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Deep XMM Observations of Draco rule out a dark matter decay origin for the 3.5 keV line

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ABSTRACT
We searched for an X-ray line at energies around 3.5 keV in deep, ~ 1.6 Msec XMM-Newton observations of the dwarf spheroidal galaxy Draco. No line was found. The data in this energy range are completely consistent with a simple power law X-ray background, dominated by particle background, plus instrumental lines; the addition of a ~ 3.5 keV line feature gives no improvement to the fit. The corresponding upper limit on the line flux rules out a dark matter decay origin for the 3.5 keV line found in observations of clusters of galaxies and in the Galactic Center at greater than 99% C.L..

Key words: X-rays: galaxies; X-rays: galaxies: clusters; X-rays: ISM; line: identification; (cosmology:) dark matter

1 INTRODUCTION

The detection of a line with an energy between 3.50 – 3.57 keV (hereafter indicated as "the 3.5 keV line" for brevity) in the X-ray data from individual and stacked observations of clusters of galaxies (Bulbul et al. 2014), from the Galactic center (Jeltema & Profumo 2015) and, tentatively, from M31 (Boyarsky et al. 2014) (see however Jeltema & Profumo 2015; Jeltema & Profumo 2014) has triggered widespread interest: the line might be associated with a two-body radiative decay including one photon of a dark matter particle with a mass of around 7 keV and a lifetime of about $6-8\times10^{27}$ sec. Such a particle has a natural theoretical counterpart in sterile neutrino models, a class of dark matter candidates whose motivation goes beyond that of explaining the missing non-baryonic matter in the universe (see e.g. Boyarsky et al. 2009, for a review).

Jeltema & Profumo (2015) pointed out early on that atomic de-excitation lines from He-like Potassium ions (K XVIII) are a plausible counterpart to the 3.5 keV line both in clusters of galaxies and in the Milky Way. This possibility was initially discarded by Bulbul et al. (2014) based on estimates of the required K abundance that relied on photospheric K solar abundances, and on multi-temperature models biased towards high temperatures. The latter, as demonstrated in Jeltema & Profumo (2014), artificially suppress the brightness of the K XVIII de-excitation lines by up to more than one order of magnitude. Additionally, coronal K abundances are larger by about one order of magnitude than photospheric K solar abundances, as recently pointed out by Phillips et al. (2015). As a result, the case for K XVIII as the culprit for the 3.5 keV line appears at present quite plausible.

Additional circumstantial evidence against a dark matter decay origin for the 3.5 keV line has also emerged. Malyshev et al. (2014) searched for the line in stacked, archival XMM observations of dwarf spheroidal galaxies, reporting a null result that highly constrained a dark matter decay origin for the line. Anderson et al. (2015) analyzed stacked observations of galaxies and galaxy groups, systems where the thermal emission would be too faint to produce a detectable line from e.g. K XVIII, and also failed to find any evidence for a 3.5 keV line. Urban et al. (2015) studied Suzaku data from X-ray-bright clusters, confirming that the 3.5 keV signal could naturally be ascribed to K, and questioning the compatibility of the line morphology with the dark matter decay hypothesis. Finally, Carlson et al. (2015) studied in detail the morphology of the 3.5 keV emission from the Perseus cluster of galaxies and from the Galactic center, finding a notable correlation with the morphology of bright elemental emission lines, and excluding a dark matter decay origin even for cored Galactic dark matter density profiles. A recent study of charge exchange processes indicates that an additional possibility is that the 3.5 keV line originates from a set of high-n S XVI transitions (populated by charge transfer between bare sulfur ions and neutral hydrogen) to the ground state (Gu et al. 2015).

It is important to acknowledge that null results obtained so far are still compatible with a non-standard origin for the 3.5 keV line. Notably, axion-like particle conversion in magnetic fields (Alvarez et al. 2015) could reproduce the morphology of the 3.5 keV line in Perseus reported in Carlson et al. (2015); other possibilities include, for example, inelastic excited dark matter (Finkbeiner & Weiner 2014). In all such instances, the signal strength scales non-trivially with the integrated dark matter mass along the line of sight, or it depends sensitively on astrophysical conditions such as the magnetic field strength.

