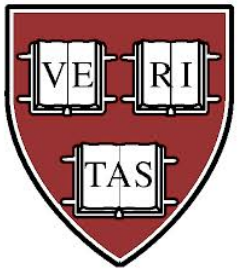
# Dark Matter Searches in the X-ray Band & the 3.55 keV Line




Esra Bulbul

Harvard-Smithsonian CfA

- Zwicky: "missing mass" in the orbital velocities of galaxies
- Total mass of a galaxy cluster ~ 100 times the mass in stars

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# ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

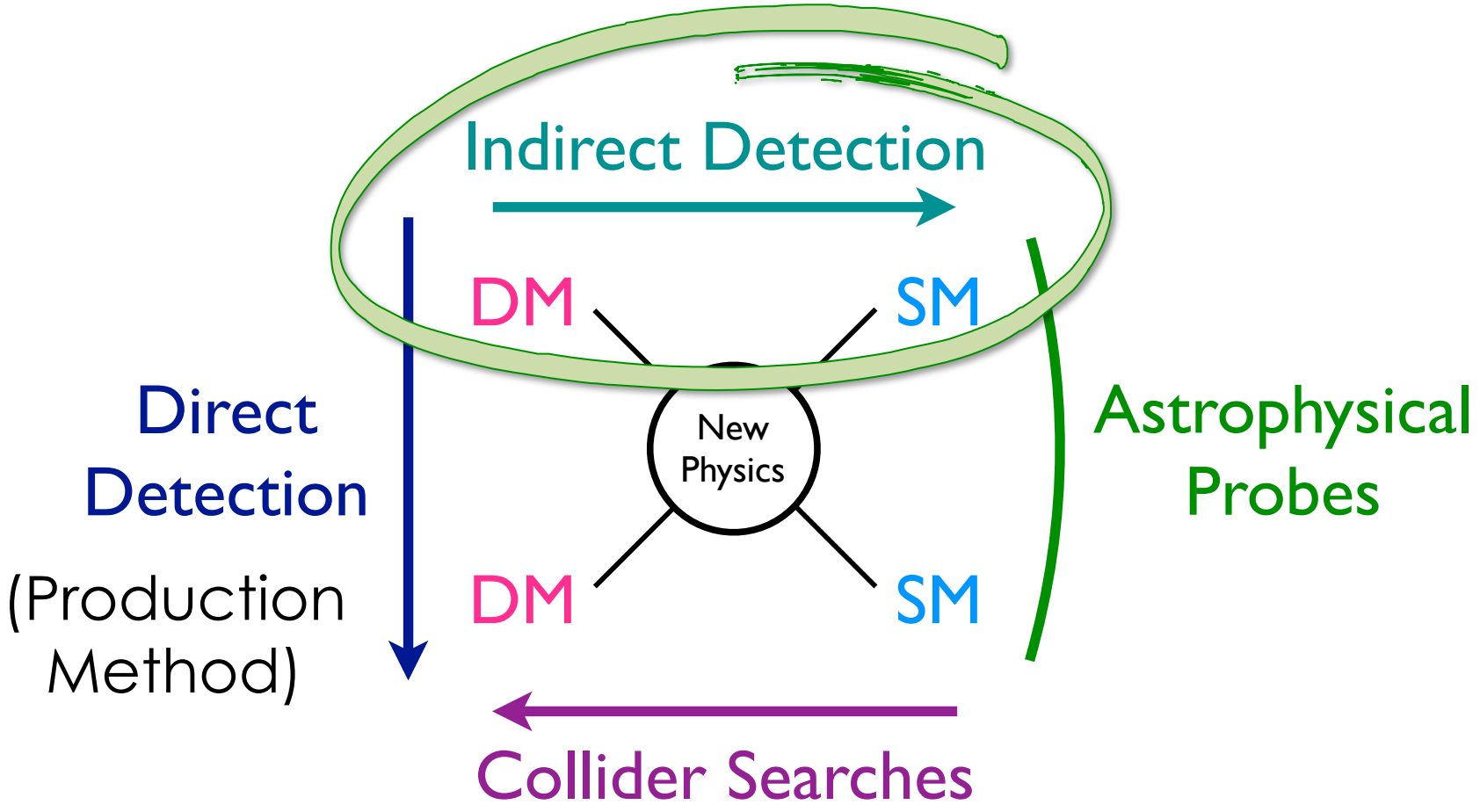
F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

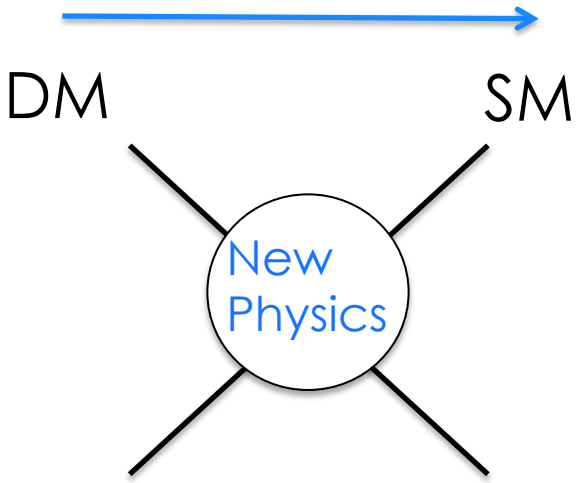

NASA/CXC/ Clowe & Markevitch et al. 2006; Optical: NASA/STScI

# How to Catch A DM Particle?



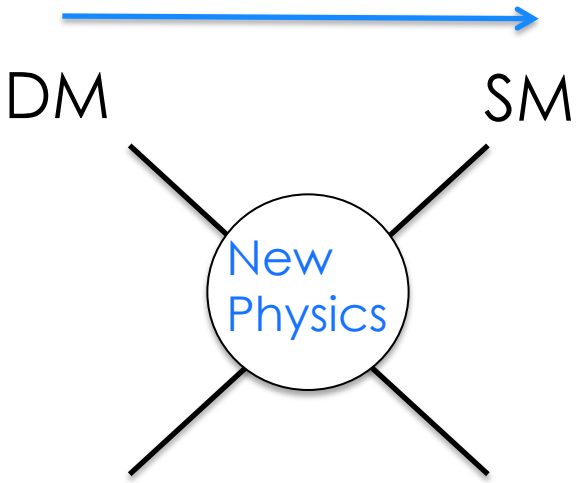
# Indirect Detection

- Look for the secondary products of annihilation or decay



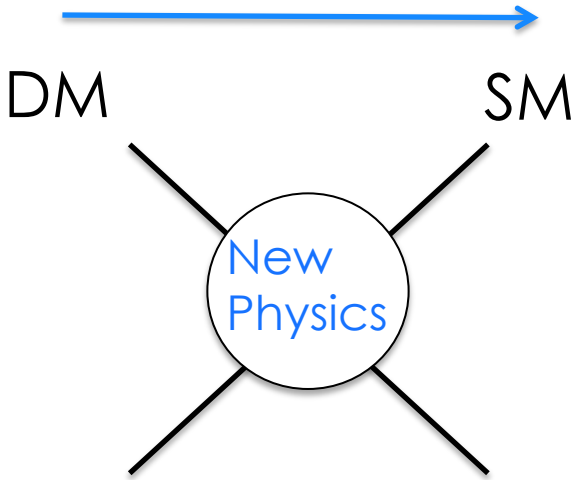
# Indirect Detection

- Look for the secondary products of annihilation or decay
- Deep observations of astrophysical probes



# Indirect Detection

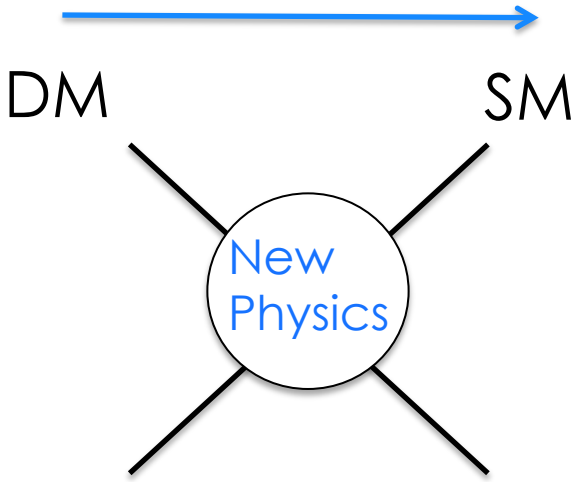
- Look for the secondary products of annihilation or decay
- Deep observations of astrophysical probes
- Cold DM:  WIMPs, axions
- Hot DM: $e$, $\mu$, $\tau$ neutrinos
- Warm DM: sterile neutrinos



# Sterile Neutrino

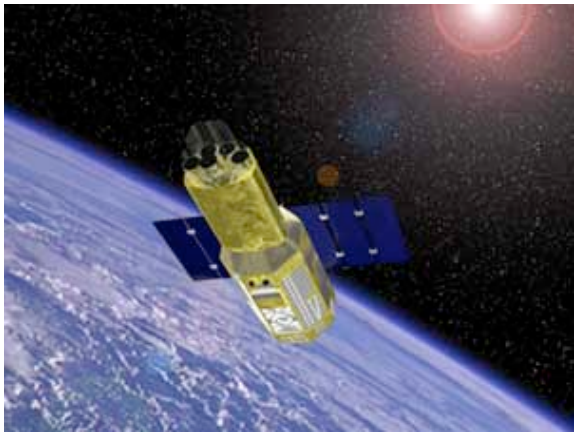
From astrophysical considerations:

- Mass is in keV range
- Decays into a photon
- $E = m_s / 2$ and a standard neutrino
- Decay rate is such that it may be detectable from galaxy clusters, etc.

