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New emission line at ∼3.5 keV — observational status, connection with radiatively decaying dark matter and directions for future studies

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Recent works of Bulbul et al. (2014) and Boyarsky et al. (2014), claiming the detection of the extra emission line with energy ∼3.5 keV in X-ray spectra of certain clusters of galaxies and nearby Andromeda galaxy, have raised a 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 summarise 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 the known elementary particles constitute the bulk of dark matter. Despite this fact, the most plausible[1] hypothesis is that dark matter made of elementary particles, which implies the extension of the Standard Model of particle physics and is of considerable interest for particle physicists.

Dozens of Standard Model extensions proposed so far range according to their 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[2] through emitting a photon. For a 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 the dark matter particle and the redshift of the dark matter halo (i. e. if one neglects the mass of other decay product, the line position is $\frac{m_{\rm DM}c^2}{2(1+z)}$), having different scaling with redshift z compared with instrumental features;
- Its intensity should be proportional to dark matter column density[3] $\mathcal{S}_{\rm DM} = \int \rho_{\rm DM} d\ell$; 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 solely on astrophysical measurements.

The search for decaying dark matter in X-rays lasts for approximately one decade, starting from pioneering proposals in [2, 43]. The searches prior to February 2014 are summarised in Table I of [82]; the only exception is a recent study of [57]. These

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[1] Viable alternative theories include modified laws of gravity and/or Newtonian dynamics (see e.g. [12, 48, 77, 78]), primordial black holes (see e.g. [26, 28]) etc.

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

[3] Dark matter column densities for different dark matter-dominated objects are compiled in [22].

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 [88] about the excess of FeXXVI Lyγ line at 8.7 keV in Suzaku spectrum of Galactic Center [67] compared with the standard ionization and recombination processes. Results of existing X-ray telescope observations are inconclusive with regards to the nature of this excess, so the claim of [88] should be tested with new instruments having better spectral resolution, discussed in e. g. [19].

OBSERVATIONAL STATUS OF ~3.5 KEV LINE

In February 2014, the situation changed dramatically: two groups [21, 24] 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 enabled [24] to reach unprecedented sensitivity, as compared with previous line searches in galaxy clusters. As a result, a 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, [21] 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 [24]). Following this, the same group [17] has presented another evidence for extra line at ~3.5 keV by looking at the central part of our Galaxy. Another recent study [96] detected the 3.5 keV line in the central part of the Perseus cluster[4] observed by Suzaku. These studies have been accompanied by claims of several other groups [6, 63, 75, 90] which have not detected the extra line at ~3.5 keV in several different datasets of dark matter objects. Basic properties of all of these datasets are summarised in Table 1.

POSSIBLE EXPLANATIONS

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

(1) The possibility that the new line is *not* from astrophysical emission has first been studied in pioneering papers [21, 24]. Using detailed computations of line intensities in thermal plasma hosted by galaxy clusters based on atomic line database ATOMDB v.2.0.2 [51], [24] argued that possible contributions from astrophysical lines near 3.5 keV are a factor $\gtrsim 30$ smaller than the detected flux of the extra line. In addition, [21] showed that the angular distribution of ~ 3.5 keV line in the Perseus galaxy outskirts is much more consistent with decaying dark matter distribution than with astrophysical emission.

However, these conclusions of [21, 24] were questioned in [63], in which the authors argue that (a) it is possible to explain the new line in the central part of our Galaxy and in combined dataset of [24] by the contribution of KXVIII and ClXVII lines[5], and (b) the extra line from M31 centre seen by [21] can be lowered to <90% confidence by adjusting the X-ray continuum over a narrow energy range near the line (3–4 keV).

