Observation of the new emission line at \( \sim 3.5 \) keV in X-ray spectra of galaxies and galaxy clusters

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The detection of an unidentified emission line in X-ray spectra of cosmic objects would be a 'smoking gun' signature for particle physics beyond the Standard Model. More than a decade of its extensive searches results in several narrow faint emission lines reported at 3.5, 8.7, 9.4 and 10.1 keV. The most promising of them is the emission line at \( \sim 3.5 \) keV reported in spectra of several nearby galaxies and galaxy clusters. Here I summarize its up-to-date status, overview its possible interpretations, including an intriguing connection with radiatively decaying dark matter, and outline future directions for its studies.

**Key words:** X-rays: general, dark matter, line: identification.
INTRODUCTION

The origin of dark matter – the major (yet of unknown origin) gravitating substance in the Universe \[1,23\] – still has to be revealed. If dark matter is made of elementary particles, the corresponding particle should be massive (to form over-densities in process of gravitational collapse), long-lived (to be stable for at least the age of the Universe) and neutral with respect to strong and electromagnetic interactions (to be sufficiently ‘dark’). The only known massive, long-lived and neutral particles are the usual (left-handed) neutrinos, but they are too light to form small dark matter haloes \[24,27\]. As a result, the hypothesis of dark matter particle implies an extension of the Standard Model of particle physics. Dozens of the Standard Model extensions proposed so far to contain a valid dark matter particle candidate. However, as Fig. 1 of \[28\] demonstrates, the masses of dark matter particle candidates and their interaction strengths with Standard Model particles cover a huge region of parameter space. This results in a large variety of observational methods developed to search for dark matter particles.

The specific example considered in this review is radiatively decaying dark matter. If a dark matter particle interacts with electrically charged particles, it may \[1\] possess a radiative decay channel. If a non-relativistic dark matter particle decays to a photon and another particle, slight \((v/c \lesssim 5 \times 10^{-3})\) Doppler broadening due to non-zero velocities of dark matter particles in halos would cause a narrow dark matter decay line. Such a decay line possesses several specific features allowing to robustly distinguish it from emission lines of astrophysical origin (see e.g. \[29,30\]) or from instrumental line-like features:

- its position in energy is solely determined by the mass of dark matter particle and the redshift of dark matter halo (i.e. if one neglects the mass of the other decay product, the line position is \(m_{\text{DM}}c^2/2(1+z)\), having different scaling with halo redshift \(z\) compared with instrumental line-like features;
- its intensity is proportional to dark matter column density \(\rho_{\text{DM}} = \int \rho_{\text{DM}} dl\); due to different 3D distributions of dark and visible matter, comparison of the new line intensity within the given object and among different objects would allow to choose between its decaying dark matter and astrophysical origins;
- it is broadened with the characteristic velocity of dark matter different from that of visible matter.

The above-mentioned characteristics allow to directly detect the radiatively decaying dark matter relying on astrophysical measurements. This motivates the extensive search for new lines in X-ray spectra of cosmic objects proposed about 15 years ago \[31,33\], see Table 1. An example is the analysis of the line candidate at \(\sim 2.5\) keV initially reported by \[34\] in X-ray spectrum of the Willman 1 dwarf spheroidal at 2.5σ level. Further non-observation of this line candidate in central part and outskirts of Andromeda galaxy, Fornax and Sculptor dwarf spheroidal galaxies \[35\] excludes the decaying dark matter origin of the \(\sim 2.5\) keV signal at high significance level (above 14σ). This result is further strengthened by the authors of \[36\] who reanalyzed the same observations of Willman 1 as \[33\] (and did not find the \(\sim 2.5\) keV line) and the authors of \[37\] who analysed another dwarf spheroidal, Segue 1. Finally, the authors of \[38\] ruled out the dark matter origin of the \(\sim 2.5\) keV feature by looking at Willman 1 with better statistics. The probable origin of the \(\sim 2.5\) keV line, according to \[38\], is purely instrumental, being the result of under-modelling of the time-variable soft proton background (see e.g. \[34\]) in some observations combined with an apparent dip at \(\sim 2.5\) keV in the effective area of existing X-ray instruments.

