New emission line at \( \sim 3.5 \) keV – observational status, connection with radiatively decaying dark matter and directions for future studies

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Recent works of [1, 2], claiming the detection of the extra emission line with energy \( \sim 3.5 \) keV in X-ray spectra of certain clusters of galaxies and nearby Andromeda galaxy, have raised considerable interest in astrophysics and particle physics communities. A number of new observational studies claim detection or non-detection of the extra line in X-ray spectra of various cosmic objects. In this review I summarize existing results of these studies, overview possible interpretations of the extra line, including intriguing connection with radiatively decaying dark matter, and show future directions achievable with existing and planned X-ray cosmic missions.

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

INTRODUCTION

We still have to explore the origin of dark matter – gravitationally interacting substance which constitutes the major fraction of non-relativistic matter in the Universe. None of known elementary particles constitutes the bulk of dark matter. Despite that fact, the most plausible hypothesis is the dark matter made of elementary particles which implies the extension of Standard Model of particle physics and is of considerable interest for particle physicists.

Dozens of Standard Model extensions proposed so far range by main parameters – mass of dark matter particles and their interaction strength with Standard Model particles – by tens of orders of magnitude. Astrophysical observations of dark matter objects can probe some of them. An interesting example is radiatively decaying dark matter. If a dark matter particle interacts with electrically charged Standard Model particles, it usually decays emitting a photon. For 2-body radiative channel, Doppler broadening of dark matter in haloes will cause a narrow dark matter decay line. Such a line possesses a number of specific properties allowing to distinguish it from astrophysical emission lines or 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 other decay product, the line position is \( \frac{m_{\text{DM}} c^2}{2(1+z)} \), having different scaling with redshift \( z \) compared with instrumental features;
- its intensity should be proportional to dark matter column density \( S_{\text{DM}} = \int \rho_{\text{DM}} dl \); due to different 3D distributions of dark and visible matter, comparison of line intensity within a given object and among different objects allows to choose between decaying dark matter and astrophysical origin of the line;
- it is broadened with characteristic velocity of dark matter usually different from that of visible matter.

The above properties allow to reliably establish that the line comes from decaying dark matter. In other words, we can directly detect radiatively decaying dark matter relying on astrophysical measurements.

The search for decaying dark matter in X-rays lasts for about a decade starting from pioneering proposals in [10, 11]. The searches prior to February 2014 are summarized in Table I of [12]; the only exception is

1Viable alternatives include modified laws of gravity and/or Newtonian dynamics (see e.g. [3–6]), primordial black holes (see e.g. [7, 8]) etc.

2A widely-known examples where this is not the case are dark matter particles holding a new quantum number conserved by Standard Model interactions, such as R-parity for supersymmetric models, Kaluza-Klein number for extra dimensions, etc. In this case, dark matter decays are exactly forbidden by special structure of the theory, and the main astrophysical effect for such dark matter candidates is annihilation of dark matter particles with their antiparticles.

3Dark matter column densities for different dark matter-dominated objects are compiled in [9].
recent study of [13]. These searches have not revealed the presence of viable candidate lines from decaying dark matter and obtained only upper bounds on radiative decay lifetime of dark matter particles. The only exception is the claim of [14] about the excess of Fe XXVI Lyman-γ line at 8.7 keV in Suzaku spectrum of Galactic Center [15] compared with the standard ionization and recombination processes. Existing X-ray telescopes do not allow to reach any reliable conclusion about the nature of this excess, so the claim of [14] should be tested with new instruments having better spectral resolution, discussed in e.g. [16].

