Recent Updates on the 3.5 keV Line

Esra Bulbul
MIT

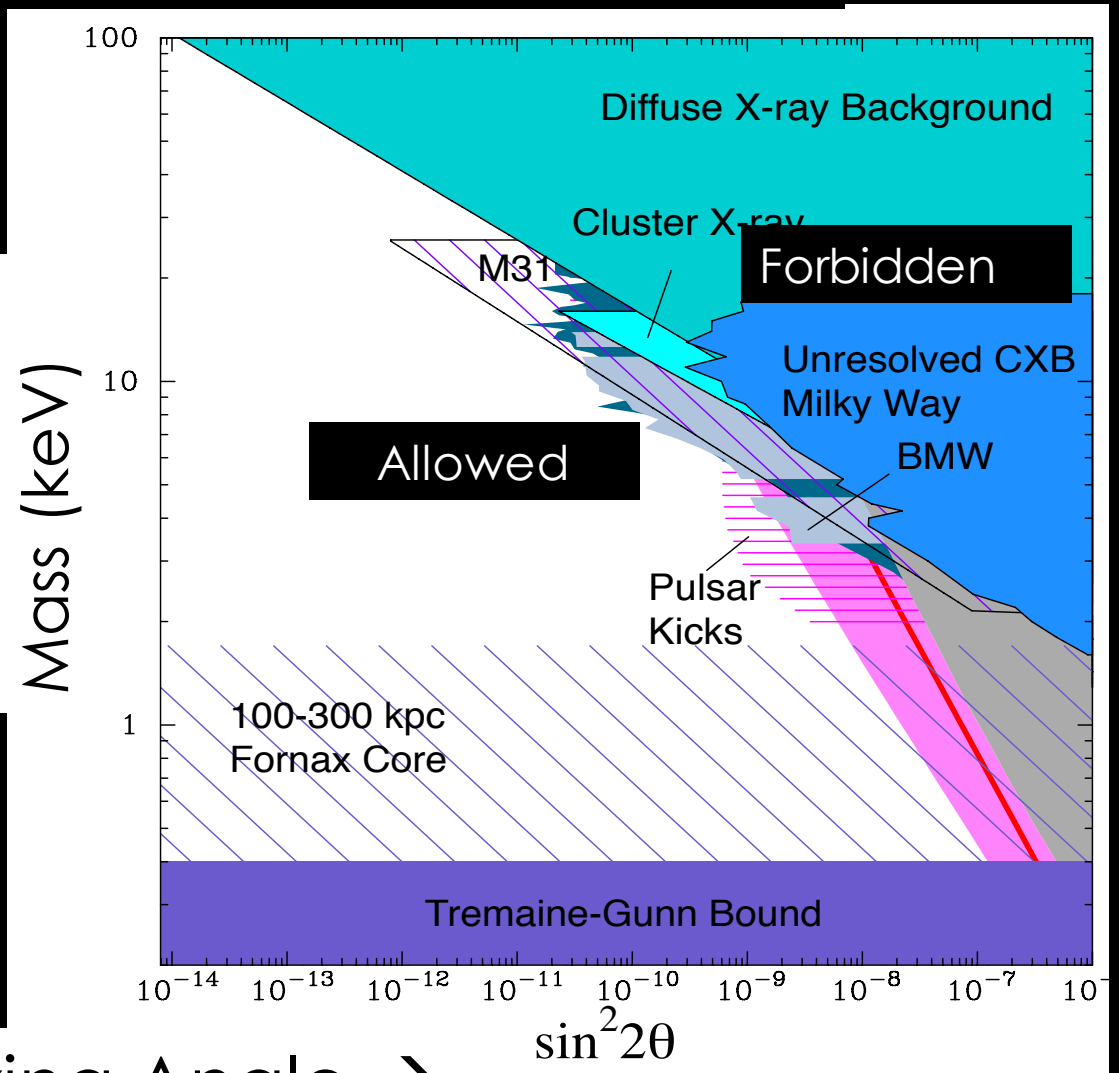
Fourth Type of Neutrino as Dark Matter

- Decay of DM particles

Decay rate

$$F_{DM} = \frac{M_{DM}}{4\pi D^2}\frac{\Gamma}{m_s}(1+z)$$

Mixing angle: $\Gamma \propto Sin^2\theta\, m_s^5$

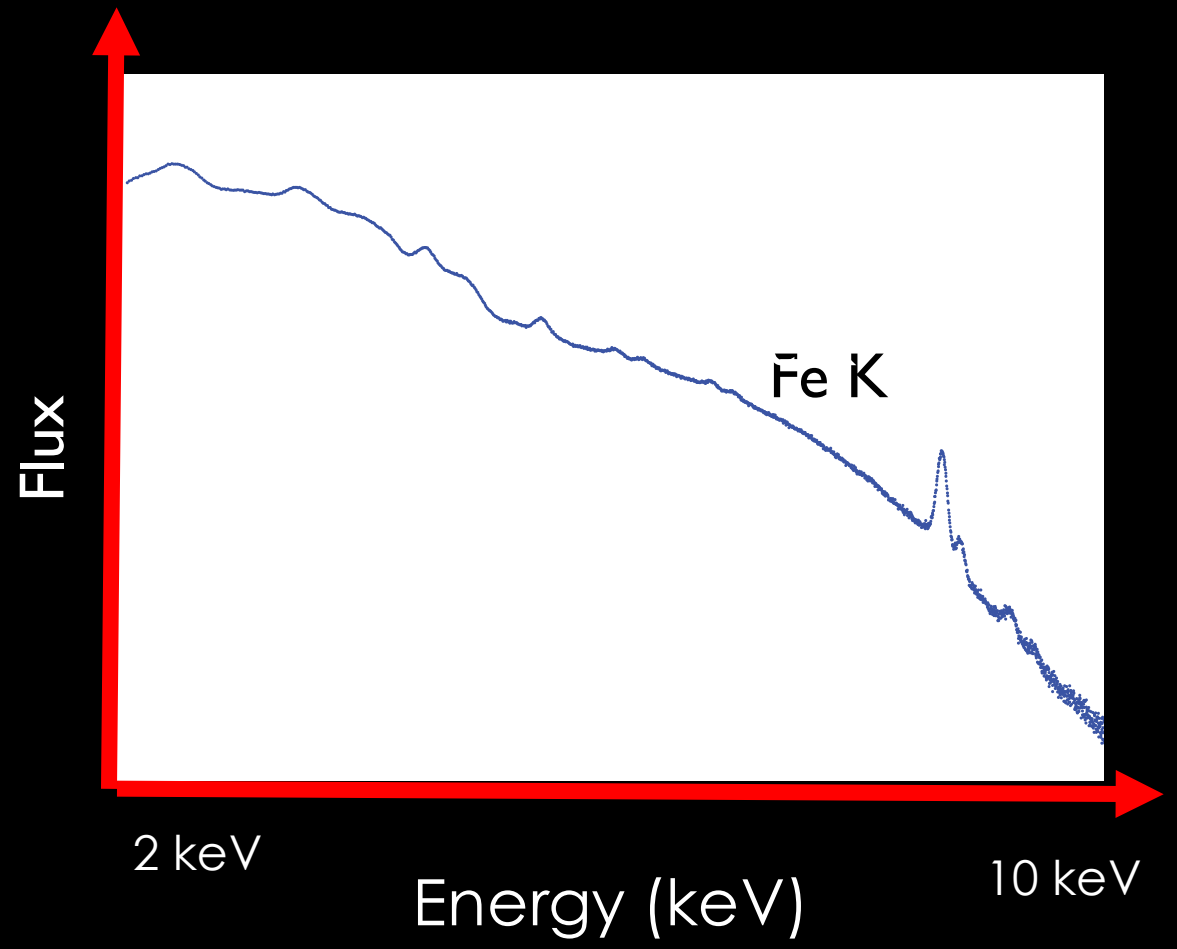


Mixing Angle →

Abazajian 2009

