Revisiting the expected *Micro-X* signal from the 3.5 keV line

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ABSTRACT

One of the future instruments to resolve the origin of the unidentified 3.5 keV emission line is the *Micro-X* sounding rocket telescope. According to the estimate made in 2015, *Micro-X* will be able to detect on average about 18.2 photons from the 3.5 keV line during its 300-second-long planned observation. However, this estimate is based on the extrapolation of the 3.5 keV line signal from the innermost Galactic Centre (GC) region available in 2015. With newly available reports on the 3.5 keV line emission in five off-centre regions, we find that similar *Micro-X* payload will result in 3.4–4.3 counts on average, depending on the dark matter distribution. Therefore, we show that the 3.5 keV line is unlikely to be detected with a single *Micro-X* launch using an original *Micro-X* payload. Increasing its field-of-view from 20° to 33° and its repointing out of GC (to avoid the brightest X-ray point source on the sky, Sco X-1) will increase the expected number of counts from 3.5 keV line to 7.5–7.9, which corresponds to its expected marginal (≈ 2σ) detection within a single *Micro-X* observation.

Key words: dark matter – line: identification – instrumentation: detectors

1 INTRODUCTION

The origin of the unidentified 3.5 keV emission line remains debated, see Drewes et al. (2017); Abazajian (2017); Boyarsky et al. (2019) for reviews. So far, this line is reported from a variety of cosmic objects, such as the combined spectrum of bright galaxy clusters and the central part of Perseus cluster (Bulbul et al. 2014), the central part of Andromeda galaxy and the outskirts of Perseus cluster (Boyarsky et al. 2014), the innermost part of our Galaxy (Riemer-Sorensen 2016; Jeltema & Profumo 2015; Boyarsky et al. 2015), a number of nearby individual galaxy clusters (Urban et al. 2015; Iakubovskyi et al. 2015), and the parts of Galactic halo far away from the Galactic Center (Neromov et al. 2016; Cappelluti et al. 2018) and close to the Galactic Center (Boyarsky et al. 2018; Hofmann & Wegg 2019) (see, however, the results of Dessert et al. (2018), who had not reported the presence of the 3.5 keV line in 5° – 45° region). While initially the 3.5 keV line was interpreted as a signal from decaying dark matter (Bulbul et al. 2014; Boyarsky et al. 2014, 2015), other hypotheses about the line origin, including emission by highly excited Potassium (Jeltema & Profumo 2015; Phillips et al. 2015) and Sulphur (Gu et al. 2015; Shah et al. 2016) ions, also attracted much attention.

Unfortunately, the moderate energy resolution (with the full width at half maximum (FWHM) about 50–100 eV) of modern CCD-based X-ray telescopes, such as XMM-Newton and *Chandra*, does not allow one to robustly distinguish between the astrophysical and dark matter scenarios. Instead, the upcoming X-ray imaging spectrometers with several-eV FWHM energy resolution were proposed to resolve the 3.5 keV origin, see, e.g., Bulbul et al. (2014); Iakubovskyi (2015); Speckhard et al. (2016). While the *Hitomi* (former *Astro-H*) satellite, because of its unexpected abrupt failure, did not collect enough data to significantly detect the 3.5 keV line (Aharonian et al. 2017), other cosmic missions with eV-scale resolution spectrometers, such as *Micro-X,1 XRISM2* (former *Hitomi* recovery mission), and *Lynx3* are planned to be launched during the forthcoming several years.

Figuerola-Felciano et al. (2015) estimate the observed 3.5 keV signal for the earliest among the planned missions — the *Micro-X* sounding rocket-based spectrometer. Specifically, they expect 18.2 counts from the planned 300 second-long observation of the circular region around the Galactic Centre with 20° field-of-view (FoV) radius. For comparison, the 2σ line detection limit calculated by Figueroa-Felciano et al. (2015) is only about 6 counts at 3.5 keV.

