The 3.5 keV line — claims and counterclaims

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June 10, 2015

The Astrophysical Journal, 789:13 (23pp), 2014 July 1 doi:10.1088/0004-637X/789/1/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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Received 2014 February 10; accepted 2014 April 28; published 2014 June 10

Zwicky (1933, 1937): Universe is dominated by “missing mass”

- Total mass of a galaxy cluster ~ 100 times the mass in stars
- “Missing mass” is not concentrated in galaxies

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

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.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics. Method iii is based on the *virial theorem* of classical mechanics. The application of

Bullet Cluster: missing mass is *not* in intergalactic gas + modified gr.

most of visible mass is in hot gas,

but grav. potential is peaked elsewhere → there is dark matter (Clowe+ 04, 06)

image from NASA / Chandra press release, August 2006

Dark matter = hypothetical sterile neutrino? (Dodelson & Widrow 94)

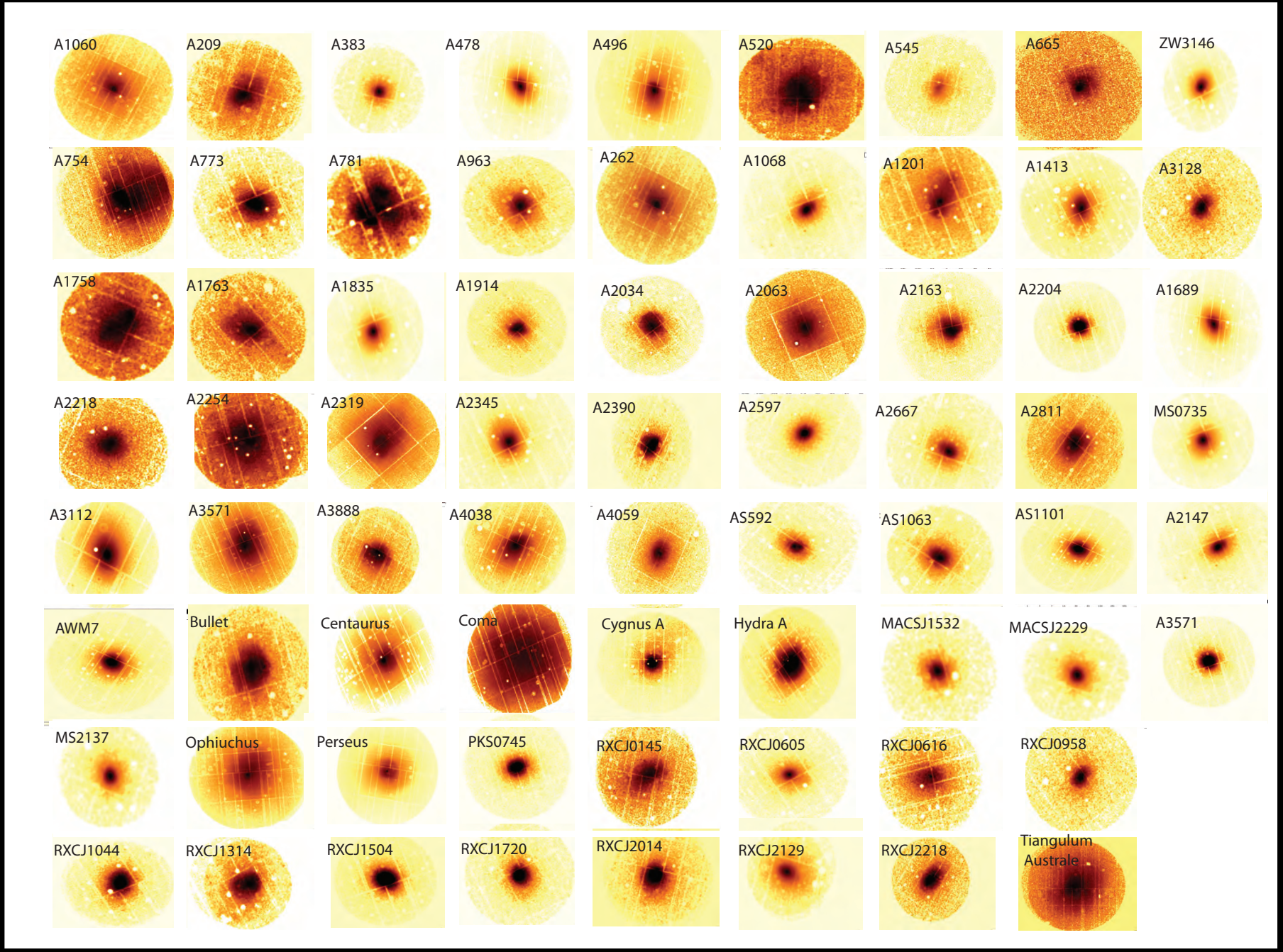
Warm Dark Matter — would help explain cores of dwarf galaxies and lack of (or unexpected mass distribution of) Milky Way satellites

- From astrophysical considerations, m_s 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.

... so an X-ray observer has a lammpost to look under (a different one from that used by WIMP observers)

Past searches in individual clusters, galaxies, dwarf galaxies, Milky Way resulted only in upper limits (Abazajian, Boyarsky, et al. 2001–2013)