**OBSERVATIONAL STATUS OF ∼3.5 keV LINE**

In February 2014, the situation has changed dramatically: two groups [1, 2] have claimed the presence of an extra line at ∼3.5 keV. Stacking X-ray spectra of central parts of 81 galaxy clusters (observed by XMM-Newton and Chandra) in emitter’s rest frame allowed [1] to reach unprecedented sensitivity, compared to previous line searches in galaxy clusters. As a result, new line has been detected in independent subsets – Perseus galaxy cluster, the sum of three nearby galaxy clusters (Coma, Centaurus and Ophiuchus), and the rest of galaxy clusters of their sample. On the other hand, [2] presented analysis of several independent datasets – the nearby Andromeda galaxy, outskirts of the Perseus cluster and the new blank-sky dataset – observed by XMM-Newton, and claimed the detection of new line in Perseus outskirts (using set of observations completely different from that of [1]). After that, the same group [19] has presented another evidence for extra line at ∼3.5 keV by looking at the central part of our Galaxy. Other recent study [22] detected the 3.5 keV line in the central part of the Perseus cluster observed by Suzaku. These studies have been accompanied by claims of several other groups [17, 18, 20, 21] that have not detected the extra line at ∼3.5 keV in several different datasets of dark matter objects. Basic properties of all these datasets are summarized in Table 1.

**POSSIBLE EXPLANATIONS**

The following possibilities for the origin of new line have been considered:

1. The possibility that new line is not from astrophysical emission has first been studied in pioneering papers [1, 2]. Using detailed computations of line intensities in thermal plasma hosted by galaxy clusters based on atomic line database ATOMDB v.2.0.2 [24, 1] argued that possible contributions from astrophysical lines near 3.5 keV are factor > 30 smaller than the detected flux of the extra line. In addition, [2] showed that the angular distribution of ∼ 3.5 keV line in Perseus galaxy outskirts is much better consistent with decaying dark matter distribution than that with astrophysical emission.

But, these conclusions of [1, 2] were questioned in [18], in which the authors argue that a) it is possible to explain new line in central part of our Galaxy and in combined dataset of [1] with contribution of K XVIII and Cl XVII line[3] and b) extra line from M31 center seen by [3] can be lowered to <90% confidence by adjusting X-ray continuum over small energy range near the line (3-4 keV).

The criticism of [18] have stimulated the immediate comment of [23]. Here, claim b) of [18] is repudiated by showing that both the X-ray continuum of [18] selected at 3-4 keV is significantly overestimated at larger energies, and that the extra line flux is at least an order of magnitude less than expected from astrophysical lines near 3.5 keV. The other concern a) of [18] has recently been commented in [26] showing that the analysis of [18] suffers from their use of the approximate atomic data from ATOMDB [25] website. In contrast, full version of ATOMDB used by [1, 18, 23] leads to significant lack of astrophysical emission to explain observed line at ∼3.5 keV in combined dataset of galaxy clusters of [1]. These comments, in turn, have been replied in [24]. By using larger energy range proposed by [2, 19, 24] recovered the initial result of [2] about the 3.5 keV line significance; however, unlike [2, 27] obtained much more significant line-like negative residual below 3 keV. The origin of this discrepancy is to be found. A probable reason is the slope of instrumental component seen in Fig. 2 of [27] from its fiducial value $E^{-0.2}$, see e.g. [28], which can, due to ∼ 5% dip in effective area (see e.g. Fig. 1 of [21]), mimic such a large negative residual. On the other hand, by

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[3] Also analyzed Suzaku observations of Coma, Ophiuchus and Virgo galaxy clusters. In fact, the faint extra line at ∼3.45 keV (rest-frame) was found in Coma and Ophiuchus spectra, see their Fig. 3. Because the position of this extra line coincides with other detections within Suzaku energy resolution (≃ 150 eV), we included the detections in Coma and Ophiuchus into Table 1. Taking into account this fact and the level actual uncertainty between X-ray and weak lensing modeling at virial radius [24], the results of [22] are consistent with decaying dark matter hypothesis.

[4] The fact that emission near 3.5 keV from Galactic Center region is consistent with adding K XVIII lines at 3.47 and 3.51 keV was first mentioned in [17]. [2] also mentioned that fact and showed that using Galactic Center data alone it was not possible to neither claim the existence an unidentified spectral line on top of the element lines, nor constrain it.
### Table 1: Properties of ~3.5 keV line searched in different X-ray datasets observed by MOS and PN cameras on-board XMM-Newton observatory, ACIS instrument on-board Chandra observatory and XIS instrument on-board Suzaku observatory. All error bars are at 1σ (68%) level.

