Testing the origin of $\sim 3.55$ keV line in individual galaxy clusters observed with XMM-Newton

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If the unidentified emission line at $\sim 3.55$ keV previously found in spectra of nearby galaxies and galaxy clusters is due to radiatively decaying dark matter, one should detect the signal of comparable strength from many cosmic objects of different nature. By studying existing dark matter distributions in galaxy clusters we identified top-19 of them observed by XMM-Newton X-ray mission, and analyzed the data for the presence of the new line. In 8 of them, we identified $> 2 \sigma$ positive line-like residuals with average position $3.52 \pm 0.08$ keV in the emitter’s frame. Their observed properties are unlikely to be explained by statistical fluctuations or astrophysical emission lines; observed line position in M31 and Galactic Center makes an additional argument against general-type systematics. Being interpreted as decaying dark matter line, the new detections correspond to radiative decay lifetime $\tau_{DM} \approx (3.5 - 6) \times 10^{27}$ s consistent with previous detections.

The origin of missing mass in cosmic objects ranging from dwarf galaxies to galaxy clusters, large-scale structure and the observable part of our Universe, remains unknown. Assuming Newtonian/Einsteinian gravity and dynamics to be valid one has to introduce new type of matter – the dark matter – presumably in form of new elementary particles beyond the Standard Model of particle physics. Non-zero interaction strength of dark matter particles with Standard Model particles may lead to 2-body radiative decay of the dark matter. Because present-day velocities of dark matter particles in haloes should be highly non-relativistic, such process would produce the narrow dark matter decay line. This motivates extensive ongoing studies of such lines in spectra of cosmic objects with established dark matter contribution.

The most intriguing dark matter decay line candidate reported so far is the $\sim 3.55$ keV line detected in central part of the Perseus galaxy cluster and different combinations of galaxy clusters $[1]$, Andromeda galaxy and Perseus galaxy cluster outskirts $[2]$, Galactic Center $[3]$, Perseus, Coma, and Ophiuchus galaxy clusters $[4]$ $^1$, see also $[5]$. Although decaying dark matter can naturally explain basic properties of the line in these objects – correct scaling of the line signal with object redshift and projected dark matter mass density – several alternative hypotheses invoking standard or anomalously enhanced astrophysical line emission $[6-8]$, decay of excited dark matter states $[9]$, annihilating dark matter $[10, 11]$, dark matter decaying into axion-like particles with further conversion to photons in magnetic field $[12]$ have been proposed thereafter, see $[5]$ and references therein.

To further check the decaying dark matter origin of the $\sim 3.55$ keV line, we identified cosmic targets having the largest expected decaying dark matter signal. We used public observations of European Photon Imaging Camera (EPIC) $[13, 14]$ on-board XMM-Newton X-ray observatory $[15]$ – the most sensitive existing instrument to search narrow faint X-ray lines $[16]$.

**Object selection.** For distant objects, the dark matter decay flux $[\text{in photons cm}^{-2} \text{s}^{-1}]$ is

$$F = \frac{S_{DM} \Omega_{fov} \sqrt{\Delta N_{back}}}{4 \pi m_{DM} \tau_{DM}} ,$$

where $S_{DM} = \int \rho_{DM}(l) dl$ is the dark matter column density along the line of sight, $\Omega_{fov} \ll 1$ is the Field-of-View of the instrument, $m_{DM}$ - mass of the dark matter particle, $\tau_{DM}$ - radiative dark matter decay lifetime.

