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Checking the Dark Matter Origin of a 3.53 keV Line with the Milky Way Center

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We detect a line at 3.539 ± 0.011 keV in the deep exposure data set of the Galactic center region, observed with the x-ray multi-mirror mission Newton. The dark matter interpretation of the signal observed in the Perseus galaxy cluster, the Andromeda galaxy [A. Boyarsky *et al.*, Phys. Rev. Lett. 113, 251301 (2014)], and in the stacked spectra of galaxy clusters [E. Bulbul *et al.*, Astrophys. J. 789, 13 (2014)], together with nonobservation of the line in blank-sky data, put both lower and upper limits on the possible intensity of the line in the Galactic center data. Our result is consistent with these constraints for a class of Milky Way mass models, presented previously by observers, and would correspond to the radiative decay dark matter lifetime, $\tau_{\rm DM} \sim 6 - 8 \times 10^{27}$ sec. Although it is hard to exclude an astrophysical origin of this line based on the Galactic center data alone, this is an important consistency check of the hypothesis that encourages us to check it with more observational data that are expected by the end of 2015.

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Recently, two independent groups [1,2] reported a detection of an unidentified x-ray line at energy 3.53 keV in the long-exposure x-ray observations of a number of dark matter (DM) dominated objects. The authors of [2] have observed this line in a stacked x-ray multi-mirror mission (XMM) spectrum of 73 galaxy clusters spanning a redshift range 0.01–0.35 and separately in subsamples of nearby and remote clusters. Reference [1] has found this line in the outskirts of the Perseus cluster and in the central $14'$ of the Andromeda galaxy. The global significance of detection of the same line in the data sets of Ref. [1] is 4.3σ (taking into account the trial factors); the signal in [2] has significance above 4σ based on completely independent data.

The position of the line is correctly redshifted between galaxy clusters [2] and between the Perseus cluster and the Andromeda galaxy [1]. In a very long-exposure blank-sky observation (15.7 Msec of cleaned data) the feature is absent [1]. This makes it unlikely that an instrumental effect is at the origin of this feature (e.g., an unmodeled wiggle in the effective area).

To identify this spectral feature with an atomic line in galaxy clusters, one should assume a strongly supersolar abundance of potassium or some anomalous argon transition [2]. Moreover, according to the results of [1] this should be true not only in the center of the Perseus cluster considered in [2], but also (i) in its outer parts up to at least 1/2 of its virial radius and (ii) in the Andromeda galaxy.

This result triggered significant interest as it seems consistent with a long-sought-for signal from dark matter decay [3–47], annihilation [11,35,48], deexcitation [11,49–58], or conversion in the magnetic field [59–61]. Many particle physics models that predict such properties for the dark matter particle have been put forward, including sterile neutrino, axion, axino, gravitino, and many others; for reviews see, e.g., [37,62] and references therein. If the interaction of dark matter particles is weak enough (e.g., much weaker than that of the standard model neutrino), they need not to be stable as their lifetime can exceed the age of the Universe. Nevertheless, huge amounts of dark matter particles can make the signal strong enough to be detectable even from such rare decays.

The omnipresence of dark matter in galaxies and galaxy clusters opens the way to check the decaying dark matter hypothesis [63]. The decaying dark matter signal is proportional to the *column density* $\mathcal{S}_{\rm DM} = \int \rho_{\rm DM} d\ell$—the integral along the line of sight of the DM density distribution (unlike the case of annihilating dark matter, where the signal is proportional to $\int \rho_{\rm DM}^2 d\ell$). As long as the angular size of an object is larger than the field of view, the distance to the object drops out which means that distant objects can give fluxes comparable to those of nearby ones [64,65]. It also does not decrease with the distance from the centers of objects as fast as, e.g., in the case of annihilating DM where the expected signal is concentrated towards the centers of DM-dominated objects. This, in principle, allows one to check the dark matter origin of a signal by comparison between objects and/or by studying the angular dependence of the signal within one object, rather than trying to exclude all possible astrophysical explanations for each target [66–69].

Clearly, after years of systematic searches for this signal (Refs. [66,70–95]; see Fig. 4 in [1]) any candidate line can be detected only at the edge of the possible sensitivity of the method. Therefore, to cross-check the signal one needs long-exposure data. Moreover, even a factor 2 uncertainty in the expected signal (which is impossible to avoid) can result in the necessity to have significantly more statistics than in the initial data set in which the candidate signal was found.