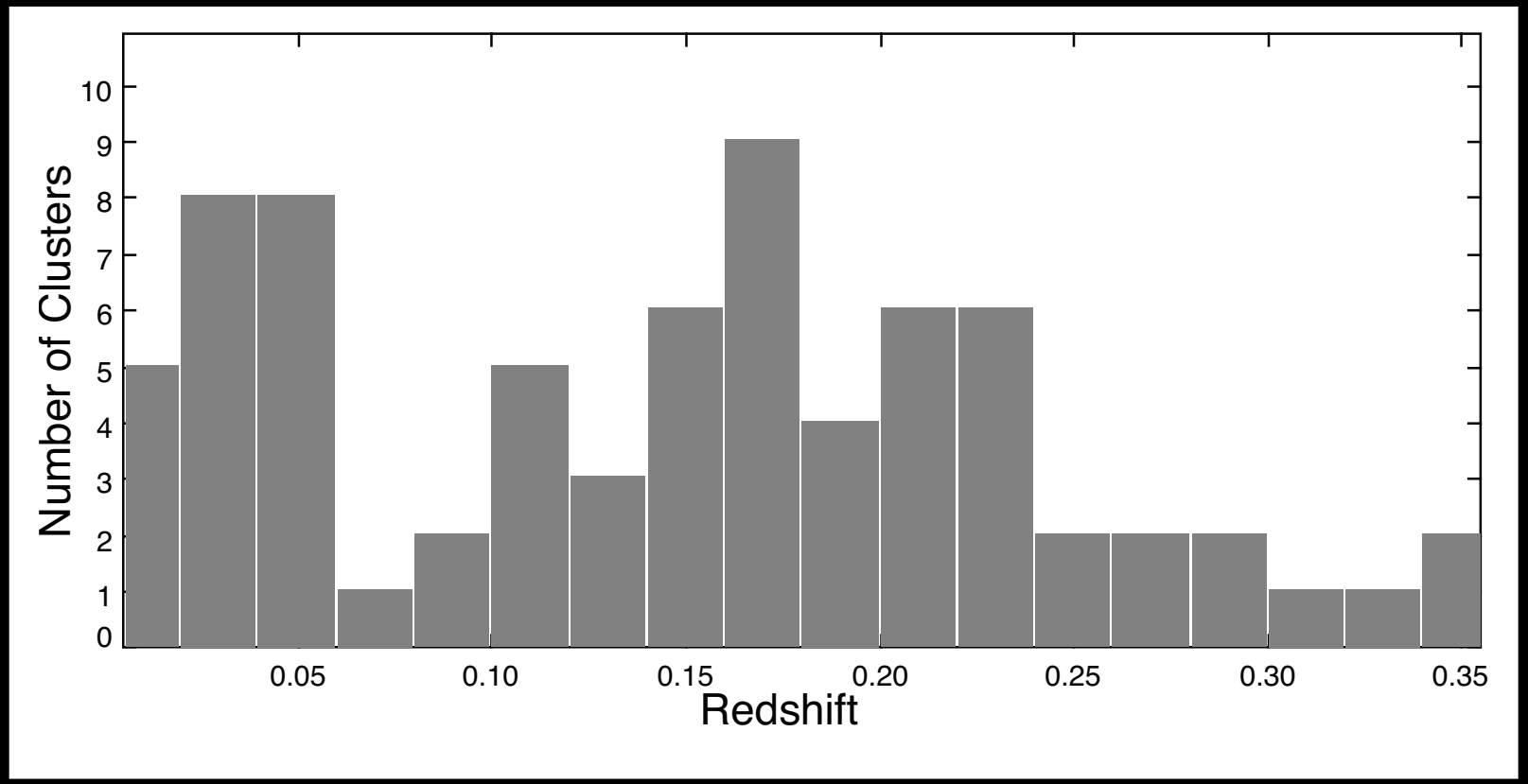
Bright XMM clusters



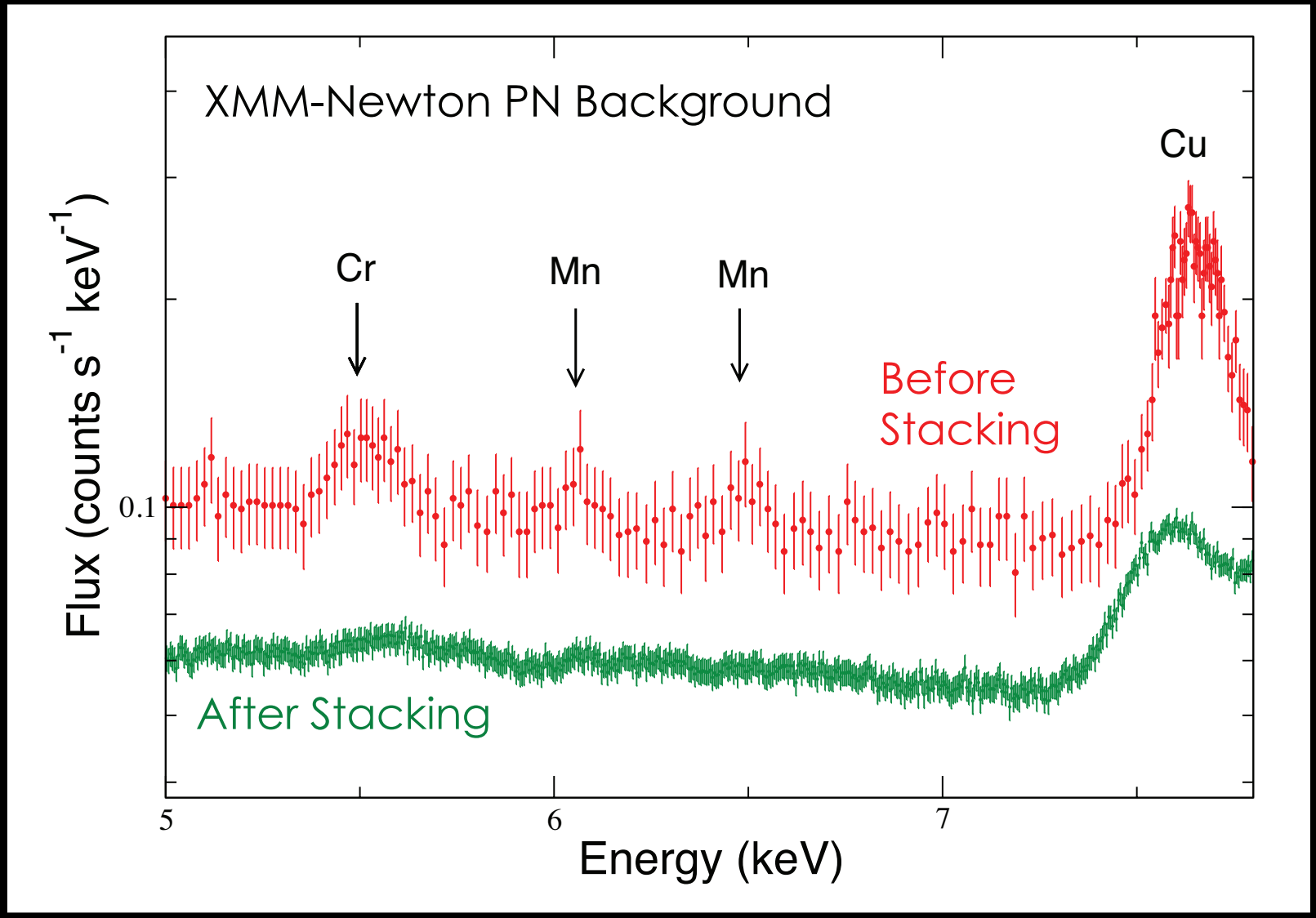
Stacked XMM spectra (MOS and PN) of 73 bright galaxy clusters,

blue-shifted to the same cluster rest frame

Cluster redshift distribution



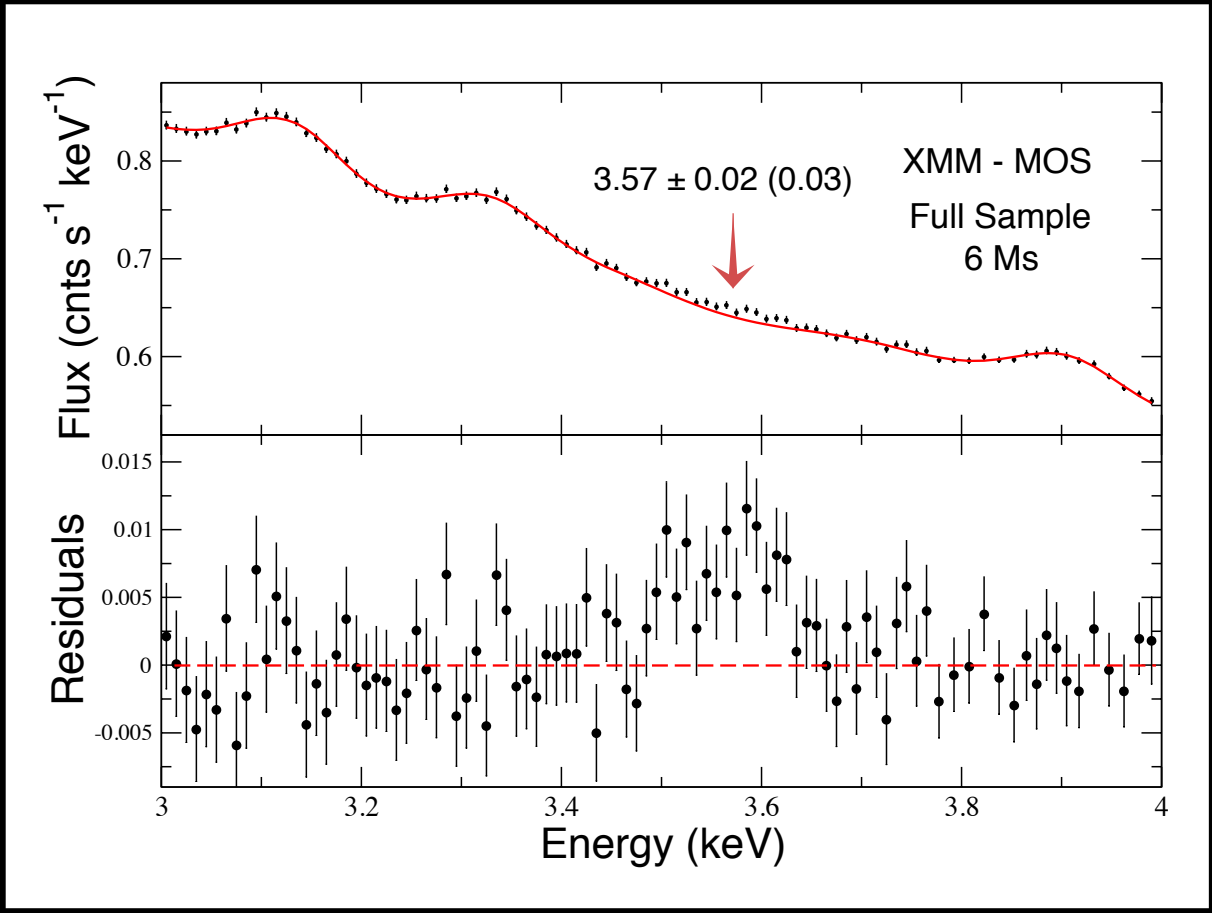
Detector features smeared by cluster *z* distribution