We define signal-to-noise ratio as

$$SNR = \frac{N_{line}}{\Delta N_{back}},$$

where $N_{line} \propto S_{DM} t_{obs}$ is the number of counts expected from decaying dark matter during observation time $t_{obs}$ and $\Delta N_{back}$ is the uncertainty of background counts. Neglecting systematical errors and assuming Gaussian statistics, we obtained $\Delta N_{back} = \sqrt{B_{obs}}$, where $B$ is background count rate (in cts/s) measured in 3.4-3.65 keV in object’s rest frame. So the signal-to-noise ratio is proportional to

$$SNR \propto S_{DM} \sqrt{\frac{t_{obs}}{B}}.$$

Because of strong dependence of $SNR$ from $S_{DM}$, we first identified objects with the largest column density in XMM-Newton/EPIC Field-of-View. In this paper, we concentrated on galaxy clusters – the objects having the largest column densities inside the charachteristic radius of dark matter haloes $[17, 18]$. For each of these objects, we calculated dark matter column densities $S_{obj}$ inside the innermost 14” radius circle $R_{14}$ (roughly corresponding to the XMM-Newton/EPIC Field-of-View) using dark matter distributions.

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$^1$ Based on observed $\sim 60 - 100$ eV shift between line positions, $[5]$ found improbable that their detections in Coma and Ophiuchus are of the same origin as in Perseus.
available in [17], see Appendix A and broadened the obtained column density ranges by 0.15 dex to account typical residual uncertainties in dark matter distributions [17]. We then calculated the foreground column density \( S_{\text{DM}} \) from Milky Way halo by using the newest dark matter distribution compiled in [3]. Because in most of objects XMM-Newton/EPIC energy resolution is comparable to the energy split between the expected dark matter decay signals from object and the Milky Way halo, we multiplied the latter by a correction factor:

\[
S_{\text{DM}} = S_{\text{obj}} + S_{\text{MW}} \times \exp \left( -\frac{z_{\text{obj}}}{\sigma_{\text{line}}} \right),
\]

where \( z_{\text{obj}} \) is the object redshift, \( E_{\text{line}} \approx 3.55 \) keV is the line position, \( \sigma_{\text{inst}} \) is the Gaussian dispersion width corresponding to energy resolution of the instrument\(^2\). According to Fig. 5.24 of [19], for XMM-Newton/EPIC imaging spectrometers \( \sigma_{\text{inst}} \approx 60 \) eV at the energies of our interest.

We identified 20 galaxy clusters with the largest \( S_{\text{DM}} \), one of them – Abell 539 – was not observed by XMM-Newton. The basic properties of the remaining 19 objects are summarized in Table II.

**Data reduction.** For objects of our interest, we first downloaded all public observation data files for MOS [13] and PN [14] cameras of XMM-Newton X-ray observatory [15], and processed them using Extended Sources Analysis Software (ESAS) package [20] publicly available as part of XMM-Newton Science Analysis System (SAS) v.14.0.0. Time intervals affected by highly variable background component – soft proton flares [20] – are filtered using ESAS scripts mos-filter and pn-filter. We used the standard filters and cuts provided by ESAS software. We excluded bright point sources detected with the standard SAS procedure edetect_chain, extracted source spectra and produced response matrices inside the 14’ radius circle around the NASA Extragalactic Database (NED) source position using ESAS procedures mos-spectra and pn-spectra. Background spectra were prepared by ESAS scripts mos_back and pn_back. For PN camera, we additionally corrected the obtained spectra for out-of-time events. Finally, for each object we combined spectra and response files from MOS and PN cameras using addspec FTOOL procedure similar to [2, 3], and grouped the obtained spectra by 60 eV per energy bin to make the bins roughly statistically independent.

