The 3.5keV line in Perseus:

Evidence for Fluorescent Dark Matter

Nicholas Jennings

with Marcus Berg, Joseph Conlon, Francesca Day, Sven Krippendorf, Markus Rummel

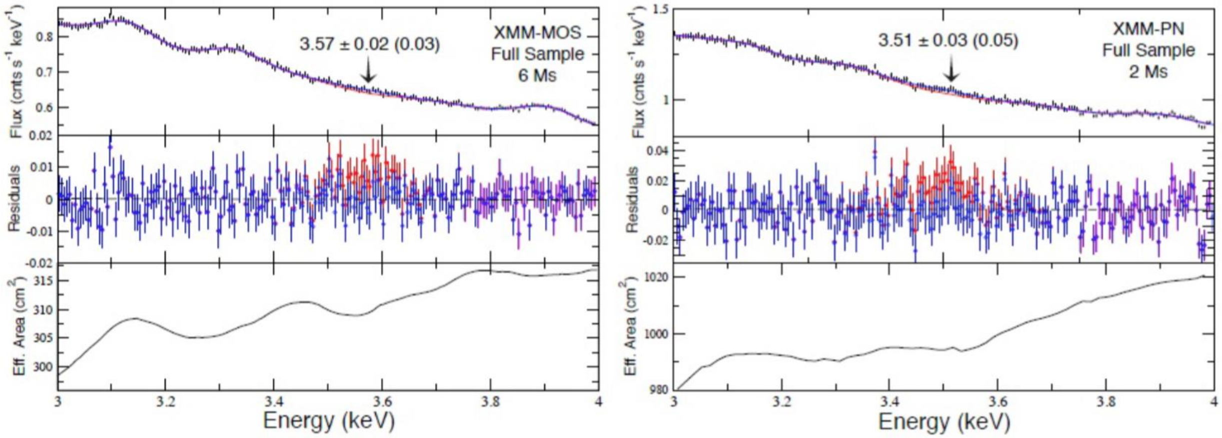
University of Oxford

Dark Matter in X-rays?

(Bulbul 2014, Boyarsky 2014): detection of unidentified emission line at energy (3.55 -3.57) ± 0.03 keV.

Seen in stacked sample of 73 clusters, M31, and Perseus cluster.

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



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

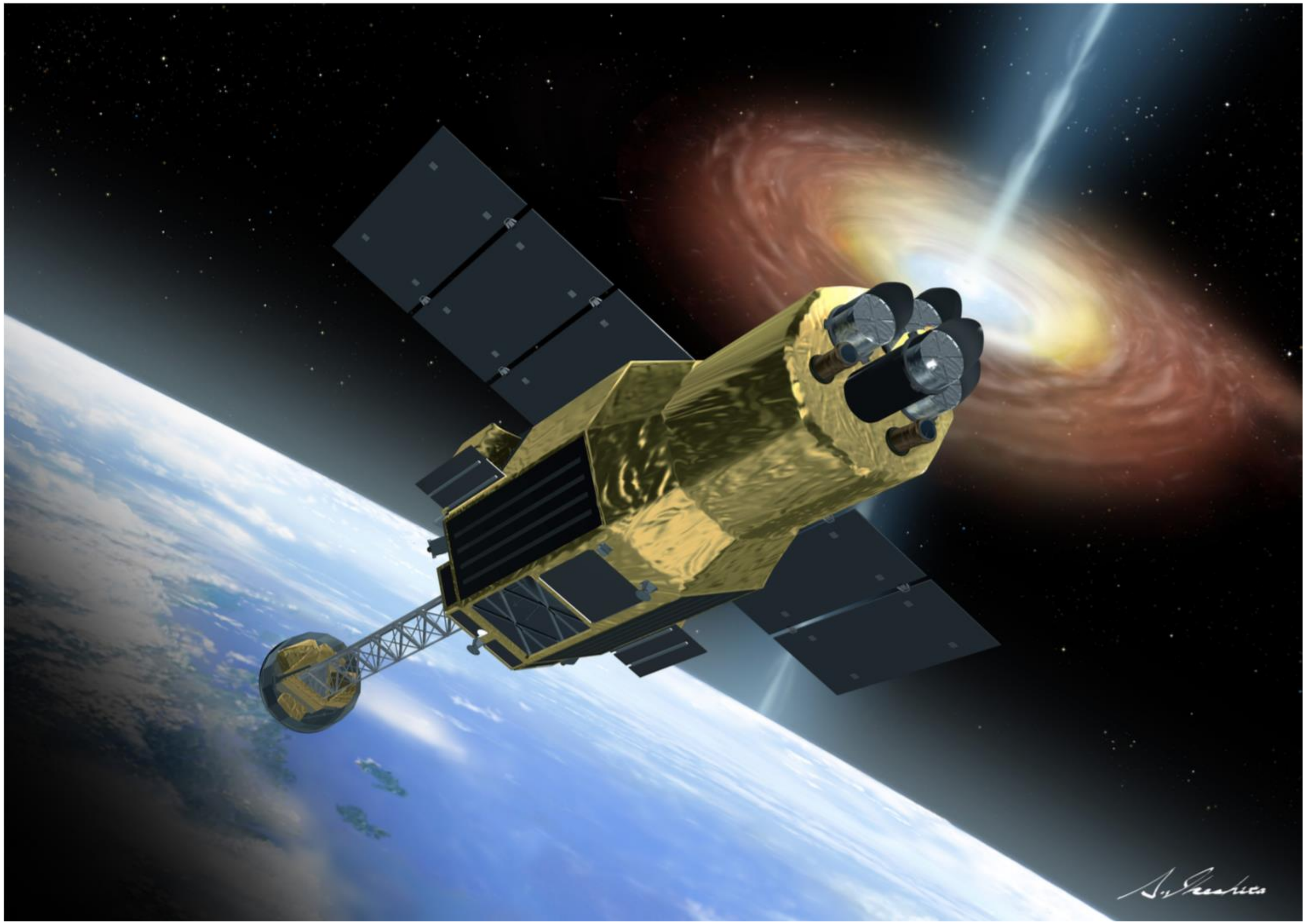
It occurs in interaction of cold neutral gas with hot fully ionised gas.

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%)