The criticism of [63] has stimulated the immediate comment of [18]. Here, claim (b) of [63] is repudiated by showing both that the X-ray continuum of [63] 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 [63] has recently been commented in [25] showing that the analysis of [63] suffers from their use of the approximate atomic data from ATOMDB [51] website. In contrast, the full version of ATOMDB used by [17, 18, 24] leads to a significant lack of astrophysical emission to explain the observed line at ~ 3.5 keV in the combined dataset of galaxy clusters of [24]. These comments, in turn, have been replied to in [62]. By using a wider energy range proposed by [17, 21], [62] reproduced the initial result of [21] with regards to the prominence of the 3.5 keV line; however, unlike [21], [62] obtained a much more prominent line-like negative residual below 3 keV. The origin of this discrepancy remains unsolved. A probable reason is the slope of the instrumental component seen in Fig. 2 of [62] from its fiducial value $E^{-0.2}$, see e. g. [73], which can, due to ~ 5% dip in the effective area (see e. g. Fig. 1 of [62]), mimic such a large negative residual. On the other hand, the use of the full ATOMDB version [62] presented an additional argument of the initial claim of [63] based on new CaXIX/CaXX line ratios, so a 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 mor-

[4][96] also analysed 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 line coincides with other detections within Suzaku energy resolution ($\simeq$ 150 eV), we included the detections in Coma and Ophiuchus into Table 1. Taking into account this fact and the level of actual uncertainty between X-ray and weak lensing modelling at a virial radius [83], the results of [96] are consistent with the decaying dark matter hypothesis.

[5]The fact that emission near 3.5 keV from Galactic Centre region is consistent with adding KXVIII lines at 3.47 and 3.51 keV was first mentioned in [90]. [21] also mentioned that fact and showed that using Galactic Centre data alone it was not possible to neither claim the existence an unidentified spectral line on top of the element lines, nor constrain it.

phology. In [27], XMM-Newton observations of the central part of the Perseus cluster and the Galactic Centre have been analysed. [27] 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 [27] 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, [27] demonstrated that the 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 of line-free energy bands. Based on these findings, [27] claimed the exclusion of decaying dark matter origin of 3.5 keV in the Galactic Centre and the Perseus cluster.

(2) Linear scaling of line position with the redshift observed by [21, 24] is an important argument against the instrumental origin of $\sim$ 3.5 keV line. The fact that this line has not been found in the long blank-sky dataset of [21] provides additional evidence against its instrumental origin.

(3) The authors of [17, 21, 24] argue that all basic properties of the detected $\sim$ 3.5 keV line — its position, line strength, scaling with redshift, angular distribution inside extended objects (Perseus cluster outskirts, centre vs. off-centre of Andromeda galaxy, Galactic Centre vs. blank-sky dataset), scaling among different objects, and even its non-observation in some datasets of [21, 24] — are all consistent with an explanation in terms of a radiatively decaying dark matter line.

The predictive power of the decaying dark matter scenario motivated several groups of researchers [6, 27, 63, 75, 90, 96] to study X-ray spectra of various dark matter-dominated objects. Their studies are summarised in Table 1. At the moment, no further confirmation of decaying dark matter origin after the papers [17, 21, 24] has been presented. While [27, 63, 90, 96] found a line at $\sim$ 3.5 keV (though interpreted it as a sum of astrophysical lines), [75] and [6] 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 3.55 keV by [75] is still consistent with decaying dark matter hypothesis; to rule it out, even quoting [75][6], 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 the $\sim$ 3.5 keV line in the dataset of [6] (see their Fig. 4) may be interpreted as a tension with decaying dark matter hypothesis and therefore motivates more detailed study. According to [58], where combined dataset of galaxies with comparable exposure has been analysed, at exposures larger than $\sim$ 10 Msec line-like systematic errors start to dominate over statistical errors. As a result, the usual method of determination of continuum level (by simply minimizing χ^2, as [6] did) is no longer appropriate. Previous studies of line in M31 centre [18, 21, 63] show that precise determination of the 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 modelling in a way similar to [58]: to decrease the level of continuum below the best-fit in order 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 [58], such analysis would produce 3σ upper bounds for 3.5 keV line flux close to $\sim 1.5\times10^{-6}$ ph/sec/cm^2 per XMM-Newton field-of-view, still consistent with line observation in M31 centre [21].