**Spectral modeling.** For each object, we modeled separately its combined MOS and PN spectra in Xspec spectral package with the sum of non-thermal (powerlaw) and thermal (line-free apec) continuum components, and several narrow zgaussian lines of astrophysical origin and the new line absorbed with phabs model and folded with response files. The powerlaw index \( \Gamma = 1.41 \) and normalization \( 1.16 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1} \) at 1 keV are fixed to best-fit values of [21]. We chose the modeled energy range 2.1-6.0 keV avoiding strong emission lines. To account residual line-like calibration uncertainties we added 0.4% (MOS) and 0.25% (PN) systematic errors in quadratures using Xspec parameter systematic, according to Sec. 5.3.5 of [19]. The absorption hydrogen column density was fixed at weighted Leiden-Argentine-Bonn survey [22] value obtained through nH tool of the NASA High Energy Astrophysics Science Archive Research Center (HEASARC). The redshifts of apec and zgaussians were fixed at values from NASA Extragalactic Database (NED). The new line position is allowed to vary in 3.35-3.70 keV. To calculate the contribution of other astrophysical lines in this region, we used the bright ‘reference’ S XV line complex at \( \sim 2.63 \) keV detected in majority of our combined spectra, see Appendix B for details.

Fit quality, plasma temperatures, maximal expected fluxes from K XVIII line complex at 3.51 keV, new line positions and normalizations, and increase of \( \chi^2 \) statistics due to the new line are summarized in Table III. If no line is detected at 1σ level, we put 2σ upper bounds instead.

**Discussion.** Assuming decaying dark matter origin of the line at \( \sim 3.55 \) keV previously reported by [4], we identified 19 galaxy clusters with the largest expected significance of dark matter decay signal. Using publicly available XMM-Newton observations of their central parts, we confirmed previous detections in Perseus [1, 4] and Coma [4] clusters, and found \( >2 \sigma \) positive line-like residuals in 6 new objects, see Table III for details. We consider the following traditional origins of new line detections: (a) pure statistical fluctuations; (b) contribution from nearby astrophysical emission lines; (c) (unknown) systematical effect.

To check whether pure statistical fluctuations may cause our detections, we simulated cluster spectra using FTOOL fakeit for all objects shown in Table III based on our best-fit models without adding a new line in 3.40-3.65 keV, looked for \( \Delta \chi^2 \) increase caused by adding the new narrow zgaussian line in the energy range 3.40-3.65 keV (thus accounting for the look-elsewhere effect). The average value of 3 maximal \( \Delta \chi^2 \) for each simulation is in the range 2.1-5.2, much smaller than 13.6 (12.5) obtained from our MOS (PN) observations. Therefore, we conclude that pure statistical fluctuations alone can not be responsible for line detections in Table III.

Explanation of the new lines with astrophysical line contribution is also unlikely. The maximal contribution of the most promising astrophysical line candidate – K XVIII line complex at \( \sim 3.51 \) keV – is already included to our model, see Table III Other astrophysical lines are both too faint and should produce detectable signatures at other energies. For example, to explain the excess in Virgo cluster (also consistent with

\(^2\) For Gaussian line, the energy resolution is characterized by full width at half-maximum (FWHM) of the line which is \( 2\sigma \sqrt{2\log(2)} \approx 2.35\sigma_{\text{inst}} \).
TABLE I: Galaxy clusters observed by XMM-Newton ranged by expected significance of decaying dark matter signal from their central parts.

