The Detection of an Unexpected 3.56 keV Emission Line

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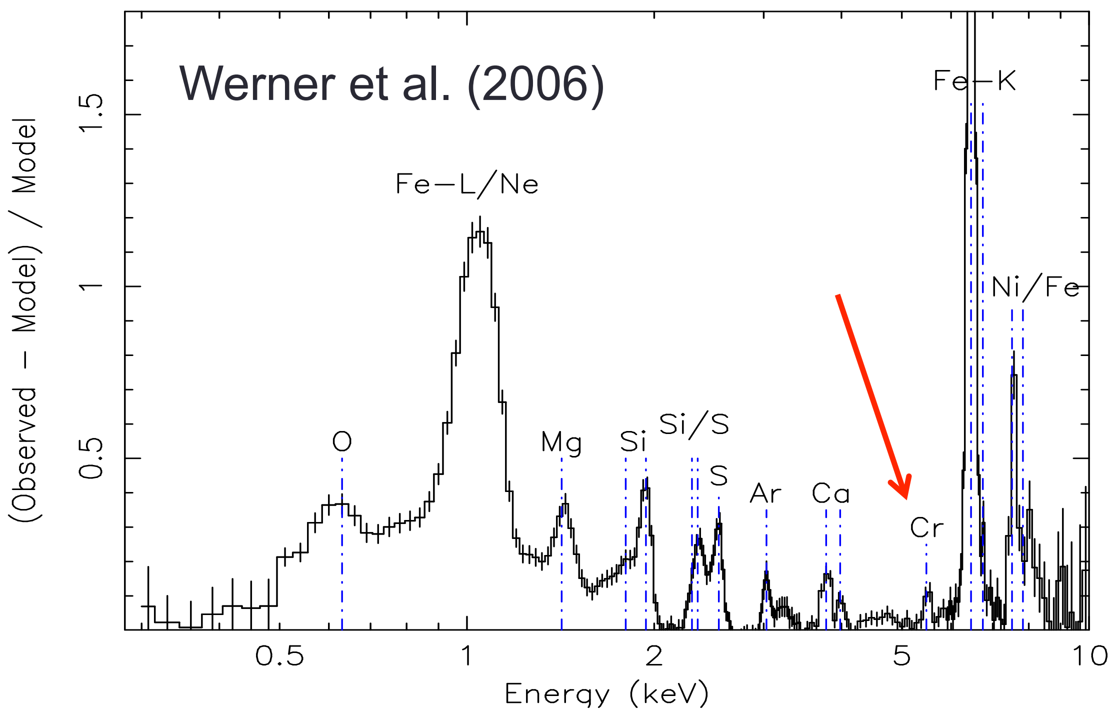
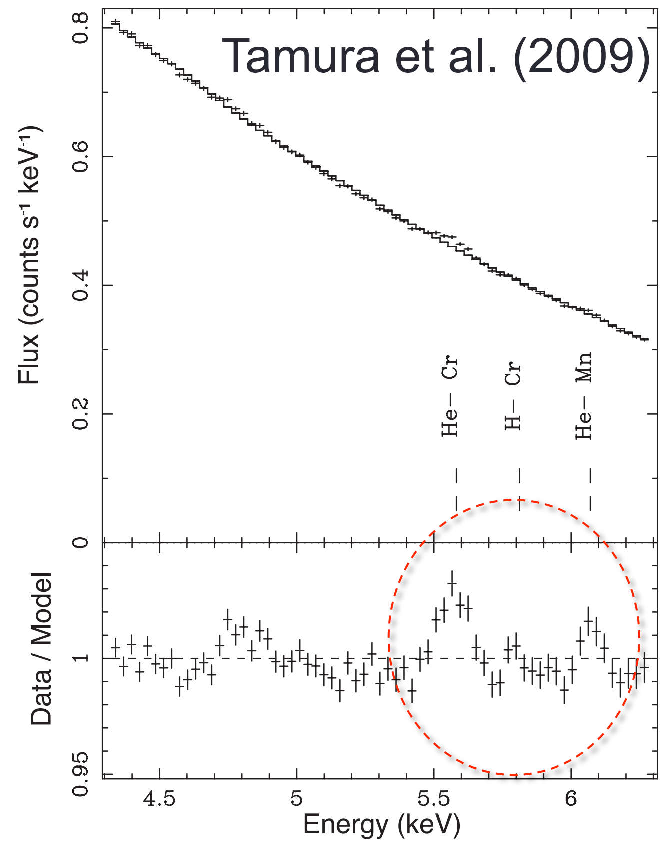
X-ray Line Searches in Galaxy Clusters

- Clusters are the largest aggregations of hot ICM and DM
- Gas is enriched mainly via SN explosions in galaxies
- Weak emission lines are now being discovered via X-ray spectroscopy

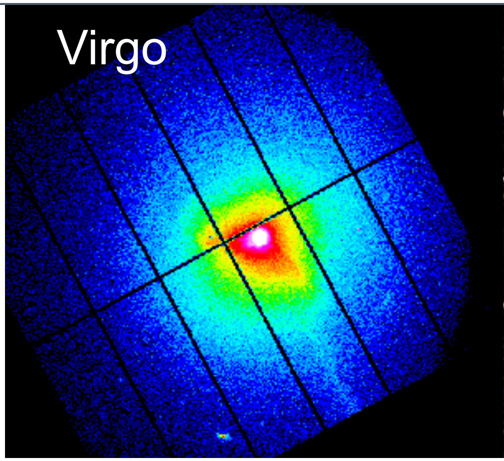




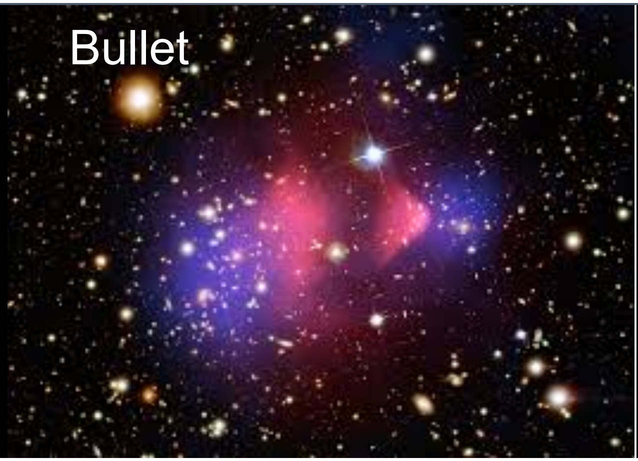
Prior Sterile Neutrino Decay Signal Searches

- Sterile neutrinos (a warm dark matter candidate) could decay into an active neutrino and an X-ray photon
- If we're lucky, this would make an emission line detectable in the X-rays

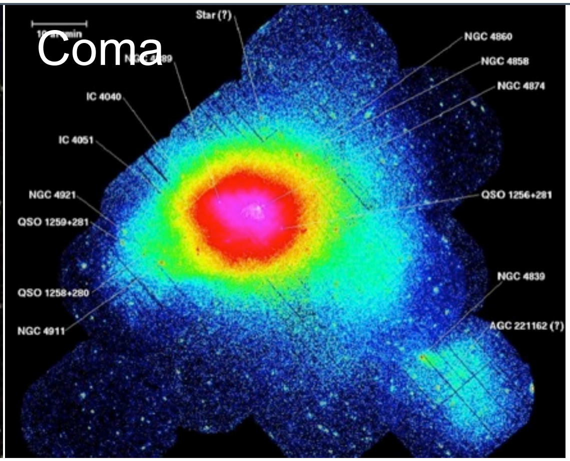
Sterile Neutrino Mass (m_s)	Source	Reference
< 10 keV	A1835	Riemer-Sorensen et al. (2007)
< 6.3 keV	Coma, Virgo, Bullet	Boyarsky et al. (2006, 2008)
< 8.2 keV	Virgo	Abazajian et al. (2001)



Boehringer et al. (2001)



Markevitch et al. (2004), Clowe et al. (2004)



Briel et al. (2000)

Why Stacking?

- Increase S/N!
- Combining observations of galaxy clusters over a redshift range of 0.01–0.35 smears all non-source features
  - at 3.56 keV, smearing ranges from 35 eV to 1.2 keV
  - blurs instrumental and background features
  - reduces effective area variations

By enhancing the S/N throughout and reducing the effect of features not from the source itself, our ability to detect a weak line is enhanced