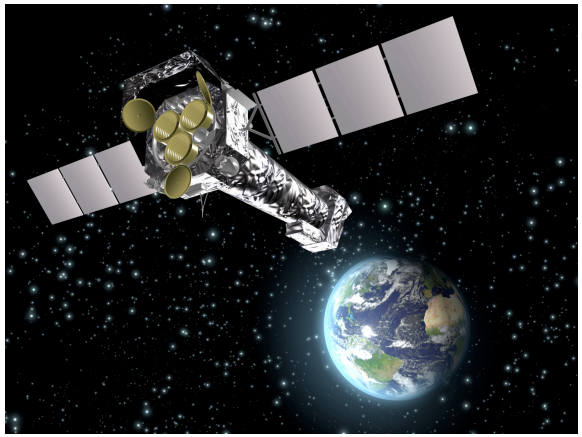


# X-ray View of the Universe

Chandra
0.5 – 7 keV
ACIS-S, ACIS-I



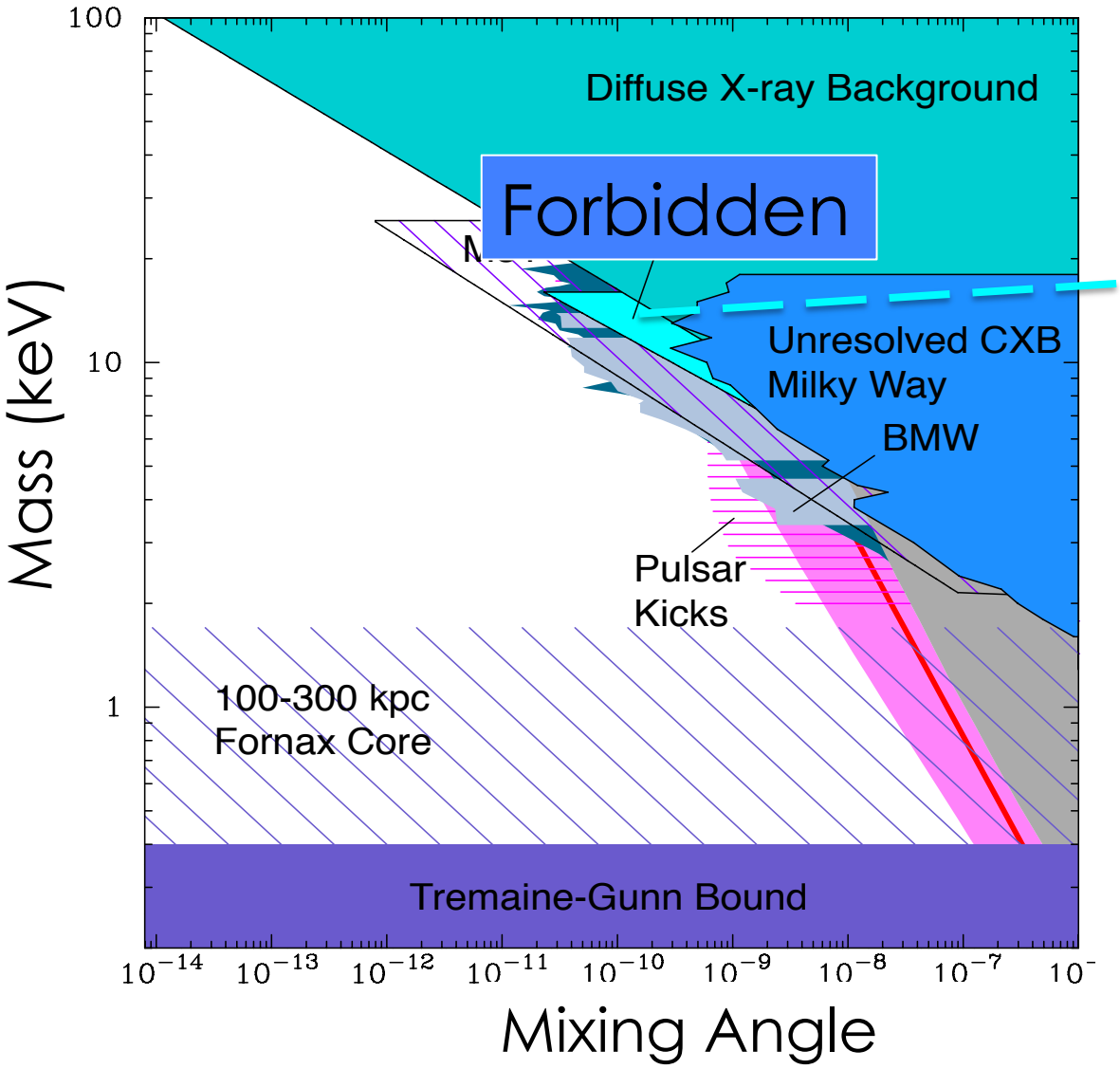
Suzaku
0.5 – 7 keV
XIS 0, 1, 3



XMM-Newton
0.3 – 10 keV
MOS, PN

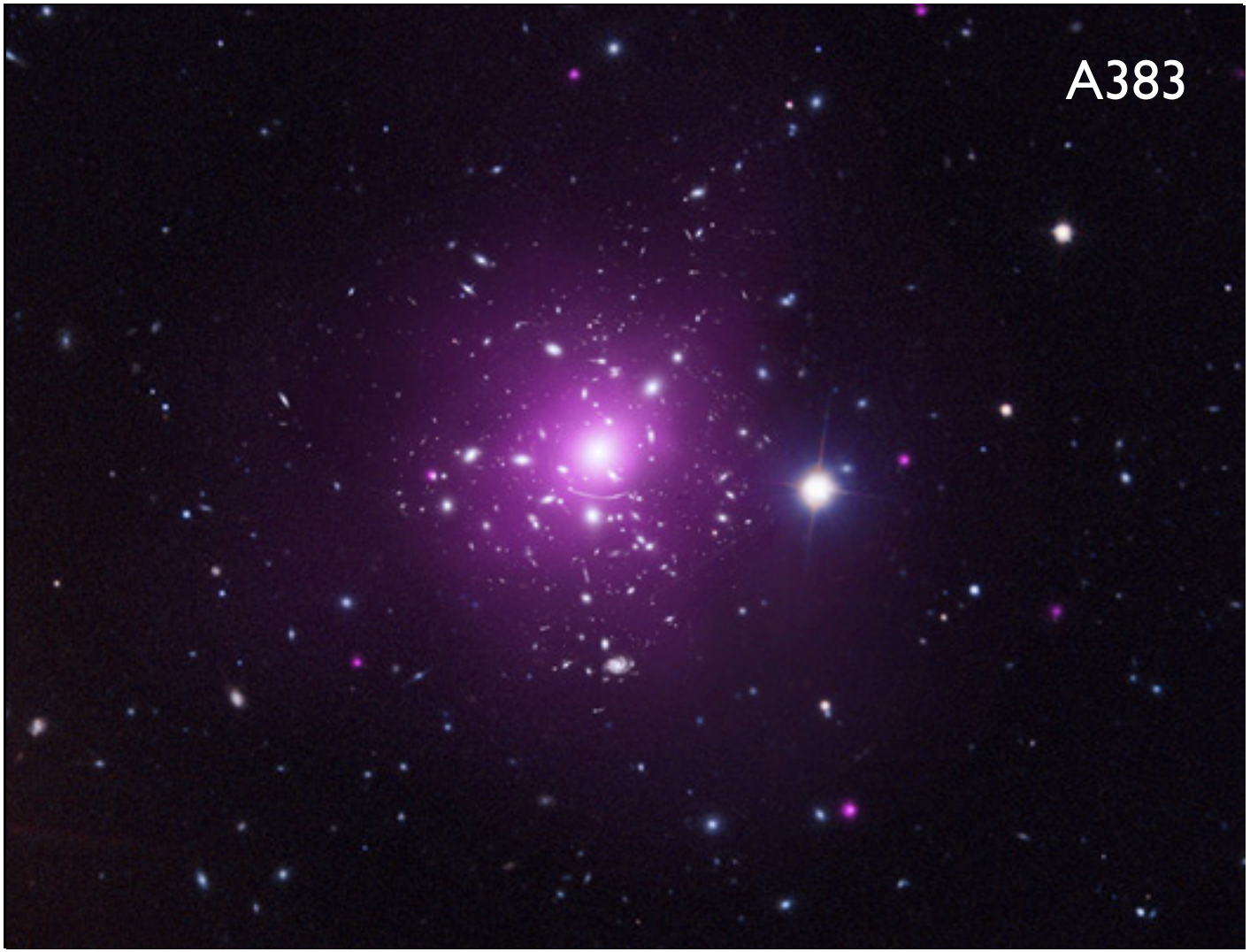
# Dark Matter Searches in the X-ray band