OBSERVATIONAL EVIDENCE FOR THE LINE AT \(\sim 3.5\) KEV

The new emission line at \(\sim 3.5\) keV is reported by two different groups \[70,71\] in February 2014. In \[70\], the authors combine X-ray emission from the sample of nearby galaxy clusters observed by the European Photon and Imaging Camera (EPIC) on-board the XMM-Newton X-ray cosmological observatory \[71\] with the largest number of counts (\(> 10^5\) counts for redshifts \(z < 0.1\) and \(> 10^4\) counts for redshifts \(0.1 < z < 0.4\)). The stacking is made in the cluster’s rest frame. As a result, the emission from instrumental lines is smeared out, while cosmic lines appear more prominent. This method allows \[70\] to detect 28 emission lines of astrophysical origin in 2-10 keV band, much more than in individual galaxy clusters, see e.g. \[72\]. Apart of them, \[70\] identify the new line located at \(3.57\pm0.02\) keV in XMM-Newton/MOS \[72\] cameras and at \(3.51\pm0.03\) keV in XMM-Newton/PN \[73\] camera at the level \(\gtrsim 10\) larger than predicted by two complexes of nearby astrophysical emission lines located at 3.51 keV (K XVIII).
| Ref. | Object | Instrument | Cleaned exposure, ks |
|------|--------|------------|---------------------|
| [40] | Diffuse X-ray background | HEAO-1, XMM-Newton/EPIC | 224, 1450 |
| [41] | Coma, Virgo | XMM-Newton/EPIC | 20, 40 |
| [42] | Large Magellanic Cloud | XMM-Newton/EPIC | 20 |
| [43] | Milky Way | Chandra/ACIS-S3 | Not specified |
| [44] | M31 (central 5') | XMM-Newton/EPIC | 35 |
| [45] | Abell 520 | Chandra/ACIS-S3 | 67 |
| [46] | Milky Way, Ursa Minor | XMM-Newton/EPIC | 547, 7 |
| [47] | Milky Way | Chandra/ACIS | 1500 |
| [48] | 1E 0657-56 (“Bullet cluster”) | Chandra/ACIS-I | 450 |
| [49] | Milky Way | X-ray micro-calorimeter | 0.1 |
| [50] | Milky Way | INTEGRAL/SPI | 5500 |
| [51] | M31 (central 5 – 13') | XMM-Newton/EPIC | 130 |
| [52] | Milky Way | INTEGRAL/SPI | 12200 |
| [53] | Ursa Minor | Suzaku/XIS | 70 |
| [54] | Draco | Chandra/ACIS-S | 32 |
| [55] | Willman 1 | Chandra/ACIS-I | 100 |
| [56] | M31, Fornax, Sculptor | XMM-Newton/EPIC, Chandra/ACIS | 400, 50, 162 |
| [57] | Willman 1 | Chandra/ACIS-I | 100 |
| [58] | Segue 1 | Swift/XRT | 5 |
| [59] | M33 | XMM-Newton/EPIC | 20-30 |
| [60] | M31 (12 – 28' off-centre) | Chandra/ACIS-I | 53 |
| [61] | Willman 1 | XMM-Newton/EPIC | 60 |
| [62] | Ursa Minor, Draco | Suzaku/XIS | 200, 200 |
| [63] | Stacked galaxies | XMM-Newton/EPIC | 8500 |
| [64] | M31 | Chandra/ACIS-I | 404 |
| [65] | Stacked dSphs | XMM-Newton/EPIC | 410 |
| [66] | Stacked galaxies | XMM-Newton/EPIC, Chandra/ACIS-I | 14600, 15000 |
| [67] | Perseus | Suzaku/XIS | 520 |
| [68] | Milky Way, Draco | Fermi/GBM, Suzaku/XIS | 4600, 31500 |
| [69] | Milky Way | XMM-Newton/EPIC | 87 |
| [70] | 1E 0657-56 (“Bullet cluster”) | NuSTAR | 266 |
| [71] | Draco | XMM-Newton/EPIC | 1660 |

Table 1: Summary of searches for dark matter decay line in X-ray observations conducted so far. This Table is an update of Table 1 in [69].
and 3.62 keV (Ar XVII). The new line is also detected at > 3σ local significance in several different sub-samples of their combined XMM-Newton/EPIC cluster dataset, see e.g. Fig. 1 and in Chandra/ACIS spectrum of Perseus cluster, see Table 2 for details.

