Observations of the **3.5 keV emission line & excess** in the X-ray spectra of Galaxy Clusters

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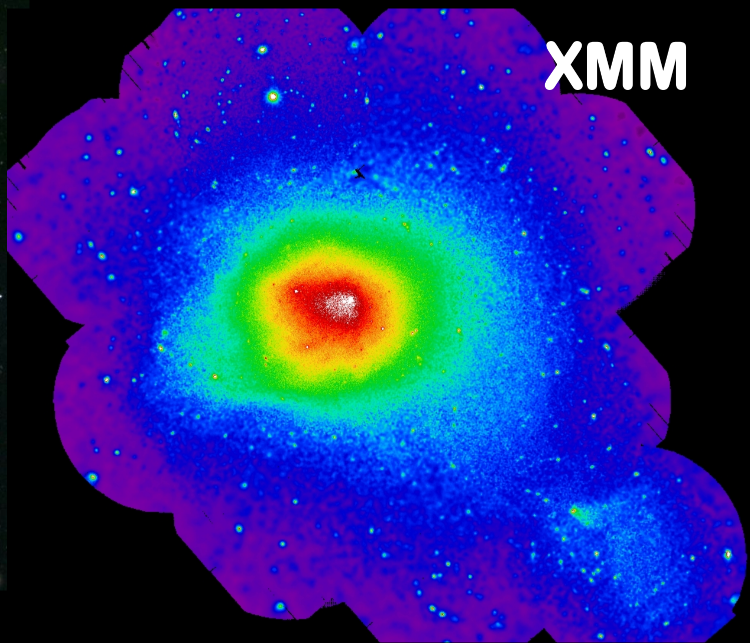
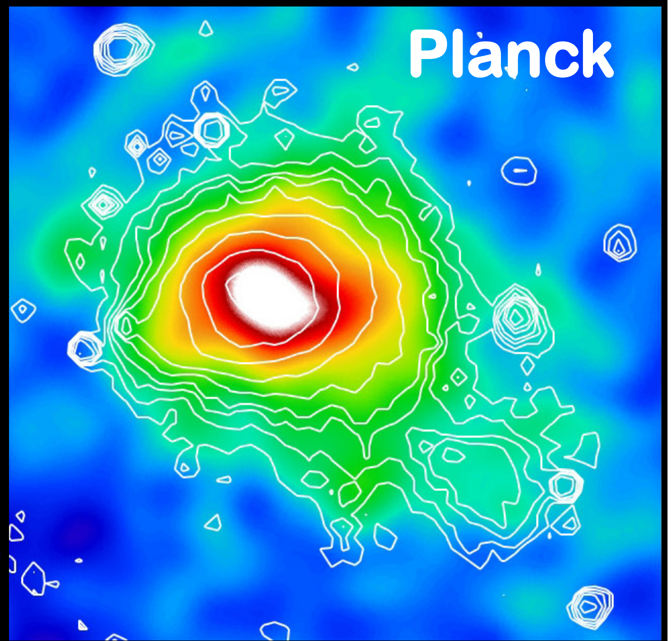
Special thanks to
Max Bonamente (University of Alabama)
Esra Bulbul (MIT Kavli Institute)
Fabio Gastaldello (INAF-IASF Milano)



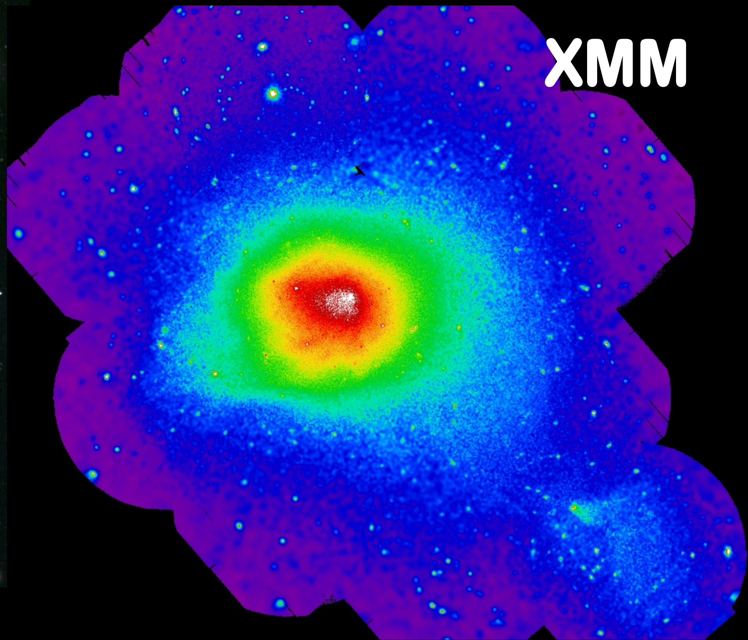


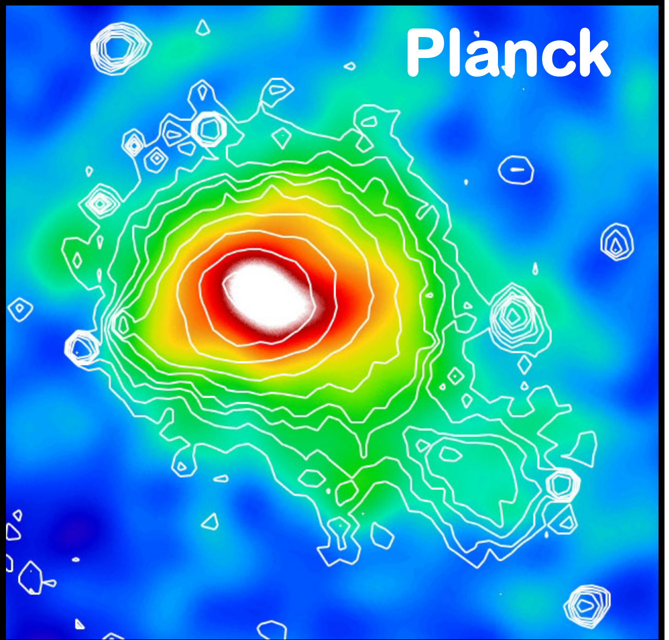
Outline

3.55 keV line: *observations & controversy*

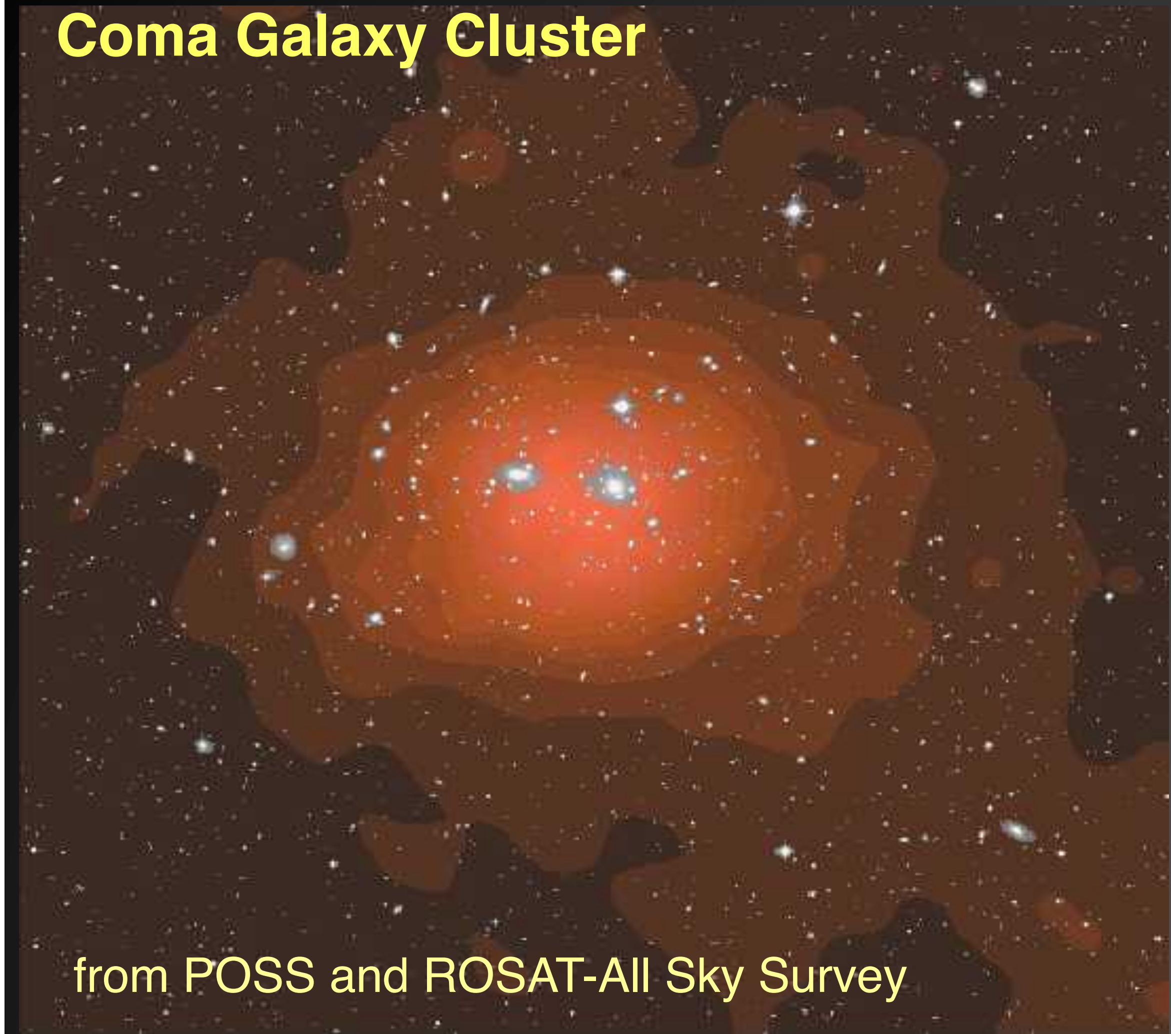
Soft Excess: *observations & interpretation*

Hard Excess: *observations & interpretation*





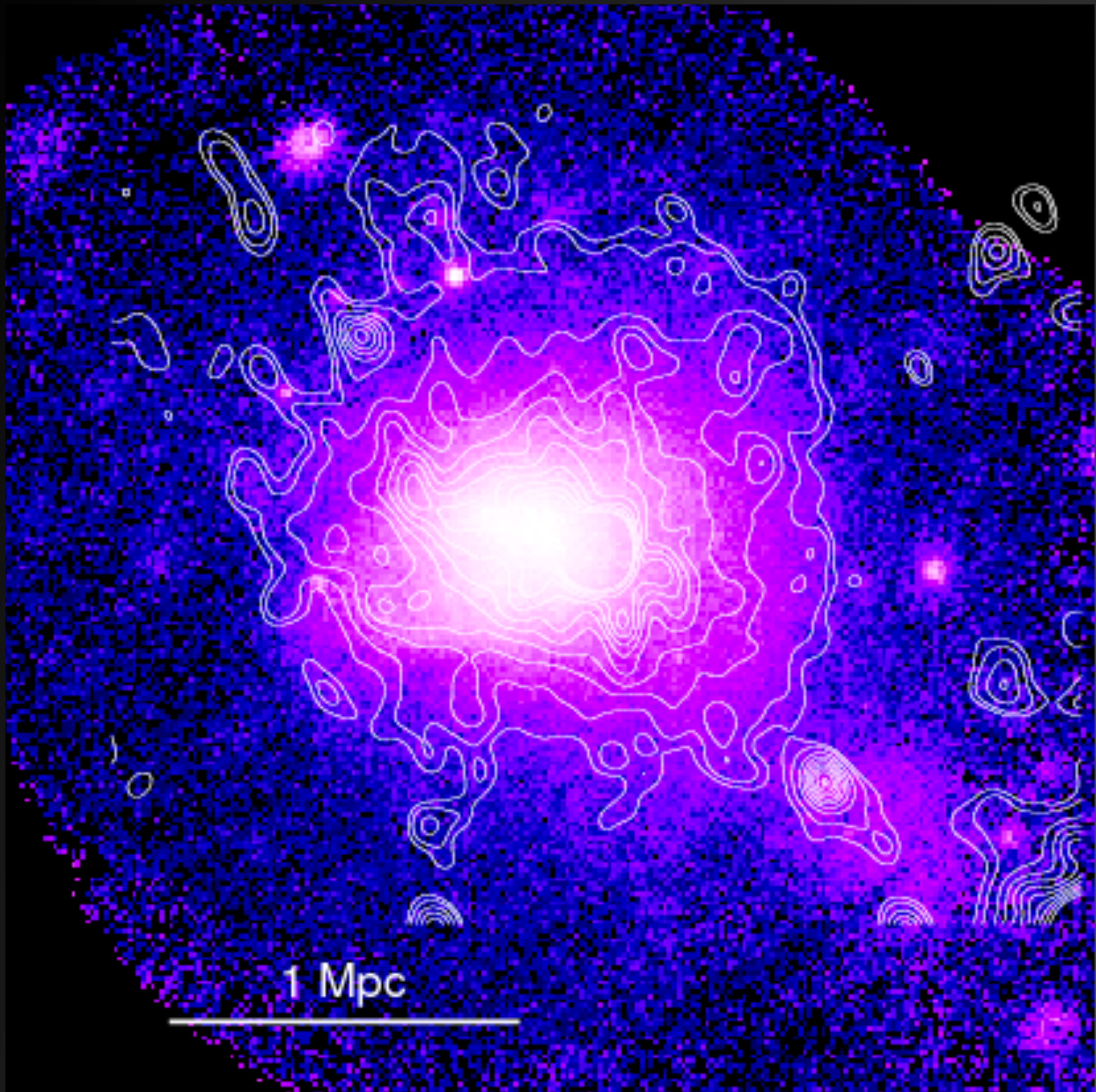
Clusters of galaxies



74 – 83% = Dark Matter
15 – 20% = *hot* ICM
2 - 6% = *cold* galaxies

The hot gas is thermalized and trapped in the halo potential well

Clusters of galaxies



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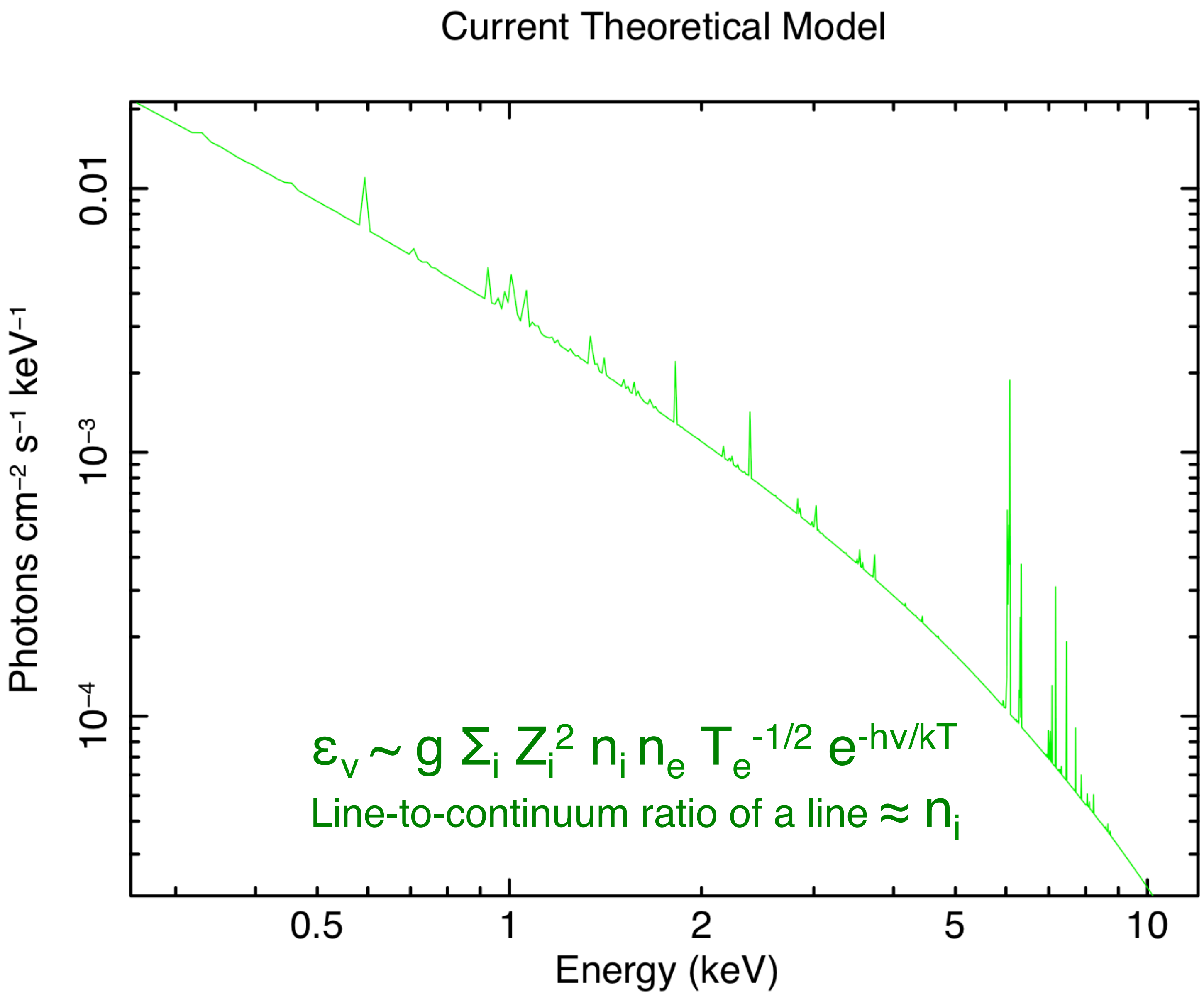
Observations in the radio bands (0.3-1.4 Ghz) reveal Mpc-scale **synchrotron radiation** due to the presence of relativistic electrons.

Diffusion timescale >> energy-loss t for γ>1e4 electrons: in situ acceleration, either via merger shock fronts +turbulence (*several observed correlations support it*) OR secondary e^- produced from decay of π generated from CR-ions & ICM.

CRs are also expected to be confined in the cluster volume through large-scale magnetic fields (**B~μG**). CRs are accelerated in shock waves induced by cluster mergers and during the accretion of material from the cluster environment. CRs can also be injected into the cluster volume by central AGNs and SNe.

