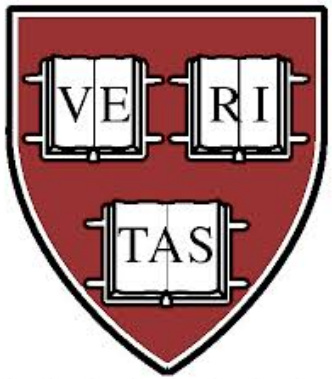
The Detection of Mysterious 3.56 keV Emission Line

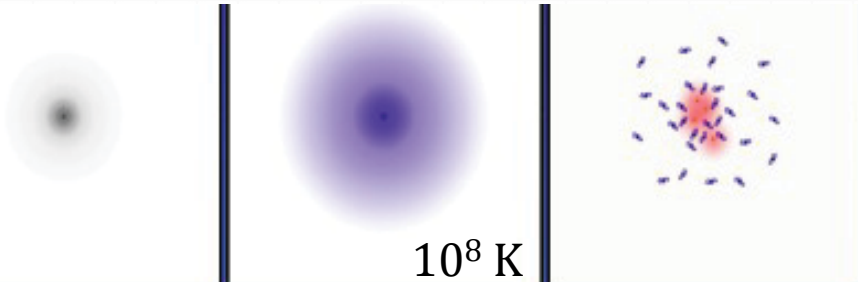


Esra Bulbul
Harvard-Smithsonian Center for Astrophysics

Maxim Markevitch (NASA/GSFC), Adam Foster (CfA), Randall Smith (CfA), Mike Loewenstein (NASA/GSFC), Scott Randall (CfA)

Galaxy Clusters

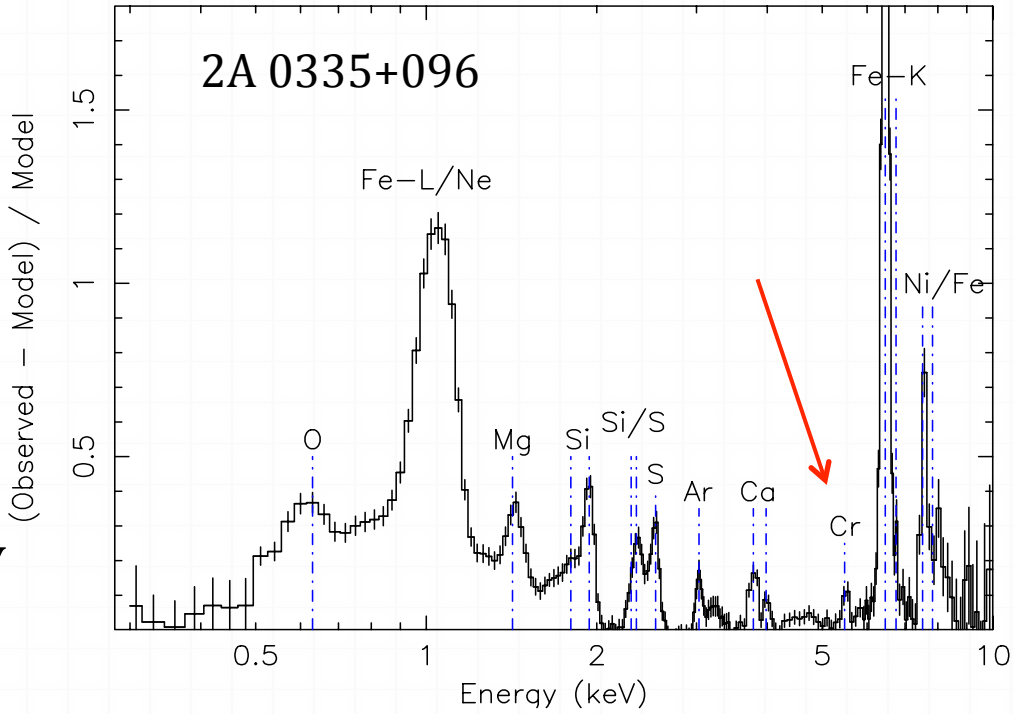
- Largest gravitationally bound aggregations of hot ICM and DM
- ICM: T~10^8 K
- ICM: Collisionally ionized in full equilibrium
- Masses up to ≈ $10^{15} M_\odot$



Credit: PenCredit: X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScl

Line Searches in X-ray Observations of Clusters

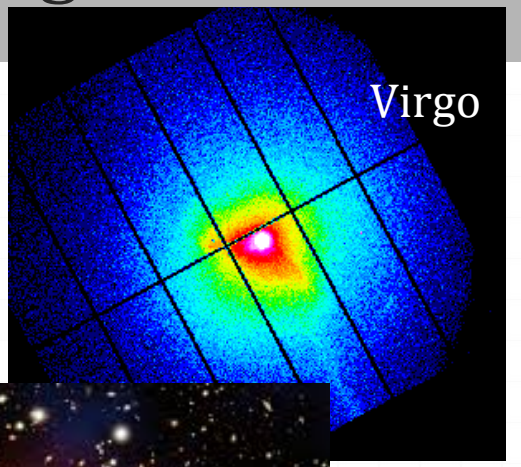
- Gas is enriched mainly via SN explosions by metals produced by stars in galaxies
- Weak emission lines are now being discovered through X-ray spectroscopy

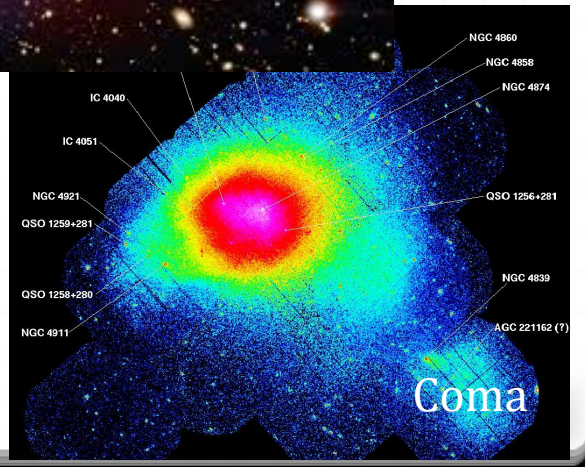


Werner et al. (2006)

Sterile Neutrino Decay Signal Search

- Warm dark matter candidate sterile neutrinos decay into an active neutrino and an X-ray photon

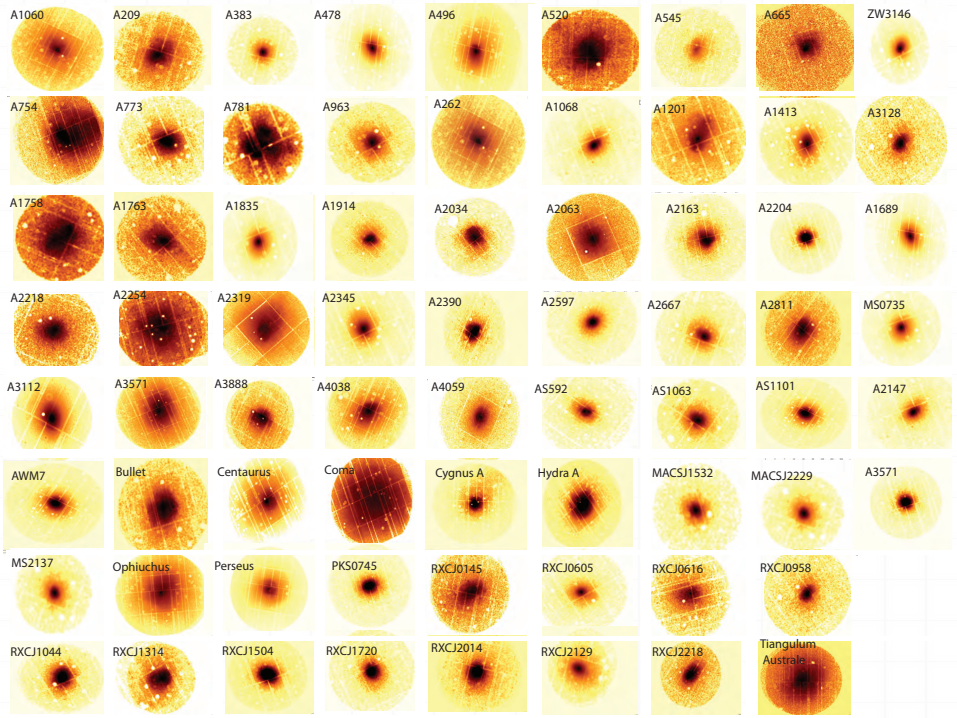




Sterile Neutrino Mass (m_s)	**Source**	**Reference**
< 6.3 keV	Coma, Virgo, Bullet	Boyarsky et al. (2006, 2008)
< 8.2 keV	Virgo	Abazajian et al. (2001)

Why Stacking?

- Stacked XMM-Newton observations of 73 galaxy clusters at their rest frame
- Redshift range of 0.01 to 0.35 smears the non-source features, e.g. instrumental, background
- Increased signal-to-noise!



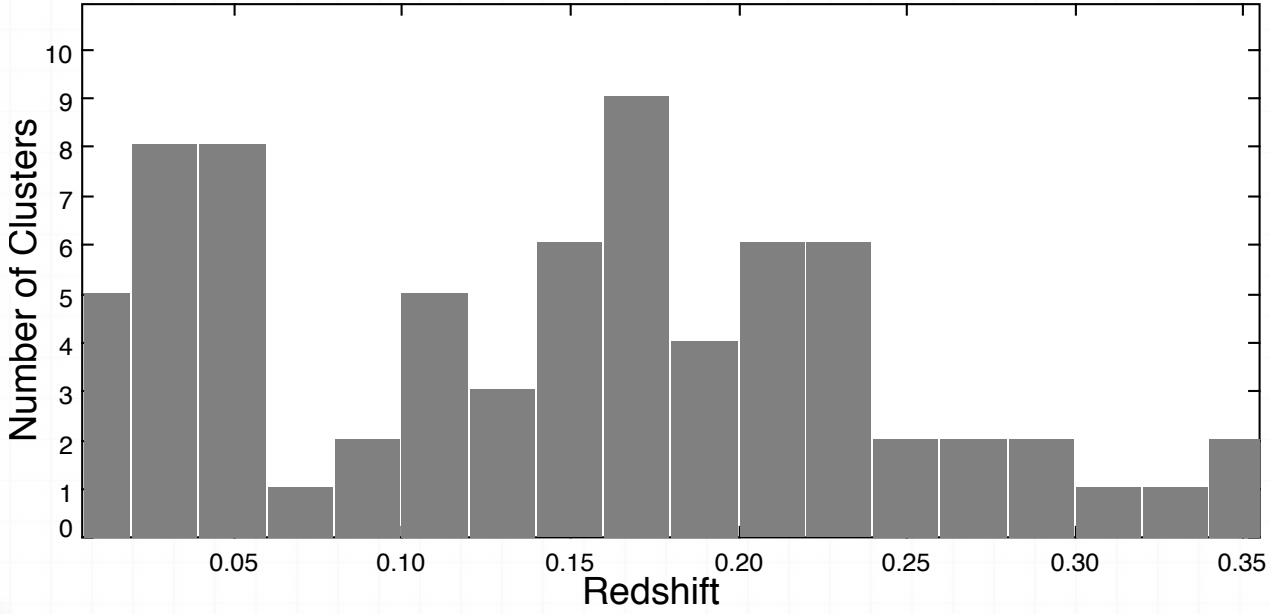
XMM-Newton Stamp Images of 73 Galaxy Clusters

Sample Selection

- 10^5 counts per observation for clusters for z < 0.1
- 10^4 counts per observation for clusters for 0.1 < z < 0.4
- XMM-Newton Observations of 73 galaxy clusters
- Chandra observations of the Perseus and Virgo clusters

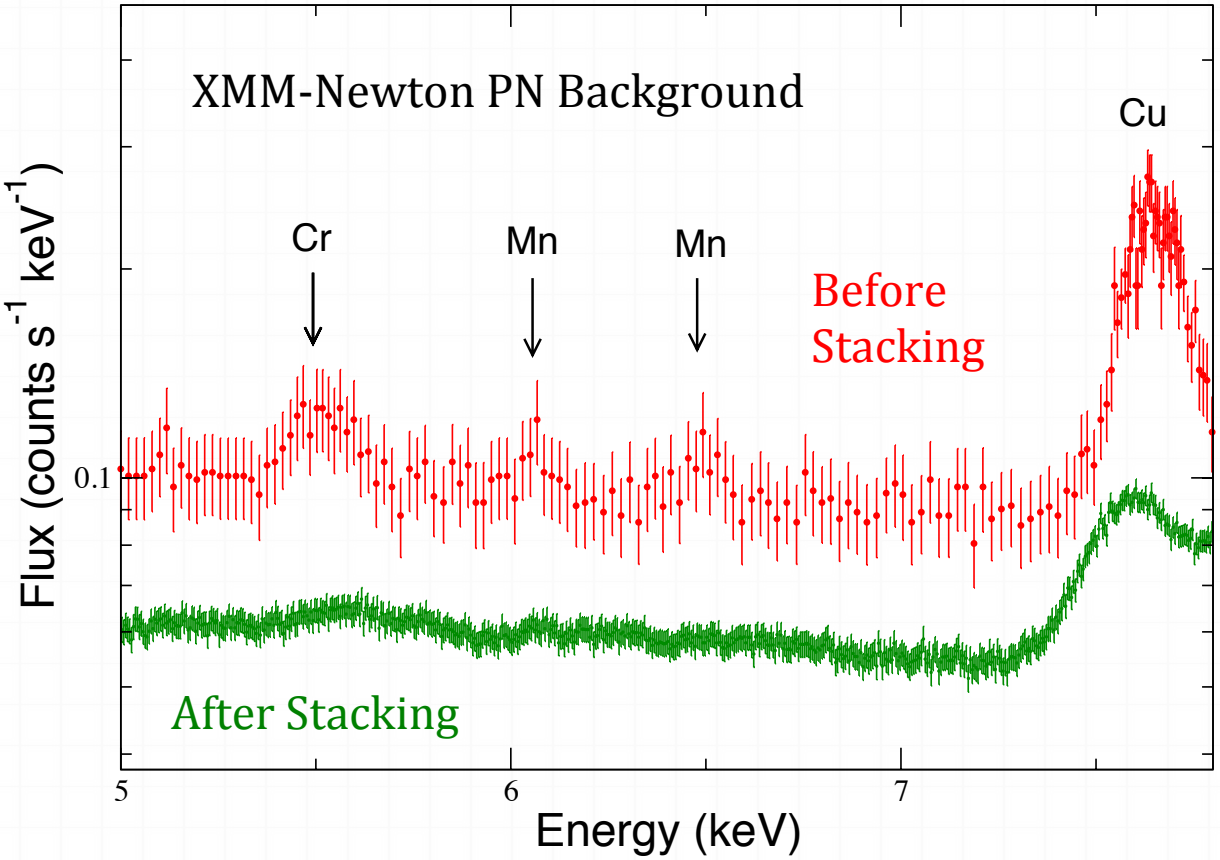
MOS and PN on board of XMM-Newton

ACIS-S and ACIS-I on board of Chandra



Background Emission

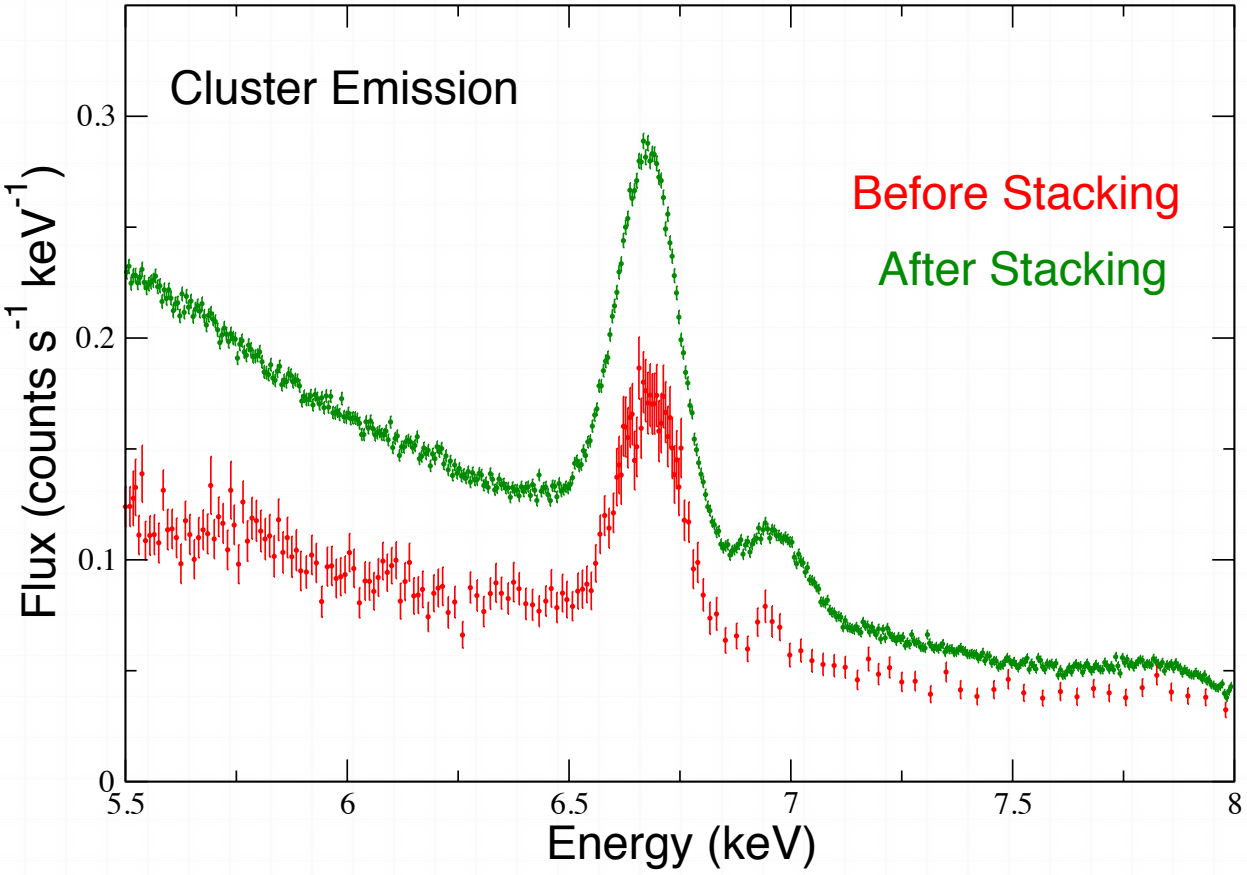
- XMM-Newton PN background spectra before and after stacking
- Background lines are smeared after stacking



MOS and PN are two different CCD detectors on XMM-Newton

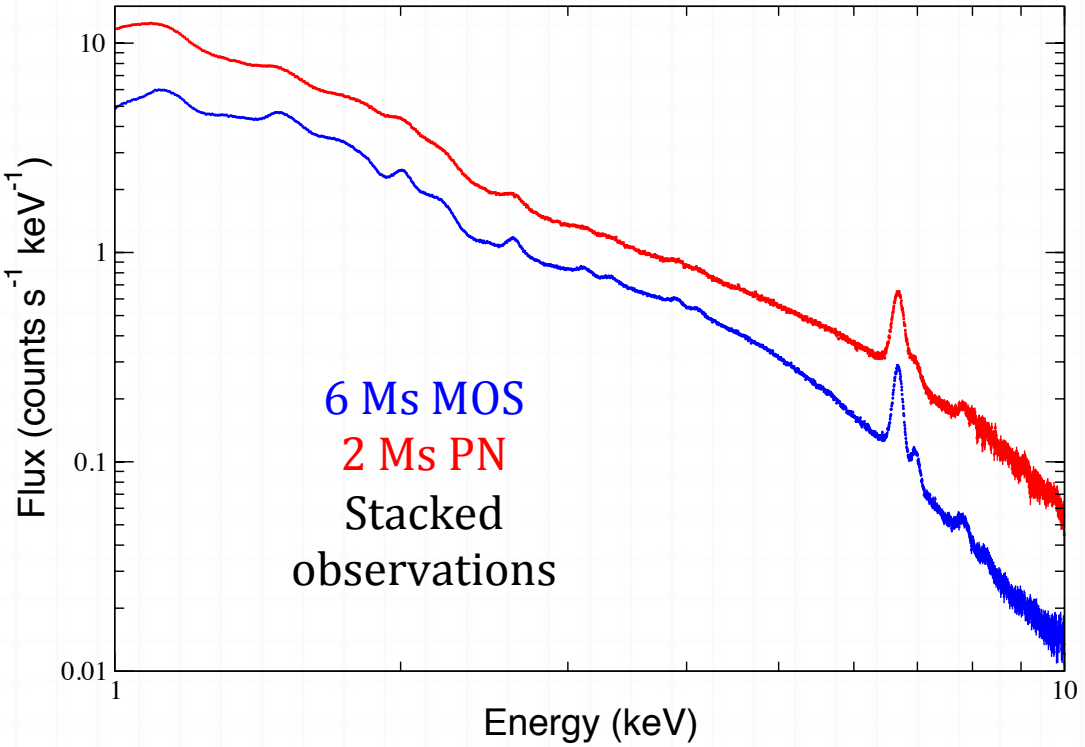
Cluster Emission

- XMM-Newton MOS cluster emission spectra before and after stacking
- Increased signal-to-noise!