![Fig. 1](image1.png)

Fig. 1: The combined MOS spectrum of Perseus cluster scaled to 3-4 keV energy range. On top of their best-fit model, the series of the single-bin residuals corresponding to the extra emission line at 3.57 keV is shown in red. (Adapted from Figure 7 in [70]).

The authors of [71] detect the new line at 3.53 ± 0.03 keV in the central part of Andromeda galaxy (see Fig. 2), and in the outskirts of Perseus cluster, see Table 2. [71] exclude the central part of Perseus cluster (analysed in [70]) because of its rather complex structure in X-rays, so the two datasets used in [70, 71] are totally independent enhancing the statistical significance for the new line. Another important result of [71] is the radial dependence of the new line flux in Perseus that appears more consistent with decaying dark matter profile than with astrophysical emission.

The encouraging results of [70, 71] have stimulated several groups to look on other dark matter-dominated objects. The following searches report the presence of the line at ~3.5 keV, see Table 3.

1. The central part of the Virgo cluster observed by Chandra/ACIS [71], Suzaku/XIS [83] and XMM-Newton/EPIC [85], as well as other 10 galaxy clusters from [85].
2. Combined spectrum from dwarf spheroidal galaxies [60].
3. Outskirts of galaxies [61, 71].
4. Combined blank-sky observations [63, 71].
5. Prolonged XMM-Newton/EPIC observations of Draco dwarf spheroidal galaxy [68, 89]; although the authors of [89] report a line-like excess at 3.54 ± 0.06 keV with Δχ^2 = 5.3 in PN camera, see Table 2 this finding is not supported by an independent analysis of [68] and is not accompanied with similar excess in Draco spectra seen by MOS camera [68, 89].
| Ref. | Object | Redshift | Instrument | Exposure, Ms | Line position, keV | Line flux, 10^{-6} ph/s/cm² |
|------|--------|----------|------------|--------------|-------------------|-----------------------------|
| [70] | Full stacked sample | 0.009-0.354 | MOS | 6 | 3.57±0.02 | 4.0±0.8 |
| [70] | Full stacked sample | 0.009-0.354 | PN | 2 | 3.51±0.03 | 3.9±0.6 |
| [70] | Coma+Centaurus+Ophiuchus | 0.009-0.028 | MOS | 0.5 | 3.57^a | 15.9±3.4 |
| [70] | Coma+Centaurus+Ophiuchus | 0.009-0.028 | PN | 0.2 | 3.57^a | < 9.5 (90%) |
| [70] | Perseus (< 12') | 0.016 | MOS | 0.3 | 3.57^a | 52.0±24.1 |
| [70] | Perseus (< 12') | 0.016 | PN | 0.05 | 3.57^a | < 17.7 (90%) |
| [70] | Perseus (1-12') | 0.016 | MOS | 0.3 | 3.57^a | 21.4±10.3 |
| [70] | Perseus (1-12') | 0.016 | PN | 0.05 | 3.57^a | < 16.1 (90%) |
| [70] | Rest of the clusters | 0.012-0.354 | MOS | 4.9 | 3.57^a | 2.1±0.4 |
| [70] | Rest of the clusters | 0.012-0.354 | PN | 1.8 | 3.57^a | 2.0±0.3 |
| [70] | Perseus (> 1') | 0.016 | ACIS-S | 0.9 | 3.56±0.02 | 10.2±3.7 |
| [70] | Perseus (< 9') | 0.016 | ACIS-I | 0.5 | 3.56^a | 18.6±4.8 |
| [70] | Virgo (< 500') | 0.003-0.004 | ACIS-I | 0.5 | 3.56^a | < 9.1 (90%) |
| [71] | M31 (< 14') | -0.001^b | MOS | 0.5 | 3.53±0.03 | 4.9±1.6 |
| [71] | M31 (10-80') | -0.001^b | MOS | 0.7 | 3.50-3.56 | < 1.8 (2σ) |
| [71] | Perseus (23-102') | 0.017^b | MOS | 0.3 | 3.50±0.04 | 7.0±2.6 |
| [71] | Perseus (23-102') | 0.017^b | PN | 0.2 | 3.46±0.04 | 9.2±3.1 |
| [71] | Perseus, 1st bin (23-37') | 0.017^b | MOS | 0.2 | 3.50^a | 13.8±3.3 |
| [71] | Perseus, 2nd bin (42-54') | 0.017^b | MOS | 0.1 | 3.50^a | 8.3±3.4 |
| [71] | Perseus, 3rd bin (68-102') | 0.017^b | MOS | 0.03 | 3.50^a | 4.6±4.6 |
| [71] | Blank-sky | — | MOS | 7.8 | 3.45-3.58 | < 0.7 (2σ) |