X-ray observables

Let's take a cluster with kT=5 keV, L_{bol}=5e44 erg/s @z=0.1



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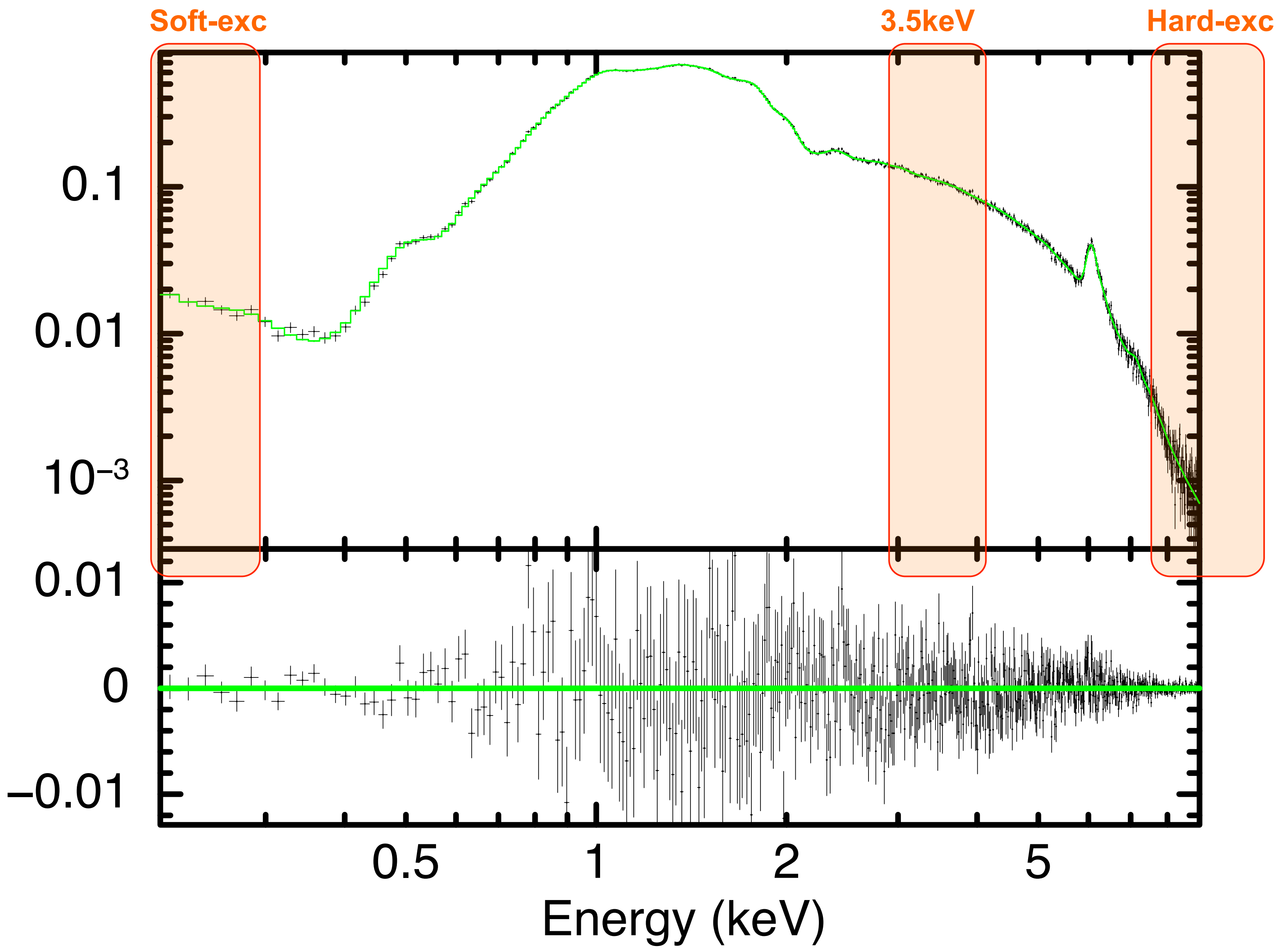

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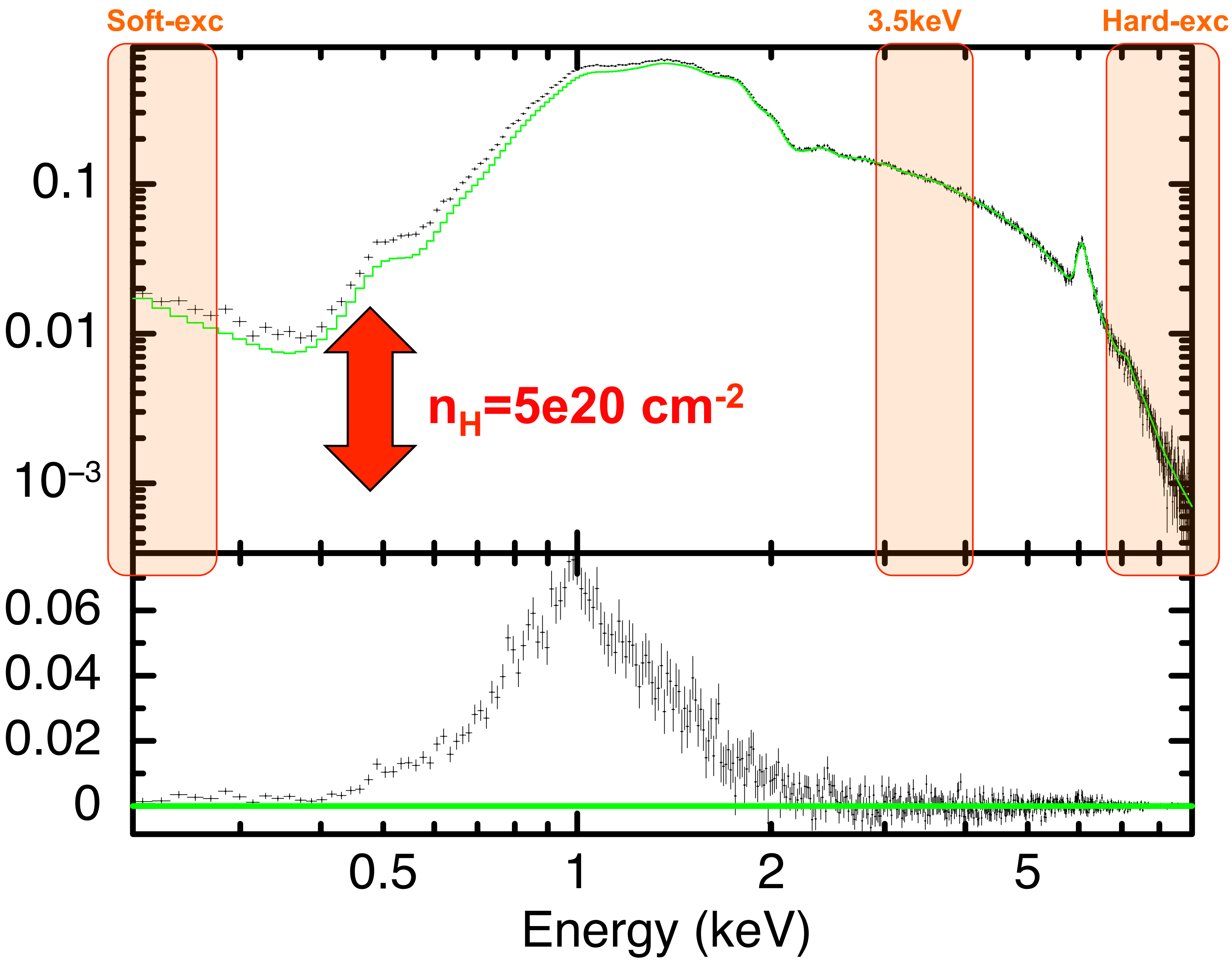

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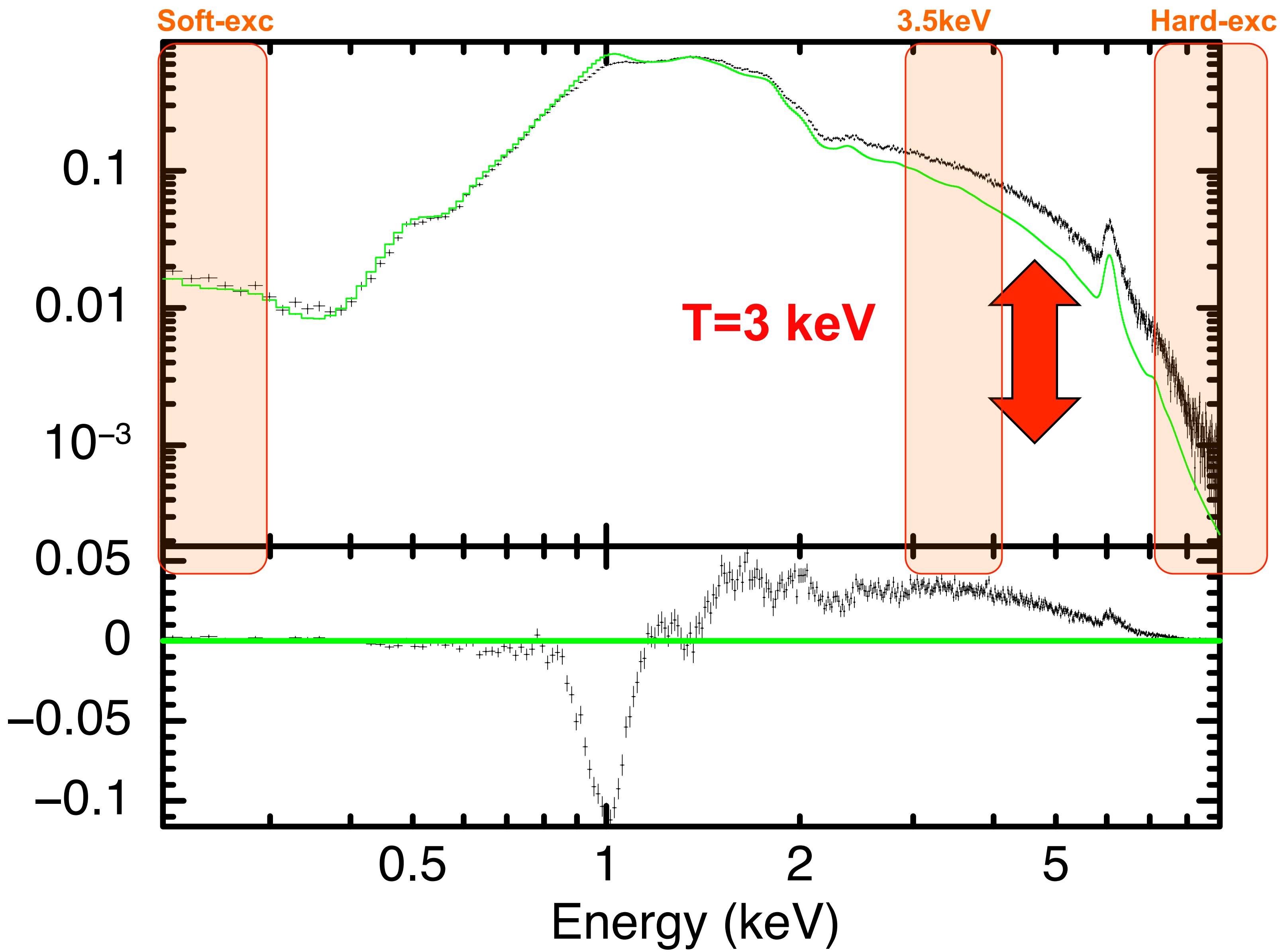

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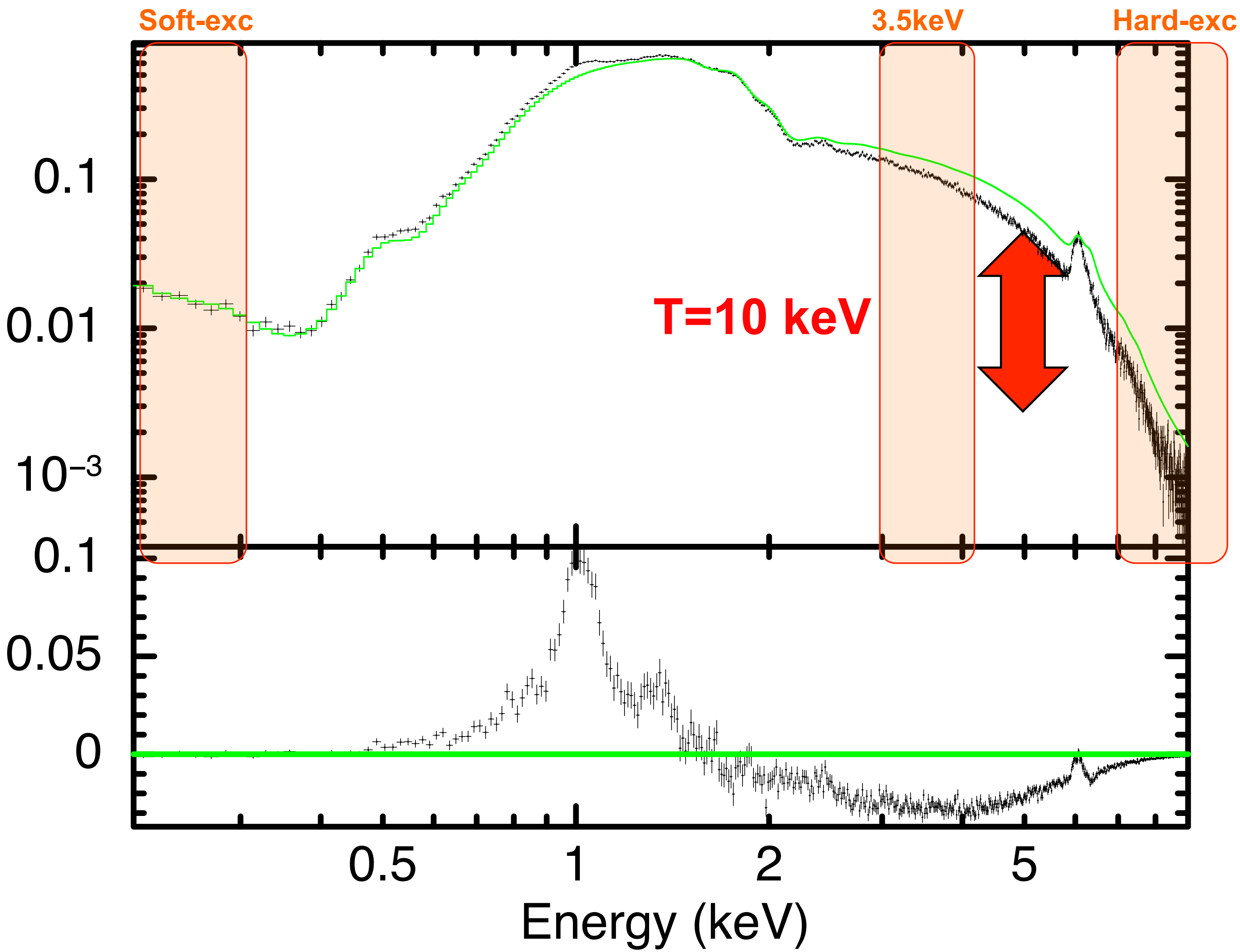

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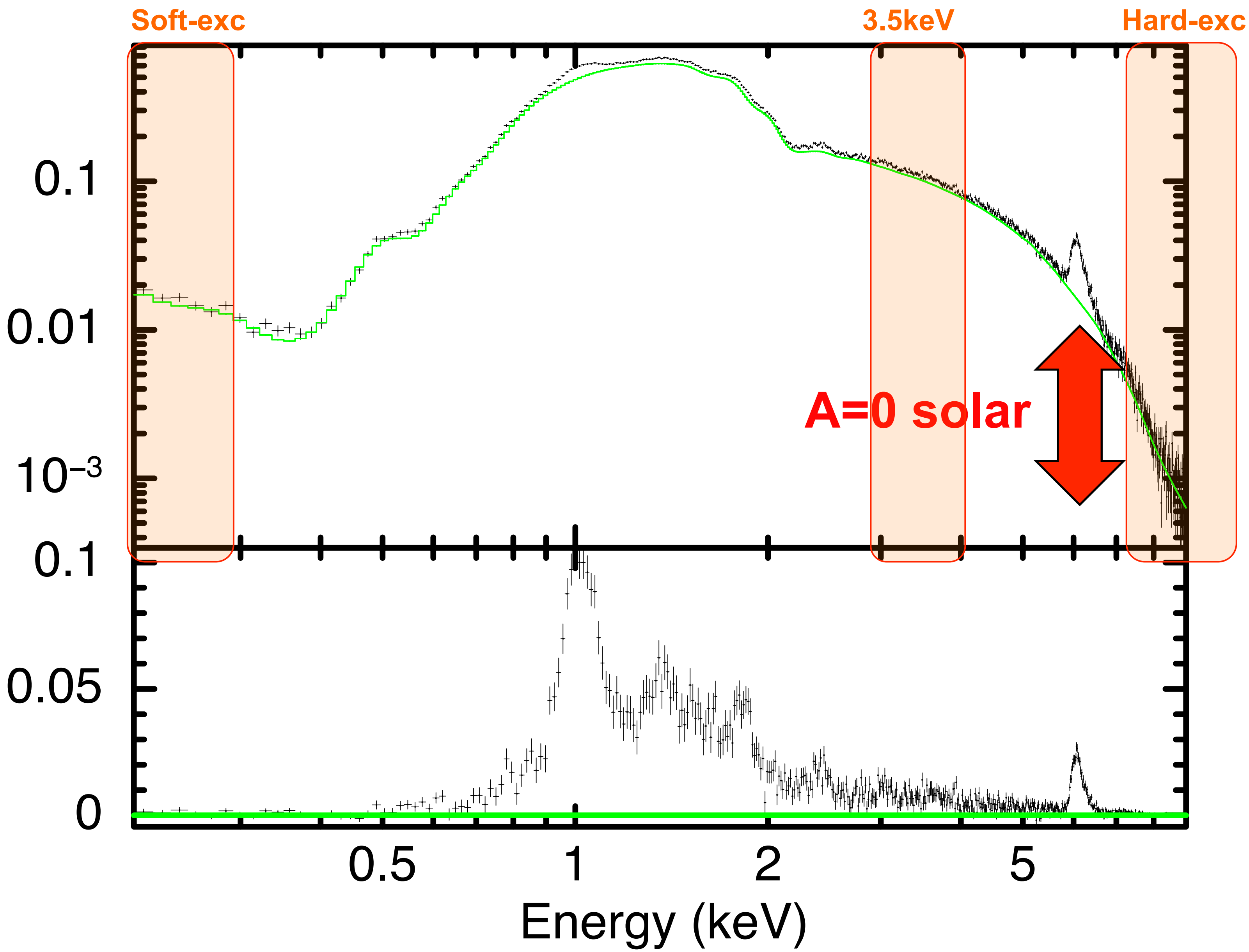

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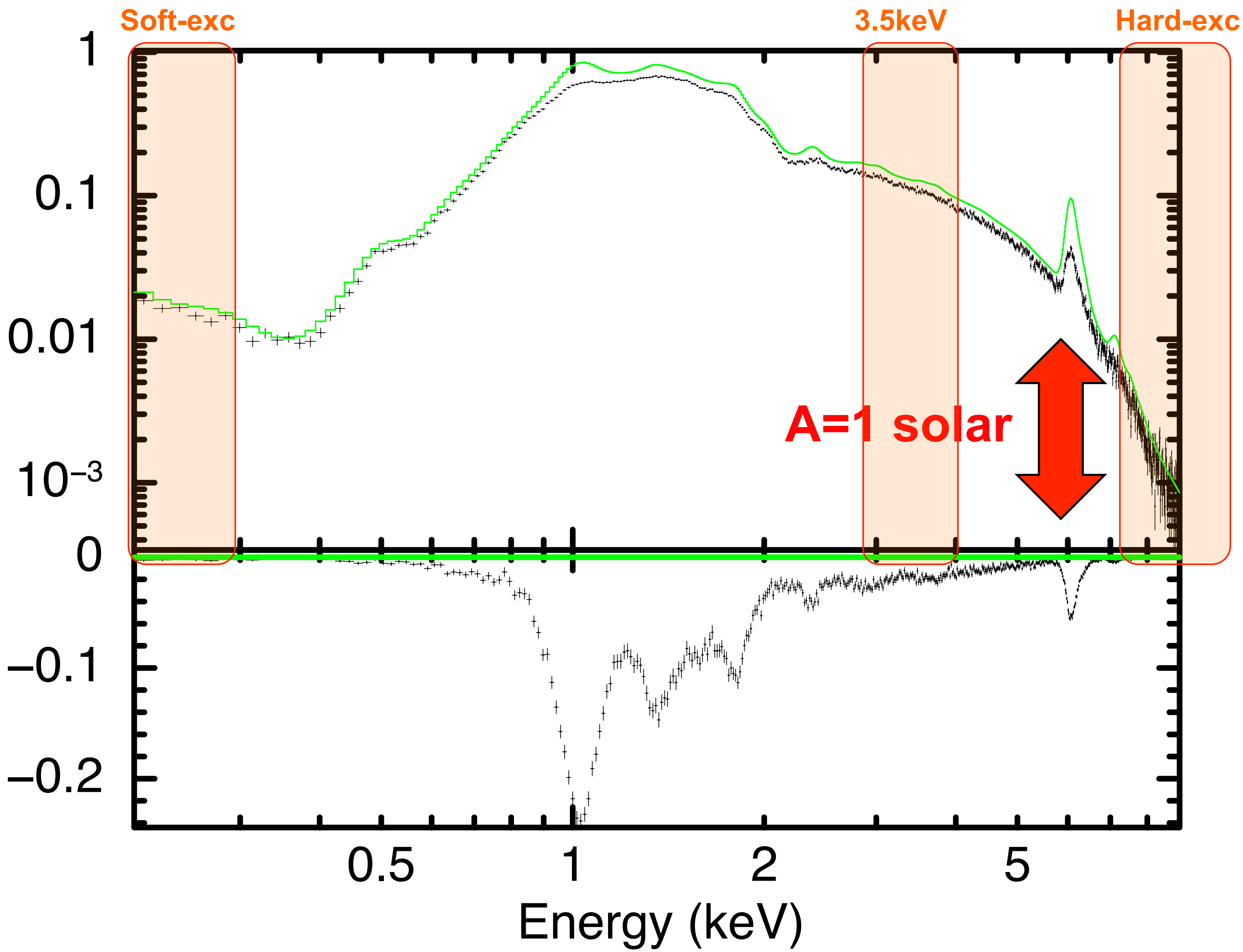
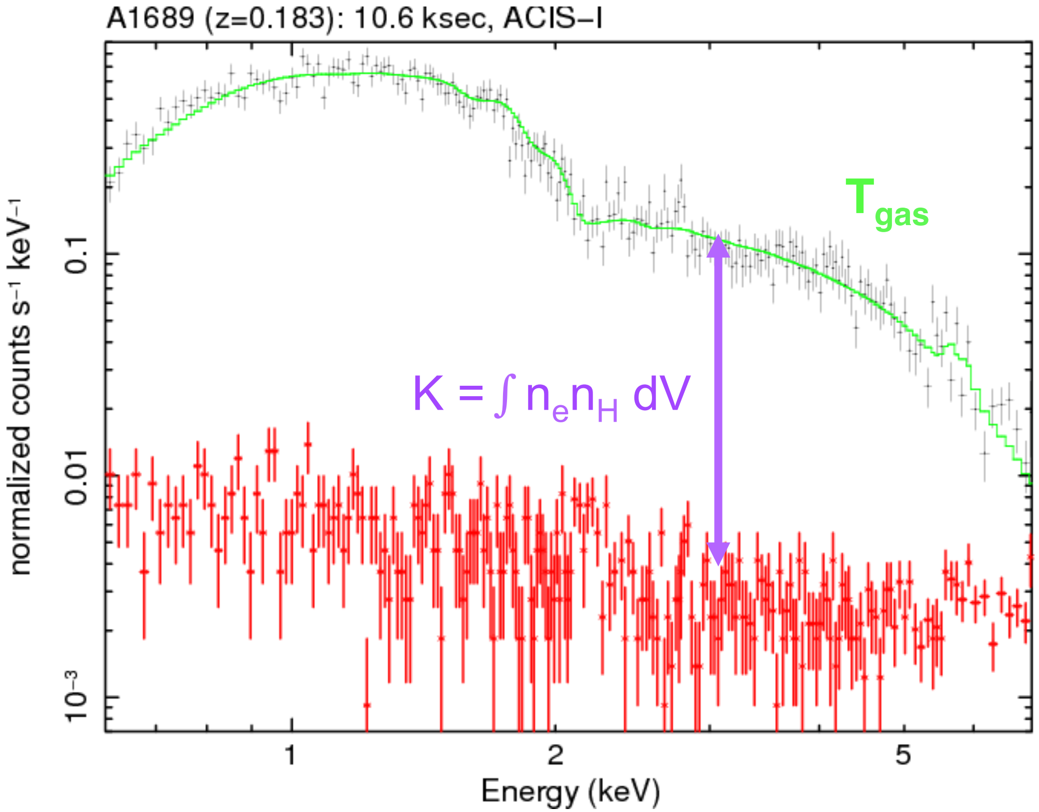
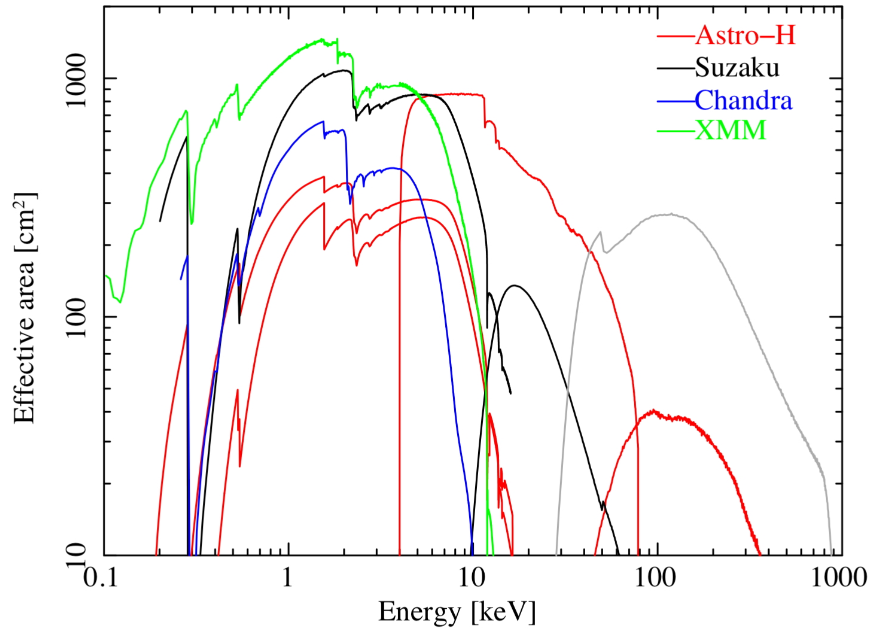
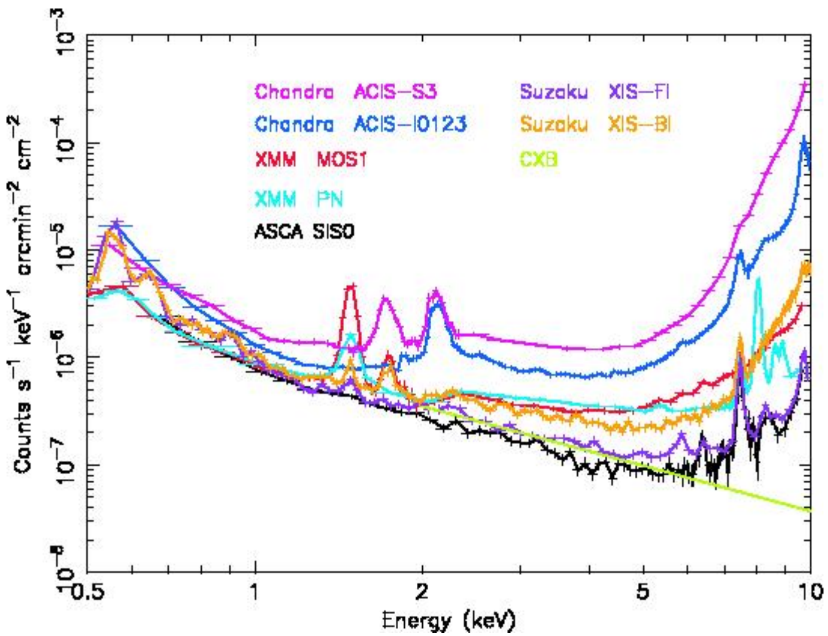