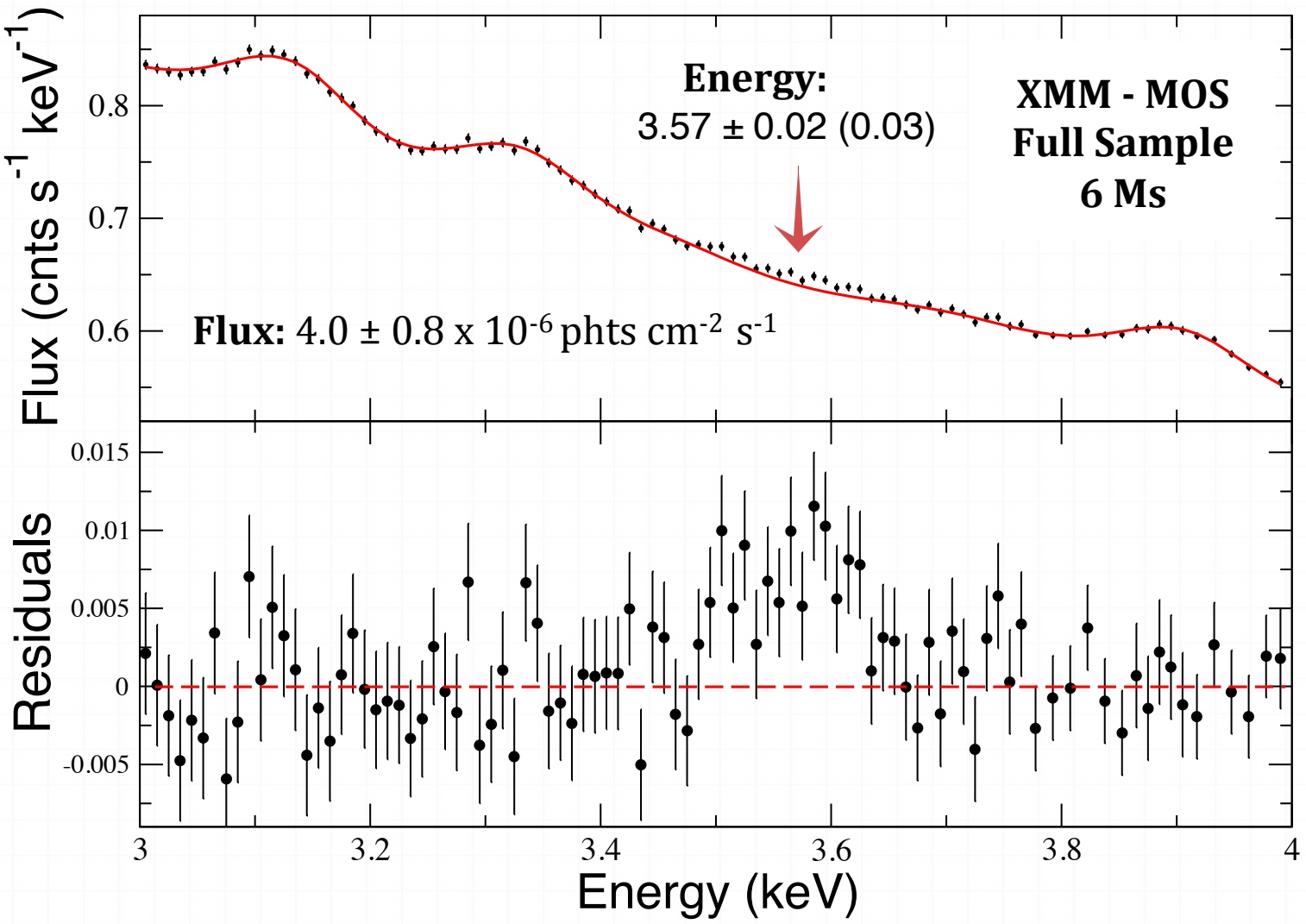


Fitting the Spectra

- Subtracted the particle background
- Fit the line-free thermal (apec) model for continuum and 28 Gaussian models for emission lines
- Energy Band: 2 - 10 keV
- Significant unidentified emission feature at ~3.56 keV
- Estimated the flux of nearby lines based on the AtomDB (K and Ar lines in 3.4-3.7 keV)

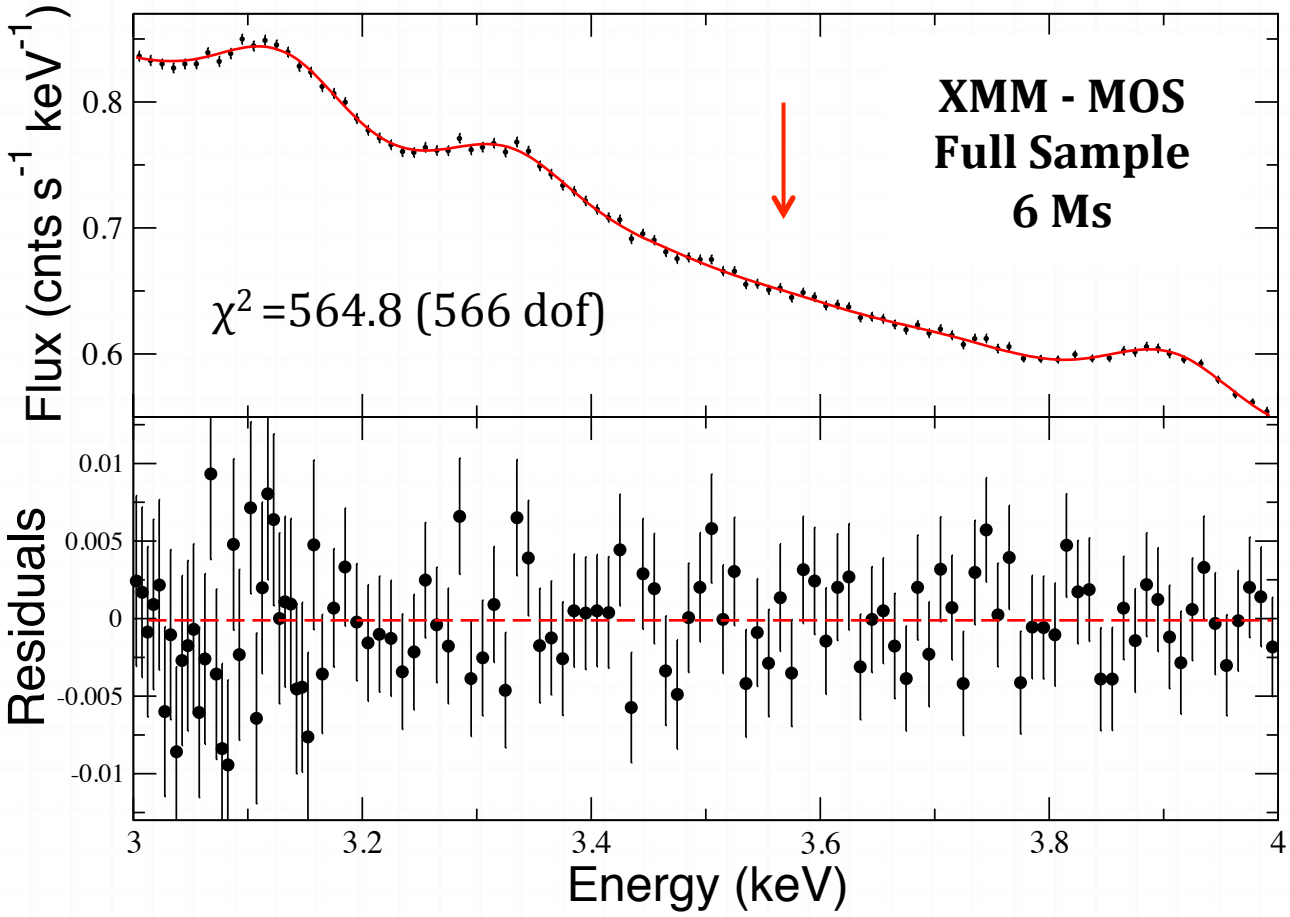


Detection of An Unidentified Emission Line



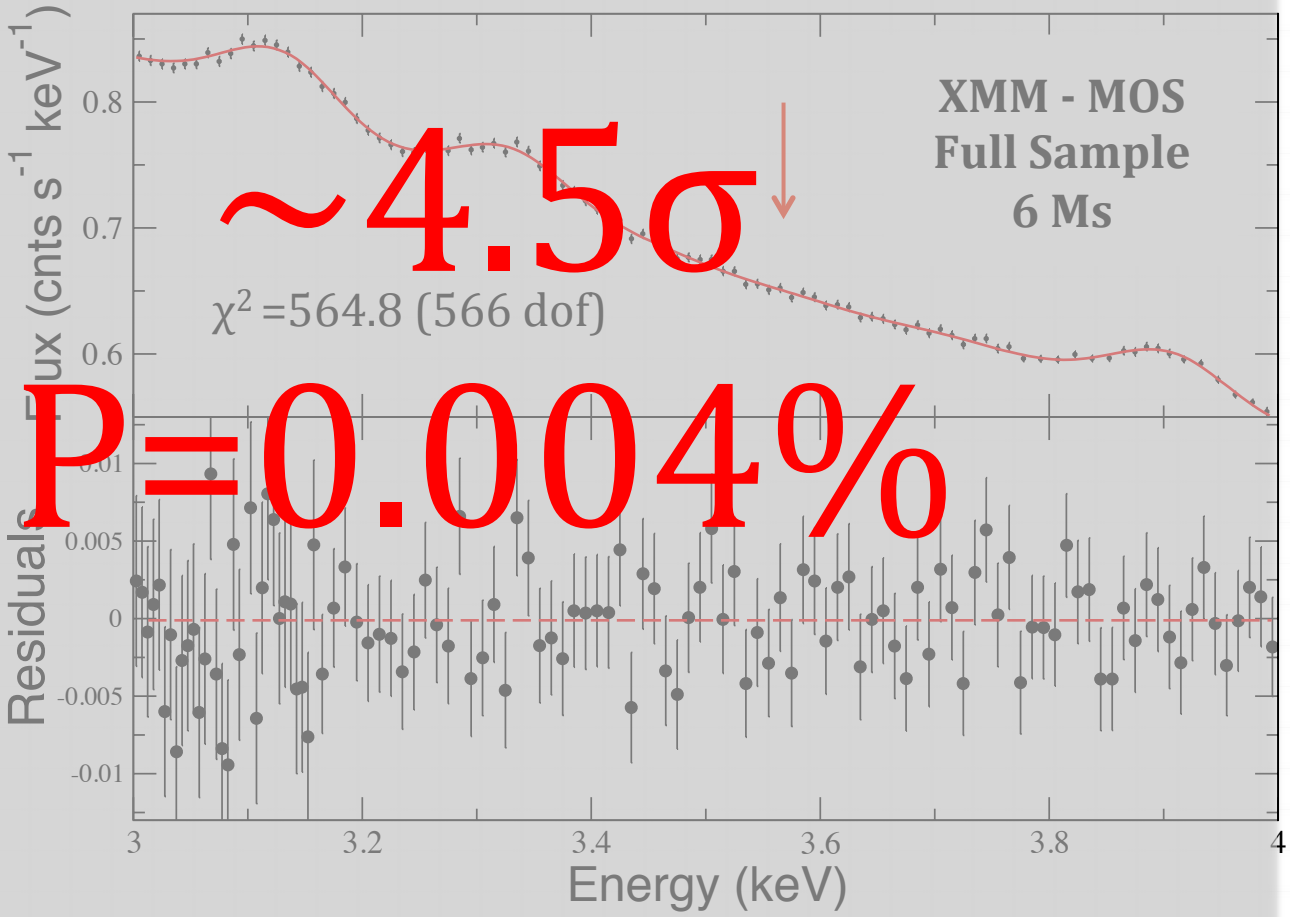
MOS Full Sample with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for energy and flux
- Obtained a good fit with a χ^2 of 564.8 for 566 dof
- The change in the $\Delta\chi^2$ is 22.8 for 2 dof



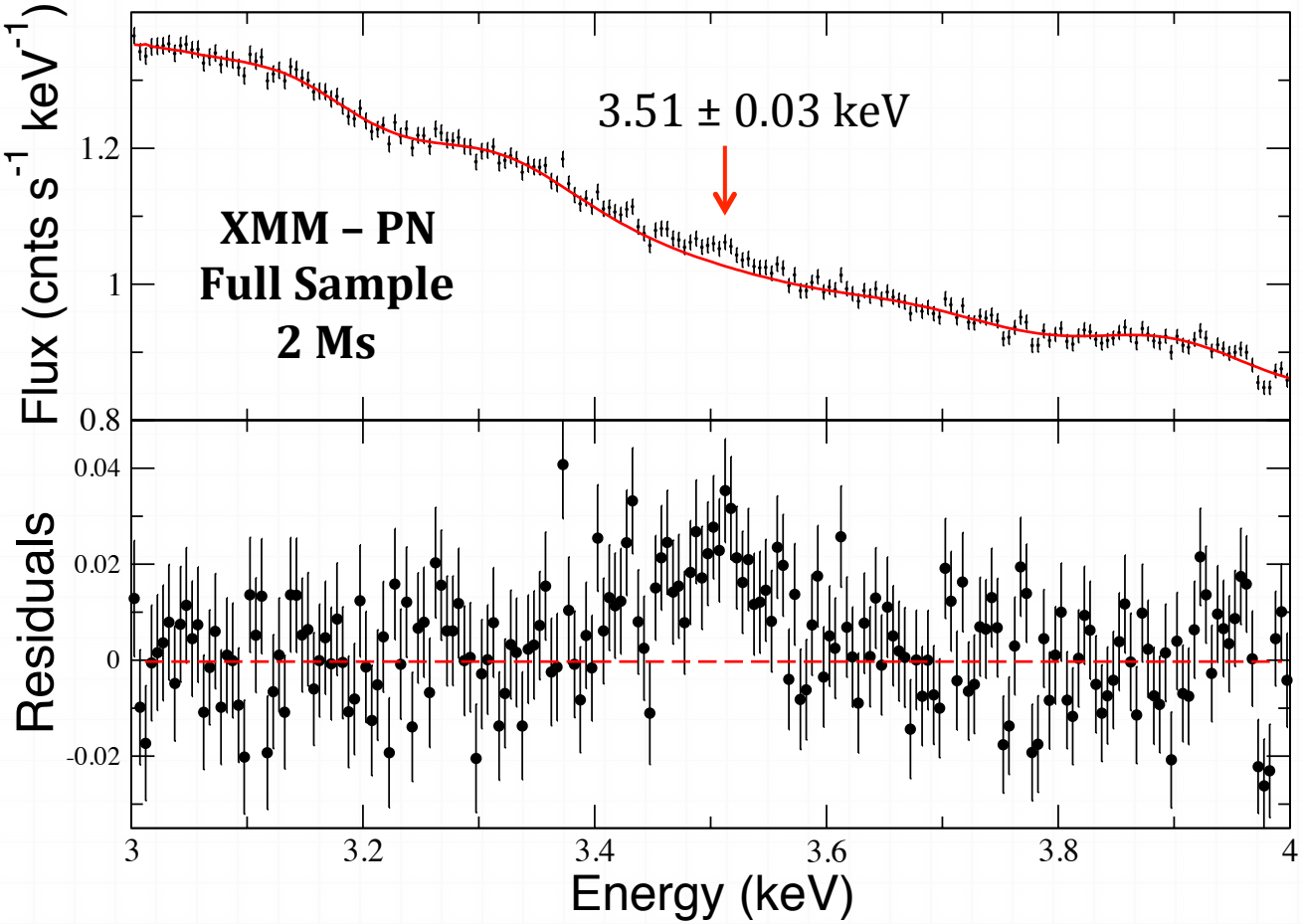
MOS Full Sample with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for energy and flux
- Obtained a good fit with a χ^2 of 564.8 for 566 dof
- The change in the $\Delta\chi^2$ is 22.8 for 2 dof



Detected in PN Observations of the Full Sample

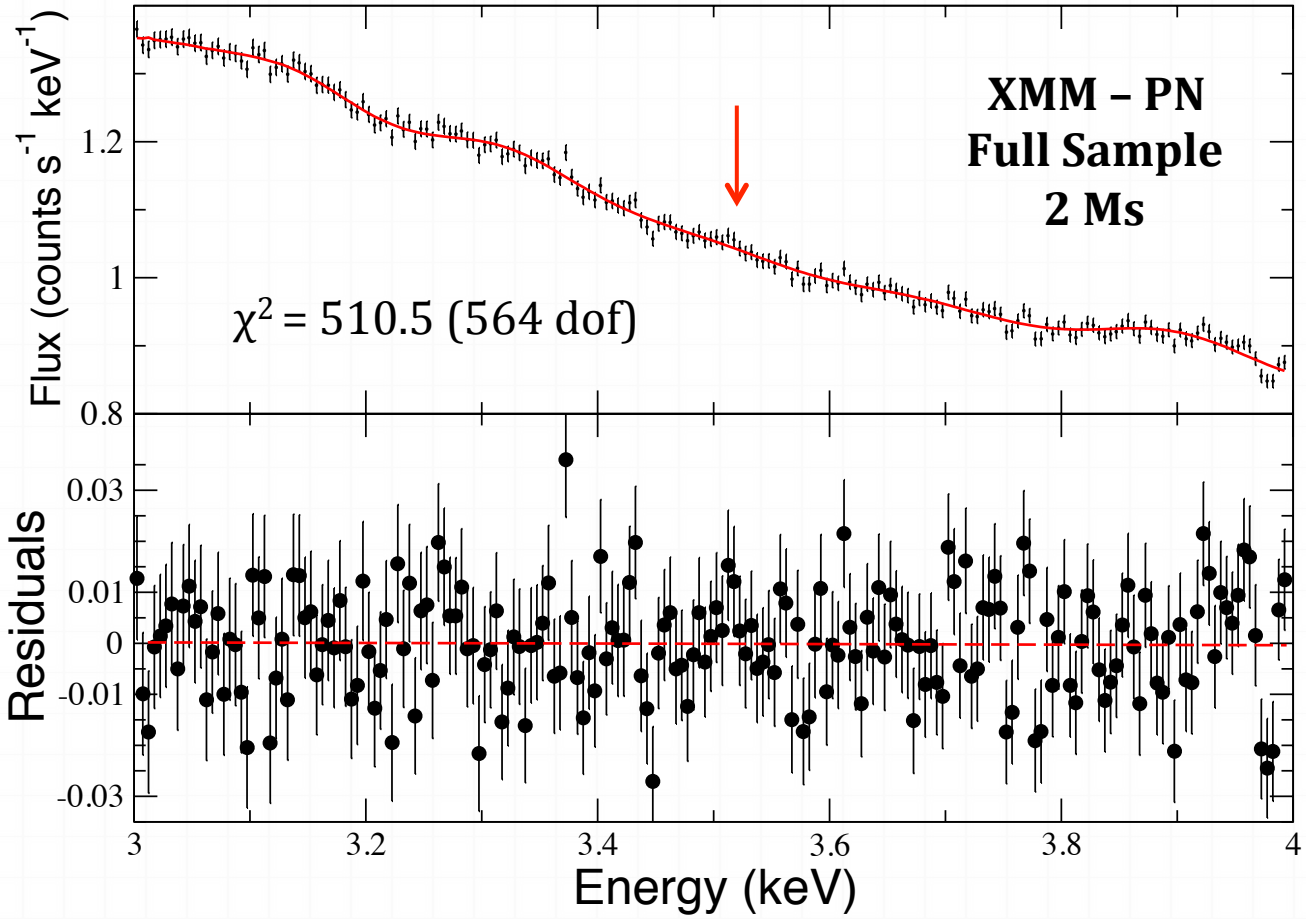
- The line is detected in **independent** PN observations of 73 clusters
- **Energy:** 3.51 ± 0.03 keV
- **Flux:** $3.9 \pm 0.9 \times 10^{-6}$ pht cm^{-2} s^{-1}