Table 2: Properties of the ~3.5 keV line reported by [70, 71]. For their analysis, the authors of [70, 71] use different X-ray datasets observed by MOS [73] and PN [72] cameras on-board XMM-Newton observatory [74] and ACIS instrument [76] on-board Chandra observatory [77]. All error bars are at 1σ (68%) level.

^a The line position is fixed at given value.

^b The redshift is fixed at NASA Extragalactic Database (NED) value.
Table 3: Properties of ∼3 keV line searched after February 2014 in different X-ray datasets observed by MOS [73] and PN [72] cameras on-board XMM-Newton observatory [74], ACIS [76] instrument on-board Chandra observatory [77] and XIS instrument [91] on-board Suzaku observatory [92]. All error bars are at 1σ (68%) level.

| Ref. | Object | Redshift | Instrument | Exposure, Ms | Line position, keV | Line flux, 10^-6 ph/s/cm^2 |
|------|--------|----------|------------|-------------|------------------|--------------------------|
| 78   | Galactic centre (2.5-12') | 0.0      | ACIS-I     | 0.8         | 3.51             | ≃ 10^a                   |
| 79   | Galactic centre (0.3-15') | 0.0      | MOS        | 0.7         | 3.51             | 45 ± 4^c                |
| 79   | Galactic centre (0.3-15') | 0.0      | PN         | 0.5         | 3.51             | 39 ± 7^e                |
| 79   | M31     | 0.0      | MOS        | 0.5         | 3.53±0.07       | 2.1±1.5^c               |
| 80   | Galactic centre (< 14')  | 0.0      | MOS        | 0.7         | 3.539±0.011     | 29±5                    |
| 83   | Perseus core (< 6')      | 0.0179b  | XIS        | 0.74        | 3.510±0.023     | 32.5±3.7                |
| 83   | Perseus confined (6-12.7') | 0.0179b  | XIS        | 0.74        | 3.510±0.008     | 32.5±4.3                |
| 83   | Coma (< 12.7')           | 0.0231b  | XIS        | 0.164       | ≃ 3.45^d        | ≃ 30^d                  |
| 83   | Ophiuchus (< 12.7')      | 0.0280b  | XIS        | 0.083       | 3.45^d          | ≃ 40^d                  |
| 83   | Virgo (< 12.7')          | 0.0036b  | XIS        | 0.09        | 3.55^a          | < 6.5 (2σ)              |
| 85   | Abell 85 (< 14')         | 0.0551b  | MOS        | 0.20        | 3.44±0.06       | 6.3±3.9                 |
| 85   | Abell 2199 (< 14')       | 0.0302b  | MOS        | 0.13        | 3.41±0.04       | 10.1±3.1                |
| 85   | Abell 496 (< 14')        | 0.0329b  | MOS        | 0.13        | 3.55±0.06       | 7.5±5.1                 |
| 85   | Abell 496 (< 14')        | 0.0329b  | PN         | 0.08        | 3.45±0.03       | 16.8±6.4                |
| 85   | Abell 3266 (< 14')       | 0.0589b  | PN         | 0.06        | 3.53±0.03       | 8.7±4.5                 |
| 85   | Abell S805 (< 14')       | 0.0139b  | PN         | 0.01        | 3.63±0.06       | 17.1±5.1                |
| 85   | Coma (< 14')             | 0.0231b  | MOS        | 0.17        | 3.49±0.05       | 23.7±10.5               |
| 85   | Abell 2319 (< 14')       | 0.0557b  | MOS        | 0.08        | 3.59±0.05       | 18.6±7.4                |
| 85   | Perseus (< 14')          | 0.0179b  | MOS        | 0.16        | 3.58±0.08       | 25.2±12.5               |
| 85   | Virgo^c (< 14')          | 0.0036b  | PN         | 0.06        | —               | < 9.3                   |
| 89   | Draco (< 14')            | 0.0      | PN         | 0.65        | 3.54±0.06       | 1.65±0.67±0.70          |
| 84   | Perseus (< 8.3')         | 0.0179b  | XIS        | 1.67        | 3.54±0.01       | 27.9±3.5                |
| 84   | Perseus (< 2')           | 0.0179b  | XIS        | 1.67        | 3.51±0.02       | 9.3±2.6                 |
| 84   | Perseus (2'-4.5')        | 0.0179b  | XIS        | 1.67        | 3.55±0.02       | 16.7±2.9                |
| 84   | Perseus (4.5'-8.3')      | 0.0179b  | XIS        | 1.67        | 3.58±0.02       | 16.1±3.3                |
| 90   | Stacked clusters         | 0.01-0.45| XIS        | 8.1         | 3.54f           | 1.0±0.5                 |