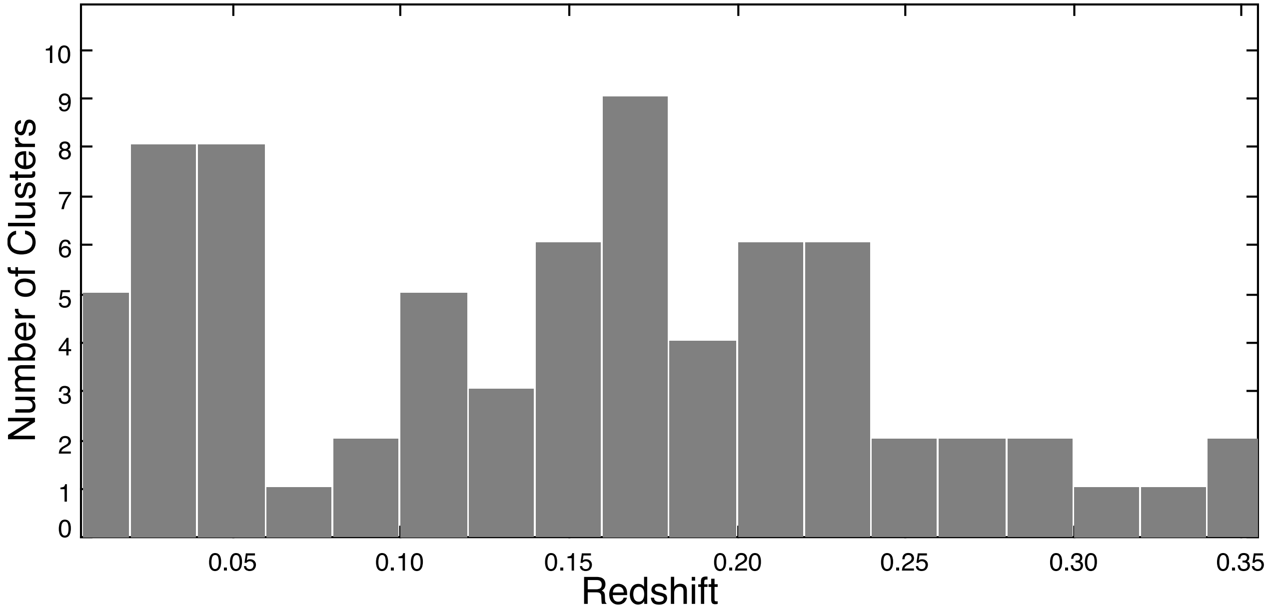
Sample Selection

XMM-Newton Archive

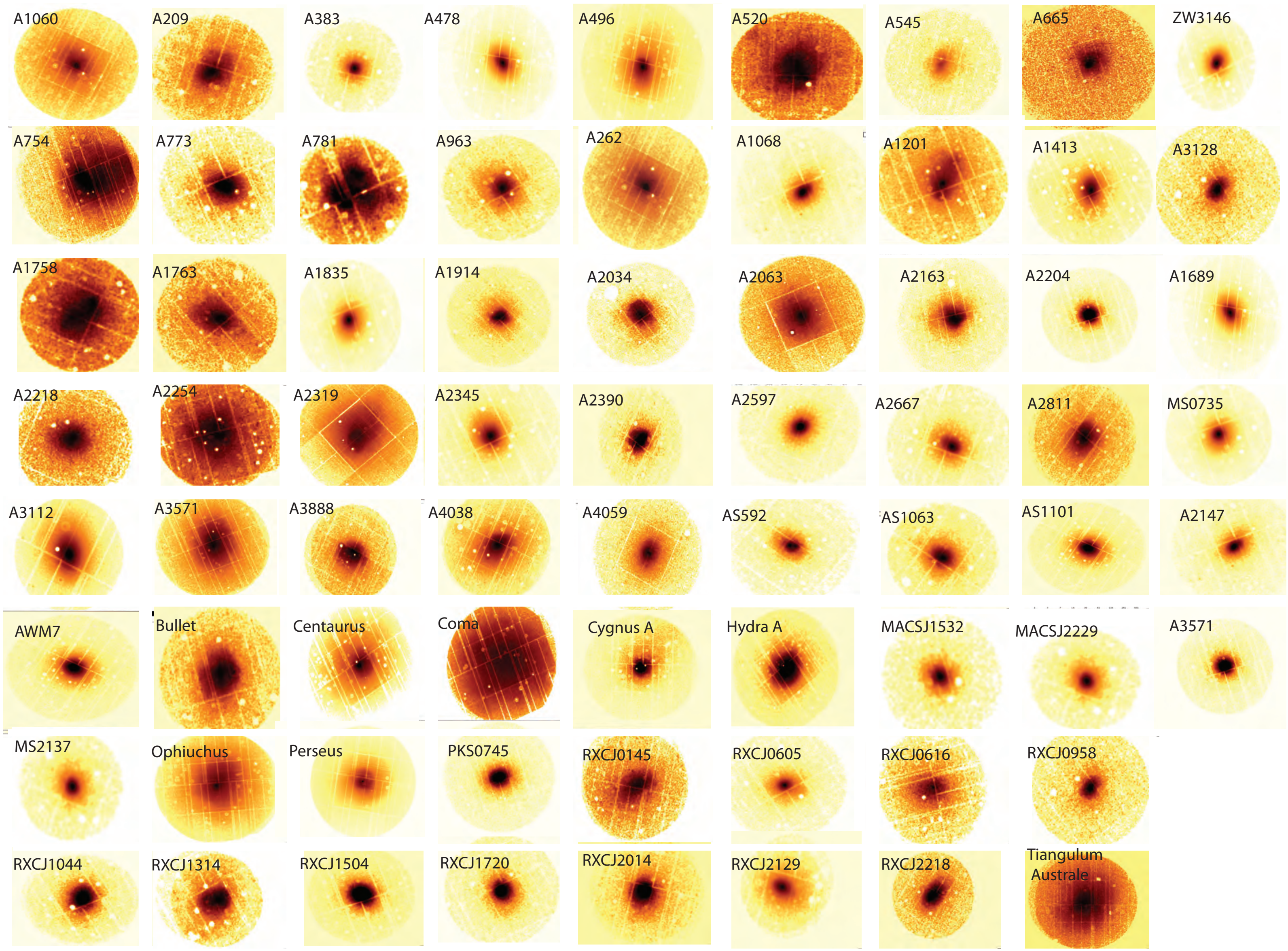
- 10^5 counts per cluster for clusters for z < 0.1
- 10^4 counts per cluster for clusters for 0.1 < z < 0.4
- 73 bright galaxy clusters

Chandra Archive

- Perseus cluster
- Virgo cluster

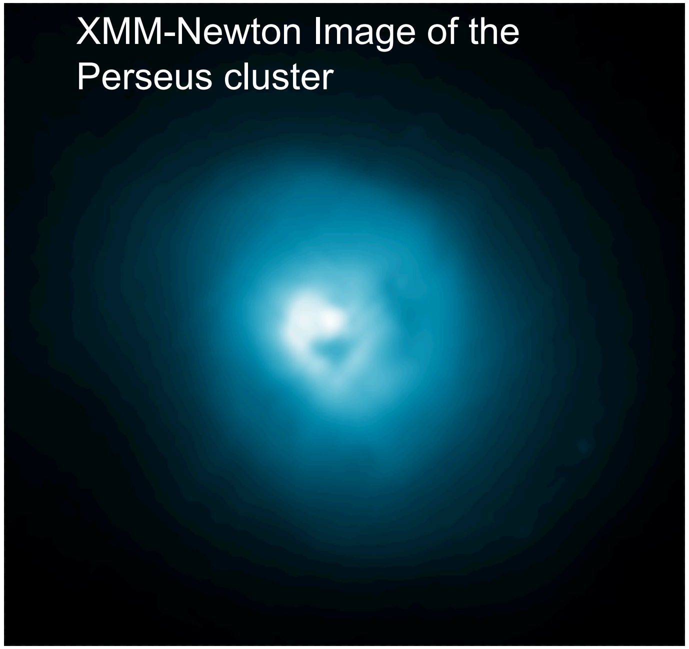


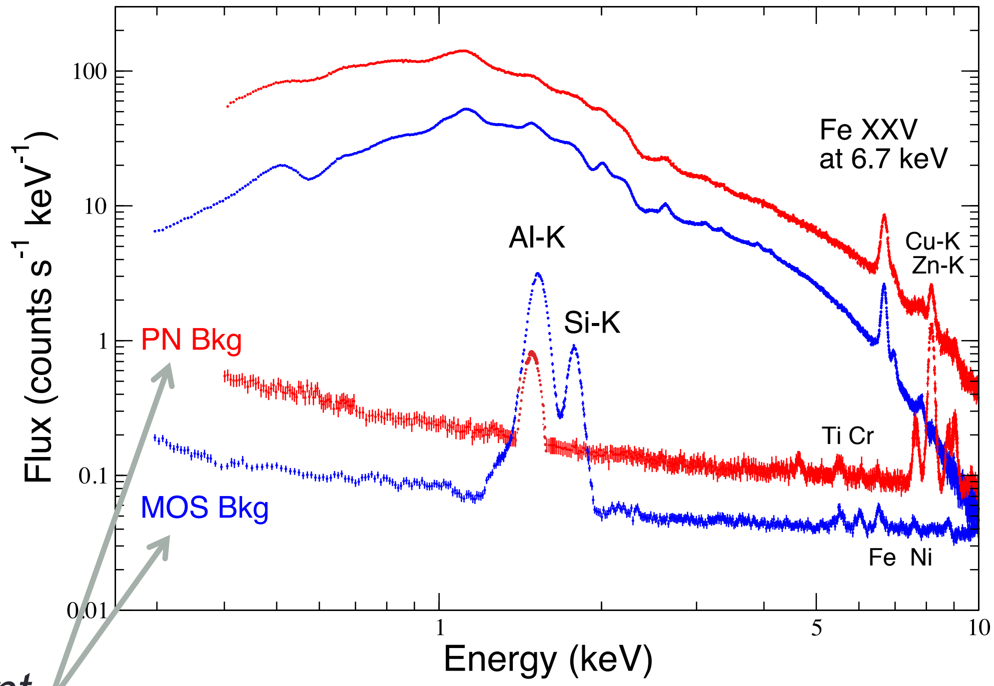
Sample Selection



Scaling and Stacking

- Determine the best fit X-ray redshifts of each observation
- Scale the event energies to the rest frame (z=0)
- Extract spectra $r < R_{500}$ or full FOV
- Co-add source and background spectra into single stacked spectra





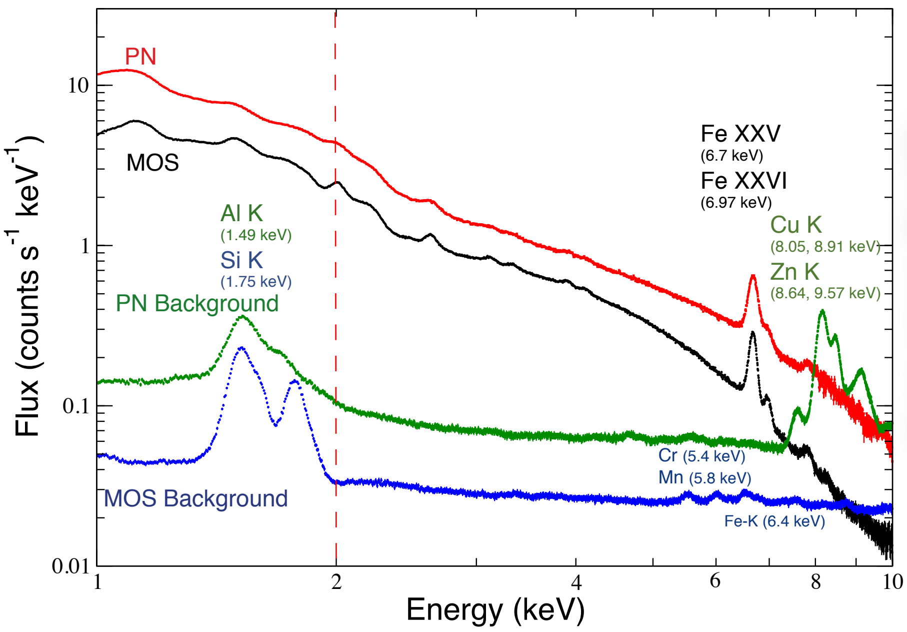
MOS, PN are two different CCD detectors on XMM