Although the results of [21, 24] are formulated for a specific dark matter candidate — right-handed (sterile) neutrinos (see [23, 19] for recent reviews), they can be applied for any type of radiatively decaying dark matter, see e.g. [1, 3, 4, 9, 10, 11, 14, 29, 30, 31, 32, 39, 40, 42, 45, 46, 47, 49, 52, 53, 54, 55, 56, 59, 60, 61, 64, 65, 66, 68, 69, 70, 79, 80, 81, 84, 87, 86, 89, 91, 92, 94]. The difference among these models can be further probed by:

- Changes in line morphology due to non-negligible initial dark matter velocities, see e. g. [72, 74];
- Other astrophysical tests such as Ly_α method, see e. g. [3, 76, 97];
- Search of "smoking gun" signatures in accelerator experiments, see e. g. [15] for the minimal neutrino extension of the Standard Model, νMSM [7, 8, 23].

(4) Recently proposed alternatives to radiatively decaying dark matter currently include decay of excited dark matter states [13, 34, 35, 36, 50, 85, 93], annihilating dark matter [10, 44, 52], dark matter decaying into axion-like particles with further conversion to photons in magnetic field [5, 33, 37, 38]. These models predict substantial difference in the $\sim$ 3.5 keV line morphology, compared with the radiatively decaying dark matter. For example, their line profiles should be more concentrated towards the centres of dark matter-dominated objects due to larger dark matter 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 argument in favour of these models.

[6] Given large uncertainties in dark matter modelling, the obtained bounds are usually (see e. g. [19, 20]) diluted by an extra factor of 2, contrary to [75].

CONCLUSIONS AND FUTURE DIRECTIONS

A new emission line at $\sim$3.5 keV in spectra of galaxy clusters and central parts of the Andromeda galaxy recently reported by [21, 24] remains unexplained in terms of astrophysical emission lines or instrumental features (see however recent works [27, 62]). 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 the case of radiatively decaying dark matter, further detection of the 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. [71]) although one should take detailed care on various systematic effects that could mimic or hide the new line.

The alternative is to use newer 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 been formulated in [16]. The imaging spectrometer on-board the new X-ray mission Astro-H [95] scheduled to launch in 2015 meets only the second requirement, having an energy resolution of an order of magnitude better ($\sim$ 5 eV) compared with that of existing instruments. This will allow Astro-H to precisely determine the line position in the brightest objects, with prolonged observations (according to [24], 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. Another interesting possibility is proposed in [21]: one should see the decaying dark matter signal in the Milky Way halo in every Astro-H observation, therefore their combination could also reveal the radiatively decaying dark matter nature of new line. Yet another possibility is to use the planned LOFT mission [98] whose high grasp and moderate energy resolution would enable to detect the new line at much smaller intensities [82]. Finally, an "ultimate" imaging spectrometer proposed in e. g. [19] would reveal the detailed structure of $\sim$3.5 keV line.