Limits are taken from Abazajian et al. (2009)



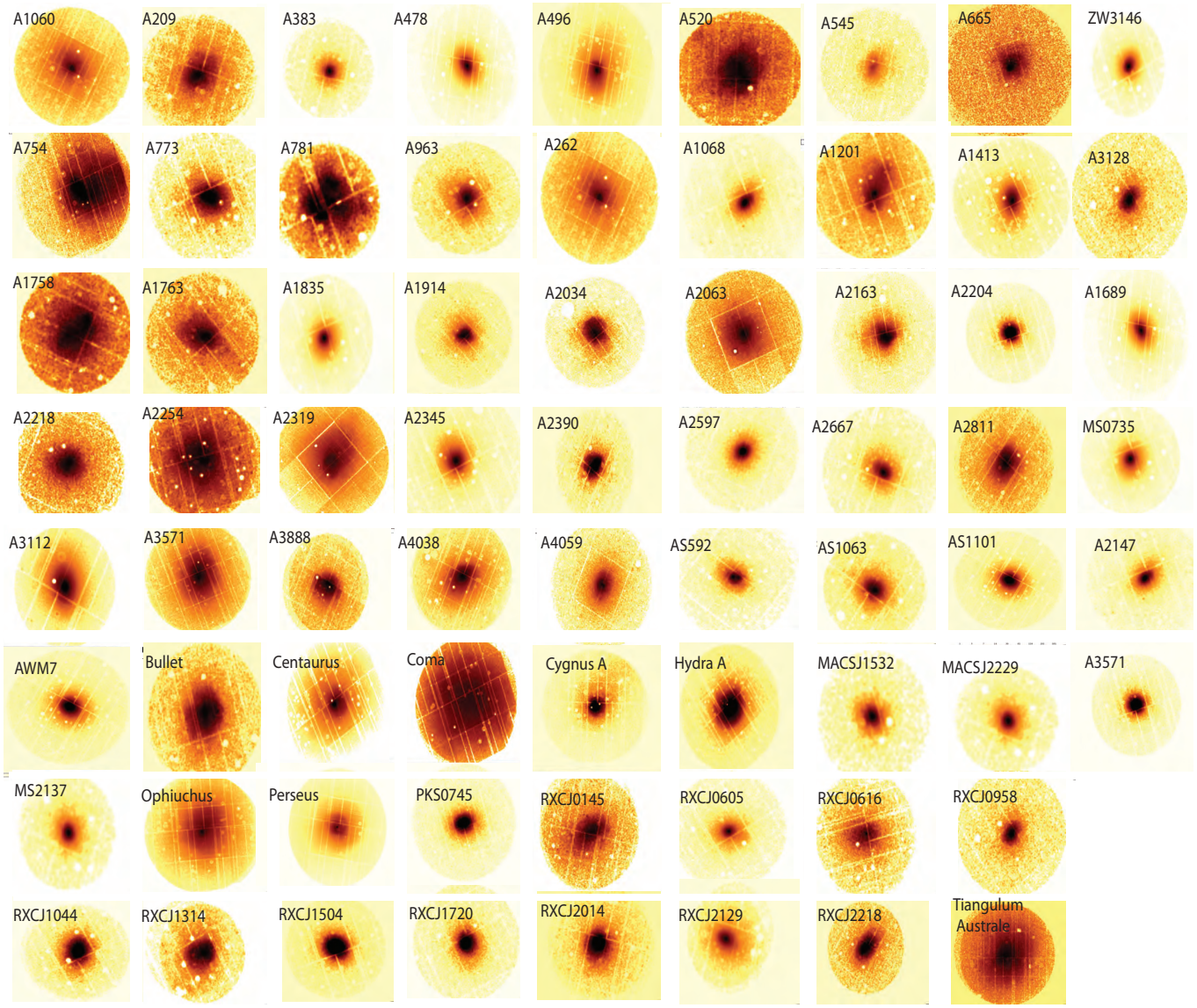

Previous Upper Limits from Clusters

# Galaxy Clusters Composite (%15)

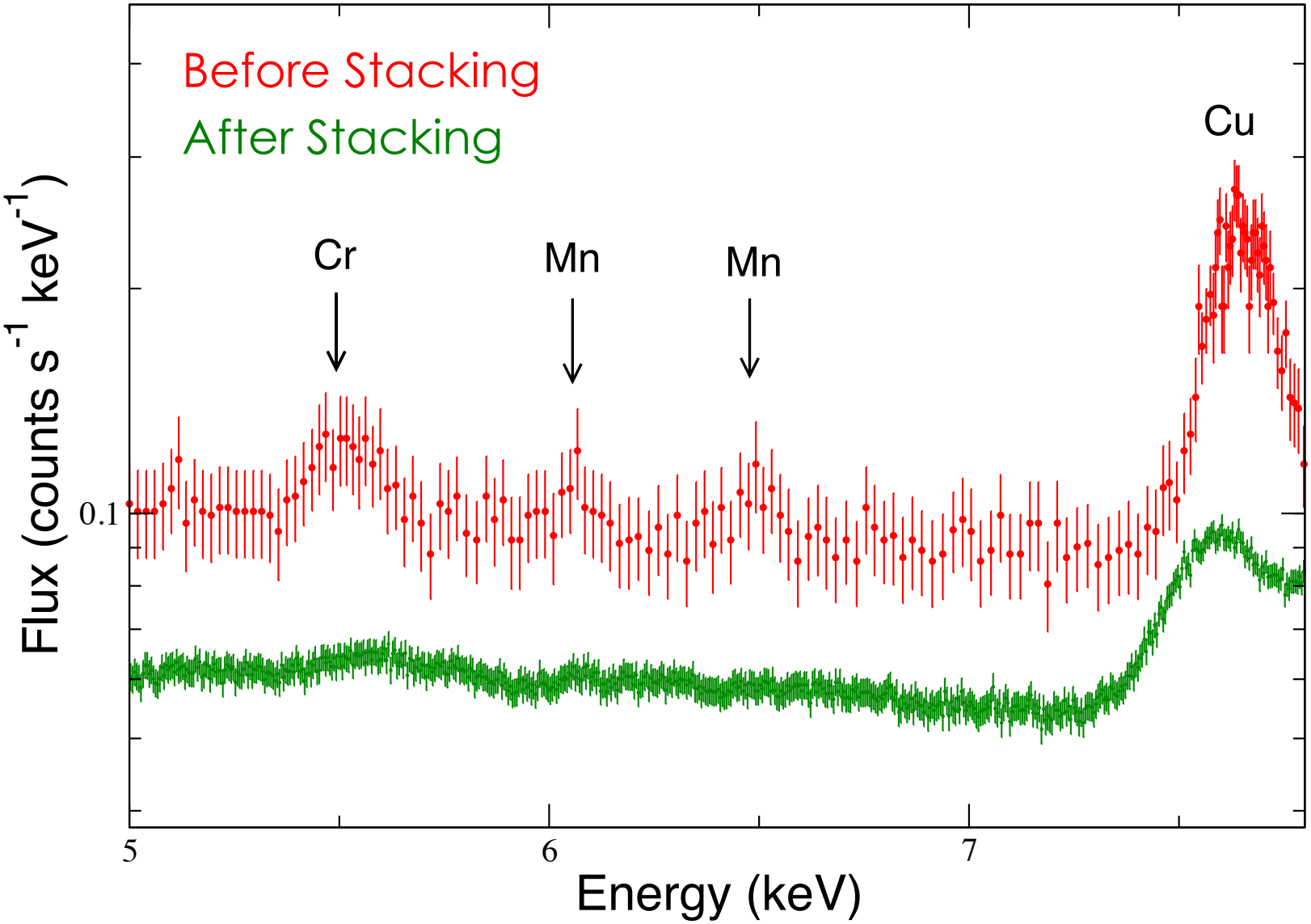


# Bright XMM-Newton Clusters

- 73 Clusters
- $0.01 < z < 0.35$
- ~ 6 MS
- $>10^6$ photons
- Redshift Smearing!