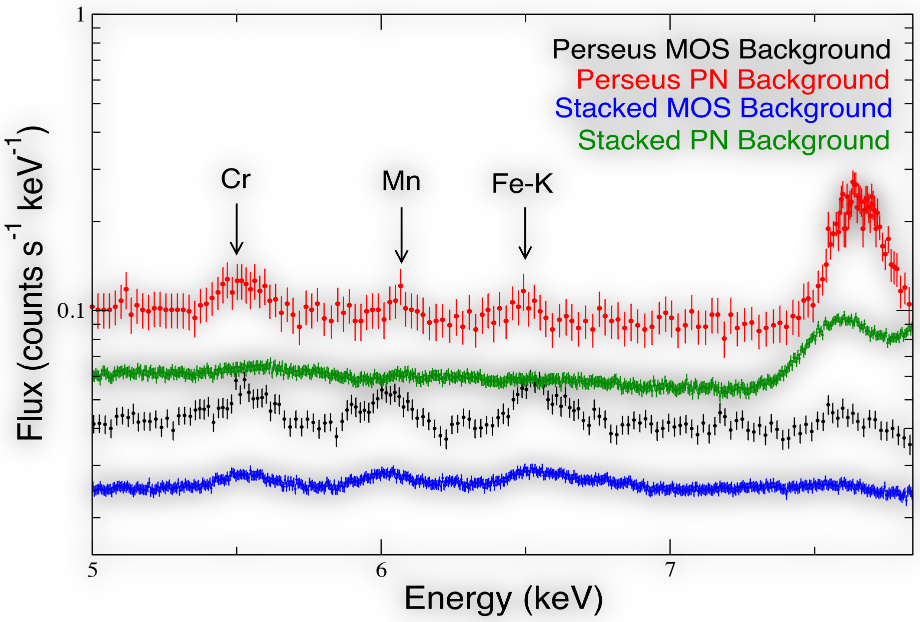
Perseus cluster at the rest frame

Scaling and Stacking

Detector responses were remapped to the source frame and stacked, with weighting set by the total counts in 2-10 keV band.

$$S_i = \alpha \; \omega_{i,dm} \; e_{tot} \; A_i, \qquad A_\omega = \sum_i \frac{\omega_i}{\omega_{tot}} A_i,$$





Fitting

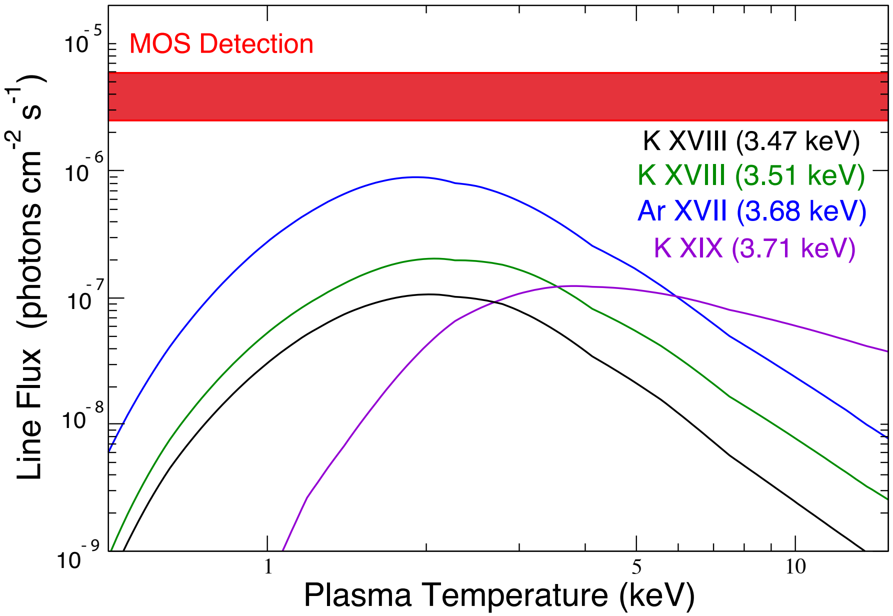
- Flux below 2 keV ignored (too complex)
- Used Line-free thermal (apec) model for continuum
- Added 28 Gaussians for emission lines($>5\times10^{-19}$ ph cm^{3} s^{-1})

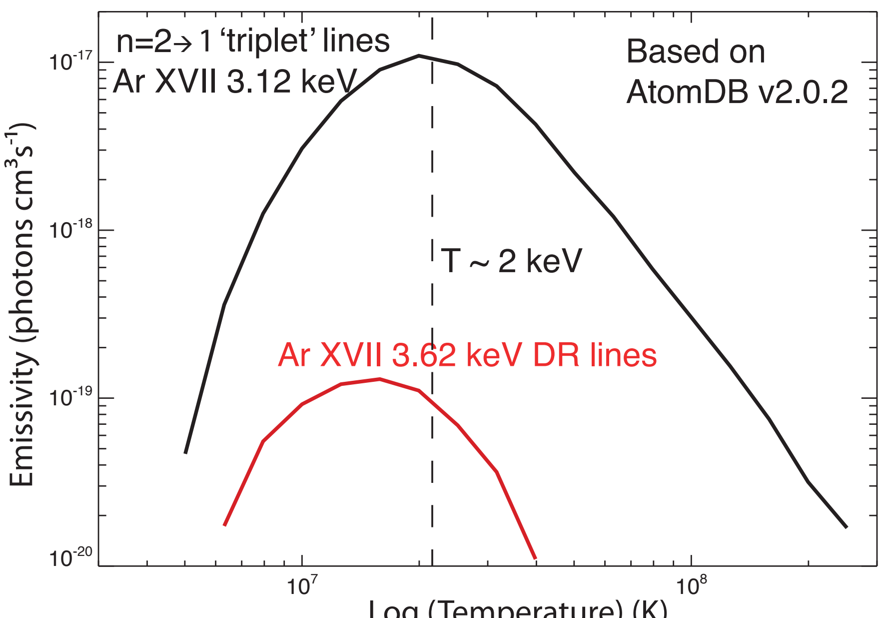
- Detected a significant emission feature at ~3.55-3.57 keV

- Estimated the flux of nearby lines based on the measured temperatures and AtomDB (http://www.atomdb.org)

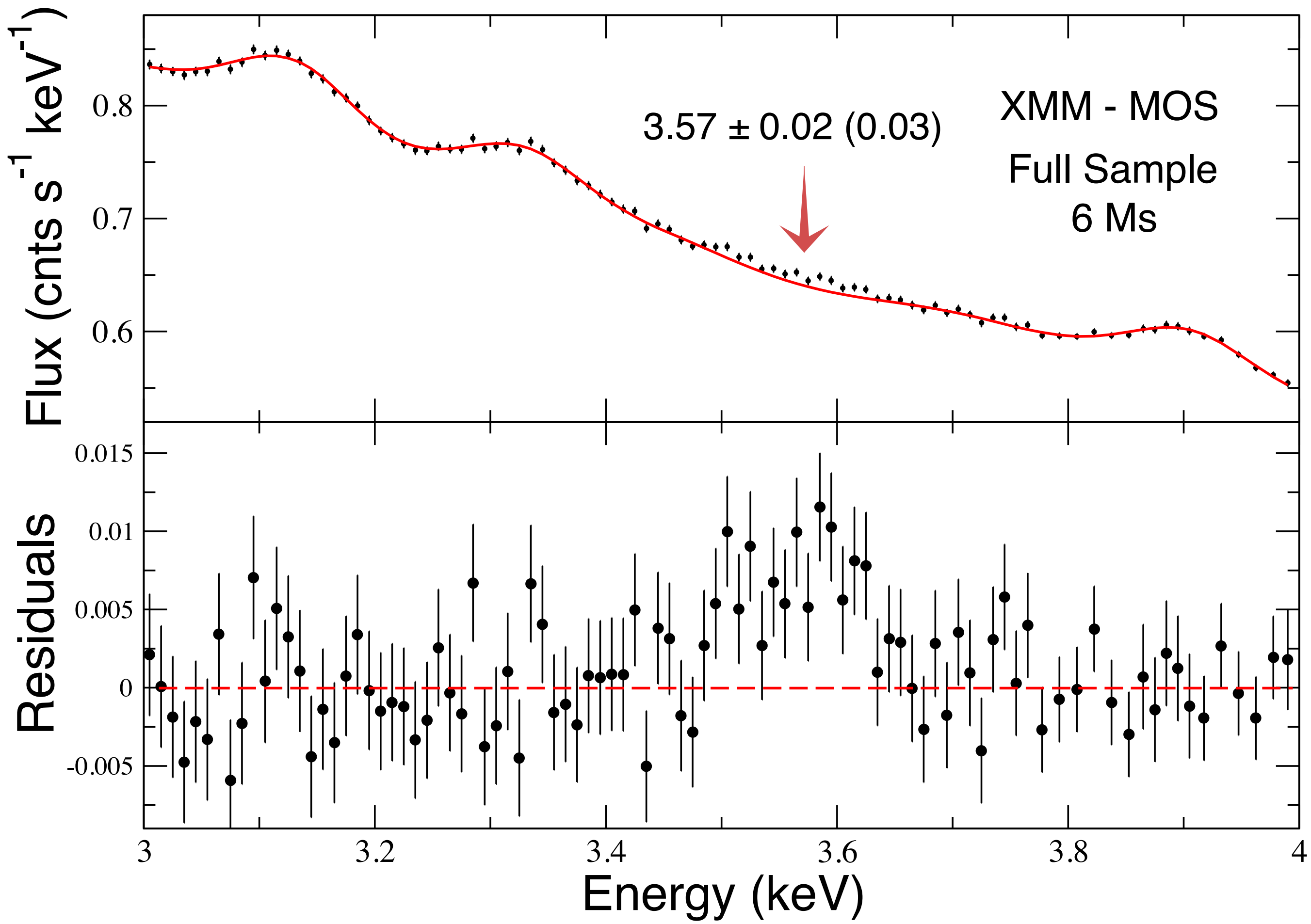
  K XVIII at 3.47 keV
  K XVIII at 3.51 keV
  Ar XVII at 3.62 keV
  Ar XVII at 3.68 keV
  K XIX at 3.72 keV

Fluxes of Nearby Lines





Detection of An Unidentified Emission Line



Flux of the Unidentified Line

Counts-scaled response matrices were used to model known emission lines

Response matrices weighted with estimated DM photon flux used to model the unidentified line