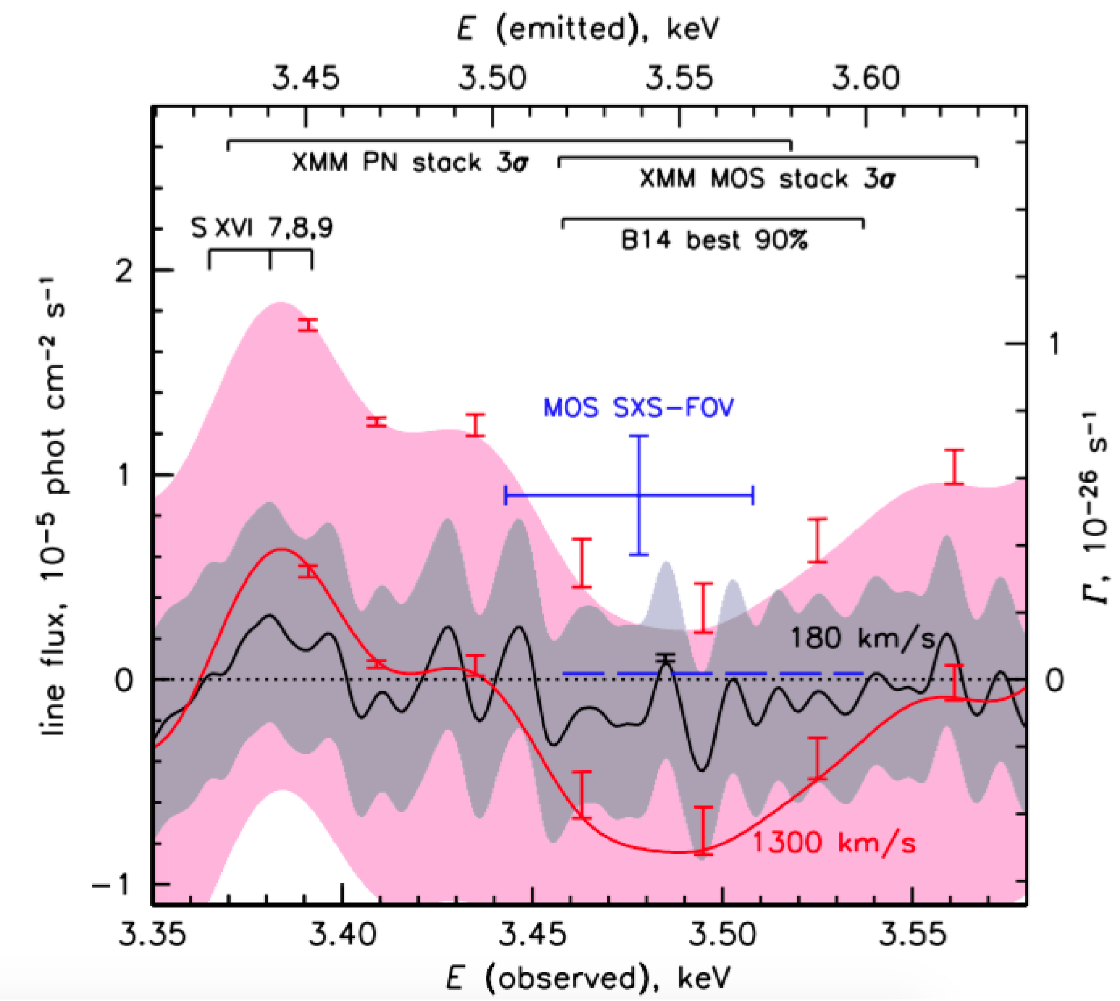
The Hitomi Satellite



Comparing satellites

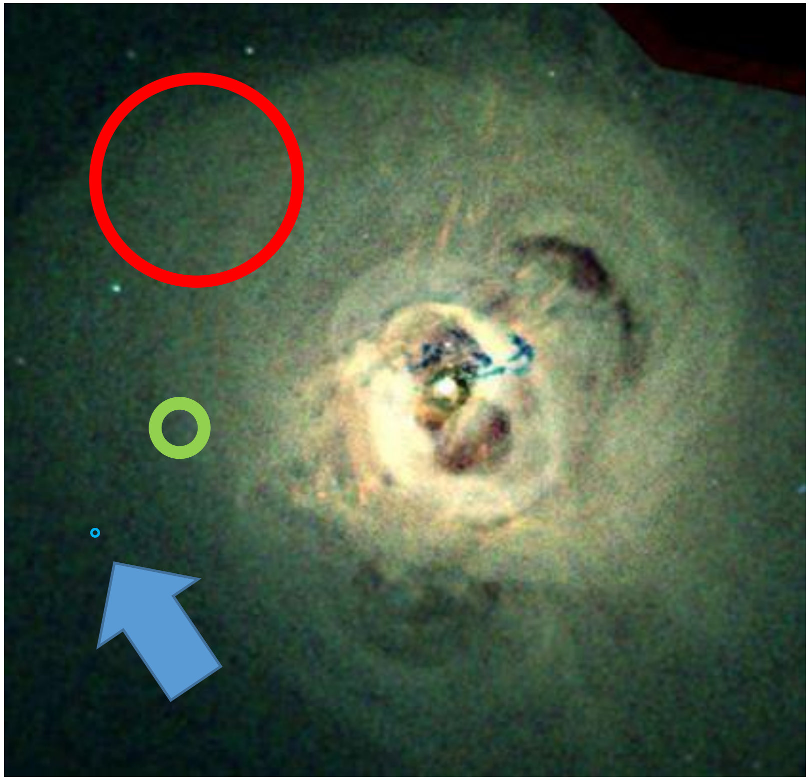
	Chandra	XMM-Newton	Hitomi
Date of launch	23rd July 1999	10th Dec 1999	17th Feb 2016
Technology	CCD	CCD	Microcalorimeters
Energy resolution	$\sim$100 eV	$\sim$100 eV	$\sim$5 eV
Angular resolution (HPD)	1 arcsecond	17 arcseconds	1.2 arcminutes

Hitomi Spectrum



Comparing satellites

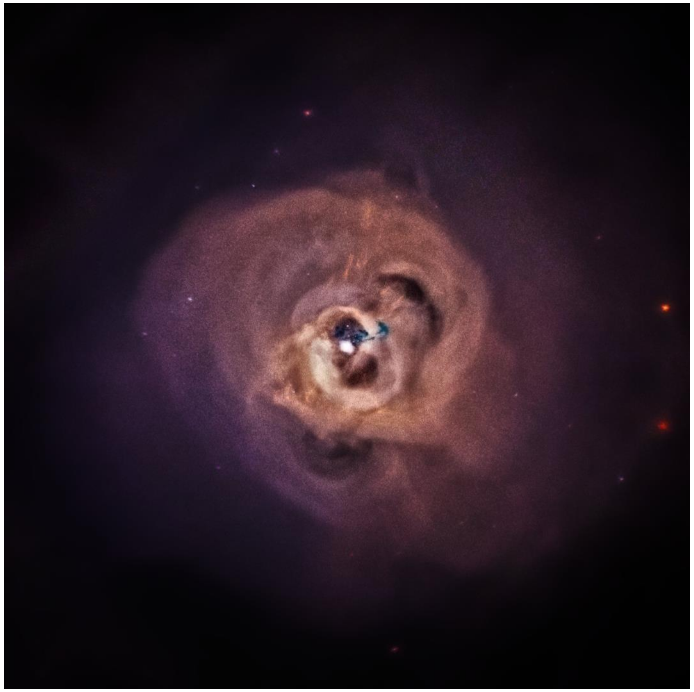
- Hitomi
- XMM-Newton
- Chandra



nicholas.jennings@physics.ox.ac.uk

Point source removal

- Bulbul et al. detect a line at 3.5keV in diffuse emission of Perseus cluster, using data from *XMM-Newton* and *Chandra* satellites.
- IMPORTANT: looked at the cluster EXCLUDING the central AGN.



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Analysis of AGN spectrum

Analysis of AGN spectrum

NGC1275 spectrum

- Central galaxy of Perseus, with an AGN unobscured in our direction.

- Basic components to X-ray spectrum are:

  1. Power-law.

  2. Reflection spectrum (incident photons illuminate accretion disc, resulting in fluorescent emission) – in practice manifest as neutral Fe Kα line at 6.4 keV.

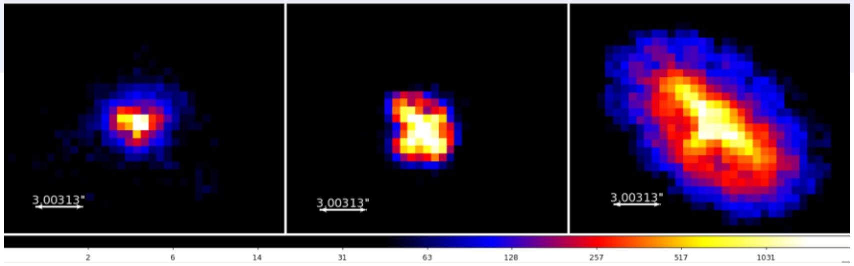
  3. Thermal soft excess (origin not entirely known).

The data

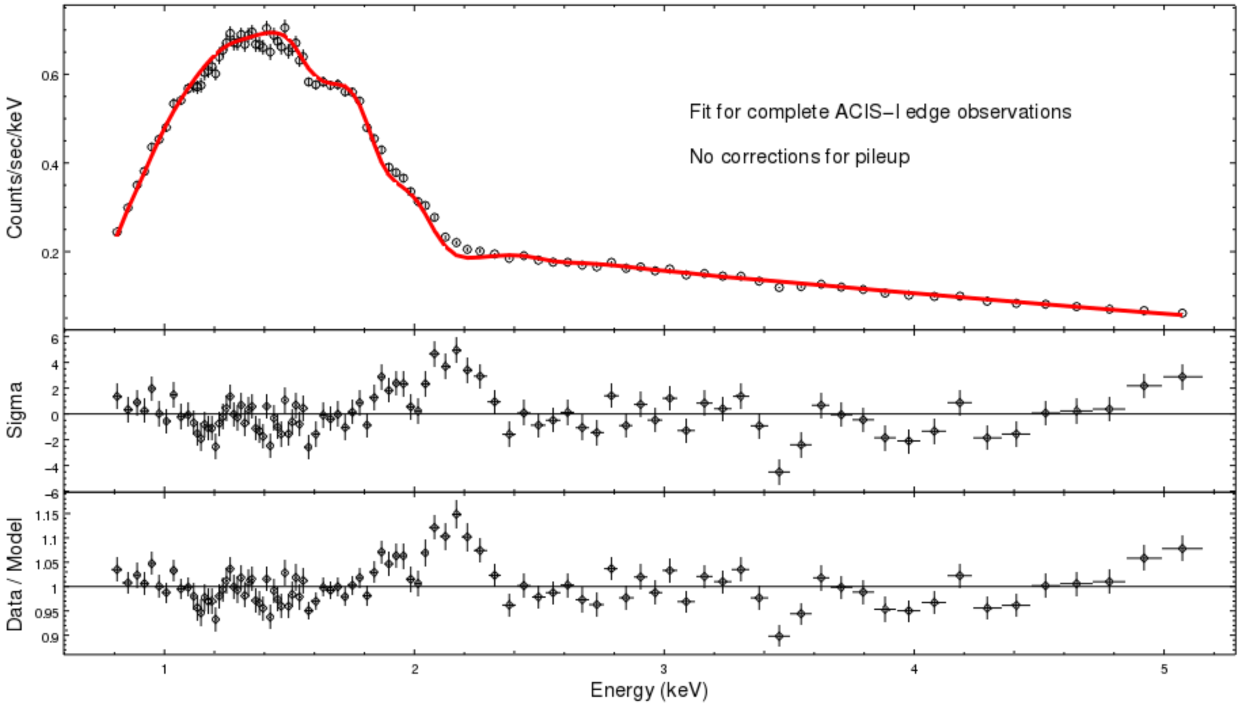
- Chandra satellite: 1 Ms with ACIS-S in 2002 and 2004, 500 ks with ACIS-I in 2009.