Lovell et al. (2015) used N-body simulations from the Aquar-

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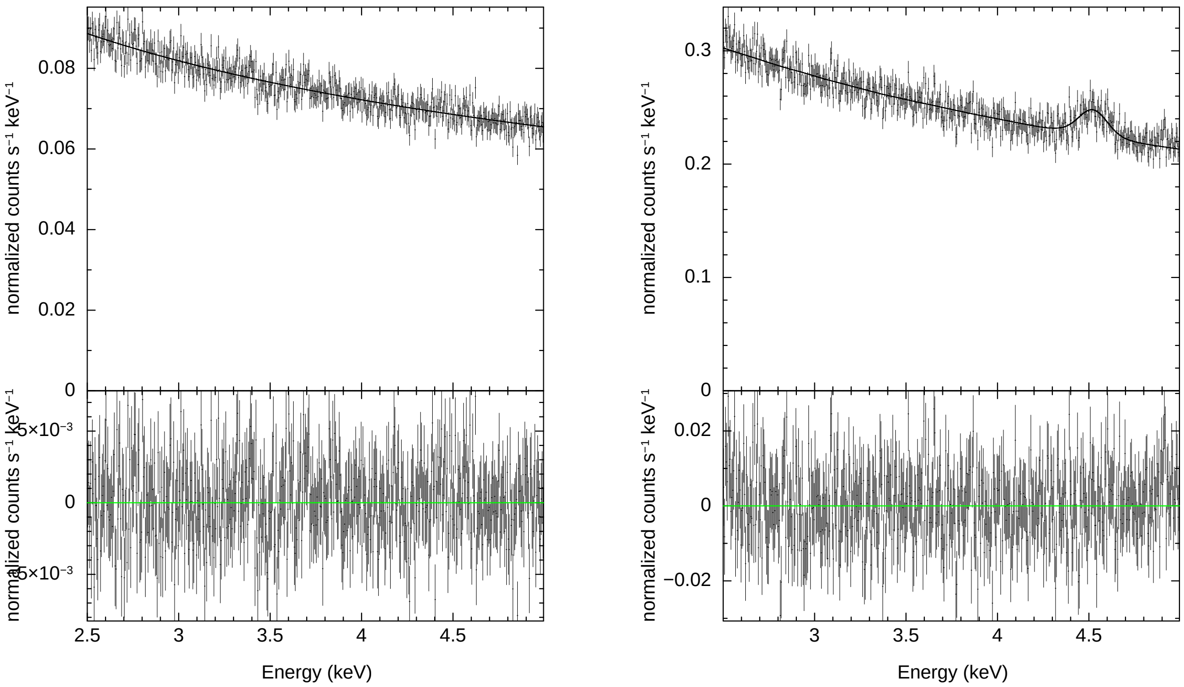

Figure 1. *Left*: Combined MOS spectrum and residuals in the 2.5-5.0 keV energy range fit to an unfolded, single power law. *Right:* Combined PN spectrum and residuals in the 2.5-5.0 keV energy range fit to an unfolded single power law plus an instrumental line due to Ti Kα emission at 4.51 keV. A weaker Ti Kβ line can be seen at 4.93 keV but has no effect on the 3.5 keV line constraints.

ius project (Springel et al. 2008) to estimate the flux ratio for a standard dark matter decay process across different targets, including for the Draco dwarf spheroidal galaxy (dSph) and the Galactic center (GC). This ratio has a certain statistical distribution, which depends on the choice of the placement of the observer. The central finding of that study is that a 1.3 Ms long XMM-Newton observation of the Draco dSph would enable the discovery or exclusion at the 3σ level of a dark matter decay interpretation of the 3.5 keV signal.

Here, we utilize recent, deep archival XMM-Newton observations of the Draco dSph to test a dark matter decay origin for the 3.5 keV line. We find no evidence of a line in either the MOS or PN data, and we are able to rule out a dark matter decay origin at greater than the 99% confidence level.

The remainder of this manuscript has the following structure: we describe the XMM observations and data reduction in the following section 2; we then describe our flux calculation and compare with the flux limits from the XMM MOS and PN data in section 3, and we present our conclusions in the final section 4.