| Object      | redshift | \(S_{\text{tot}}, \text{M/pc}^2\) | XMM-Newton ObsID | MOS/PN exposure, ks | MOS/PN S/N, arb. units |
|-------------|----------|----------------------------------|-------------------|---------------------|------------------------|
| Virgo       | 0.0036   | 624-1338                         | 0108260201, 0110930701, 0210270101 | 193.2 / 62.9         | 3.1-6.7 / 2.3-5.0      |
| Centaurus   | 0.0114   | 818-1721                         | 0046340101, 0406200101 | 348.2 / 123.7        | 2.9-6.0 / 2.2-4.6      |
| Abell 85    | 0.0551   | 130-777                          | 0065140101, 0723802101, 0723802201 | 401.6 / 136.7        | 0.6-3.8 / 0.5-2.7      |
| Abell 478   | 0.0881   | 83-969                           | 0109880101         | 111.8 / 43.2         | 0.3-3.5 / 0.2-2.7      |
| Abell 2199  | 0.0302   | 123-826                          | 0008030201, 0008030301, 0008030601, 0723801101, 0723801201 | 254.4 / 97.5         | 0.5-3.4 / 0.4-2.6      |
| Abell 496   | 0.0329   | 124-772                          | 0135120201, 0506260301, 0506260401 | 250.6 / 81.0         | 0.5-3.1 / 0.4-2.2      |
| 2A0335+096  | 0.0363   | 75-608                           | 0109870101, 0109870201, 0147800201 | 225.2 / 89.0         | 0.4-2.9 / 0.3-2.4      |
| Abell 1060  | 0.0126   | 451-1420                         | 0206230101         | 66.7 / 24.7          | 0.9-2.8 / 0.8-2.4      |
| Abell 3266  | 0.0589   | 385-768                          | 0105260701, 0105260801, 0105260901, 0105261001, 0105261101, 0105262101, 0105262201, 0105262501 | 179.8 / 63.9         | 1.4-2.8 / 1.1-2.2      |
| Abell S805  | 0.0139   | 286-660                          | 0405550401, 0694610101 | 92.2 / 12.5          | 1.2-2.7 / 0.5-1.1      |
| Coma        | 0.0231   | 191-1193                         | 0124711401, 0153750101, 0300530101, 343.8 / 122.0 | 0.4-2.6 / 0.3-2.1    |
| Abell S239  | 0.0635   | 256-553                          | 0501110201         | 81.0 / 28.1          | 0.9-1.9 / 0.6-1.3      |
| Abell 2142  | 0.0909   | 88-573                           | 0674560201         | 104.8 / 40.9         | 0.3-1.7 / 0.2-1.3      |
| Abell 2319  | 0.0557   | 359-716                          | 0302150101, 0302150201, 0600040101 | 159.7 / 60.7         | 0.8-1.5 / 0.6-1.2      |
| Abell 1795  | 0.0625   | 83-589                           | 0097820101         | 71.7 / 23.2          | 0.2-1.5 / 0.2-1.1      |
| Abell 209   | 0.2060   | 67-500                           | 0084230301         | 33.5 / 11.2          | 0.2-1.4 / 0.1-1.0      |
| Perseus     | 0.0179   | 418-871                          | 0093620101         | 18.6 / —             | 0.3-0.6 / —            |
| PKS0745-191 | 0.1028   | 59-458                           | 0105870101         | 31.9 / 5.2           | 0.1-0.8 / 0.1-0.5      |
| Triangulum  | 0.0510   | 379-757                          | 0093620101         | 18.6 / —             | 0.3-0.6 / —            |

FIG. 1: Examples of spectral dataset with identified extra line, see Table II for details. The spectra are binned by 60 eV and presented in detector’s frame similar to [2]. Blue and red residuals (bottom) are shown with respect to the best-fit model with and without adding an extra line, respectively. Left: MOS spectrum of Abell 2199. Right: PN spectrum of Abell 496.

pure statistical fluctuation), one should assume 3.398 keV astrophysical line from S XVI \(\sim 5\) times higher than the maximal contribution from the bright S XV line complex at \(\sim 2.63\) keV obtained from Fig. 4. On the other hand, one cannot exclude the possibility of strongly super-solar abundance because there can be variations of Potassium abundance up to 1 dex [24, 25]. According to [26], further studies of the new line using forthcoming observations of Soft X-ray spectrometer on-board Astro-H X-ray observatory [27] of Micro-X sound-
TABLE II: Model parameters of MOS/PN combined spectra of galaxy clusters listed in the previous Table. Line positions are given in cluster’s rest frame. Column (4) shows our estimate on maximal K XVIII line flux at 3.51 keV using prominent S XVI line complex at 2.63 keV, see Appendix B for details. Errors on line position and flux are given at 1σ level for 2 d.o.f. calculated using Δχ^2 = 2.3. Line fluxes are in 10^{-16} ph cm^{-2} s^{-1}, abundances are in Solar values given by [23]. The new line is detected at > 2σ (corresponding to Δχ^2 > 6.2) in 8 objects (marked in bold), confirming previous detections in Perseus [1,4] and Coma [4].

