Surface brightness profile of the 3.5 keV line in the Milky Way halo

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based on Boyarsky, Iakubovskyi, Ruchayskiy, Savchenko, arXiv:1812.10488

Objective

[1] reported the 3.5 keV line in the innermost Galaxy (14' inner circle around Sgr A*) while [2] reported the 3.5 keV line in blank-sky observations located about 120° off-center. To further check the origin of the 3.5 keV line, it is important to study the line distribution in areas between these observations. Here we concentrate on the region spanned until 35° off-center.

The 3.5 keV line in the spectra of cosmic objects

- Detected in early 2014 by [3, 4] in the spectra of cosmic objects of different nature (galaxies, clusters of galaxies).
- There is **no general description** for each of the objects
  . . . **except the DM decay**
  . . . taking into account the uncertainty of the DM distribution in the individual objects.
- *XMM-Newton* observations inside the 30 pc (14') radius circle around Sgr A*: consistent with astrophysical line expectations (from K XVIII emission line complex at 3.47-3.52 keV).
- Possible connection with decaying dark matter signal is less clear due to a strong and patchy absorption across the 10' circle region which correspond to 3.5 keV line attenuation by up to a factor ~ 2.

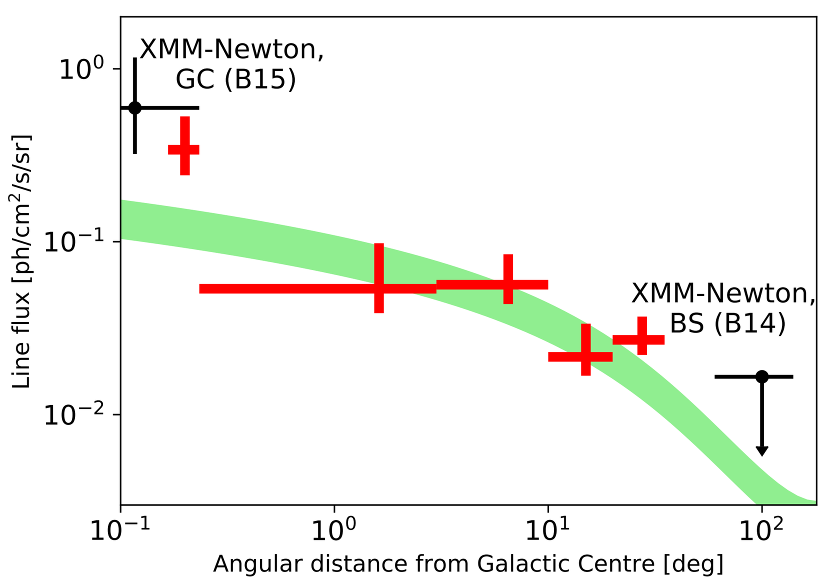
Data analysis

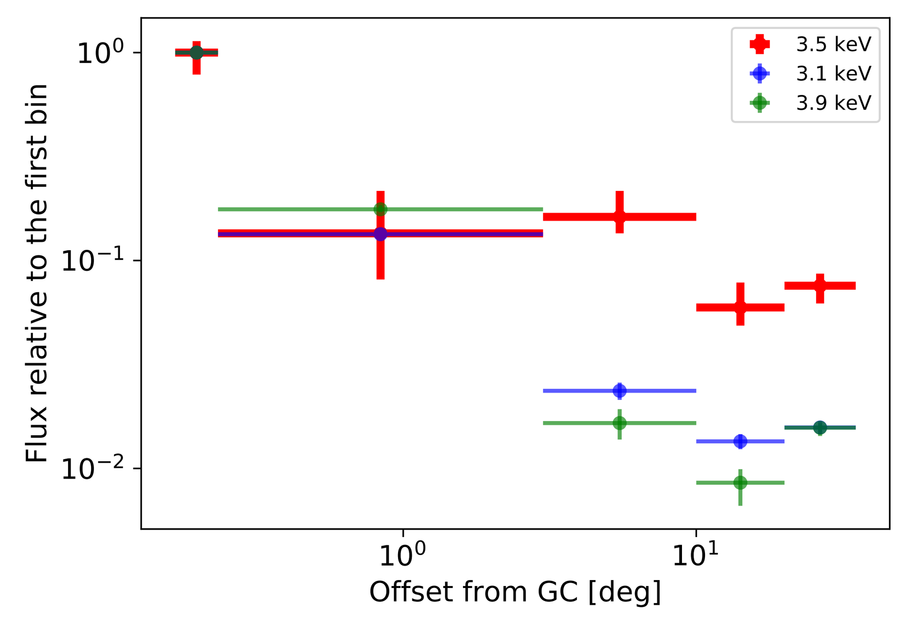
- 795 *XMM-Newton* observations from the inner 35° around Sgr A* with total exposure more than 31.4 Msec (MOS camera) and 8.9 Msec (PN camera).
- Data processing using the standard Extended Sources Analysis Software (ESAS), a part of XMMSAS.
- Variable proton component cleaning: `mos-filter` and `pn-filter`.
- Point sources detection and removal: `edetect_chain`.
- Source spectra and response matrices inside the region overlapping the corresponding annulus: `mos-spectra` and `pn-spectra`, background spectra generated by `mos_back` and `pn_back`.
- Data cleaning: For every obtained spectra we calculated the count rate normalized by the value of `BACKSCALE` keyword. The obtained values were compared and the high count rate outliers were removed from analysis. The lightcurve and count rate histogram plots, produced by `mos-filter` and `pn-filter` were visually inspected to ensure the correctness of flared interval automatic removal procedure. Exposures with potential residual soft proton contamination were dropped from further analysis.
- Individual observation spectra and response files were combined and binned by 45 eV per energy bin in each (similar to [1]) of the regions of interest by using the `addspec` procedure.