Searched for any unidentified emission lines in 2–10 keV band

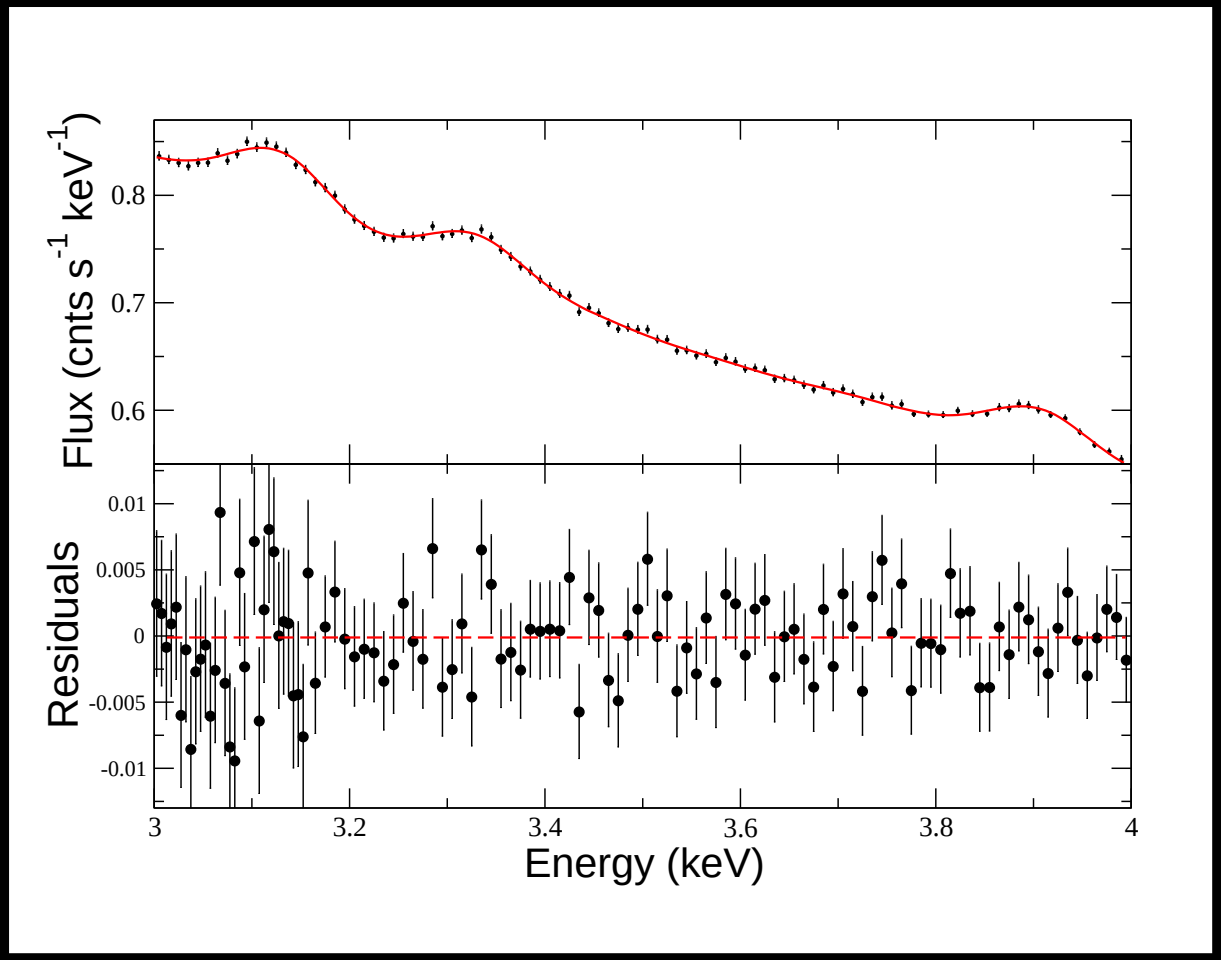
Detected a very weak line at E = 3.55–3.57 keV rest-frame energy

Line in stacked XMM spectra, full cluster sample



No line added

Line in stacked XMM spectra, full cluster sample



Gaussian line added

Line seen at same energy at $>3\sigma$ in 5 statistically indepentent subsamples:

XMM MOS: Perseus, Coma+Centaurus+Ophiuchus, distant sample

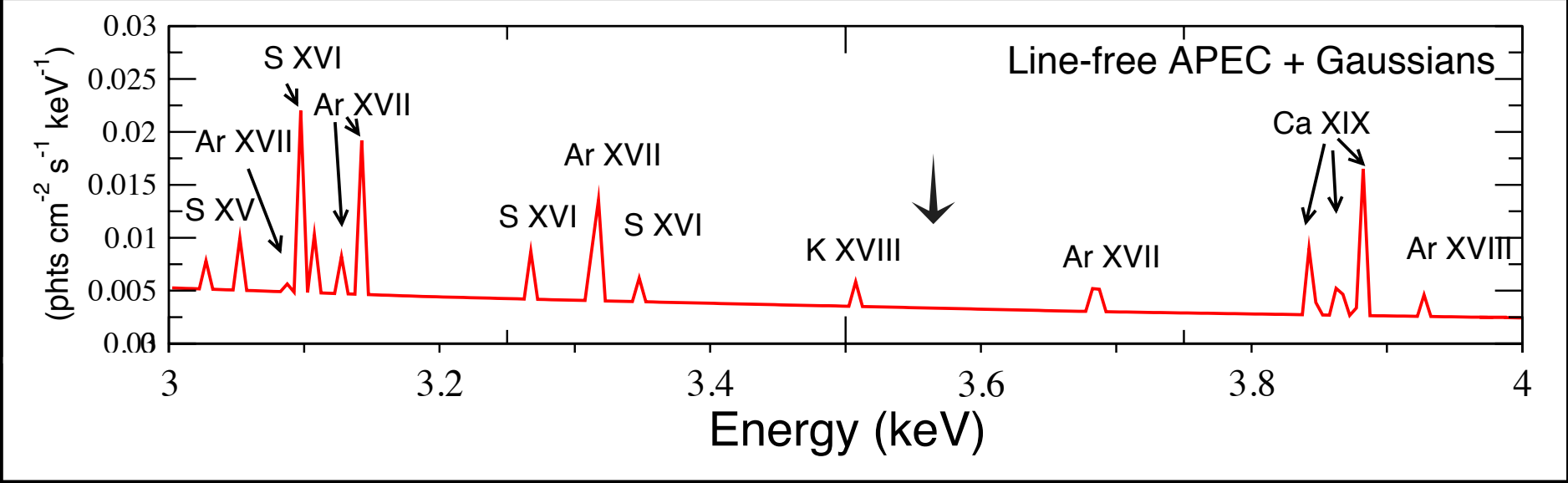
XMM PN: distant sample

Chandra ACIS-I (a different instrument): Perseus

Caveats (a full journal page in Bulbul et al.)

- Line is really faint – equivalent width $\sim$1 eV, or $\sim$1% bump over the continuum, which therefore must be modeled very well
- Line is within 50–110 eV of known plasma lines
- Calibration uncertainties are significant for single clusters like Perseus (less so for stacked spectra)

The crowded spectral interval



Thermal plasma line?

Two faint atomic lines within the resolution element: K XVIII (3.51 keV) and Ar XVII dielectronic recombination (3.62 keV).

- The expected flux for K XVIII was estimated from the observed lines of S XVI (2.63 keV), Ca XIX (3.90 keV) and Ca XX (4.11 keV)
- The expected flux for Ar DR line estimated from the observed Ar XVII line (3.12 keV)
- These estimates were multiplied by 3 and allowed in the fit. The 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.

But:

"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 not included
- Various line ratios indicate wide and inconsistent plasma temperatures, therefore one can't restrict the temperature range and use other lines to predict the K XVIII flux. For example, there may be a very cool component which will produce a much brighter K line.

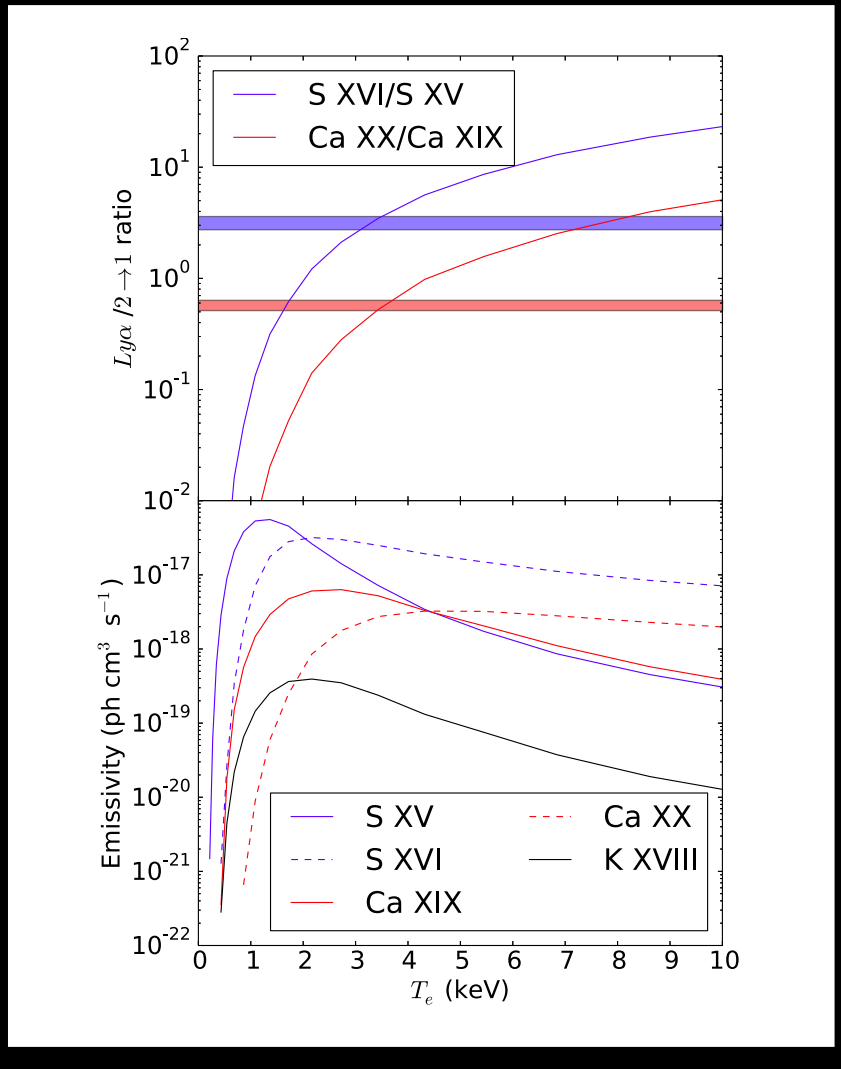
Bulbul et al. response (arxiv:1409.4143):

- Cl XVII at 3.51 keV is a Ly β line, but we don't see a much brighter Ly α

Bulbul et al. response (continued):

- The line ratio temperatures in JP are inconsistent because JP used incorrect atomic data — in fact, different ratios (for ions of the same element) are in agreement:

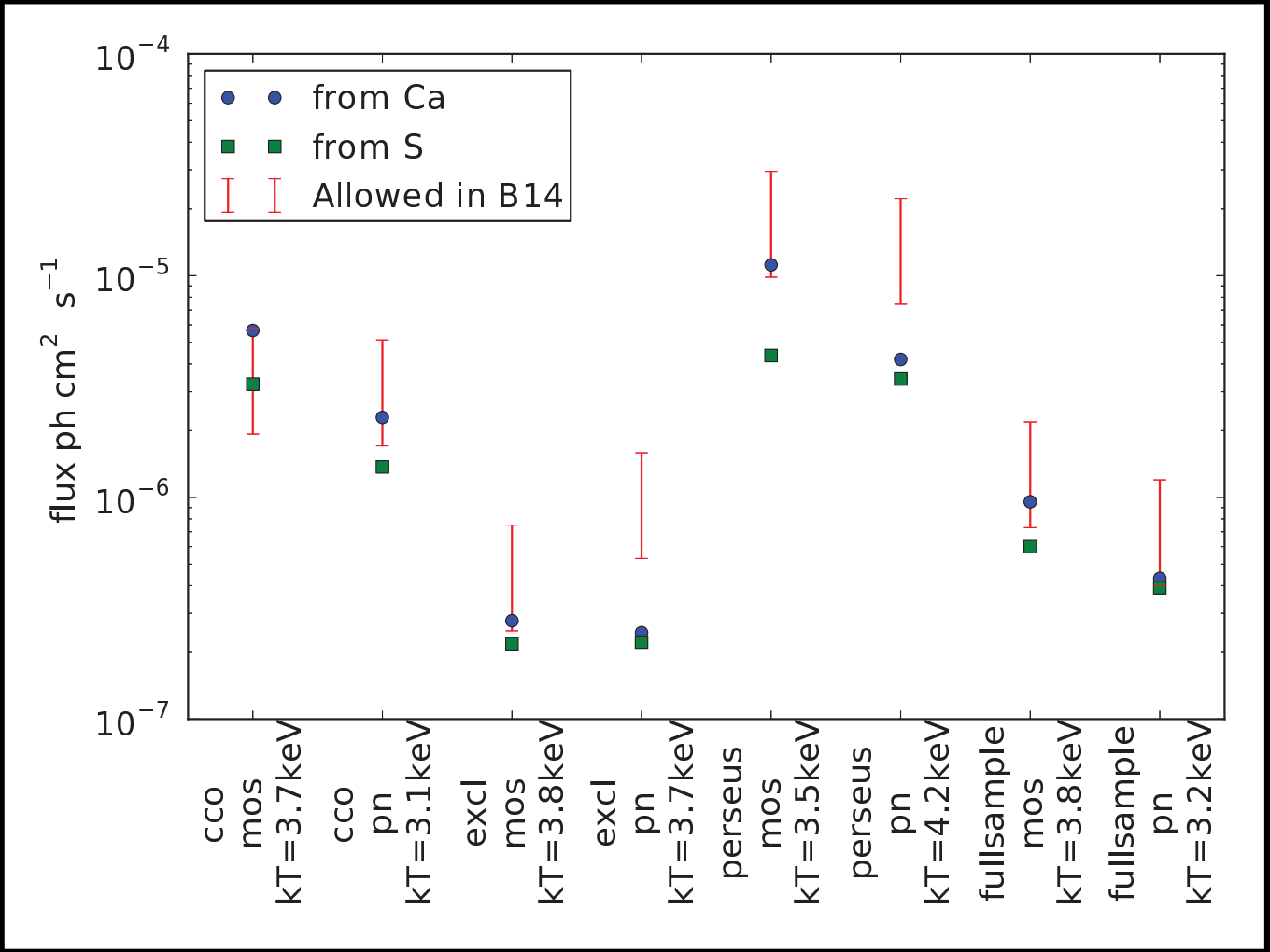
XMM MOS Perseus, including cool core



- S XV–XVI and Ca XIX–XX are excellent tracers of K XVIII

- S XV peaks at $T \sim 1$ keV. The S line ratio indicates absence of significant quantities of such gas even in the Perseus cool core (as well as in other subsamples).

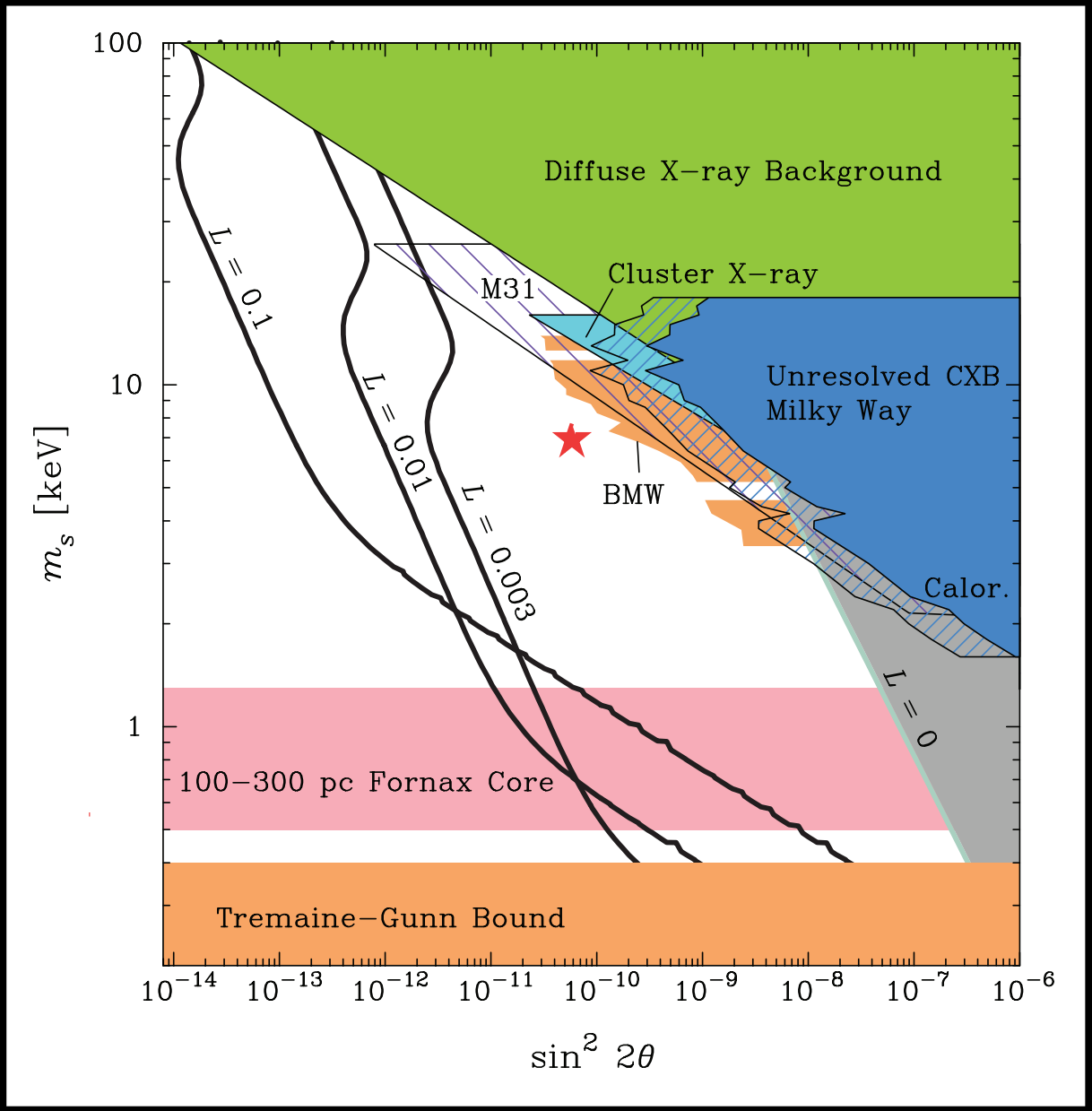
The allowed ranges for K XVIII flux in different subsamples of B14
vs. alternative estimates, e.g., using *T* from the Ca XX / XIX line ratios:



- 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 ...

