Status of the 3.5 keV Line

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Dark Matter in X-rays?

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DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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ABSTRACT

We detect a weak unidentified emission line at $E = (3.55-3.57) \pm 0.03$ keV in a stacked *XMM-Newton* spectrum of 73 galaxy clusters spanning a redshift range 0.01 – 0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum.

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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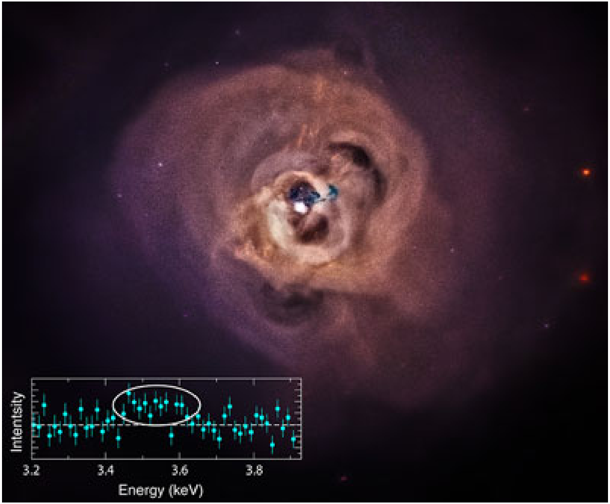
We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters.

1402.2301, 1402.4119

Dark Matter in X-rays?



Dark Matter in X-rays?

Various models of dark matter can lead to monochromatic emission lines in the X-ray regime.

Original claim (Bulbul et al 2014, Boyarsky et al 2014):

New, unidentified emission line found from both individual and stacked samples of galaxy clusters.

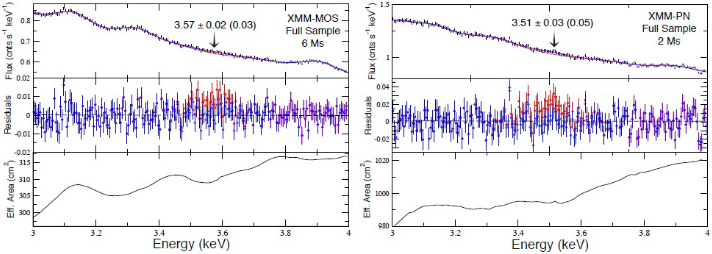
Energy of line is $(3.55 - 3.57) \pm 0.03$ keV.

Line found in stacked sample of 73 clusters, in both centre and outskirts of Perseus cluster, in stacked sample of Coma, Ophiuchus and Centaurus cluster, and in M31.

Dark Matter in X-rays?

Small signal on a large background...requires careful statistics and modelling of background

Line is a 1% effect above the continuum - requires background to be modelled to a similar precision



Dark Matter in X-rays?

Most detailed evidence for signal comes from analyses involving galaxy clusters

- Stacked sample of 73 clusters in Bulbul et al. paper
- Two XMM instruments - MOS and PN
- Individual subsamples of Perseus, Coma+Ophiuchus+Centaurus, All Others
- Perseus reconfirmed with deep Chandra observations, both ACIS-S and ACIS-I
- Boyarsky et al finds line in outskirts of Perseus cluster (XMM-MOS, XMM-PN)
- Line also found in M31 by Boyarsky et al

Significance Counting

Sample	Instrument	Energy	$\Delta\chi^2$	N
Bulbul et al.				
All cluster	XMM-MOS	3.57 ± 0.02	22.8	2
All cluster	XMM-PN	3.51 ± 0.03	13.9	2
Perseus	XMM-MOS	3.57	15.7	1
3 Bright Clusters	XMM-MOS	3.57	17.1	1
Other 69	XMM-MOS	3.57	16.5	1
Other 69	XMM-PN	3.57	15.8	1
Perseus	Chandra ACIS-I	3.56 ± 0.02	11.8	2
Perseus	Chandra ACIS-S	3.56	6.2	1
Boyarsky et al.				
Perseus outskirts	XMM-MOS	3.50 ± 0.04	9.1	2
Perseus outskirts	XMM-PN	3.46 ± 0.04	8.0	2
M31	XMM-MOS	3.53 ± 0.03	13.0	2

Sterile Neutrino?

