Technical comment on the paper of Dessert et al. 
"The dark matter interpretation of the 3.5 keV line is inconsistent with blank-sky observations"

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Abstract

An unidentified line at energy around 3.5 keV was detected in the spectra of dark matter-dominated objects. Recent work [1] used 30 Msec of XMM-Newton blank-sky observations to constrain the admissible line flux, challenging its dark matter decay origin. We demonstrate that these bounds are overestimated by more than an order of magnitude due to improper background modeling. Therefore, the dark matter interpretation of the 3.5 keV signal remains viable.

An X-ray line at \( E \approx 3.5 \) keV has been found in 2014 [2, 3]. Many consistency checks, as well as follow-up detections, have been reported, while non-detections have not ruled out the dark matter interpretation of the signal (see [4] for review). Ref. [1] (DRS20 in what follows) recently reported bounds on the decay lifetime, which are about an order of magnitude below those required for dark matter interpretation. The improvements of these bounds compared with the previous results are much stronger than one would expect based solely on the increase of the exposition. We demonstrate that such a strong increase is mainly an artifact of overly restrictive background modeling.

We use 17 Msec of XMM-Newton MOS observations pointing 20° – 35° off the Galactic Center.¹ This dataset contains 57% of the total exposure of DRS20, including 503 of their 534 observations. Thus, we expect the flux upper limit to differ by \( \approx \sqrt{30/17} \approx 1.32 \). Different dark matter profiles are consistent with each other in this region making the limits more robust.

¹For the list of observations see [5].
Figure 1: Upper limits (95% CL) on the extra line flux against the models, described in Table 1 (colors coincide with the model names). Data points show the energies where the lines are detected at more than 3σ level over the continuum of the corresponding color (errorbars are ±1σ).

Table 1: Four background models for line search.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Model components</th>
<th>Interval</th>
<th>χ²/dof</th>
<th>Line at Efid?</th>
<th>95% CL at Efid $10^{-6}$ cm⁻² s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>Powerlaw</td>
<td>3.3-3.8 keV</td>
<td>88.76/96</td>
<td>No</td>
<td>0.16</td>
</tr>
<tr>
<td>Green</td>
<td>Powerlaw</td>
<td>3.3-3.8 keV</td>
<td>68.86/96</td>
<td>No (0.8σ)</td>
<td>0.70</td>
</tr>
<tr>
<td>Red</td>
<td>Powerlaw</td>
<td>3.3-3.8 keV</td>
<td>68.86/94</td>
<td>No (1.3σ)</td>
<td>1.41</td>
</tr>
<tr>
<td>Magenta</td>
<td>Powerlaw</td>
<td>3.0-4.0 keV</td>
<td>163.0/193</td>
<td>Yes (4.0σ)</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Our results are shown in Fig. 1, while Table 1 summarizes the details of our modeling and shows 95% CL at fiducial energy $E_{fid} = 3.48$ keV.

First, we searched for a narrow line atop of a folded powerlaw (plus an instrumental continuum fixed at high energies) across the interval 3.3-3.8 keV. Our limits (“blue model”) are consistent with DSR20: strong constraints around 3.5 keV, lines at ∼ 3.3 and 3.68 keV detected with significance ≥ 3σ, consistently with significant weakening on the DRS20 limits at these energies. Such lines (Ar XVIII and S XVI complexes around 3.3 keV, and Ar XVII plus K XIX around 3.68 keV) are detected in astrophysical plasma both in galaxy clusters [2,6,7] and in our Galaxy [8–11]. Besides, the presence of the weak instrumental lines – K Kα at 3.3 keV...
and Ca Kα at 3.7 keV has been reported, see [11] and refs. therein.