- We subtract source spectrum from nearby cluster emission background and fit spectrum with absorbed power-law.

- Total counts:
  230000 for 2009 ACIS-I 'edge-of-chip' observations – cleanest.
  242000 for 2009 ACIS-I 'midway' observations– pileup contamination.
  183000 for 2002-4 ACIS-S on-axis observations – most pileup contamination.



Complete extraction for ACIS-I edge



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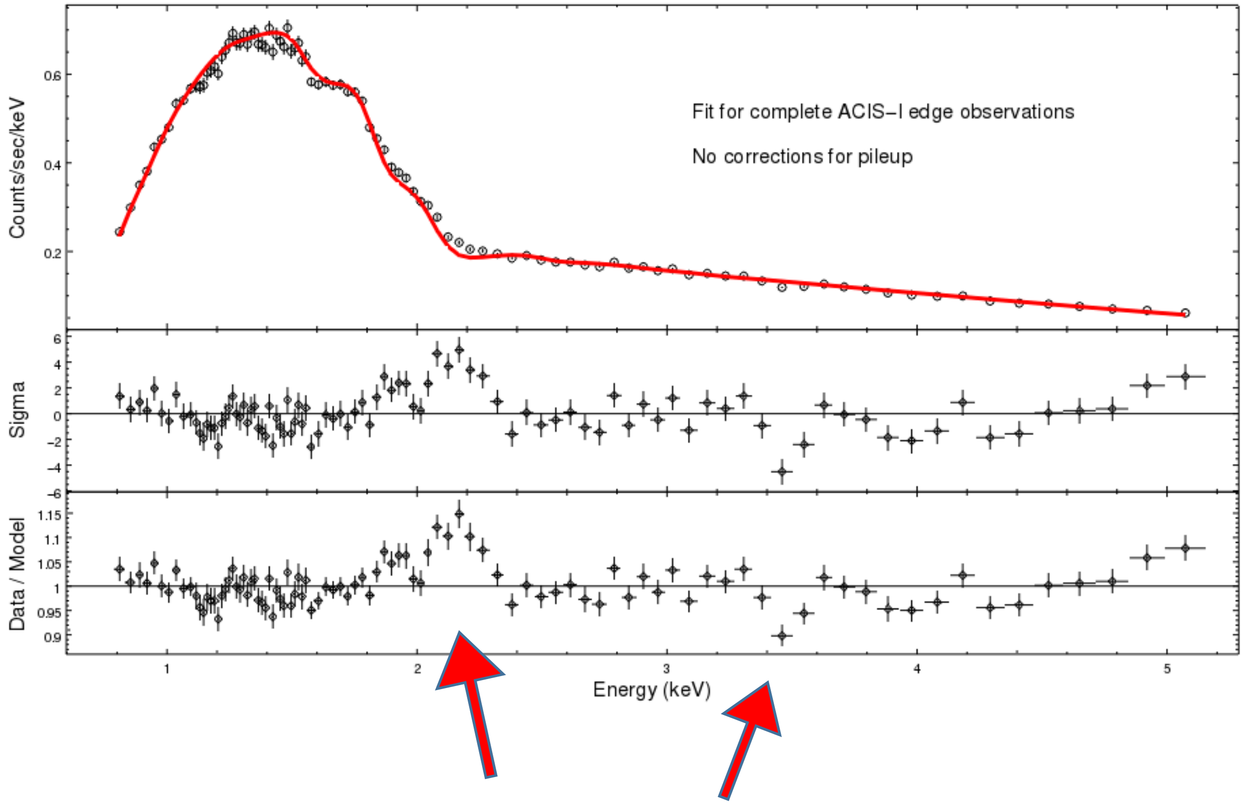
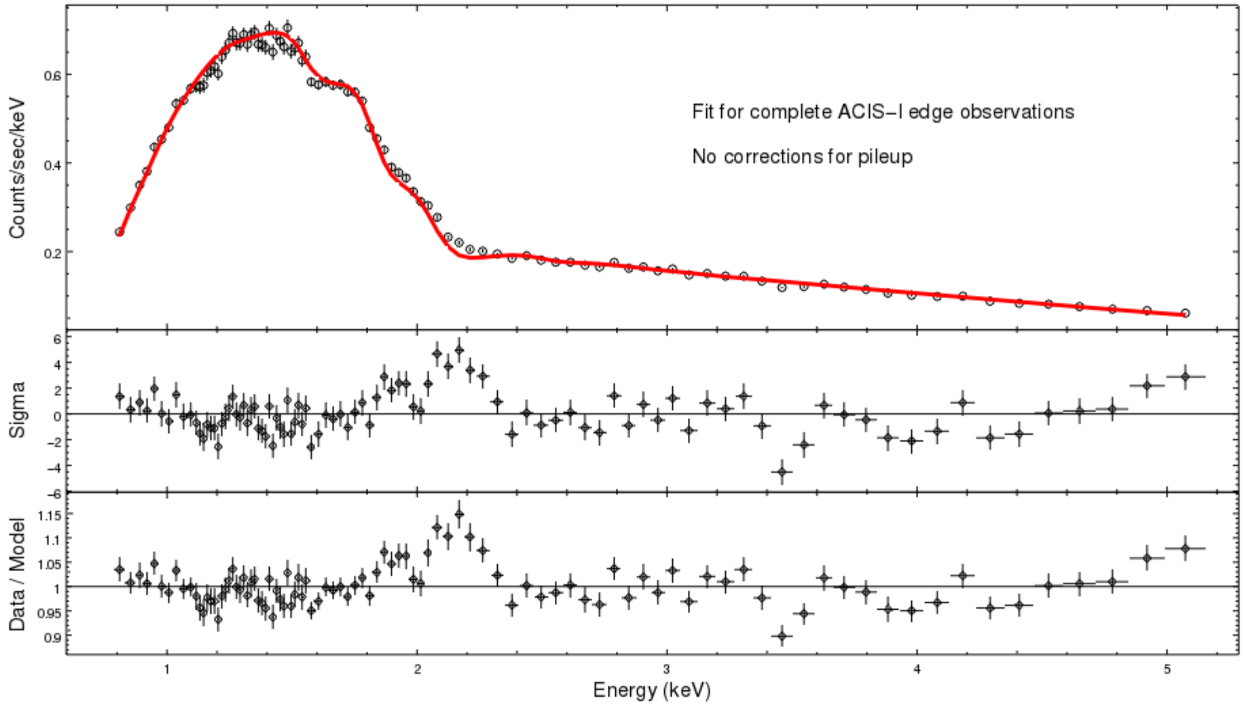


Features!