X-ray spectra of GC







- few tens of cts are needed to have detection & to make a measure of n_{gas} ($L_x \sim n_{gas}^2$)

- few hundreds of cts: T_{gas}

3.55 keV line

Note: the 3.5 keV band is ***free*** of *strong thermal lines* and *instrumental issues*

Bulbul E. et al. 2014, ApJ, 789, 13
(arXiv:1402.2301, submitted on 10 Feb 2014; **# cit: 263**)

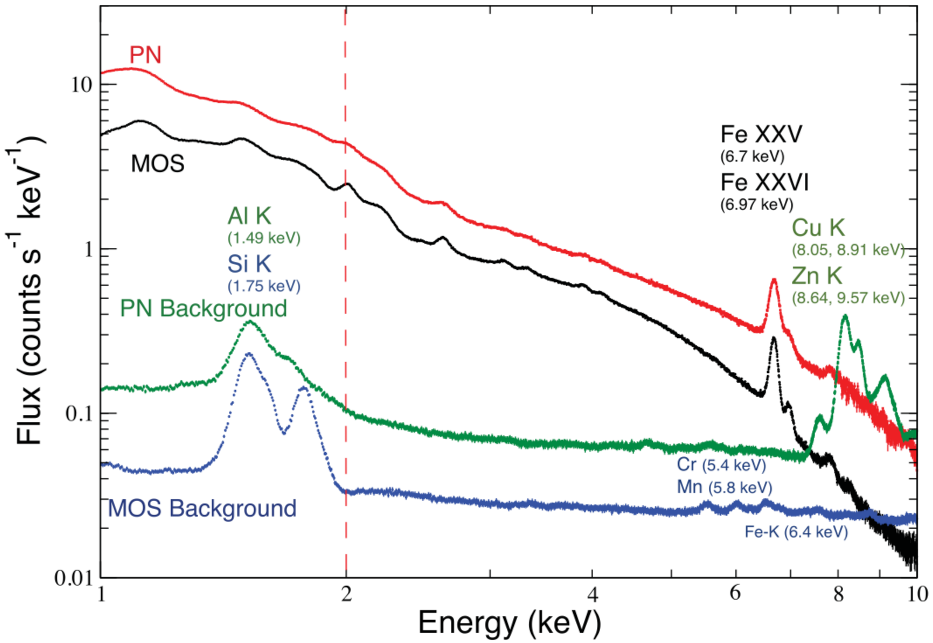
"We detect a weak unidentified emission line at E = (3.55–3.57) ± 0.03 keV **in a stacked *XMM-Newton* spectrum of 73 galaxy clusters spanning a z-range 0.01–0.35**. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at >3σ statistical significance in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the *Chandra* spectra of the Perseus Cluster. However, it is very weak and located within 50–110 eV of several known lines."

Boyarsky A. et al., 2014, PhRvL, 113, 1301B
(arXiv:1402.4119, submitted on 17 Feb 2014; **# cit: 254**)

"We report a weak line at 3.52 ± 0.02 keV in x-ray spectra of the **Andromeda galaxy** and the **Perseus galaxy cluster** observed by MOS and PN CCD cameras of *XMM-Newton*. It becomes stronger towards the centers of the objects; is stronger for Perseus than for M31; is absent in the spectrum of a deep "blank sky" data set.

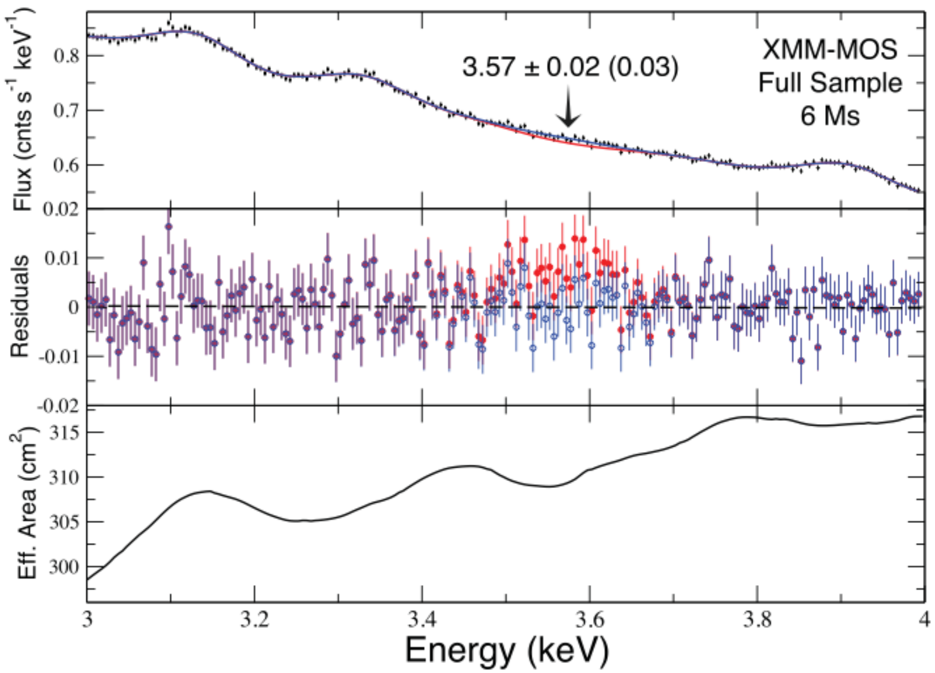
3.55 keV line

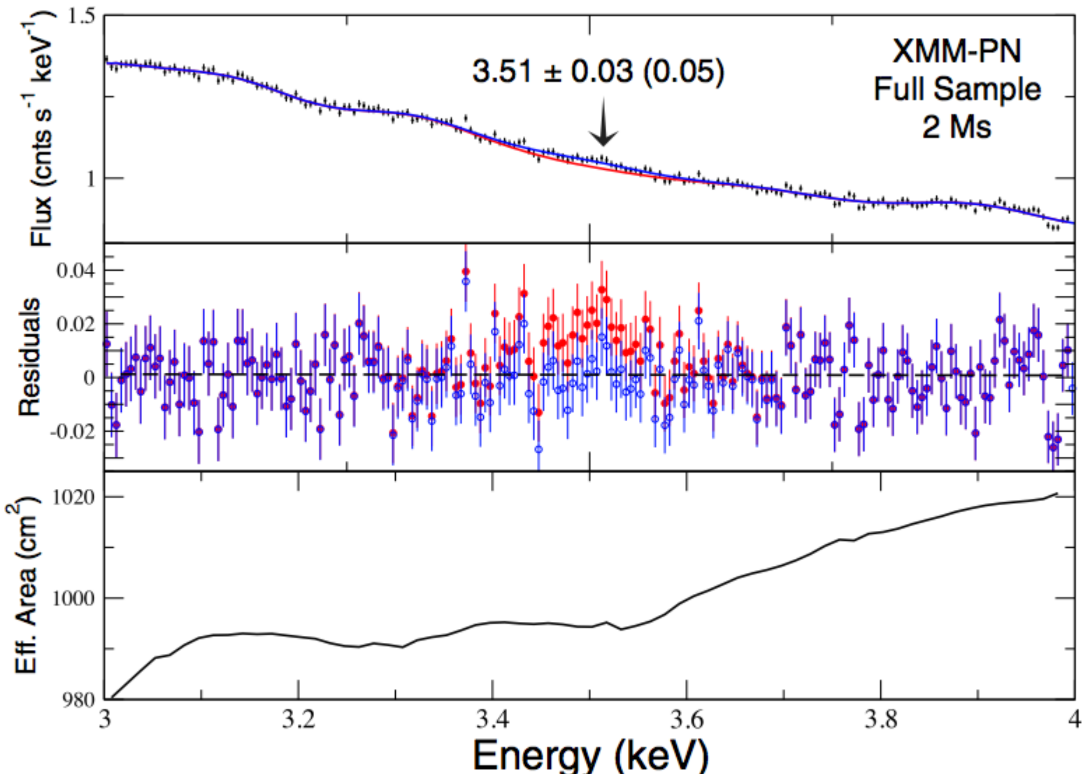
Bulbul+14



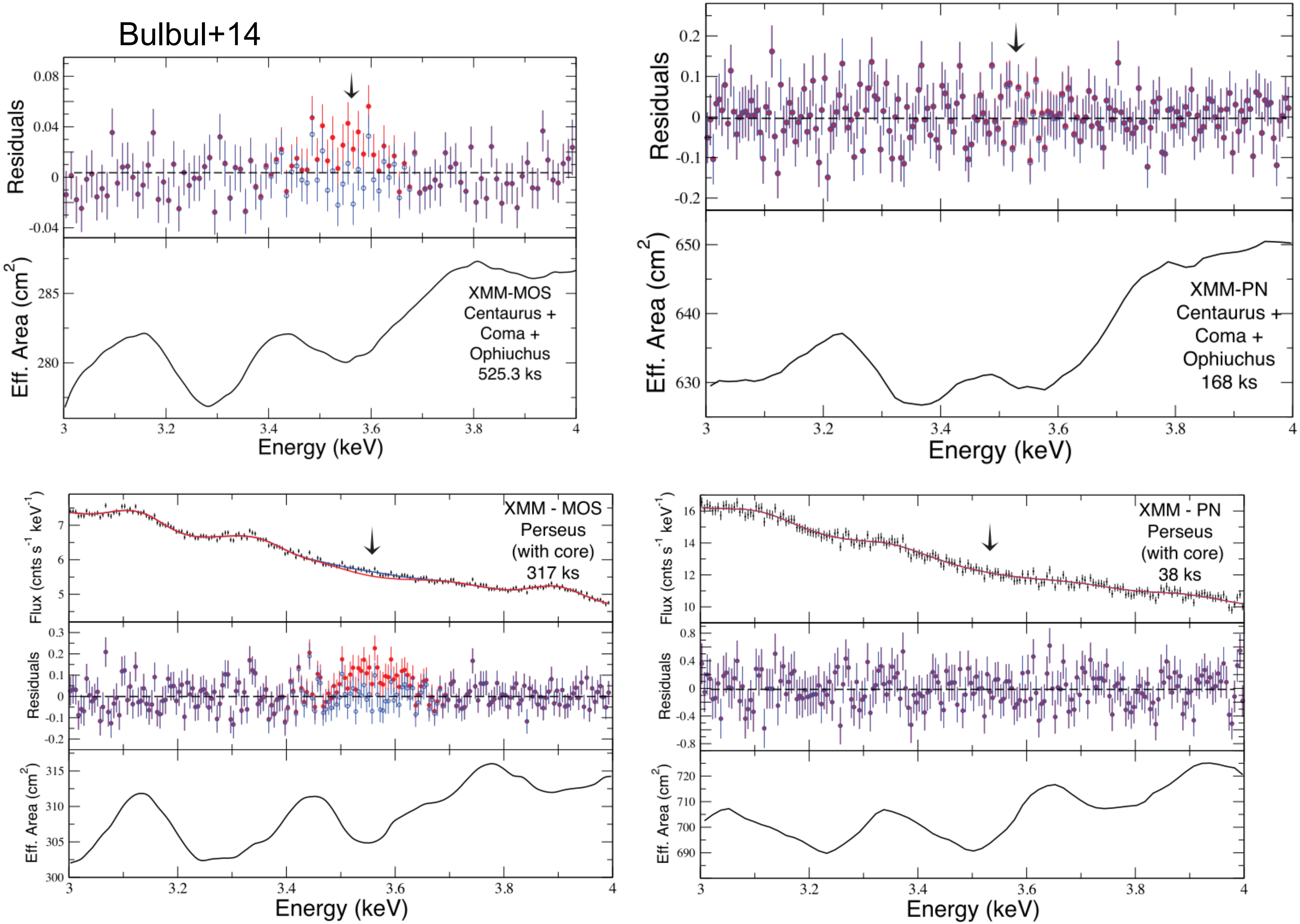
Stacked spectra in the source ref-frame, smearing uncalibrated features / instrumental / bkg lines.

The line is very weak (3-4σ), ~1% bump above the continuum. Critical to model it properly in the immediate vicinity of the line





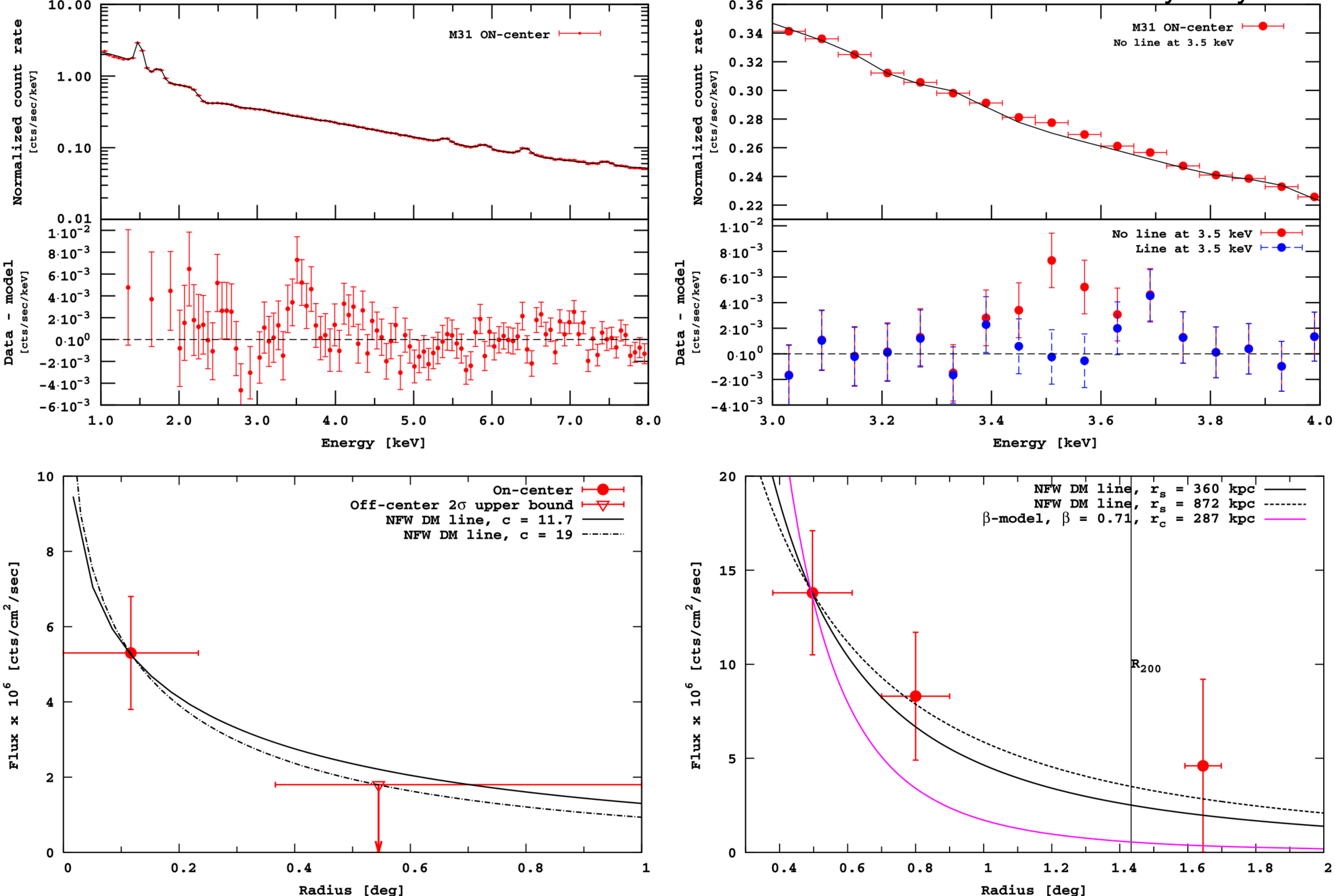
3.55 keV line



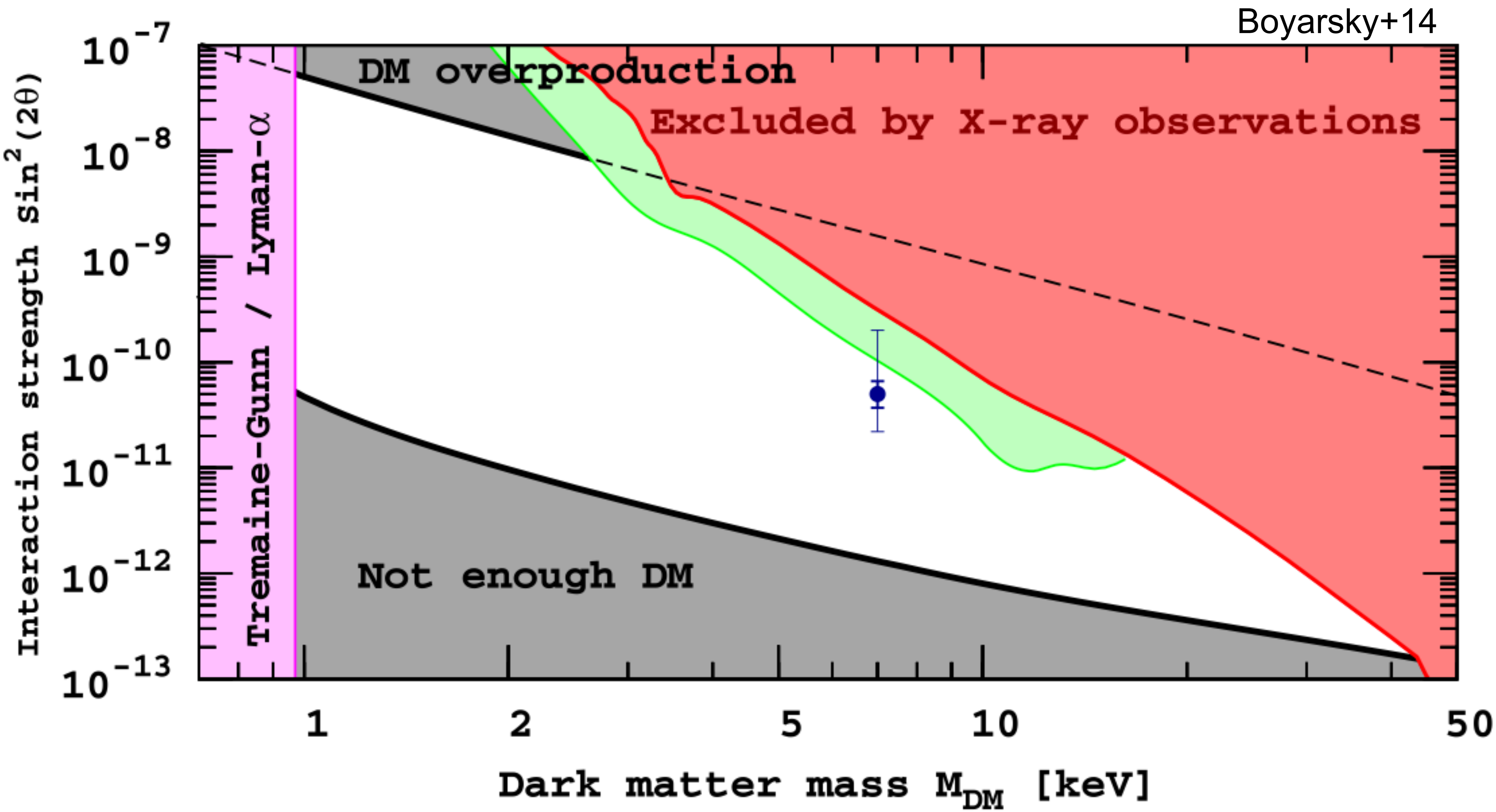
Bulbul+14
Residuals
Eff. Area (cm^2)
XMM-MOS
Centaurus +
Coma +
Ophiuchus
525.3 ks
Energy (keV)
XMM-PN
Centaurus +
Coma +
Ophiuchus
168 ks
Flux (cnts s^{-1} keV^{-1})
XMM - MOS
Perseus
(with core)
317 ks
XMM - PN
Perseus
(with core)
38 ks