Galaxy Clusters: Good Targets for Dark Matter Search

- Galaxy clusters are the largest reservoirs of DM



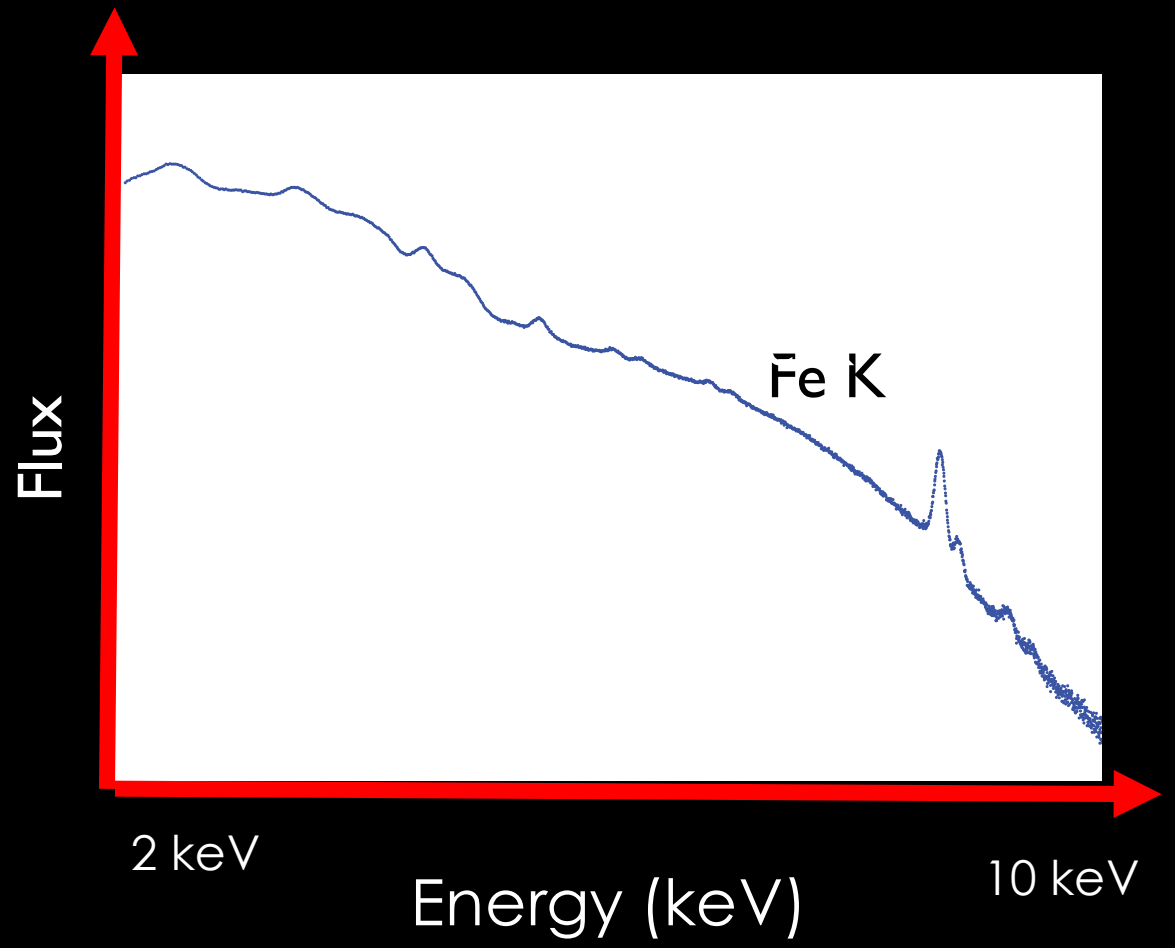
Galaxy Clusters

15% of their total mass is in baryons

Galaxy Clusters: Good Targets for Dark Matter Search

- Galaxy clusters are the largest reservoirs of DM
- Thermal Bremsstrahlung

  +atomic emission lines
- Very weak emission lines from dark matter decay



The Deepest Search in Galaxy Clusters

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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[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
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Received 2014 February 10; accepted 2014 April 28; published 2014 June 10