MOS and PN are two different CCD detectors on XMM-Newton

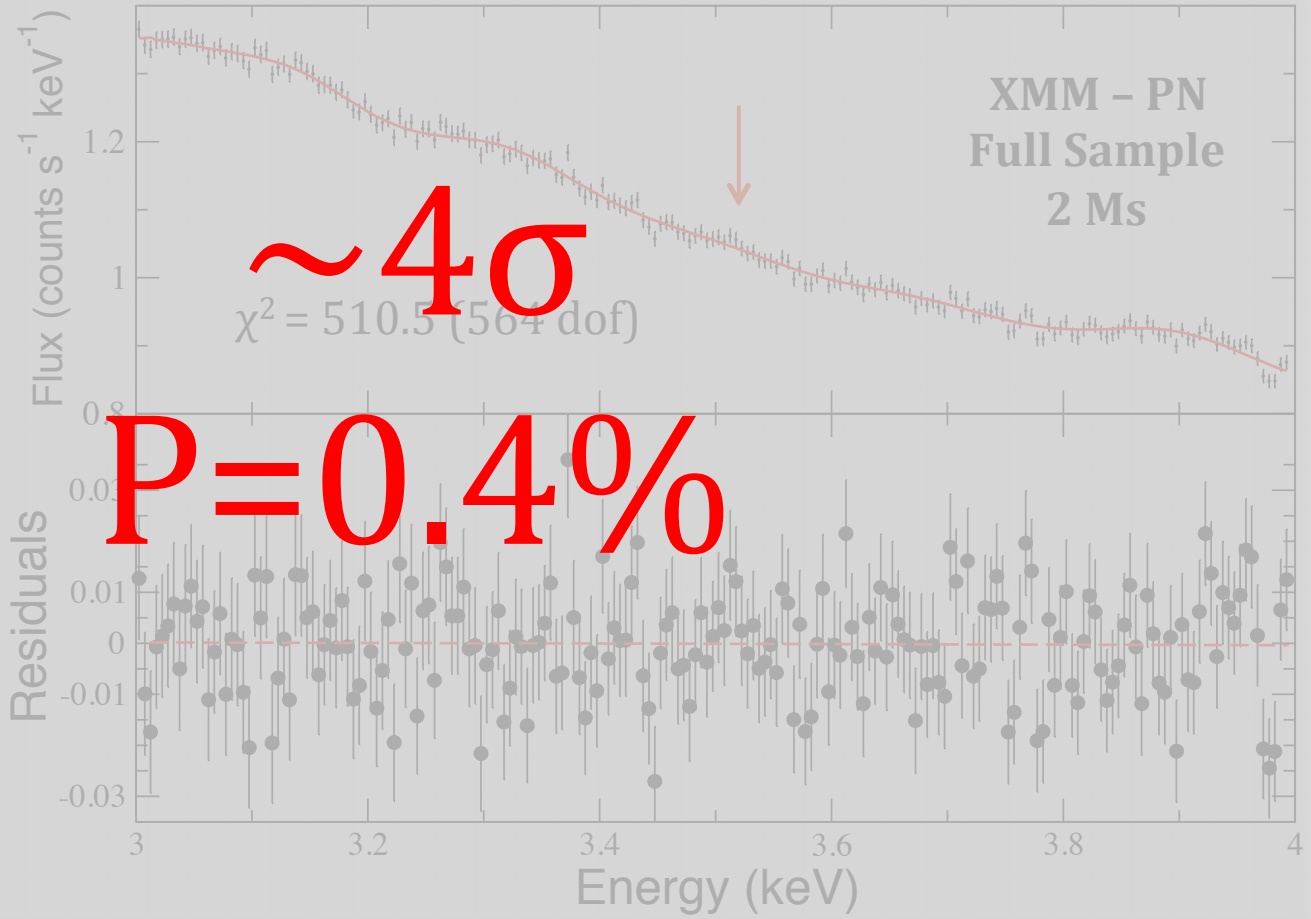
PN Full Sample with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for energy and flux
- Obtained a good fit with a χ^2 of 510.5 for 564 dof
- The change in the $\Delta\chi^2$ is 13.9 for 2 dof



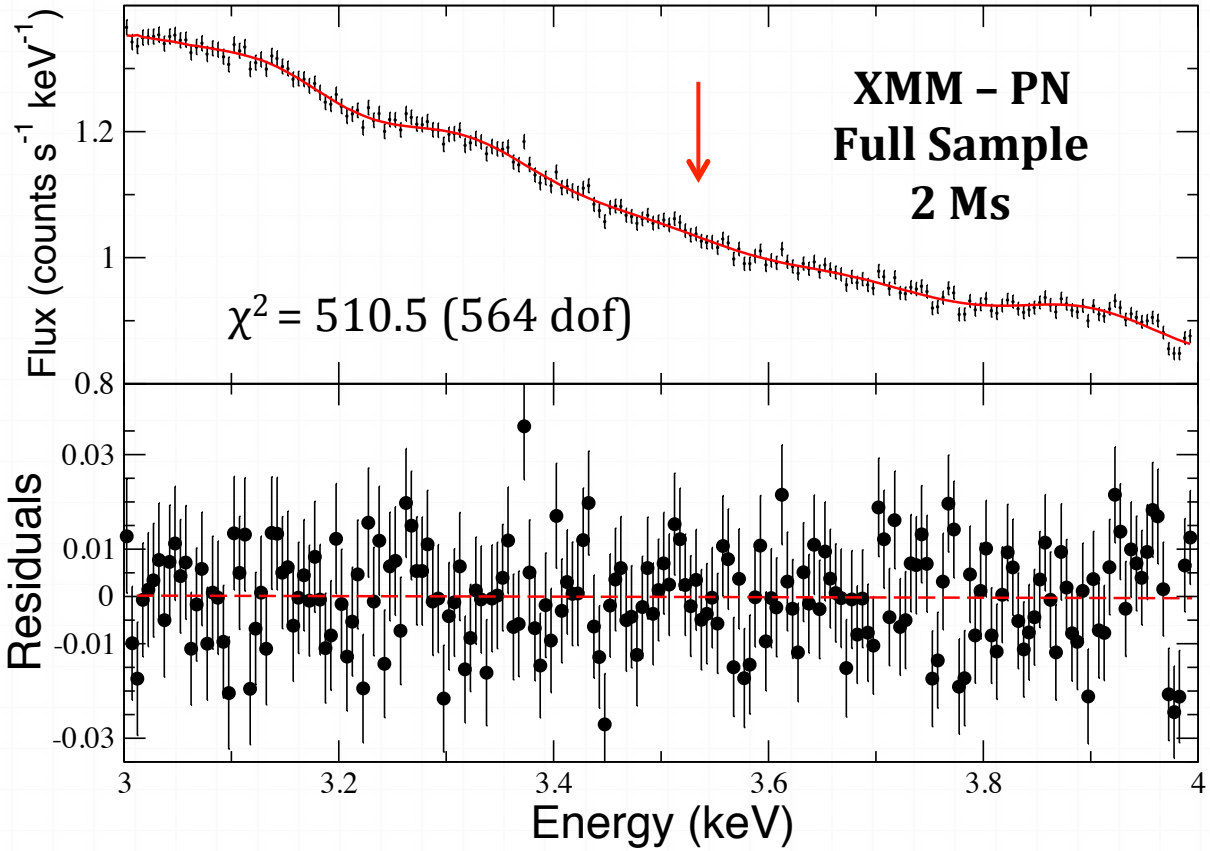
PN Full Sample with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for energy and flux
- The change in the $\Delta\chi^2$ is 13.9 for 2 dof
- ***not*** *a background feature*



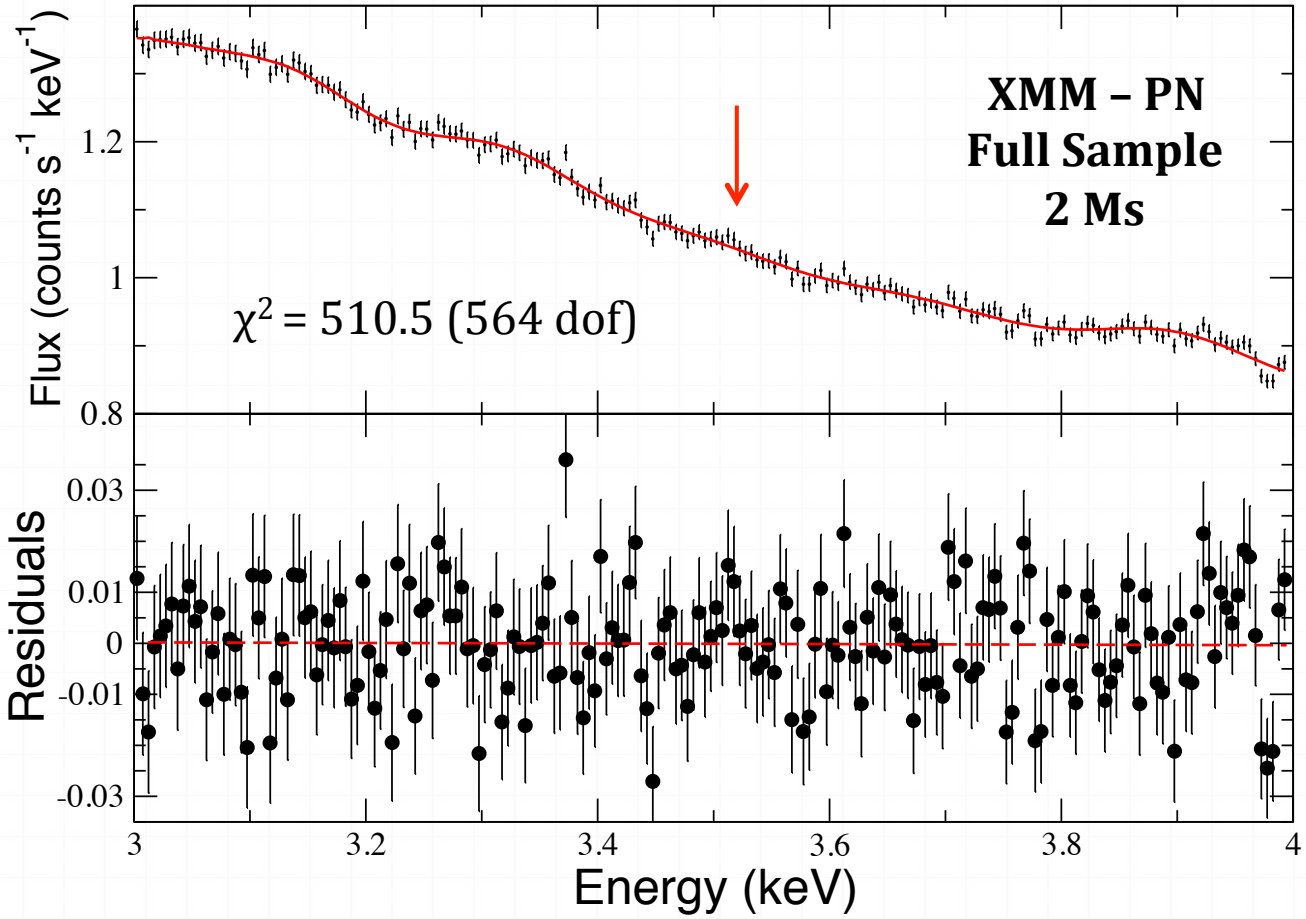
MCMC Simulations of PN Observations

- 1000 realizations
- Fit with no additional Gaussian
- Fit with an additional Gaussian line at an arbitrary location and flux
- Compared the change in the χ^2
- 4 out of 1000 realizations $\Delta\chi^2$ of the fit with an additional Gaussian line was improved by $\Delta\chi2$ of 13.9
- Corresponds to 0.4% detection probability



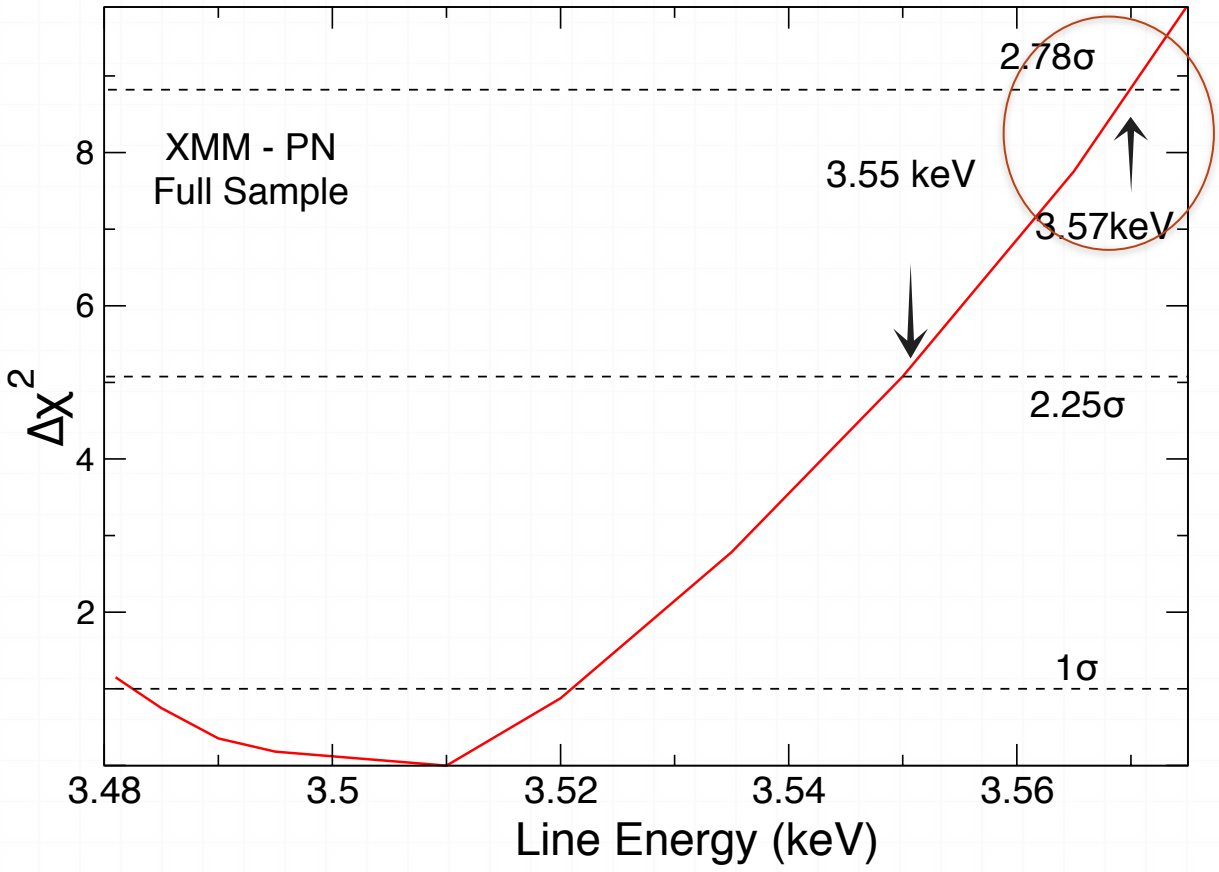
PN Full Sample with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for energy and flux
- The change in the $\Delta\chi^2$ is 13.9 for 2 dof
- ***not*** *a background feature*



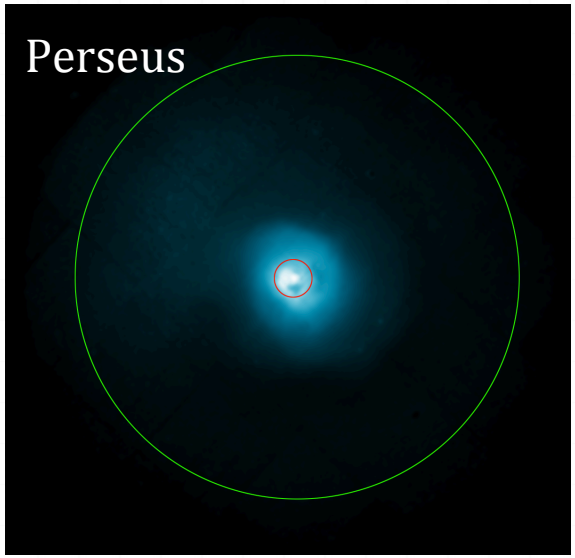
Tension in the Line Energy

- The change in the goodness-of-fit statistics as a function of line energy
- Line energy is 2.2σ and 2.8σ away from the MOS detection

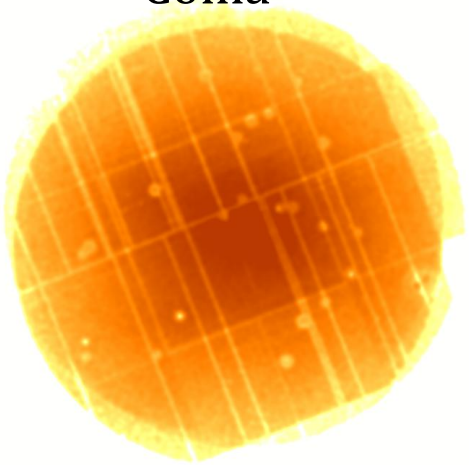


Subsamples

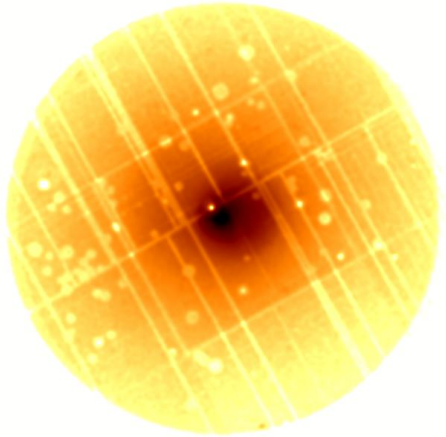
- Divided the XMM-Newton Full Sample
  1- Brightest clusters (Ophiuchus +Coma +Centaurus)
  2- Perseus (Full FOV and core excised)
  3- All the Rest (69 Clusters)



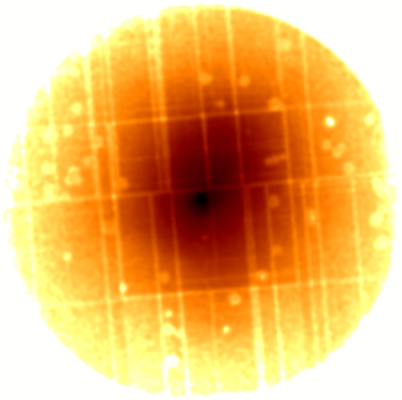
Coma



Centaurus

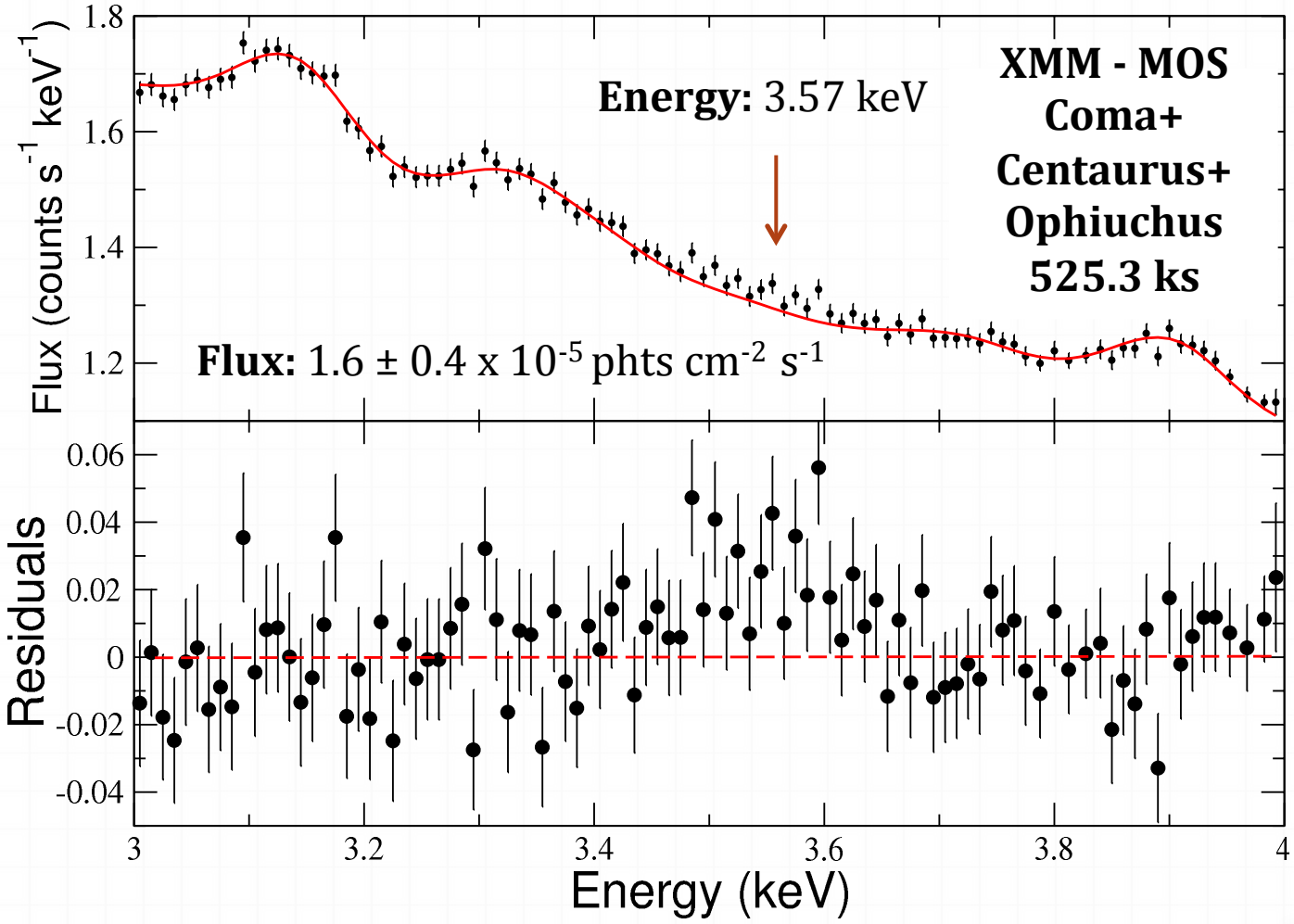


Ophiuchus



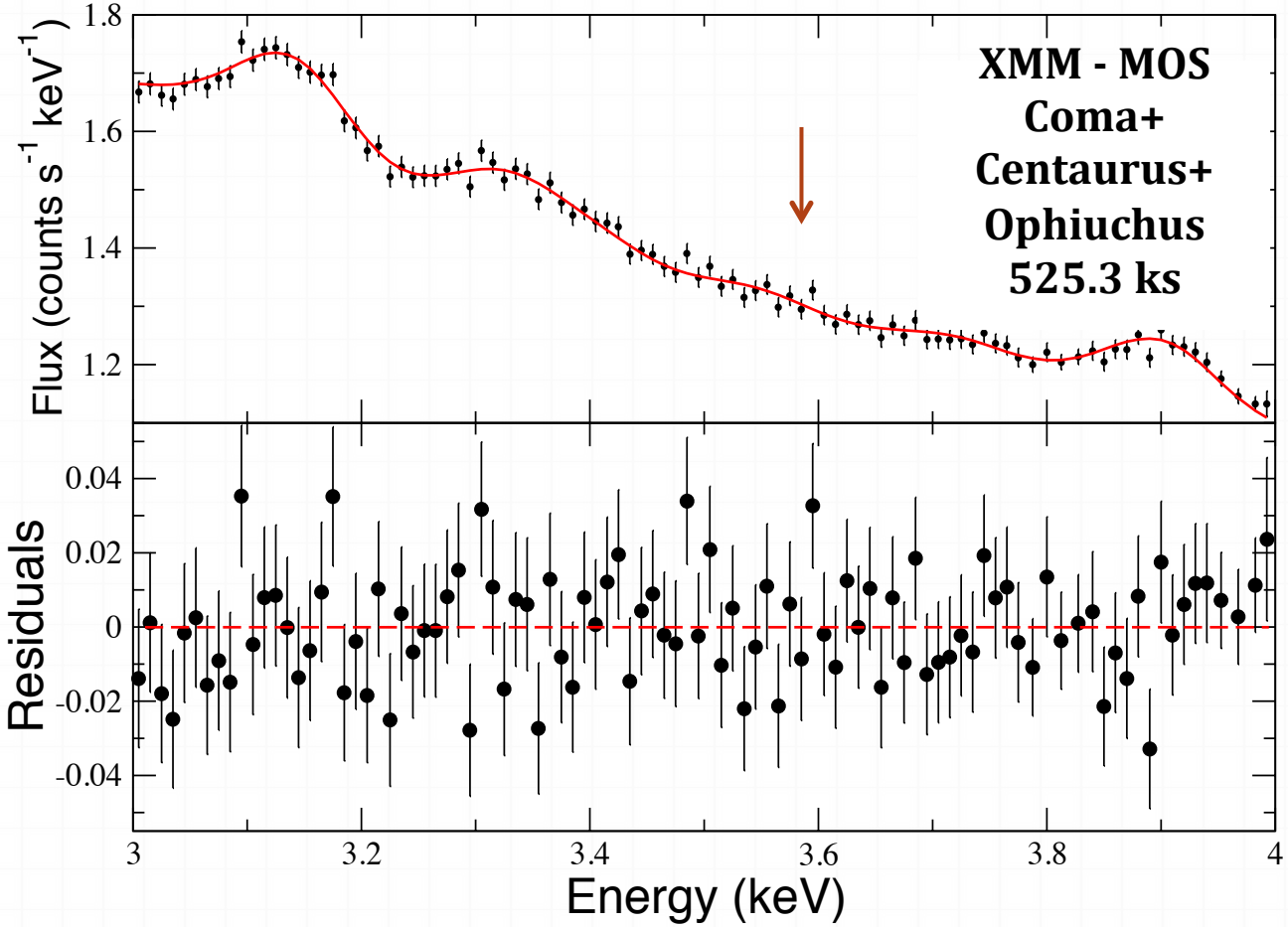
Detected in Brightest Clusters with MOS

- Detected in the stacked observations of the brightest clusters; Coma + Centaurus + Ophiuchus
- **Flux:** $1.6 \pm 0.4 \times 10^{-5}$ pts cm^{-2} s^{-1} at 3.57 keV (consistent when scaled)