3.55 keV line

Boyarsky+14

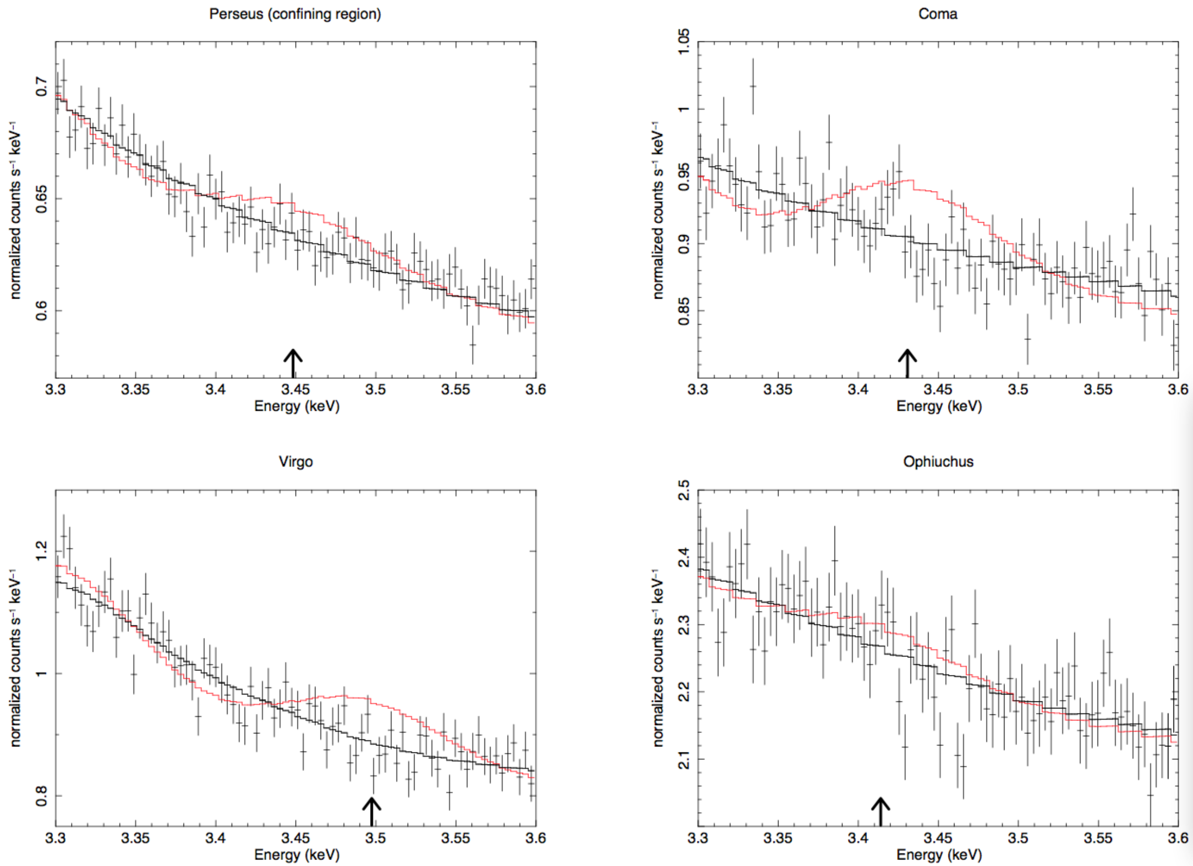


3.55 keV line


Boyarsky+14
DM overproduction
Excluded by X-ray observations
Not enough DM
Tremaine-Gunn / Lyman-α
Interaction strength Sin²(2θ)
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
1
2
5
10
50
Dark matter mass M_DM [keV]

3.55 keV line
is it there?

- *Urban+14*: deep *Suzaku* X-ray spectra for the central regions of the four X-ray brightest galaxy clusters: **Perseus**, Coma, Virgo and Ophiuchus.



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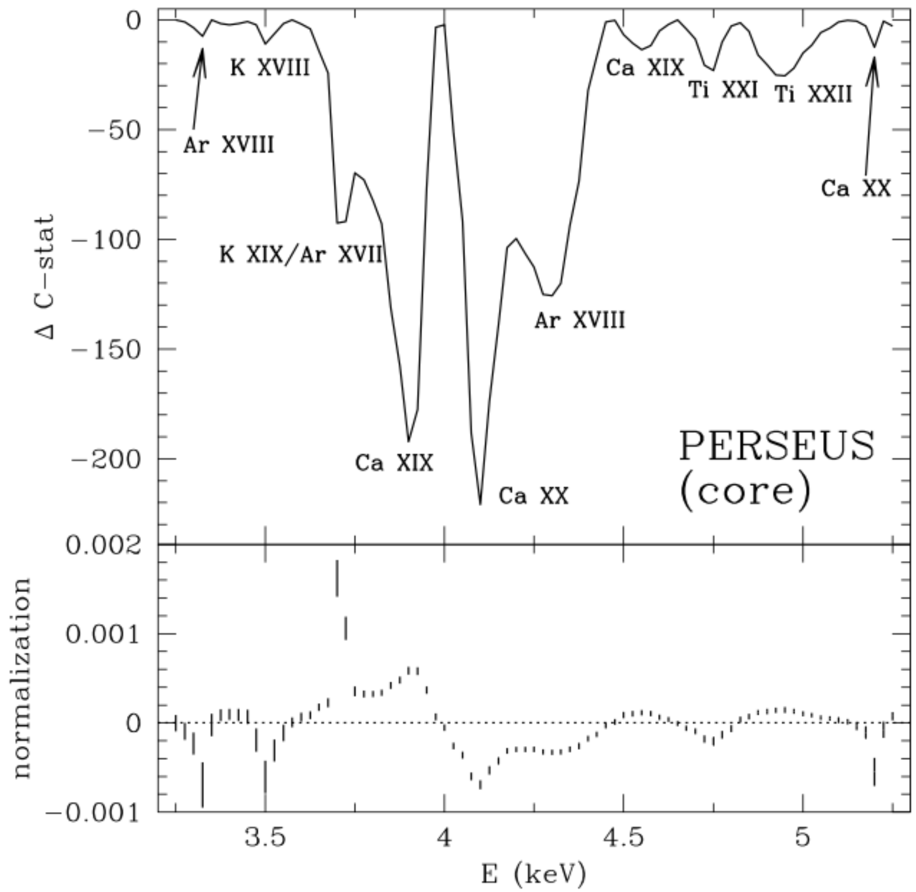

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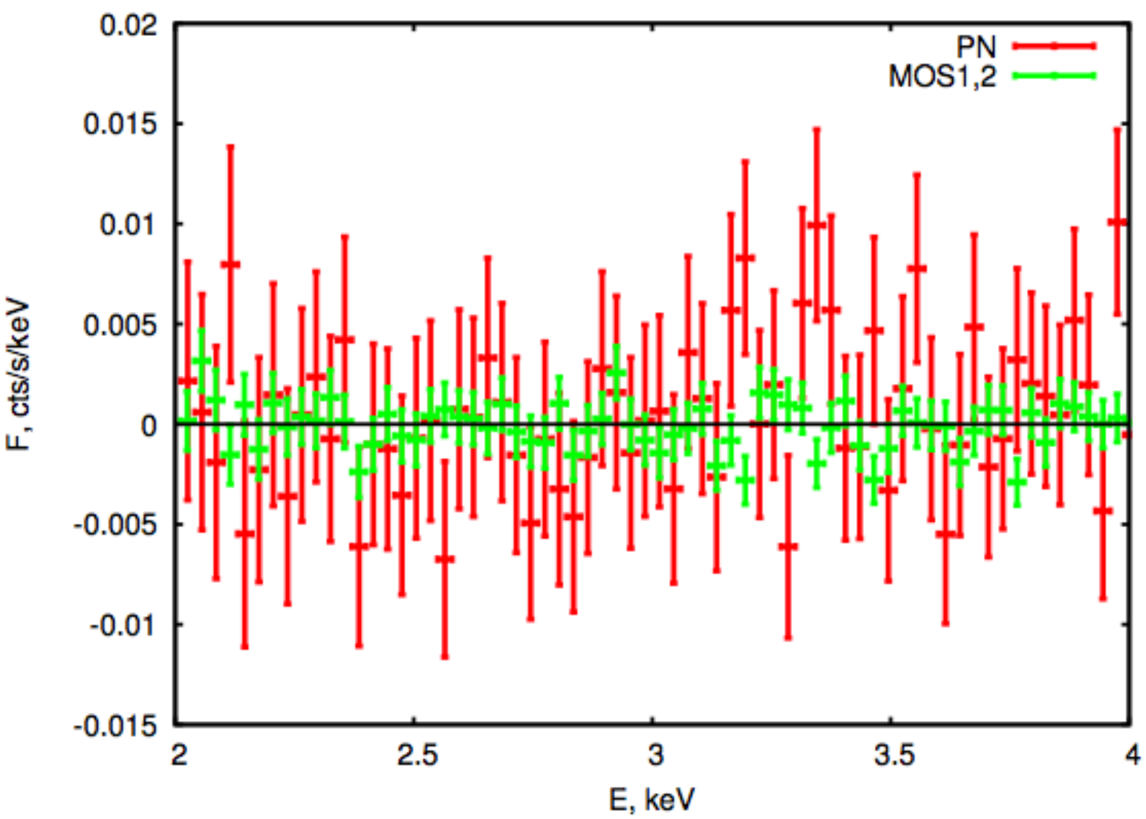

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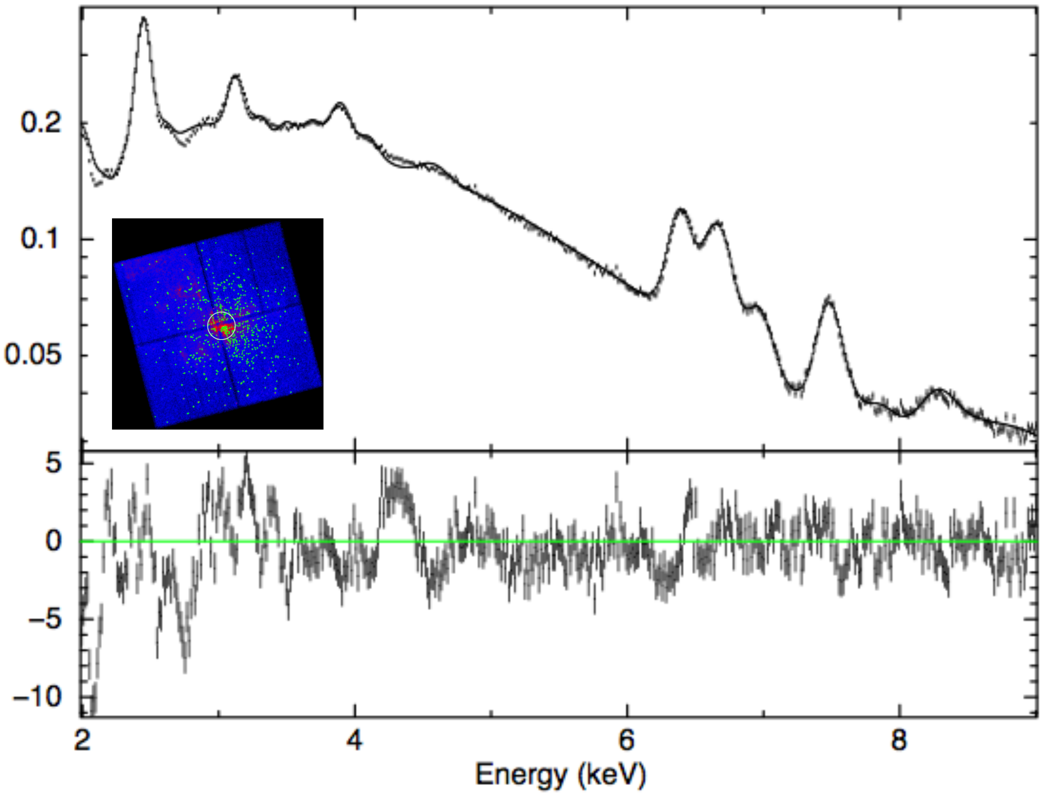

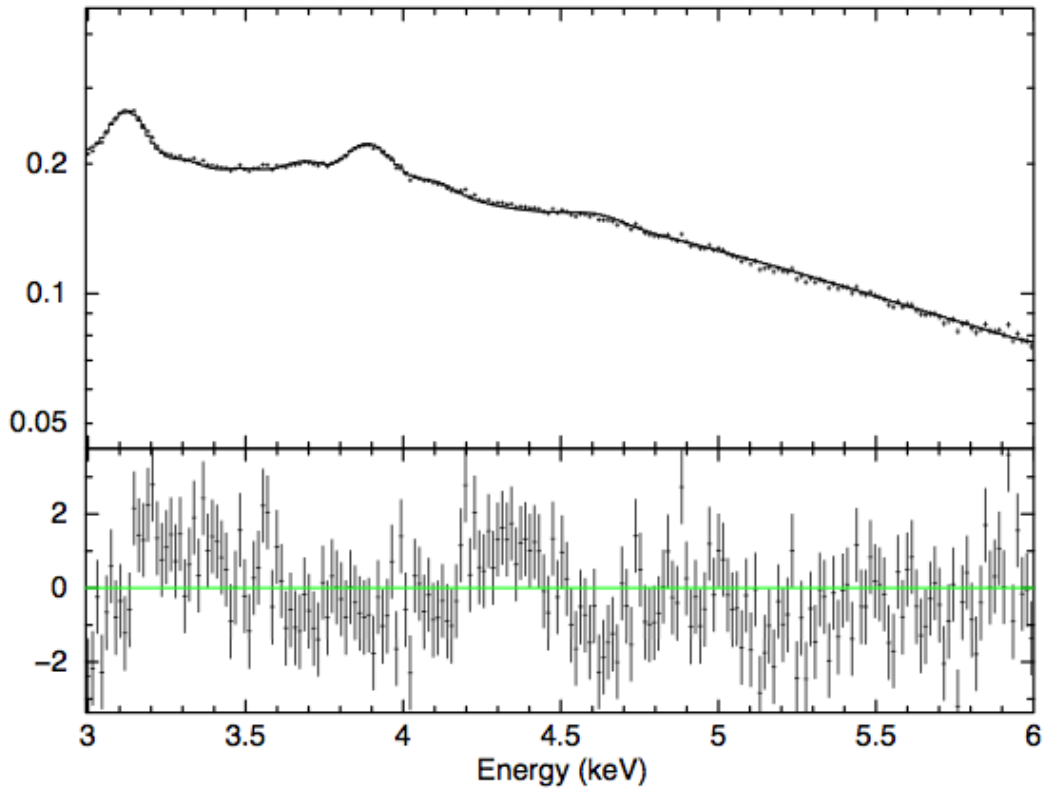

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- *Jeltema & Profumo+14*: **including K XVIII lines at 3.48 and 3.52 keV** provides a satisfactory fit to the *XMM* data of MW; no line in M31; ***detect a 3.55 keV line from Tycho SN, which points to possible systematic effects in the flux determination of weak lines***, or to relative elemental abundances vastly different from theoretical expectations

3.55 keV line
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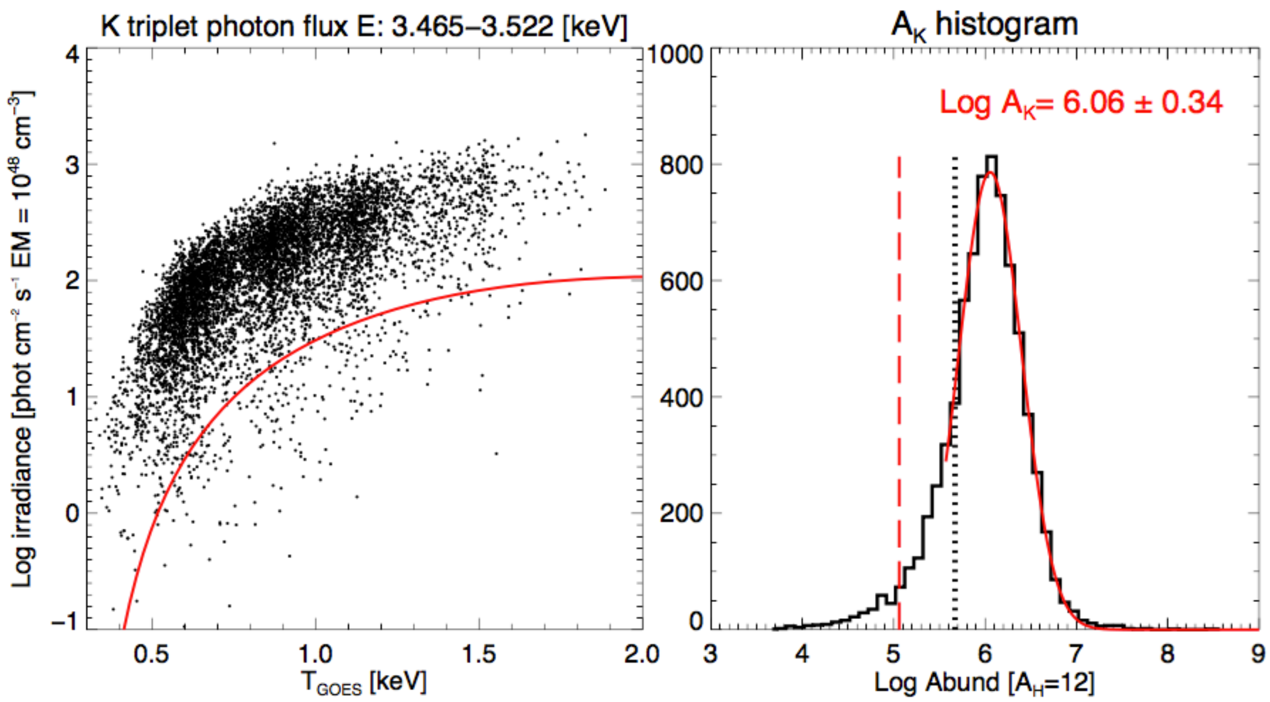

