Searching for Decaying Axionlike Dark Matter from Clusters of Galaxies

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(Received 13 March 2007; revised manuscript received 10 August 2007; published 28 September 2007)

We constrain the lifetime of radiatively decaying dark matter in clusters of galaxies inspired by generic Kaluza-Klein axions, which have been invoked as a possible explanation for the solar coronal x-ray emission. These particles can be produced inside stars and remain confined by the gravitational potential of clusters. By analyzing x-ray observations of merging clusters, where gravitational lensing observations have identified massive, baryon poor structures, we derive the first cosmological lifetime constraint on this kind of particles of $\tau \gtrsim 10^{23}$ sec.

DOI: 10.1103/PhysRevLett.99.131301 PACS numbers: 95.35.+d, 14.80.Mz, 95.85.Nv, 98.65.Cw

Introduction.—Cosmological observations have determined that there is approximately six times as much dark matter as baryonic matter, but its particle nature remains a mystery. An apparently unrelated issue is "the solar corona problem": in order to explain the quiet solar x-ray spectrum, one may need to invoke new physics, such as introducing massive axions of the Kaluza-Klein (KK) type [1,2]. The standard axions with the remaining rest mass window in the sub-eV range live far too long to solve this problem [3]. KK-axions appear in the framework of large extra dimensions [4,5] where it is assumed that only gravity propagates in the higher-dimensional space, while the standard-model fields are confined to our $(3 + 1)$-dimensional subspace. Since axions are singlets under the standard-model gauge group, they can also propagate in the higher-dimensional space. As a result of compactification with radius R, the higher-dimensional axion field is decomposed into a KK tower of states with the mass spacing of order $1/R$ [5,6]. All KK excitations have the same coupling strength to matter, and a source of axions will therefore emit all KK states up to the kinematic limit.

We address the possibility that part of the dark matter in galaxy clusters are like KK-axions which can be produced in normal stars and accumulated over the lifetimes of these stars [1,7,8]. Part of the so produced axions are confined by the gravitational potential of the host galaxy clusters, where they stay until they eventually decay spontaneously. These KK-axions are predicted to decay into two photons, producing a broad characteristic spectrum which happens to peak just where current astrophysical x-ray instruments are most sensitive, i.e., in the few keV range. We consider x-ray observations of merging clusters, from which weak gravitational lensing observations have provided strong evidence for a nonbaryonic matter component. Assuming that parts of this dark matter is of the KK-axion type, we can derive the first cosmological constraints on the lifetime of this kind of dark matter particles.

Radiatively decaying particles.—All of the massive KK-axions produced in the Sun as a possible explanation for the quiet solar x-ray spectrum can decay radiatively [1]. From the assumed production mechanism, the resulting photon spectrum can be calculated (lower curve in Fig. 1). The peak energy is ≈ 4.5 keV, and for $E_\gamma \geq 2.0$ keV, the derived spectrum is well represented by the following expression:

$$F_{\rm der}(E_\gamma > 2.0\ {\rm keV}) = 2.2 \times 10^8 E_\gamma^{-8.1} e^{-(32.0/E_\gamma)}. \quad (1)$$

Solar x-ray observations made with the Yohkoh solar x-ray mission fit the general feature of the radial distribution of the massive solar axion model, except at low photon energies (below 4 keV), where the bulk of the quiet and not-quiet solar x-ray spectrum is emitted (see the upper curve of Fig. 1 and discussion in Ref. [9]). The shape of the spectrum of the predicted KK-axion spectrum is tightly

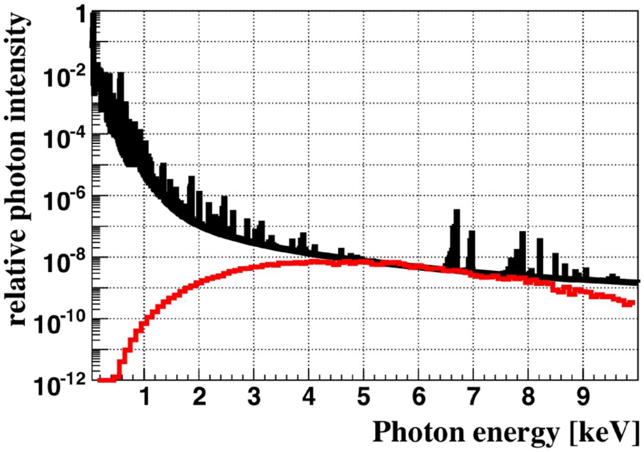

FIG. 1 (color online). The reconstructed quiet Sun x-ray spectrum (upper curve) [25] and the expected flux from decaying massive axions of the Kaluza-Klein type (lower curve) [1].

bound by solar physics processes. The normalization depends on the coupling of the KK-axions and can for our purpose be treated as a free parameter. Assuming the Sun to be a "typical" star in cosmos, which is a reasonable assumption, Eq. (1) can be applied to KK-axions produced in stars and confined by the dark matter gravitational dark well in clusters of galaxies.