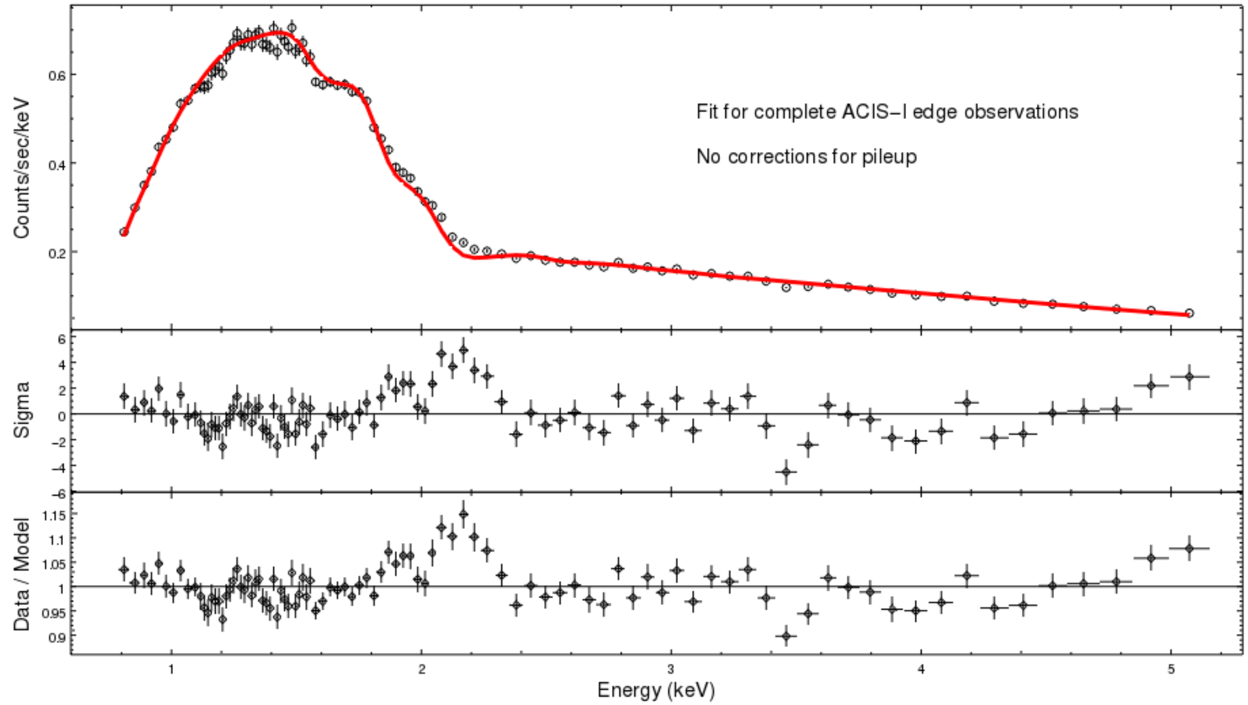
Complete extraction for ACIS-I edge



At 2.0–2.2 keV: five data points in a row 3-5 sigma high

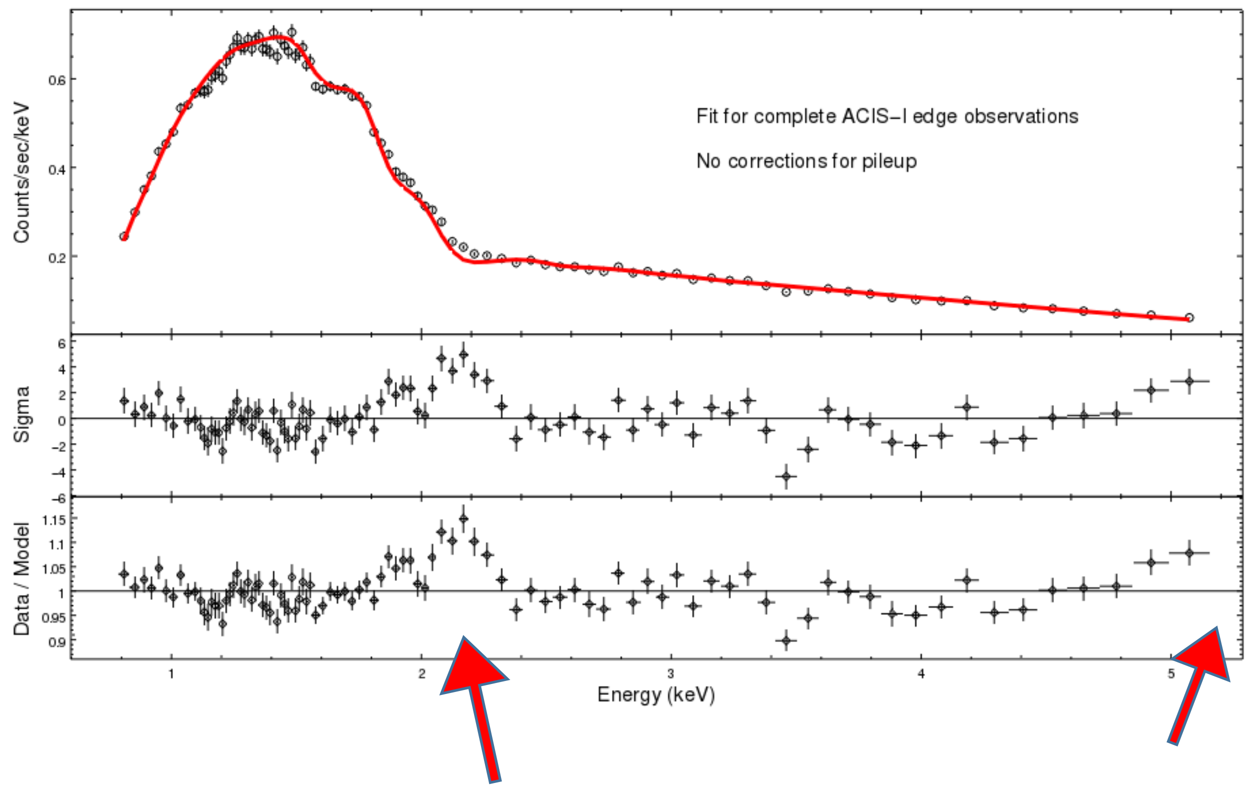
At 3.4–3.5 keV: two data points low, 4.5, 2.6 sigma

Complete extraction for ACIS-I edge



However….

Complete extraction for ACIS-I edge



Evidence of pileup contamination

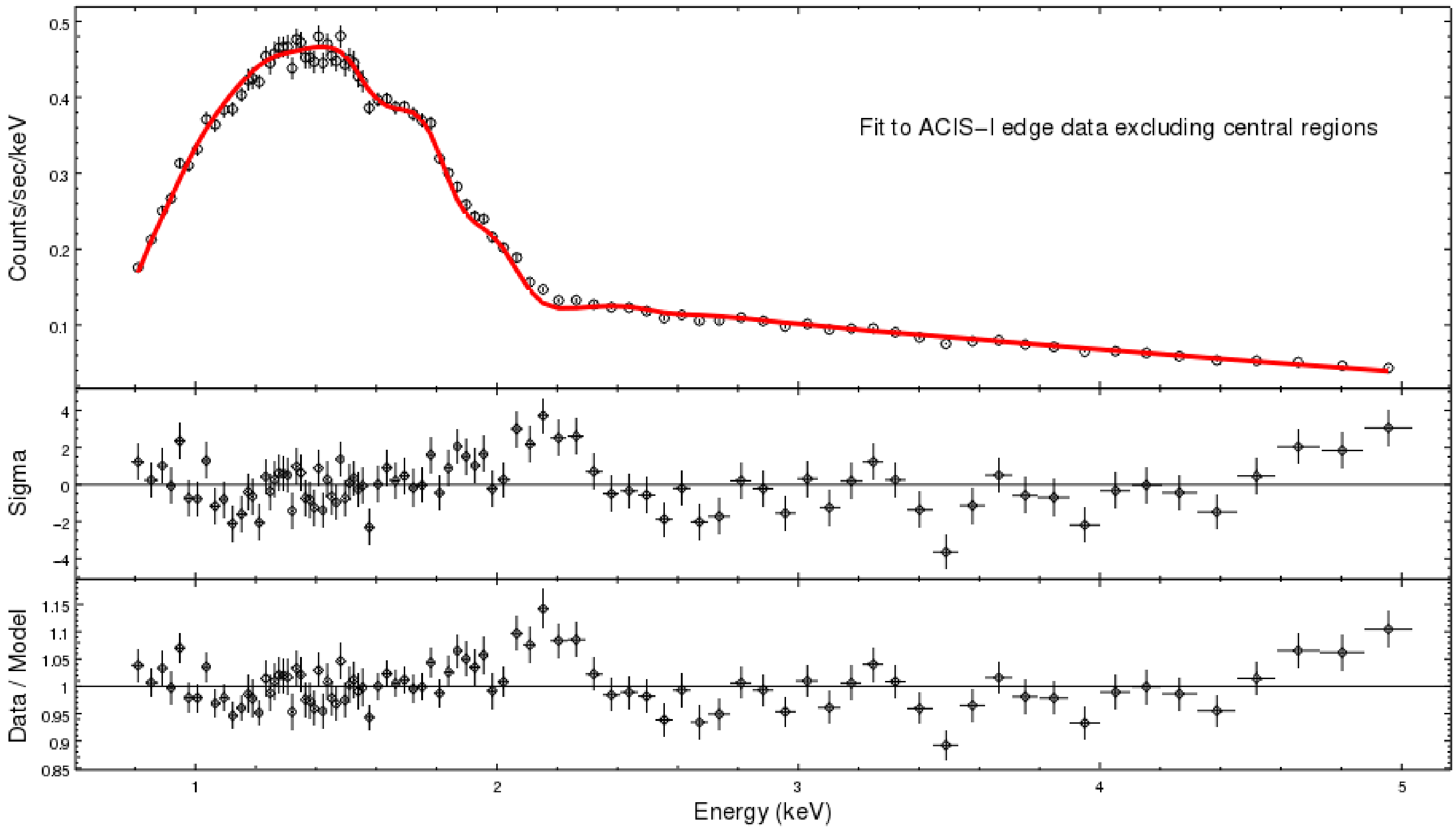
Pileup contamination

- If two or more photons arrive during the detector read-out time (3.1s), they are registered as one photon.