The canonical new physics explanation....

Sample	Instrument	$\sin^2 2\theta$ $\times 10^{-11}$
Bulbul paper		
All others stacked (69 clusters)	XMM-MOS	$6.0^{+1.1}_{-1.4}$
All others stacked (69 clusters)	XMM-PN	$5.4^{+0.8}_{-1.3}$
Perseus	XMM-MOS	$23.3^{+7.6}_{-8.9}$
Coma + Centaurus + Ophiuchus	XMM-MOS	$18.2^{+4.4}_{-5.9}$
Perseus	Chandra ACIS-I	$28.3^{+11.8}_{-12.1}$
Perseus	Chandra ACIS-S	$40.1^{+14.5}_{-13.7}$

Signal strength appears different between clusters

In particular, signal is stronger for central regions of bright, nearby cool-core clusters

Original Data Evaluation

- (+) Line seen by four instruments (XMM-MOS, XMM-PN, Chandra ACIS-I, Chandra ACIS-S)
- (+) Line seen independently by two separate collaborations
- (+) Line seen from at least five different sources at consistent energy
- (+) Line absent in deep 16Ms blank sky observations

However - need excellent control over backgrounds:

- (-) Signal one percent above continuum
- (-) X-ray atomic lines from hot gas at similar energies
- (-) Detector backgrounds also generate X-ray lines
- (-) Effective area wiggles can mimic signal

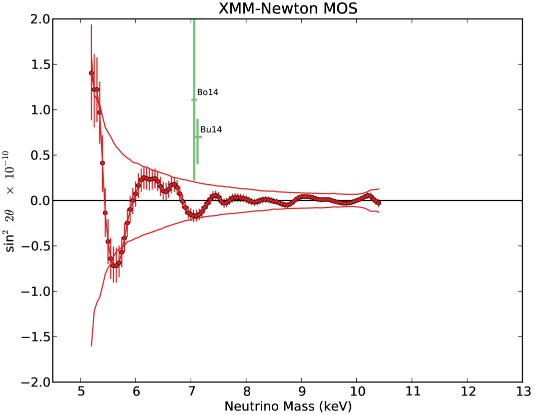
Dark Matter in X-rays?

There have been many subsequent searches for the line in various locations:

- No 3.5 keV line in Chandra data of Milky Way centre (1405.7943)
- 3.5 keV line in XMM-Newton data of Milky Way centre (1408.1699, 1408.2503) - K XVIII or dark matter?
- No line in M31 from 3-4 keV fit, bananas in clusters (1408.1699)
- No 3.5 keV line in dwarf spheroidals, stacked galaxies (1408.3531, 1408.4115)
- Yes line in M31, 3-4 keV fit lacks precision (1408.4388)
- No bananas in clusters - use correct atomic data instead (1409.4143)

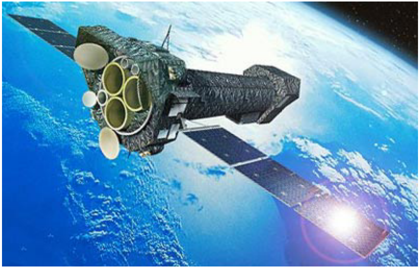
Stacked Galaxies

Anderson et al. stack 16 Ms of XMM-Newton observations of galaxies: no evidence for excess 3.5 keV emission (3 σ deficit) and formal 11σ exclusion



Draco

An ultra-deep 1.3 Ms observation of the Draco dwarf galaxy was carried out in 2015 by XMM-Newton.



No positive evidence for excess emission at $E \sim 3.5\mathrm{keV}$.