Data analysis.—We have analyzed *Chandra* x-ray observations of the two galaxy clusters Abell 520 and the "Bullet Cluster" (also known as 1E0657-558). Basic data on the clusters and the observations are specified in Table I for a cosmology with $H_0 = 71$ km/s/Mpc, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ [14]. The data were retrieved from the public *Chandra* archive and processed using standard data reduction methods with CIAO version 3.3 [10].

As seen from the x-ray images in Fig. 2, the clusters are merging systems [15,16]. In such disturbed systems, the hot x-ray emitting intracluster plasma (which is the dominating baryonic component in clusters) is displaced from the stars and the dark matter, leaving mass concentrations practically devoid of baryons. These so-called "dark matter blobs" are ideal environments for dark matter studies [12,16,17] since they have a high dark matter density and a low contamination of x-ray "noise" from baryonic matter. In Fig. 2, the blob regions selected for the analysis are shown in white. For easy comparison to the results of [12], the region covering the dark matter blob of the Bullet Cluster is chosen identical to their SUB region, i.e., as the large circle centered on the mass peak with the smaller circle centered on the bullet boundary subtracted.

For Abell 520, the masses of the regions were determined from weak gravitational lensing. The values are based on measuring the overdensity in the regions with respect to the mean density in a surrounding annulus with inner and outer radius of 0.85 arc min (168 kpc) and 4 arc min (792 kpc), respectively. Hence, the mass value can be regarded as a conservative lower limit on the mass contained within the region. A mass map generated using the method of [18] shows a 4σ detection of mass in this region, compared to noise maps based on randomized shear values. A detailed description of the data and methodology of the weak lensing analysis is given elsewhere [19]. Two independent weak lensing analyses of Abell 520 [20,21] confirm the existence of the blob, centered at a slightly different position, but with a significant amount of dark matter within the blob region used here. The mass of the Bullet Cluster blob region (SUB) is taken from [12].

The dominating baryonic component in clusters of galaxies is the hot x-ray emitting intra cluster gas. However, the generally observed gas mass fraction is only $f_{\rm gas} \approx 0.11$ [22]. In the merging galaxy cluster systems, the gas has been displaced from the blob regions, so the gas mass can be neglected, and the dark matter mass is taken to be the total mass of the blobs as determined from gravitational lensing.

For Abell 520, the blob region spectrum is shown in Fig. 3 (black, squares). The blob region spectra were compared to the spectra of a reference region in the same cluster (triangles in Fig. 3) of same size and shape and of similar x-ray flux as the blob regions, but with much smaller masses (rightmost circles in Fig. 2). For both clusters, there is a mass contrast of an order of magnitude between the dark matter dominated blob region and the reference region in which the baryons are the dominating source of x-ray emission. As seen from Fig. 3, there are no outstanding differences between the emission from the two regions.

The dark matter in the Milky Way halo also contributes to the possible signal [23], and we must first remove such contamination. Before extracting the spectra, a background region with small mass and no significant x-ray emission is chosen from the same observation and subtracted. This simplifies the expected signal from decaying dark matter as only one source redshift has to be considered.

The blob region spectrum shown in Fig. 3 is clearly different from the expected axion spectrum shown in Fig. 1, so there must be an additional (baryonic) contribution to the emission. However, the most conservative con-

TABLE I. The obtained values as described in Sec.

	Abell 520	Bullet Cluster
Redshift	$0.2^{\rm a}$	$0.29^{\rm b}$
D_A, [Mpc]	662	872
Region radius, $\delta\theta$ [arcmin]	0.85	0.66
Chandra observation id[c]	4215	5356 + 5361
Exposure time [ksec]	67	179
$M_{\rm blob}$ $[10^{13} M_\odot]$	6.7 ± 2.1	$5.8 \pm 0.9^{\rm b}$
Redχ^2/dof, basis model	0.78/33	1.04/512
Redχ^2/dof, basis + expected	0.77/32	1.05/511
3σ total luminosity upper limit $[10^{44}$ erg/sec$]$	0.2	0.9

[a] from [11].
[b] from [12].
[c] from [13].