# Smearing Background Features



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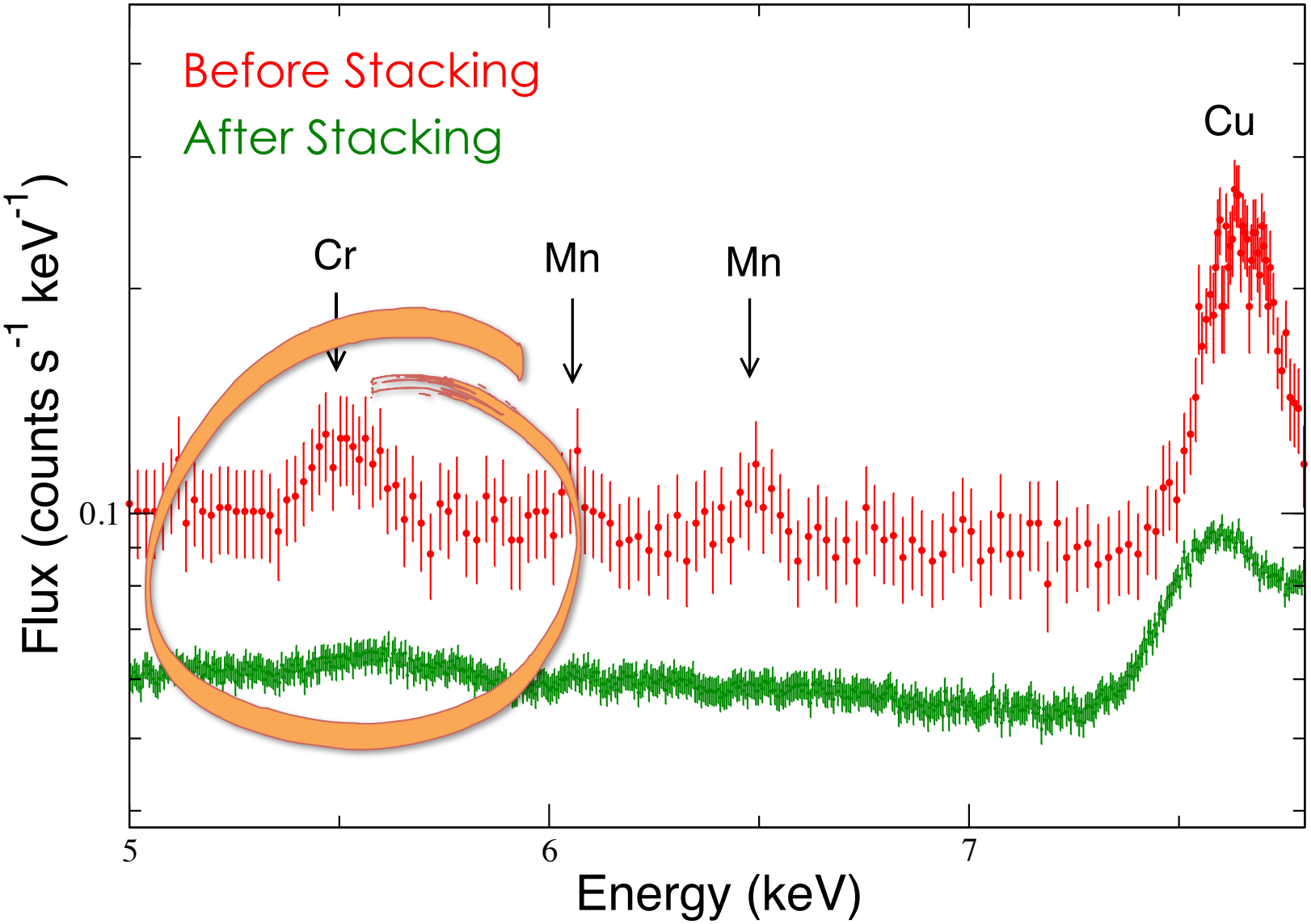
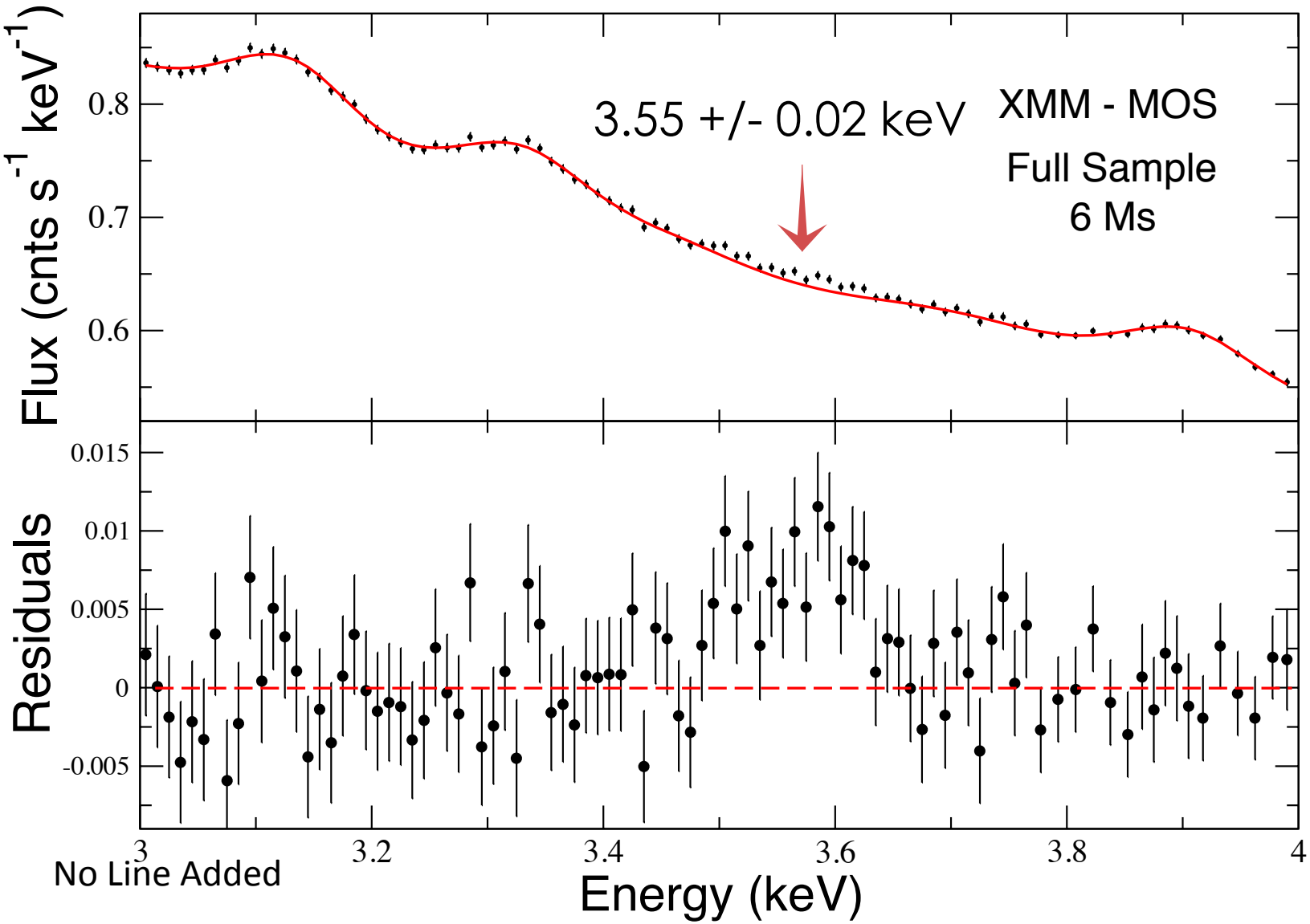
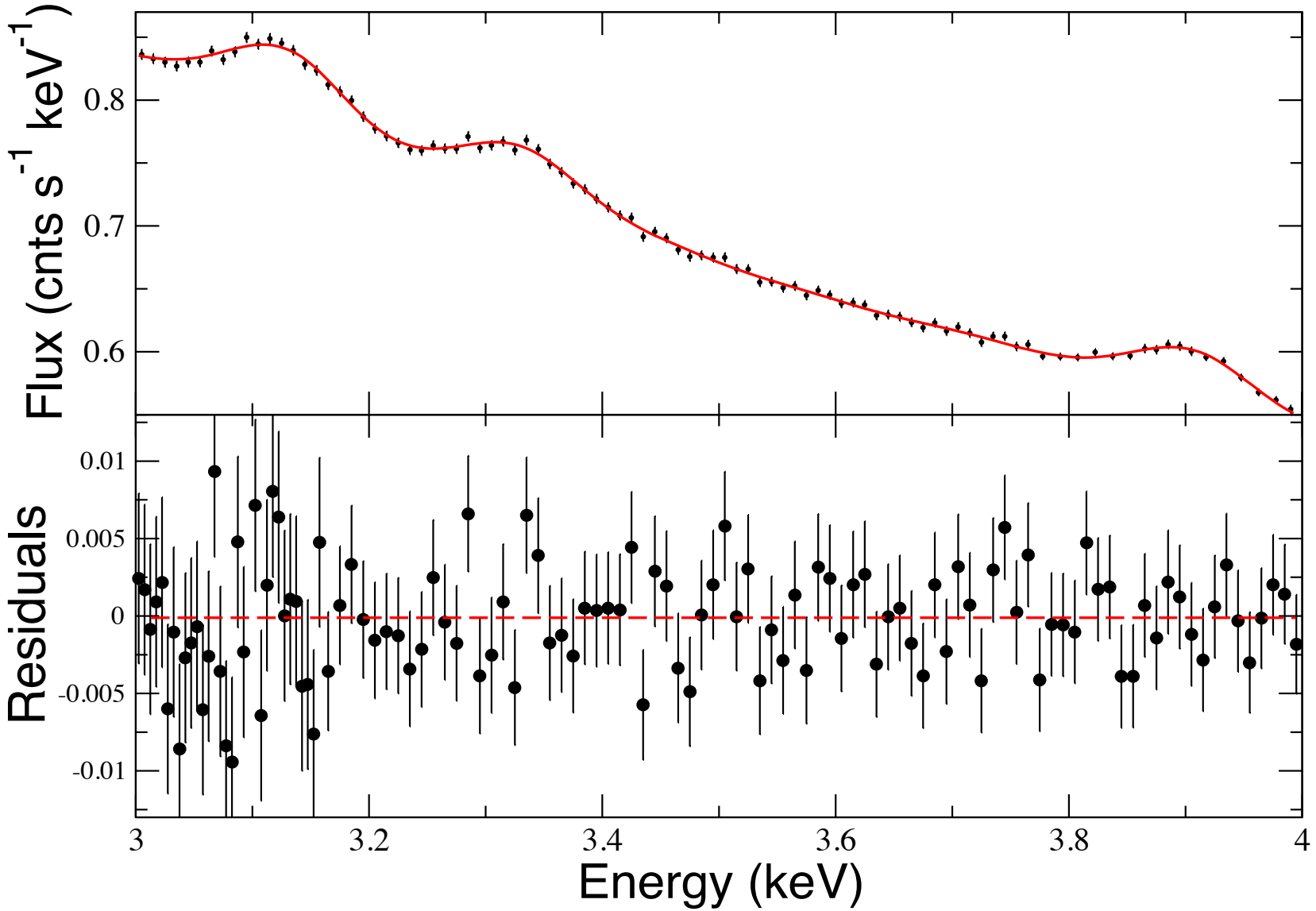


- Detected a weak excess
  at ~3.55 keV (rest frame energy)!