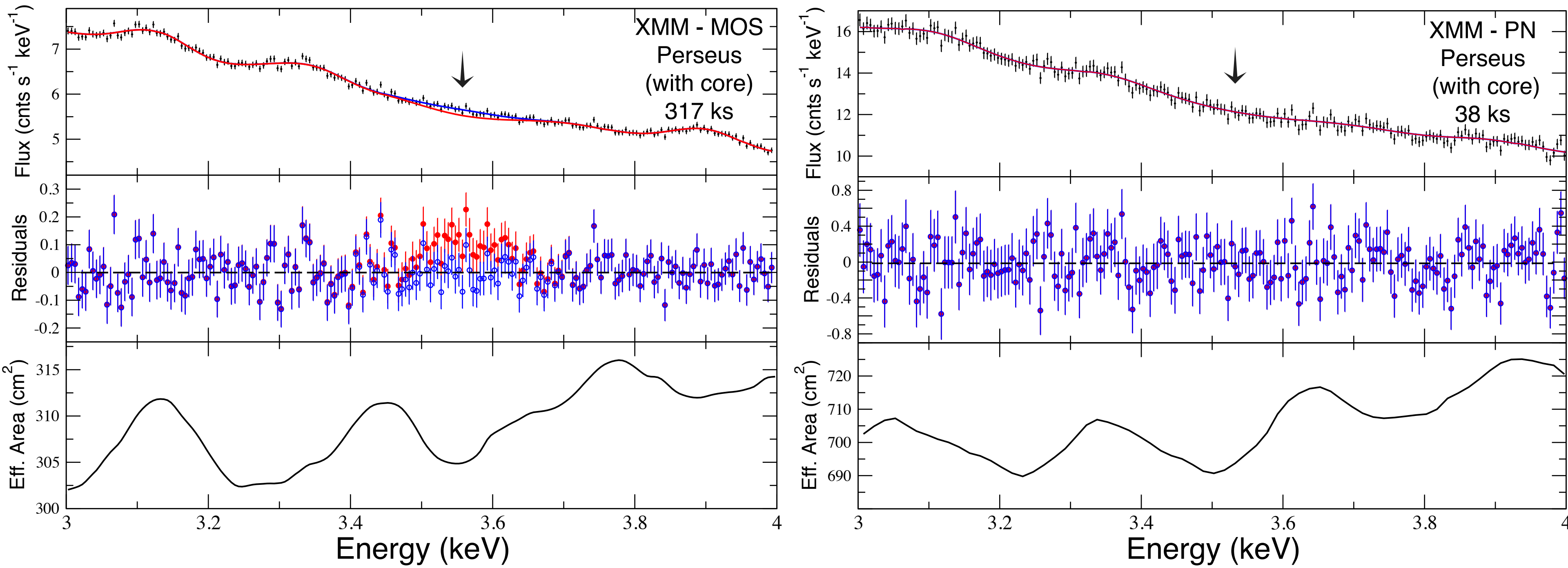
DM Photon Flux:

$$F_{DM} = \frac{M_{DM}^{FOV}}{4\pi D_L^2} \frac{\Gamma_\gamma}{m_s}(1+z) \quad \text{photons cm}^{-2}\ \text{s}^{-1}$$

Weights weighted by DM flux:

$$\omega_{i,dm} = \frac{M_{i,DM}^{proj}(< R_{ext})(1+z_i)}{4\pi D_{i,L}^2} \; \frac{e_i}{e_{tot}}.$$

Detection in the Full Perseus Cluster



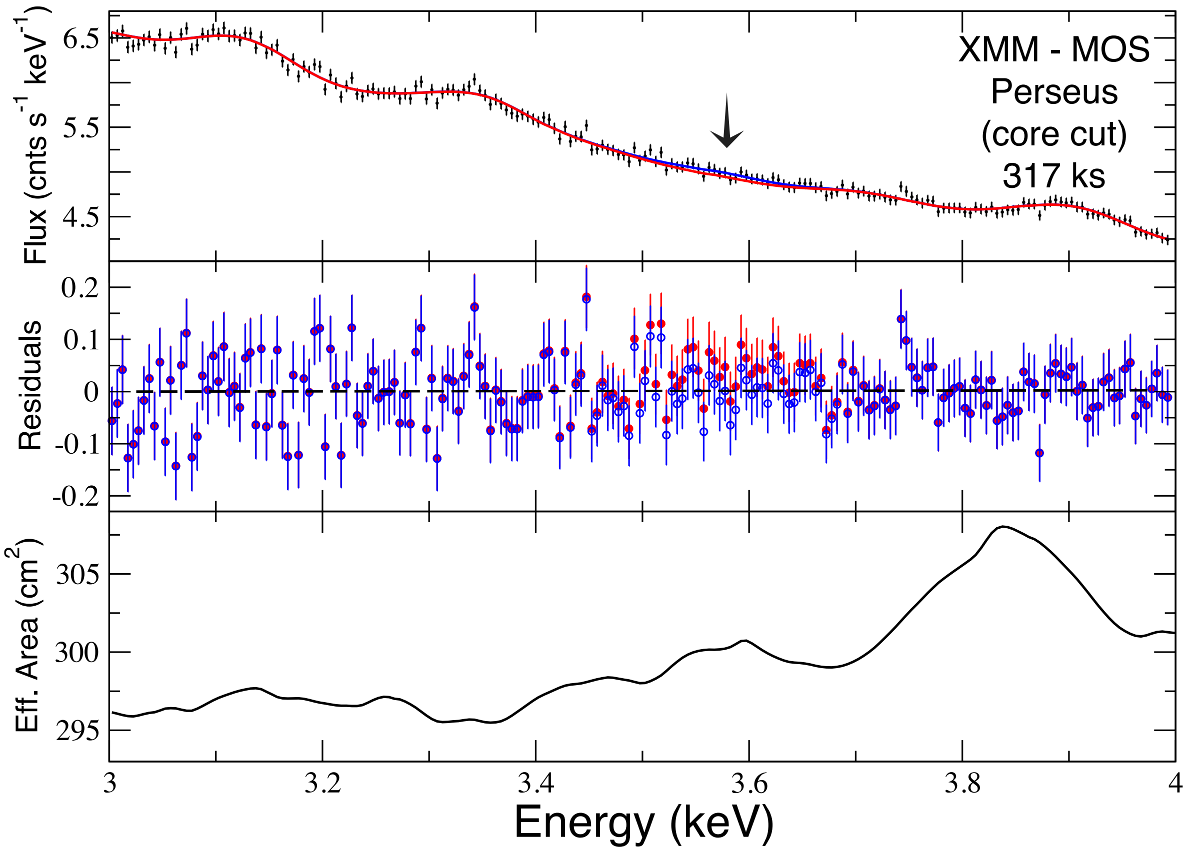
But this is from a single source spectrum. Could it be an:

- Feature only in the cluster core?
- Effective area feature?
- Background feature?

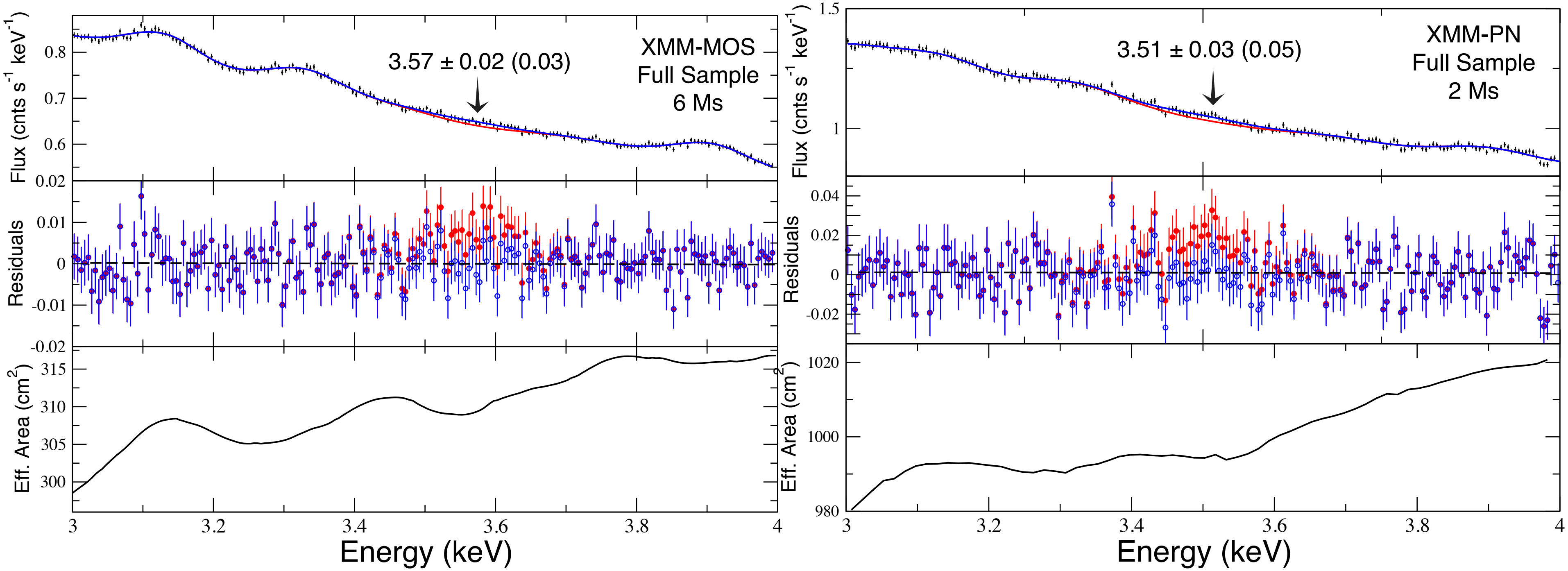
Feature only in the cluster core?

Although the core is extremely bright, the feature is not just coming from the central 1’ region of the cluster.