- **Data modelling:** a sum of absorbed cosmic **continuum** (consisting of thermal and non-thermal component), an **instrumental background**, and several narrow emission **lines** of our interest — in addition to the 3.5 keV line, these are the astrophysical emission lines at 3.12, 3.32, 3.68, 3.90 and 4.11 keV.
- To increase the statistical significance of the lines, we modeled **together** *XMM-Newton* spectra from MOS and PN cameras.

Results

The line is detected in 5 regions with local significance ranging **from 2.1σ to 5σ**. The positions of line in all 5 regions are consistent with the weighted average being at $E = (3.49 \pm 0.05)$ keV. We also detect known astrophysical line complexes and are able to compare their radial behavior. We see that **the flux in 3.5 keV line drops slower than the flux in the astrophysical lines** with the distance from the Galactic center.
The flux in the innermost region (10'-14' annulus) is consistent with [1] and somewhat higher than the prediction based on other regions. The prediction for the off-center region is lower than the flux detected by Chandra [2] and NuSTAR [5] in the blank-sky observations. Clearly not consistent with [6], probably due to the very different approaches to the background modeling.

Region	10' – 14'	14' – 3°	3° – 10°	10° – 20°	20° – 35°
MOS/PN clean exposure [Msec]	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1
MOS/PN clean FoV [arcmin^2]	205/197	398/421	461/518	493/533	481/542
Total χ^2 and d.o.f.	179/161	184/174	193/184	171/145	139/131
3.5 keV position [keV]	$3.52^{+0.01}_{-0.01}$	$3.48^{+0.02}_{-0.03}$	$3.51^{+0.02}_{-0.01}$	$3.56^{+0.03}_{-0.02}$	$3.46^{+0.02}_{-0.01}$
3.5 keV flux [cts/sec/cm^2/sr]	$0.37^{+0.05}_{-0.08}$	$0.05^{+0.03}_{-0.02}$	$0.06^{+0.02}_{-0.01}$	$0.022^{+0.007}_{-0.004}$	$0.028^{+0.004}_{-0.005}$
3.5 keV $\Delta\chi^2$	19.4	4.5	12.4	15.6	25.1
3.1 keV flux [cts/sec/cm^2/sr]	$8.89^{+0.09}_{-0.09}$	$1.19^{+0.04}_{-0.05}$	$0.21^{+0.02}_{-0.02}$	$0.12^{+0.01}_{-0.01}$	$0.14^{+0.01}_{-0.01}$
3.3 keV flux [cts/sec/cm^2/sr]	$1.40^{+0.07}_{-0.08}$	$0.32^{+0.04}_{-0.04}$	$0.11^{+0.02}_{-0.01}$	$0.053^{+0.005}_{-0.007}$	$0.065^{+0.004}_{-0.004}$
3.7 keV flux [cts/sec/cm^2/sr]	$1.30^{+0.07}_{-0.06}$	$0.30^{+0.02}_{-0.03}$	$0.033^{+0.013}_{-0.013}$	$0.026^{+0.007}_{-0.007}$	$0.050^{+0.007}_{-0.010}$
3.9 keV flux [cts/sec/cm^2/sr]	$3.63^{+0.06}_{-0.06}$	$0.64^{+0.03}_{-0.02}$	$0.06^{+0.01}_{-0.01}$	$0.031^{+0.005}_{-0.007}$	$0.057^{+0.003}_{-0.005}$
4.1 keV flux [cts/sec/cm^2/sr]	$0.62^{+0.06}_{-0.06}$	$0.17^{+0.02}_{-0.03}$	$0.013^{+0.013}_{-0.010}$	$0.019^{+0.007}_{-0.005}$	$0.017^{+0.003}_{-0.004}$