# Line Detected in the Full Sample



# with a Gaussian Line Added…



# Detections (Bulbul+14)

- XMM MOS → Full Sample
  Bright nearby Clusters
  (Coma+Ophiuchus+Centaurus)
  Distant Clusters
  Perseus Cluster
- XMM PN → Full Sample
  Distant Clusters
- Chandra → Perseus cluster
- Suzaku → Perseus cluster (Franse & Bulbul+15)

Line detected in five different subsamples with >3 $\sigma$ with six different detectors (Bulbul+2014)

- No plausible astrophysical lines at this energy

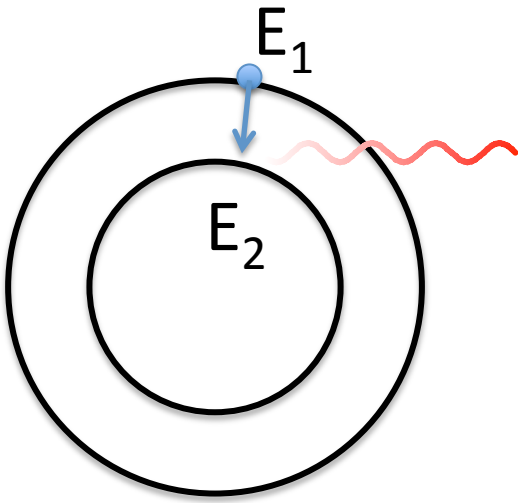
- No plausible astrophysical lines at this energy
- What is the origin of the line?

# Possible Interpretations

- Instrumental/Background  Artifact
- Nearby Astrophysical Lines
- Dark Matter?

# Astrophysical Origin?

- Radiative Recombination Feature
- Charge Exchange




Nearby Lines?

- K XVIII at 3.51keV
- Ar XVII DR at 3.62 keV
- Cl XVII Ly $\beta$ at 3.51keV

# Astrophysical Line?

- Flux of KVIII:

  S XVI (2.63 keV), Ca XIX (3.90 keV) & Ca XX (4.11 keV)
- Flux of Ar DR:

  observed Ar XVII line (3.12 keV)
- multiplied by 3 and allowed in the fit.
- 3.55 keV line is required by the fit at a flux well above these lines.
- **Bulbul 14 conclusion:**

  To explain the 3.55 keV line, the K XVIII and/or Ar XVII DR lines should be brighter than expected by factor >10.

# Counter Arguments

- "*Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line*" (Jeltema & Profumo arxiv:1408.1699) *(a.k.a. "Discovery of a 3.5 keV line in the Galactic Center and a critical look at the origin of the line across astronomical targets", 2015 MNRAS 450, 2143)*
- Possible contribution of Cl XVII at 3.51 keV
- Line ratios indicate wide and inconsistent plasma temperatures
- a very cool component

# Bulbul et al. response(arxiv:1409.4143)

- Cl XVII at 3.51 keV is a
  Ly $\beta$ line, no brighter
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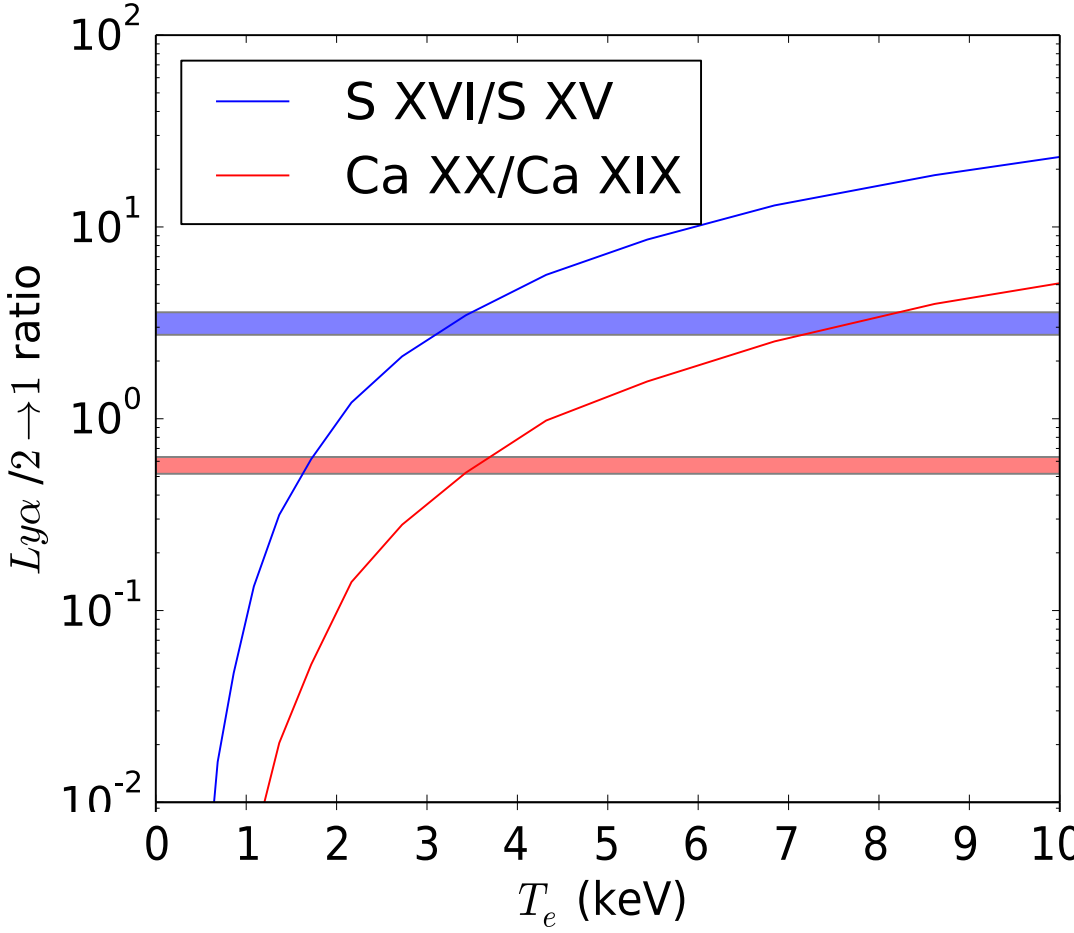