2 XMM DATA ANALYSIS

Draco was observed by XMM-Newton in 31 separate observations, 5 in 2009 (PI Dhuga) and 26 in 2015 (PI Boyarsky), with individual exposure times ranging from 17 to 87 ksec and a total time in all observations of 1.66 Msec. We reprocessed all 31 observations using standard procedures and utilizing the XMM SAS[1] and ESAS (Snowden et al. 2008; Kuntz & Snowden 2008) software packages. Starting from the Observation Data Files, the raw EPIC data was pipeline-processed with the `emchain` and `epchain` tasks. Flare filtering was carried out with the ESAS tasks `mos-filter` and `pn-filter`; these time periods of increased particle background due to soft protons can lead to background levels elevated by two orders of magnitude and are thus removed from the data. Unfortunately, in the case of Draco particle background flaring was significant in many of the observations. For the two MOS detectors, two observations (ObsID 0603190401 and 0770190601) were almost entirely contaminated by flaring, and we removed these from our final data set; the other observations had reduced usable exposure times. The net exposure time after filtering was a little over one Msec for each MOS detector with a total time for both detectors of 2.1 Msec. The PN detector is typically more effected by particle flaring than the MOS detectors, and we found that only 20 of 31 observations had flares satisfactorily removed by `pn-filter`; for these observations the net usable exposure time for PN was 0.58 Msec.

Point sources were detected and removed separately from each observation using the ESAS task `cheese`; point source detection was run on broad-band images (0.4-7.2 keV) with a flux limit of 10^{-14} erg cm^{-2} s^{-1} and a minimum separation of 10 arcsec. Low exposure regions are likewise masked by `cheese`. Spectra were extracted from the full field-of-view from each detector in each flare-filtered observation; however, for the MOS1 detector CCDs 3 and 6 were excluded due to micrometeroid damage. Spectra and corresponding redistribution matrix files (RMF) and ancillary response files (ARF) for the 0.4-7.2 keV range were created using `mos-spectra` and `pn-spectra` in the ESAS package. The individual spectra and response files were co-added using the routines `mathpha`, `addrmf`, and `addarf` in the `FTOOLS` package (Blackburn 1995). Combined RMF and ARF files were weighed by the relative contribution of each observation to the total exposure

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[1] http://xmm.esac.esa.int/sas/

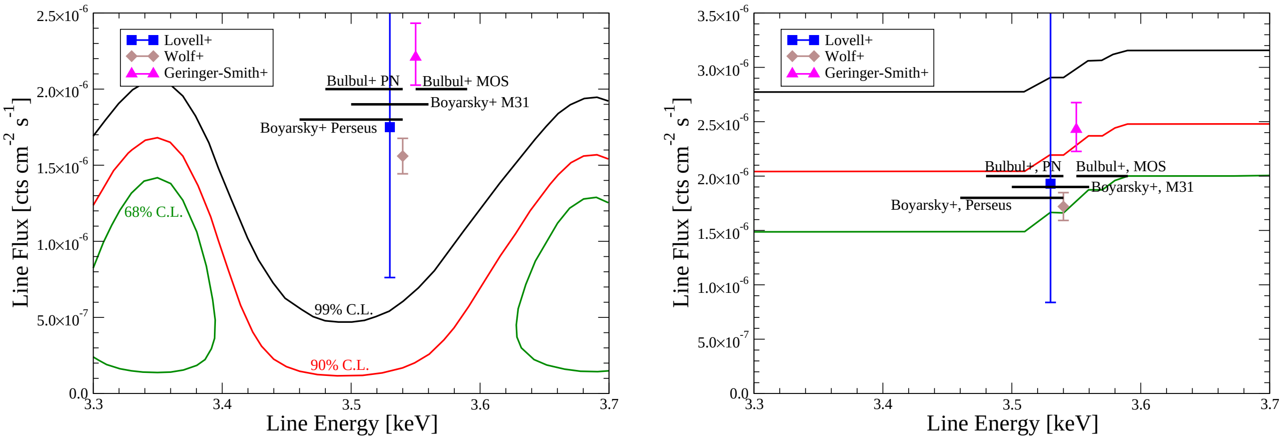

Figure 2. *Left*: Limits on the flux of a line in the energy range between 3.3 and 3.7 keV from MOS observations of the Draco dSph, at the 68%, 90% and 99% C.L. (green, red and black lines, respectively) and predictions for the flux of a 3.5 keV line assuming a dark matter decay origin for the line detected at that energy from stacked clusters of galaxies and from the Milky Way center (see text for details). The horizontal black lines indicate the 1σ energy range for the line position as inferred by Boyarsky et al. 2014 for Perseus (3.50 ± 0.04 keV) and for M31 (3.53 ± 0.03 keV) and by Bulbul et al. 2014 from cluster observations (3.57 ± 0.02 and 3.51 ± 0.03 keV for their "full sample" MOS and PN results, resepctively); *Left*: same, for PN observations (note the difference in vertical scale).

time. The spectra and responses for the MOS1 and MOS2 cameras were combined in to a single summed MOS spectrum, while the spectra and responses for the PN detector were combined separately.