Suzaku Observations of Perseus

Three sets of analyses of Suzaku observations of Perseus:

1411.0050 Urban et al:

Strong signal from Perseus core,
$E = (3.51 \pm 0.02)$ keV, $\Delta\chi^2 \sim 60$

Weaker signal from Perseus outskirts,
$E = (3.59 \pm 0.03)$ keV, $\Delta\chi^2 \sim 10$.

1412.1869 Tamura et al:

No excess emission observed

1604.01759 Franse et al:

Strong signal from Perseus,
$E = (3.54 \pm 0.02)$ keV, $\Delta\chi^2 \sim 60$

Astrophysical Explanations I

Possible astrophysical explanation:

Thermal emission from ionised K XVIII ion at 3.51 keV

Possibility analysed extensively in original Bulbul et al paper - they argue that it would require cold gas and unphysically high K abundances.

If K is substantially more abundant than for other elements, then emission from ionised potassium at 3.51 keV could be responsible for the signal.

Astrophysical Explanations II

Possible astrophysical explanation:

Sulphur charge exchange at 3.44 - 3.47 keV - transitions from high n=9,10,11 levels of S to ground state

Charge exchange involves known lines in unfamiliar ratios

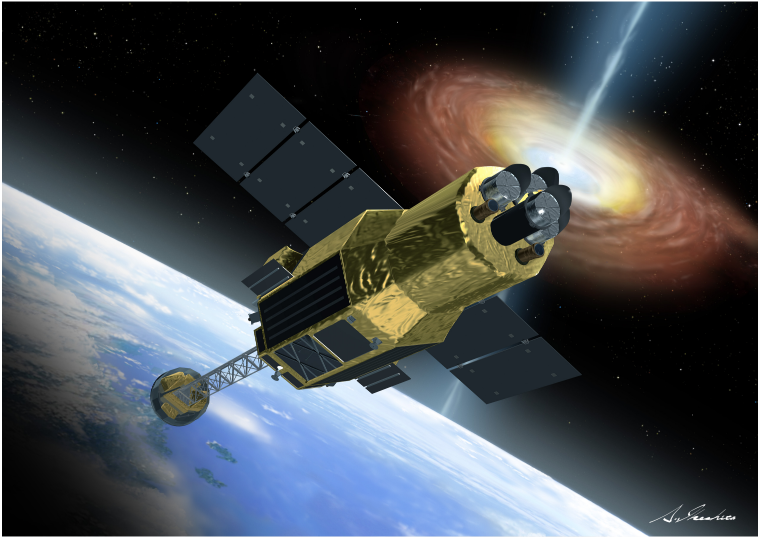
It occurs in interaction of cold neutral gas with hot fully ionised gas.

Electrons are transferred from the cold gas to high-n orbitals of the ionised gas, generating X-ray lines as they transition back to the ground.

Sterile Neutrino?

Sample	Instrument	$\sin^2 2\theta$ $\times 10^{-11}$
All others stacked (69 clusters)	XMM-MOS	$6.0^{+1.1}_{-1.4}$
All others stacked (69 clusters)	XMM-PN	$5.4^{+0.8}_{-1.3}$
Perseus	XMM-MOS	$23.3^{+7.6}_{-8.9}$
Perseus	XMM-PN	< 18 (90 %)
Coma + Centaurus + Ophiuchus	XMM-MOS	$18.2^{+4.4}_{-5.9}$
Coma + Centaurus + Ophiuchus	XMM-PN	< 11(90%)
Perseus	Chandra ACIS-I	$28.3^{+11.8}_{-12.1}$
Perseus	Chandra ACIS-S	$40.1^{+14.5}_{-13.7}$
M31 on-centre	XMM-Newton	2–20
Stacked galaxies	XMM-Newton	< 2.5 (99%)
Stacked galaxies	Chandra	< 5 (99%)
Stacked dwarves	XMM-Newton	< 4 (95%)
Draco	XMM-Newton	$\lesssim 2 - 5$ (95%

The Planned Resolution of the 3.5 KeV Line



The Planned Resolution of the 3.5 KeV Line

Japanese satellite ASTRO-H was launched on February 17th 2016 from Tanegashima Space Centre, and renamed Hitomi after launch launch.