Table 3: Properties of ∼3 keV line searched after February 2014 in different X-ray datasets observed by MOS [73] and PN [72] cameras on-board XMM-Newton observatory [74], ACIS [76] instrument on-board Chandra observatory [77] and XIS instrument [91] on-board Suzaku observatory [92]. All error bars are at 1σ (68%) level.

a Best-fit line flux at fixed position 3.51 keV coinciding with the brightest K XVIII line.

b Redshift was fixed at NASA Extragalactic Database (NED) value.

c The line is detected at < 90% confidence level. Such a low flux (compared with [71]) is because of non-physically enhanced level of continuum in 3-4 keV band used in [70], see [93] for details.

d Parameters estimated from Fig. 3 of [88].

e Given an example of the new line non-detection, see Table II of [55] for more details.

f Line position is fixed at the best-fit energy detected in Suzaku observations of the Perseus cluster by [84].
6. Combined dataset of 33 galaxy clusters observed by Chandra/ACIS [94].

At the moment, it is unclear whether these negative searches rule out the decaying dark matter hypothesis of the new line. While the bounds obtained in [68] are mildly consistent with the decaying dark matter origin of the detections in [70, 71], the results of [60] formally exclude the decaying dark matter hypothesis of the ~3.5 keV line imposing the very strict 3σ bound, \( \tau_{\text{DM}} > 1.8 \times 10^{28} \) s. Taking into account systematic effects in spectra (e.g., causing significant negative residuals) obtained by [61] and the apparent uncertainty in their dark matter distributions [63] would result in much weaker bound, see e.g., \( \tau_{\text{DM}} > 3.5 \times 10^{27} \) s [65] using the stacked dataset of nearby galaxies of [55] with comparable exposure, still consistent with existing detections. The uncertainty in dark matter distributions also helps to reconcile the results of the other negative searches [56, 59, 65] with ~3.5 keV line detections using the decaying dark matter paradigm. There is also no clarity with the new prolonged (~1.4 Ms) XMM-Newton/EPIC observation of Draco dwarf spheroidal galaxy – the object having both well-measured dark matter distribution [97] and proven low X-ray background [54, 60, 82, 98]. While [68] reports an exclusion of dark matter hypothesis at 99% level having 2σ upper bound on radiative dark matter decay lifetime \( \tau_{\text{DM}} > 2.7 \times 10^{27} \) s, the results of [89] suggest \( \tau_{\text{DM}} \approx (7-9) \times 10^{27} \) s, the value still compatible with all existing observations.

"STANDARD" EXPLANATIONS OF THE LINE AT ~3.5 KEV

There are three possible "standard" explanations of the new line detections at ~3.5 keV:

1. statistical fluctuations;
2. general-type systematic effects;
3. astrophysical emission line.