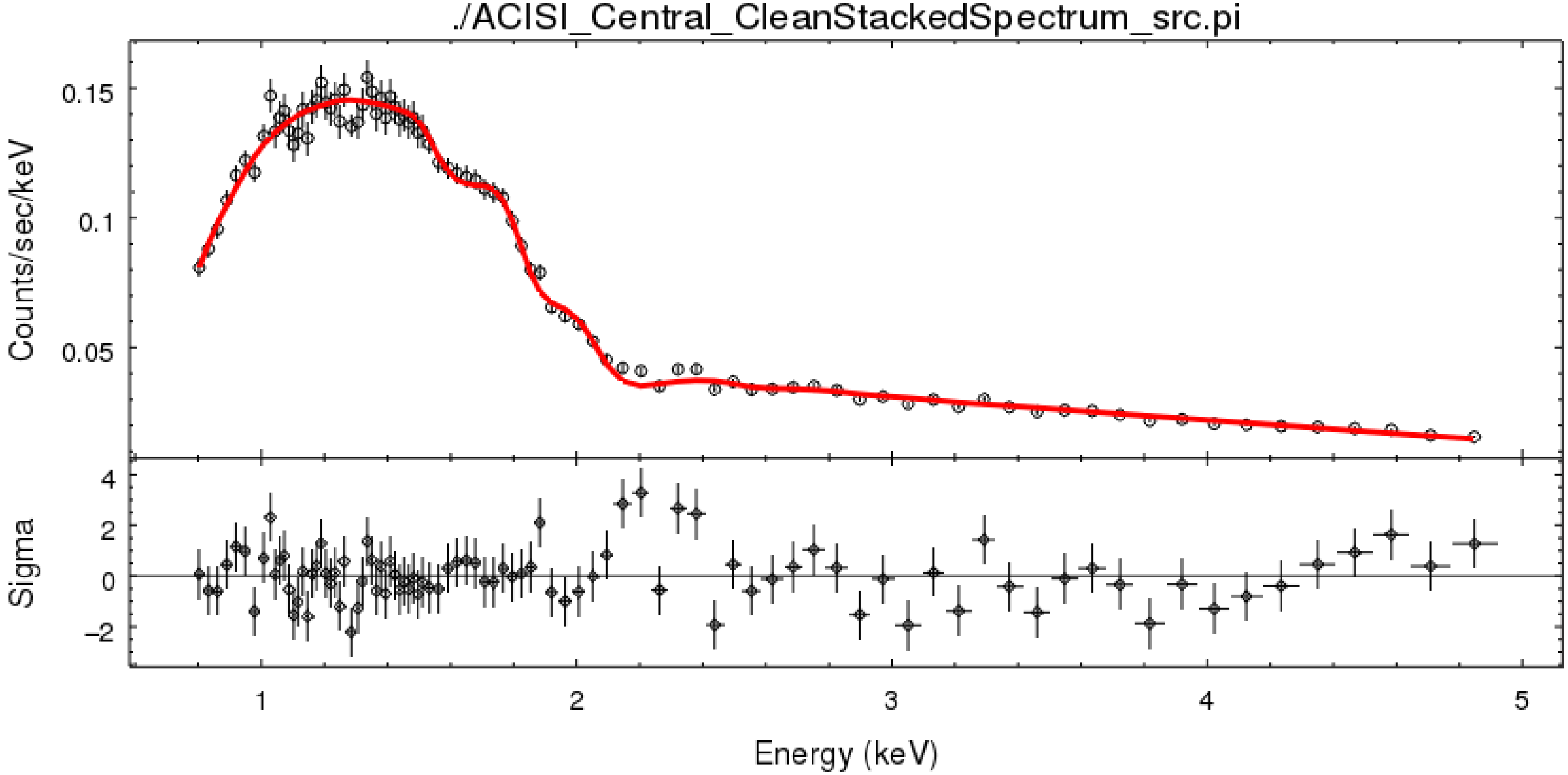
- Two ways to ameliorate this:

  - Discard central pixels with highest flux.
  - Model pile-up effects with jdpileup model.

Extraction for ACIS-I edge excluding centre

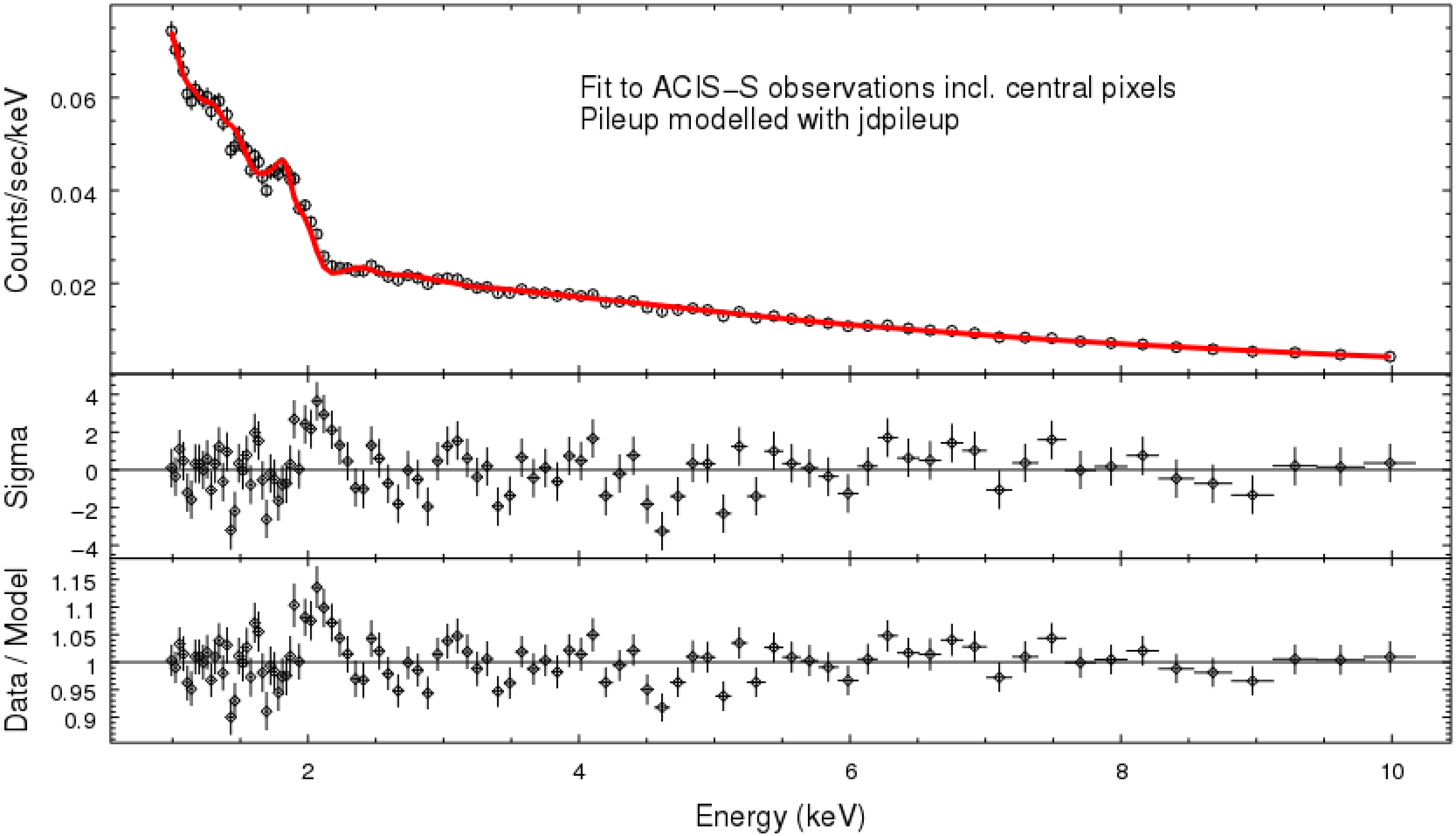


ACIS-I midway excluding centre

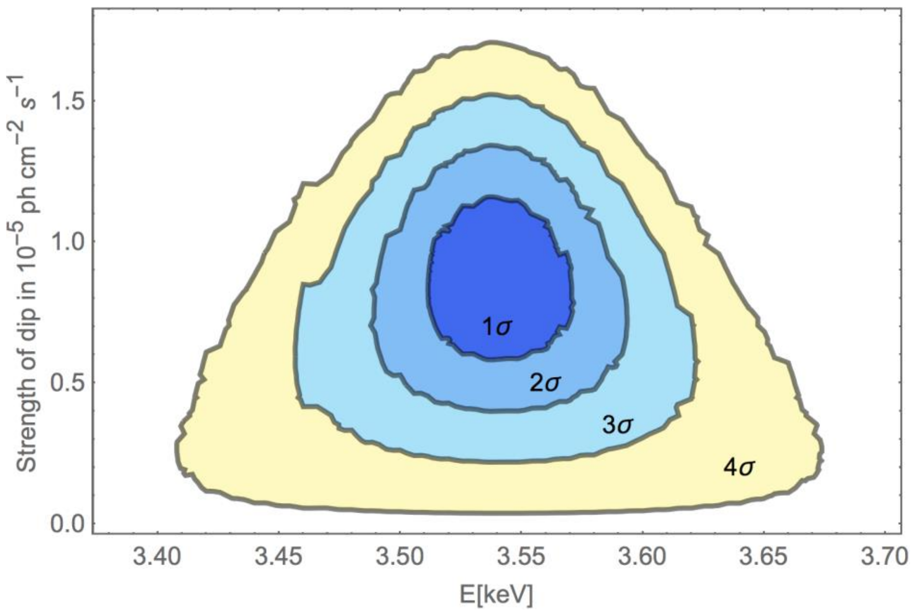


50% reduction in data when central regions are excluded.