This figure shows the Perseus spectrum after the central arcminute is removed from the data



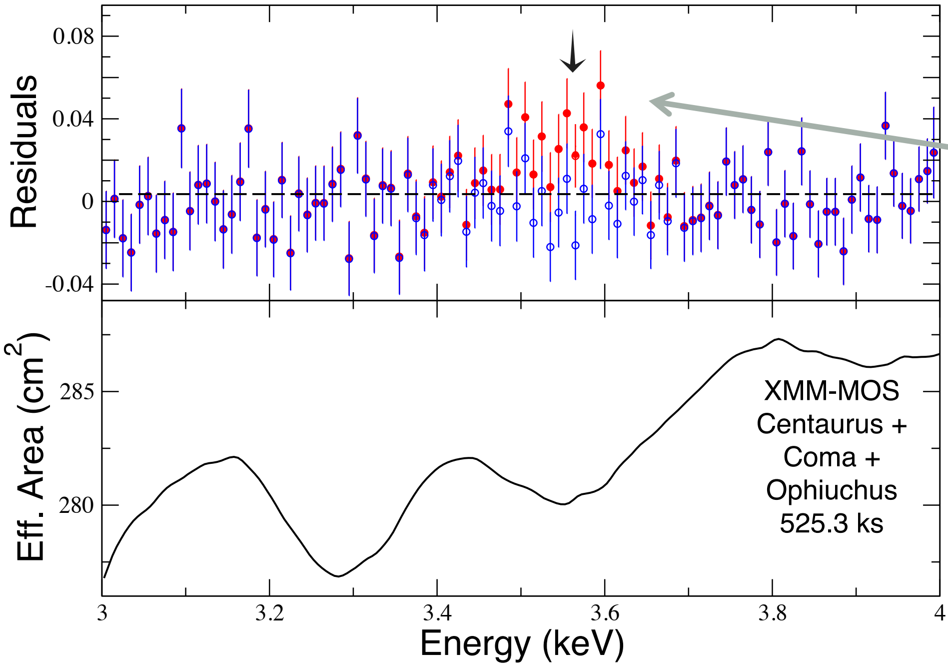
Effective Area or Background Feature? Examining the Full Sample



Any instrumental features (effective area, bkgnd) have been smeared by stacking multiple redshifts.

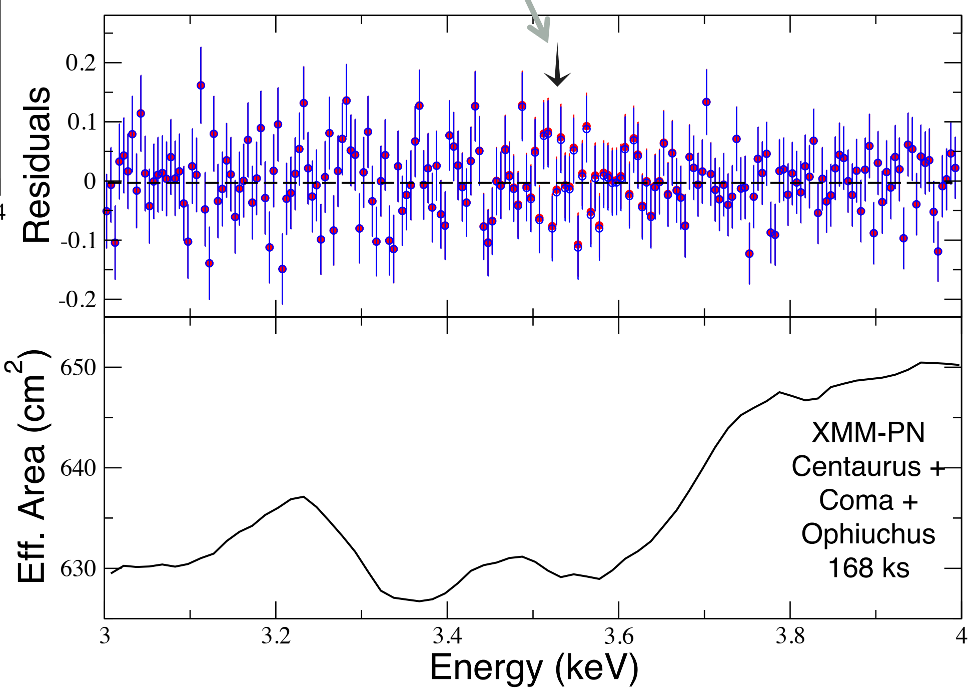
But does it come from one dominant nearby source (e.g. only in Perseus?)

Nearby Clusters without Perseus



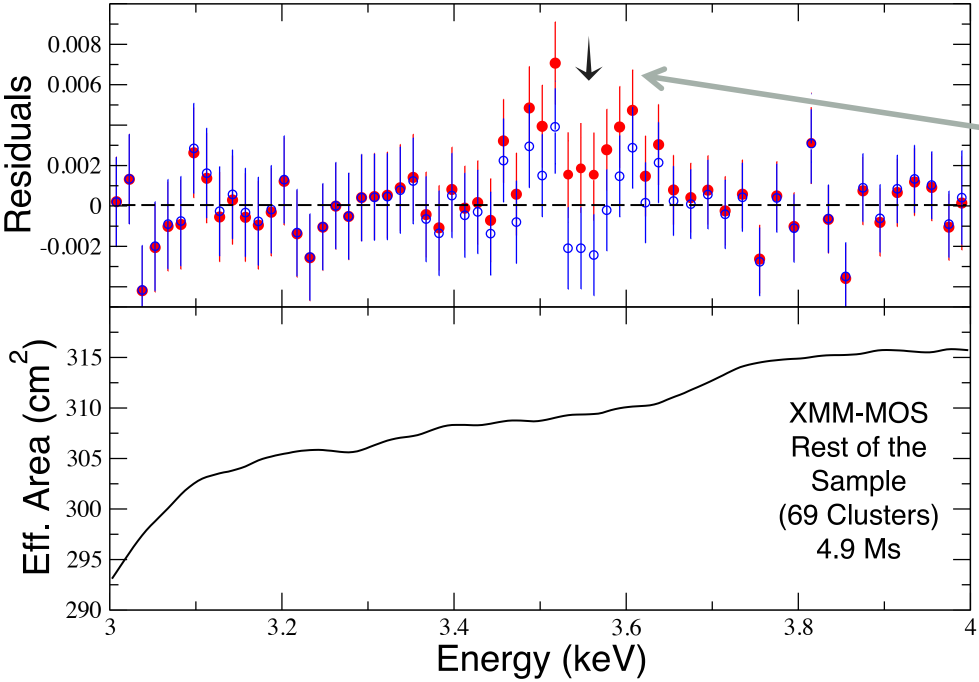
The feature is seen in the stacked spectra of the Centaurus, Coma & Ophiucus clusters in the MOS data.

But not in the lower-quality PN data



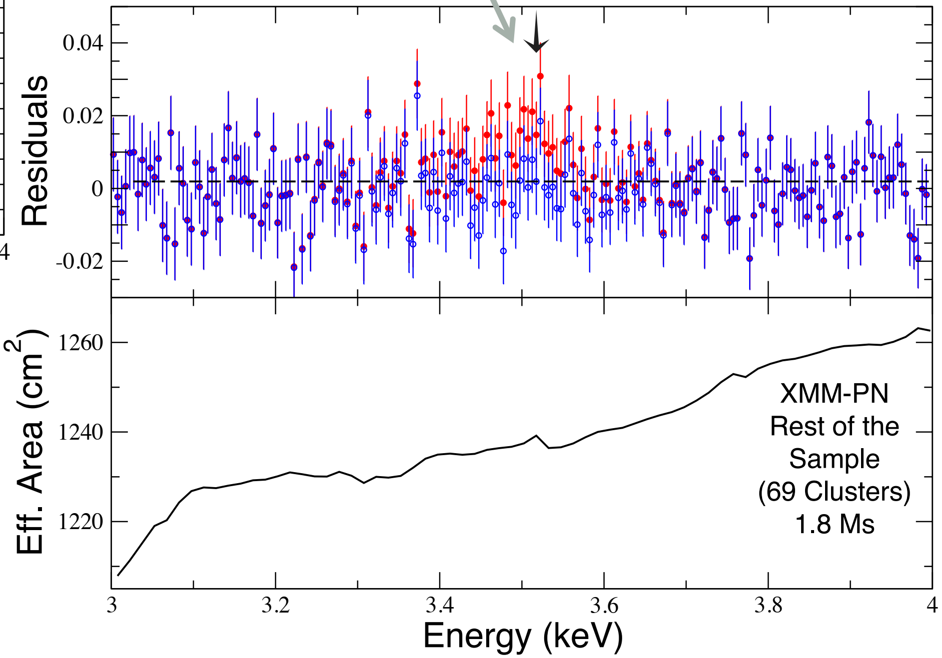
Maybe it's only seen in nearby clusters?

More Distant Clusters Only



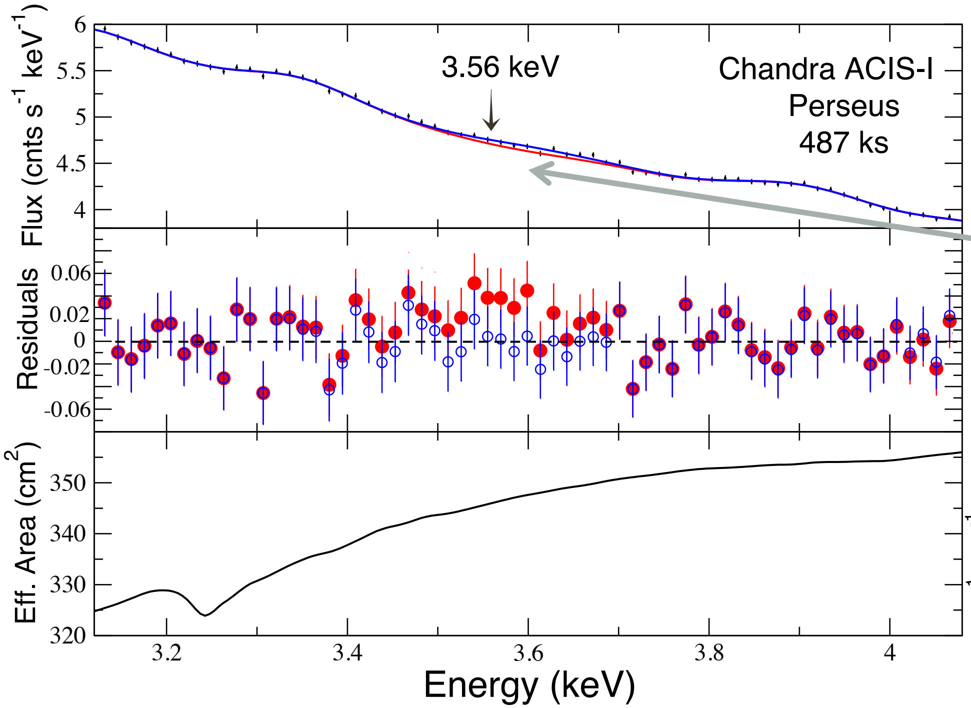
The feature is seen in the stacked spectra all other clusters in the MOS data.

And in the PN data as well.