With recent increase of positive detections reported by [89], it is very hard to explain all of the detections with purely statistical fluctuations. Nevertheless, statistical fluctuations may be responsible for new line detections or non-detections in some individual objects, as well as for variations of the detected line position up to \( \sim 110 \text{ eV} \) [89], see Fig. 5—the effect that should be properly taken into account when searching for the new line (unlike [60, 61, 83]).

The systematic origin of the line is carefully investigated because of the previous study of the line-like residual at ~2.5 keV in the Willman 1 dwarf...
Fig. 5: The position of new line detected in [85] (in the frame of emitting galaxy cluster) as a function of cluster redshift. The red and black dashed lines show the expected behaviour in case of purely systematic and cosmic line origins (assuming the line position 3.52 keV in the detector frame expected from [71, 80], respectively. (Adapted from Figure 3 in [85]).

spheroidal, see Sec. 4 for details. However, the explanation of the ∼3.5 keV line with general-type systematics suggested in [70] is unlikely. For example, its position (in the frame of emitting object) remains remarkably constant with redshift [71, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74].

On the other hand, the explanation of the new line with the K X VIII line complex at ∼3.5 keV suggested by [79] (see also an extensive discussion in [71, 73]) is still possible, at least for Galactic Centre region and galaxy clusters, contrary to initial claims of [70, 74]. The reason is that the emission flux from the K XVIII line complex at ∼3.51 keV suggested by [73] is highly uncertain due to large uncertainties of the Potassium abundance, see e.g. [101, 102] for a potential level of uncertainty. Moreover, unlike other possible emission lines of astrophysical origin near ∼3.5 keV such as Cl XVII lines

2 The results of [102] indicate an order of magnitude over-abundance of Potassium in solar corona compared to solar photosphere. Based on this result, [102] suggested that the Potassium abundance in hot plasma in galaxies and galaxy clusters may have also been enhanced compared to the solar photospheric values. However, because at the moment there is no established mechanism that could effectively provide such an enhancement, the results of [102] only indicate the potential level of uncertainty, similar to the measurements in [101].

at 3.51 keV found largely sub-dominant in Galactic Centre region [79] and in galaxy clusters ([99]), K XVIII line complex does not have stronger counterparts at other energies and can hardly be excluded by measurements of other lines, the strongest of them is the K XIX line complex at 3.71 keV of comparable strength [103]. The same is true about the charge exchange of S XVI ions recently suggested by [104].

An alternative approach is to study the line morphology. At the moment, two different methods have been used. The first method [71, 74] is to split the region covered by astrophysical sources onto several independent subregions, large enough to detect the line at in each of them, and to model their spectra separately looking for a line-like excess in each of them. As a result, [70] show that the ∼3.5 keV line in Perseus cluster is somewhat more concentrated compared to decayed dark matter distributed according to Navarro-Frenk-White [80, 81] profile. By studying the ∼3.5 keV line emission from Perseus cluster outskirts [71], we obtain that such distribution is better consistent with radiatively decaying dark matter distributed according to the well-established Navarro-Frenk-White profile than with astrophysical continuum emission distributed according to the isothermal β-model of [105]. The recent detailed study [81] confirms this result and expands it to the central region of Perseus cluster.

The second method to study the line morphology [81] deals with spatial distribution of the ‘line plus continuum’ X-ray emission in Perseus cluster and Galactic Centre region with further eliminating continuum component by either assuming it spatially smooth or cross-correlating the ‘line plus continuum’ images in several energy bands (including those dominated by astrophysical line emission). By using the second method, the authors of [81] show that adding decaying dark matter distribution from a smooth dark matter profile (Navarro-Frenk-White, Einasto, Burkert) does not improve the fit quality in both objects, and demonstrate that distribution of the events in 3.45-3.6 keV bands correlates with that in the energy bands of strong astrophysical emission, rather than with that in line-free energy bands. Based on these findings, Ref. [81] claims the exclusion of decaying dark matter origin of 3.5 keV in Galactic Centre and Perseus cluster.