Extraction for ACIS-S with pileup model



Analysis of AGN spectrum



- Combining all the *Chandra* datasets reveals a dip in the AGN spectrum at 3.5keV of $> 3\sigma$.
- Such a dip from the AGN would cancel out the 3.5 keV line in the cluster, meaning all observations to date are consistent.

Quick summary of systematics

- Pileup – no effective area features near 3.5keV
- Effective area miscalibration – but a dip is not present in the background spectra (excess!).
- Missubtraction of cluster background – high SNR, background now measured by Hitomi.
- Miscalibration of gain in high-flux regions – but feature far away from effective area feature. Also Fe Kα line at 6.4 keV as expected.

Possible astrophysical explanations

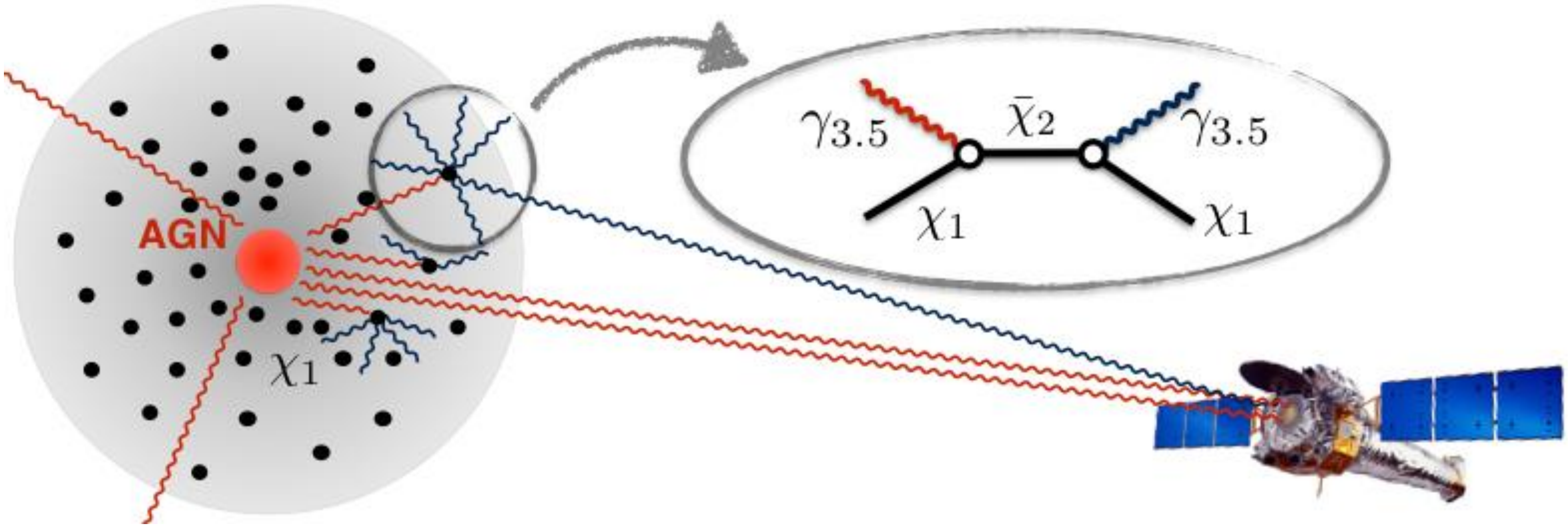
- Atomic lines – measured by Hitomi. Abundances not great enough to cause the dip.
- Sulphur charge exchange - transition from n>9 states to ground states touted as explanation of 3.5keV dip. But no reason for sulphur to preferentially absorb 3.5keV photons.
- The equivalent width is 15eV, too broad for an astrophysical explanation, as gas velocities not sufficient.

Fluorescent Dark Matter

- 2-state dark matter model (χ_1 and χ_2).
- The lower state χ_1 absorbs a 3.54 keV photon to enter the excited state χ_2, which then decays rapidly by re-emission of the photon.
- Sample Lagrangian:

$$\mathcal{L} \supset \frac{1}{M}\overline{\chi_2}\sigma^{\mu\nu}\chi_1 F_{\mu\nu}$$

Fluorescent Dark Matter



Going forward

- The 3.5keV luminosity has a much sharper central peak for Fluorescent DM than for decaying or annihilating DM.

- Anisotropy in the 3.5 keV line strength would indicate FDM.

- Sadly no more *Hitomi,* but *Chandra* observations of the AGN can be optimised:
  - Shorter read-out time.
  - Off-axis pointing.

- The AGN is twice as luminous as in 2009, so the future is BRIGHT!

Thank you

References

E. Bulbul et al., Astrophys. J. 789, 13 (2014), 1402.2301.

O. Urban et al., Mon. Not. Roy. Astron. Soc. 451, 2447 (2015), 1411.0050.

F. A. Aharonian et al. (Hitomi) (2016), 1607.07420.

M. Berg, J. P. Conlon et al., (2016), 1605.01043.

J. P. Conlon et al. (2016), 1608.01684.

Extra Slides

Dark Matter in X-rays?

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?

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)

Original Data Evaluation

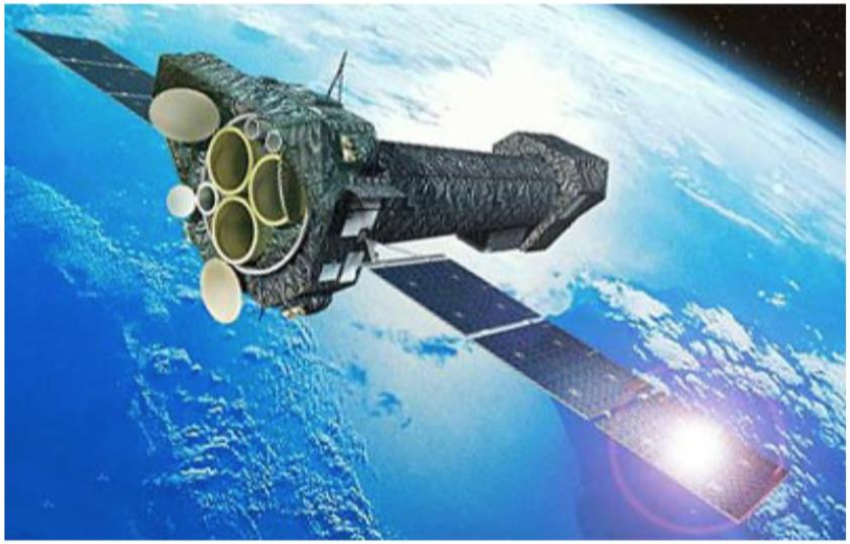
- (+) Line seen by four instruments (XMM-MOS, XMM-PN, Chandra ACIS-I, Chandra ACIS-S)
- (+) Line seen independently by two separate collaborations
- (+) Line seen from at least five different sources at consistent energy
- (+) Line absent in deep 16Ms blank sky observations

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

Draco

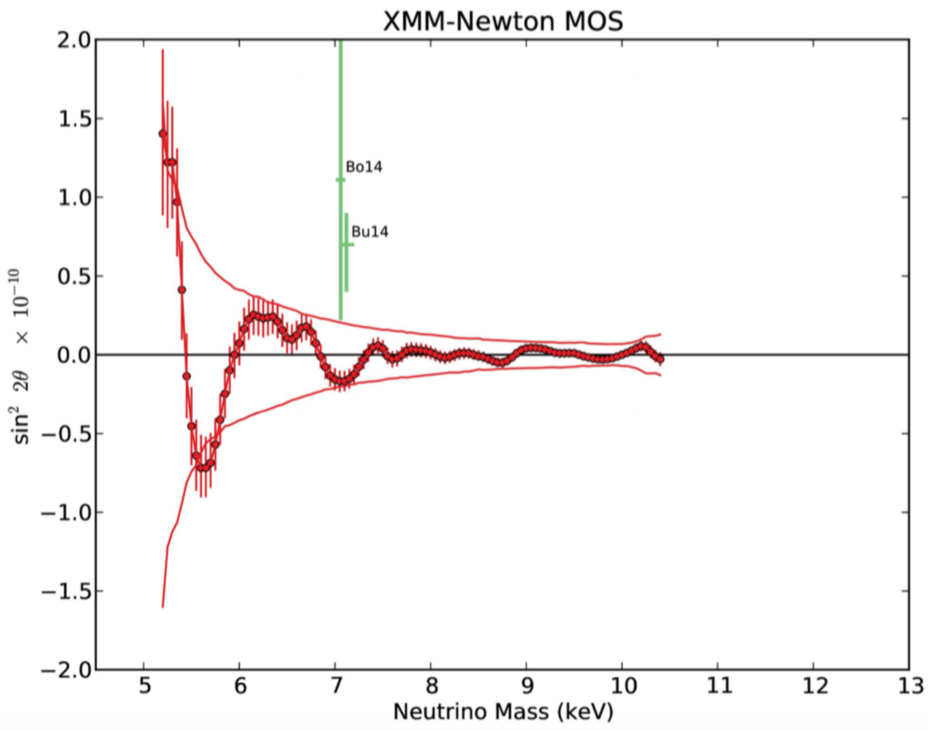
An ultra-deep 1.3 Ms observation of the Draco dwarf galaxy was carried out in 2015 by XMM-Newton.