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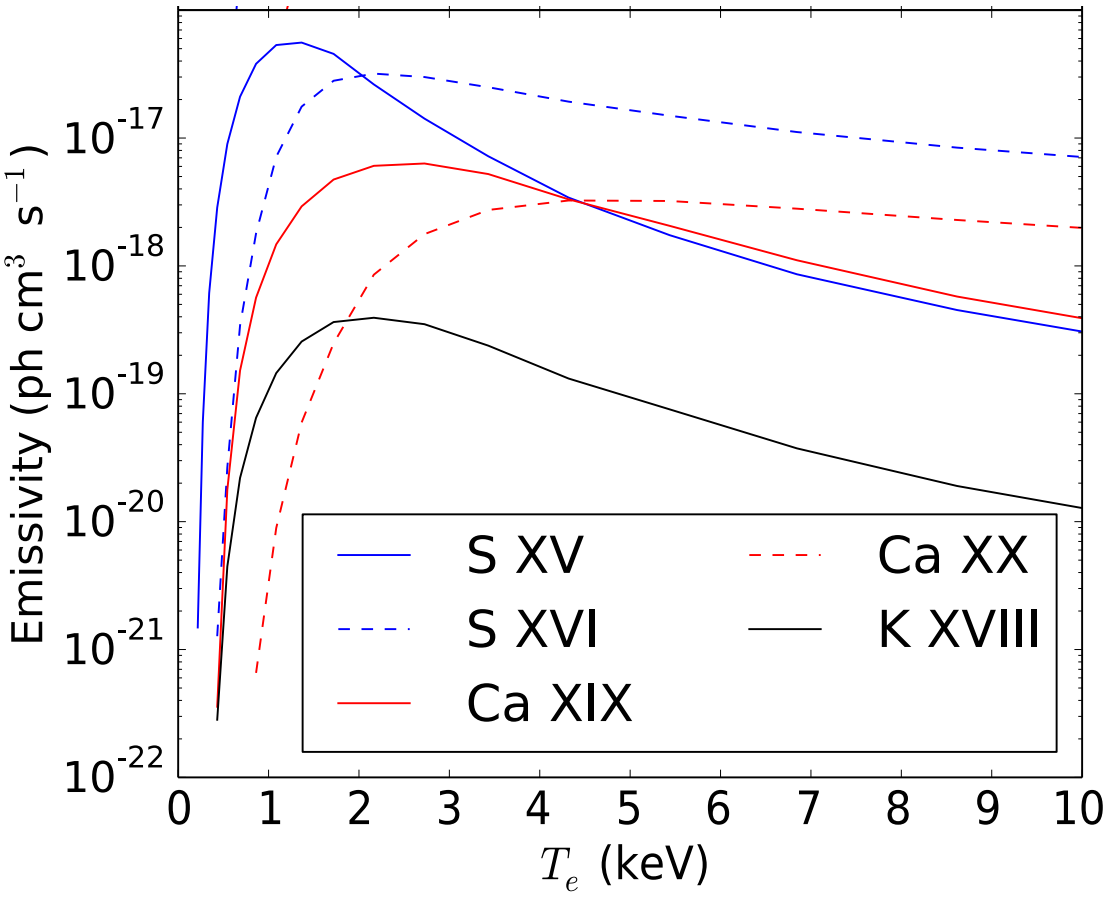
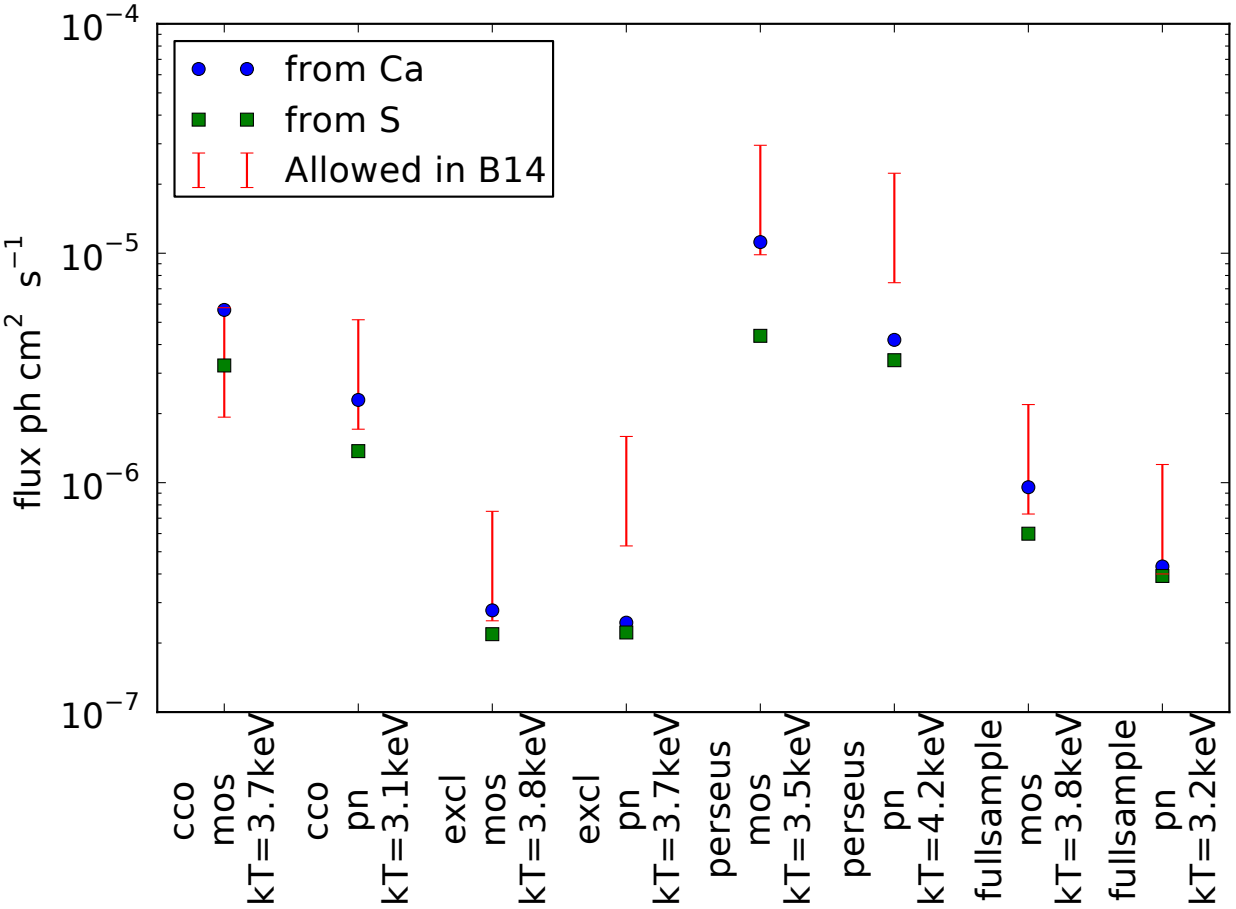
- Cl XVII at 3.51 keV is a Ly $\beta$ line, no brighter Ly $\alpha$
- The line ratio temperatures in JP are inconsistent because JP used incorrect atomic data
- S XV/ SXVI and Ca XIX/ Ca XX are excellent tracers of K XVIII



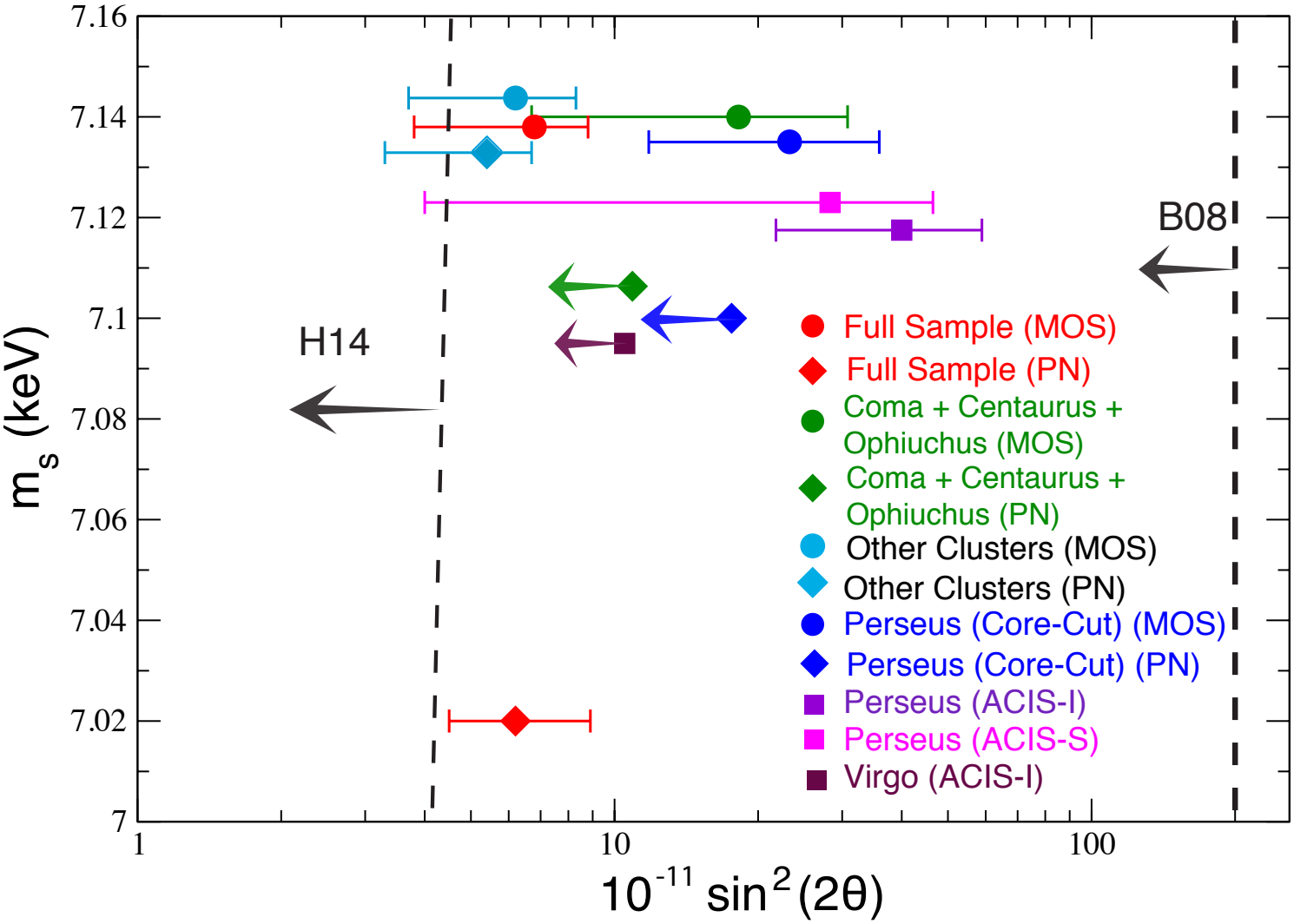
# Bulbul et al. response(arxiv:1409.4143)

- 3.55 keV line is required on top of very conservative allowance for the K line
- A further mistake in the Ca line ratio to temperature conversion in v2 of the J&P paper ...