To ultimately check the astrophysical origin of the ∼3.5 keV line, new observations with high-resolution imaging spectrometers such as Soft X-ray Spectrometer (SXS) [105] on-board the recently launched Hitomi (former Astro-H) mission [111]. Micro-X sounding rocket experiment [112] and the X-ray Inte-

3 Grating spectrometers such as Chandra/HETGS [108] have excellent spectral resolution for point sources; however, for extended (>1 arcmin) sources their spectral resolution usually degrades to that for existing imaging spectrometers, see e.g. [102].

4 Although Hitomi is now broken apart, it had observed Perseus cluster before the break-up [104, 110].
**Possible Implications for New Physics**

If none of “conventional” explanations discussed in the previous Sec. were valid, the existence of the new line at ~3.55 keV will be an indication of a new physics beyond the Standard Model.

Historically, the first model discussed in connection with ~3.5 keV detection is the neutrino minimal extension of the Standard Model with three right-handed (sterile) neutrinos (the νMSM) \([121, 123]\). In this model, the lightest sterile neutrino with mass in keV range forms the bulk of dark matter while two heavier sterile neutrinos are responsible for two other established phenomena beyond the Standard Model – neutrino oscillations and generation of asymmetry between baryons and anti-baryons in the early Universe. Sterile neutrinos decay possess the 2-body radiative channel \(N \to \gamma + \nu\), so the observation of ~3.5 keV decay line would imply the existence of light sterile neutrino dark matter particles with mass ~7.1 keV.

The simplest production scenario of sterile neutrino dark matter – via non-resonant oscillations of usual (active) neutrinos in the early Universe \([31, 33, 124, 126]\) – is already excluded by the combination of X-ray measurements \([31]\), measurements of Lyman-\(\alpha\) forest \([127, 132]\) and the phase-space bound from dwarf spheroidal galaxies \([20, 133, 136]\). The realistic scenario of dark matter production within the νMSM now involves resonant oscillations of active neutrinos in hot primeval plasma with significant lepton asymmetry generated by decays of heavier sterile neutrinos \([137–141]\). The parameters of observed ~3.5 keV line are consistent with νMSM predictions, see Fig. 7 for details. Because the interaction of sterile neutrino dark matter with Standard Model particles is orders of magnitude weaker than that of ordinary neutrinos, its prospects for direct detection in a particle physics experiment are very far from the existing experimental technique, see \([112, 149]\).

To confirm the νMSM, a search for heavier sterile neutrinos in GeV range is needed, handled by e.g. planned Search for Hidden Particles (SHiP) experiment \([147, 148]\) and Future electron-positron \(e^+e^-\) Circular Collider (FCC-ee) \([149]\).

However, the confirmation of decaying dark matter origin of the new line does not imply the existence of νMSM sterile neutrinos as there are plenty of other alternatives which can potentially explain the ~3.55 keV line, see e.g. \([80, 96, 146]\) and the references therein. Differences among these models can be further probed by:

- changes in the new line morphology because of non-negligible initial dark matter velocities, see e.g. \([150, 151]\).

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**Fig. 6:** Line emissivities (in arbitrary units) broadened with energy resolution of Soft X-ray Spectrometer (SXS) on-board Hitomi (former Astro-H). \(\sigma_{SXS} = 5\) eV as functions of energy for three-component model of [72] of Galactic Centre. The relative S, Ar, Cl and K abundances are set to 1/3 : 1 : 1 : 3, according to Sec. 2.2 of [72]. Thin dashed line shows the total line emissivity. (Adapted from Figure 2 in [103]).

**Other Extra Line Candidates in X-ray Range**

Although the line at ~3.5 keV receives the largest attention of the community, there are three other line candidates in X-rays which origin is also not established:

1. According to [117], intensity of the \(\text{Fe XXVI Ly-\(\gamma\) line} at 8.7\) keV observed in Suzaku/XIS spectrum of the Milky Way centre [118] cannot be explained by standard ionization and recombination processes, and dark matter decay may be a possible explanation of this excess.