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

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



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

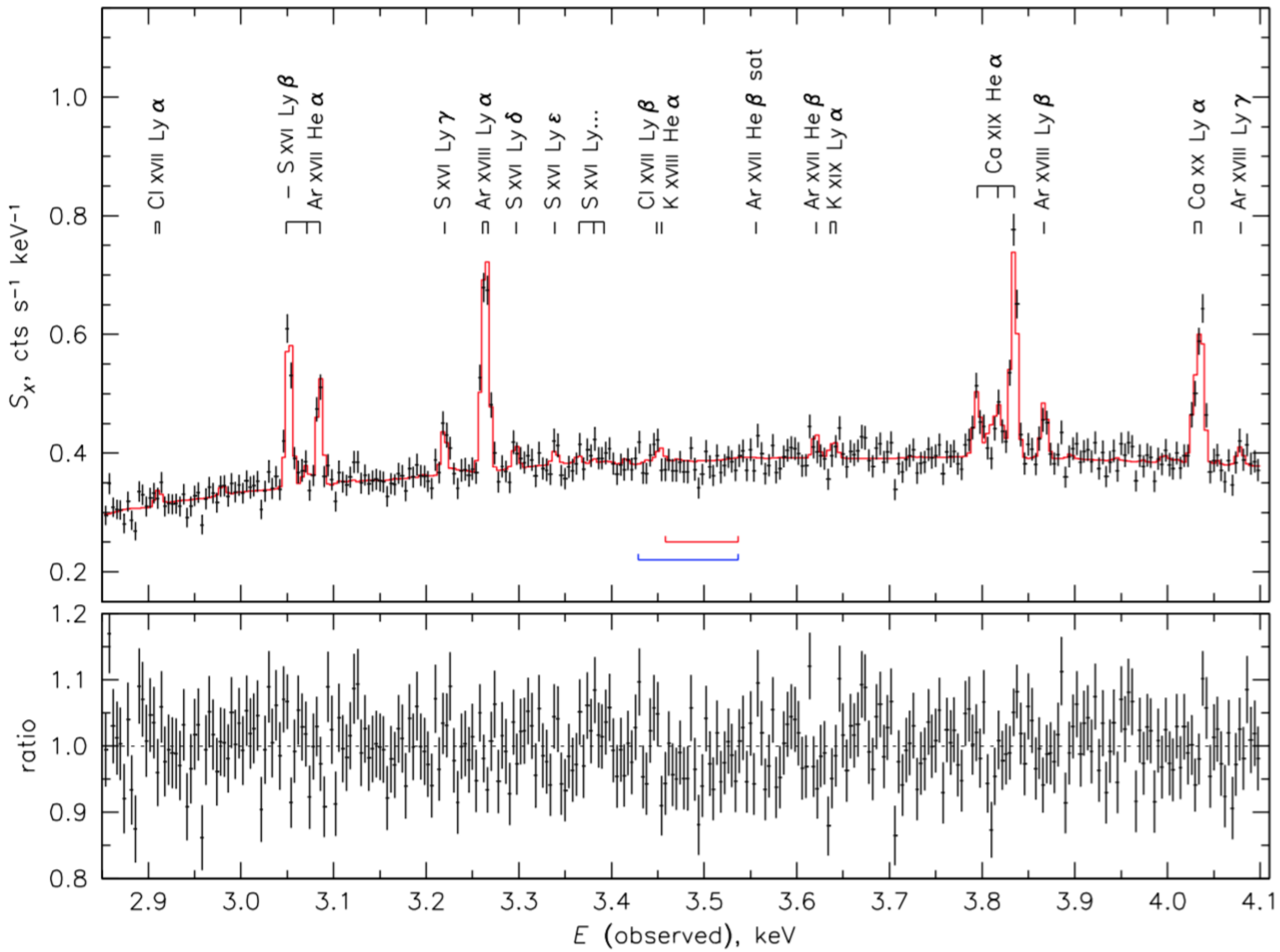
It had unprecendented spectroscopic resolution (7eV compared to 100eV for CCD technology of XMM-Newton, Chandra, Suzaku)

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

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 $kT = (3.48 \pm 0.07)\mathrm{keV}$, $Z = 0.54 \pm 0.03$, $\sigma_v = (179 \pm 16)\mathrm{kms}^{-1}$

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*apparently!

Comparing data from different satellites

- For XMM-Newton and Chandra datasets, point source removal software was used to exclude the region containing the central galaxy NGC1275 and its AGN.

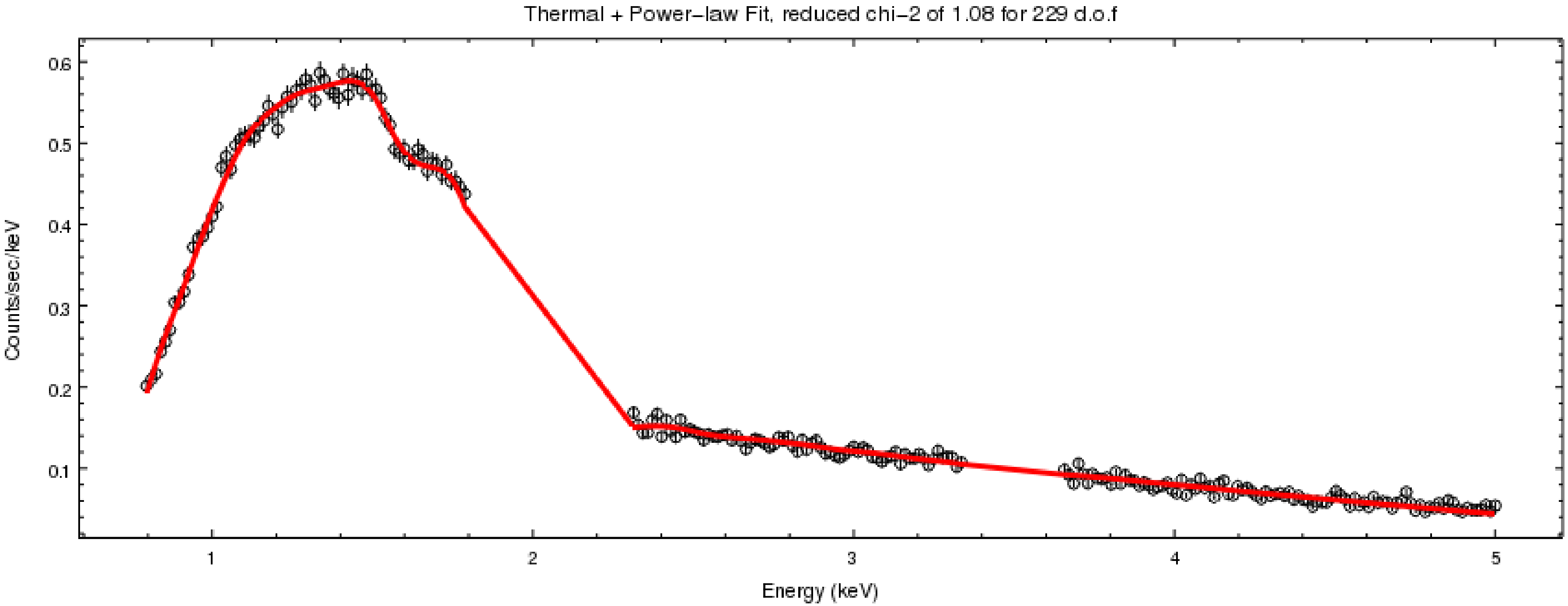
- Due to the poor optics of Hitomi, it is impossible to exclude the central AGN from the data.

- Therefore direct comparison of the data requires no features in the AGN spectrum at 3.5keV.

Background modelling

- Instead of subtracting the background, we can model the cluster thermal emission directly using parameters determined by Hitomi.
- The temperature and abundance are fixed and the norm allowed to float.
- Better method as statistical noise is reduced, and Hitomi much better instrument for determining thermal spectrum than Chandra.