Figures: Surface brightness profile of the 3.5 keV line (red crosses). The black points are the results of previous works [1, 3]. The green area shows the expected flux from the best fitting NFW profile.
The right plot shows a comparison of the behaviors of 3.5 keV line and detected known astrophysical lines.

We performed a **combined fit** to all 5 spatial regions with relative normalization of the line in different region fixed **in accordance with a Milky Way DM density profile**. We able to obtain a good fit with a significant improvement for the quality of fit when adding a new line to the model.

Profile	Sign. in σ	Line position [keV]	Decay width Γ [10^{-28} sec^{-1}]
NFW($r_s = 20$ kpc)	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert ($r_B = 9$ kpc)	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto ($r_s = 14.8$ kpc, $\alpha = 0.2$)	6.9σ	$3.494^{+0.002}_{-0.009}$	$0.40^{+0.04}_{-0.06}$

Signal explanations

- The combination of several "ordinary" effects, e.g. systematics in Milky Way and M31 but astrophysical signal in clusters (the abundances of K and S are in general unknown).
- νMSM **Dark Matter decay signal**
- Other "new physics"

The **νMSM preserves the Standard Model** success on the accelerators and **explains basic problems beyond it**: neutrino masses, baryonic asymmetry in the Universe, Dark Matter. And there is no new particles required (except of 3 right-handed massive neutrino states).
Many other models beyond Standard Model predicts such signal. The **X-ray data itself can't distinguish them.** The dedicated experiments, such as SHiP experiment at CERN are required.

Conclusions

- **We detected the 3.5 keV line in the new areas around Galactic center with a total significance of 7σ.**
- **We are able to jointly fit the signal in all regions assuming realistic DM density profile.**
- **The 3.5 keV line remains promising dark matter signal candidate.**

References

[1] A. Boyarsky, J. Franse, D. Iakubovskyi and O. Ruchayskiy, *Checking the Dark Matter Origin of a 3.53 keV Line with the Milky Way Center*, *Phys. Rev. Lett.* **115** (2015) 161301, [`1408.2503`].

[2] N. Cappelluti, E. Bulbul, A. Foster, P. Natarajan, M. C. Urry, M. W. Bautz et al., *Searching for the 3.5 keV Line in the Deep Fields with Chandra: the 10 Ms observations*, *Astrophys. J.* **854** (2018) 179, [`1701.07932`].

[3] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, *Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster*, *Phys. Rev. Lett.* **113** (2014) 251301, [`1402.4119`].

[4] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S. W. Randall, *Detection of an Unidentified Emission Line in the Stacked X-Ray Spectrum of Galaxy Clusters*, *Astrophys. J.* **789** (2014) 13, [`1402.2301`].

[5] A. Neronov, D. Malyshev and D. Eckert, *Decaying dark matter search with NuSTAR deep sky observations*, *Phys. Rev. D* **94** (2016) 123504, [`1607.07328`].

[6] C. Dessert, N. L. Rodd and B. R. Safdi, *Evidence against the decaying dark matter interpretation of the 3.5 keV line from blank sky observations*, `1812.06976`.