| Ref. | Object | Redshift | Instrument | Exposure, Msec | Line position, keV | Line flux, 10^{-6} ph/sec/cm^2 |
|------|--------|----------|------------|----------------|-------------------|-------------------------------|
| 1    | Full stacked sample | 0.009-0.354 | MOS | 6 | 3.57±0.02 | 4.0±0.8 |
| 2    | Full stacked sample | 0.009-0.354 | PN | 2 | 3.51±0.03 | 3.9^{+0.6}_{-1.0} |
| 3    | Coma+Centaurus+Ophiuchus | 0.009-0.028 | MOS | 0.5 | 3.57 | 15.9^{+3.4}_{-3.8} |
| 4    | Coma+Centaurus+Ophiuchus | 0.009-0.028 | PN | 0.2 | 3.57 | < 9.5 (90%) |
| 5    | Perseus (< 12') | 0.016 | MOS | 0.3 | 3.57 | 52.0^{+24.1}_{-15.2} |
| 6    | Perseus (< 12') | 0.016 | PN | 0.05 | 3.57 | < 17.7 (90%) |
| 7    | Perseus (1-12') | 0.016 | MOS | 0.3 | 3.57 | 21.4^{+7.0}_{-6.3} |
| 8    | Perseus (1-12') | 0.016 | PN | 0.05 | 3.57 | < 16.1 (90%) |
| 9    | Rest of the clusters | 0.012-0.354 | MOS | 4.9 | 3.57 | 2.1^{+0.4}_{-0.5} |
| 10   | Rest of the clusters | 0.012-0.354 | PN | 1.8 | 3.57 | 2.0^{+0.3}_{-0.5} |
| 11   | Perseus (> 1') | 0.016 | ACIS-S | 0.9 | 3.56±0.02 | 10.2^{+3.7}_{-3.3} |
| 12   | Perseus (< 9') | 0.016 | ACIS-I | 0.5 | 3.56 | 18.6^{+8.0}_{-8.0} |
| 13   | Virgo (< 500') | 0.003-0.004 | ACIS-I | 0.5 | 3.56 | < 9.1 (90%) |
| 14   | M31 (< 14') | -0.001 | MOS | 0.5 | 3.53±0.03 | 4.9^{+1.3}_{-1.3} |
| 15   | M31 (10-80') | -0.001 | MOS | 0.7 | 3.50-3.56 | < 1.8 (2σ) |
| 16   | Perseus (23-102') | 0.0179 | MOS | 0.3 | 3.50±0.04 | 7.0±2.6 |
| 17   | Perseus (23-102') | 0.0179 | PN | 0.2 | 3.46±0.04 | 9.2±3.1 |
| 18   | Perseus, 1st bin (23-37') | 0.0179 | MOS | 0.2 | 3.50 | 13.8±3.3 |
| 19   | Perseus, 2nd bin (42-54') | 0.0179 | MOS | 0.1 | 3.50 | 8.3±3.4 |
| 20   | Perseus, 3rd bin (68-102') | 0.0179 | MOS | 0.03 | 3.50 | 4.6±4.6 |
| 21   | Blank-sky | — | MOS | 7.8 | 3.45-3.58 | < 0.7 (2σ) |
| 22   | Galactic center (2.5-12') | 0.0 | ACIS-I | 0.8 | ≥ 3.5 | < 25 (2σ) |
| 23   | Galactic center (0.3-15') | 0.0 | MOS | 0.7 | ≥ 3.5 | < 41 |
| 24   | Galactic center (0.3-15') | 0.0 | PN | 0.5 | ≥ 3.5 | < 32 |
| 25   | M31 | 0.0 | MOS | 0.5 | 3.53±0.07 | 2.1±1.5^c |
| 26   | Galactic center (< 14') | 0.0 | MOS | 0.7 | 3.539±0.011 | 29±5 |
| 27   | Combined dSphs | 0.0 | MOS+PN | 0.4±0.2 | 3.55 | < 0.254 (90%) |
| 28   | Combined galaxies (≥ 0.01R_{vir}) | 0.0 | MOS | 14.6 | ≥ 3.5 | unknown^d |
| 29   | Combined galaxies (≥ 0.01R_{vir}) | 0.0 | ACIS-I | 15.0 | ≥ 3.5 | unknown^d |
| 30   | Perseus core (< 6') | 0.0179 | XIS | 0.74 | 3.510^{+0.023}_{-0.008} | 32.5^{+3.7}_{-4.3} |
| 31   | Perseus confined (6-12.7') | 0.0179 | XIS | 0.74 | 3.510^{+0.023}_{-0.008} | 32.5^{+3.7}_{-4.3} |
| 32   | Coma (< 12.7') | 0.0231 | XIS | 0.164 | ≥ 3.45 | ≥ 30^c |
| 33   | Ophiuchus (< 12.7') | 0.0280 | XIS | 0.083 | ≥ 3.45 | ≥ 40^c |
| 34   | Virgo (< 12.7') | 0.0036 | XIS | 0.09 | 3.55 | < 6.5 (2σ) |