ABSTRACT

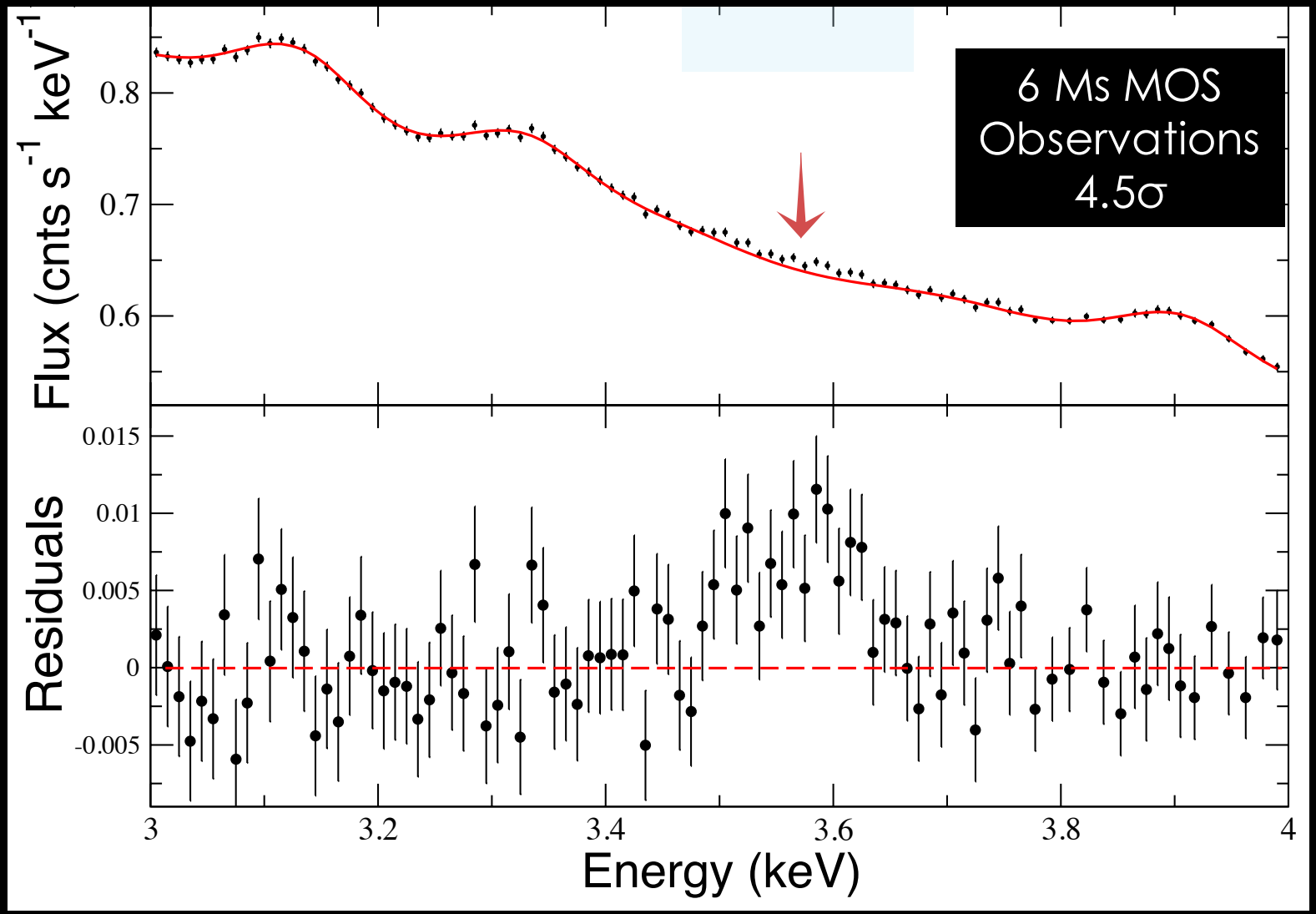
We detect a weak unidentified emission line at $E = (3.55–3.57) \pm 0.03$ keV in a stacked *XMM-Newton* spectrum of 73 galaxy clusters spanning a redshift range 0.01–0.35. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $>3\sigma$ 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. The detection is at the limit of the current instrument capabilities. We argue that there should be 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. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection corresponds to a neutrino decay rate consistent with previous upper limits. However, based on the cluster masses and distances, the line in Perseus is much brighter than expected in this model, significantly deviating from other subsamples. This appears to be because of an anomalously bright line at $E = 3.62$ keV in Perseus, which could be an Ar XVII dielectronic recombination line, although its emissivity would have to be 30 times the expected value and physically difficult to understand. Another alternative is the above anomaly in the Ar line combined with the nearby 3.51 keV K line also exceeding expectation by a factor of 10–20. Confirmation with *Astro-H* will be critical to determine the nature of this new line.