Spectral modeling employed the energy range between 2.5 keV and 5 keV. This energy range was chosen to exclude strong instrumental emission lines while being much, much broader than the energy resolution of the detectors ($\sim$ 100 eV). At these energies, the X-ray background is dominated by the quiescent particle background (Kuntz & Snowden 2008) which we model with an unfolded, power law (no vignetting) in `XSPEC` (version 12.8.1p, Arnaud 1996). As shown in Fig. 1, the combined MOS spectrum in the 2.5-5 keV range is well fit by an unfolded, single power law alone with reduced $\chi^2 = 0.96$ ($\chi^2 = 475/497$ degrees of freedom). Adding a Gaussian line between 3.4 and 3.6 keV gives no improvement to the fit, and a line at these energies with a flux greater than $\sim 10^{-6}$ photons cm^{-2} s^{-1} is excluded, as shown in Fig. 2. The combined PN spectrum is well fit by an unfolded power law plus an instrumental line due to Ti Kα emission (4.51 keV), which we model as a narrow Gaussian (Fig. 1, right). The reduced χ^2 for this fit is 0.99 ($\chi^2 = 490/495$ degrees of freedom). Again, adding a Gaussian line between 3.4 and 3.6 keV gives no significant improvement to the fit. The fit is somewhat improved by adding a second instrumental line, Ti Kβ, at 4.93 keV, but this feature has no effect on the 3.5 keV line constraints. As can be seen from Fig. 2, right the upper limit on the flux of a line near 3.5 keV from the PN data is weaker than from the MOS data given the shorter usable exposure time but does serve as additional confirmation of the lack of a 3.5 keV line from Draco.

3 FLUX LIMITS AND CONSTRAINTS ON DARK MATTER DECAY

We utilize three distinct predictions for the 3.5 keV line flux that should have been observed with the XMM observations described above for a dark matter decay origin . The first one makes use of the results of Lovell et al. (2015), which calculated the flux expected from a 14 arcmin angular region around Draco given the brightness of the 3.5 keV line observed from the Galactic Center and the ratio of the flux from Draco-like halos and from the Galactic center as extrapolated from the Aquarius simulation. The resulting distribution in predictions is bracketed by the range

$$F = (1.0 - 5.2) \times 10^{-6}\ \mathrm{cts\ cm^{-2}\ s^{-1}},$$

where the lower and upper values bracket 95% of the predictions, and with the most-probable value being $F = 2.3 \times 10^{-6}$ cts cm^{-2} s^{-1} (see especially their Appendix C3 for additional details on assumptions and method). We calculated that the point source masking we adopt and the non-uniform coverage (e.g. from the lost MOS CCDs and chip gaps) described in the previous section suppress the predicted flux to 77% of its un-masked value (we neglect the additional signal from the annulus between 14 and 15 arcmin).

Secondly, we use predictions from Malyshev et al. (2014), which compound, for the direction of Draco, the flux from dark matter within the Milky Way in the direction of Draco, and that from the Draco dSph itself, as modeled using the mass estimates in Wolf et al. (2010) and in Geringer-Sameth et al. (2015) with the "favored NFW" Milky Way dark matter halo of Klypin et al. (2002), and normalize, as in Malyshev et al. (2014), to the parameters corresponding to the best-fit point of the cluster observations of Bulbul et al. (2014). In this case we again account for masking, but we also account for the larger angular region we utilize compared to the flux predictions in Malyshev et al. (2014).

We illustrate our results in Fig. 2. We indicate with green, red and black lines the 68%, 90% and 99% Confidence Level (C.L.) limits on the maximal allowed flux associated with a line at the energy indicated by the x-axis. We also show the predictions for the line flux described above as well as the range of energies for the line reported from cluster observations as described in Bulbul et al. (2014) and the range obtained by Boyarsky et al. (2014) from observations of the Perseus cluster and of M31.

As can be seen in Fig. 2, the lack of a detected line in the MOS data rule out at higher than 99% confidence level a line with even the most conservative predicted fluxes based on a conservative range of possible density profiles for the Draco dwarf. Therefore, a generic dark matter decay origin of the 3.5 keV line feature is highly unlikely.