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^a Line position was fixed at given value.

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

^c The line was detected at < 90% confidence level. Such a low flux (compared with [2]) was due to unphysically enhanced level of continuum at 3-4 keV band used in [18], see [23] for details.

^d [23] only quoted the “minimal probed values” of sterile neutrino mixing angle sin^2(2θ) ≲ 2 × 10^{-11} by XMM-Newton/MOS and ≲ 5 × 10^{-11} by Chandra/ACIS-I. For XMM-Newton dataset with average dark matter column density in field-of-view equal to 100 M⊙/pc^2, these values would correspond to upper bound on ~3.5 keV line flux ~ 3.0 × 10^{-7} and ~ 7.5 × 10^{-7} ph/sec/cm^2, respectively.

^e Parameters estimated from Fig. 3 of [22], see text.
using full ATOMDB version 27 presented an additional argument of the initial claim of 18 based on new Ca XIX/Ca XX line ratios, so more detailed investigation (including e.g. systematic uncertainties on ion emissivities) is required to finally resolve this issue.

An alternative approach is to study the line morphology. In 29, XMM-Newton observations of the central part of the Perseus cluster and the Galactic Center have been analyzed. 29 collected all events (either cosmic or instrumental origin) in narrow energy ranges (roughly corresponding to the energy resolution), and looked for the best-fit approximation with the rescaled continuum obtained from several adjacent line-free bands. The main result of 29 is that adding decaying dark matter distribution from a smooth DM profile (Navarro-Frenk-White, Einasto, Burkert) does not improve the fit quality in both objects. In addition, 29 demonstrated 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, 29 claimed the exclusion of decaying dark matter origin of 3.5 keV in the Galactic Center and the Perseus cluster.

2. Linear scaling of line position with the redshift observed by 1, 2 is an important argument against the instrumental origin of ∼ 3.5 keV line. The fact that this line has not been found in long blank-sky dataset of 2 provides additional evidence against its instrumental origin.

3. The authors of 1, 2, 19 argue that all basic properties of detected ∼ 3.5 keV line – its position, line strength, scaling with redshift, angular distribution inside extended objects (Perseus cluster outskirts, center vs off-center of Andromeda galaxy, Galactic Center vs blank-sky dataset), scaling among different objects, and even its non-observation in some datasets of 1, 2 – are all consistent with an explanation in terms of radiatively decaying dark matter line.

The predictive power of the decaying dark matter scenario motivated several groups of researchers 17, 18, 20, 22, 29 to study X-ray spectra of different dark matter-dominated objects. Their studies are summarized in Table 1. At the moment, no further confirmation of decaying dark matter origin after the papers 1, 2, 19 has been presented. While 17, 18, 22, 29 found a line at ∼ 3.5 keV (though interpreted it as a sum of astrophysical lines), 20 and 21 have not detected the line in combined datasets of dwarf spheroidal galaxies (dSphs) and spiral galaxies, respectively, placing only upper bounds on dark matter lifetime. Non-detection of the line at 3.5 keV by 20 is still consistent with decaying dark matter hypothesis; to rule it out, even quoting 21, one needs to increase the sensitivity by a factor ∼ 2 (which means a factor ∼ 4 increase of exposure assuming similar dark matter column density). On the other hand, non-observation of ∼ 3.5 keV line in the dataset of 21 (see their Fig. 4) may be interpreted as a tension with decaying dark matter hypothesis and therefore motivates more detailed study. According to 31, where combined dataset of galaxies with comparable exposure has been analyzed, at exposures larger than ∼ 10 Msec line-like systematic errors start to dominate over statistical errors. As a result, usual method of determination of continuum level (by simply minimizing χ², as 21 did) is no longer appropriate. Previous studies of line in M31 center 2, 18, 23 shows that precise determination of continuum level is important to quantify the intensity of 3.5 keV line. Therefore, the only way to put robust exclusions to line intensity is to perform continuum modeling in a way similar to 31: to decrease level of continuum below the best-fit to ensure absence of significant negative residuals, and to add systematic errors to account non-Gaussian distribution of positive residuals. According to Fig. 5.26 of 31, such analysis would produce 3σ upper bounds for 3.5 keV line flux close to ∼ 1.5 × 10⁻⁶ ph/sec/cm² per XMM-Newton field-of-view, still consistent with line observation in M31 center.