Key words: dark matter – elementary particles – line: identification – neutrinos – X-rays: galaxies: clusters

Online-only material: color figures

- Stacked clusters at their rest frame
- Smeared non-source signal
- Analysis is sensitive to weak lines

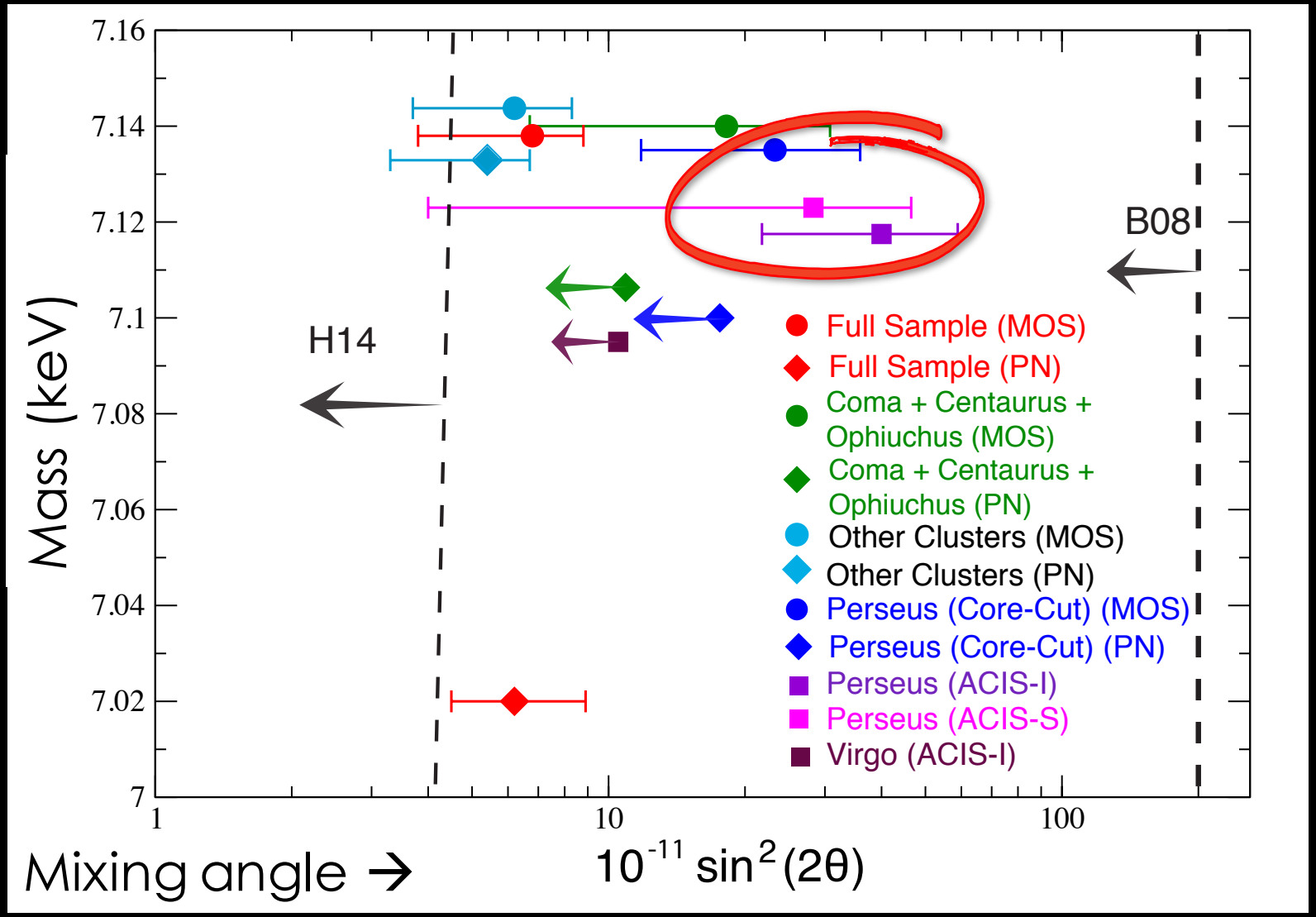
An Unidentified Emission Line is Discovered



No Line Added

Bulbul+2014

Comparison of Perseus with Others



Perseus is anomalously bright!