| No  | Object       | χ^2/d.o.f. | T_e,keV | max K flux at 3.51 keV | New line position, keV | New line flux | Δχ^2
|-----|--------------|------------|---------|------------------------|------------------------|---------------|------|
| 1   | Virgo        | 68.9/48 / 60.0/43 | 1.4 / 1.4 | < 0.9 / < 0.7         | 3.38^{+0.05-0.07} / --- | 4.2^{+3.1-3.4} / < 9.3 | 3.8 / 0.4 |
| 2   | Centaurus    | 64.1/47 / 64.3/46 | 2.2 / 2.2 | < 5.8 / < 5.6         | 3.51^{+0.12-0.10} / --- | 25.2^{+19.7-24.2} / < 15.6 | 2.9 / 0.1 |
| 3   | Abell 85     | 37.5/49 / 61.9/46 | 2.2 / 3.4 | < 0.7 / < 0.9         | 3.44^{+0.06-0.05} / --- | 6.3^{+3.9-3.6} / < 4.2 | 7.0 / 0.0 |
| 4   | Abell 478    | 54.1/47 / 48.9/49 | 2.2 / 1.4 | < 0.4 / < 0.5         | --- / ---               | < 20.4 / < 13.6 | 0.1 / 0.4 |
| 5   | Abell 2199   | 46.8/47 / 70.6/52 | 2.7 / 2.7 | < 1.8 / < 1.6         | 3.41^{+0.04-0.04} / --- | 10.1^{+5.1-4.8} / < 10.0 | 10.2 / 0.1 |
| 6   | Abell 496    | 36.3/45 / 66.7/48 | 3.4 / 2.2 | < 1.3 / < 0.5         | 3.55^{+0.06/0.06-0.04/0.03} / 3.45^{+0.04/0.03} | 7.5^{+6.1-4.4} / 16.8^{+5.9-6.4} | 6.2 / 18.8 |
| 7   | 2A0335+096   | 70.9/49 / 65.3/49 | 2.2 / 2.7 | < 1.5 / < 1.3         | --- / ---               | < 15.5 / < 10.7 | 0.5 / 1.6 |
| 8   | Abell 1060   | 67.4/48 / 63.0/50 | 2.2 / 2.7 | < 2.9 / < 1.8         | --- / ---               | < 27.1 / < 21.2 | 0.2 / 0.0 |
| 9   | Abell 3266   | 40.7/47 / 67.2/50 | 1.7 / 1.7 | < 0.3 / < 0.3         | 3.64^{+0.05-0.06/0.04-0.06} / 3.53^{+0.04-0.05/0.04-0.05} | 6.5^{+4.3-5.3} / 8.7^{+5.1-4.5} | 3.9 / 8.0 |
| 10  | Abell S805   | 49.0/45 / 33.4/26 | 1.7 / 1.4 | < 0.2 / < 0.3         | --- / ---               | < 16.5 / < 11.7 | 0.3 / 1.8 |
| 11  | Coma         | 41.2/37 / 54.7/48 | 2.2 / 4.3 | < 1.9 / < 2.0         | 3.69^{+0.04-0.04/0.03-0.04} / 3.41^{+0.06-0.06/0.06-0.06} | 23.7^{+10.7/9.0} / 14.9^{+5.9/4.6} | 16.6 / 3.5 |
| 12  | Abell S239   | 56.7/48 / 60.8/52 | 1.4 / 1.7 | < 0.1 / < 0.2         | --- / ---               | < 12.3 / < 13.6 | 0.3 / 0.5 |
| 13  | Abell 1241   | 63.9/50 / 56.9/50 | 1.4 / 1.3 | < 0.3 / < 0.3         | --- / ---               | < 9.8 / < 17.4 | 0.0 / 0.8 |
| 14  | Abell 2319   | 49.4/47 / 61.6/51 | 1.4 / 2.2 | < 0.4 / < 1.4         | 3.59^{+0.05-0.06/0.04-0.06} / 3.53^{+0.05-0.04/0.04-0.04} | 18.6^{+10.7/9.0} / 10.5^{+12.6-10.0} | 13.9 / 2.4 |
| 15  | Abell 1795   | 61.5/51 / 64.6/50 | 1.7 / 1.7 | < 0.3 / < 0.5         | --- / ---               | < 12.4 / < 16.5 | 0.7 / 0.0 |
| 16  | Abell 209    | 62.3/50 / 68.0/48 | 1.4 / 1.4 | < 0.5 / < 0.2         | --- / ---               | < 17.4 / < 9.4 | 0.6 / 0.0 |
| 17  | Perseus      | 69.6/48 / 81.2/47 | 2.7 / 2.7 | < 4.5 / < 6.1         | 3.58^{+0.05-0.05} / --- | 25.2^{+12.5-12.5} / < 70.4 | 9.8 / 0.7 |
| 18  | PKS0745-191  | 68.9/47 / 56.0/53 | 2.2 / 1.4 | < 0.9 / < 1.5         | 3.63^{+0.07-0.06} / --- | 12.5^{+11.0-12.0} / < 40.7 | 2.4 / 1.6 |
| 19  | Triangulum   | 56.7/49 / ---    | 2.2 / --- | < 1.4 / ---          | --- / ---               | < 47.1 / --- | 0.7 / --- |