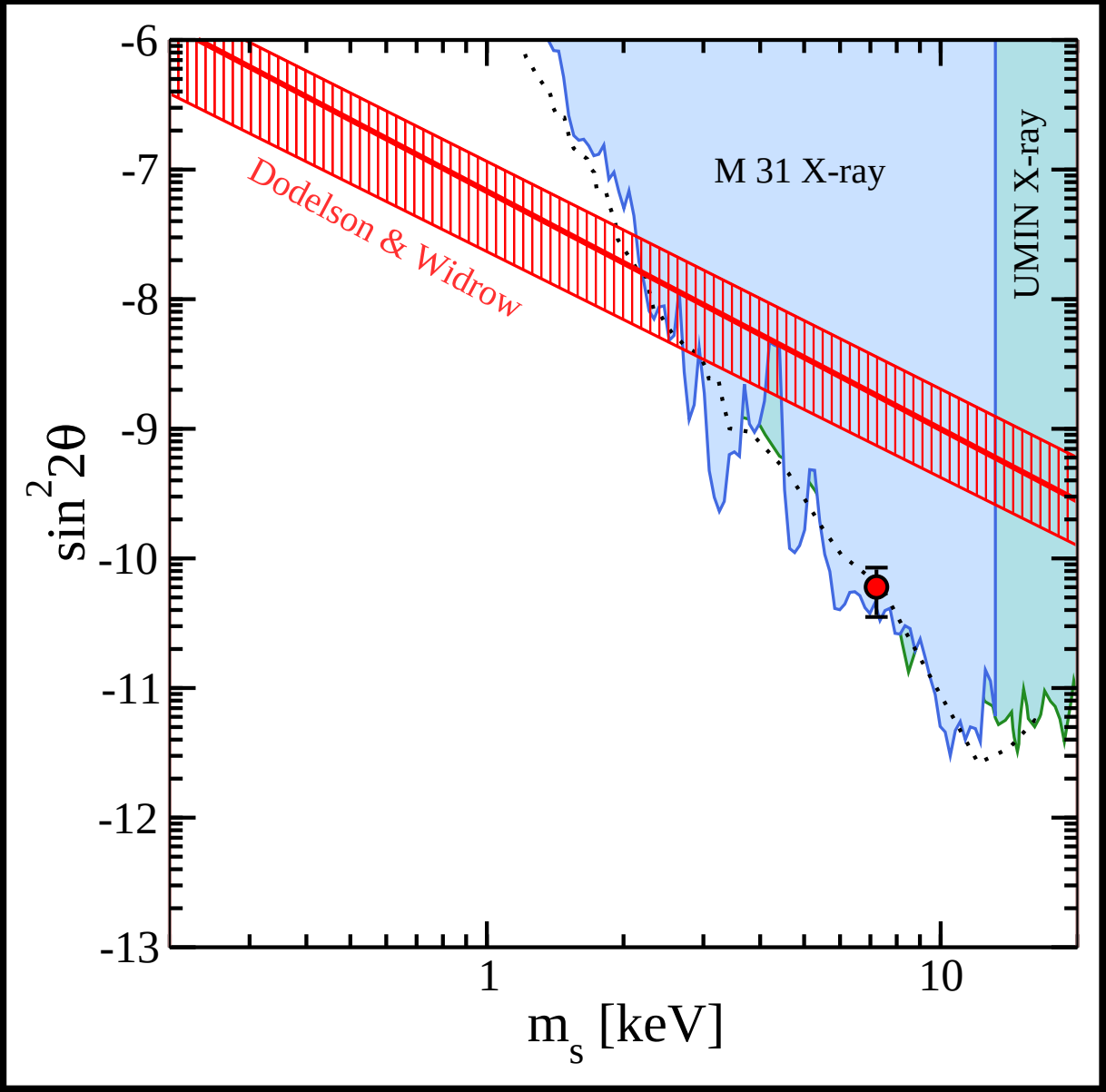
Sterile neutrino?

Our detection and earlier limits on sterile neutrino



Earlier (historic) limits from Abazajian 07

Our detection and earlier limits on sterile neutrino



Recent limits from Horiuchi 14

Independent detections (and nondetections) of the 3.5 keV line:

\+ M31 and Perseus cluser outskirts with *XMM*
(Boyarsky et al. 2014, PRL 113, 251301)
used region of Perseus different from that in Bulbul et al.

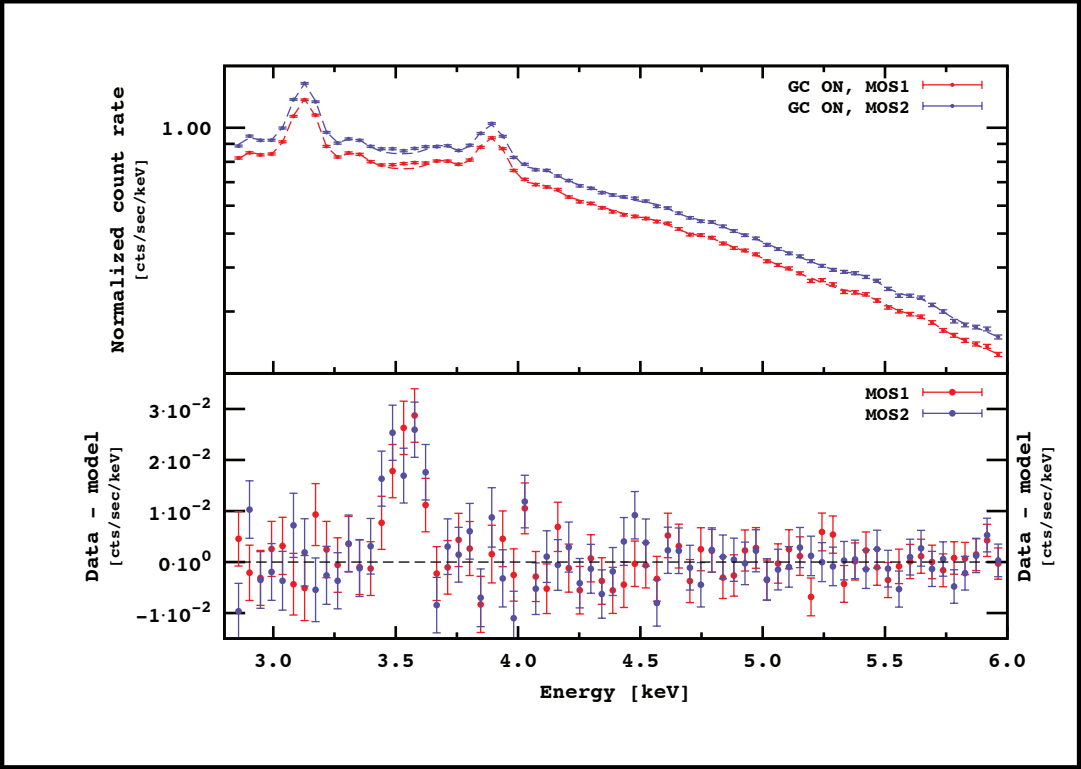
\+ Detection of line in Perseus with *Suzaku* (but not in Coma, Virgo, Ophiuchus)
(Urban et al. arxiv:1411.0050)

\- But, a non-detection in the same *Suzaku* Perseus dataset
(Tamura et al. 2015, PASJ 67, 23).

\+ Bulbul & Franse (in prep) do see the line in Perseus *Suzaku*; the difference with Tamura is in details of model fitting
recall the line is a ~1% bump above the continuum, so one has to model the continuum and the other lines extremely well!

Independent detections (and nondetections) of the 3.5 keV line:

+ Line from the Galactic Center *XMM* spectra (Boyarsky et al. arxiv:1408.2503):



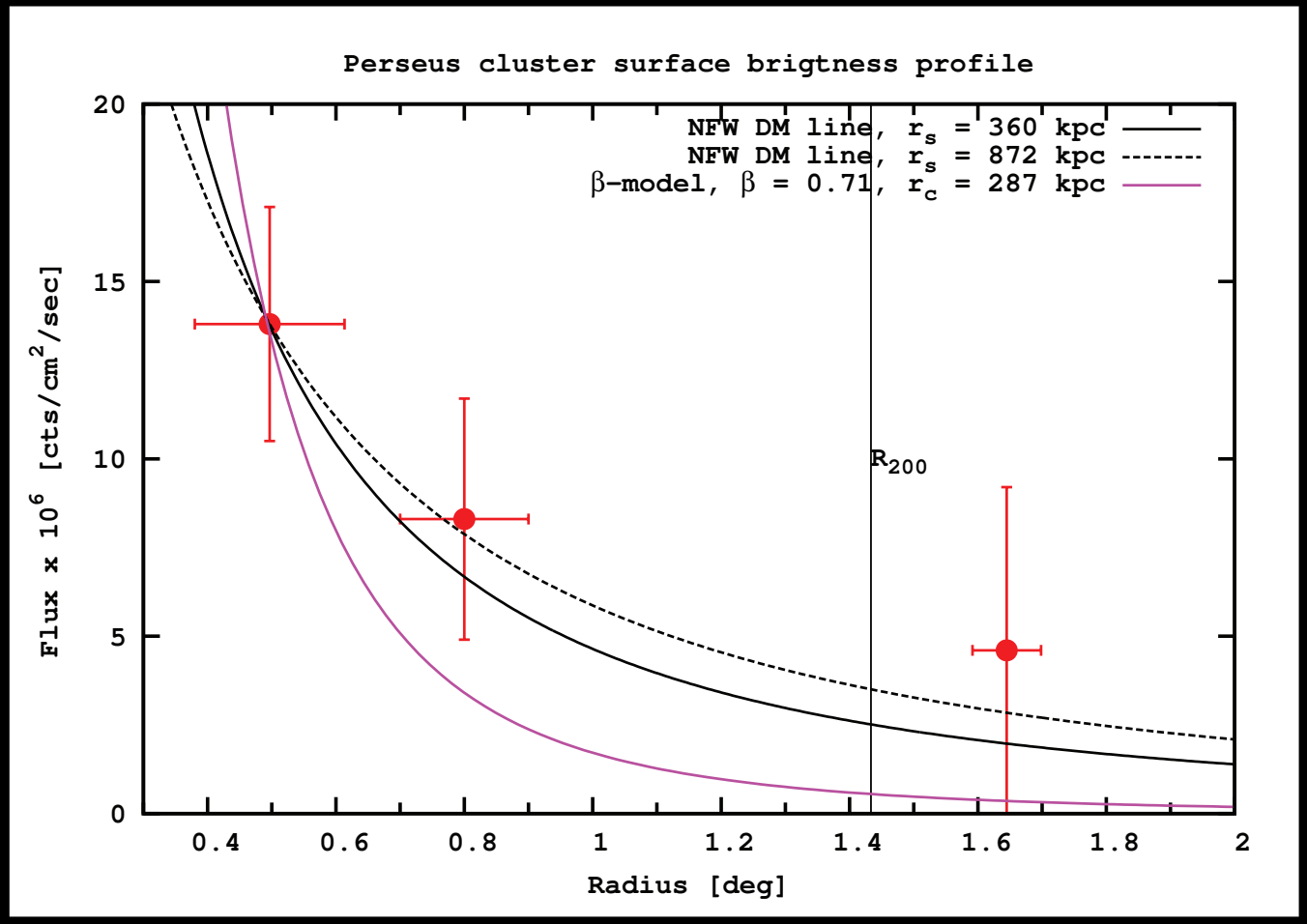
- *Chandra* non-detection in GC by Riemer-Sorensen (arxiv:1405.7943) is consistent with Boyarsky's detection once Galactic absorption is included

- The absorbing column density toward GC as measured in X-rays is much higher than that from 21 cm.