1 https://microx.northwestern.edu/
2 https://heasarc.gsfc.nasa.gov/docs/xrism/about/
3 https://wwwastro.msfc.nasa.gov/lynx/
However, the signal estimate by Figueroa-Feliciano et al. (2015) is based on the extrapolation of the 3.5 keV line intensity reported by Boyarsky et al. (2015) in a much smaller (14° radius) circle around the Galactic Centre. After the work by Boyarsky et al. (2018), more detections out of Galactic Centre (up to 35° radius) became available. This allows us to improve the signal estimate by Figueroa-Feliciano et al. (2015), avoiding extrapolations.

2 REVISITING THE EXPECTED 3.5 KEV SIGNAL

The total number of counts from a decaying dark matter observation is (see, e.g., Boyarsky et al. 2008)
\[ C_{\text{DM}} = \frac{A_{\text{eff}} T_{\text{exp}} \Gamma_{\text{DM}}}{4 \pi m_{\text{DM}}}, \quad I = \int \frac{\nu(\theta) \rho_{\text{DM}}(\theta)d^3r}{|r|^2}. \] 
(1)

where \( T_{\text{exp}} \) is the observation time, \( \Gamma_{\text{DM}} \) is the radiative dark matter decay width, \( m_{\text{DM}} \) is the mass of dark matter particle, \( \rho_{\text{DM}} \) is the dark matter mass density distribution, \( r \) is the radius-vector calculated from the observer’s position, \( A_{\text{eff}} \) is the effective area of the Micro-X micro-calorimeter for an off-axis source, \( \theta \) is the angle between \( r \) and the field-of-view (FoV) axis, and \( \nu(\theta) = A_{\text{eff}}(r)/A_{\text{eff}} \) is the vignetting correction factor.

Similar to Figueroa-Feliciano et al. (2015), we choose \( \nu(\theta) = 1 \). Then the integral \( I \) in Eq. (1) is equal to
\[ 2\pi \int_0^{\theta_{\text{FoV}}} \sin \theta d\theta \int_0^{\theta(\theta)} d\rho_{\text{DM}} \left( \sqrt{r_0^2 + z^2} - 2z r_0 \cos \theta \right). \] 
(2)

where \( \theta(\theta) = r_0 \cos \theta + \sqrt{r_{\text{max}}^2 - r_0^2 \sin^2 \theta} \), \( \theta_{\text{FoV}} \) is the FoV radius (in radians), \( r_0 \) is the distance to the Galactic Centre, \( r_{\text{max}} \) is the maximal radius of the dark matter halo (which we assumed to coincide with the halo virial radius). As a reference value, we take \( r_0 = 8.127 \pm 0.031 \) kpc, from Abuter et al. (2018).

Similarly to Boyarsky et al. (2018), we used three types of dark matter distributions:

(i) Navarro–Frenk–White (NFW) profile (Navarro et al. 1996, 1997);
(ii) Burkert (BURK) profile (Burkert 1996);
(iii) Einasto (EIN) profile (Einasto 1965).

For each of these profiles, we use the characteristic parameters and values of \( \Gamma_{\text{DM}} \) that correspond to their best-fit of 3.5 keV line fluxes reported in five concentric circles with 10°–14°, 14°–3°, 3°–10°, 10°–20° and 20°–35°, see Table II of Boyarsky et al. (2018) for details. We also use the same planned observation duration (300 s) and effective area (1 cm²) of a micro-calorimeter on-board Micro-X as in the original paper by Figueroa-Feliciano et al. (2015).

4 Varying \( r_0 \) by \(-0.1\) kpc, one changes the expected Micro-X numbers of counts change by \(-0.6\) cts (\(-15\%\)).