Testing for Decaying Dark Matter

Detections (≥3σ)

1- Perseus Cluster – too bright
(Bulbul+2014a, Urban+2015, Franse+2016)

2- Stacked clusters (Bulbul+2014a) ✓

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

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

5- M31 (Boyarsky+2014) ✓

6- NuSTAR Galactic Halo (Neronov+2016) ✓

7- NuSTAR Bullet Cluster (Wik+2014) ✓

8- Chandra Galactic Halo Observations
(Cappelluti +2017) ✓

Non- Detections (≥ 3σ)

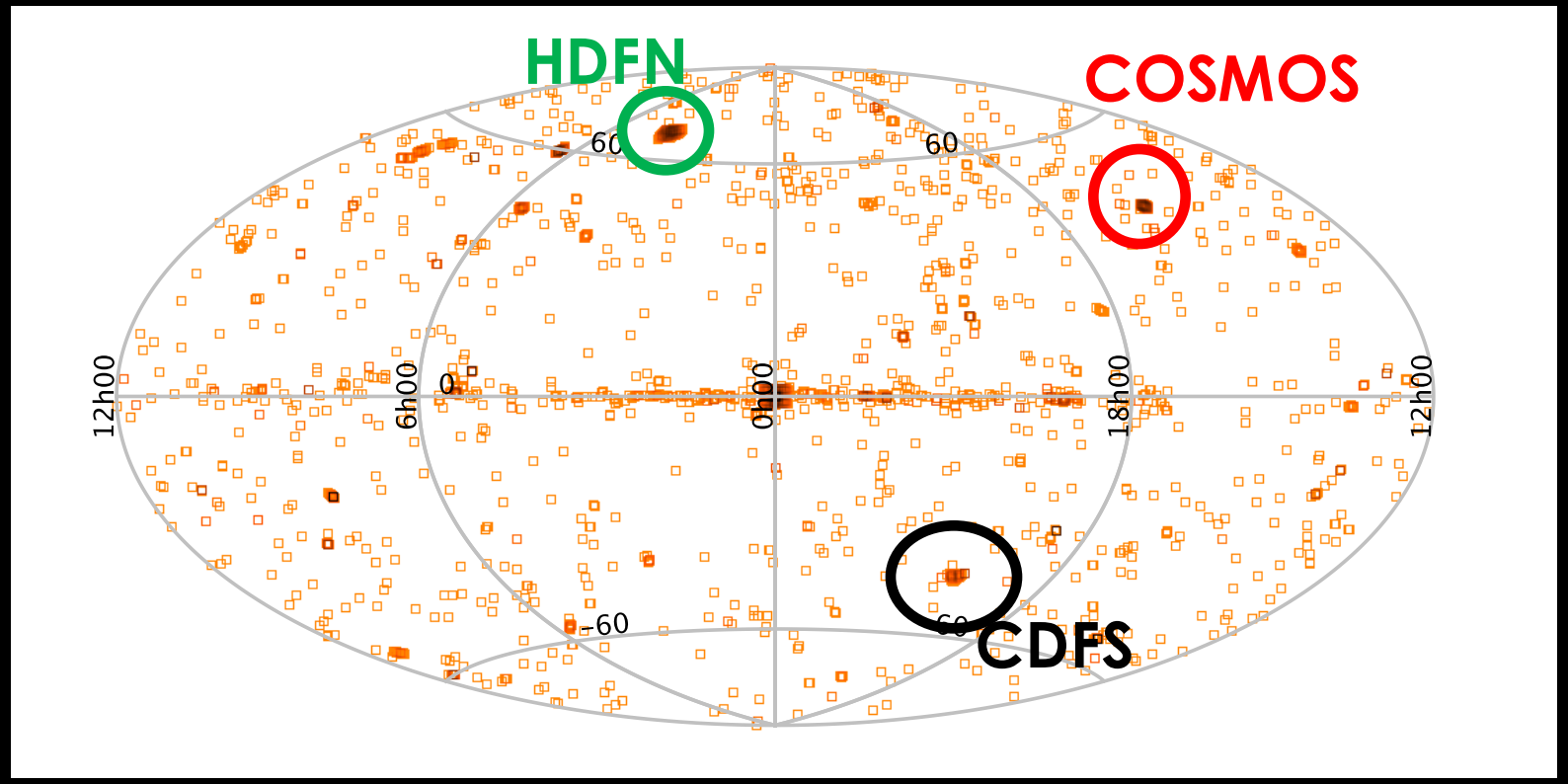
1- Virgo Cluster
(Bulbul+2014a) consistent ✓