The absorption at E = 3.5 keV is factor 2–3 (compared to 10% implied by 21 cm surveys)

Signal from dark matter should scale with radius as mass

Boyarsky's *XMM* Perseus line:

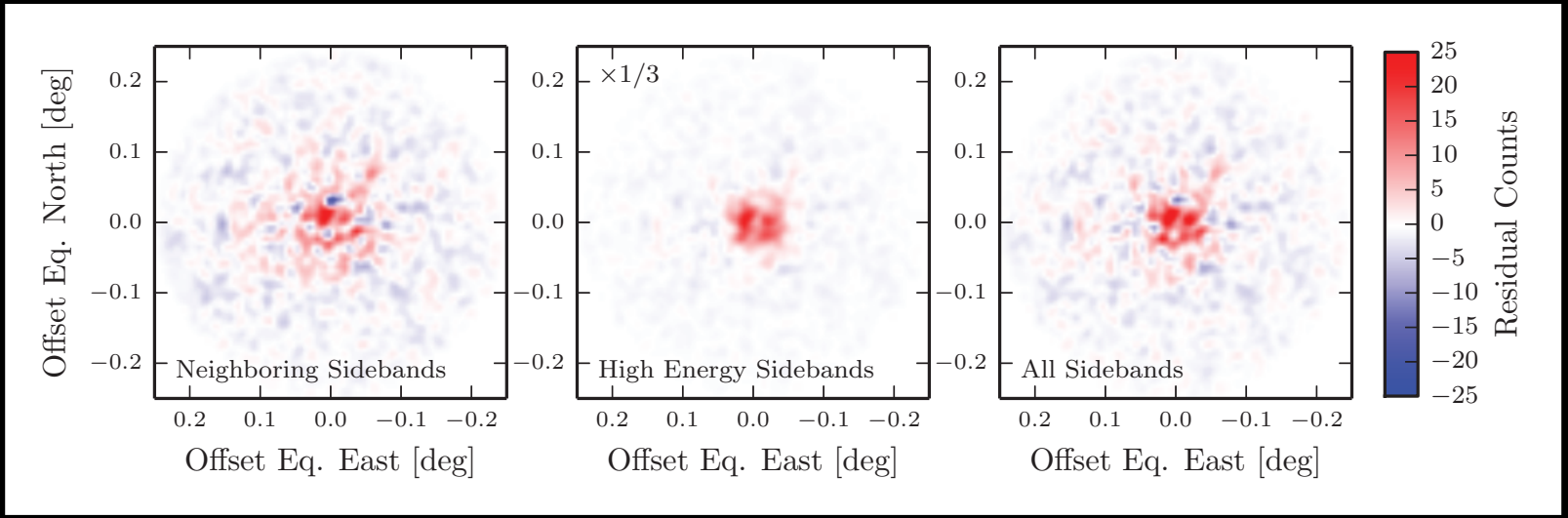


- Scaling as DM is mildly preferred (compared to gas), but errors are big

“Where do the 3.5 keV photons come from?
A morphological study of the Galactic Center and of Perseus”

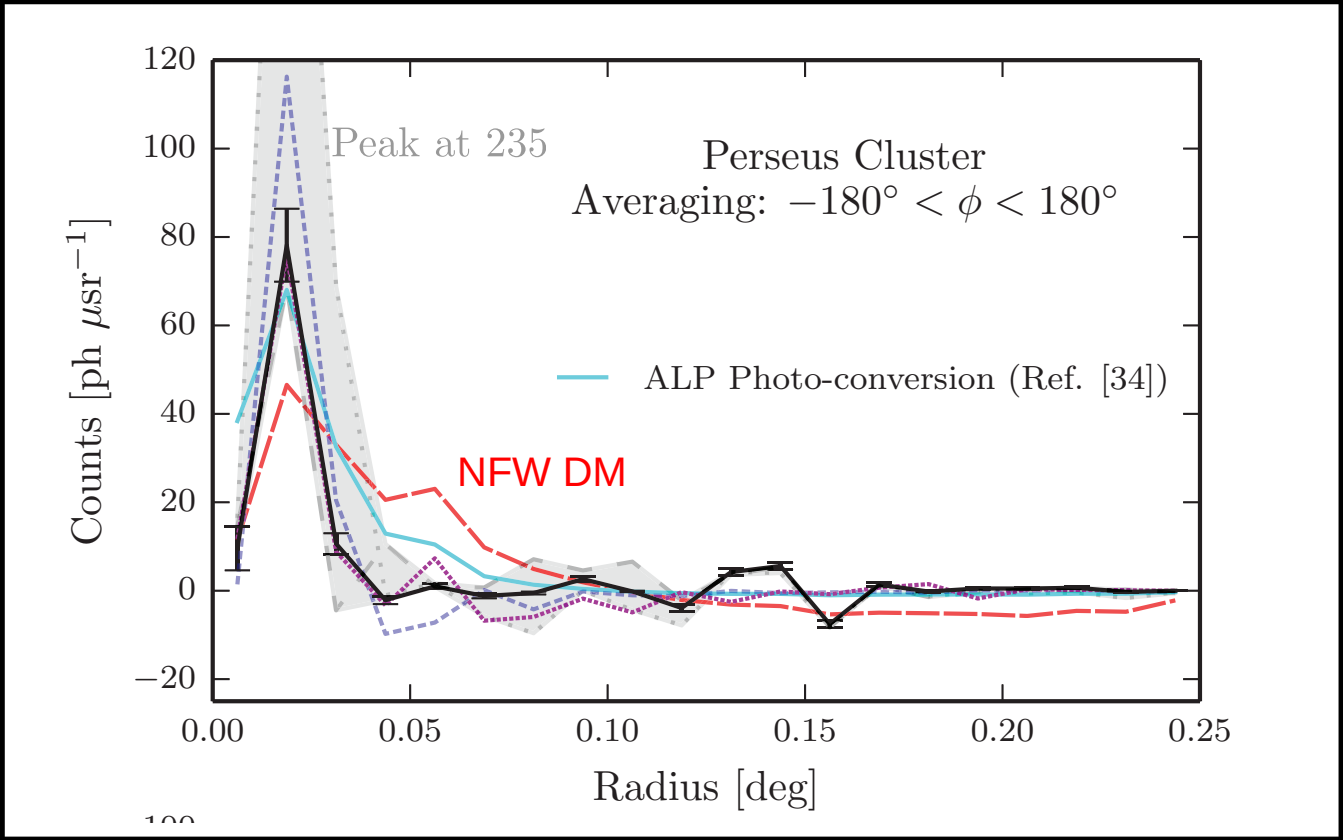
(Carlson, Jeltema & Profumo arxiv:1411.1758)

Residual 3.5 keV in Perseus after subtracting various models for continuum:



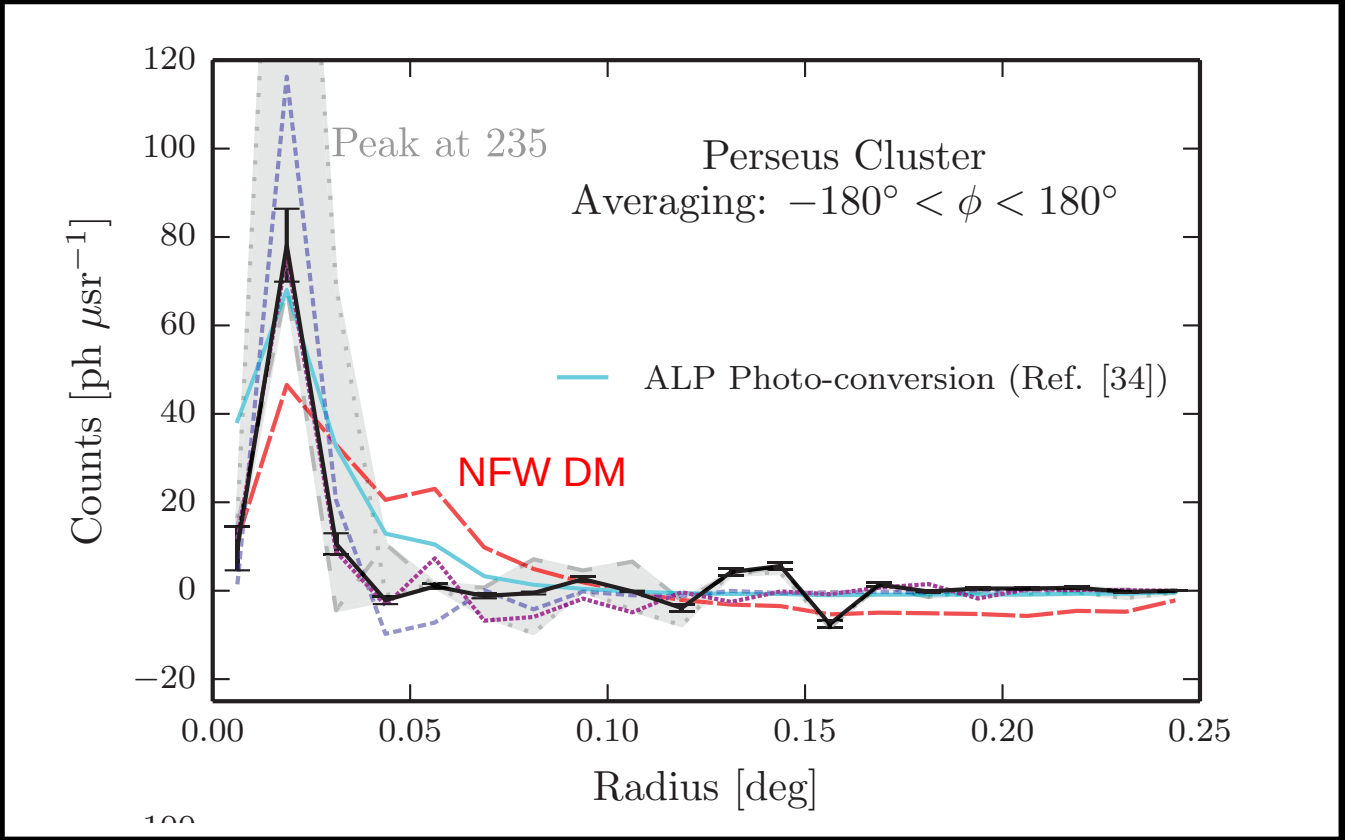
Carlson, Jeltema & Profumo (cont.)

Radial profile of the residual 3.5 keV emission:



Carlson, Jeltema & Profumo (cont.)

Radial profile of the residual 3.5 keV emission:

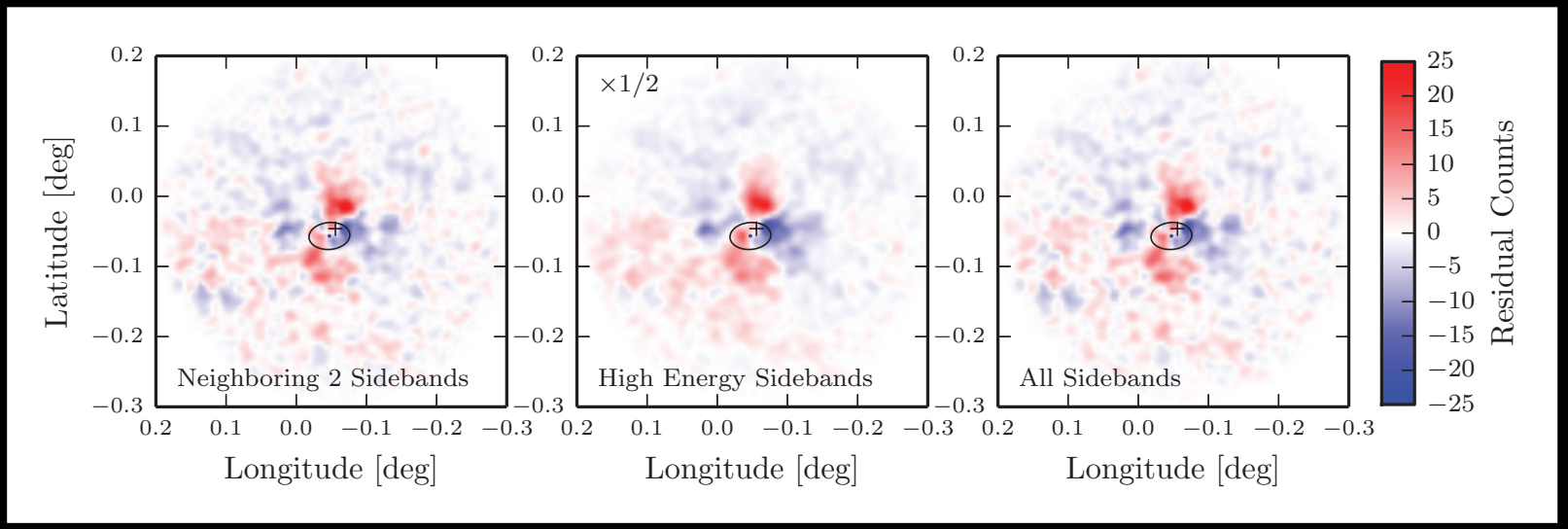


- 3.5 keV line is ~1% of continuum, so any errors of continuum > few % will result in mapping the astrophysical continuum, not the line

- The line from the whole Perseus cluster is detected at 4σ significance, so those small error bars on the profile cannot represent the line signal

Carlson, Jeltema & Profumo (cont.)

Residual 3.5 keV in GC after subtracting various models for continuum:

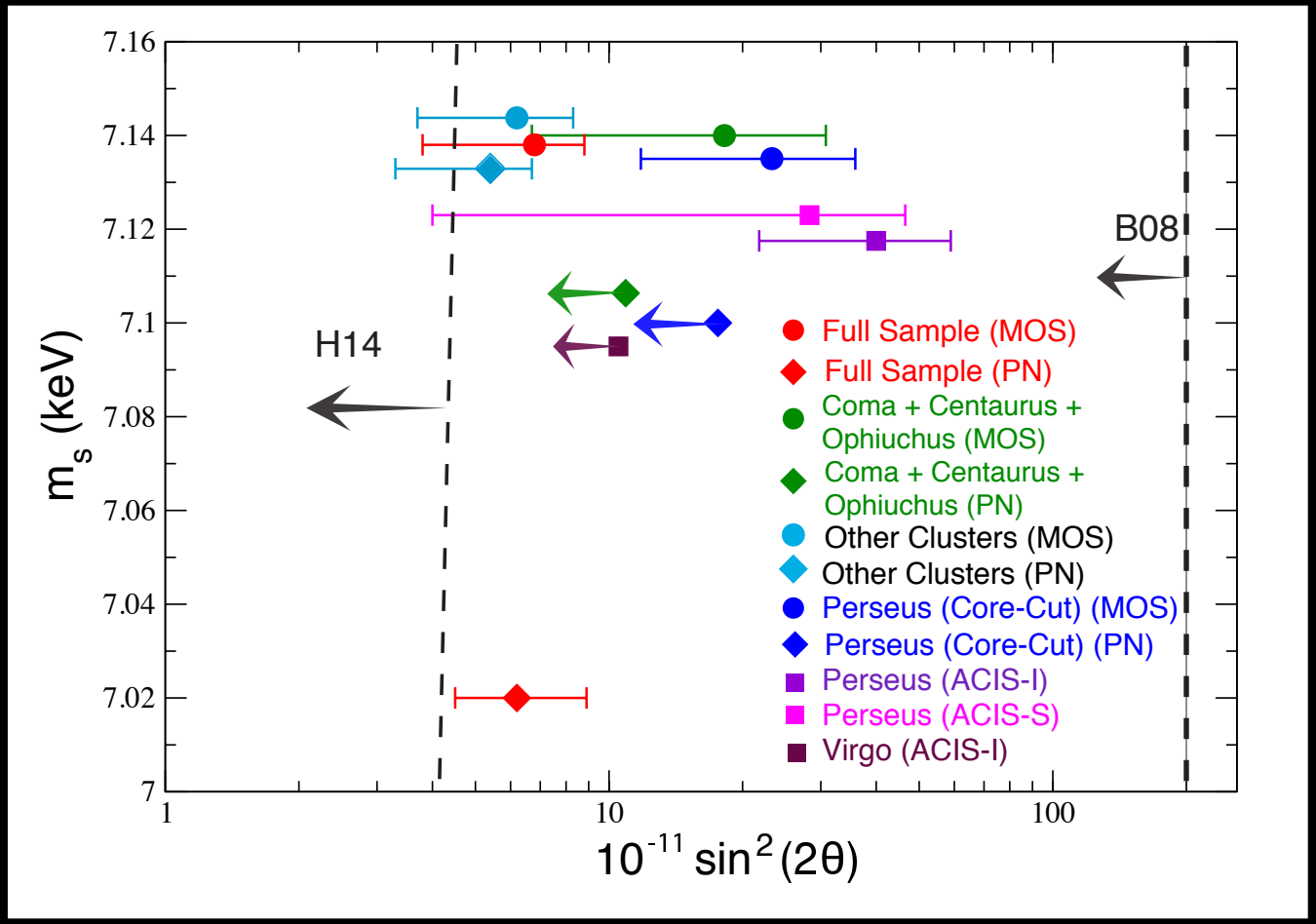


(DM signal should be spherical, but looks quadrupolar)

