent of the cluster temperature or matter distribution. The model predicts that the soft excess should be largest in cluster regions with large magnetic fields and small electron densities, and its spatial extent should be coterminous with the magnetic field. Magnetic field strengths of the order of 0.5 μG have measured in the "bridge" region of the Coma-Abell 1367 supercluster, at a radius of $\sim$1.5 Mpc from the central region of the Coma cluster [34]. Thus, our model appears consistent with the large radial extent of the Coma soft excess emission.

The formula Eq. (5) is probabilistic, and could therefore fluctuate depending on the details of the actual realization of the magnetic field (discussed, for example, in [35]). This could have a significant effect on observations of a point source. However, for the case of clusters the effects of such stochastic fluctuation should be softened when performing an angular average of the soft excess at a fixed radius from the cluster center.

In this model x-ray photons arise nonthermally from $a \to \gamma$ conversion. It is therefore a clear prediction that it should not be possible to associate any thermal emission lines (e.g., from O_{VII} at 561, 569, and 574 eV) to the soft excess.

Furthermore, the CAB axions are redshifting, and used to be more energetic by $(1 + z)$ and more dense by $(1 + z)^3$. It is then a prediction that the energy scale of the soft excess should grow as $(1 + z)$ and, if other aspects of cluster physics are identical, the overall energy in the soft excess should grow as $(1 + z)^4$.

In addition to cluster spectra, $a \to \gamma$ conversion in large-scale cosmological magnetic fields may also contribute to the diffuse unresolved cosmic x-ray background (CXB) in the same 0.1–1 keV band.

In the 0.5–2 keV region the diffuse CXB is $8.2 \times 10^{-12}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,deg^{-2}}$, or in total, $3.4 \times 10^{-7}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. After subtracting the Chandra and HST sources, the diffuse CXB is essentially removed in the 1–2 keV band but remains present in the 0.5–1 keV band, suggesting a different and genuinely diffuse origin for the unresolved CXB below 1 keV [36–38]. In [37] the residual 0.65–1 keV diffuse intensity was given as $(1.0 \pm 0.2) \times 10^{-12}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,deg^{-2}}$.

Here we compute the $a \to \gamma$ contribution to the CXB for certain illustrative parameters. We take $B_\perp = 1$ nG magnetic fields and $L = 10$ Mpc scales, although we caution that the actual magnitude of cosmological magnetic fields is unknown. For an electron density equal to the cosmological baryon density $n_B = 2.5 \times 10^{-7}\ \mathrm{cm^{-3}}$, and $m_{\mathrm{eff}} = \omega_{\mathrm{pl}}$, we find that the $a \to \gamma$ conversion probability is 2.0×10^{-6} per coherent domain for $M = 10^{13}$ GeV. As a rough approximation, we assume that these conditions have held for 10^{10} years, and we average over the direction of the magnetic field to obtain the total conversion probability per axion,

$$P(a \to \gamma) = 6.1 \times 10^{-4}\left(\frac{B}{\sqrt{2}\ \mathrm{nG}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2.$$

As the axion flux on Earth is $4.1 \times 10^{-4}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, the axion contribution to the CXB is given by

$$6.1 \times 10^{-12}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,deg^{-2}}\left(\frac{B}{\sqrt{2}\ \mathrm{nG}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2,$$

again showing that even for $M \gg 10^{11}$ GeV is it easy to generate an observationally significant flux provided cosmological magnetic fields are close to the upper limit of 1 nG.

To conclude, primordial axions from modulus decay at $z \sim 10^{12}$ are a well-motivated scenario of dark radiation which predicts a present-day cosmic axion background with energies between 0.1–1 keV. Conversion of axions into photons in astrophysical and cosmic magnetic fields makes the CAB manifest through quasithermal soft x-ray excesses. This mechanism may be responsible for the soft x-ray excesses observed in galaxy clusters, and can generate a truly diffuse contribution to the 0.1–1 keV cosmic soft x-ray background. Assuming reheating by decays of a Planck-coupled particle, the detection of a cosmic axion background at a scale E_a would also imply the existence of a modulus with mass $m_\Phi \sim (T_{\mathrm{CMB}}/E_a)^2 M_{\mathrm{Pl}}$.

We thank Konstantin Zioutas for informing us about the soft x-ray excess from galaxy clusters. We thank Jo Dunkley and Alexander Schekochihin for discussions. We thank the Royal Society and the European Research Council for funding support.