Although the results of 1, 2 are formulated for a specific dark matter candidate – right-handed (sterile) neutrinos (see 16, 32 for recent reviews), they can be applied for any type of radiatively decaying dark matter, see e.g. 33, 74. The difference among these models can be further probed by:

1. changes in line morphology due to non-negligible initial dark matter velocities, see e.g. 75, 76;
2. other astrophysical tests such as Ly-α method, see e.g. 35, 77, 78;
3. search of “smoking gun” signatures in accelerator experiments, see e.g. 73 for the minimal neutrino extension of the Standard Model, νMSM 32, 80, 81.

4. Recently proposed alternatives to radiatively decaying dark matter currently include decay of excited dark matter states 82, annihilating dark matter 42, 61, 89, dark matter decaying into axion-like particles with further conversion to photons in magnetic field 91, 93. These models predict substantial difference in ∼ 3.5 keV line morphology compared to the radiatively decaying dark matter. For example, their line profiles should be more concentrated towards the centers of dark matter-dominated objects due to larger dark matter

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*Given large uncertainties in dark matter modeling, the obtained bounds are usually (see e.g. 16, 32) diluted by an extra factor of 2, contrary to 20.
density (for exciting and annihilating dark matter) and larger magnetic fields (for magnetic field conversion of axion-like particles). Further non-observation of the $\sim 3.5$ keV line in outskirts of dark matter-dominated objects would therefore an agrument in favour of these models.

CONCLUSIONS AND FUTURE DIRECTIONS

New emission line at $\sim 3.5$ keV in spectra of galaxy clusters and central parts of Andromeda galaxy recently reported by [1, 2] remains unexplained in terms of astrophysical emission lines or instrumental features (see however recent works [27, 29]). Its properties 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 detection of new emission line in other objects would lead to direct detection of new physics. Specially dedicated observations by existing X-ray missions (such as XMM-Newton, Chandra, Suzaku) still allow such detection (see e.g. [3]) 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 $^7$ – have first formulated in [96]. The imaging spectrometer on-board new X-ray mission Astro-H [97] scheduled to launch in 2015 meets only second requirement having energy resolution by an order of magnitude better ($\sim 5$ eV) compared to existing instruments. This will allow Astro-H to precisely determine the line position in brightest objects with prolonged observations (according to [1], a 1 Msec observation of the Perseus cluster is required) and thus Astro-H will finally close the question whether the new line is from new physics or from (anomalously enhanced) astrophysical emission. Other interesting possibility is proposed in [2]: one should see decaying dark matter signal from the Milky Way halo in every Astro-H observation, therefore their compination could also reveal the radiatively decaying dark matter nature of new line. Another possibility is to use planned LOFT mission [88] which high grasp and moderate energy resolution would allow to detect new line at much smaller intensities [12]. Finally, an “ultimate” imaging spectrometer proposed in e.g. [16] would reveal the detailed structure of $\sim 3.5$ keV line.

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$^7$ Grating spectrometers such as Chandra/HETGS have excellent spectral resolution for point sources; however, for extended ($\gtrsim 1$ arcmin) sources their spectral resolution usually degrades to that for existing imaging spectrometers, see e.g. [93].
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