![FIG. 2: Position of new line detections in cluster’s rest frame as function of redshift.](image)

The systematic origin of the new line is shown unlikely in pioneering papers [1,2]. In addition, we plotted in Fig. 2 the dependence of the line position from the object’s redshift. If the new line were due to systematic effects, one would expect the corresponding new line in nearby (z = 0) objects at ~3.40 keV, in apparent tension with observations (3.53 ± 0.03 keV for M31 [2] and 3.539 ± 0.011 keV for Milky Way [3]) which in turn are better consistent with the new line generation in cosmic objects. The mean value of the line positions in Fig. 2 is 3.52 keV. The average spread between line positions is 75 eV close to σ_{inst} ≈ 60 eV and consistent with our simulations, according to that the position of ~ 3σ line can be recovered with ±110 eV precision in 90% of cases.

Interpreting the new line due to decaying dark matter [1] gives the radiative decay lifetime $\tau_{DM} \approx (3 - 6) \times 10^{27}$ s consistent with previous detections [1,4,29]. The non-detection of the line in some of our galaxy clusters does not exclude the dark matter line origin; the strongest 2σ upper bound for our objects comes from Virgo cluster: $\tau_{DM} \gtrsim 3.5 \times 10^{27}$ s.

Non-detection of ~3.55 keV line in stacked dSphs by [30] is also mildly consistent with these results; planned observations of Draco dSph would reveal the decaying dark matter nature of the line. The absence of the new line in stacked galaxy spectra of [31] formally excludes $\tau_{DM} < 1.8 \times 10^{28}$ s but taking into account systematical effects in spectra (e.g.
No negative detections are shown here; the strongest restriction on $\tau_{DM} \gtrsim 3.5 \times 10^7$ s comes from Virgo cluster, see text.

FIG. 3: Dependence of the new line flux from the expected projected dark matter mass. This Figure is taken from [3]; overplotted are the ranges for our $> 2\sigma$ MOS (green) and PN (magenta) detections. No negative detections are shown here; the strongest restriction on $\tau_{DM} \gtrsim 3.5 \times 10^7$ s comes from Virgo cluster, see text.

causing significant negative residuals) and apparent uncertainty in dark matter distributions [17] produces much weaker bounds, e.g. $\tau_{DM} \gtrsim 3.5 \times 10^7$ s [5] using stacked dataset of nearby galaxies of [19] with comparable exposure. Other bounds on decaying dark matter in $\sim 3.55$ keV energy range (see [19, 32, 33] and references therein) are also consistent with our detections after taking into account residual systematic effects and/or uncertainties of dark matter distributions.