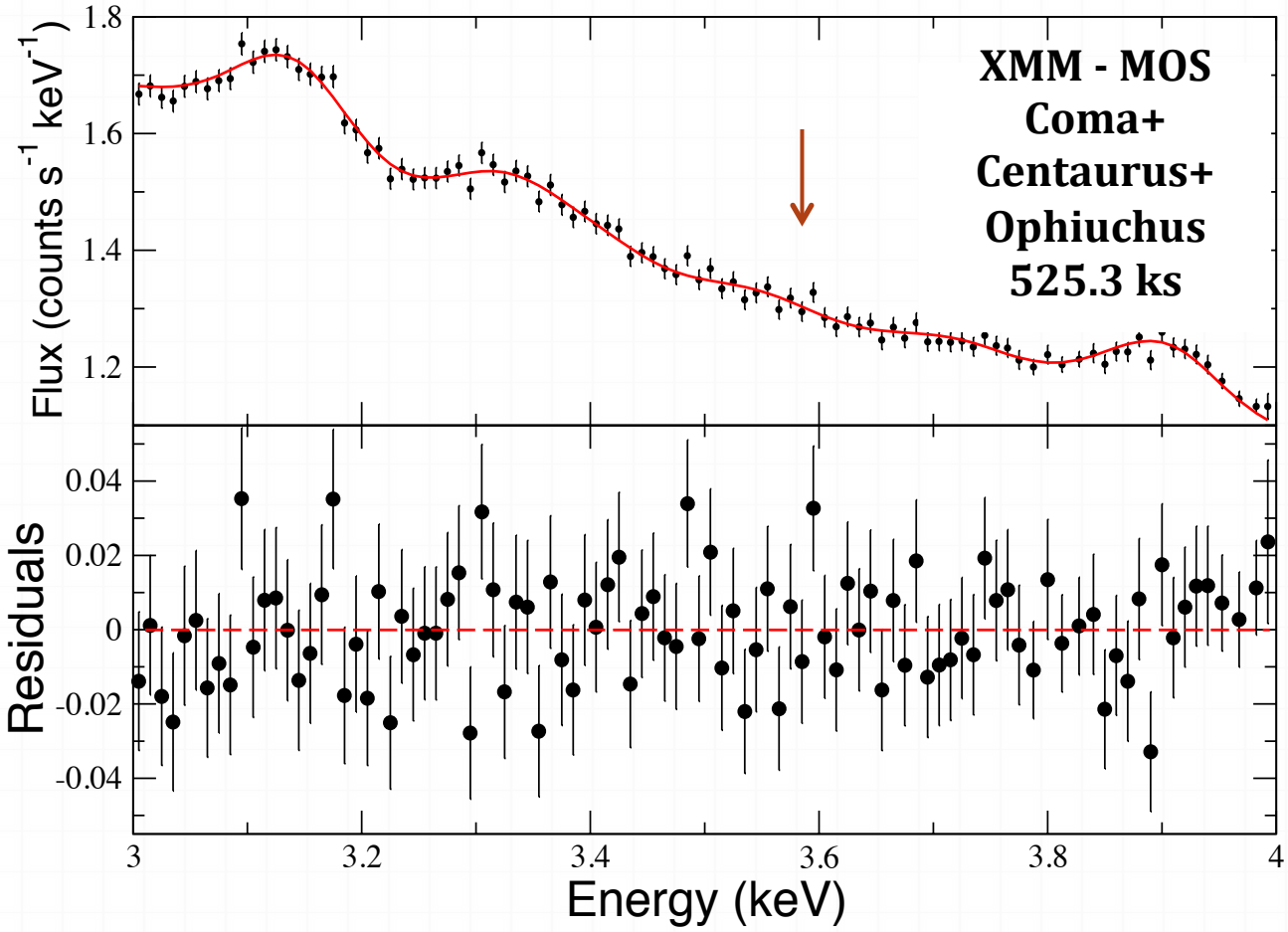
MOS Brightest Clusters with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for flux
- Obtained a good fit with a χ^2 of 562.3 for 569 dof
- The change in the $\Delta\chi^2$ is 17.1 for 1 dof



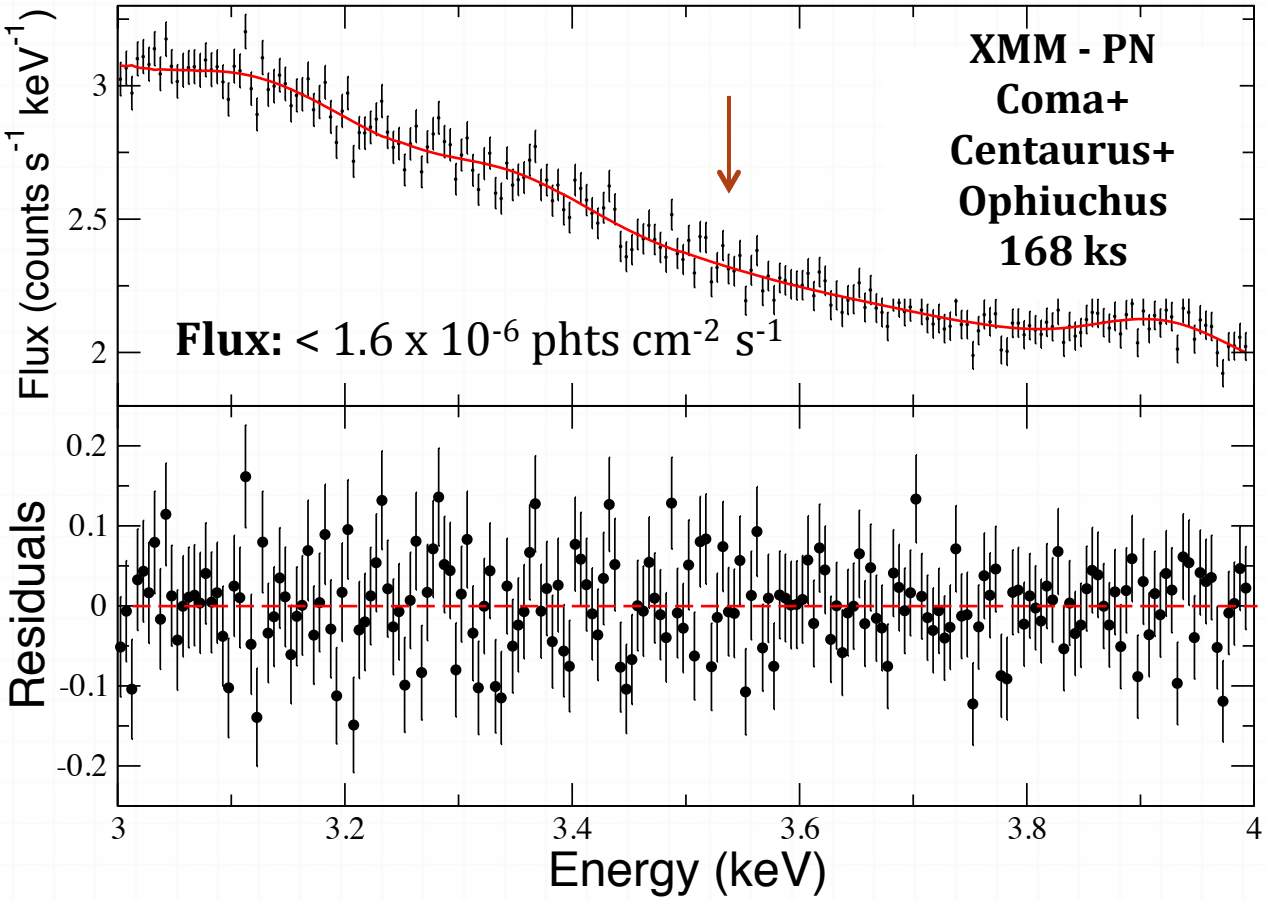
MOS Brightest Clusters with an Additional Gaussian

- An extra Gaussian line is added to the model
- Fit for flux
- Obtained a good fit with a χ^2 of 562.3 for 569 dof
- The change in the $\Delta\chi^2$ is 17.1 for 1 dof
- *Detected significantly in the brightest clusters!*



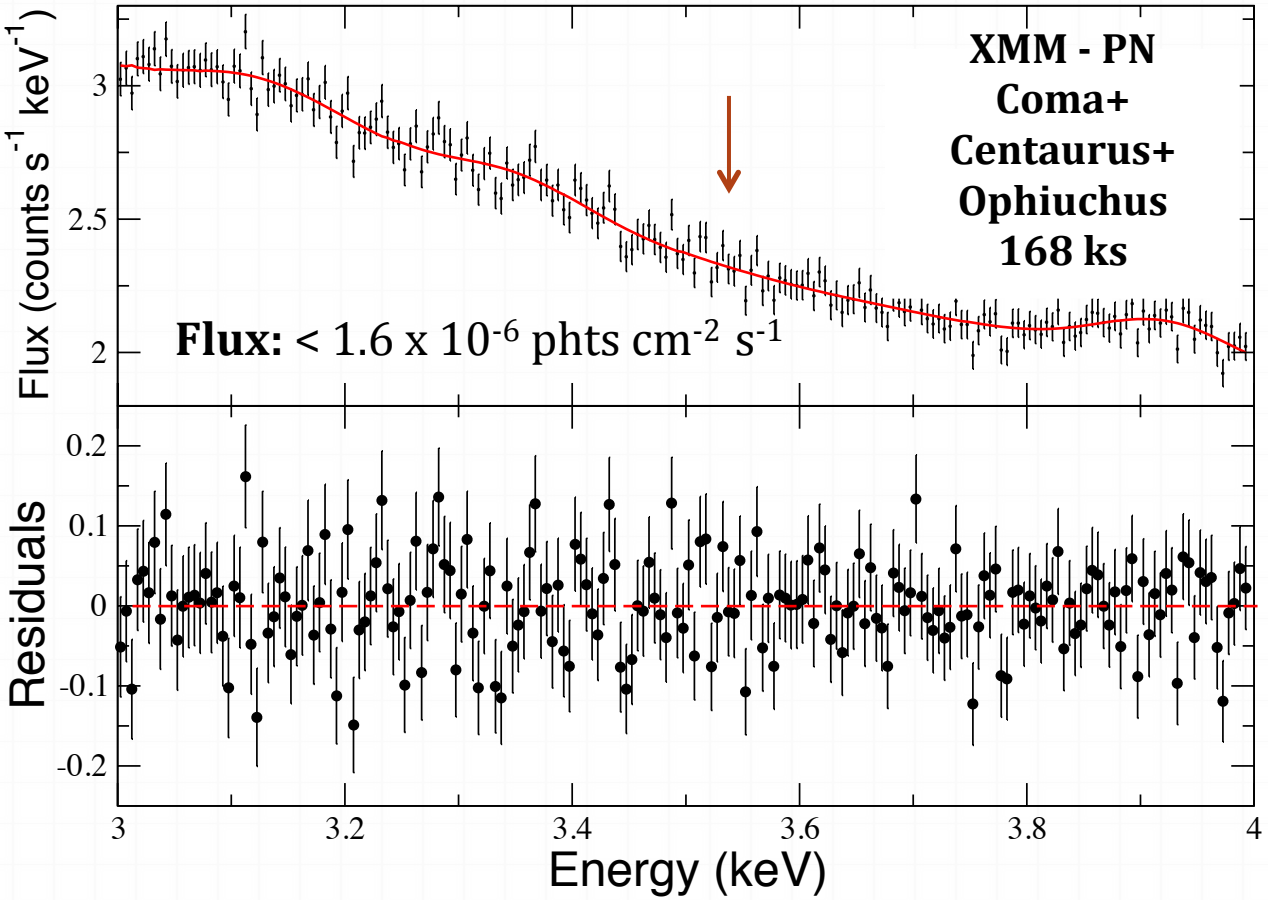
No Detection in Brightest Clusters with PN

- Total exposure time 168 ks
- No Detection!
- Upper limit to the flux
- Obtained a good fit with a χ^2 of 539.1 (553 dof)



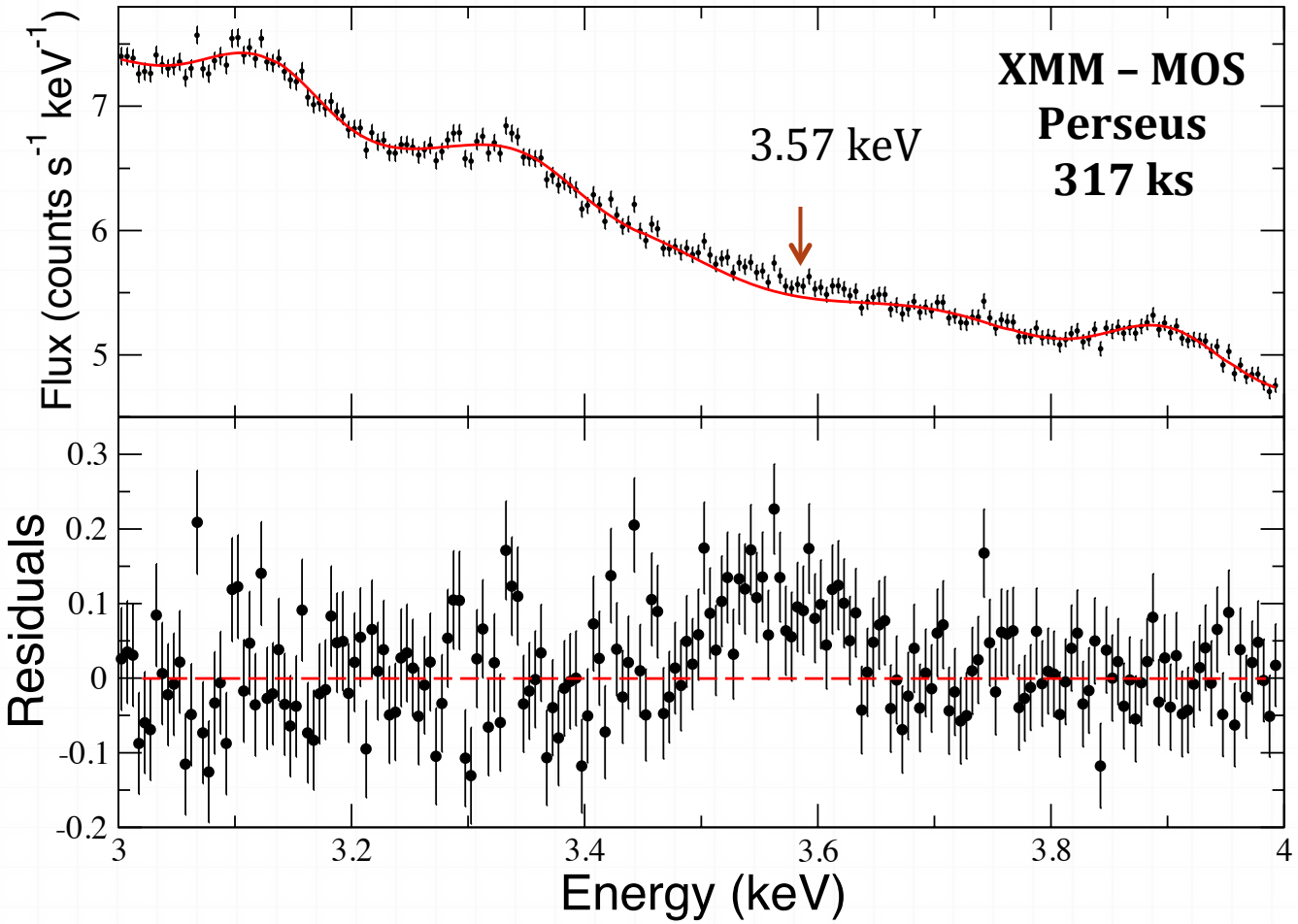
No Detection in Brightest Clusters with PN

- Total exposure time 168 ks
- No Detection!
- Upper limit to the flux
- Obtained a good fit with a χ^2 of 539.1 (553 dof)
- *Not enough signal-to-noise!*



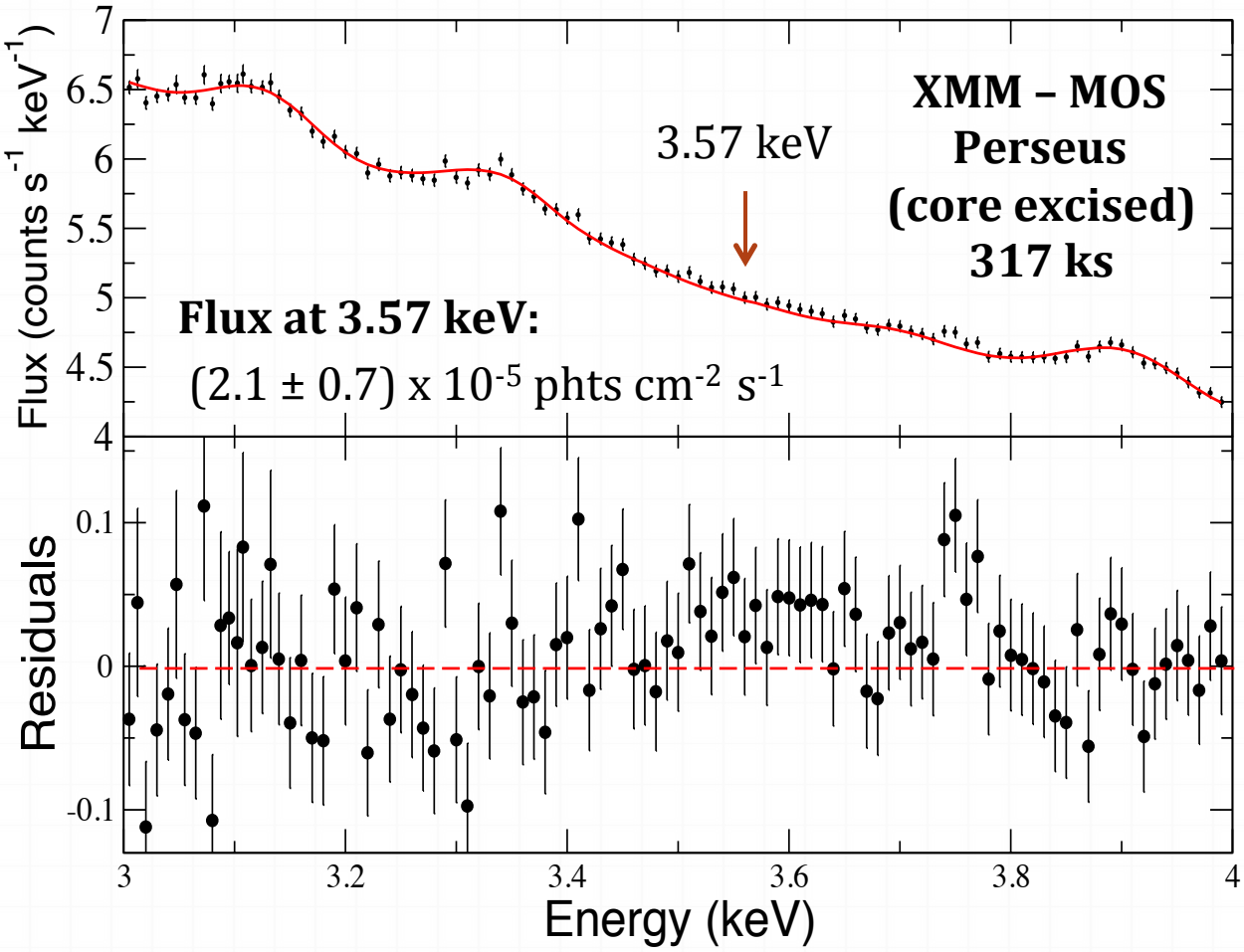
Perseus MOS Observations (FULL FOV)