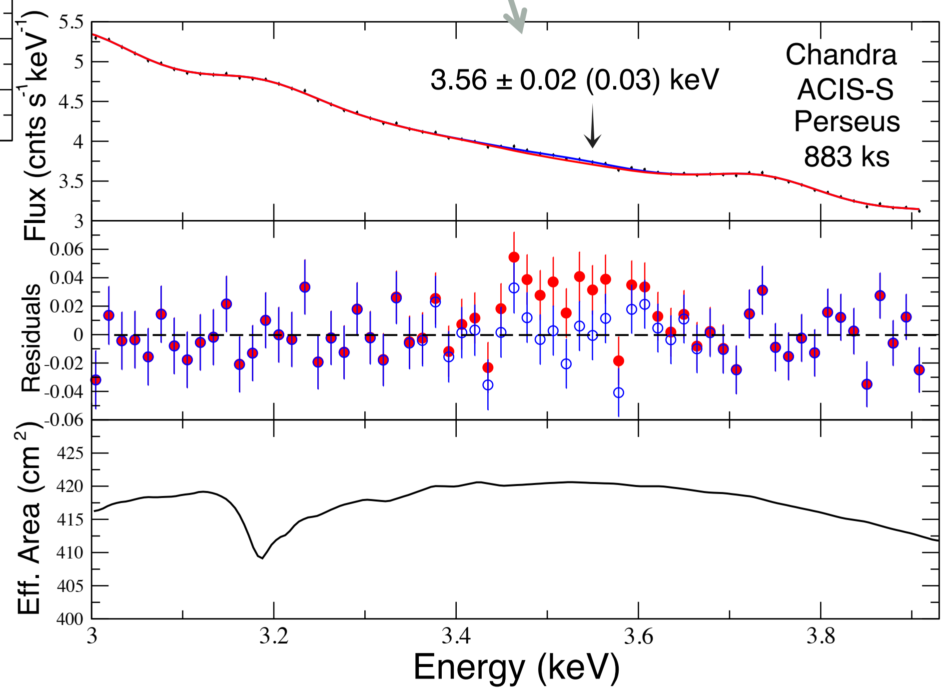
Maybe it's due to some feature of XMM-Newton that isn't affected by the redshift smearing?

Chandra Detection



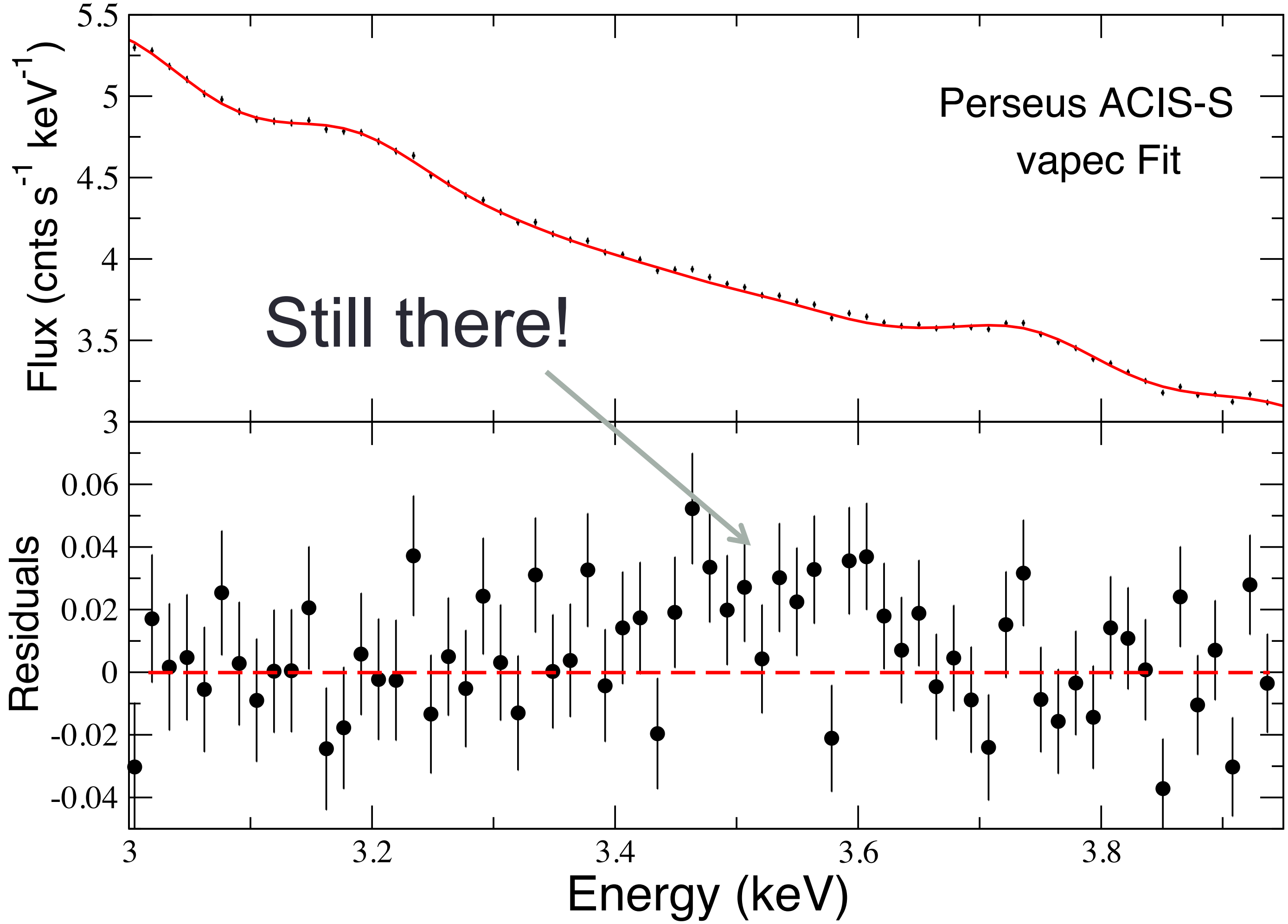
The feature is seen in the Chandra ACIS-I data for Perseus

And in the ACIS-S data as well.



Perhaps it's because we're using a continuum plus Gaussian modeling approach, and using a pure thermal plasma model wouldn't find it.

Fitting with a 'Normal' Thermal Plasma Model

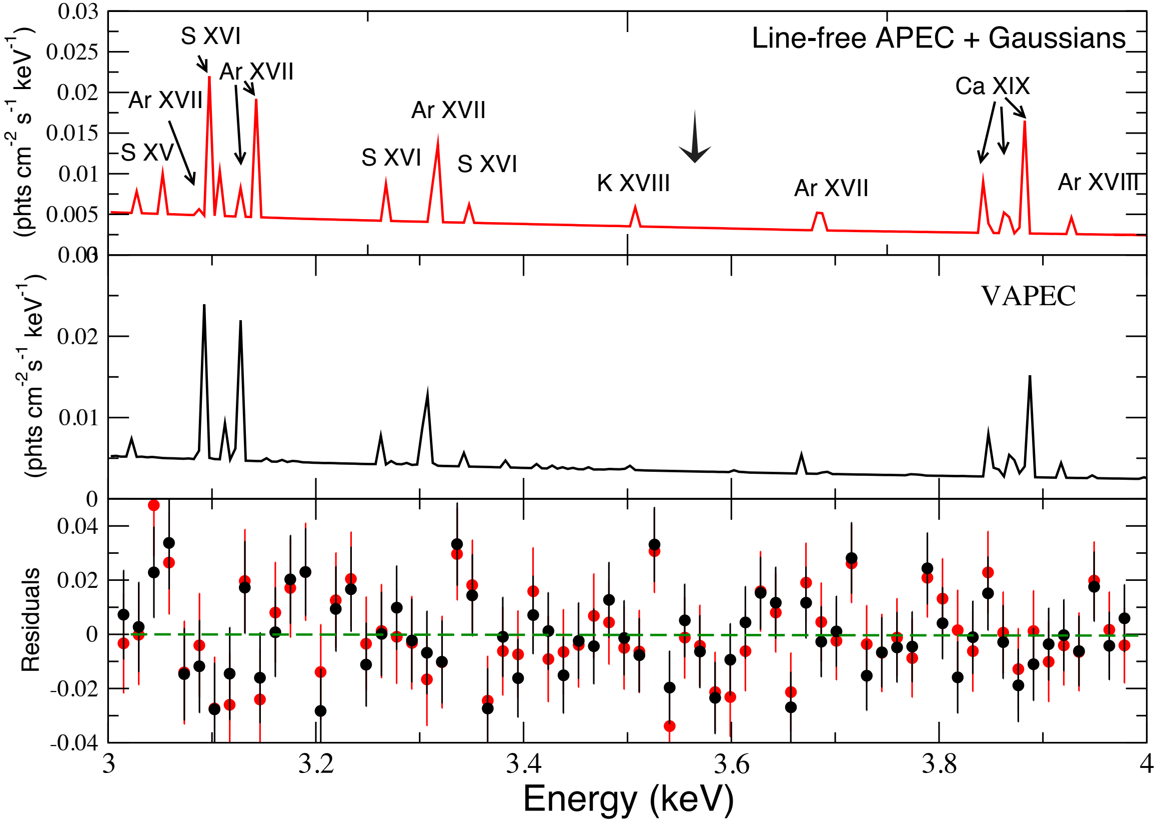


Chandra Observations of Virgo

There is one case where we don't see the line although we expected it – the Virgo cluster.

M_{DM}/FOV is high, but we find no detection.

Upper limit from the Virgo cluster is 9.1×10^{-6} ph/cm^2/s



Equivalent to $\sin^2(2\theta) < 1.1 \times 10^{-10}$
(full sample finds $\sin^2(2\theta) \sim 7 \times 10\text{-}11$)

So what is the origin of the signal?

- Unknown plasma emission line
- Emission lines of strong hydrogen- and helium-like ions
- Ar XVII DR line at 3.62 keV
- Radiative Recombination Continuum edge
- Charge exchange
- Sterile neutrino decay signature

Unknown plasma emission line

- **Max emissivity Λ = 3.3×10^{-18} photons cm^{3} s^{-1}**

$$F = EM \times \Lambda(T) = \frac{1}{4\pi D^2} \int n_e n_H \Lambda(T)$$

- Equivalent to the Ca xx Lyα line at 4.1 keV.

- Ca xx Lyα has been seen in individual galaxy cluster spectra (e.g. Perseus, Tamura et al. 2009), so a line this strong at ~3.56 keV would have been observed …

  had it been expected.

Perhaps an unexpected atomic line?

- The L-shell (n=2) and M-shell (n=3) lines are difficult to calculate exactly; these could be problematic.
- The highest-Z element is Zn (Z=30);
- The binding energy of the 2s electron in Li-like Zn ($1s^2 2s$) is only 2.782 keV
- Transition lines of all lighter elements or less ionized species **must be at lower energies than this.**
- The line at 3.56 keV CANNOT be an L-shell or M-shell transition.