So far, the DM interpretation of the signal of [2] and [1] is consistent with the data: it has the correct scaling between the Perseus cluster, Andromeda, and the upper bound from the nondetection in the blank-sky data [1], and between different subsamples of clusters [2]. The mass and lifetime of the dark matter particle that is implied by the DM interpretation of the results of [1] is consistent with the results of [2]. The signal has radial surface brightness profiles in the Perseus cluster and Andromeda [1] that are consistent with a dark matter distribution. Although the significance of this result is not sufficient to confirm the hypothesis, they can be considered as successful sanity checks. More results are clearly needed to perform a convincing checking program as described above.

A classical target for DM searches is the center of our Galaxy. Because of its proximity it is possible to concentrate on the very central part and therefore, even for decaying DM, one can expect a significant gain in the signal if the DM distribution in the Milky Way happens to be steeper than a cored profile. The Galactic center (GC) region has been extensively studied by the XMM and several megaseconds of raw exposure exist. On the other hand, the GC region has strong x-ray emission as many complicated processes occur there [96–104]. In particular, the x-ray emitting gas may contain several thermal components with different temperatures; it may be more difficult to constrain the abundances of potassium and argon reliably than in the case of an intercluster medium. Therefore, the GC data alone would hardly provide a convincing detection of the DM signal, as even a relatively strong candidate line could be explained by astrophysical processes. In this Letter, we pose a different question: are the observations of the Galactic center consistent with the dark matter interpretation of the 3.53 keV line of [1,2]?

The DM interpretation of the 3.53 keV line in M31 and Perseus provides a prediction of the *minimal* expected flux from the GC. On the other hand, the nondetection of any signal in the off-center observations of the Milky Way halo (the blank-sky data set of [1]) provides the prediction of the *maximal* possible flux in the GC, given observational constraints on the DM distribution in the Galaxy. Therefore, even with all the uncertainties on the DM content of the involved objects, the expected signal from the GC is bounded from both sides and provides a nontrivial check for the DM interpretation of the 3.53 keV line.

We use XMM-Newton observations of the central 14′ of the Galactic center region with a total cleaned exposure of 1.4 Msec. We find that the spectrum has a $\sim 5.7\sigma$ linelike excess at the expected energy. The simultaneous fitting of the GC, Perseus, and M31 provides a $\sim 6.7\sigma$ significant signal at the same position, with the detected fluxes being consistent with the DM interpretation. The fluxes are also consistent with the nonobservation of the signal in the blank-sky and M31 off-center data sets, if one assumes a steeper-than-cored DM profile (for example, the Navarro-Frenk-White profile of Ref. [105]).

Below we summarize the details of our data analysis and discuss the results.

Data reduction.— We use all archival data of the Galactic center obtained by the EPIC MOS cameras [106] with Sgr A* less than 0.5′ from the telescope axis (see [107], Table I). The data are reduced by the standard SAS [134] pipeline, including screening for the time-variable soft proton flares by espfilt. We removed the observations taken during the period MJD 54000–54500 due to the strong flaring activity of Sgr A* (see [107], Fig. 1). The data reduction and preparation of the final spectra are similar to [1]. For each reduced observation we select a circle of radius 14′ around Sgr A* and combine these spectra using the FTOOLS [135] procedure addspec.

Spectral modeling.— To account for the cosmic-ray induced instrumental background we have subtracted the latest closed filter data sets (exposure: 1.30 Msec for MOS1 and 1.34 Msec for MOS2) [136]. The rescaling of the closed filter data has been performed such that the flux at energies $E > 10$ keV reduces to zero (see [137] for details). We model the resulting physical spectrum in the energy range 2.8–6.0 keV. The x-ray emission from the inner part of the Galactic center contains both thermal and nonthermal components [98,99]. Therefore, we chose to model the spectrum with a thermal plasma model (vapec) and a nonthermal power law component modified by the phabs model to account for the Galactic absorption [138]. We set the abundances of all elements—except for Fe—to zero but model the known astrophysical lines with Gaussians [1,2,140]. We selected the $\geq 2\sigma$ lines from the set of astrophysical lines of [2,104] (see [141]). The intensities of the lines are allowed to vary, as are the central energies to account for uncertainties in detector gain and limited spectral resolution. We keep the same position of the lines between the two cameras.