Acknowledgments. We thank Jeroen Franse, Denys Malyshev, Maxim Markevitch and Oleg Ruchayskiy for careful reading of the manuscript and their comments. This work was supported by the Swiss National Science Foundation grant SCOPE IZ7370-152581, the Program of Cosmic Research of the National Academy of Sciences of Ukraine, the State Fund for Fundamental Research of Ukraine and the State Programme of Implementation of Grid Technology in Ukraine.

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Appendix A: Dark matter distributions in galaxy clusters

To describe dark matter distribution in galaxy clusters used in our work we compiled in Table III dark matter distributions from the literature using the extended dataset of [17].

All cluster distributions are described with Navarro-Frenk-White (NFW) profile [34]

\[
\rho_{\text{NFW}}(r) = \frac{\rho_s r_s}{r^2 (1 + r/r_s)^2} \tag{A1}
\]

parametrised by \(\rho_s\) and \(r_s\).

The dark matter column density inside \textit{XMM-Newton} field-of-view radius \(R_{14} = D_L \times \frac{14}{600 \times 180}\) is derived as

\[
S = \frac{2}{R_{14}^2} \int_0^{R_{14}} rdr \int dz \rho_{\text{NFW}}\left(\sqrt{r^2 + z^2}\right) \tag{A2}
\]

For the NFW density distribution (A1):

\[
S_{\text{NFW}}(R) = 4\rho_s r_s^2 \left[ \arctan \frac{\sqrt{R^2/r_s^2 - 1}}{\sqrt{R^2/r_s^2 - 1}} + \log \left(\frac{R}{2r_s}\right) \right] \tag{A3}
\]

Dark matter distribution parameters for our Galaxy are taken from [3].

Appendix B: Modeling astrophysical lines

To check the astrophysical origin of the new line, we added narrow zgaussians corresponding to known astrophysical lines in this range. For example, according to the newest atomic database AtomDB v. 3.0.3, there are S XVI line complexes at 3.355, 3.398, 3.424, 3.441, 3.452 and 3.460 keV. Fortunately, the intensity of these lines can be robustly predicted by the measured S XV line complex at \(\sim 2.63\) keV, see Fig. 4 for details.