2. According to Sec. 1.4 of [119], two faint extra line-like excesses at 9.4 and 10.1 keV are detected in the combined Suzaku/XIS spectrum of Galactic Bulge region. Notably, positions of these excesses do not coincide with any bright astrophysical or instrumental line and their intensities can be explained in frames of decaying dark matter origin, see right Fig. 8 of [119].

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\(5\) The newest available atomic database AtomDB v.3.0.2 [120] contains several faint Ni XXVI - Ni XXVIII emission lines at 10.02-10.11 keV.
Fig. 7: Constraints on sterile neutrino dark matter within the v-MSM model \[121-123\]. In every point in the white region sterile neutrinos constitute 100% of dark matter and their properties agree with the existing bounds. The blue point corresponds to the observed line from Andromeda galaxy, while the error bars indicate statistical errors (thick) and uncertainty in dark matter distribution at the central part of Andromeda galaxy (thin). (Adapted from Figure 4 in \[71\]).

- other astrophysical and cosmological tests, see e.g. \[63, 153, 154, 152, 162\];
- search for “smoking gun” signatures in future dedicated particle physics experiments, such as SHiP \[147, 148\] and FCC-ee \[149\] experiments.

Recently proposed alternatives to radiatively decaying dark matter include: decay of excited dark matter states \[166, 173\], annihilating dark matter \[174, 175\], dark matter decaying into axion-like particles with further conversion to photons in magnetic field \[179, 182\]. These models predict substantial difference in ~3.5 keV line morphology compared to the radiatively decaying dark matter. For example, the spatial distributions of the new line in these models should be more concentrated towards the centres of dark matter-dominated objects compared to radiatively decaying dark matter, e.g. due to larger dark matter density (for excited and annihilating dark matter) or larger magnetic fields (for magnetic field conversion of axion-like particles). Further non-observation of the ~3.5 keV line in outskirts of dark matter-dominated objects would agree in favour of these models.

CONCLUSION AND FUTURE DIRECTIONS

The origin of the new emission line at ~3.5 keV reported by \[70, 71, 80, 83, 85\] remains unexplained. The observed properties of the new line are consistent with radiatively decaying dark matter and other interesting scenarios (such as, exciting dark matter, annihilating dark matter and dark matter decaying into axion-like particles further converted in cosmic magnetic fields) motivated by various particle physics extensions of the Standard Model. In case of radiatively decaying dark matter, further detections would lead to direct detection of new physics. Specially dedicated observations using existing X-ray missions (such as XMM-Newton, Chandra, Suzaku) still allow such detections although one should take detailed care on various systematic effects that could mimic or hide the new line.

The alternative is to use new better instruments. The basic requirements for such instruments – higher grasp (the product of field-of-view and effective area) and better spectral resolution – have first formulated in \[49\]. Both the soft X-ray Spectrometer \[108\] on-board the new X-ray mission Hitomi (former Astro-H) \[111, 184\] and the planned Micro-X sounding rocket experiment \[112\] meet only second requirement having the energy resolution by an order of magnitude better (~5 eV) than existing imaging spectrometers. Before being broken apart, Hitomi has already observed Perseus cluster \[169\]. It is expected \[70\] that such an observation would allow Hitomi to precisely determine the new line position in bright objects with prolonged observations and to detect the K XIX emission line complex at ∼3.71 keV. Another possible option is to resolve the intrinsic width of the new line because of its Doppler broadening in galaxies and galaxy clusters \[70, 185\]. As a result, Hitomi/SXS is able to check whether the new line comes from new physics or from (anomalously enhanced) astrophysical emission. The same is expected from the Micro-X rocket-based microcalorimeter (to be launched in 2017) which will observe the central region of our Galaxy. Another possibility is to use the planned eROSITA instrument on-board Spektrum-Röntgen-Gamma mission \[186\] and the planned LOFT mission \[187\] which high grasp and lower energy resolution would allow to detect the new line at much smaller intensities \[63, 188\]. Finally, an “ultimate” imaging spectrometer proposed in e.g. \[189\] (an example is the X-ray Integral Field Unit (X-IFU) \[113, 114\] on-board the planned Athena mission \[115, 116\]) would reveal the detailed morphology structure of the ~3.5 keV line \[190\].

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