The spectrum is binned to 45 eV to have about 4 bins per resolution element. The fit quality for the data set is $\chi^2 = 108/100$ d.o.f. The resulting values for the main continuum components—the folded power law index (for the integrated point source contribution), the temperature of the vapec model (~8 keV), and the absorption column density—agree well with previous studies [98,99].

*Results.—*The resulting spectra of the inner 14′ of the Galactic center show a $\sim 5.7\sigma$ linelike excess at 3.539 ± 0.011 keV with a flux of $(29 \pm 5) \times 10^{-6}$ cts/sec/cm^2 (see Fig. 1). It should be stressed that these 1σ error bars are obtained with the xspec command "error" (see the Discussion below). The position of the excess is very close to the similar excesses recently observed in Andromeda

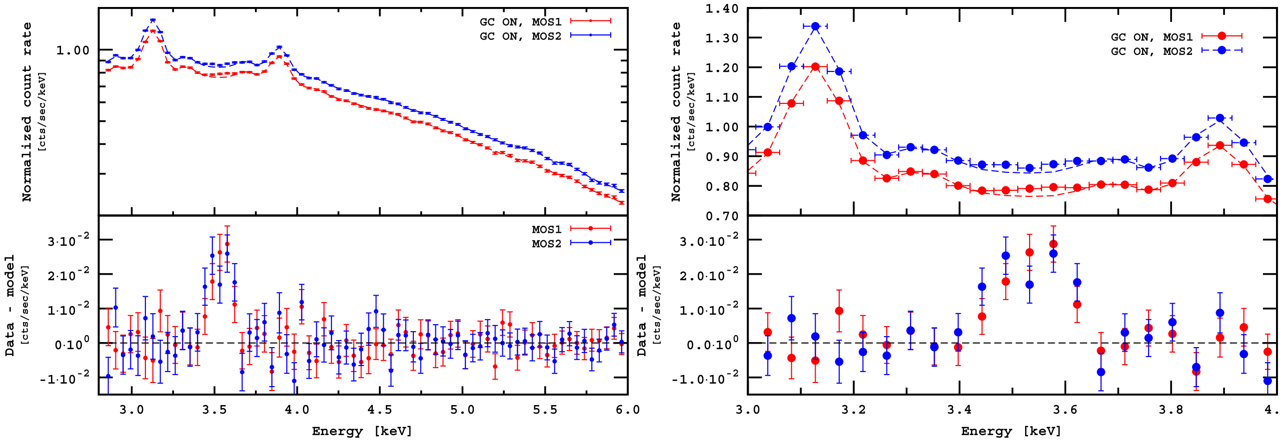

FIG. 1 (color online). Left: Folded count rate for MOS1 (lower curve, red) and MOS2 (upper curve, blue) and residuals (bottom) when the line at 3.54 keV is *not added*. The difference between the cameras is due to detector gaps and bad pixels. Right: Zoom at the range 3.0–4.0 keV.

(3.53 ± 0.03 keV) and Perseus (3.50 ± 0.04 keV) reported in [1], and is less than 2σ away from the one described in [2].

We also performed combined fits of the GC data set with those of M31 and Perseus from [1]. As mentioned, the data reduction and modeling were performed very similarly, so we suffice with repeating that the inner part of M31 is covered by almost 1 Msec of cleaned MOS exposure, whereas a little over 500 ksec of clean MOS exposure was available for Perseus (see [1] for details).

We first perform a joint fit to the Galactic center and M31, and subsequently to the Galactic center, M31, and Perseus. In both cases, we start with the best-fit models of each individual analysis without any lines at 3.53 keV, and then add an additional Gaussian to each model, allowing the energy to vary while keeping the same position between the models. The normalizations of this line for each data set are allowed to vary independently. In this way, the addition of the line to the combination of Galactic center, M31, and Perseus gives 4 extra degrees of freedom, which brings the joint significance to $\sim 6.7\sigma$.