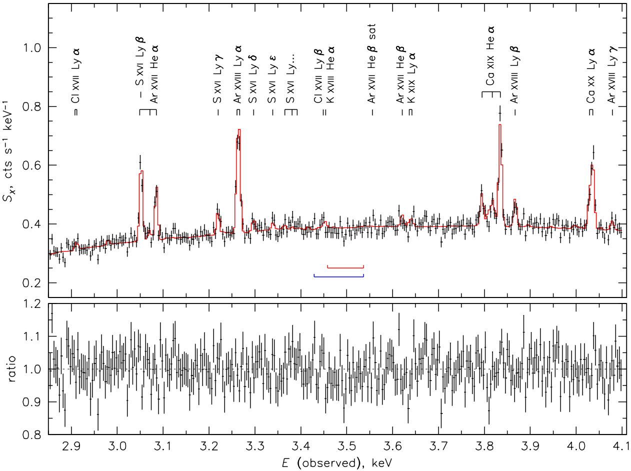
It had unprecendented spectroscopic resolution (7eV compared to 100eV for CCD technology of XMM-Newton, Chandra, Suzaku)

This was expected to determine definitively

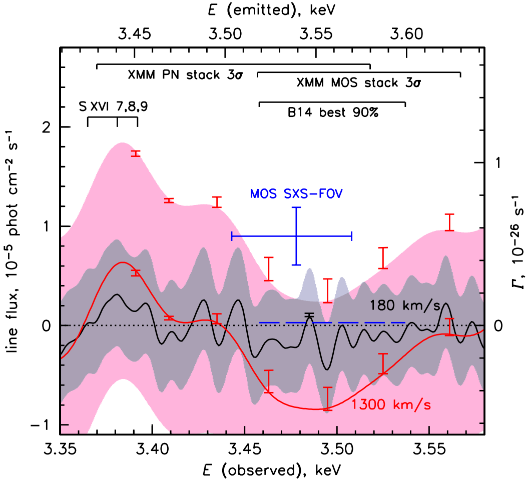
1. Whether the 3.5 keV line exists
2. What the precise energy is
3. Whether the line broadening corresponds to dark matter broadening (1300 km s^{-1} for Perseus) or gas broadening (180 km s^{-1} for Perseus)

Contact was lost on 27th March - after Hitomi returned a ground-breaking spectrum of the Perseus cluster.

Hitomi Spectrum



Hitomi Spectrum II



Hitomi Spectrum

Hitomi data

1. Is incompatible with the strong excess emission at 3.55 keV observed in Perseus with XMM-Newton, Chandra, Suzaku

2. Has a best-fit negative normalisation at 3.55 keV ($\sim 2.5\sigma$ significance)

3. Rules out K emission as the origin of the line in Perseus, as all abundances are sub-solar (thermal emission well fit by `bapec` model with $kT = (3.48 \pm 0.07)\mathrm{keV}$, $Z = 0.54 \pm 0.03$, $\sigma_v = (179 \pm 16)\mathrm{kms}^{-1}$

Summary of Perseus data

XMM-Newton - biggest collecting area

Strong positive line signal from cluster emission - $E = (3.54 \pm 0.04)\mathrm{keV}$ in core.

Chandra - best angular resolution

Strong positive line signal from cluster emission $E = (3.56 \pm 0.02)\mathrm{keV}$ in core.

Suzaku - longest exposure

Strong positive line signal from cluster emission $E = (3.54 \pm 0.02)\mathrm{keV}$ across cluster.

Hitomi - best energy resolution

No excess emission, small deficit at $E = (3.55 \pm 0.03)\mathrm{keV}$ in core.