We paid special attention to potential contribution from K XVIII lines near 3.51 keV, see e.g. [26] for details. The distance between these lines is smaller than the energy resolution of \textit{XMM-Newton}/EPIC, so we modeled the K XVIII line complex as a
| Object        | Reference | Profile | $R_{14}$ | $r_s$ | $\rho_s$ | $S_{obj}$ |
|--------------|-----------|---------|----------|-------|----------|----------|
|               |           |         | kpc      | kpc   | $10^6\text{M}_\odot/\text{kpc}^3$ | $\text{M}_\odot/\text{pc}^2$ |
| Virgo        | [35]      | NFW     | 73       | 560   | 0.32     | 808      |
| Centaurus    | [36]      | NFW     | 180      | 345   | 1.51     | 1087     |
| Abell 85     | [36]      | NFW     | 867      | 1282  | 0.25     | 549      |
| Abell 85     | [37]      | NFW     | 922      | 650   | 0.37     | 210      |
| Abell 478    | [38]      | NFW     | 1978     | 1140  | 0.85     | 686      |
| Abell 478    | [39]      | NFW     | 1518     | 488   | 0.77     | 134      |
| Abell 2199   | [36]      | NFW     | 526      | 560   | 0.76     | 552      |
| Abell 2199   | [40]      | NFW     | 509      | 214   | 1.7      | 180      |
| Abell 496    | [36]      | NFW     | 545      | 738   | 0.45     | 530      |
| Abell 496    | [37]      | NFW     | 550      | 420   | 0.48     | 191      |
| 2A0335+096   | [36]      | NFW     | 593      | 626   | 0.52     | 420      |
| 2A0335+096   | [41]      | NFW     | 593      | 130   | 3.6      | 101      |
| Abell 1060   | [42]      | NFW     | 195      | 140   | 7.2      | 899      |
| Abell 1060   | [37]      | NFW     | 211      | 140   | 5.8      | 667      |
| Abell 3266   | [36]      | NFW     | 991      | 1576  | 0.19     | 543      |
| Abell S805   | [47]      | NFW     | 232      | 190   | 2.0      | 386      |
| Coma         | [36]      | NFW     | 397      | 459   | 1.23     | 788      |
| Coma         | [43]      | NFW     | 407      | 326   | 0.85     | 275      |
| Abell S239   | [44]      | NFW     | 1095     | 792   | 0.55     | 391      |
| Abell S239   | [44]      | NFW     | 1095     | 576   | 0.98     | 361      |
| Abell 2142   | [36]      | NFW     | 1469     | 1654  | 0.18     | 406      |
| Abell 2142   | [47]      | NFW     | 1520     | 990   | 0.18     | 144      |
| Abell 2319   | [36]      | NFW     | 943      | 1301  | 0.24     | 506      |
| Abell 1795   | [36]      | NFW     | 1052     | 1024  | 0.34     | 417      |
| Abell 1795   | [45]      | NFW     | 1052     | 393   | 0.82     | 139      |
| Abell 209    | [46]      | NFW     | 3460     | 2513  | 0.18     | 408      |
| Abell 209    | [47]      | NFW     | 3435     | 502   | 0.386    | 24       |
| Perseus      | [48]      | NFW     | 305      | 360   | 1.1      | 563      |
| PKS 0745-191 | [36]      | NFW     | 1665     | 1148  | 0.33     | 324      |
| PKS 0745-191 | [49]      | NFW     | 1779     | 230   | 2.5      | 59       |
| Triangulum   | [36]      | NFW     | 856      | 666   | 0.83     | 534      |

**TABLE III:** Parameters of dark matter distributions of galaxy clusters used in this work.

A single Gaussian with mean energy 3.51 keV. Because there is no “reference” Potassium line to reproduce the 3.51 keV line flux, we fixed only the upper bound of the 3.51 keV line intensity relating it to S XVI line flux at 2.63 keV (or, if 2.63 keV is not detected in the dataset – to its 2$\sigma$ upper bound) using the procedure described in [26]. To derive electron temperature, we used flux ratios of strong elemental lines, namely S XV lines at 2.45 keV, S XVI lines at 2.63 keV, Ca XIX lines at 3.90 keV and Ca XX lines at 4.10 keV. Because 3.51/2.63 keV line ratio is a decreasing function of electron temperature $T_e$, see Fig. 4, we used minimal temperature $T_{e,line} = \min[T_{e,S}, T_{e,Ca}]$ for conservative estimate. Another source of uncertainty comes from the (largely unknown) relative K/S abundance ratio. To account possible uncertainties [6, 24, 25] we allowed this ratio to be up to 3 Solar values of [23]. Note that from comparison of columns 4 and 6 one can derive that to explain new line emission solely in terms of K XVIII line complex at 3.51 keV, one should assume strongly supersolar (Abund[K]/Abund[S] > 15 Solar) ratios for all our of detections.
FIG. 4: Line emissivity ratios for K XVIII line complex at ∼3.51 keV and other emission lines of our interest as functions of the electron temperature $T_e$ in the plasma. The line emissivities are calculated using AtomDB version 3.0.3 with line emissivities $> 10^{-22}$ ph cm$^3$/s.