To further investigate possible systematic errors on the line parameters we took into account that the Gaussian component at 3.685 keV may describe not a single line, but a complex of lines ([107], Table II). Using the steppar command we scanned over the two-dimensional grid of this Gaussian's intrinsic width and the normalization of the line at 3.539 keV. We were able to find a new best fit with the 3.685 keV Gaussian width being as large as 66 ± 15 eV. In this new minimum our line shifts to 3.50 ± 0.02 keV (as some of the photons were attributed to the 3.685 keV Gaussian) and has a flux of 24×10^{-6} cts/sec/cm^2 with a 1σ confidence interval of $(13 - 36) \times 10^{-6}$ cts/sec/cm^2. The significance of the line is $\Delta\chi^2 = 9.5$ (2.6σ for 2 d.o.f.). Although the width in the new minimum seems to be too large even for the whole complex of Ar XVII lines (see the Discussion), we treat this change of line parameters as the estimate of systematic uncertainties. To reduce these systematics one has either to resolve or to reliably model a line complex around 3.685 keV instead of representing it as one wide Gaussian component.

As was argued in [1], an interpretation of the signal as an unmodeled wiggle in the effective area is not favored because it should have produced a very significant signal in the blank-sky data set as well. This is because an effect like this would produce a linelike residual proportional to the continuum level. In addition, the line would not be redshifted properly for Perseus [1] and the cluster stack from [2].

Discussion.— The intensity of the DM decay signal should correlate with the DM content of the probed objects. In order to check this we took DM distributions for Perseus, M31, and the Milky Way from Refs. [105,142–152] (see the Supplemental Material for details) and plotted the line intensity vs mass in the field of view divided by the distance squared (*projected DM density*), Fig. 2. We see that decaying DM with a lifetime $\tau_{\rm DM} \sim 6 - 8 \times 10^{27}$ sec would explain the signals from the GC, Perseus, and M31 and the nonobservation in the blank-sky data set. A considerable spread of projected DM masses is due to scatter between the distributions in the literature. For the GC the estimates are based on extrapolations, as there are no measurements of the DM distribution within the inner few kpc. The correlation between the GC and blank-sky projected DM densities is necessary, since these are different parts of the same halo. From comparing our GC signal with the blank-sky upper limit we see that this requires a cuspy (rather than cored) density profile of the Milky Way. Figure 2 shows an example of a profile consistent with both the GC detection and blank-sky upper limit, Ref. [142].

M31 and Milky Way are expected to have similar distributions, providing another consistency check. Reference [1] showed that in order to explain the signal from central 14′ and nonobservation from M31 outskirts, the Andromeda DM density profile should be cuspy, as predicted also for the Milky Way. Figure 2 shows that,

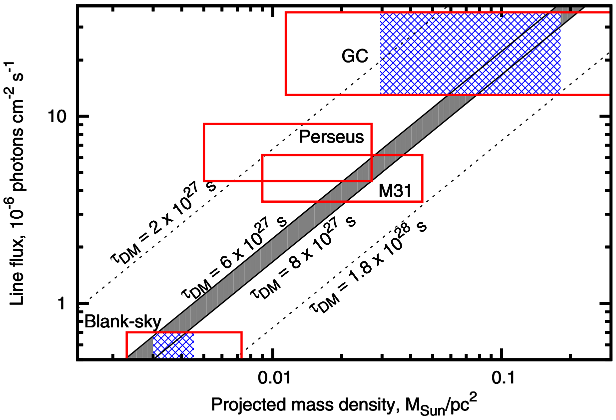

FIG. 2 (color online). The flux of the 3.53 keV line in the spectra of the GC (this work), the Perseus cluster outskirts, M31, and the blank sky [1] as a function of the DM projected mass. Diagonal lines show the expected behavior of a decaying DM signal for a given DM particle lifetime. The vertical sizes of the boxes are $\pm 1\sigma$ statistical error on the line's flux—or the 2σ upper bound for the blank-sky data set. The horizontal sizes of the boxes bracket the *scatter* in the literature mass modeling (see text and Supplemental Material). The Milky Way halo contribution is included for M31 but not for Perseus, where it would be redshifted. The projected mass density for the GC and the Milky Way outskirts (blank sky) are correlated. The blue shaded regions show a particular NFW profile of the Milky Way [142]; its horizontal size indicates uncertainties in galactic disk modeling. Other *cuspy* profiles are consistent with these flux ratios as well (c.f. [153]). The lifetime $\tau_{\mathrm{DM}} \sim (6-8) \times 10^{27}$ sec is consistent with all data sets.

indeed, a large projected DM mass (i.e., cuspy profile) is preferred for M31.