3 RESULTS AND CONCLUSIONS

First, we assumed the same radius of Micro-X FoV (20° circle), pointed towards the Galactic Centre, as in Figueroa-Feliciano et al. (2015). However, the calculated expected number of counts from the 3.5 keV line is much smaller compared to the result of Figueroa-Feliciano et al. (2015) (18.2 counts). Specifically, for our NFW profile, we expect only 3.8 counts for a single Micro-X observation. The expected numbers for BURK and EIN profiles are 3.4 and 4.3 counts, respectively.

The reason behind the significant decrease of the estimated number of counts compared to the work by Figueroa-Feliciano et al. (2015) is a much steeper decline of the observed 3.5 keV line flux outside the innermost 14° circle, compared to the extrapolation by Figueroa-Feliciano et al. (2015). Fig. 1 of this paper illustrates this behaviour.

All of our new 3.5 keV line count estimates are below the 2σ detection limit by Micro-X of about 6 counts, see Fig. 11 from Figueroa-Feliciano et al. (2015) for details. This means that a single Micro-X observation of the Galactic Centre region with 20° FoV radius is very unlikely to detect the 3.5 keV line. A straightforward approach will thus require a combination of many Micro-X observations to detect the line. An alternative is to increase the FoV of the Micro-X; for example, its predecessor, XQC, has about 33° FoV radius (Figueroa-Feliciano et al. 2015). The problem, however, is in the presence of a very bright X-ray object — Sco X-1 — located only about 24° from the Galactic Centre. To limit the background counts, the increase in the Micro-X FoV will also require its re-pointing away from the Galactic Centre. For example, using the same dark matter distributions from Boyarsky et al. (2018), the expected number of 3.5 keV line counts from a 33° FoV located 13° away from the Galactic Centre (to avoid emission from Sco X-1) is 7.5–7.9. In combination with a modest increase of the number of expected background counts in larger FoV (in the absence of bright X-ray sources), such an increase of the instrument FoV with its subsequent re-pointing may lead to marginal (~2σ) detection of 3.5 keV line even with a single Micro-X launch.

When this paper was finished, we were aware of the forthcoming paper of Micro-X collaboration (Adams et al. 2019). Remarkably, our results agree with those presented in Table 2 of Adams et al. (2019). For example, for their Micro-X North target (\( l = 31°, b = 40° \)), we calculated that a single Micro-X observation with 33° radius circle FoV will collect 4.5 cts for NFW, 5.9 cts for BURK and 4.2 cts for EIN profile from 3.5 keV line. For their Micro-X South target (\( l = 0°, b = -12° \)) we expect 7.5–7.9 counts from a single observation.

Throughout this paper we have used the 3.5 keV line intensities, obtained by Boyarsky et al. (2018) using XMM-Newton data. While the reported values are consistent with recent result of Hofmann & Wegg (2019) (who detected the signal in Chandra data), there is an apparent discrepancy between the results of Boyarsky et al. (2018) and the findings of Dessert et al. (2018), who have not reported the line in the XMM-Newton observations of the 5°–45° region. In Boyarsky et al. (2018) we describe in details our view on discrepancies with Dessert et al. (2018), which, we believe,
Revisiting the expected Micro-X signal from the 3.5 keV line

Figure 1. Expected 3.5 keV line fluxes (as functions of the angular distance from the Galactic Centre) obtained for different dark matter distributions, including NFW, EIN and BURK profiles used in this paper, and the NFW15 profile used in Figueroa-Feliciano et al. (2015). The red crosses show datapoints from Boyarsky et al. (2018). The black square corresponds to the reference flux used by Figueroa-Feliciano et al. (2015) to obtain their estimates. The black cross corresponds to the flux also reported in Boyarsky et al. (2015), with possible contribution from the widened Ar XVII line complex at 3.685 keV taken into account, similarly to Boyarsky et al. (2018).

are in choice of the underlying background model. As fig. 5 in Boyarsky et al. (2018) demonstrates, by using narrow fitting interval of 3.3–3.8 keV, as in Dessert et al. (2018), one tend to over-predict the background level, effectively “masking” the 3.5 keV signal.

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