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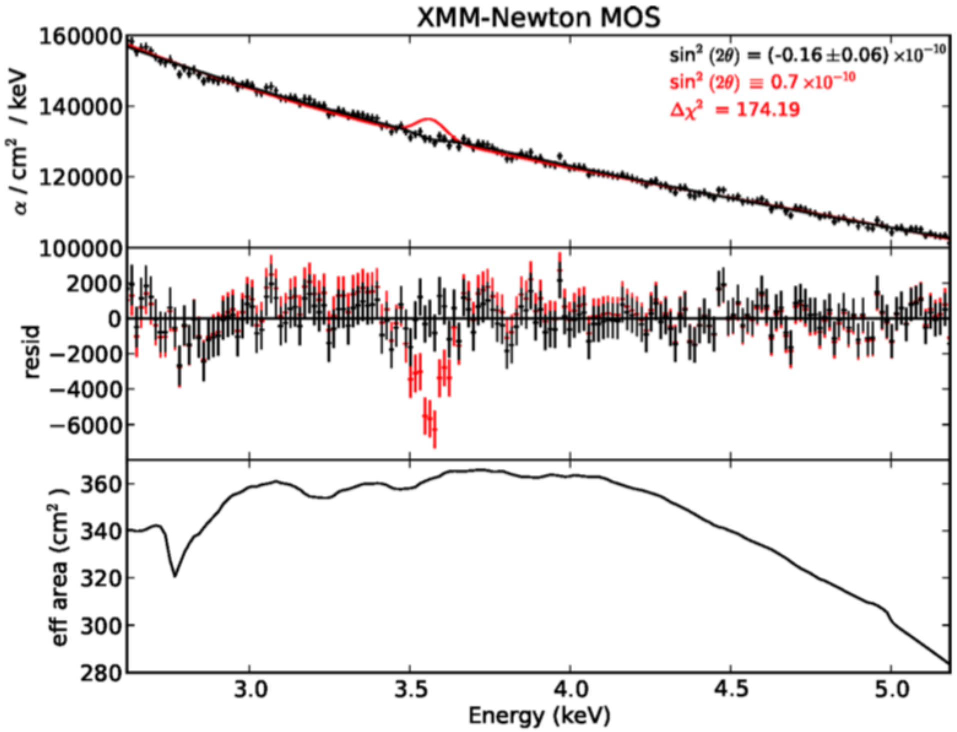

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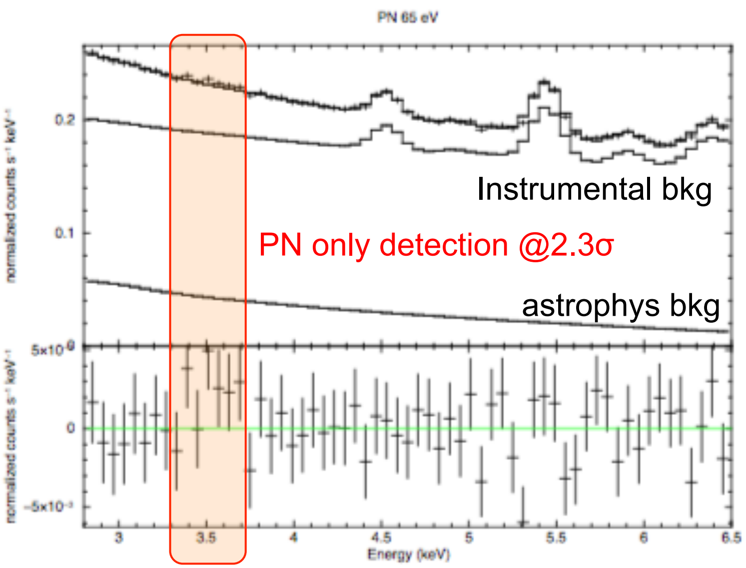

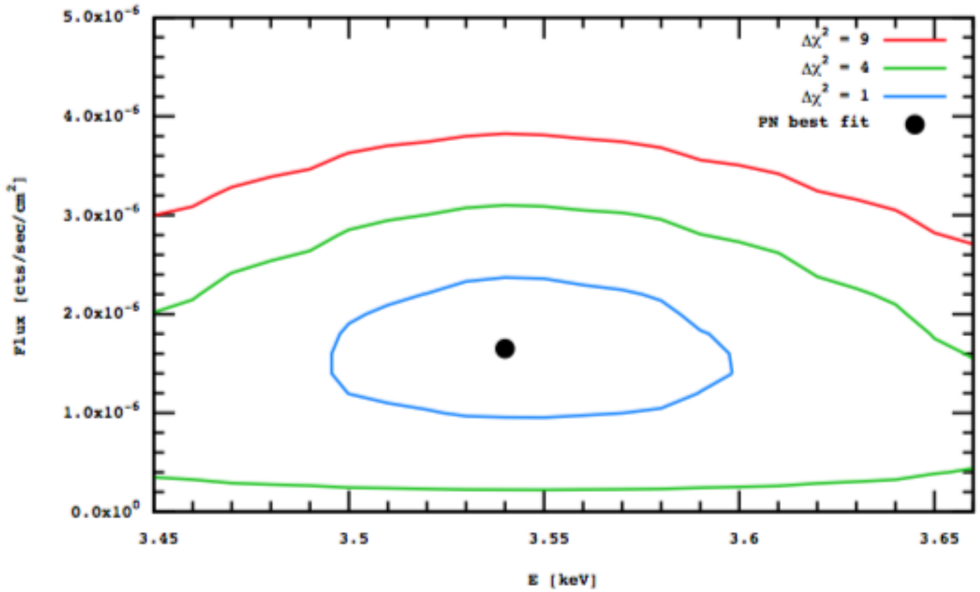

3.55 keV line *is it there?*

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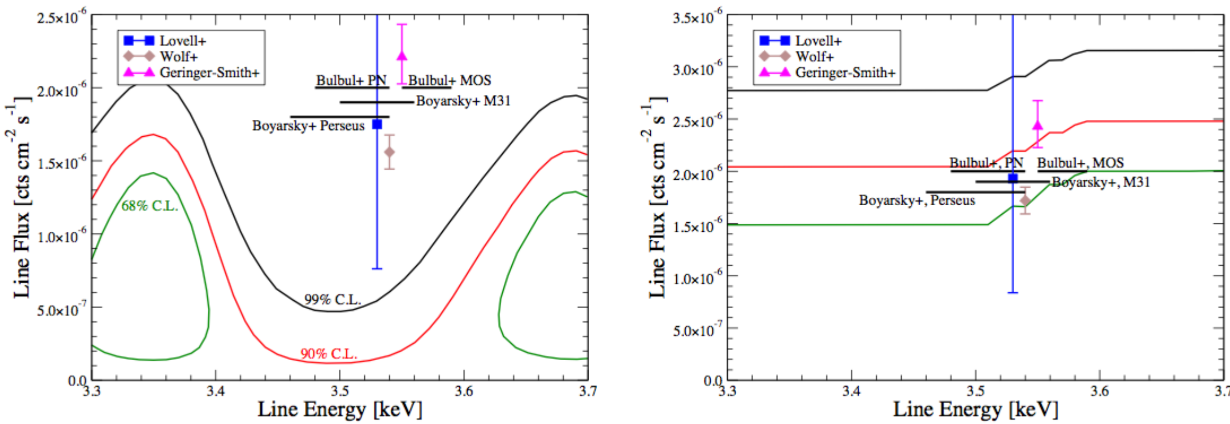

Figure 2. *Left*: Limits on the flux of a line in the energy range between 3.3 and 3.7 keV from MOS observations of the Draco dSph, at the 68%, 90% and 99% C.L. (green, red and black lines, respectively) and predictions for the flux of a 3.5 keV line assuming a dark matter decay origin for the line detected at that energy from stacked clusters of galaxies and from the Milky Way center (see text for details). The horizontal black lines indicate the 1σ energy range for the line position as inferred by Boyarsky et al. 2014 for Perseus (3.50 ± 0.04 keV) and for M31 (3.53 ± 0.03 keV) and by Bulbul et al. 2014 from cluster observations (3.57 ± 0.02 and 3.51 ± 0.03 keV for their "full sample" MOS and PN results, resepctively); *Right*: same, for PN observations (note the difference in vertical scale).

3.55 keV line
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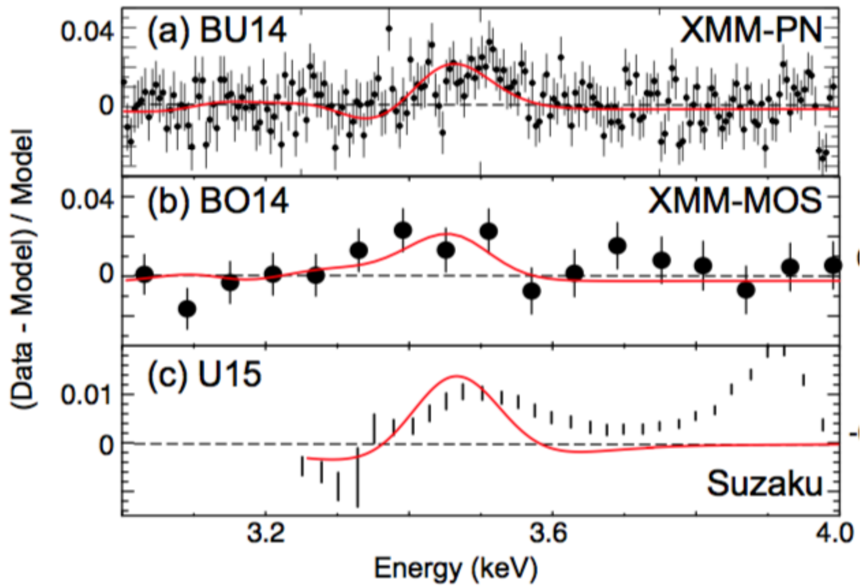
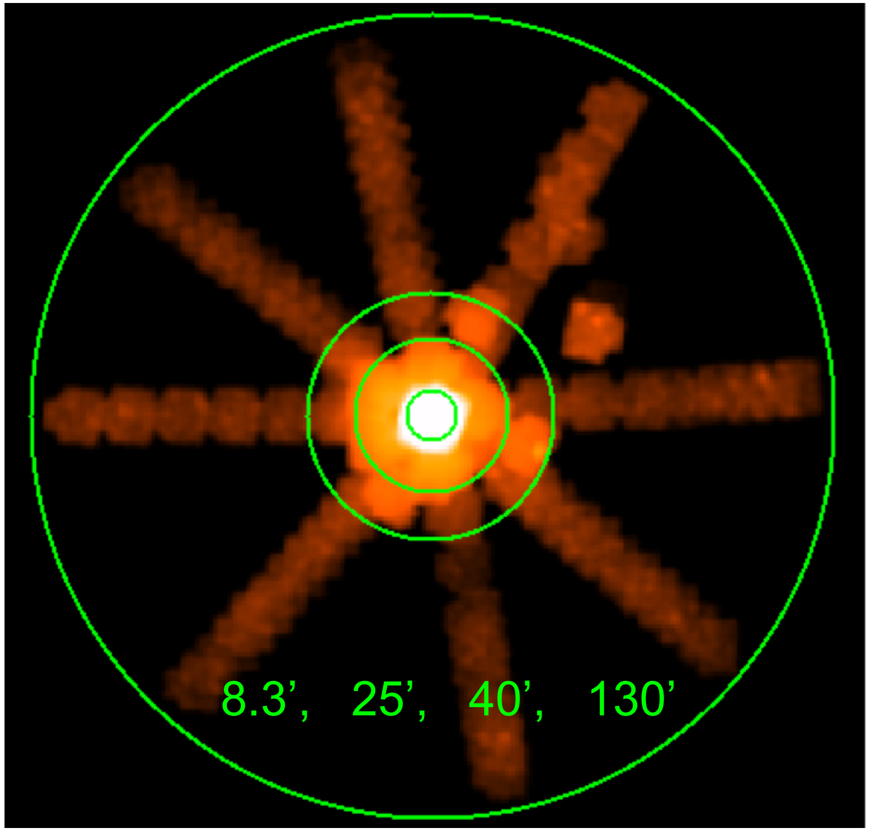
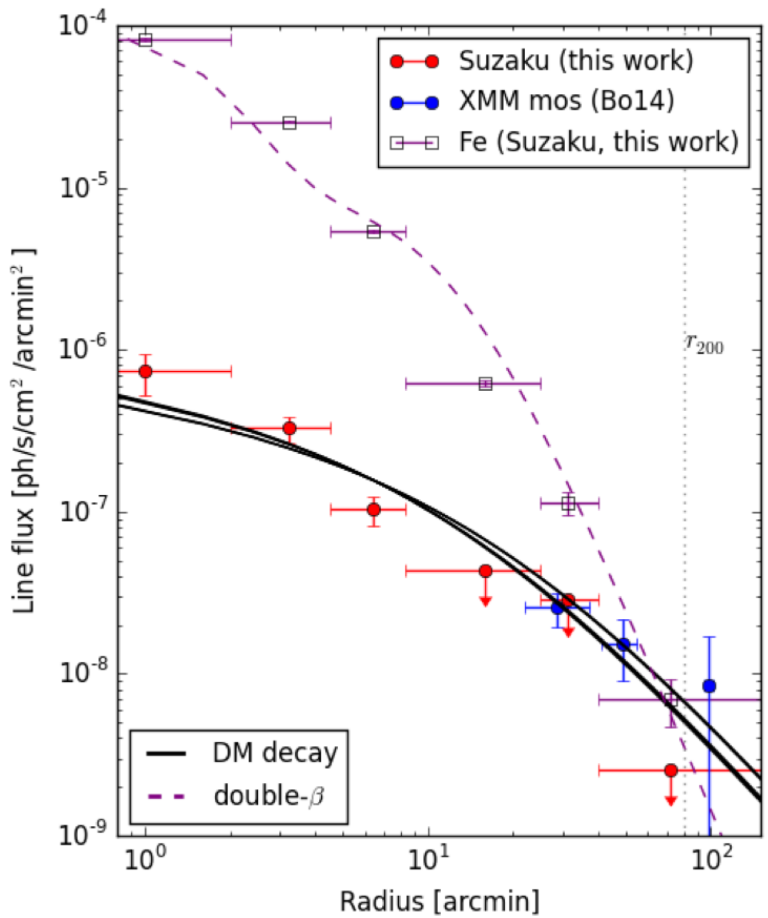
- *Gu, Kaastra +16*: novel plasma model **incorporating a CX component** obtained from theoretical scattering calculations; S XVI transitions from principal quantum numbers $n \geq 9$ to the ground. In this scenario, the observed 3.5 keV line flux in clusters can be naturally explained by an interaction in an effective volume of ~1 kpc^3 between a ~3 keV temperature plasma and cold dense clouds moving at a few hundred km/s



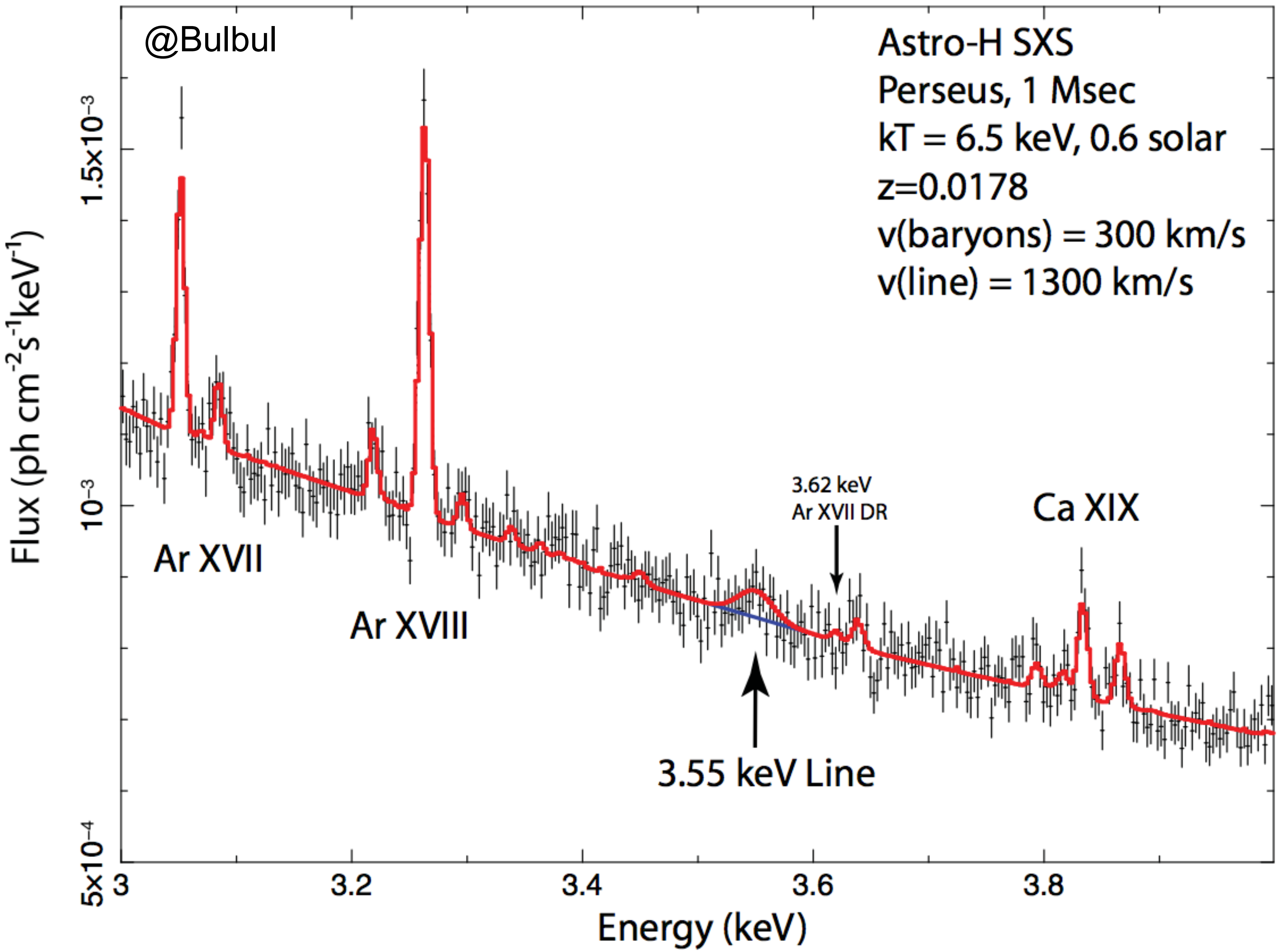
3.55 keV line
is it there?

Franse, Bulbul+16: “We examine **the flux distribution of the 3.55 keV line in the deep Suzaku observations of the Perseus cluster** in detail. **The 3.55 keV line is observed in three concentric annuli in the central observations**, ***although the observations of the outskirts of the cluster did not reveal such a signal***. We establish that these detections and the upper limits from the non-detections are consistent with a dark matter decay origin.”



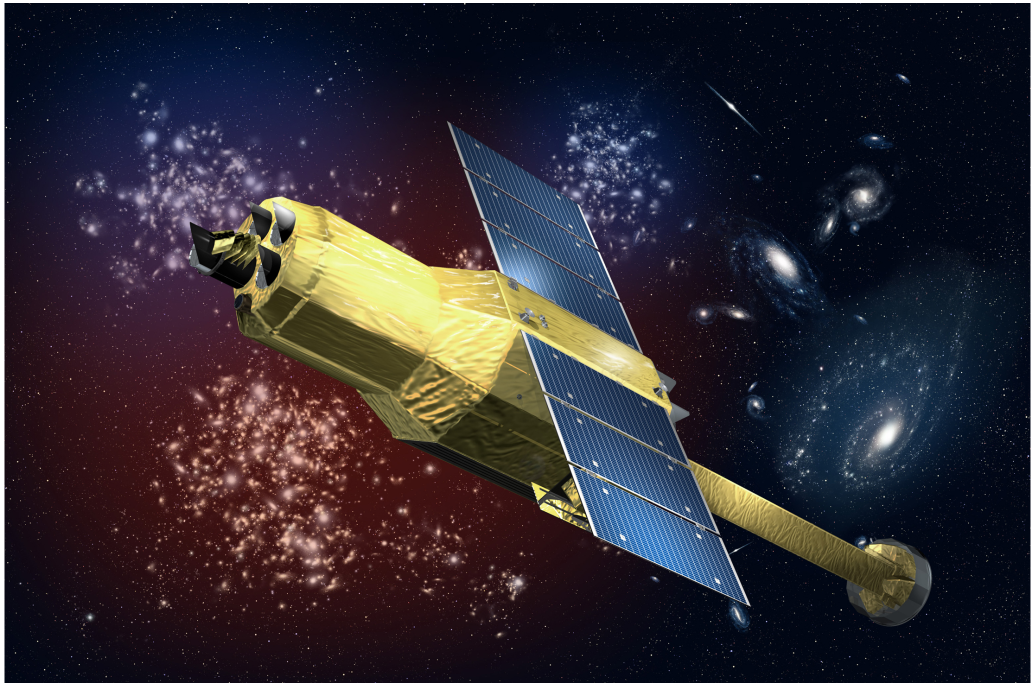


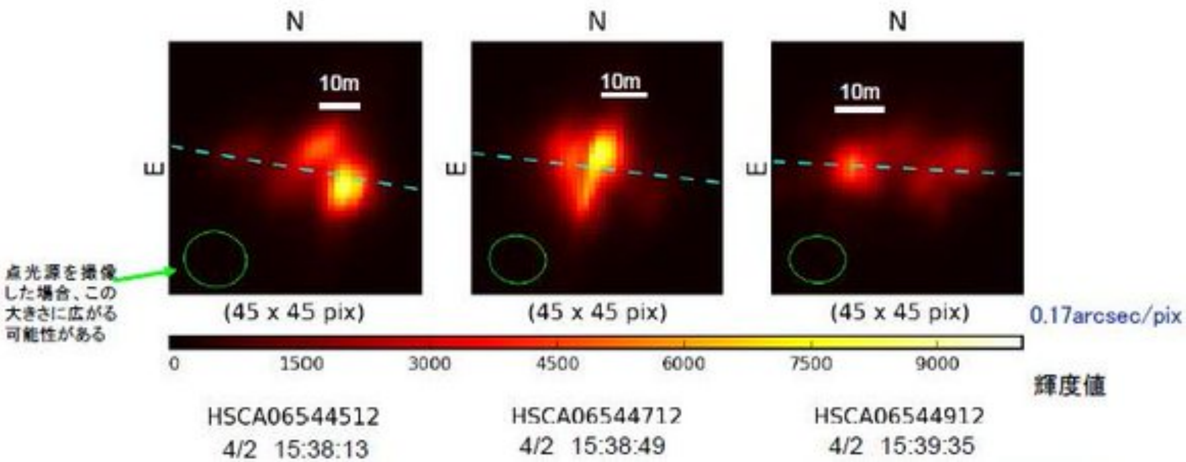
3.55 keV line


@Bulbul
Astro-H SXS
Perseus, 1 Msec
kT = 6.5 keV, 0.6 solar
z=0.0178
v(baryons) = 300 km/s
v(line) = 1300 km/s
Ar XVII
Ar XVIII
3.62 keV
Ar XVII DR
Ca XIX
3.55 keV Line
Flux (ph cm-2s-1keV-1)
1.5×10-3
10-3
5×10-4
3
3.2
3.4
3.6
3.8
Energy (keV)