Emission Line from K-shell transitions

- Consider a K-shell (1s electron) with a transition at 3.56 keV
  - the hydrogen-like ion and the neutral Kα fluorescence transitions must bound 3.56 keV

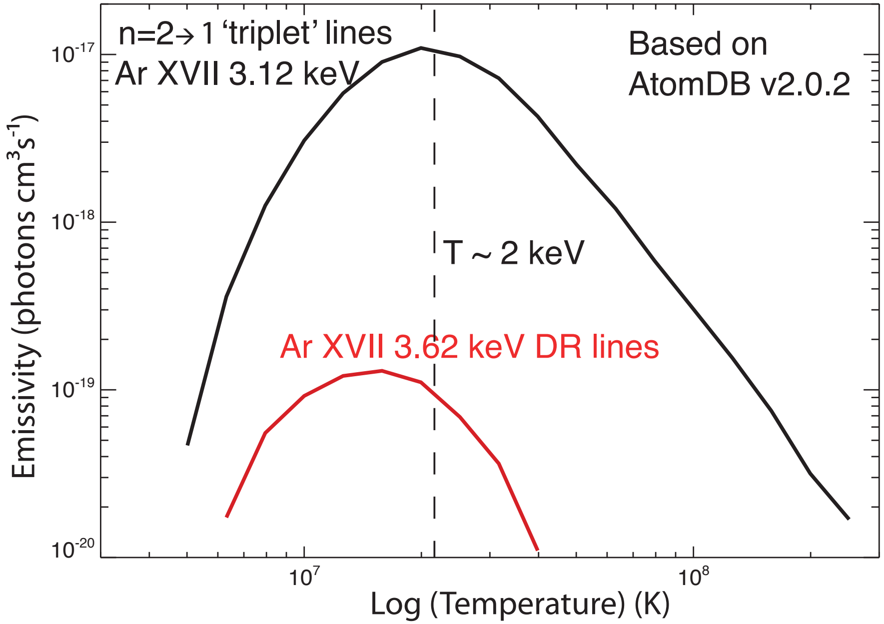
- This means Cl, Ar, & K are the **only candidates**.

- Cl XVI has emission lines at 3.56 keV from $n = 5 \rightarrow 1$ transitions
  - Such features could be generated by charge exchange…
  - But where are $n=3\rightarrow1$ at 3.27 keV and $n=4\rightarrow1$ at 3.44 keV?

- Kα transitions of K XVI through K XIV ions do occur at ~ 3.57 keV
  - At any temperature above 1 keV, K XVII and K XVIII dominate.
  - To get this, then, we would need:
    - A previously unseen high abundance of K comparable to Ca
    - That is photoionized to high degree

The Case of the Ar DR Line at 3.62 keV

- Li-like Ar XVI 1s2s3p -> $1s^22s$
  - Caused by dielectronic recombination (DR) of He-like Ar (Ar XVII)
  - Or inner-shell excitation of Ar XVI
  - Fills in 3.56 keV line if it is 30% of the Ar XVII n=2->1 lines,



- Model rpredicts line is **< 1%** of the strength of the Ar XVII n=2->1 lines at 3.12 keV at 2 keV
- Maximum strength is **4%** of the Ar XVII n=2->1 lines (in collisional equilibrium)

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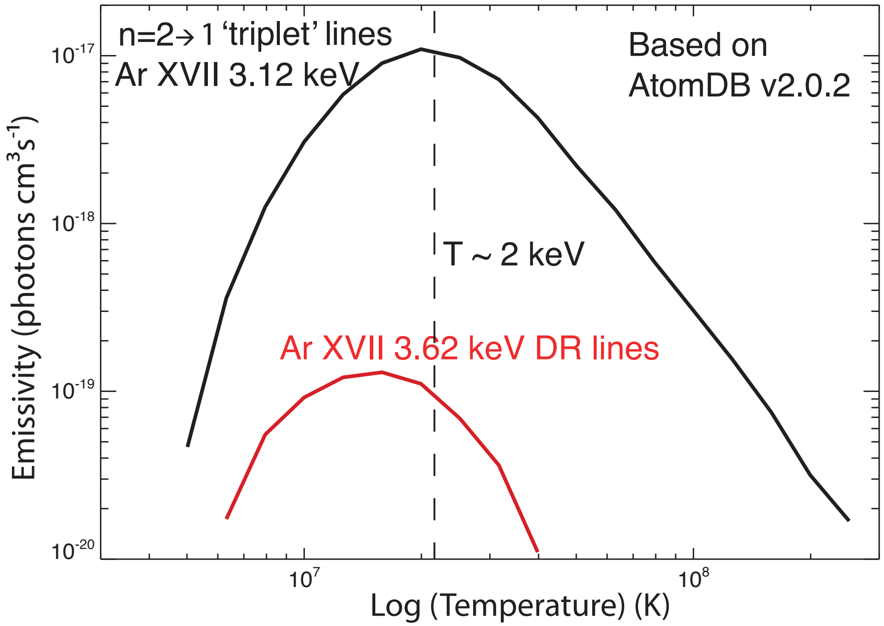


- Maximum **non-equilibrium** situation:
  - Cold electrons that are unable to collisionally excite Ar XVII lines
  - DR is still possible
  - In this case maximum is < 7% as
    - Ar XVI 1s2s2p -> $1s^2 2s$ fills in Ar XVII n=2->1 region

Radiative Recombination Continuum

- There is a S XVI recombination edge at 3.494 keV
- If it was bright enough it might fill in some of the flux in this region.

However…

- The edge is 50-80 eV from our proposed line… and !
- The feature **is already included in our models**
  - It's shape can be modified, but not in a way that makes it match the data.

Charge Exchange

- Charge exchange (CX) between ions and neutral hydrogen or helium would change the strength of the X-ray emission lines.
  - This is the Cl XVI Lyδ case, but one would also expect the remainder of the series – which we don't see.

- Could affect our assumption of equilibrium line ratios, although we have included a substantial range around the equilibrium values.

- **CX lines are not 'new,' but rather the same lines occurring in different ratios.**

- In the core of the Perseus cluster where many neutral filaments are known, CX could create a small fraction of the total X-ray emission
  - Would not create a 'new' line at 3.57 keV or the DR line at 3.62 keV.

Any Other Astrophysical Explanations?

Meet the Sterile Neutrino?

- Right-handed (***sterile***) neutrinos may be introduced in extensions of the Standard Model that account for neutrino masses.

- Sterile ν's may be thermally produced via neutrino oscillations in the early universe at a rate that depends on the active-sterile mixing angle, θ_{mix} .

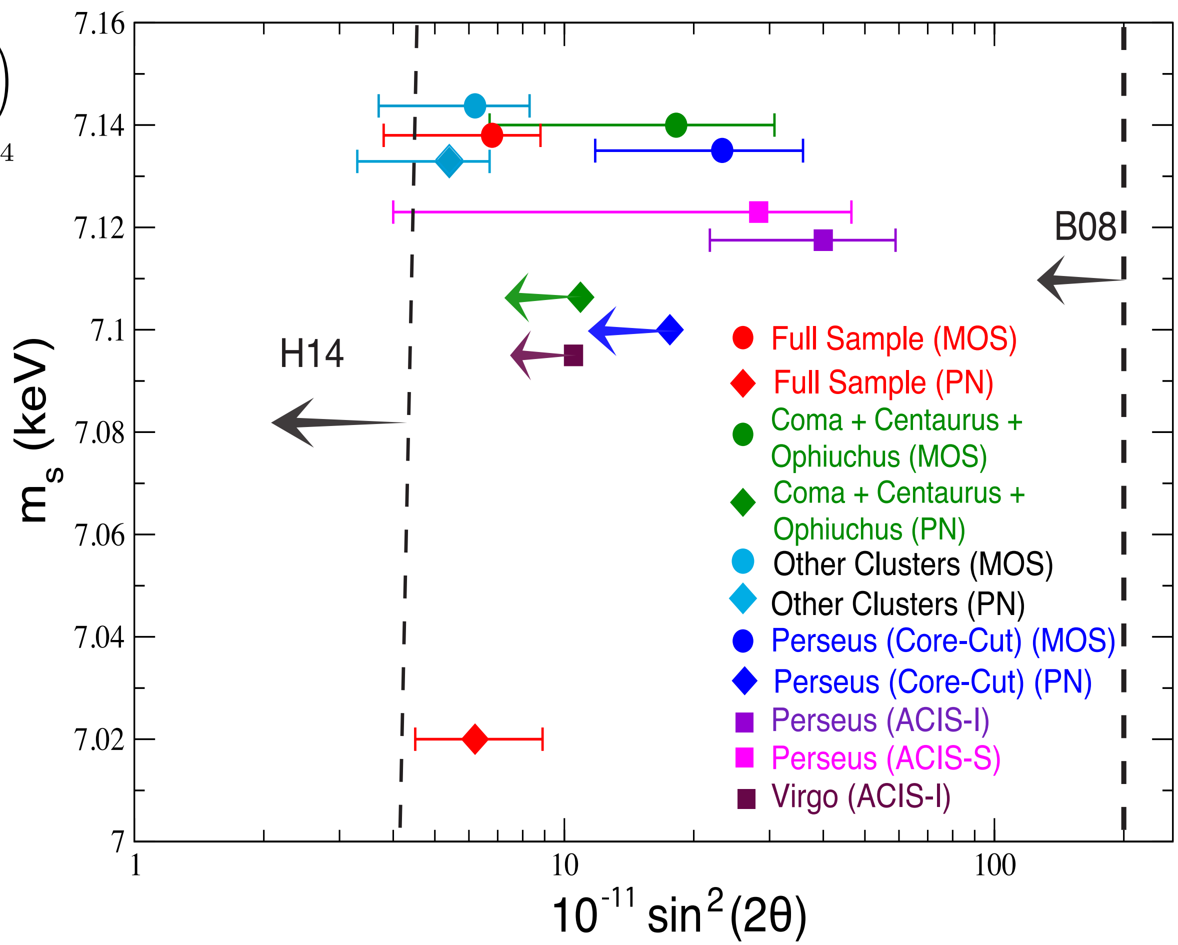
- Dodelson & Widrow (1994) showed that sterile ν's could be produced in this manner in sufficient numbers to account for dark matter if $m_{ster\text{-}\nu}$ *~1 keV*.