Modelling the 3.5 keV dip



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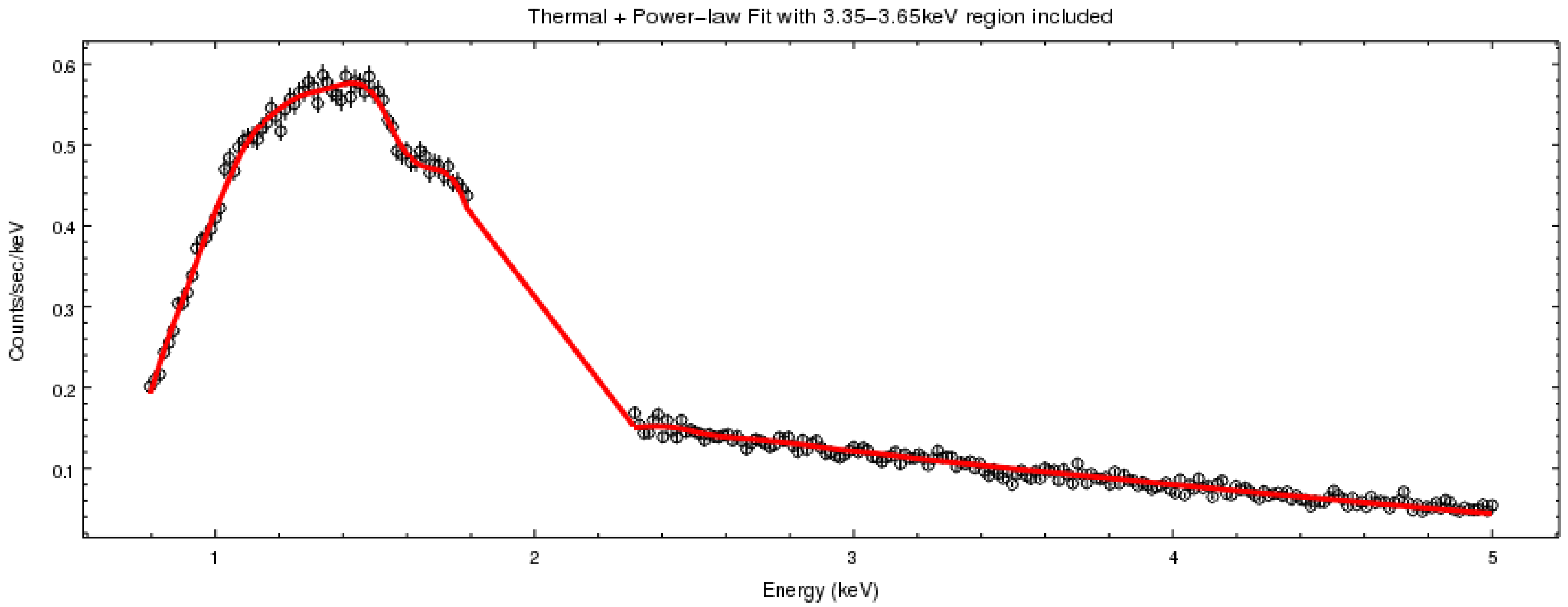

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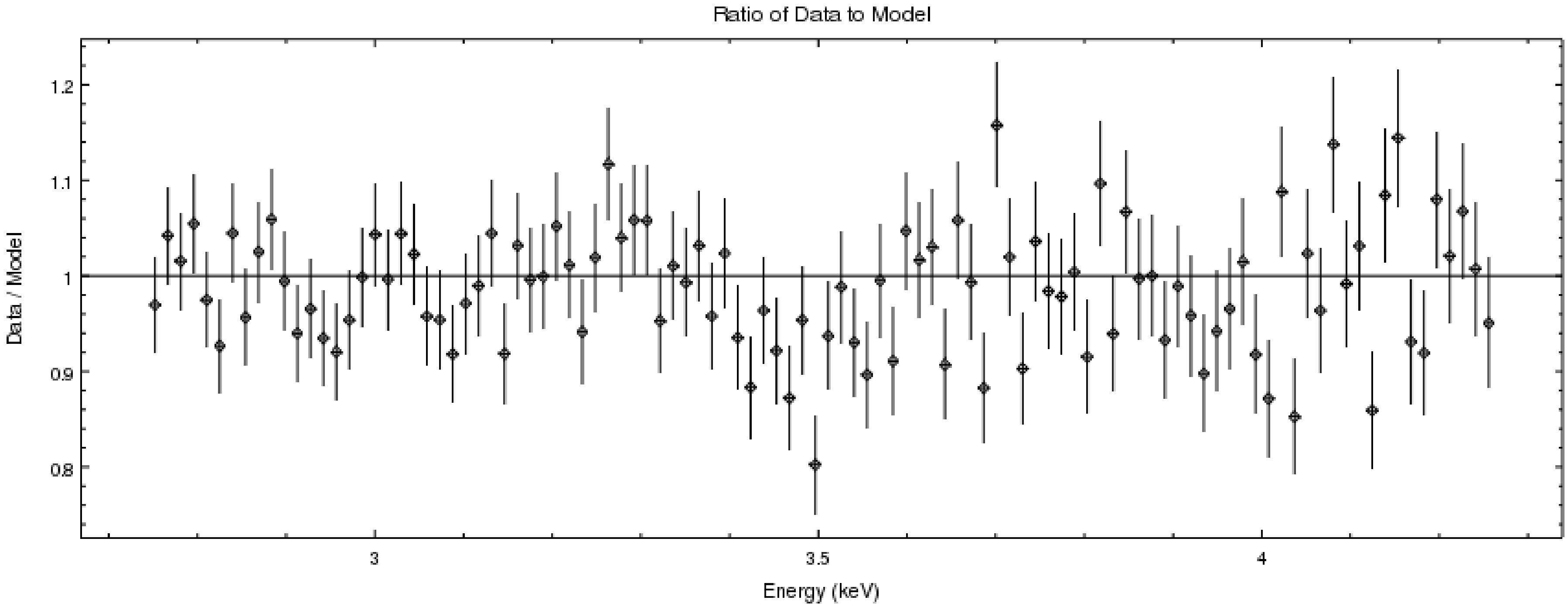
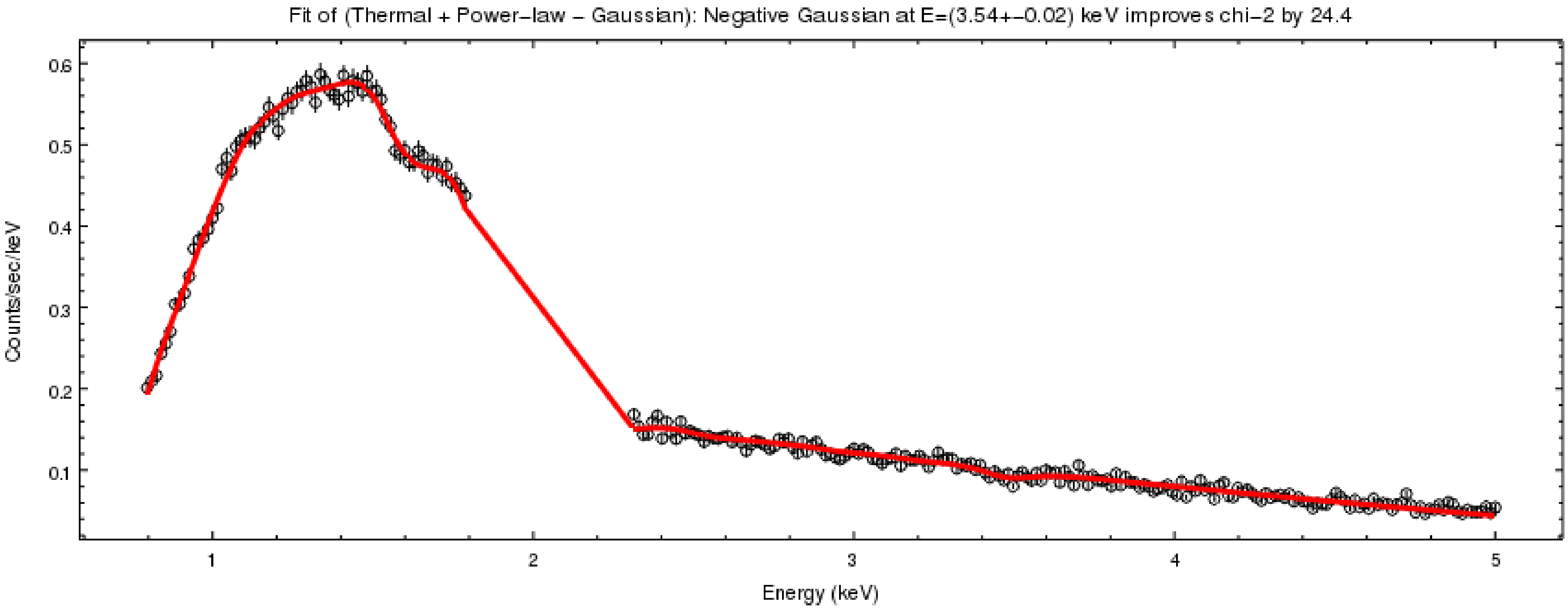


Modelling the 3.5 keV dip



Fluorescent Dark Matter

- The dip strength has equivalent width of 15 eV.
- Using the Breit-Wigner relativistic formula, and a NFW profile, we can derive:

$$\Gamma \geq \left(\frac{m_{DM}}{\text{GeV}}\right) \times \ 5.8 \ \times \ 10^{-10} \ \text{keV}$$

- The equivalent width is very close to that expected by DM broadening, hence close to saturation.
- Therefore an increase in Γ will not significantly increase absorption.