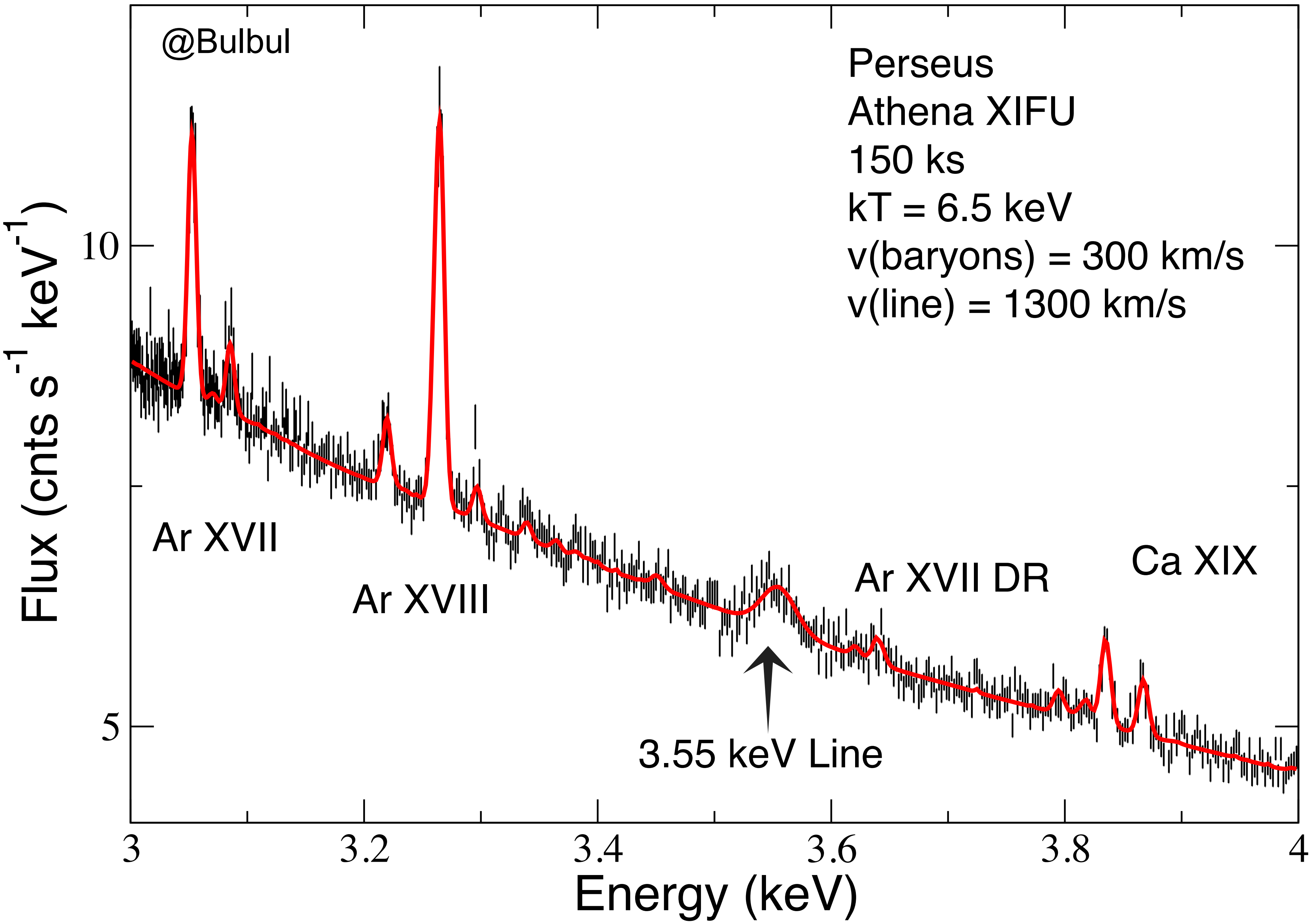
ASTRO-H / Hitomi

Launched from JAXA on Feb 17th 2016, on March 26th experienced an "attitude anomaly" as consequence of a major event that put the satellite tumbling in a different orbit; few pieces separated from main body (EOB? Solar panels?); difficult to communicate





3.55 keV line

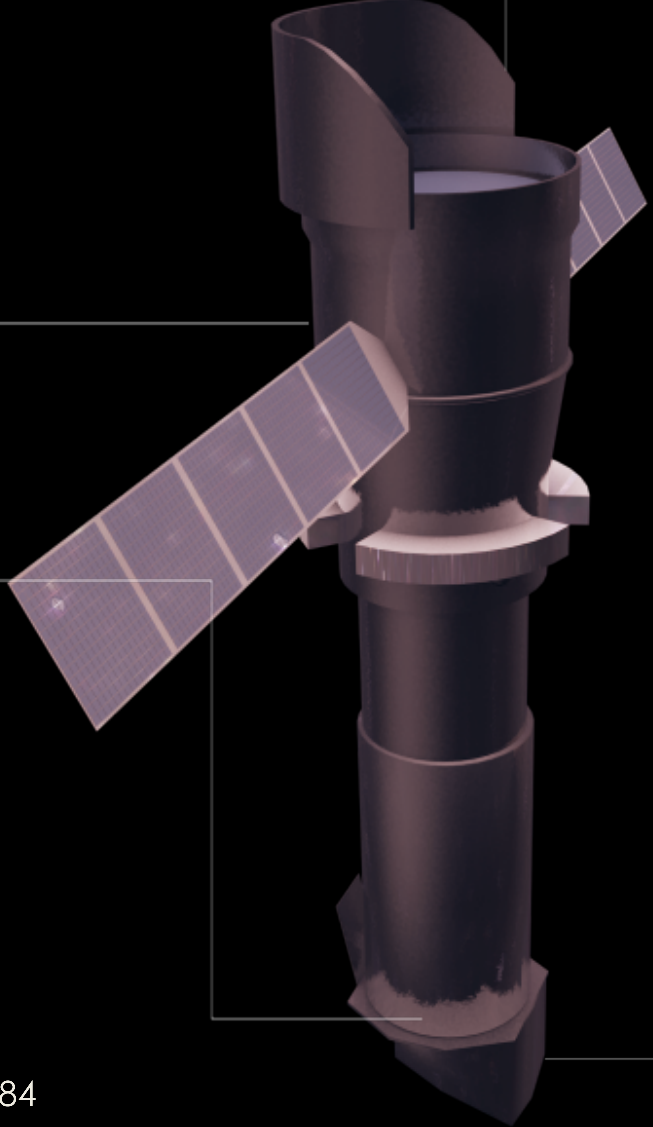

@Bulbul
Perseus
Athena XIFU
150 ks
kT = 6.5 keV
v(baryons) = 300 km/s
v(line) = 1300 km/s
Ar XVII
Ar XVIII
Ar XVII DR
Ca XIX
3.55 keV Line
10
5
3
3.2
3.4
3.6
3.8
4
Energy (keV)
Flux (cnts s^{-1} keV^{-1})

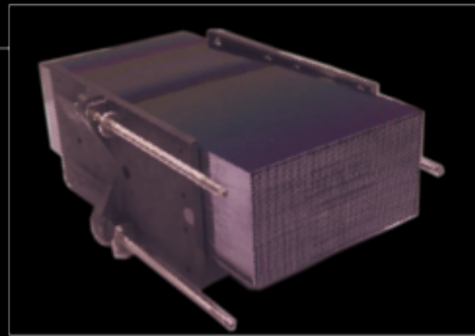
ATHENA

The Athena Observatory

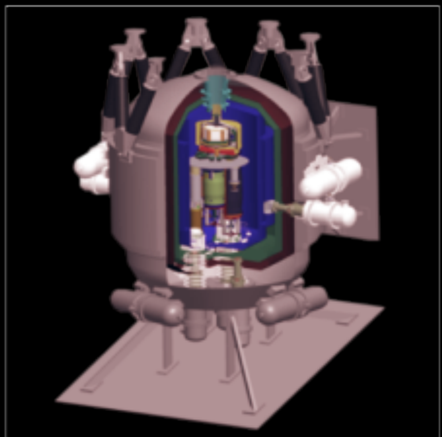
Willingale et al, 2013
arXiv1308.6785

L2 orbit Ariane V
Mass < 5100 kg
Power 2500 W
5 year mission

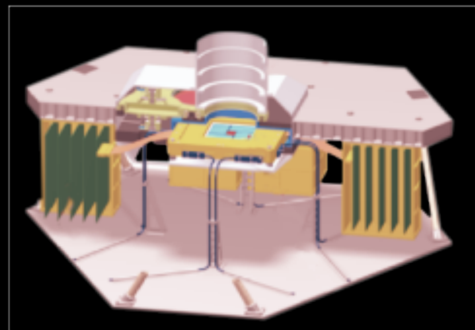




Silicon Pore Optics:
$2\ m^2$ at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: $3\ 10^{-17}$ erg $cm^{-2}\ s^{-1}$



X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk



Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin
High countrate capability

Barret et al., 2013 arXiv:1308.6784

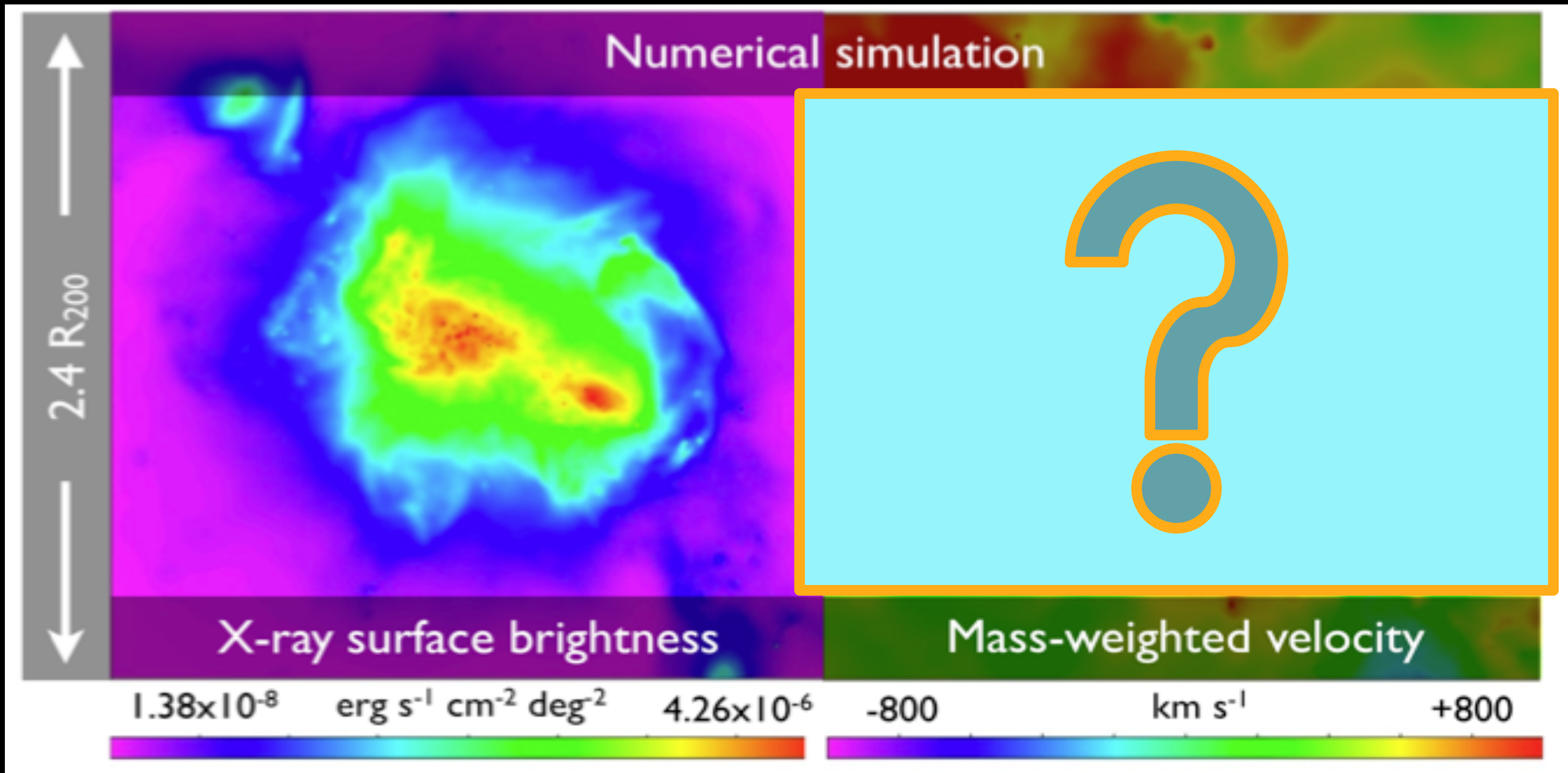
Rau et al. 2013 arXiv1307.1709

ATHENA

The formation and evolution of clusters and groups of galaxies

How and when was the energy contained in the hot intra-cluster medium generated?

Ettori, Pratt et al., 2013 arXiv1306.2322



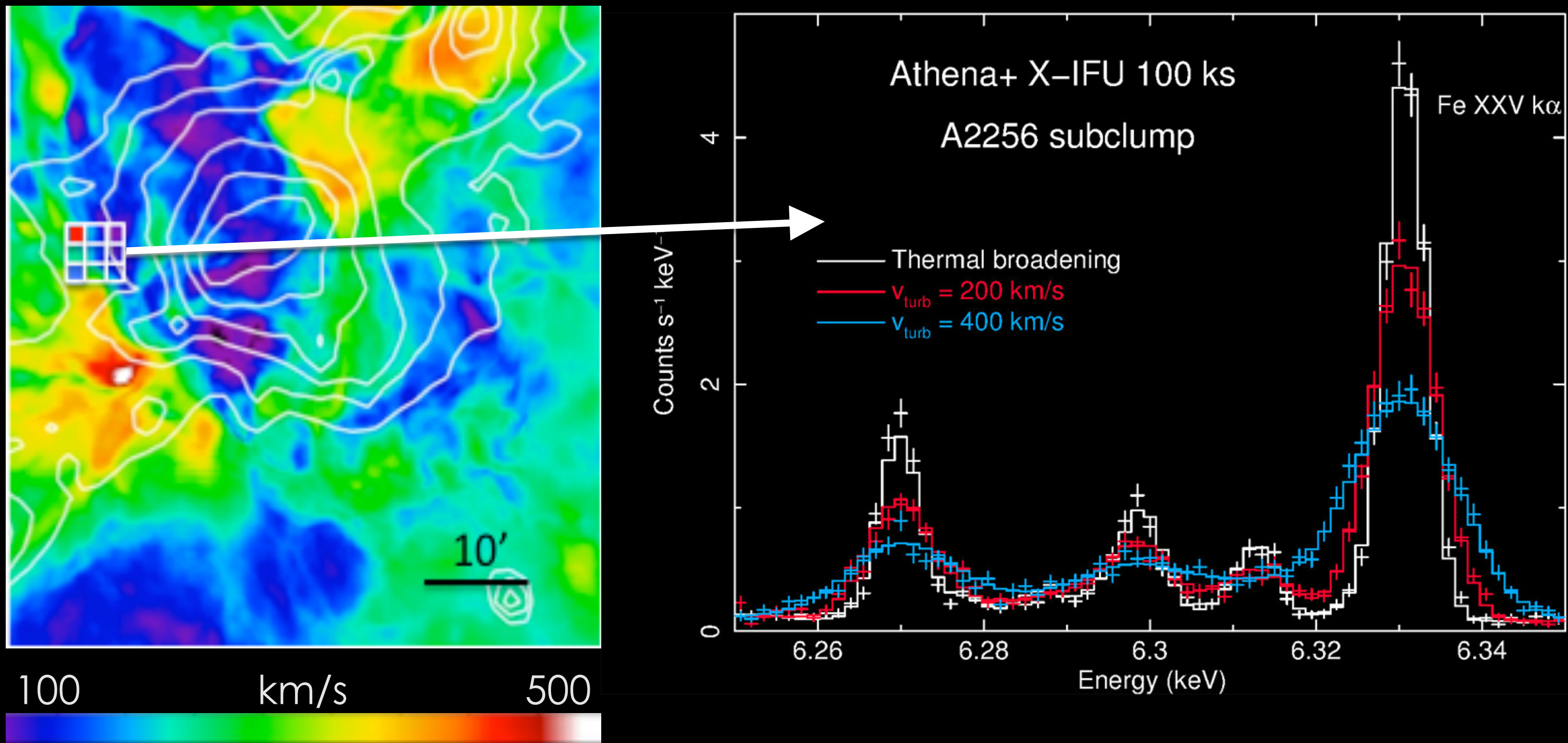
How does ordinary matter assemble into the large-scale structures that we see today?

The formation and evolution of clusters and groups of galaxies

How and when was the energy contained in the hot intra-cluster medium generated?

Simulated Velocity map

Ettori, Pratt, et al., 2013 arXiv1306.2322



Bulk motion and turbulent broadening of FeXXV Ka line.

With 100k-sec X-IFU exposure, 0^{+20}, 200±5, 400±10 km/s can be resolved.

Soft Excess

Early detections of excess EUV radiation from Virgo and Coma clusters with the EUVE DS photometer
(0.07-0.25 keV; Lieu et al. 1996, Bowyer et al. 1996)

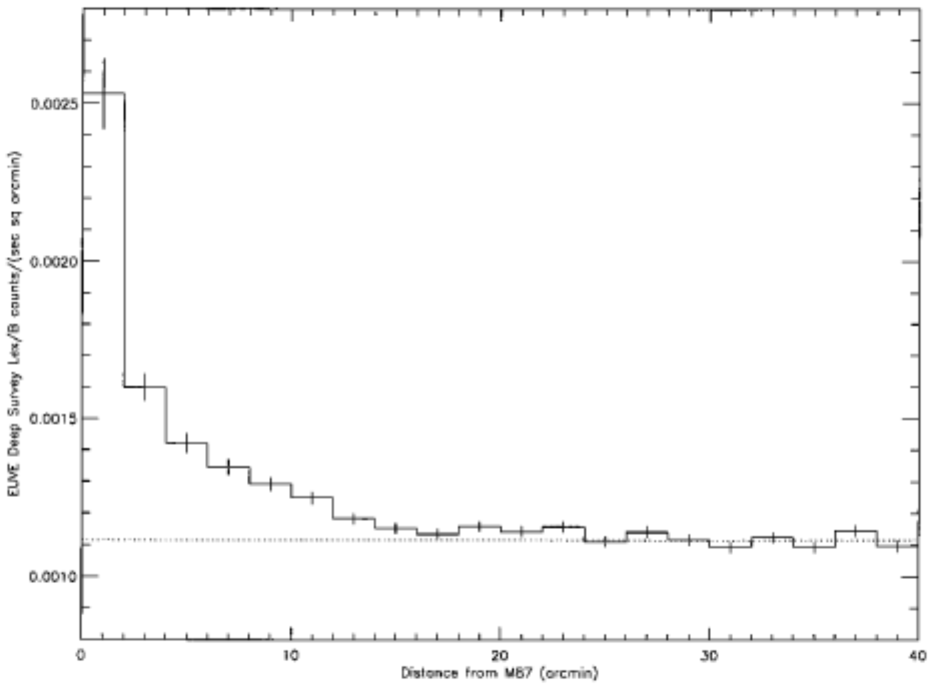


FIG. 1.—*EUVE* DS Lex/B filter count rates for concentric annuli centered at M87. Data from the innermost 2′ region are consistent with a point source. The region between 2′ and ~20′ corresponds to a diffuse excess (the EUV halo of M87). The background level is marked by a dotted line.