- Detected in the MOS Observations of the Perseus cluster
- Flux at 3.57 keV:
  $5.2 \pm 0.2 \times 10^{-5}$ pht cm^{-2} s^{-1}
- *5 times brighter than expected*



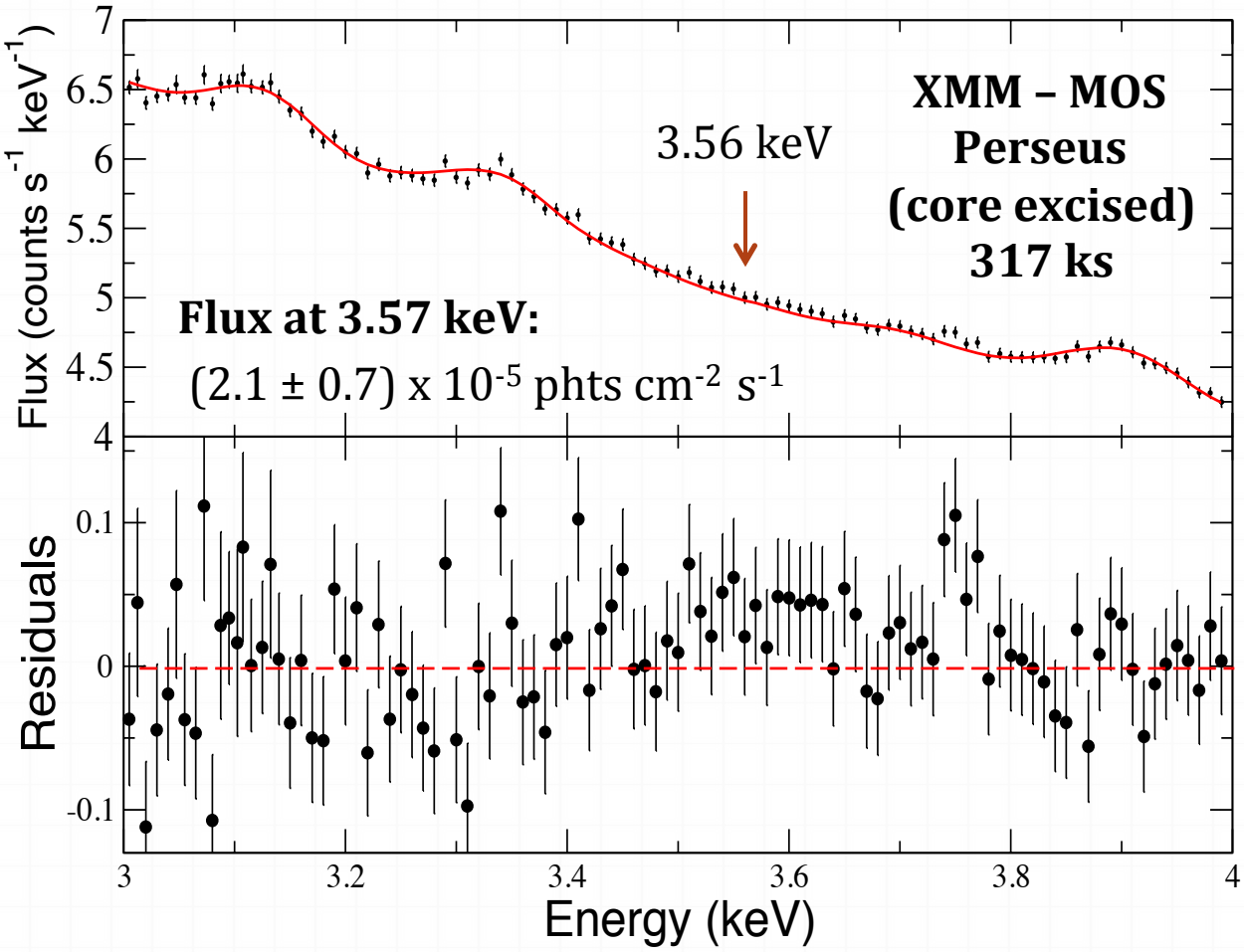
MOS Observations of Perseus (Core Excluded)

- Detected in the MOS Observations of the core-cut Perseus cluster
- **Flux at 3.57 keV:**
  $2.1 \pm 0.7 \times 10^{-5}$ phts cm^{-2} s^{-1}
- ~2.5 times brighter than expected



MOS Observations of Perseus (Core Excluded)

- Detected in the MOS Observations of the core-cut Perseus cluster
- **Flux at 3.57 keV:** $2.1 \pm 0.7 \times 10^{-5}$ phts cm^{-2} s^{-1}
- *emission is concentrated in the immediate cool core!*

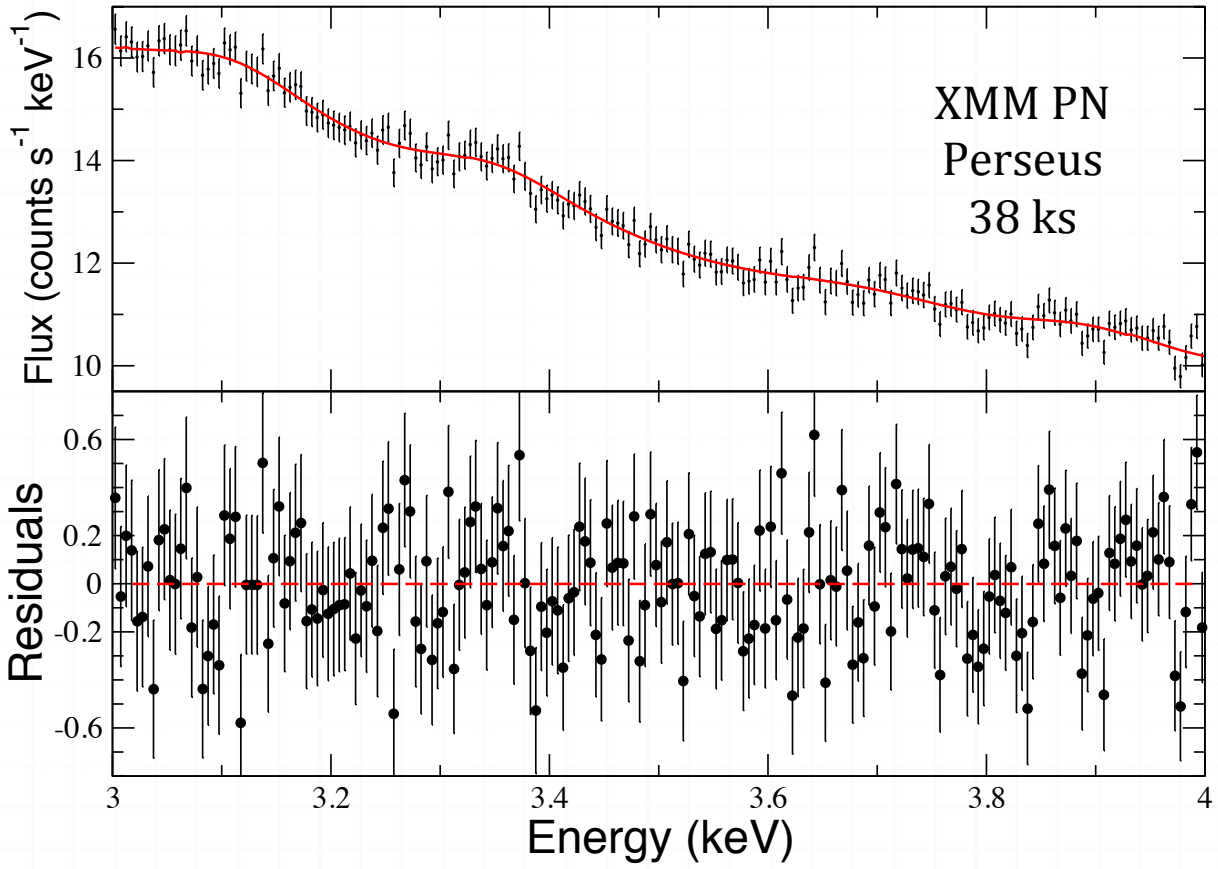


A Closer Look to the MOS Observations of Perseus

- investigated the dependence of the energy and flux of the K XVIII line at 3.51 keV and the Ar XVII DR line at 3.62 keV.
- Allowed the energy of the Gaussian component to vary produced a best-fit for an energy of 3.59 +/- 0.02 keV, with a consistent flux and similar χ^2
- Could this be Ar XVII DR line?
- The predicted maximum flux of the Ar XVII DR line for the Perseus spectrum was 1.6×10^{-6} photons s^{-1} keV^{-1}
- *30 times higher than measured!*

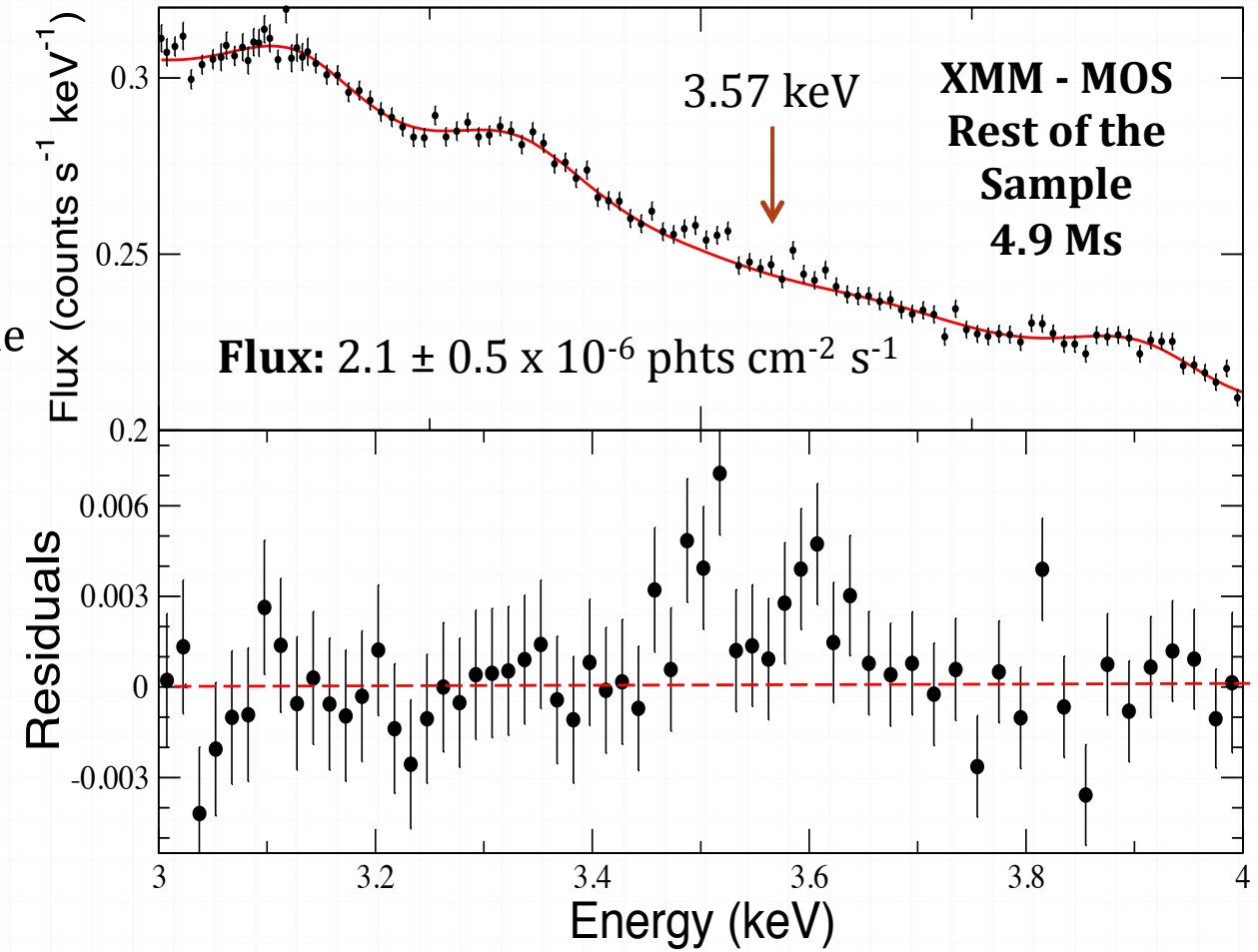
No Detection in Perseus PN

- Total exposure time 38 ks
- No Detection!
- Upper limit to the flux
- $F < 1.8 \times 10^{-5}$ photons s^{-1} keV^{-1}
- Obtained a good fit with a χ^2 of 539.1 (554 dof)
- *Data is not good enough to detect the feature*



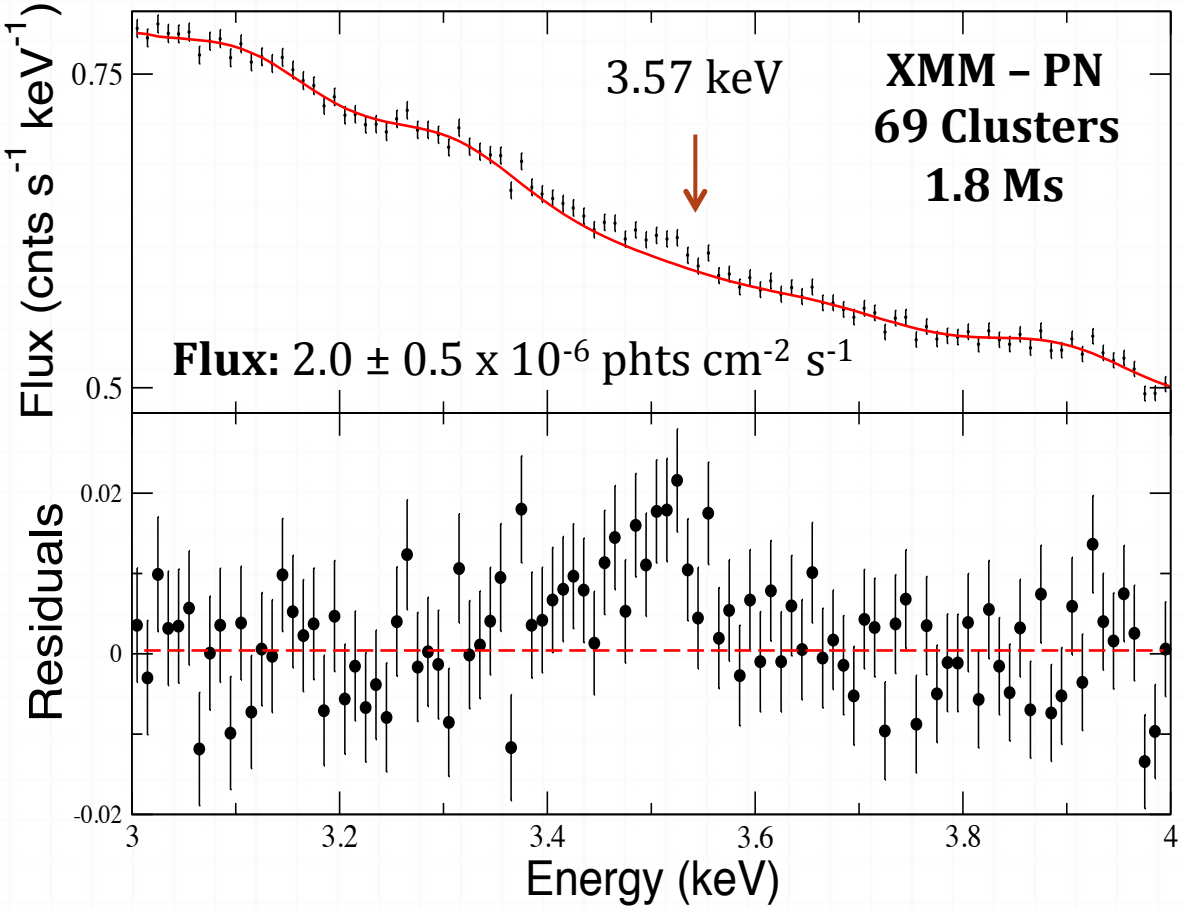
Dominant Source with MOS?

- Excluded four brightest clusters;
  Perseus, Coma,
  Centaurus,
  Ophiuchus
- The line is detected in the MOS observations of 69 clusters
- Flux at 3.57 keV:
  $2.1 \pm 0.5 \times 10^{-6}$
  pts cm^{-2} s^{-1}



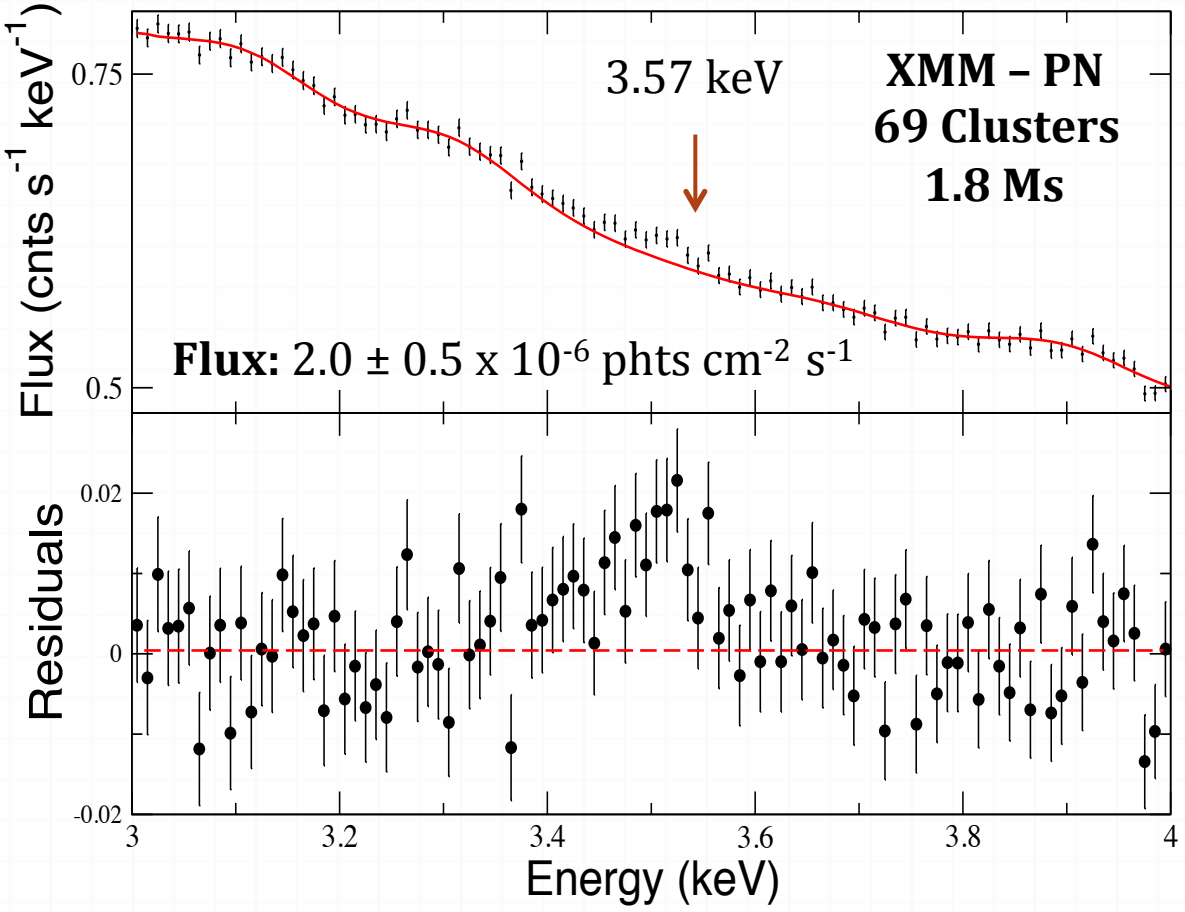
Dominant Source with PN?

- Excluded four brightest clusters;
  Perseus, Coma,
  Centaurus,
  Ophiuchus
- The line is detected in the PN observations of 69 clusters
- Flux at 3.57 keV:
  $2.0 \pm 0.5 \times 10^{-6}$ phts cm^{-2} s^{-1}
  (consistent when scaled)



Dominant Source with PN?