*j.conlon1@physics.ox.ac.uk
†david.marsh1@physics.ox.ac.uk

[1] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha, W. Li, and R. Chornock, Astrophys. J. **730**, 119 (2011); A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha, W. Li, R. Chornock, and J. M. Silverman, Astrophys. J. **732**, 129 (2011).
[2] G. Hinshaw *et al.*, arXiv:1212.5226.
[3] Z. Hou *et al.*, arXiv:1212.6267.
[4] J. L. Sievers *et al.*, arXiv:1301.0824.
[5] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5076.
[6] M. Cicoli, J. P. Conlon, and F. Quevedo, Phys. Rev. D **87**, 043520 (2013).

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

[8] T. Higaki, K. Nakayama, and F. Takahashi, arXiv:1304.7987.

[9] R. Blumenhagen, J. P. Conlon, S. Krippendorf, S. Moster, and F. Quevedo, J. High Energy Phys. 09 (2009) 007.

[10] K. Choi, A. Falkowski, H. P. Nilles, and M. Olechowski, Nucl. Phys. **B718**, 113 (2005).

[11] B. S. Acharya, P. Kumar, K. Bobkov, G. Kane, J. Shao, and S. Watson, J. High Energy Phys. 06 (2008) 064.

[12] J. P. Conlon and M. C. D. Marsh, arXiv:1304.1804.

[13] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); **52**, 695 (1984).

[14] P. Sikivie, Phys. Rev. D **32**, 2988 (1985); **36**, 974 (1987).

[15] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).

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

[17] F. Govoni and L. Feretti, Int. J. Mod. Phys. D **13**, 1549 (2004).

[18] F. Durret, J. S. Kaastra, J. Nevalainen, T. Ohashi, and N. Werner, Space Sci. Rev., **134**, 51 (2008).

[19] 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).

[20] M. Bonamente, R. Lieu, M. K. Joy, and J. H. Nevalainen, Astrophys. J. **576**, 688 (2002).

[21] M. Bonamente, R. Lieu, J. Nevalainen, and J. S. Kaastra, Astrophys. J. **552**, L7 (2001).

[22] J. Nevalainen, R. Lieu, M. Bonamente, and D. Lumb, Astrophys. J. **584**, 716 (2003).

[23] M. J. Henriksen, D. S. Hudson, and E. Tittley, Astrophys. J. **610**, 762 (2004).

[24] M. Bonamente, J. Nevalainen, and R. Lieu, Astrophys. J. **668**, 796 (2007).

[25] T. Lehto, J. Nevalainen, M. Bonamente, N. Ota, and J. Kaastra, Astron. Astrophys., **524**, A70 (2010).

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

[27] A. Bonafede, L. Feretti, M. Murgia, F. Govoni, G. Giovannini, D. Dallacasa, K. Dolag, and G. B. Taylor, arXiv:1002.0594.

[28] T. A. Ensslin, R. Lieu, and P. L. Biermann, Astron. Astrophys., **344**, 409 (1999).

[29] S. Bowyer, E. J. Korpela, M. Lampton, and T. W. Jones, Astrophys. J. **605**, 168 (2004).

[30] A. M. Atoyan and H. J. Volk, Astrophys. J. **535**, 45 (2000).

[31] M. Y. Tsay, C.-Y. Hwang, and S. Bowyer, Astrophys. J. **566**, 794 (2002).

[32] J. Han, C. S. Frenk, V. R. Eke, L. Gao, S. D. M. White, A. Boyarsky, D. Malyshev, and O. Ruchayskiy, Mon. Not. R. Astron. Soc. **427**, 1651 (2012).

[33] S. Ando and D. Nagai, J. Cosmol. Astropart. Phys. 07 (2012) 017.

[34] K.-T. Kim, P. P. Kronberg, G. Giovannini, and T. Venturi, Nature (London) **341**, 720 (1989).

[35] A. Mirizzi and D. Montanino, J. Cosmol. Astropart. Phys. 12 (2009) 004.

[36] R. C. Hickox and M. Markevitch, Astrophys. J. **645**, 95 (2006).

[37] R. C. Hickox and M. Markevitch, Astrophys. J. **661**, L117 (2007).

[38] N. Cappelluti *et al.*, Mon. Not. R. Astron. Soc. **427**, 651 (2012).