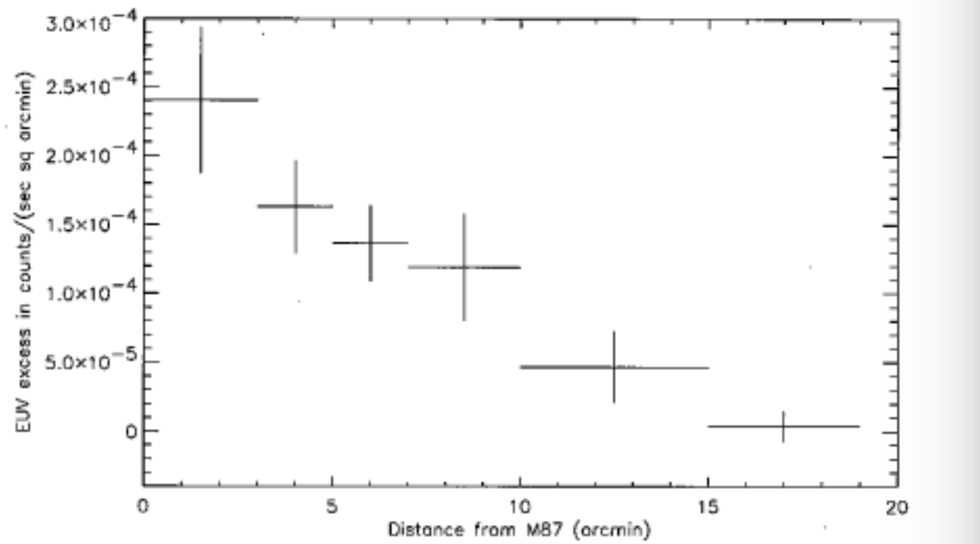


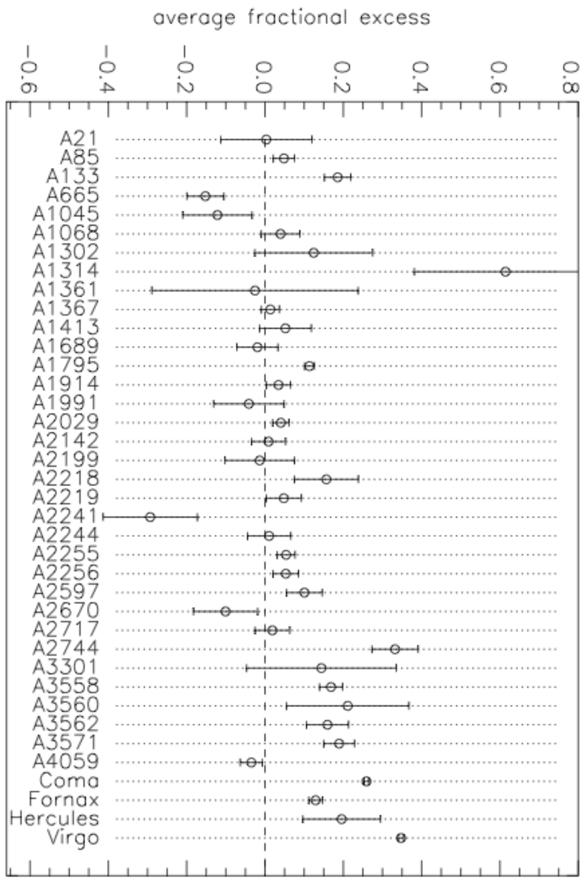
FIG. 3.—Radial profile of the surface brightness of "EUV excess," defined as the amount of diffuse emission within the DS Lex/B band above the best-fit single-temperature plasma model obtained by simultaneously fitting the DS data and the 0.18–2 keV PSPC data.

Much **controversy** about these detections:

1. Background subtraction: issue resolved with in-situ measurements at short offset from the clusters (Bowyer et al. 1999; Bonamente et al. 2001C)

2. Use of accurate HI Galactic column densities (e.g. Arabadjis & Bregman 1999; see case of AS1101, where change in n_H from DS=1.8e20 to LAB=1.15e20 bring sof/thermal from 2 to 1.15)

3. Use of accurate He cross sections. He is the main absorber of ¼ keV photons, and there is a long history of revisions of those cross-sections. Most accurate measurements by Wilms, Allen and McCrary (2000) and Yan et al. (1998) confirm the Morrison & McCammon (1983, WABS) cross-sections, while Baluchinska-Church & McCammon (1992, PHABS) has higher He cross-sections.



Ultimately the EUVE excesses were confirmed in a number of clusters, including Coma

Many detections with ROSAT, which is still to date the most suitable data to look for soft excess because of low background and wide field of view (e.g. Bonamente+02, 03)

Several detections with XMM, Suzaku and BeppoSAX (Nevalainen+03, 07, Kaastra +03, Finoguenov+03, Werner+07, Kawaharada+10; but see Takei+08, Bregman+03)

On average, the soft-excess emission ≤20% of the thermal emission

Soft Excess: Coma Cluster

Bonamente et al. (03, 09) analyzed several pointed ROSAT observations of the Coma cluster, including in situ background

* strong soft excess emission detected out to 1.5 degrees, or 2.6 Mpc (Ho=72 km/s/Mpc)
* difficult to explain the emission ***entirely*** with variation of Galactic n_H
* Thermal model for the excess emission (T=0.2 keV) preferred over PL model
* Mass budget depends on the geometry of the emitting gas
  - If the gas is within the volume of the cluster, M_{warm}/M_{hot}=0.75
  - If the gas is in filaments with density 1e-4 cm^{-3}, then M_{warm}/M_{hot}=3!!
* From RASS, emission extends up to 4deg in 0.25keV-R2 band

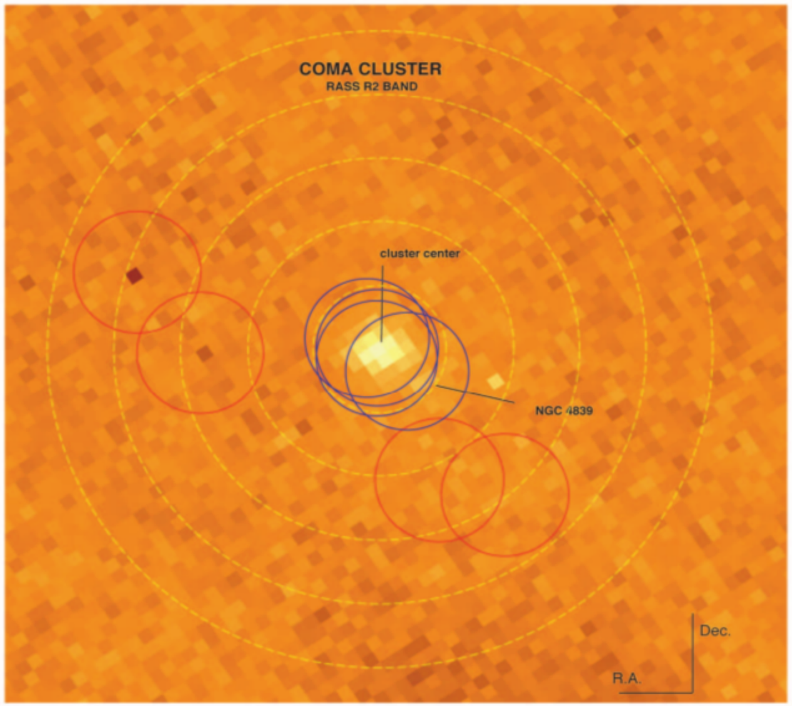


Fig. 2.—Location of *ROSAT* PSPC observations, overlaid on an RASS R2 band (0.15–0.3 keV) image of the diffuse emission of the Coma region. Dashed circles indicate distance from the cluster's center in intervals of 1°, blue circles represent the position of the pointed PSPC observations of Coma Cluster, and red circles are background observations.

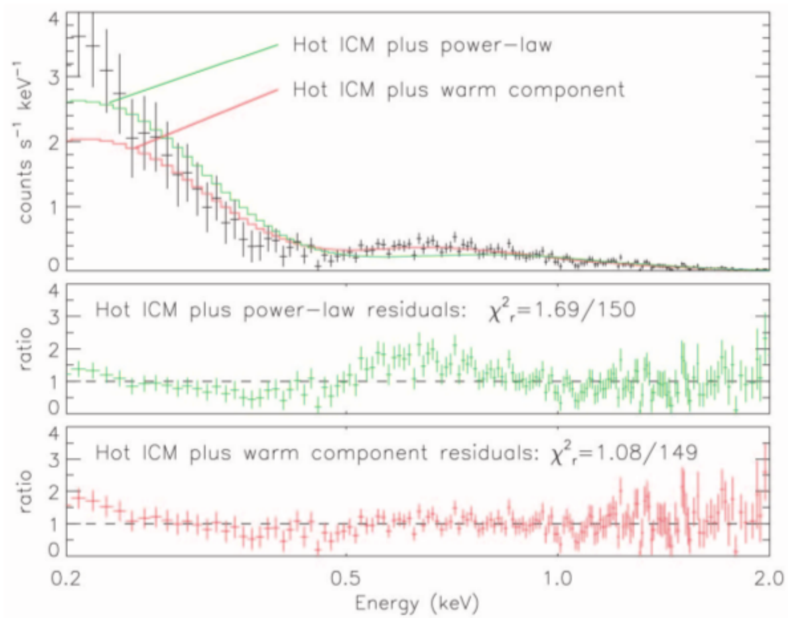


Fig. 6.—*ROSAT* PSPC spectrum of the 55′–70′ northeastern quadrant. In green is the hot ICM plus power-law model (§ 4.4), in red the hot ICM model plus a low-energy thermal component (§ 4.5).

NOTE: no current instrument has reliably detected emission lines from warm gas in Coma (or any other cluster):

- The ROSAT PSPC camera does not have sufficient spectral resolution.
- The XMM spectrometer has better resolution, and Kaastra et al. (2003) had a tentative detection of OVII emission lines in a few clusters.
- These lines were not confirmed by Suzaku (Werner 2007, Takei 2008)

The ROSAT data prefer a 0.2 keV model for the soft excess with a 1-10 % Solar abundance of heavy elements

There are strong azimuthal variations in the amount of soft excess emission

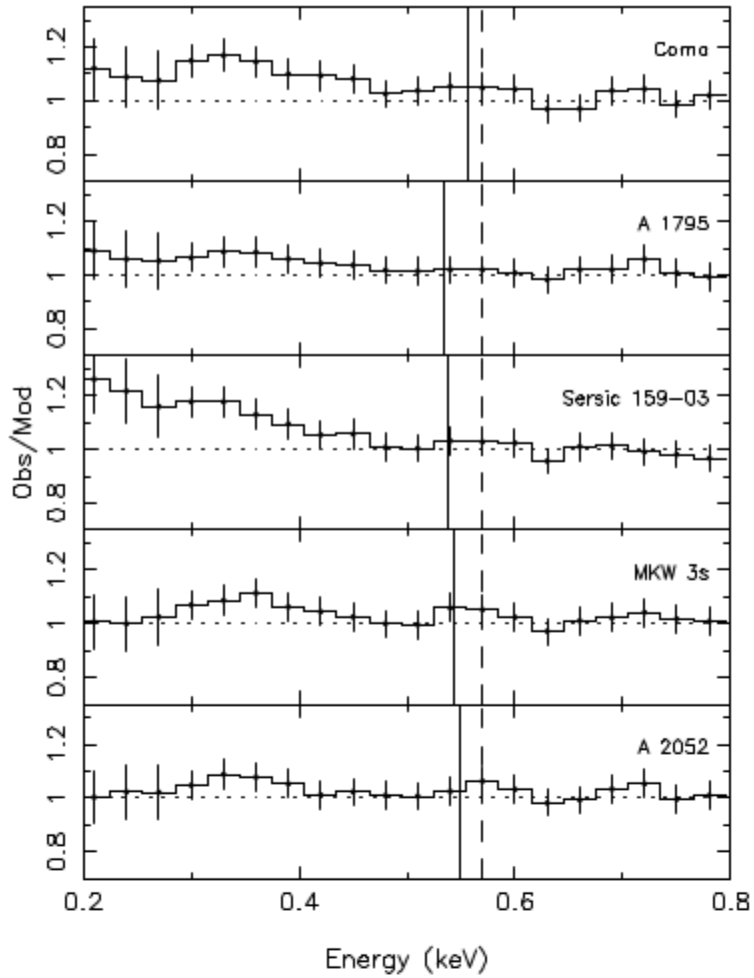
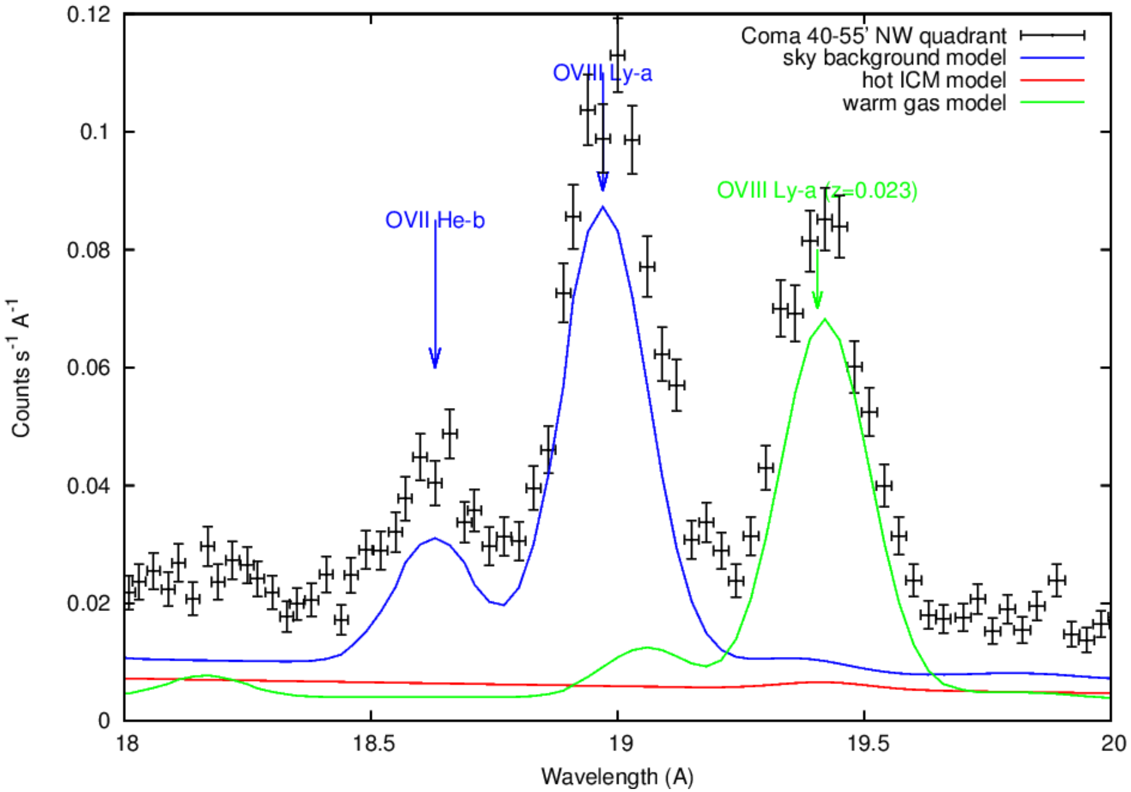


Fig. 7. Fit residuals with respect to the two temperature model for the inner 0.5–4.0′ part of five clusters. We have included the systematic background error in the fit, but have excluded it in this plot. The fit residuals for all instruments (MOS, pn) are combined. We indicate in each panel the position of the O VII triplet in the cluster restframe by a solid line and in our Galaxy's rest frame by a dashed line at 0.569 keV (21.80 Å).

Soft Excess: *ASTRO-H/Hitomi*

Major advances will be made by Astro-H/Hitomi, with its non-dispersive soft X-ray spectrometer (SXS) with micro-calorimeter detectors. Main features

* 5-7 eV resolution at 0.3-12 keV
* 0.5 arcmin angular resolution
* 2.85x2.85 sq. arcmin field of view
* Effective area at 1 keV of 200 cm^2
* “Low” background (Suzaku-type) compared to XMM or Chandra



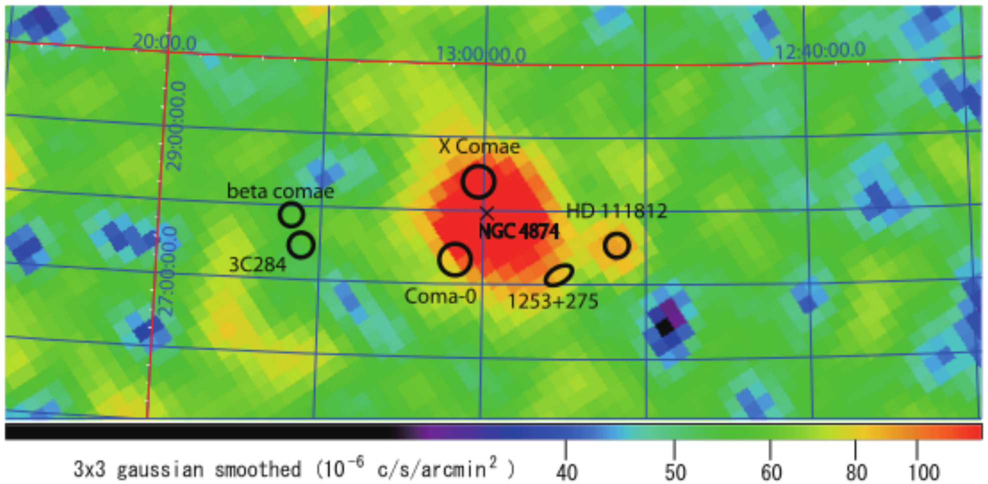
@Bonamente, 100ks simulation of the observed excess in Coma: T=0.2 keV, A=0.03 (3% Solar)

Soft Excess: *conclusions*

- ✓ Soft excess emission from galaxy clusters is a possible reservoir of warm baryons. Current X-ray missions favor thermal over non-thermal interpretation, but no conclusive evidence from emission or absorption lines yet.

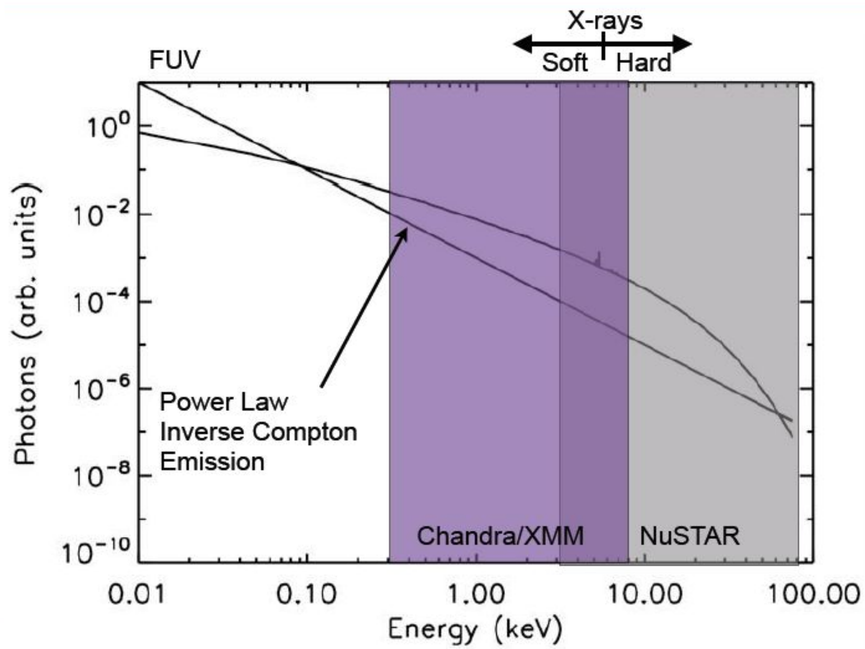
- ✓ It is possible that the soft excess is non-thermal in origin. A exciting possibility is the radiation from the interaction of a cosmic axion background (CAB) with magnetic fields in clusters Predictions of the theory are: Soft excess depends on the configuration of the magnetic field & it is independent of the ICM T & M. Angus et al. (2014) have performed complex simulations of the conversion of CAB into soft photons, which easily reproduce the observed Coma excess

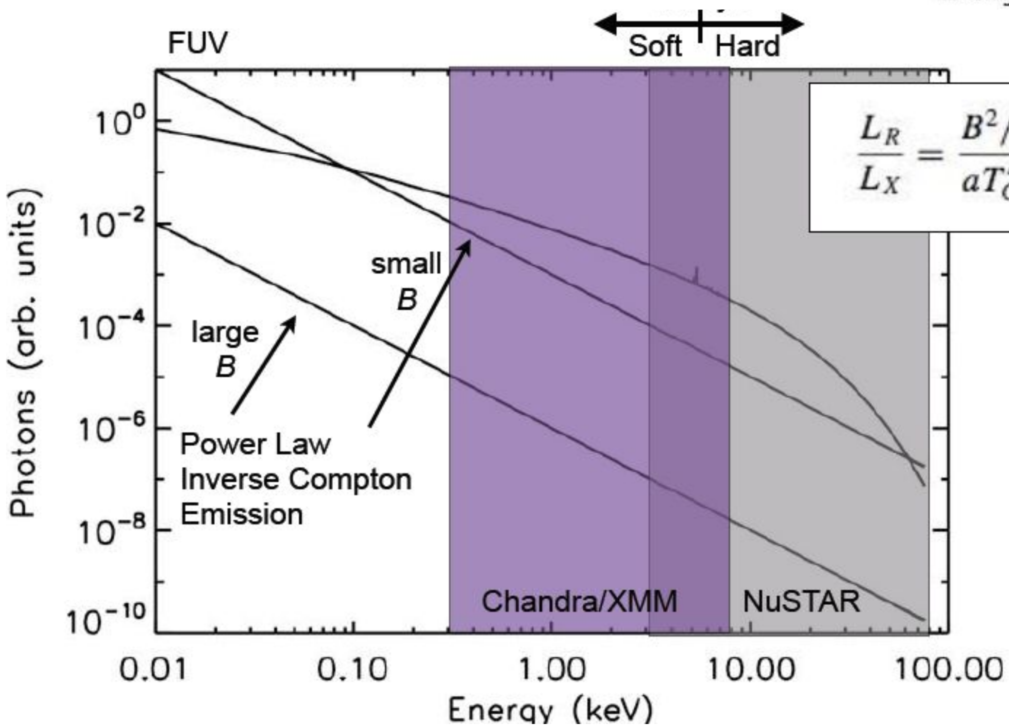
- ✓ The thermal nature of the excess is likely, but not confirmed yet. Observations with Astro-H will be able to provide conclusive evidence, both in emission and in absorption against background AGN's.