In Fig. 3, we show constraints on the sterile neutrino parameter space in terms of the particle's mass m_s and mixing angle with active neutrinos θ given the line flux limits from the MOS Draco observations, in the relevant mass range for a dark matter decay interpretation of the 3.5 keV line. The cyan shaded region is excluded at the 2σ level, and assumes the central value for the Geringer-Sameth et al. (2015) dark matter halo parameters for Draco, and the most conservative Milky Way halo considered in Malyshev et al. (2014) (corresponding to the "maximal disk model" of Klypin et al. (2002)). The blue shaded region, instead, adopts the default "favored NFW" Milky Way dark matter halo density profile (Klypin et al. 2002).

Taking the most conservative possible assumptions both for the flux from Draco and from the Milky Way Galactic halo (corresponding to the predictions of Wolf et al. (2010) for the flux from Draco and the most conservative Milky Way halo of Klypin et al. (2002)), we are able to set a lower limit on the lifetime of a 7 keV sterile neutrino decaying into a 3.5 keV line of $\tau > 2.7 \times 10^{28}$ s (95% C.L.), corresponding to a mixing angle $\sin^2(2\theta) < 1.6 \times 10^{-11}$ (95% C.L.). Our most conservative limits are thus more than a factor 4 below the favored mixing angle predicated by a dark matter decay interpretation of the 3.5 keV line signal ($\sin^2(2\theta) \approx 7 \times 10^{-11}$, Bulbul et al. 2014).

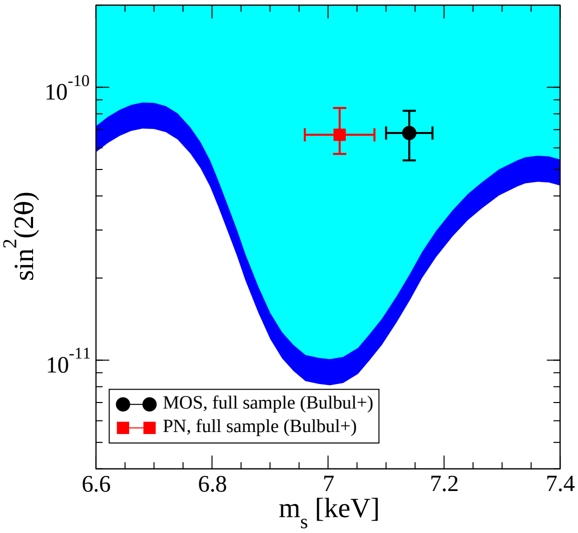

Figure 3. Constraints on the parameter space of sterile neutrinos, defined by the particle's mass m_s and mixing angle with active neutrinos, θ. The cyan-shaded region is excluded, at the 2σ level (~95% C.L.), by Draco MOS observations, using the most conservative Milky Way dark matter density profile considered in Malyshev et al. (2014), while the blue-shaded region employs the nominal "favored NFW" profile, which we also use for Fig. 2.

4 DISCUSSION AND CONCLUSIONS

Using $\sim$ 1.6 Msec observations of the Draco dSph with XMM-Newton we were able to obtain one of the most stringent constraints on a dark matter decay origin for the 3.5 keV line observed from clusters of galaxies and from the Milky Way center. Our results rule out a dark matter decay interpretation with greater than 99% C.L., and, under very conservative assumptions on the relevant dark matter density profiles, imply a lower limit on the dark matter lifetime of $\tau > 2.7 \times 10^{28}$ s at 95% C.L. for a dark matter mass of 7 keV radiatively decaying to a two-body final state with one photon.

In view of the results presented here, and in view of the recent re-assessment of the potassium abundance (Phillips et al. 2015), we conclude that the most probable counterpart to the 3.5 keV line observed towards the Milky Way center and from individual and stacked observations of clusters of galaxies are atomic de-excitation lines of the K XVIII ion. Charge-exchange processes might also provide an alternate astrophysical explanation (Gu et al. 2015). Scenarios advocating new physics where a 3.5 keV signal is suppressed in dwarf galaxies, such as an axion-like particle conversion to 3.5 keV photons in the presence of a magnetic field, are not ruled out unless Occam's razor is advocated.

Future observations of clusters and of the Galactic center with Astro-H remain a priority to pinpoint the physical origin and the nature of the 3.5 keV line, while, in view of our results, additional deep observations of local dwarf galaxies with current or future telescopes are unlikely to advance our understanding of this particular feature.

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