Finally. the Perseus signal of [1] comes from the cluster outskirts where the hydrostatic mass [150] may be underestimated [154]. This would only improve the consistency between the data sets.

The comparison of the expected DM signal from GC vs blank-sky vs Andromeda has been investigated in simulations [153], where various realizations of the galactic DM halos were considered and a high probability of finding observed flux ratios between GC and M31 and between GC and the blank-sky upper limit was found.

The nondetection of the signal in stacked dSphs by [155] rules out the central values of the decay lifetime from [2] but is consistent with [1] in the case of large project DM mass (also preferred from a comparison with other signals, Fig. 2). The signal was not detected in stacked galaxy spectra [156]. However, a novel method of [156] has pronounced systematic effects (see Supplemental Material of [156]) and is the least sensitive exactly at energies $E \sim 3.5$ keV. Reference [62] used a stacked data set of nearby galaxies from [157] and showed that systematic effects and uncertainty in dark matter distributions [64] lead to the bound $\tau_{\mathrm{DM}} \gtrsim 3.5 \times 10^{27}$ sec, consistent with our findings. Other bounds on decaying dark matter in the ~3.5 keV energy range (see [95,157,158] and references therein) are also consistent with our detections for lifetimes that we discuss in this Letter.

As mentioned in the Results, there is a degeneracy between the width of the Ar XVII complex around 3.685 keV and the normalization of the line in question. If we allow the width of the Ar XVII line to vary freely we can decrease the significance of the line at 3.539 keV to about 2σ. However, in this case the width of the Gaussian at 3.685 keV should be 95–130 eV, which is significantly larger than we obtain when simulating a complex of four Ar XVII lines. In addition, in this case the total flux of the line at 3.685 keV becomes *higher* than the fluxes in the lines at 3.130 and 3.895 in contradiction with the atomic data ([107], Table II).

Another way to decrease the significance of the line at 3.539 is to assume the presence of a potassium ion (K XVIII) with a line at 3.515 keV and a smaller line at 3.47 keV. If one considers the abundance of potassium as a completely free parameter (c.f. [140,159,160]), one can find an acceptable fit of the XMM GC data without an additional line at 3.539 keV. As described in Supplemental Material, due to the complicated internal temperature and abundance structures it is not possible to reliably constrain the overall potassium abundance of the GC to a degree that rules out the K XVIII origin of the 3.539 keV line in this data set.

However, if we are to explain the presence of this line in the spectra by the presence of K XVIII, we have to build a model that consistently explains the fluxes in this line in different astronomical environments: in galaxy clusters (in particular Perseus) at all off-center distances from the central regions [2] to the cluster outskirts up to the virial radius [1], in the central part of M31, and in the Galactic center. In addition, we need to explain that this line is not observed—and therefore that this transition *should not* be excited—in the outskirts of the Milky Way and of M31 [1]. Such a consistent model does not look convincing. In particular, in M31 spectrum there are no strong astrophysical lines in the 3–4 keV range [161]. The power law continuum is well determined by fitting the data over a wider range of energies (from 2 to 8 keV) and allows a clear detection of the line at 3.53 ± 0.03 keV with $\Delta\chi^2 = 13$ [1,161], which is also the largest linelike feature in the entire 3–4 keV range. Were this signal in M31 due to K XVIII, there should be plenty of stronger emission lines present. In addition, the authors of [2] conclude that strongly supersolar abundances of K XVIII are required to explain the observed excess of this line in their stacked cluster analysis.

In conclusion, although it is hard to exclude completely an astrophysical origin of the 3.539 keV line in the GC (due to the complicated nature of this object), the detection of this line in this object is an essential cross-check for the DM interpretation of the signal observed in Perseus and M31 [1] and in the stacked spectra of galaxy clusters [2]. A nondetection in the GC or a detection with high flux would have immediately ruled out this interpretation. As it is, the GC data rather supports DM interpretation as the line is not only observed at the same energy, but also its flux is consistent with the expectations about the DM distributions.

To settle this question, measurements with higher spectral resolution, an independent measurement of the relative abundances of elements in the GC region, and analyses of additional deep exposure data sets of DM-dominated objects are needed [153,158,162–165] with Astro-H [166] or future mission, Athena [167].

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