- this ignores the very high X-ray absorption toward GC (factor 2–3 at 3.5 keV), which may be nonuniform (and even align with the Galactic plane)

Signal from dark matter should scale with mass of the system

Decay rate from our various subsamples

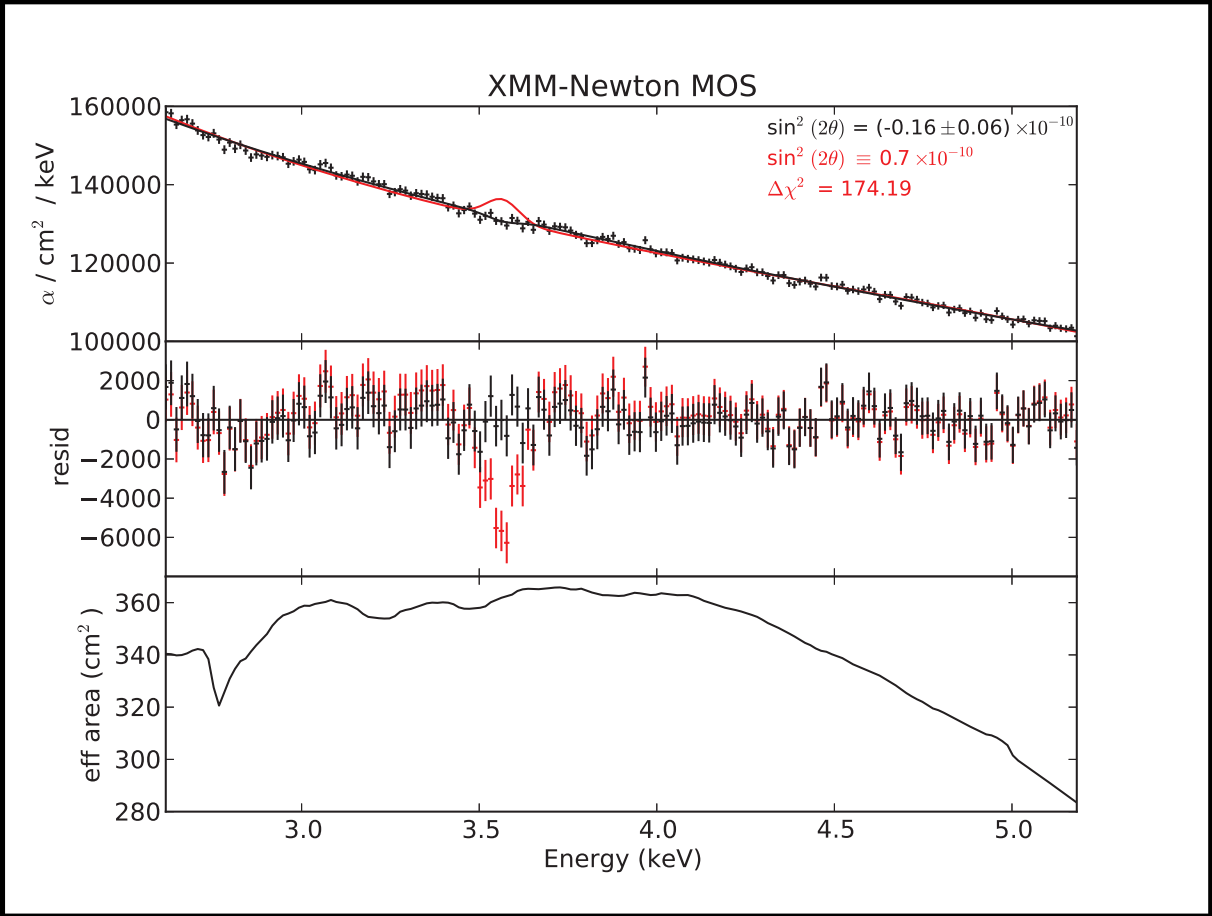


- Perseus (central region) inconsistent with others — much too bright

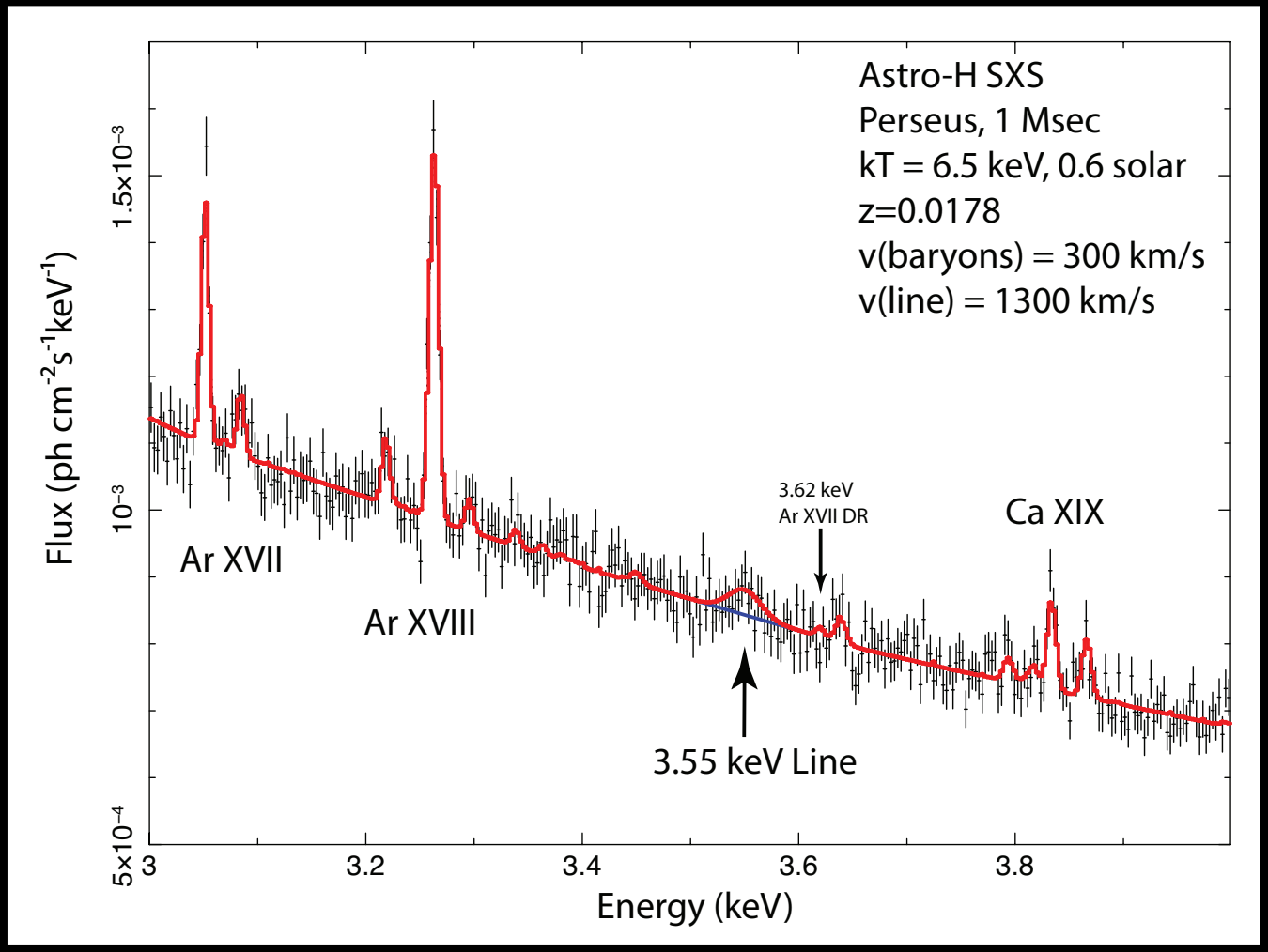
  (Ar XVII DR line >10 times brighter than expected?)

Line fluxes in our stacked clusters (ex. Perseus center), and M31, Galactic Center and Perseus outskirts (Boyarsky et al.) follow scaling for DM decay signal

Non-detection in *XMM* spectra of dwarf spheroidals (Malyshev et al. arxiv:1408.3531) inconsistent at 3σ; non-detection in spectra of galaxies, excluding their centers (Anderson et al. arxiv:1408.4115) inconsistent at 12σ:



Prediction for *Astro-H* X-ray calorimeter (to fly in January 2016)



- All contaminating lines will be easily resolved
- Dark matter line should be broadened

170+ citations to Bulbul et al., most proposing various dark matter explanations:

An X-Ray Line from eXciting Dark Matter

SIMPle Dark Matter: Self-Interactions and keV Lines

The 7 keV axion dark matter and the X-ray line signal

X-ray line signal from decaying axino warm dark matter

3.5 keV x-ray line from decaying gravitino dark matter

7 keV scalar dark matter and the anomalous extragalactic x-ray spectrum

Decaying Vector Dark Matter as an Explanation for the 3.5 keV Line

The 3.5 keV X-ray line signal from decaying moduli with low cutoff scale

Nonabelian dark matter models for 3.5 keV X-rays

Exploring X-Ray Lines as Scotogenic Signals

ν_R dark matter-philic Higgs for 3.5 keV X-ray signal

3.5-keV X-ray line from nearly-degenerate WIMP dark matter decays

X-ray Line from the Dark Transition Electric Dipole

3.5 keV X-rays as the “21 cm line” of dark atoms