- Excluded four brightest clusters;
  Perseus, Coma,
  Centaurus,
  Ophiuchus
- The line is detected in the PN observations of 69 clusters
- Flux at 3.57 keV:
  $2.0 \pm 0.5 \times 10^{-6}$
  pts cm^{-2} s^{-1}
- ***does not*** *originate from one or few dominant nearby sources*



Chandra ACIS-S Observations of Perseus

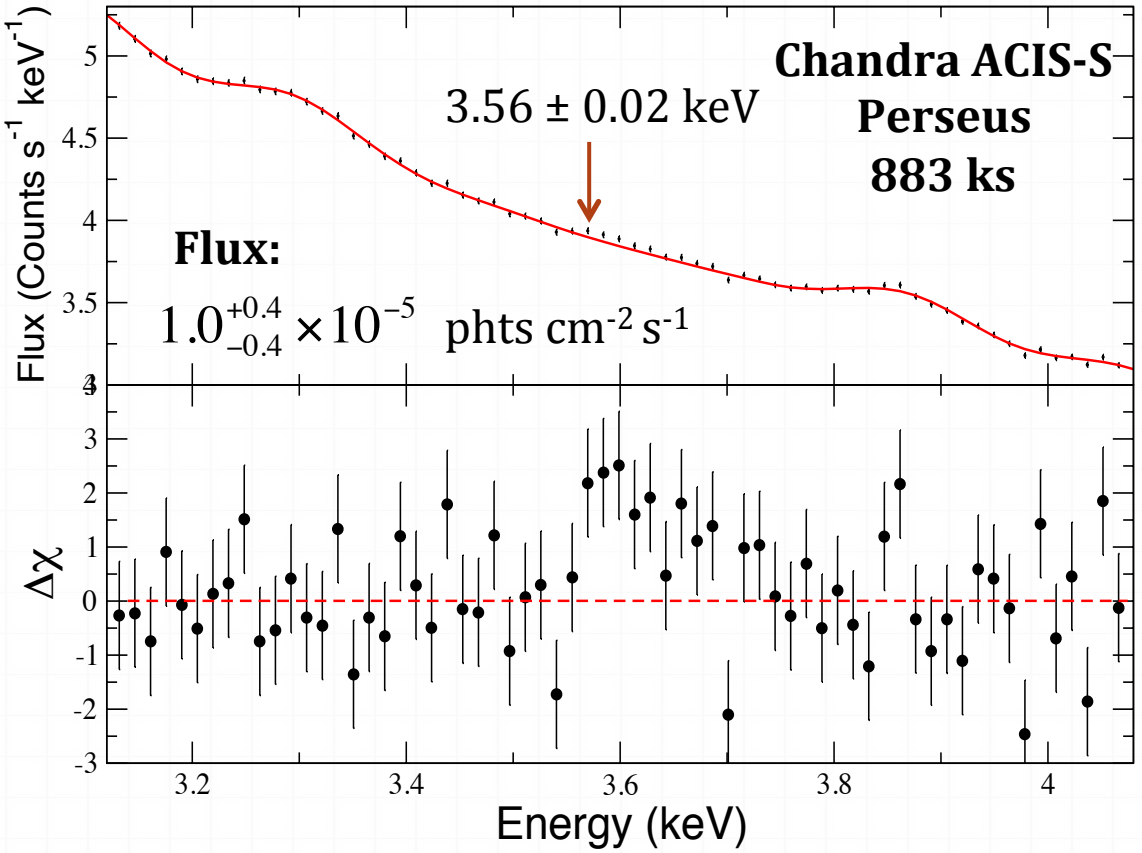
- Consistent with Chandra ACIS-S observations of the Perseus cluster

Energy:

3.56 ± 0.02 keV

Flux:

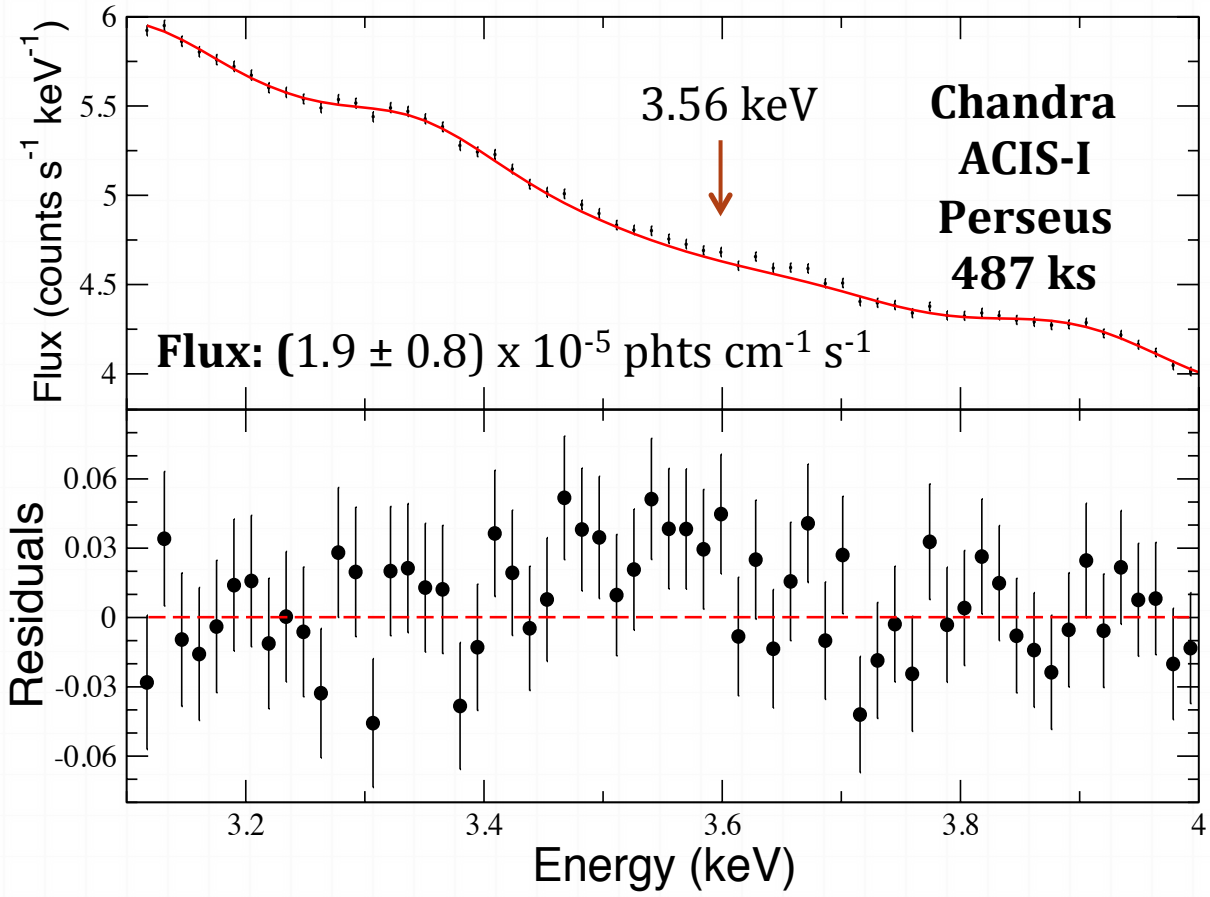
$1.0^{+0.4}_{-0.4} \times 10^{-5}$ phts cm^{-2} s^{-1}



Chandra ACIS-S Observations of the Perseus Cluster

Chandra ACIS-I Observations of Perseus

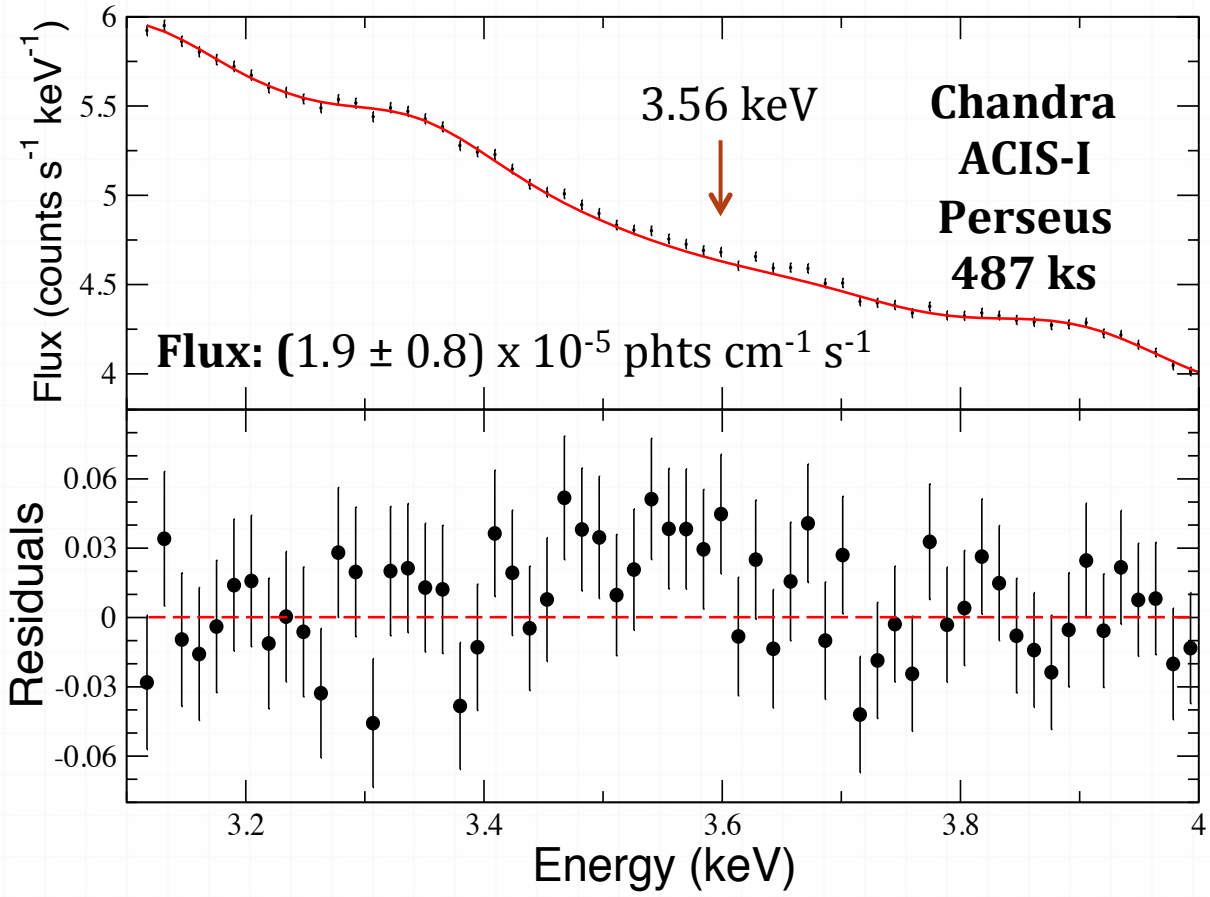
- Consistent with Chandra ACIS-I observations of the Perseus cluster
- **Flux:** $(1.9 \pm 0.8) \times 10^{-5}$ phts cm^{-1} s^{-1} at 3.56 keV



Chandra ACIS-S Observations of the Perseus Cluster

Chandra ACIS-I Observations of Perseus

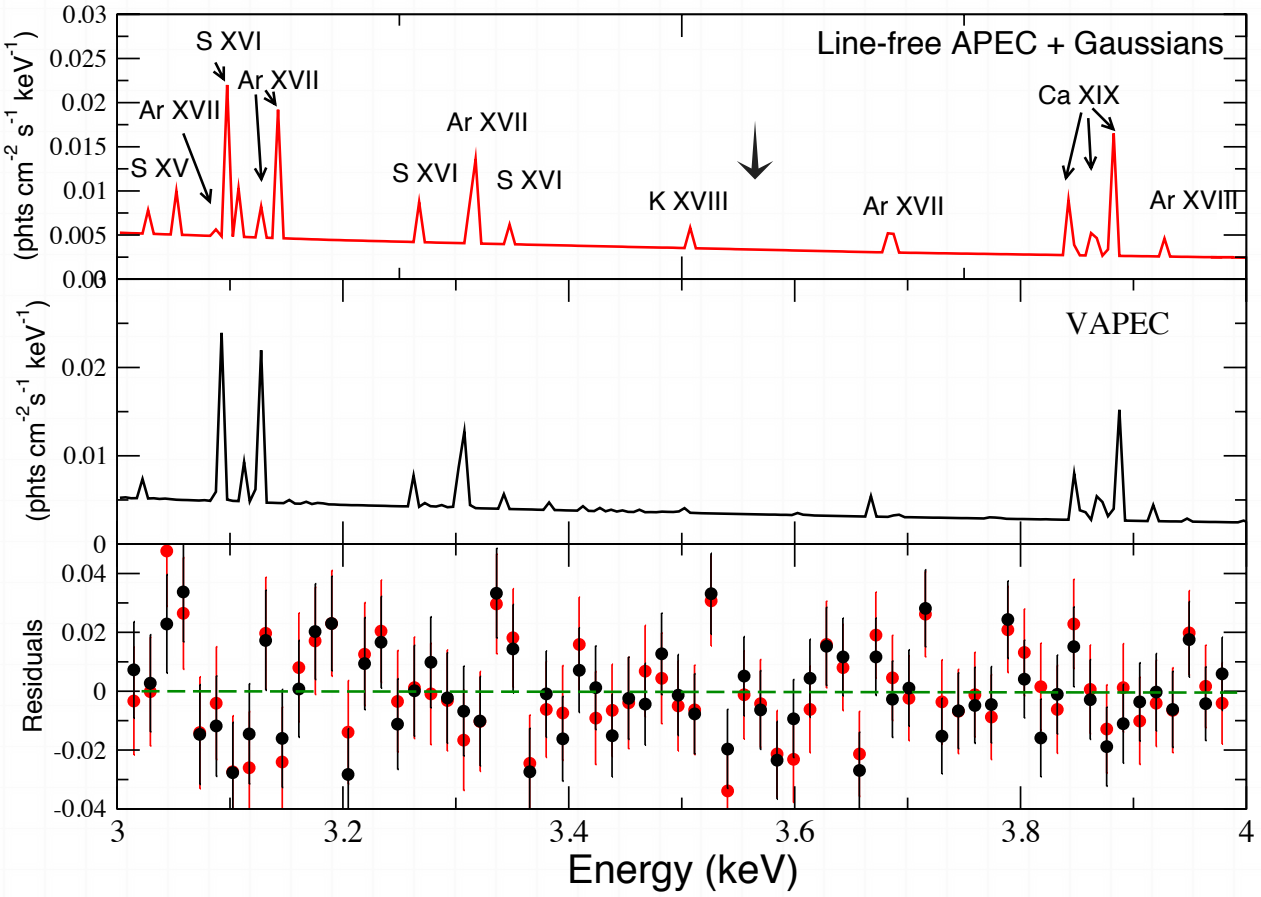
- Consistent with Chandra ACIS-I observations of the Perseus cluster
- **Flux:** $(1.9 \pm 0.8) \times 10^{-5}$ phts cm^{-1} s^{-1} at 3.56 keV
- ***not*** *a detector artifact*



Chandra ACIS-S Observations of the Perseus Cluster

Chandra Observations of Virgo

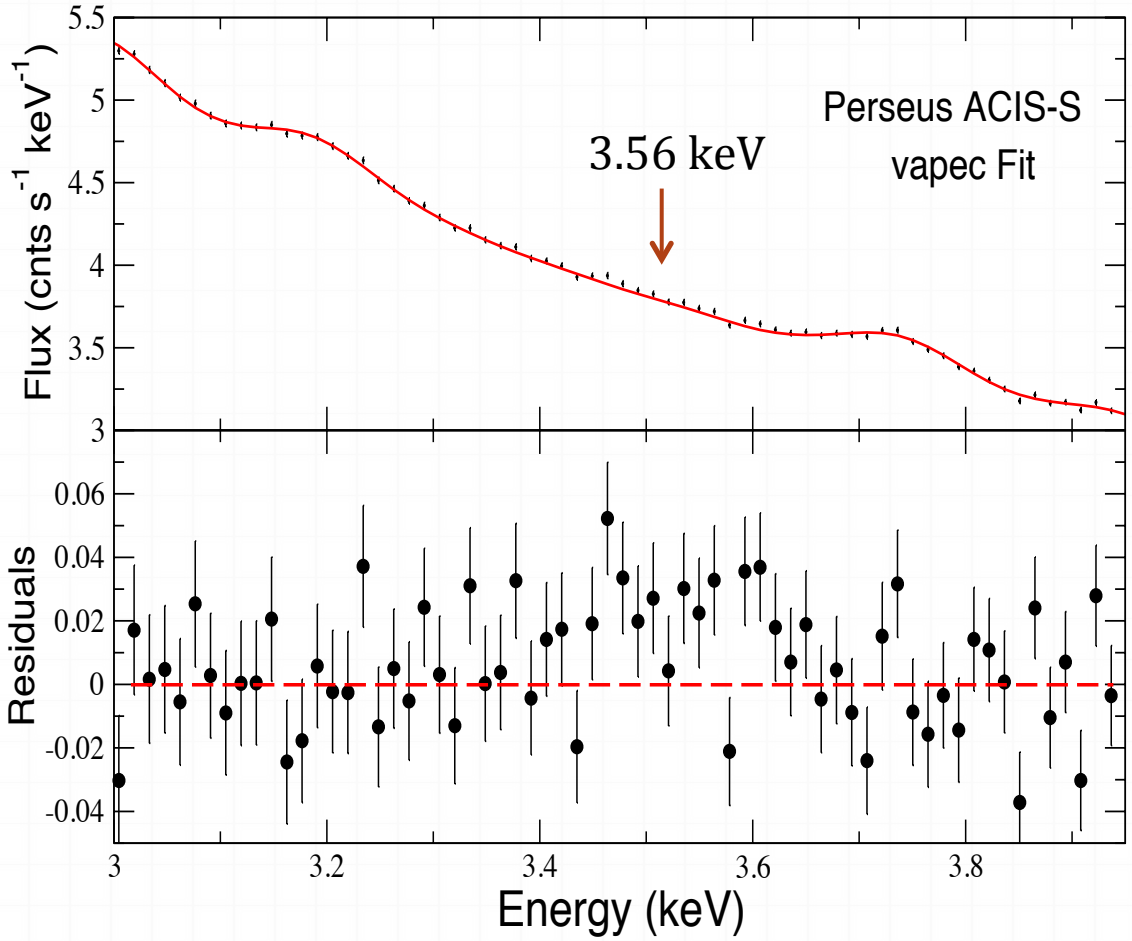
- no detection in the 500 ks Chandra ACIS-I Observations of the Virgo cluster
- **Flux at 3.56 keV:** < 9.1 x 10^{-6} ph cm^{-2} s^{-1}



Chandra ACIS-I spectrum of the Virgo cluster fit with two different approaches

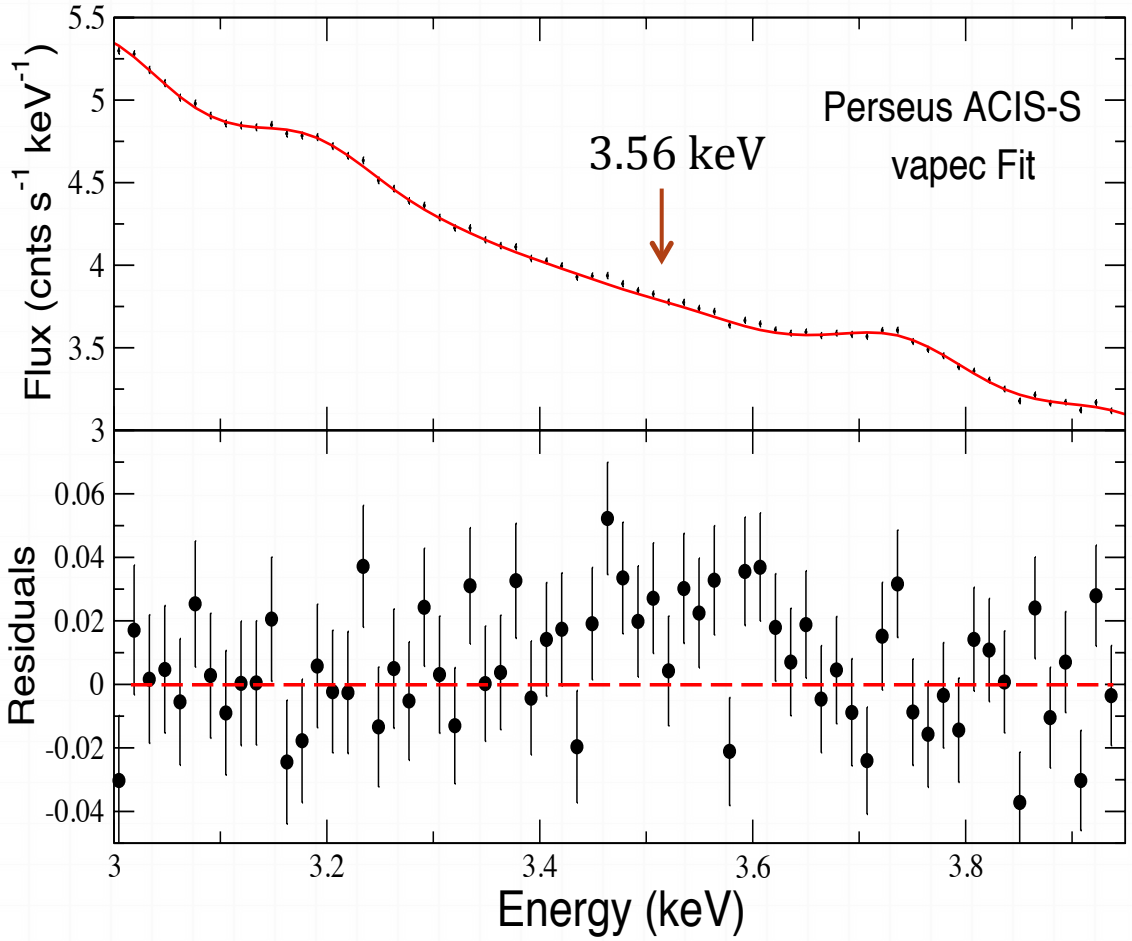
Modeling Artifact?