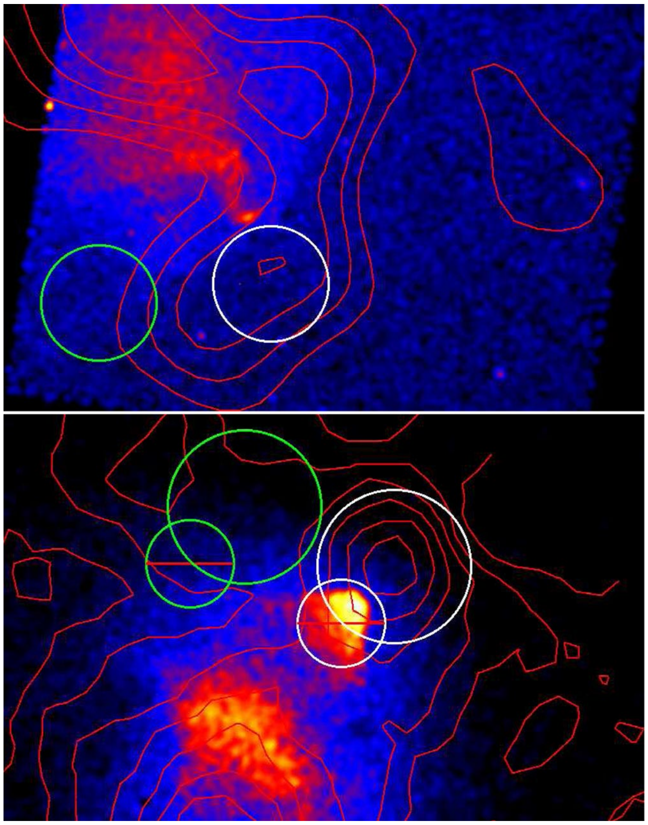

FIG. 2 (color online). The x-ray image of Abell 520 (above) and the Bullet Cluster (below) overlaid the gravitational potential from weak gravitational lensing (in units of κ, Bullet Cluster contours from [16]). The dark matter blob regions are the white leftmost circles, and the reference regions are the rightmost circles.

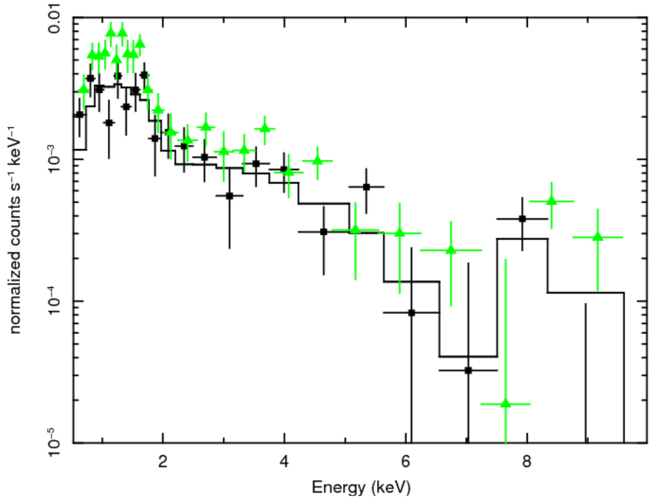

FIG. 3 (color online). The observed spectrum of the blob region (squares) of Abell 520 with the fitted "basis model" (solid, reduced $\chi^2 \approx 1$) and the spectrum of the reference region (triangles).

straint on the decaying dark matter luminosity is obtained by assuming all of the received photons to originate from decaying dark matter. This total luminosity is obtained by fitting a model consisting of a "basis" thermal emission model plus the expected axion flux to the spectrum. The "basis model" consists of a thermal plasma model and several Gaussians. No physical quantities are derived from the model. It is designed to fit the data with a reduced $\chi^2 \approx 1$ for the numerical analysis of the spectrum (solid line in Fig. 3). However, the resulting physical parameters of the basis model are typical for clusters. The expected continuous emission of decaying axions is represented by redshifting the analytic expression in Eq. (1) according to the distance of the cluster of galaxies. As seen in Fig. 1, the expected spectrum of decaying solar KK-axions is only significantly contributing for $E_\gamma = 2.0$–9.5 keV, even with the redshifts of the considered clusters taken into account. The complete model (basis + axion) is fitted to the blob region spectrum in this interval with all parameters except the redshift free in the fitting. The resulting values of the reduced χ^2/dof are given in Table I. The 3σ upper limit (with respect to the fitting residuals) on the luminosity is determined from the fit with the total model normalizations given by the fitted values plus 3σ. An attempt was also made to model the baryonic emission from the reference region spectrum and subtract it from the blob region spectrum, but the low statistics resulted in huge errors in the luminosity.