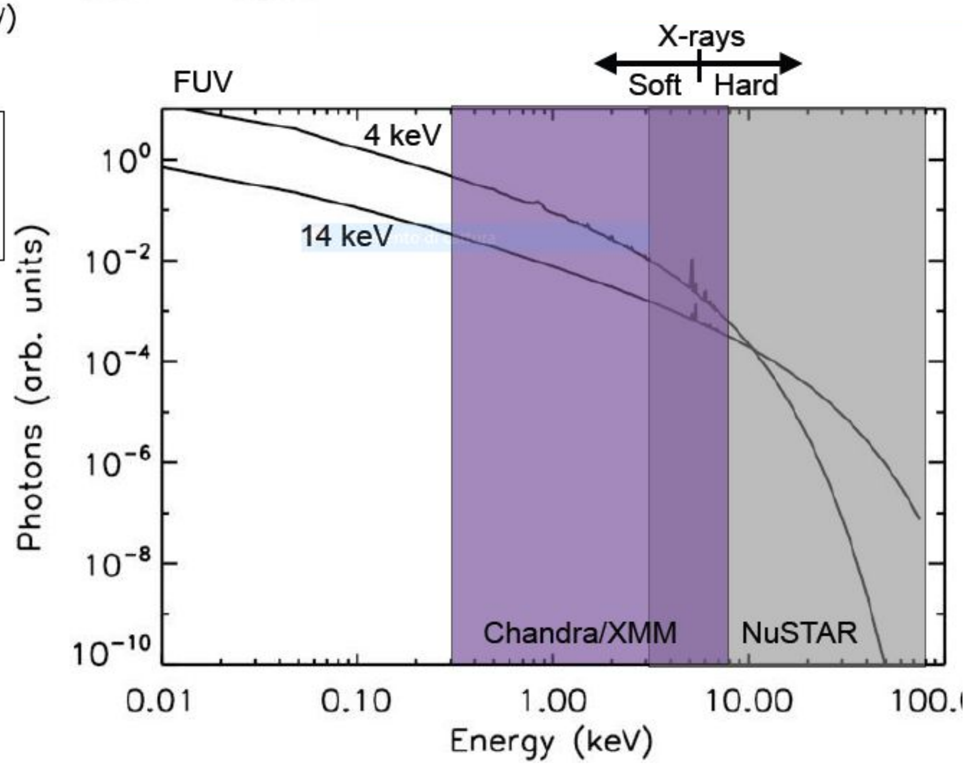
X Comae (z=0.091) in the background of the Coma cluster (z=0.023) can be used for absorption line spectroscopy. Takei+07 analyzed almost 500 ks of XMM RGS data (grating spectroscopy) and reported a tentative detection of Ne IX absorption lines in X Comae at the Coma cluster redshift. They also report a possible Ne IX emission lines in the CCD-resolution data, above the background which features the same line (indistinguishable in redshift at the CCD resolution)

Hard Excess

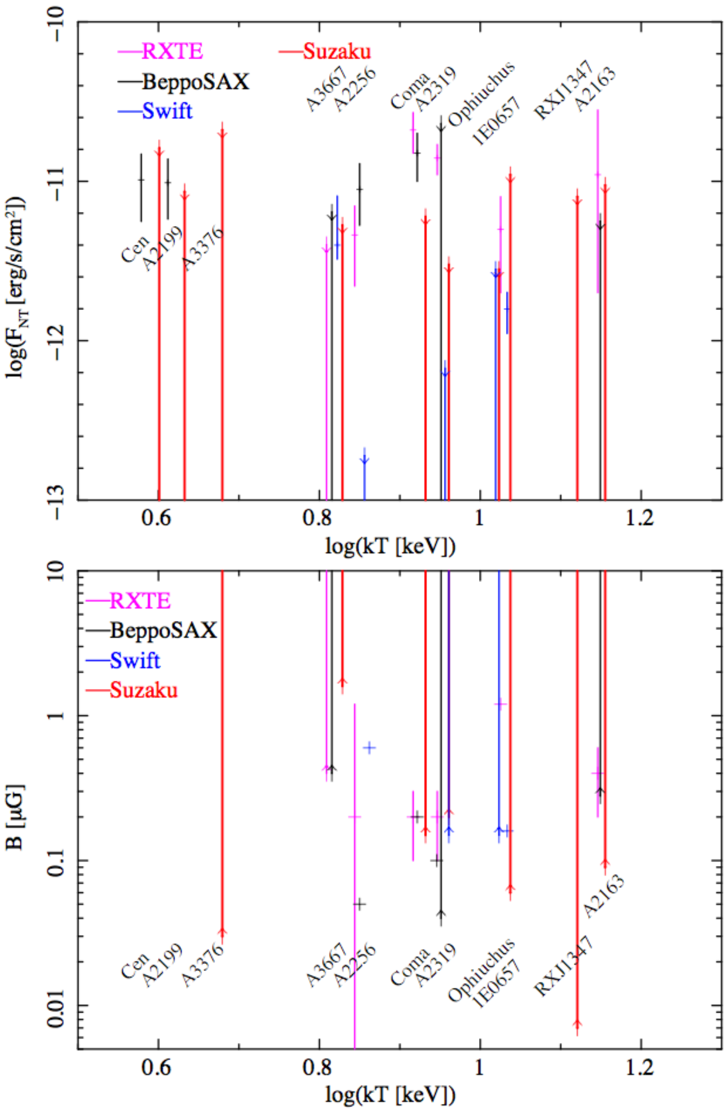




$$\frac{L_R}{L_X} = \frac{B^2/8\pi}{aT_{CMB}^4},$$



Hard Excess



The Coma cluster is the archetypal case (Rephaeli & Gruber 2002; Fusco-Femiano et al. 2004), with hard X-ray emission detected by **RXTE** and **Beppo-SAX** satellites (for review, see Rephaeli et al. 2008).

On the other hand, no significant NT X-ray emissions have been detected by the **Suzaku** and **Swift** satellites (Wik+09, 11). This discrepancy might be reconciled by considering different sizes of viewing fields (Fusco-Femiano+11).

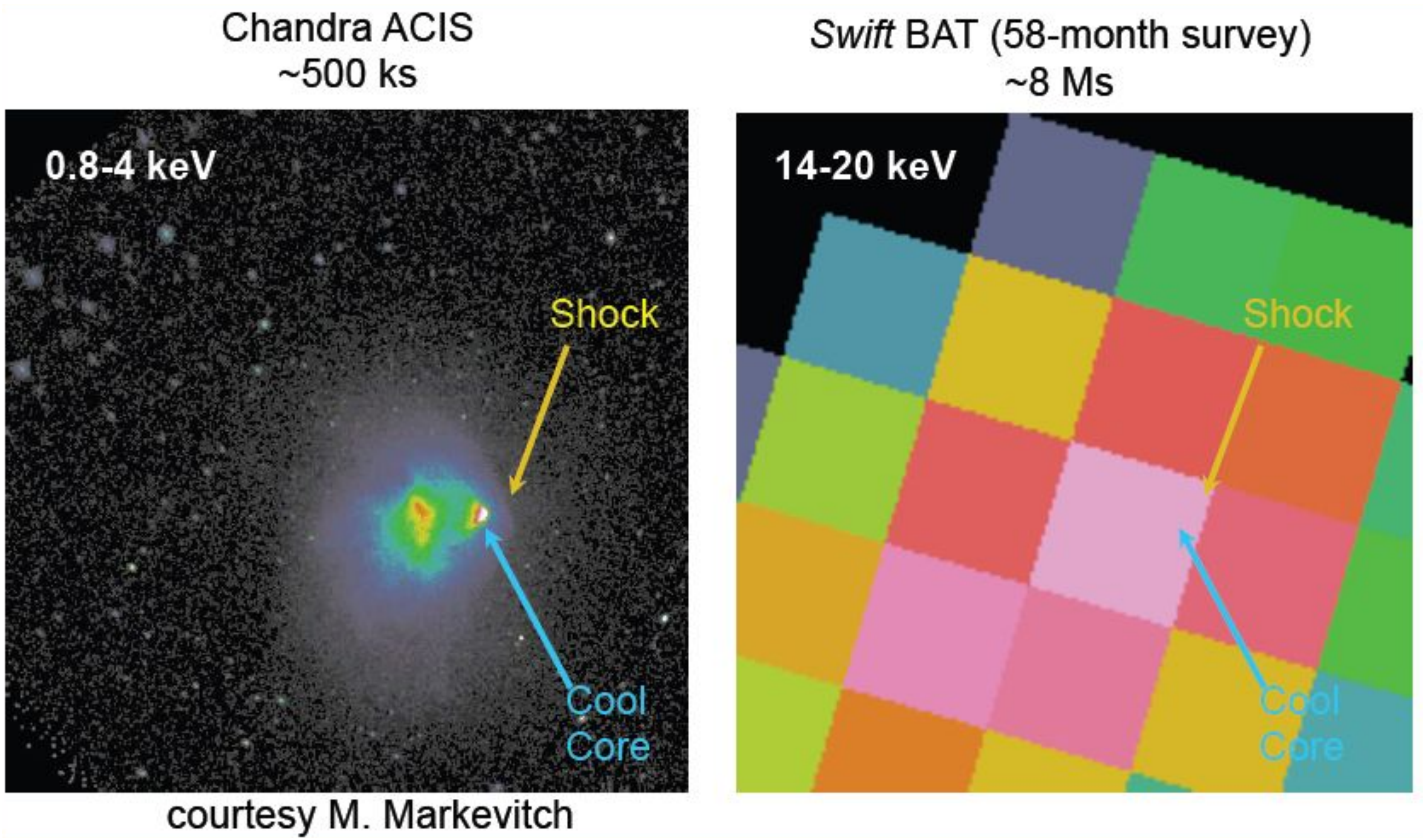
Suzaku has searched for non-thermal X-ray emissions in nine bright clusters: Centaurus cluster (Kitaguchi et al. 07), Ophiuchus cluster (Fujita et al. 08), RXJ1347.5–1145 (Ota et al. 08), A3376 (Kawano et al. 09), A2319 (Sugawara et al. 09), A3667 (Nakazawa et al. 09), Coma cluster (Wik et al. 09), Perseus cluster (Nishino et al. 10), A2199 (Kawaharada et al. 10).
The hard X-ray spectra can be explained by thermal emission; adding a non-thermal power-law component does not improve data fitting
(Ota 2012, and reference therein)

Ajello et al. (09, 10), from **Swift** observations of 20 GCs, conclude that hard X-ray emission has a thermal origin.

Stacked spectra, constructed and analyzed from ***Fermi*** data, yielded no significant γ-ray signal from clusters (Huber et al. 2013). The Fermi-LAT Collaboration et al. (2013) searched for cosmic-ray induced γ-ray emission through a combined analysis of 50 clusters to exclude hadronic injection efficiency in simple hadronic models, and also derived limits on the γ-ray flux on individual clusters.

Hard Excess

NuSTAR observation of the Buller Cluster (Wik+14) & core of Coma (Gastaldello+15): given the flat effective area and low background in the 3-20 keV band, *tight constraints on the high T* … ***NO IC DETECTION***
The global spectrum can be explained by thermal gas emission



Hard Excess

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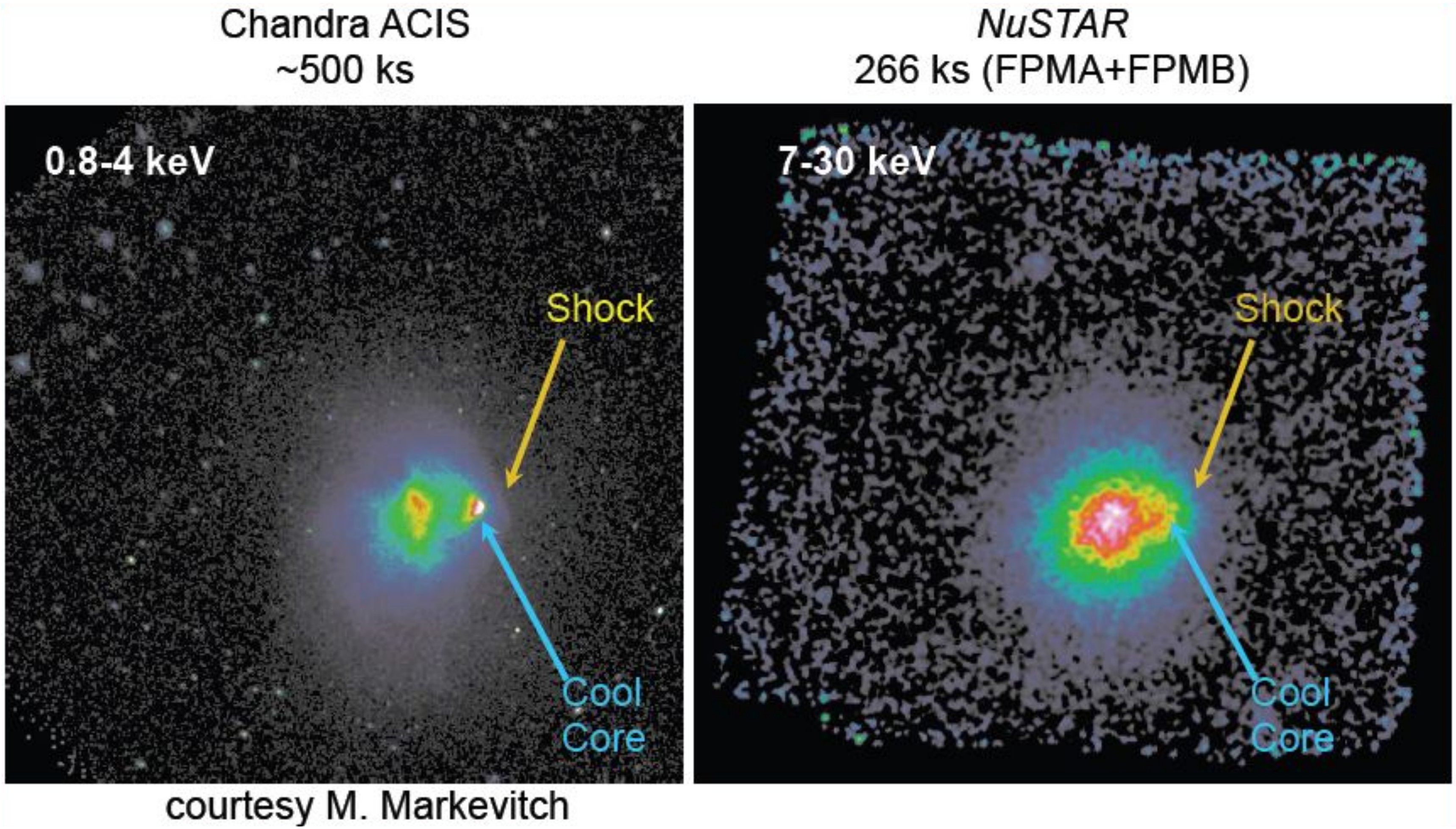

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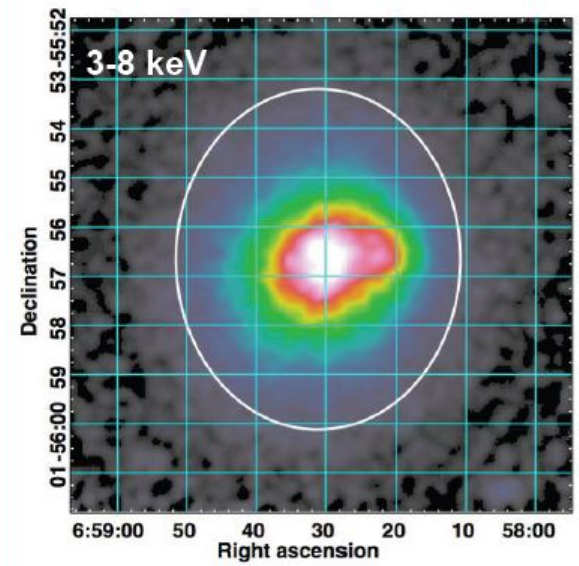
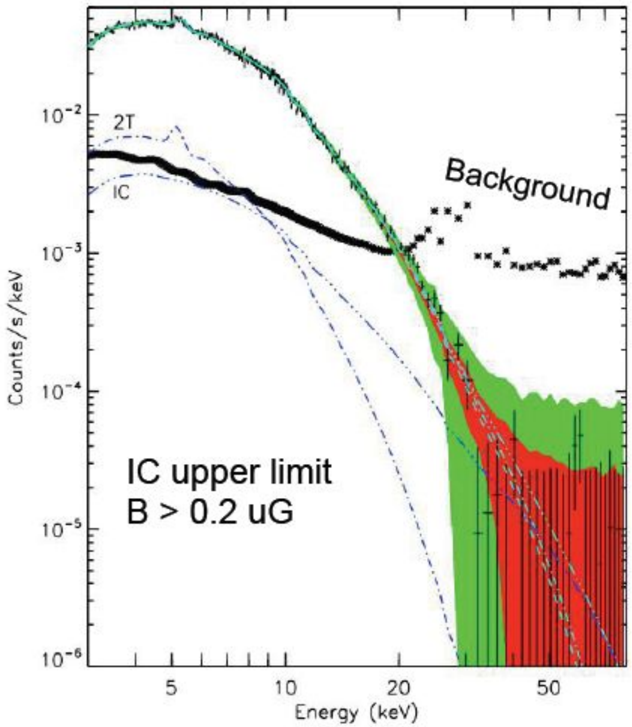


Wik et al. (2014)



Coma, Gastaldello+15

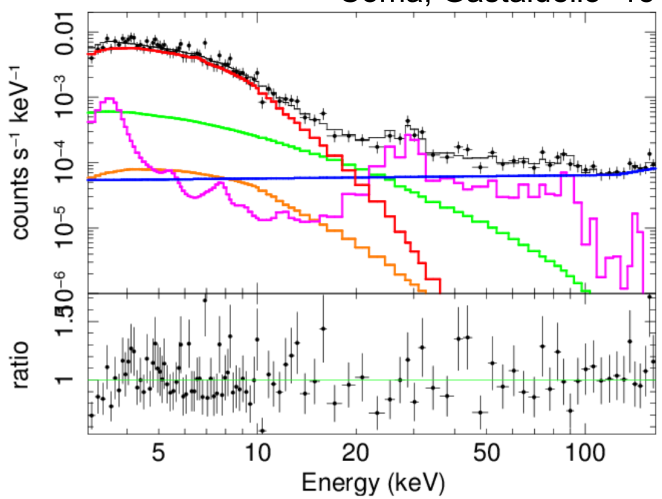
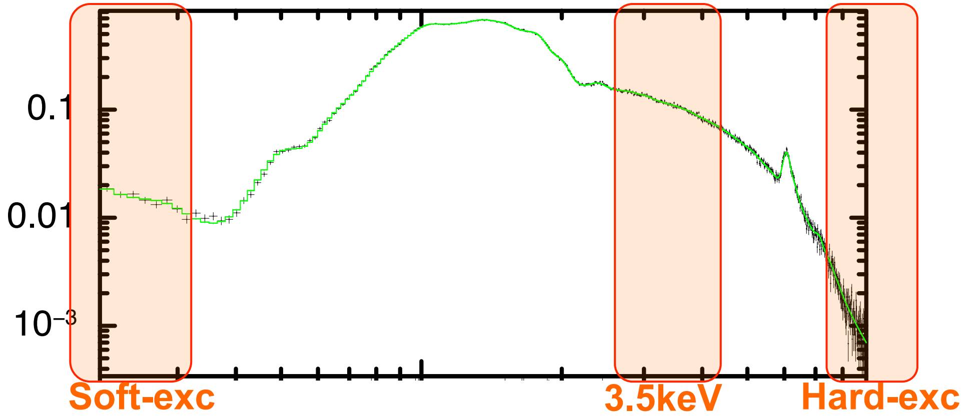


FIG. 2.— Detector B spectrum of one of the regions (region 4) shown in Figure 4 extracted to obtain the temperature map discussed in Section 4.2. The various background components have been modeled (blue: instrumental particle background continuum; magenta: instrumental lines and solar reflected component; orange: Focused Cosmic X-ray Background (FCXB); green: aperture background) and the source component is shown by the solid red line. The ratio of data over the model are also shown.

Conclusions



◆ 3.55 keV line: observations & controversy

Contradictory results: detected in the Perseus's core (too bright; not detected in other bright GCs, dwSph, MW, M31, …) with Chandra, XMM, Suzaku; no instrumental feature; nearby weak astrophysical lines (K xviii, Cl xvii, Ar xvii) hard to distinguish at CCD resolution (~100-120 eV), but required abundances~10 solar; it could be explained with more complex spectral model (including also CX)

◆ Soft Excess: observations & interpretation

Soft excess emission (~20% of the thermal component) is a possible reservoir of warm baryons. Current X-ray missions favor thermal over non-thermal interpretation, but no conclusive evidence from emission or absorption lines yet

◆ Hard Excess: observations & interpretation

Very weak evidence of any non-thermal IC component