- Chandra ACIS-S observations of the Perseus Cluster
- Standard *vapec* model was used to fit the data
- The line is detected with a different modeling approach



Modeling Artifact?

- Chandra ACIS-S observations of the Perseus Cluster
- Standard *vapec* model was used to fit the data
- The line is detected with a different modeling approach
- *The detected line is not a fitting artifact!*

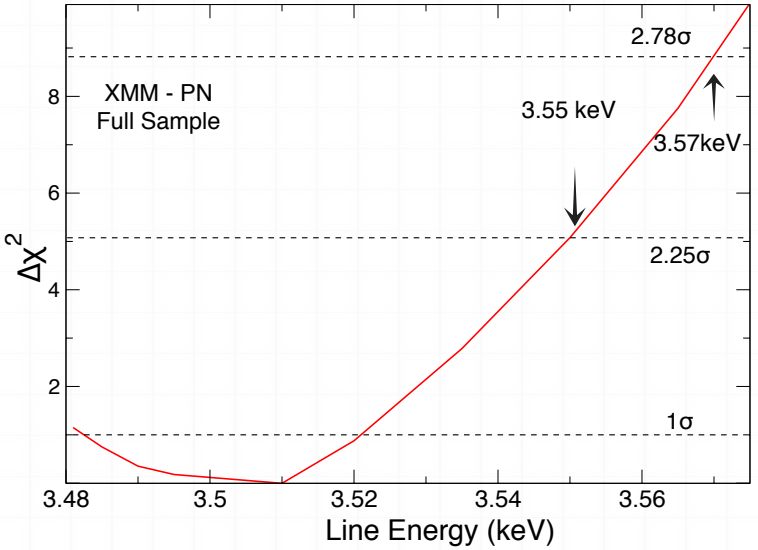


What we have learnt so far!

- Not a background feature
- Not an instrumental line
- Not a detector feature
- Not a modeling artifact
- Comes from all clusters rather than a few dominant bright clusters
- Flux is centrally concentrated
- Could be an anomaly bright Ar XVIII DR line at 3.62 keV

Re-examining the MOS Observations of the Full Sample

- Knowing that 3.62 keV line could be anomalously high from the Perseus tests, we set the flux AR XVIII DR line to the Perseus contribution
- Already 30 times higher than predicted flux
- Refit the MOS observations of the Full sample for free energy and flux
- Additional Gaussian line still improves the $\Delta\chi^2$ of the fit by 6.5 (2 dof)
- The best fit energy 3.55 ± 0.03 keV with a flux of 2.2 ± 1.6 10^{-5} photons cm^{-2} s^{-1}
- 2.5σ detection
- PN and MOS energies are now consistent



What is the origin of this Line?

- Unknown plasma emission line
- Maximum emissivity $\Lambda = 3.3\times10^{-18}$ photons cm^3 s^{-1}

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

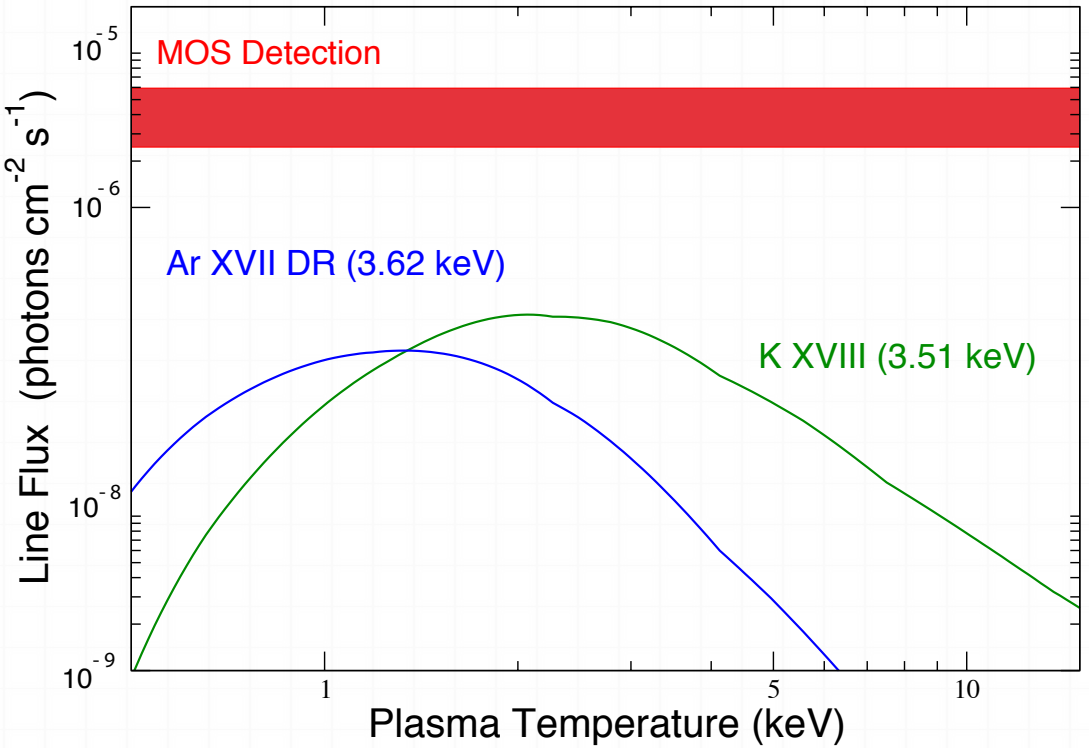
- Equivalent to the Ca XX Lyα line at 4.1 keV.

- 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.

Unlikely Astrophysical Scenarios

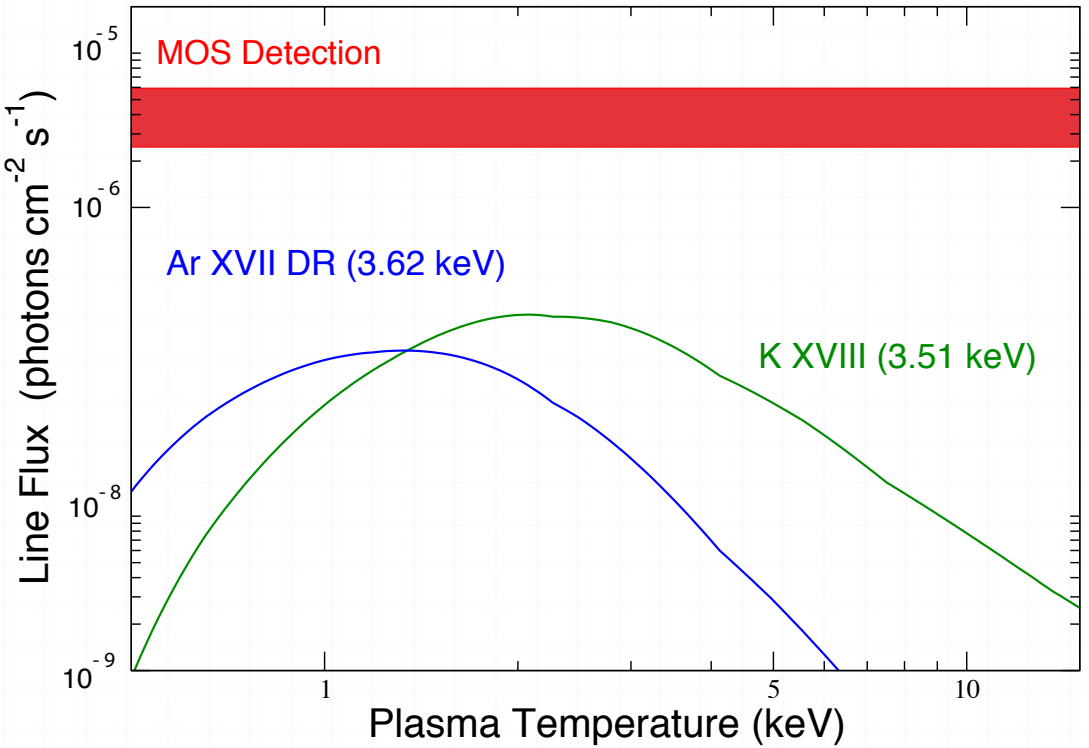
- K XVIII line at 3.51 keV



Flux Estimates of K XVIII line at 3.51 keV and Ar XVII DR line at 3.62 keV

Unlikely Astrophysical Scenarios

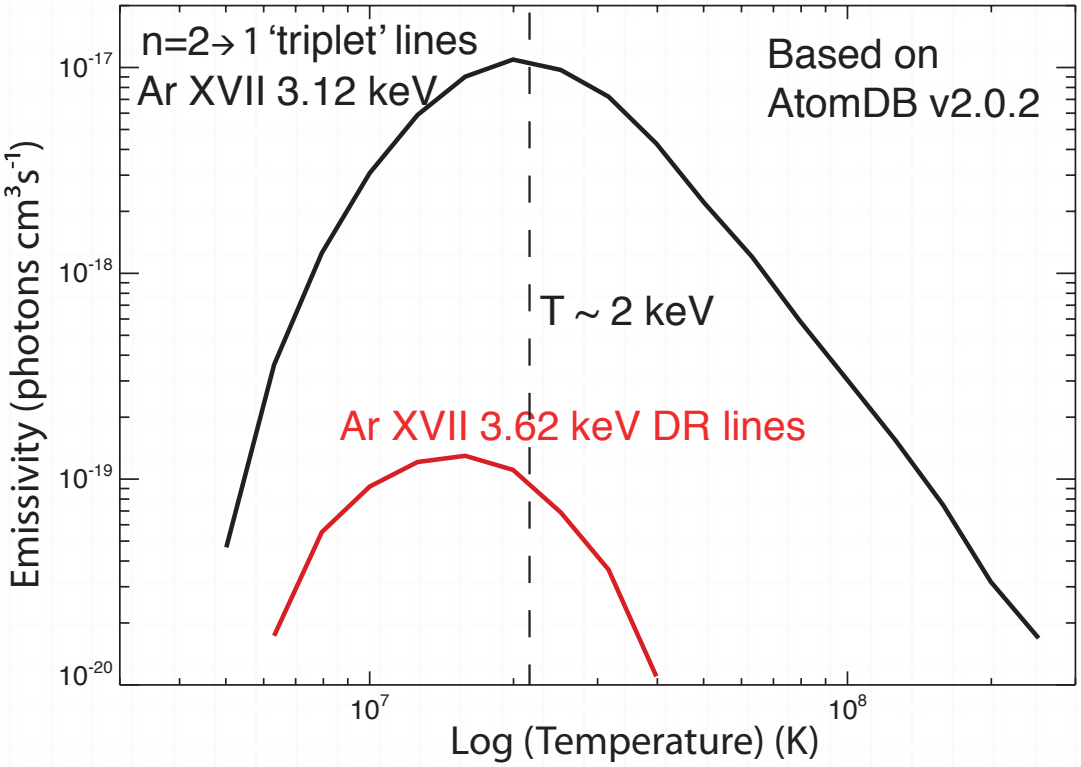
- ~~K XVIII line at 3.51 keV~~
- Ar XVII DR line at 3.62 keV



Flux Estimates of K XVIII line at 3.51 keV and Ar XVII DR line at 3.62 keV

Unlikely Astrophysical Scenarios

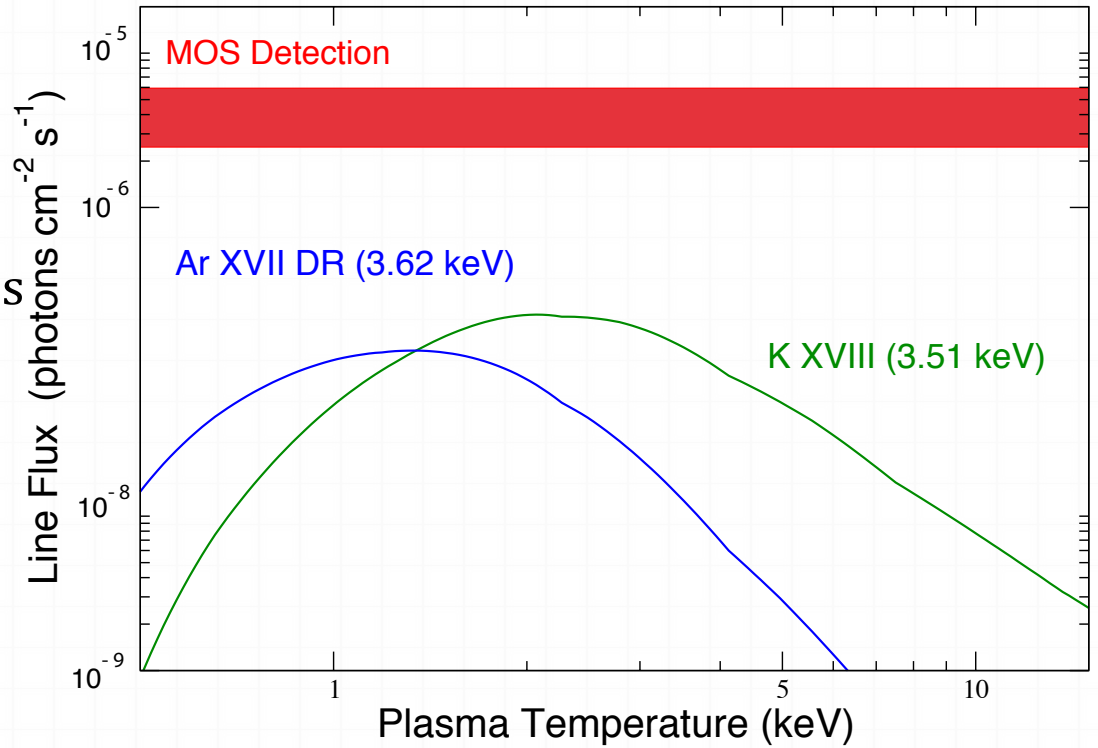
- ~~K XVIII line at 3.51 keV~~
- Ar XVII DR line at 3.62 keV



Flux Estimates of Ar XVII triplet at 3.12 keV and Ar XVII DR line at 3.62 keV

Unlikely Astrophysical Scenarios

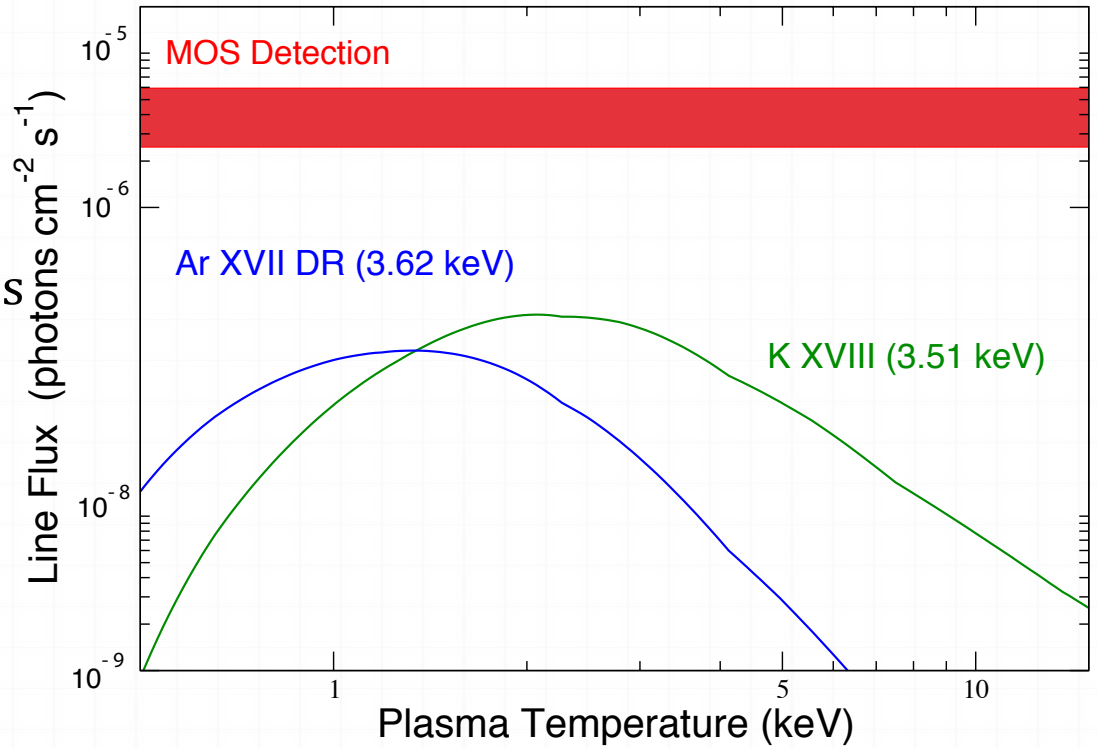
- ~~K XVIII line at 3.51 keV~~
- ~~Ar XVII DR line at 3.62 keV~~
- Emission lines of strong hydrogen- and helium-like ions



Flux Estimates of K XVIII line at 3.51 keV and Ar XVII DR line at 3.62 keV

Unlikely Astrophysical Scenarios

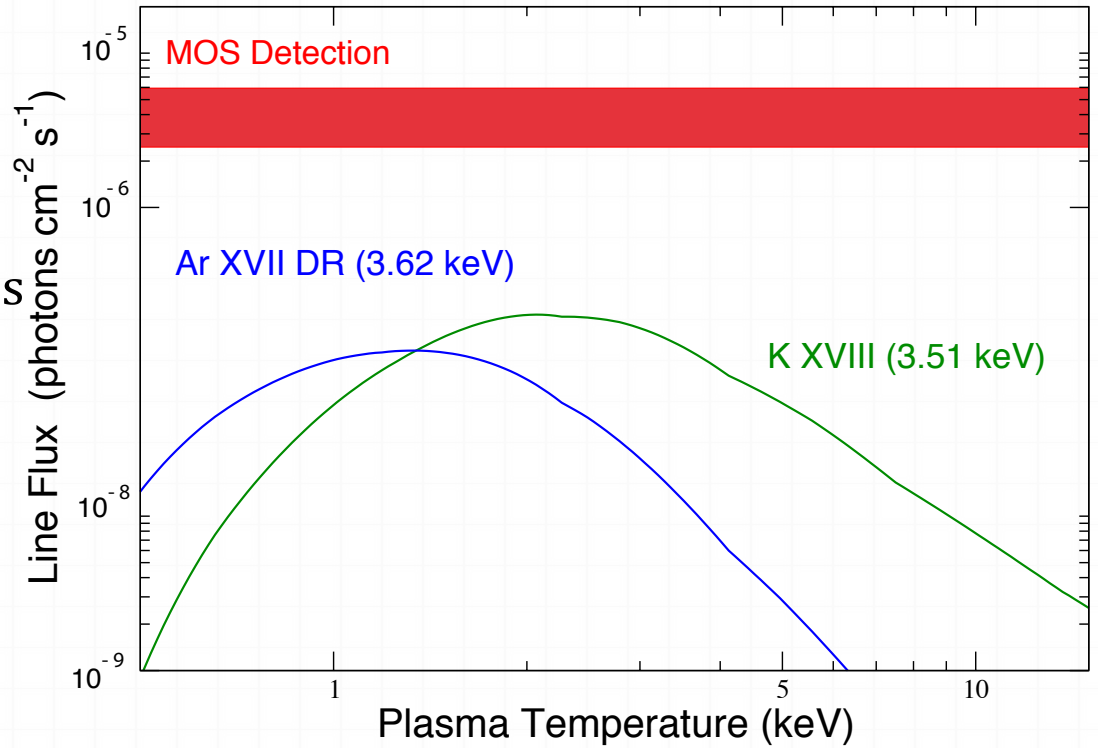
- ~~K XVIII line at 3.51 keV~~
- ~~Ar XVII DR line at 3.62 keV~~
- ~~Emission lines of strong hydrogen- and helium-like ions~~
- Charge exchange



Flux Estimates of K XVIII line at 3.51 keV and Ar XVII DR line at 3.62 keV

Unlikely Astrophysical Scenarios

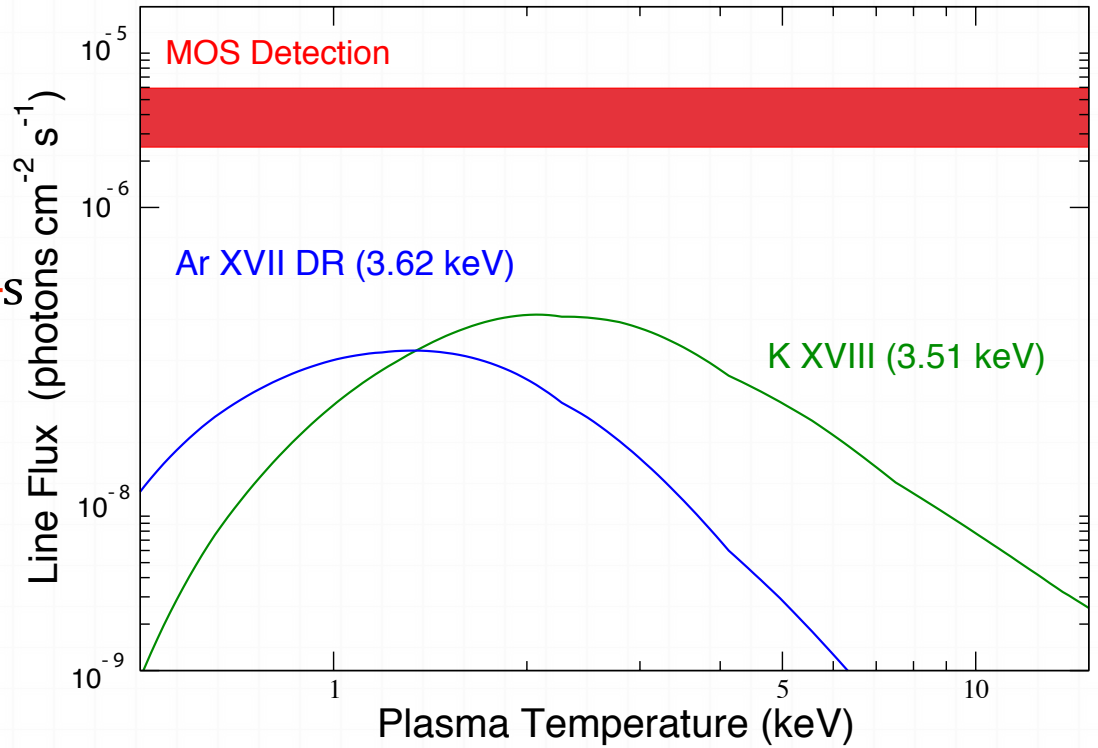
- ~~K XVIII line at 3.51 keV~~
- ~~Ar XVII DR line at 3.62 keV~~
- ~~Emission lines of strong hydrogen- and helium-like ions~~
- ~~Charge exchange~~
- Radiative recombination continuum (RRC) feature



Flux Estimates of K XVIII line at 3.51 keV and Ar XVII DR line at 3.62 keV

Unlikely Astrophysical Scenarios

- ~~K XVIII line at 3.51 keV~~
- ~~Ar XVII DR line at 3.62 keV~~
- ~~Emission lines of strong hydrogen- and helium-like ions~~
- ~~Charge exchange~~
- ~~Radiative recombination continuum (RRC) feature~~
- Any Other Astrophysical Explanations?