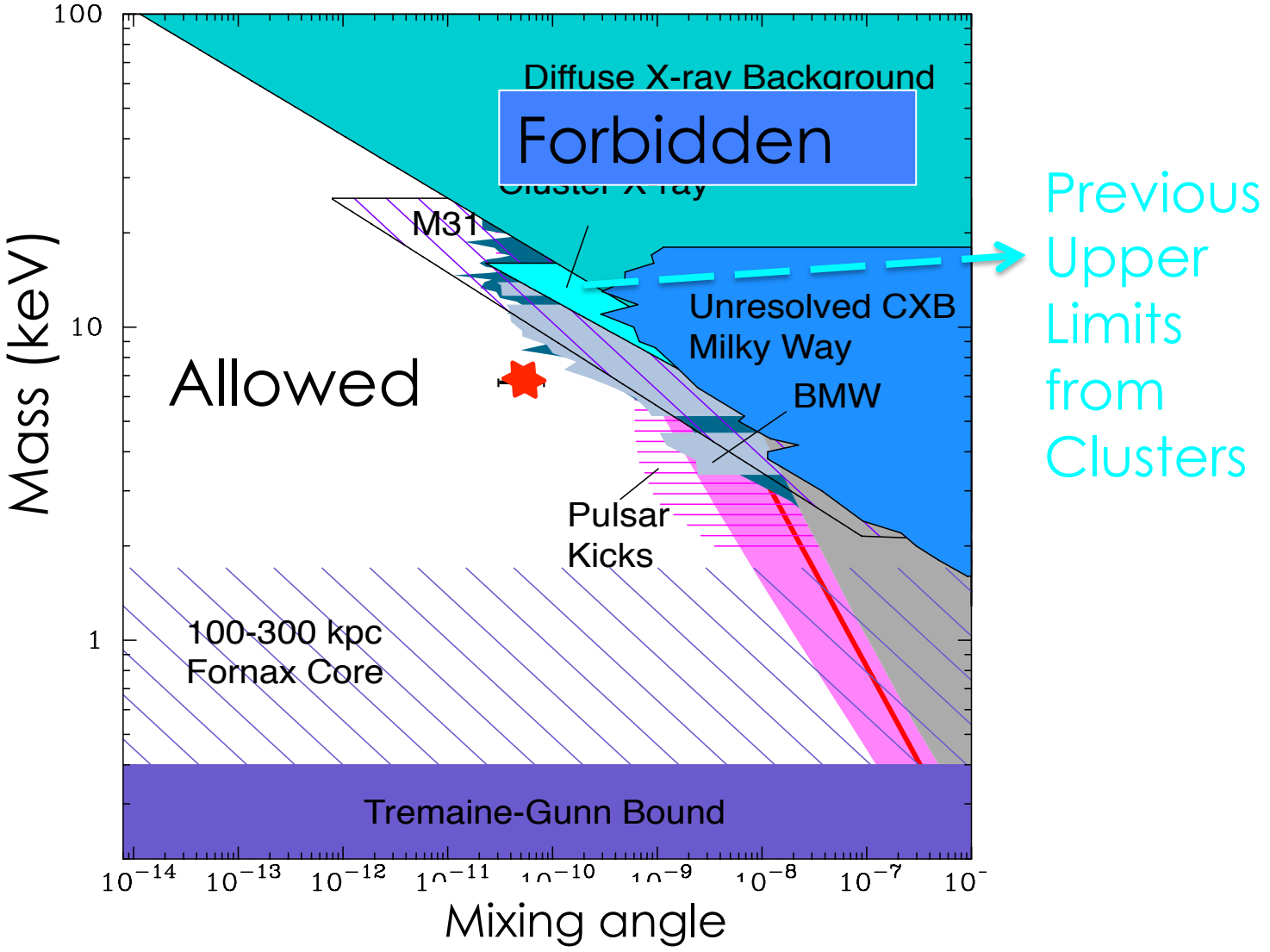


# Decaying Dark matter?

# Flux should scale with mass



# Comparison with Earlier Limits

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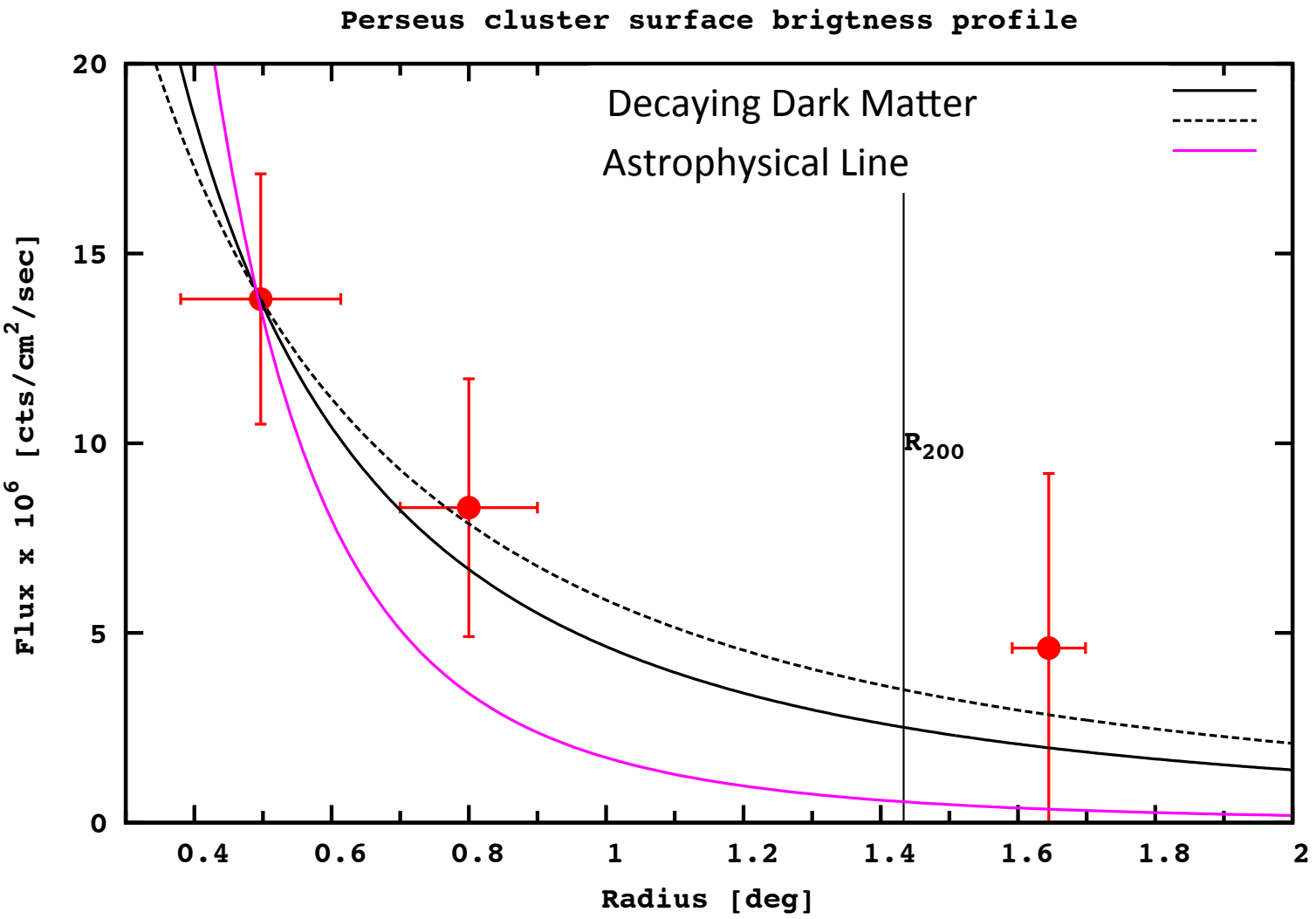
# Line Profile



# Decaying Dark Matter?

## Detections

1- Perseus Cluster ✓
(Bulbul+2014, Urban+2015, Franse & Bulbul+2015)

2- Perseus outskirts ✓
(Boyarsky+2014)

3- Stacked clusters ✓

4- Nearby Clusters ✓

5- Distant clusters ✓

6- Galactic Center ✓
(Boyarsky+2015, Jeltema & Profumo 2015)

7- Coma, A2199, and A2319 ✓
(Iakubovskyi & Bulbul+15)

8- M31 ✓
(Boyarsky+2014)

9- Ophiuchus (XMM) ✓
(Taki & Bulbul+2015, in prep)