Lifetimes.—A simple estimate of the lifetime of the dark matter particles can be derived from the observed total luminosities: $L = \Gamma E_\gamma N$, where Γ is the decay rate, E_γ is the photon energy, and N is the total number of particles. In the general case of nonrelativistic radiative dark matter two-body decays, $E_\gamma = m/2$ for a dark matter candidate of mass m, $N = XM_{\mathrm{DM}}/m$, where X is the mass fraction of the dark matter made up of the considered candidate. It is worth mentioning that we are considering the case where the many individual two-body decay modes produce a wide KK-axion bump, which has the shape of the lower curve in Fig. 1. The lifetime then becomes

$$\tau = \frac{1}{\Gamma} = \frac{2XM_{\mathrm{DM}}}{L}. \tag{2}$$

For the two clusters, the observational 3σ upper limits on the luminosities lead to a lower limit on the mean lifetime of the order of $\tau \gtrsim 10^{23}$ sec. The strongest constraint is $\tau \gtrsim 6 \times 10^{24}$ sec from Abell 520 assuming one single dark matter particle constituent and with a radiative two-body decay. The luminosity limit is a 3σ upper limit, the main uncertainty in the lifetime constraint comes from the 1σ uncertainty in the mass determination which is $\approx 30\%$ for Abell 520 and $\approx 20\%$ for the Bullet Cluster. Therefore, the uncertainty on the lifetime limit is of the order of 30% at 1σ. This is not a precision measurement, but a determination of the order of magnitude.

For solar KK-axions, the lifetime has been derived to be $\tau \approx 1.25 \times 10^{20}$ sec for a mean axion rest mass of 5 keV [1]. This is four orders of magnitude smaller than the lower limit derived from clusters of galaxies assuming the axions to account for all of the dark matter. However, the assumed axions produced in the stars (as predicted for the Sun) does not have to be (all of) the dark matter. If the axions only contribute with a small fraction of the total amount of dark matter, the lower limit relaxes and the two lifetimes can become consistent if the fraction is smaller than 0.01%, in which case the star produced axionlike contribution to the dark matter is clearly very small.

Moreover, we compare the cosmic densities of energy associated with dark matter and electromagnetic radiation [24] since it will give a crude estimate of a lower limit on the radiative lifetime of dark matter particles on a cosmic scale. We assume that the decay of dark matter particles is responsible for at least a part of the present day electromagnetic radiation of the Universe (essentially excepting the cosmic microwave background radiation since it is a primeval remnant). If we assume, in the extreme case, that all of this radiation is due to the decay of dark matter, we get a lower limit on the lifetime of dark matter particles. The total fraction of the radiation densities (relative to the critical matter density) in radio-microwave, far infrared, optical, and x-γ-rays is $d_{\mathrm{tot}} \approx 2.4 \times 10^{-6}$ [24]. With the age of the Universe taken to be 4.5×10^{17} sec [14], this gives an order of magnitude estimate of the lifetime, independent of particle type, of

$$\tau \approx \frac{\Omega_{\mathrm{DM}} \tau_{\mathrm{Universe}}}{d_{\mathrm{tot}}} \approx 4 \times 10^{22} \text{ sec}, \tag{3}$$

which is similar to the lifetimes derived above. If only the contribution from x-γ-rays (1.3×10^{-8}) is taken as an upper limit for dark matter radiation, the lifetime constraint improves by about a factor of 200.

Summary.—Dark matter blobs in merging clusters of galaxies are excellent laboratories for constraining fundamental properties of dark matter candidates, like their lifetime. One promising dark matter constituent might have properties similar to the generic KK-axion, presumably produced inside stars and proposed to explain the origin of the quiet solar x-ray spectrum which has remained elusive for decades. Trapped by the deep gravitational potential of clusters of galaxies, some of the KK-axions, or the like, eventually decay isotropically into two x-ray photons and thereby contribute to the diffuse intracluster x-ray emission. Hence, the x-ray emission from dark matter blobs can be taken as a conservative upper limit on the assumed total KK-axion luminosity, leading to a lower limit on the KK-axion lifetime of $\tau \gtrsim 6 \times 10^{24}$ sec.

We thank S. Hannestad and B. Lakic for useful comments. K. Z. thanks the Dark Cosmology Centre for hospitality in the first stage of this work. The Dark Cosmology Centre is funded by the Danish National Research Foundation. A. L. and K. Z. acknowledge support by the EU-network on direct dark matter detection of the ILIAS integrating activity. K. P. acknowledges support from Instrument Center for Danish Astrophysics.

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