Therefore, next we add to the model extra Gaussians at 3.3 keV and 3.68 keV (“green model”, Table 1) and repeat the analysis in the 3.3-3.8 energy range. The bounds weaken by a factor $\sim 4$ (Fig. 1, green line) at $E_{\text{fid}}$. This weakening is consistent with Fig. S14(A) of DRS20. A background model without these lines raises the powerlaw continuum, which artificially lowers the upper limit on any line (see [12] for the previous discussion). Indeed, Fig. S16(B) of DRS20 demonstrates that the best-fit value of the line flux at 3.5 keV parametrized by $\sin^2(2\theta)$, is negative at the level $\sim -1.5\sigma$ — background is over-subtracted. We notice that the normalization of two lines at the end of the interval was fixed to their best-fit value during this procedure.

When, instead, we let the normalization of the lines vary freely, while adding an extra line around 3.5 keV (as in [2, 3, 9, 12]) — the upper limit on the flux weakened by an extra factor of $\sim 2$ (“red model”).

Interval 3–4 keV contains two more known lines — Ca XIX complex around 3.9 keV and Ar XVII plus S XVI around 3.1 keV c.f. [2, 9, 11]. We repeat our analysis in this interval with two extra lines in the model (“magenta model”). We find a $4\sigma$ line at $E_{\text{fid}}$ and the upper limit weakens accordingly. Further extending the model to 2.8–6.0 keV, carefully modeling all astrophysical and instrumental lines and accounting for all significant line-like residuals, does not change the results.

The described above models are shown in 3 – 4 keV energy band in Fig. 2 with corresponding colours. Fig. 2 illustrates that the model with no astrophysical lines fails to ade-
quately model the data on a broader energy range, and overestimates the continuum level, as discussed above.

**Conclusion**

We demonstrate that the constraints from long exposure blank-sky observations [1] strongly depend on the background model. Namely, proper inclusion of the line complexes at 3.3 keV and 3.68 keV relaxes the bound by a factor $\sim 8$. The extension of the fitting interval to $3\text{–}4$ keV weakens the bound by more than an order of magnitude (magenta line in Fig. 1 compared to the blue line, reproducing DRS20) and also leads to the detection of the line at 3.5 keV at $4\sigma$.

DRS20 investigates the effects of these lines in the Supplementary Material. However they (i) fix normalization of their best fit background values, reducing their effect (reproduced by our “green” model) and (ii) chose to report more stringent bounds as their final result.

When claiming exclusions, one should be careful to push all systematic uncertainties in the conservative directions. In this particular case, to claim the strongest “powerlaw” bound (as done in DRS20) one should prove that other known lines are not present in a particular dataset. Moreover, if the analysis at a wider energy interval ($3\text{–}4$ keV) gives weaker constraint, we see no reason not to report it as a proper conservative bound.

Furthermore, to interpret the exclusion in terms of the decaying dark matter lifetime, one needs to adopt the most conservative density profile. In particular, the local dark matter density was adopted in DRS20 to be $0.4 \text{ GeV/cm}^3$. It has a systematic uncertainty of a factor $2\text{–}3$ [13], see also discussion in [14], which should be propagated into the final conservative bound.

The spectral resolution of modern X-ray satellites is below that, required to resolve the intrinsic shape of astrophysical or putative dark matter decay lines. Future X-ray spectrometers will be able to finally settle this question.

**Other comments**

Below we comment on other inconsistencies in DRS20. The above conclusions are not based on them.

**PN out-of-time events not subtracted?**  For the PN camera the out-of-time events were not subtracted. Indeed, the scripts d12dat.sh and spc2dat.py of DRS20 show that count rates from files pn*-obj.pi, produced by the ESAS script pn-spectra were used. Instead, out-of-time subtracted spectra, produced by pn_back (filename pattern pn*-obj-os.pi) should have been used, according to the ESAS manual.

**Wrong PN count rate?**  Fig. 2 of DRS20 shows that counts rates of stacked MOS and PN spectra are similar. However, it is known that count rate of the PN camera is $\approx 3$ times higher than of the MOS cameras, c.f. [15, Fig. 7 & Table 2] or [12, Fig. 1]. This difference is not explained in the text. DSR20 showed the count rate for the PN camera of 0bs1D 0653550301 (Fig. S11) which we reproduced. The MOS count rate for the same observation is a factor of $\sim 3$ lower.
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References