## Non- Detections

1- Virgo Cluster
(Bulbul+2014) consistent ✓

2- Coma, Ophiuchus, Virgo (Suzaku)
(Urban+2015) consistent ✓

3- Dwarf Spheroidals
(Malyshev+2015) inconsistent

4- Stacked Galaxies
(Anderson+2015) inconsistent

> 200 citations to Bulbul+2014, most proposing DM explanations:

eXciting DM: An X-Ray Line from eXciting DM

SIMPle DM: Self-Interactions and keV Lines

Axion: The 7 keV axion DM and the X-ray line signal

Axino: X-ray line signal from decaying axino warm DM

Gravitino DM: 3.5 keV x-ray line from decaying gravitino DM

Scalar DM: 7 keV scalar DM and the anomalous …

Vector DM: Decaying Vector DM as an Explanation

Moduli DM: The 3.5 keV X-ray line signal from decaying moduli …

Nonabelian DM: Nonabelian DM models for 3.5 keV X-rays

Higgs: X-Ray Lines as Scotogenic Signals DM-philic Higgs

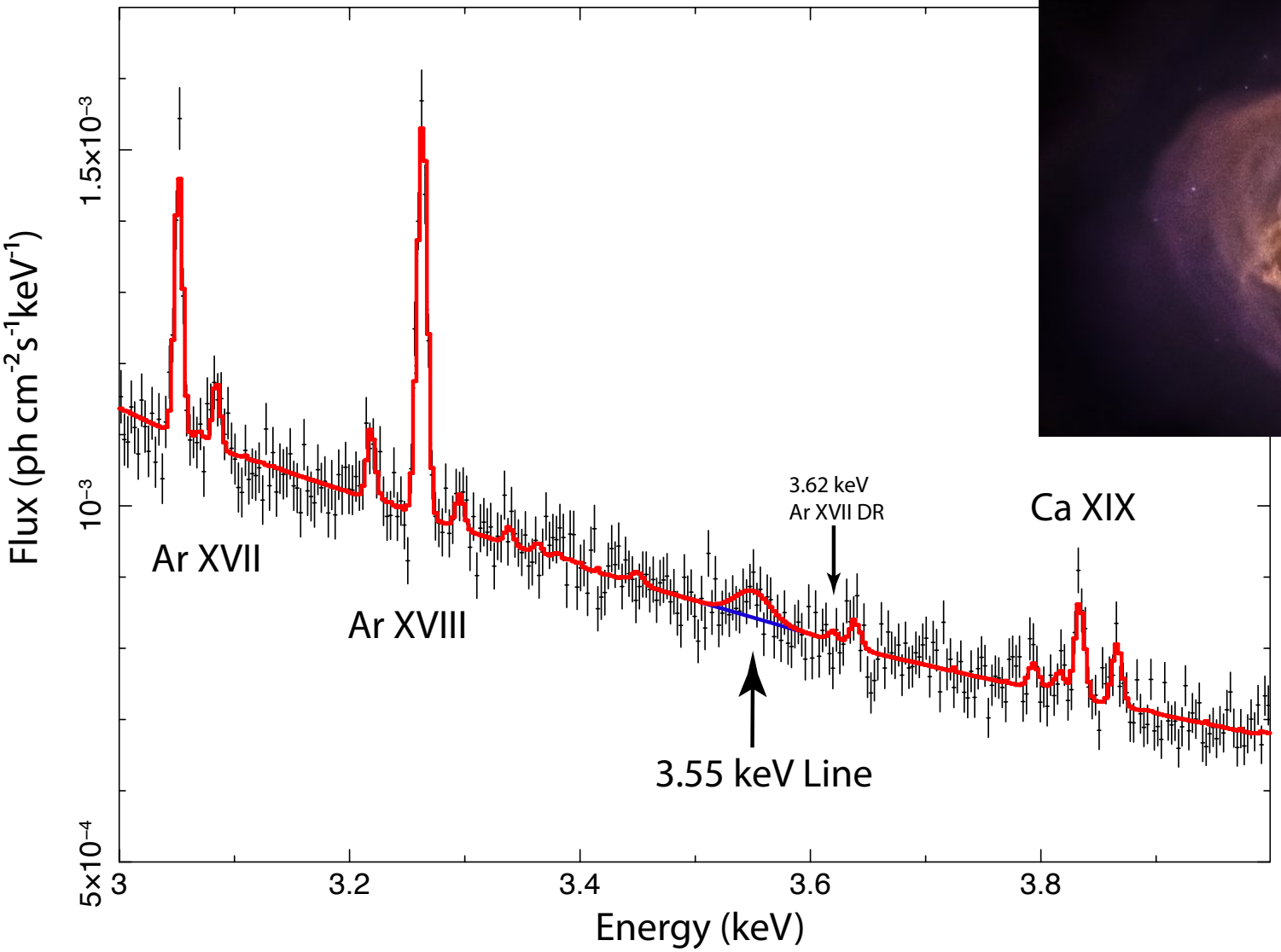
WIMP: 3.5-keV X-ray line from nearly-degenerate WIMP DM decays

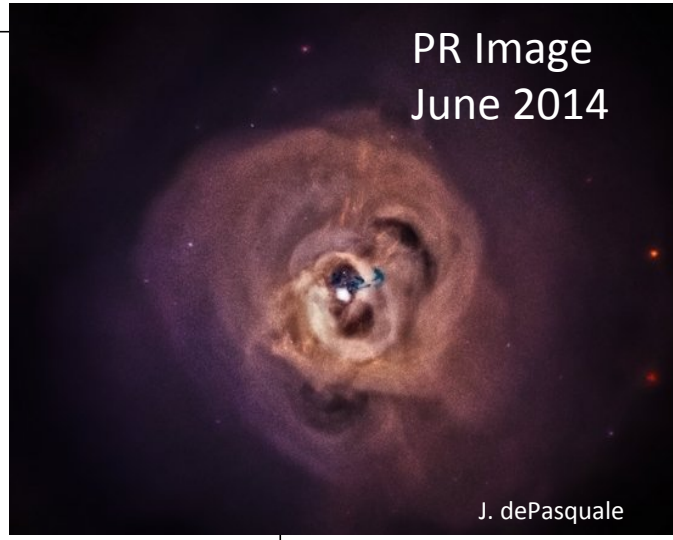
….

# Tests for Revealing the Origin

| | |
|---|---|
| **Astrophysical Origin:** | Stacked Suzaku Observations of Galaxy Clusters (Bulbul+2015) |
| **Dark Matter Origin (General):** | Perseus Line Profile with Suzaku (Franse & Bulbul+2015) |
| **Annihilating Dark Matter:** | Stacked XMM-Newton Observations of Galaxy Clusters (Taki & Bulbul+ 2015) |
| **Decaying Dark Matter:** | 1.3 Ms XMM-Newton Dwarf Draco Observations (Boyarsky & Bulbul+2016) |

# Observations with Astro-H

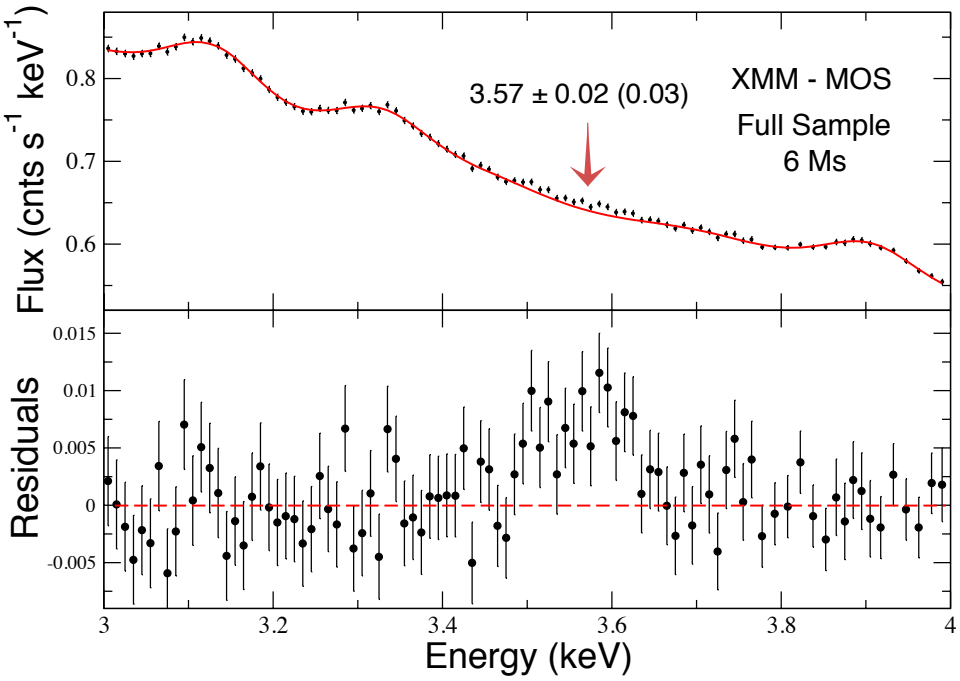



1Ms Simulations of the Perseus Custer

# Conclusions

- Attempts to refine upper limits can sometimes fail…
- Detected a weak emission line in the stacked observations of galaxy clusters
- Seen at > 3 σ in five different subsamples
- with six detectors
- No plausible atomic transitions in thermal plasma at this energy
- Could be dark matter!



# What is the Contribution of Cl XVII Ly $\beta$ ?