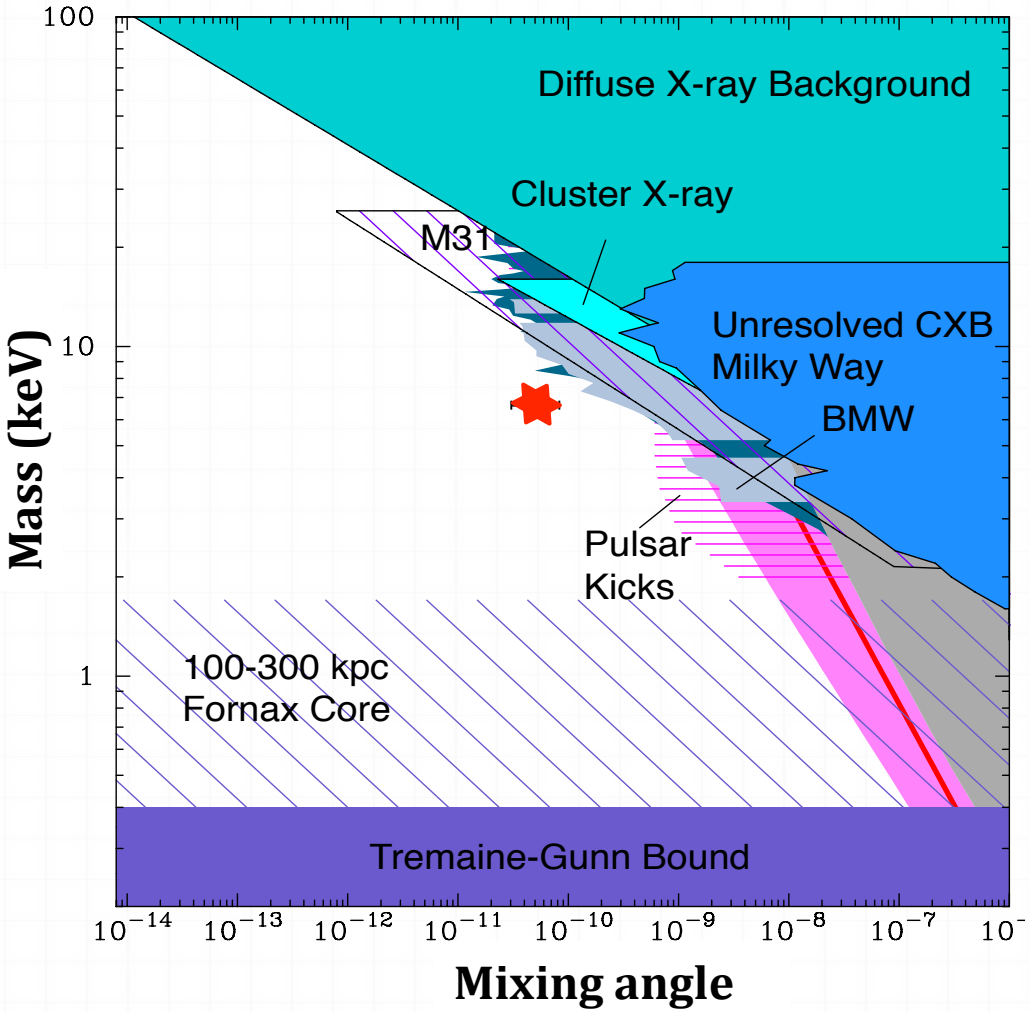
Flux Estimates of K XVIII line at 3.51 keV and Ar XVII DR line at 3.62 keV

What is the origin?

- Could this be a sterile neutrino decay signature?
- Warm dark matter candidate sterile neutrinos decay into an active neutrino and emission line
- Neutrino Properties

Mass = $2E_\gamma$

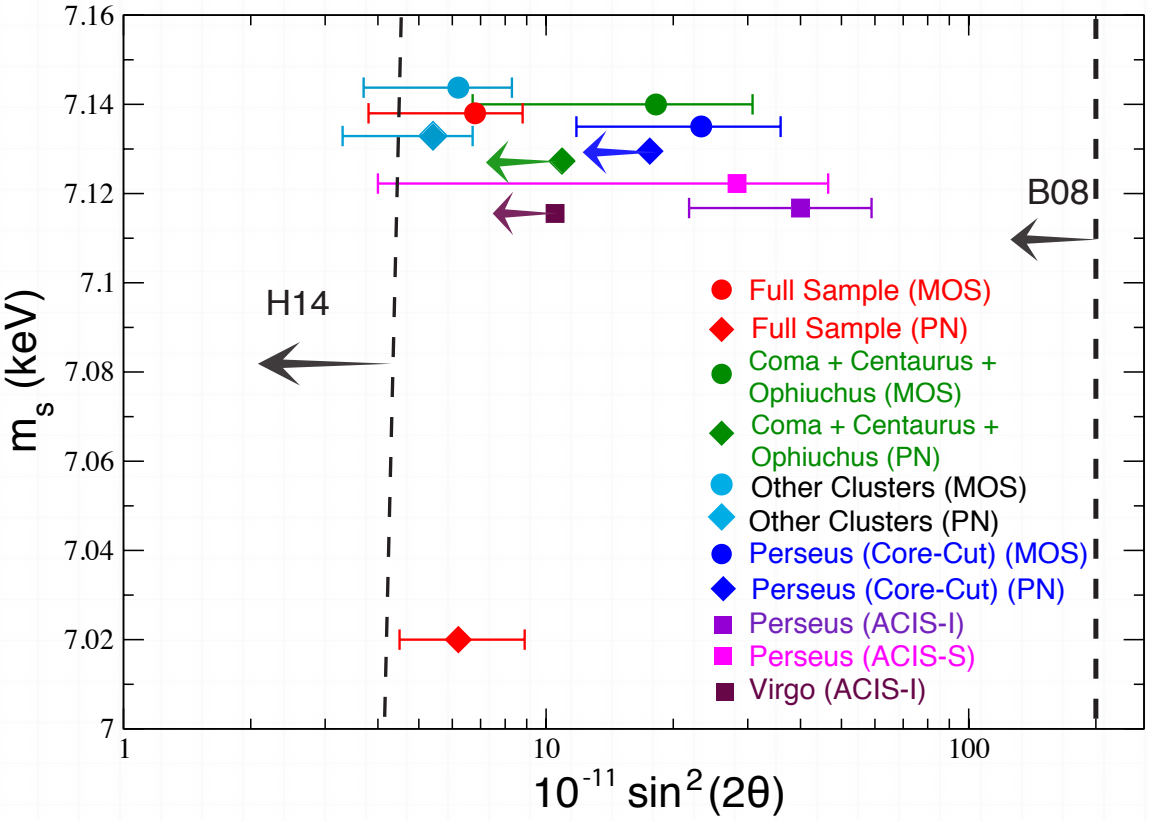
$$\text{Mixing Angle} \propto \frac{F_{DM}}{(1+z)} \frac{D_L^2}{M_{DM}^{FOV}} \frac{1}{m_s^4}$$



The diffuse X-ray background (Boyarsky et al. 2006), cluster X-ray (Boyarsky et al. 2006b), BMW (Boyarsky et al. (2007), M31 (Watson et al. 2006), the Tremaine-Gunn bound (Bode et al. 2001), and Fornax dwarf galaxy (Strigari et al. 2006)

Limits Derived from our Samples

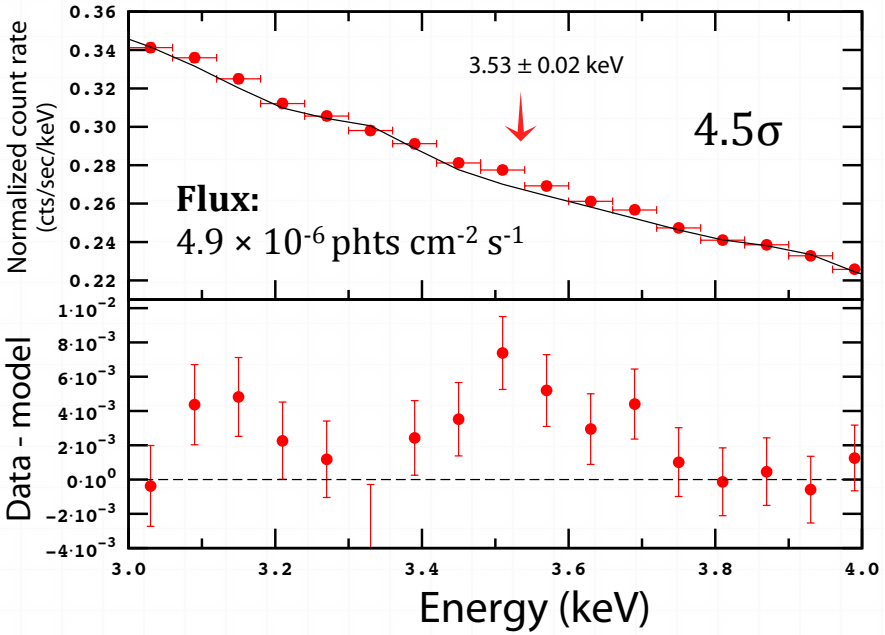
- Sterile neutrino mass and mixing angle measurements obtained from our samples.
- Compared with the limits placed by the single well exposed Bullet cluster (Boyarsky et al. 2008) and and Andromeda galaxy (Horiuchi et al. 2014)
- The line in Perseus is much brighter than expected



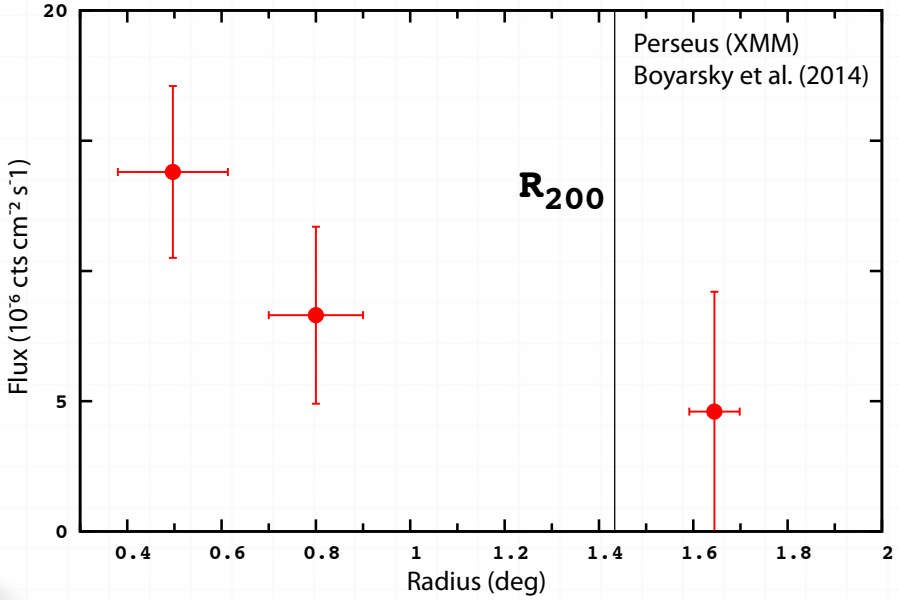
Sterile neutrino mass and mixing angle measurements and upper limits obtained from the different samples.

Confirmation by Boyarsky et al. (2014)

- Boyarsky et al. (2014) detected the line in the **independent XMM-Newton OFFSET** observations of the Perseus cluster and Adromeda galaxy



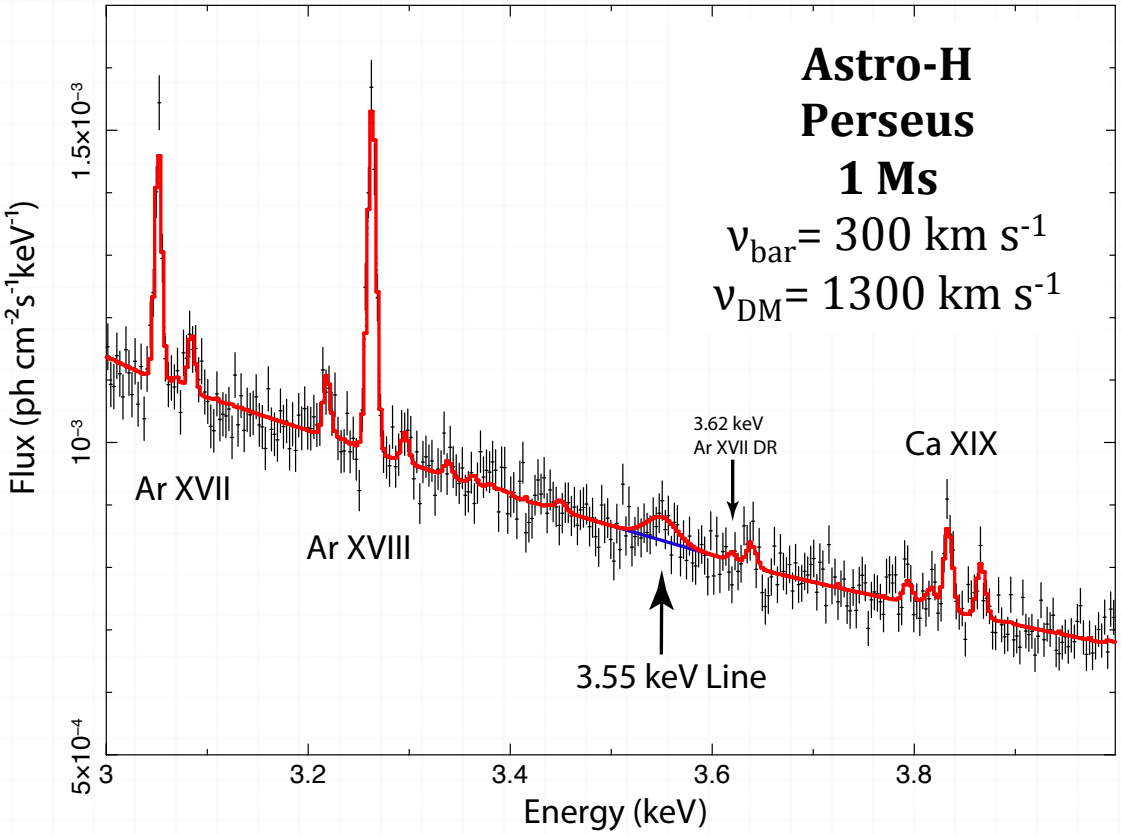
M31 XMM-Newton On-axis Spectrum



Radial Profile of the Flux from the OFFSET XMM-Newton Observations the Perseus Cluster

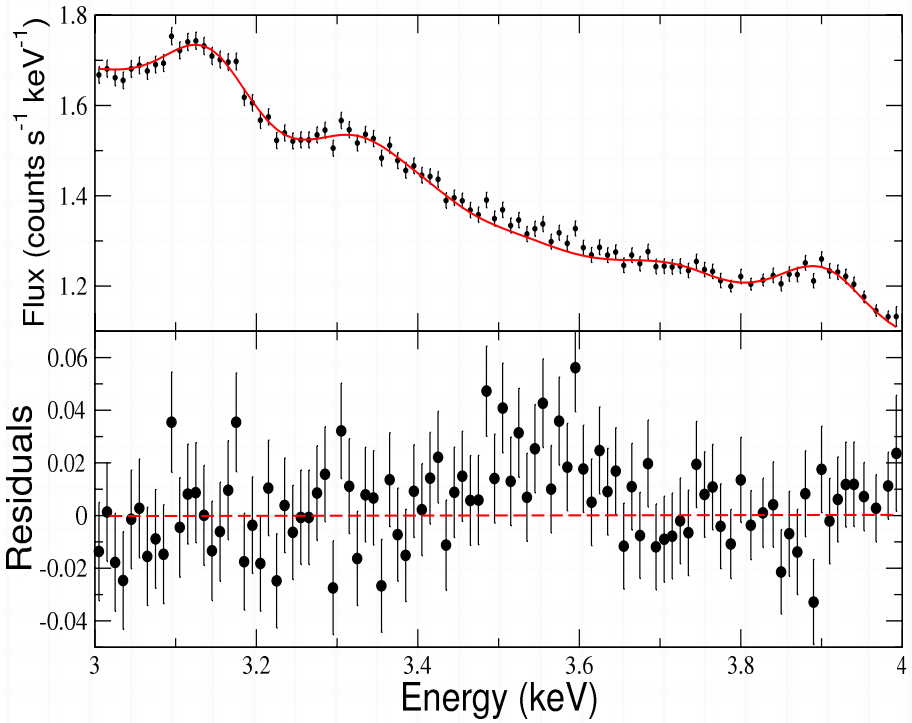
Sterile Neutrino vs Astrophysical Line?

- Future observations are needed.
- Astro-H observations with high spectral resolution are key! (T. Tamura's talk)
- Bulbul et al. (2014; arXiv:1402.2301) [**now accepted in ApJ!**] has 57 citations, ~53 of whom discuss the possibilities …



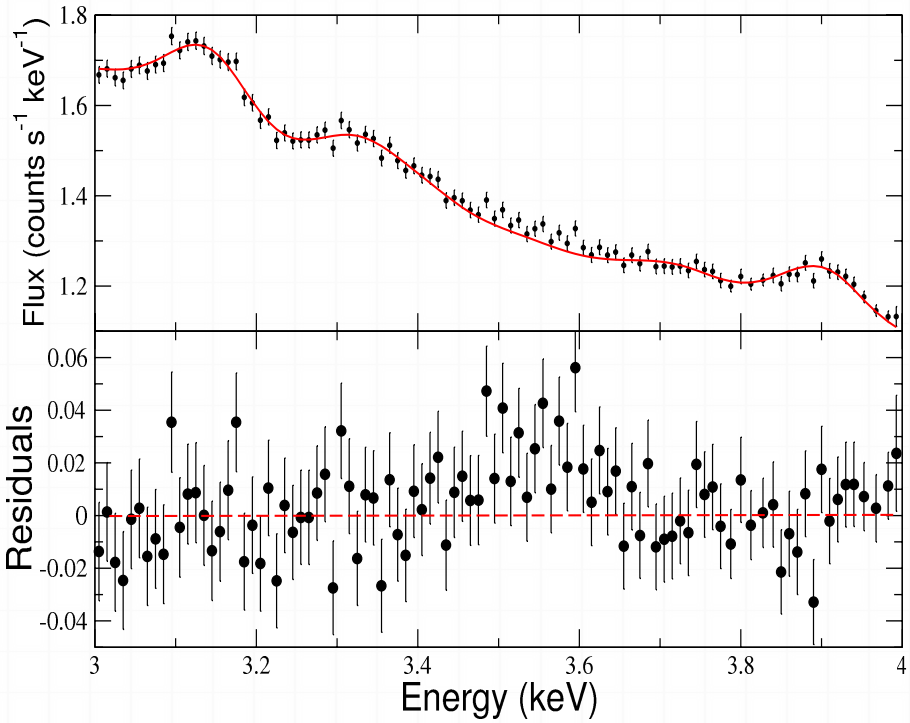
Conclusions

- Attempts to refine upper limits can sometimes fail…



Conclusions

- Attempts to refine upper limits can sometimes fail…
- Detected a weak emission line in the stacked observations of galaxy clusters
- Seen at > 3σ statistical significance in all three independent MOS spectra and the PN “all others” spectrum
- no atomic transitions in thermal plasma at this energy
- An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate.



Conclusions

- Detection corresponds to a neutrino decay rate consistent with previous upper limits
- Not detected in the Chandra observations of the Virgo Cluster (larger M^{FOV}/D^2)
- Perseus is much brighter than expected in this model, significantly deviating from other subsamples.
- Tests on Perseus suggested that an anomalously bright Ar XVII line at 3.62 keV in Perseus could be responsible for this flux deviation
- Ar XVII would have to be 30 times the expected value and physically difficult to understand.