- Sterile neutrinos decay into an active neutrino and an X-ray photon (e=m/2) -- producing an emission line

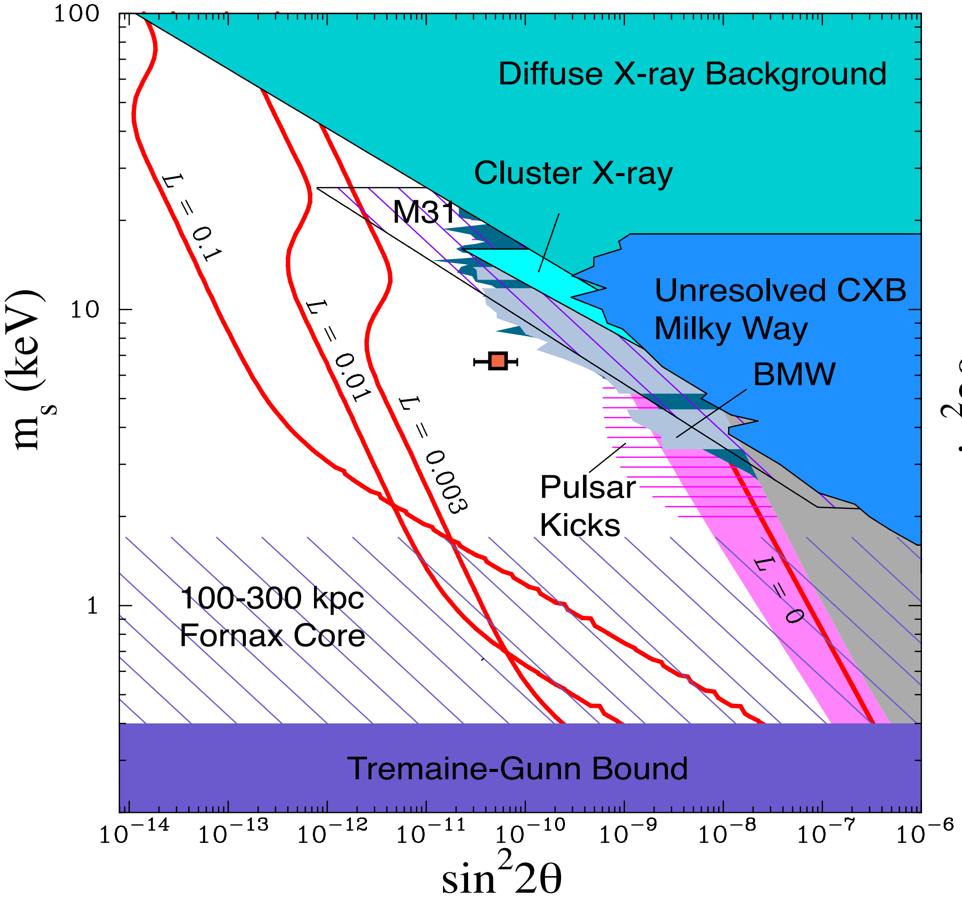
Decay of 7.12 keV Sterile Neutrino?

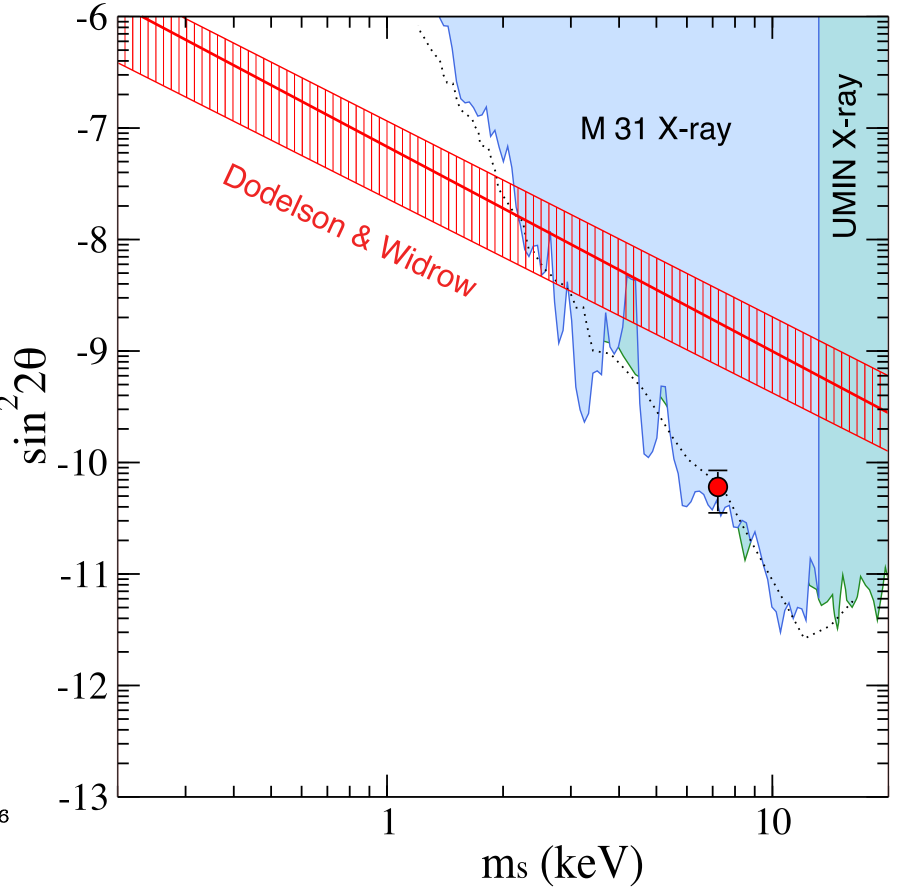
$$\sin^2(2\theta) = \frac{\mathrm{F_{DM}}}{12.76\ \mathrm{cm^{-2}\ s^{-1}}} \left(\frac{10^{14}\ \mathrm{M_\odot}}{\mathrm{M_{DM}^{FOV}}}\right) \left(\frac{D_L}{100\ \mathrm{Mpc}}\right)^2 \left(\frac{1}{1+z}\right) \left(\frac{1\ \mathrm{keV}}{m_s}\right)^4$$

Doing much better than single well exposed cluster observations (B08)
The line flux detected in our full sample corresponds to a mixing angle for the decay $\sin^2(2\theta) \sim 7 \times 10^{-11}$. This value is below the upper limits placed by the previous searches,

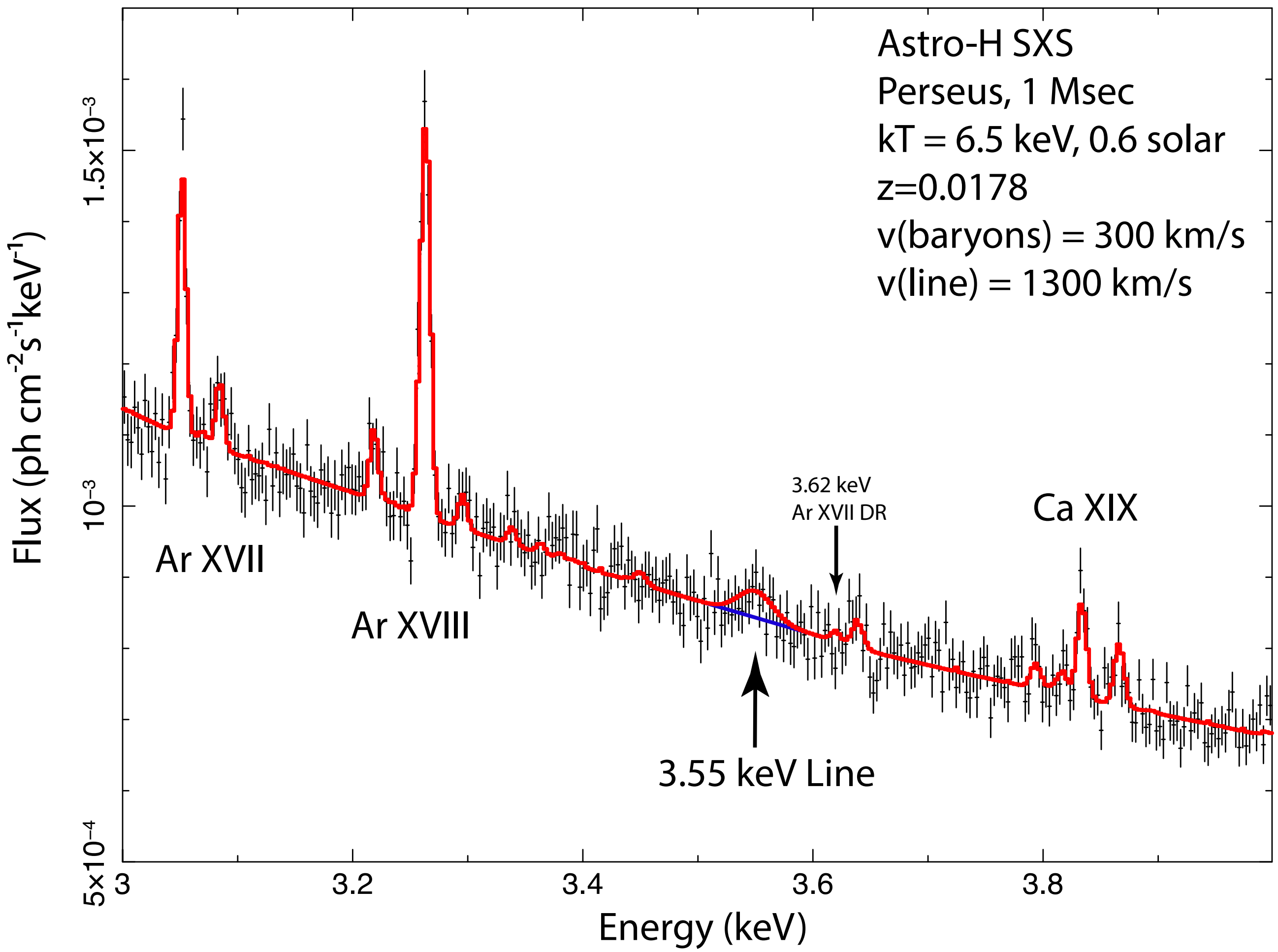


Comparison with Previous Limits





How Do We Solve This Puzzle?



Conclusions

- Attempts to refine upper limits can sometimes fail…

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- Attempts to refine upper limits can sometimes fail…
- The feature at 3.56 keV is weak but robust to multiple sources and detectors
- There is no plausible atomic feature at this energy, regardless of the atomic model used, that wouldn't create other features that are not seen.
- What is it?
  - Bulbul et al. (2014) [now accepted in ApJ!] has 45 citations, ~44 of whom discuss the possibilities…