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Ref.	Object	Redshift	Instrument	Exposure, Msec	Line position, keV	Line flux, 10^{-6} ph/sec/cm^2
[24]	Full stacked sample	0.009-0.354	MOS	6	3.57±0.02	4.0±0.8
[24]	Full stacked sample	0.009-0.354	PN	2	3.51±0.03	$3.9^{+0.6}_{-1.0}$
[24]	Coma+Centaurus+Ophiuchus	0.009-0.028	MOS	0.5	3.57^a	$15.9^{+3.4}_{-3.8}$
[24]	Coma+Centaurus+Ophiuchus	0.009-0.028	PN	0.2	3.57^a	< 9.5 (90%)
[24]	Perseus (< 12')	0.016	MOS	0.3	3.57^a	$52.0^{+24.1}_{-15.2}$
[24]	Perseus (< 12')	0.016	PN	0.05	3.57^a	< 17.7 (90%)
[24]	Perseus (1-12')	0.016	MOS	0.3	3.57^a	$21.4^{+7.0}_{-6.3}$
[24]	Perseus (1-12')	0.016	PN	0.05	3.57^a	< 16.1 (90%)
[24]	Rest of the clusters	0.012-0.354	MOS	4.9	3.57^a	$2.1^{+0.4}_{-0.5}$
[24]	Rest of the clusters	0.012-0.354	PN	1.8	3.57^a	$2.0^{+0.3}_{-0.5}$
[24]	Perseus (> 1')	0.016	ACIS-S	0.9	3.56±0.02	$10.2^{+3.7}_{-3.5}$
[24]	Perseus (< 9')	0.016	ACIS-I	0.5	3.56^a	$18.6^{+7.8}_{-8.0}$
[24]	Virgo (< 500")	0.003-0.004	ACIS-I	0.5	3.56^a	< 9.1 (90%)
[21]	M31 (< 14')	-0.001^b	MOS	0.5	3.53±0.03	$4.9^{+1.6}_{-1.3}$
[21]	M31 (10-80')	-0.001^b	MOS	0.7	3.50-3.56	< 1.8 (2σ)
[21]	Perseus (23-102')	0.0179^b	MOS	0.3	3.50±0.04	7.0±2.6
[21]	Perseus (23-102')	0.0179^b	PN	0.2	3.46±0.04	9.2±3.1
[21]	Perseus, 1st bin (23-37')	0.0179^b	MOS	0.2	3.50^a	13.8±3.3
[21]	Perseus, 2nd bin (42-54')	0.0179^b	MOS	0.1	3.50^a	8.3±3.4
[21]	Perseus, 3rd bin (68-102')	0.0179^b	MOS	0.03	3.50^a	4.6±4.6
[21]	Blank-sky	—	MOS	7.8	3.45-3.58	< 0.7 (2σ)
[90]	Galactic center (2.5-12')	0.0	ACIS-I	0.8	$\simeq 3.5$	$\lesssim 25$ (2σ)
[63]	Galactic center (0.3-15')	0.0	MOS	0.7	$\simeq 3.5$	< 41
[63]	Galactic center (0.3-15')	0.0	PN	0.5	$\simeq 3.5$	< 32
[63]	M31	0.0	MOS	0.5	3.53±0.07	2.1 ± 1.5^c
[17]	Galactic center (< 14')	0.0	MOS	0.7	3.539±0.011	29±5
[75]	Combined dSphs	0.0	MOS+PN	0.4+0.2	3.55^a	< 0.254 (90%)
[6]	Combined galaxies ($\gtrsim 0.01 R_{vir}$)	0.0	MOS	14.6	$\simeq 3.5$	unknown^d
[6]	Combined galaxies ($\gtrsim 0.01 R_{vir}$)	0.0	ACIS-I	15.0	$\simeq 3.5$	unknown^d
[96]	Perseus core (< 6')	0.0179^b	XIS	0.74	$3.510^{+0.023}_{-0.008}$	$32.5^{+3.7}_{-4.3}$
[96]	Perseus confined (6-12.7')	0.0179^b	XIS	0.74	$3.510^{+0.023}_{-0.008}$	$32.5^{+3.7}_{-4.3}$
[96]	Coma (< 12.7')	0.0231^b	XIS	0.164	$\simeq 3.45^e$	$\simeq 30^e$
[96]	Ophiuchus (< 12.7')	0.0280^b	XIS	0.083	$\simeq 3.45^e$	$\simeq 40^e$
[96]	Virgo (< 12.7')	0.0036^b	XIS	0.09	3.55^a	< 6.5 (2σ)

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.

^{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 [21]) was due to unphysically enhanced level of continuum at 3-4 keV band used in [63], see [18] for details.

^{d} [6] only qouted the "minimal probed values" of sterile neutrino mixing angle $\sin^2(2\theta) \lesssim 2\times10^{-11}$ by XMM-Newton/MOS and $\lesssim 5\times10^{-11}$ by Chandra/ACIS-I. For XMM-Newton dataset with average dark matter column density in field-of-view equal to 100 $M_\odot/\mathrm{pc}^2$, these values would correspond to upper bound on ∼3.5 keV line flux $\sim 3.0\times10^{-7}$ and $\sim 7.5\times10^{-7}$ ph/sec/cm^2, respectively.

^{e} Parameters estimated from Fig. 3 of [96], see text.