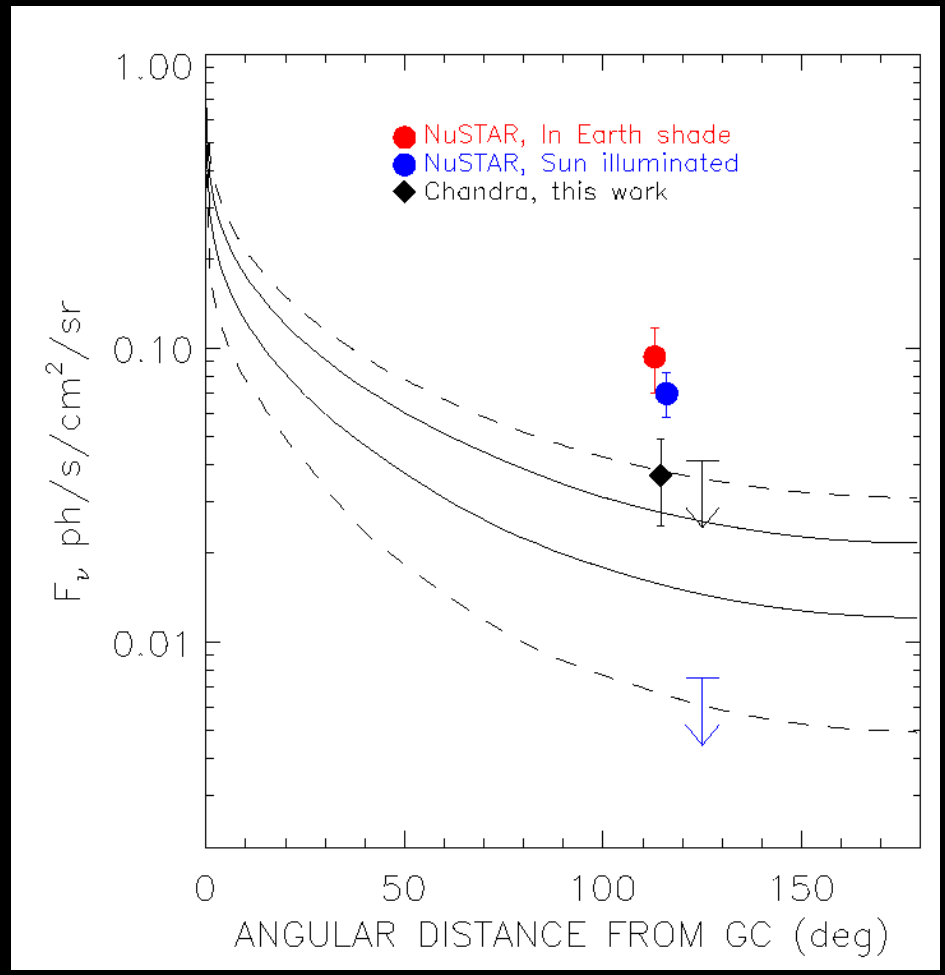
2- Coma, Ophiuchus (Suzaku)
(Urban+2015) consistent ✓

3- Stacked galaxies
(Anderson+2015) inconsistent!

4- Perseus Cluster
(Hitomi Collaboration) ✓

Detection in the 10Ms Chandra Fields

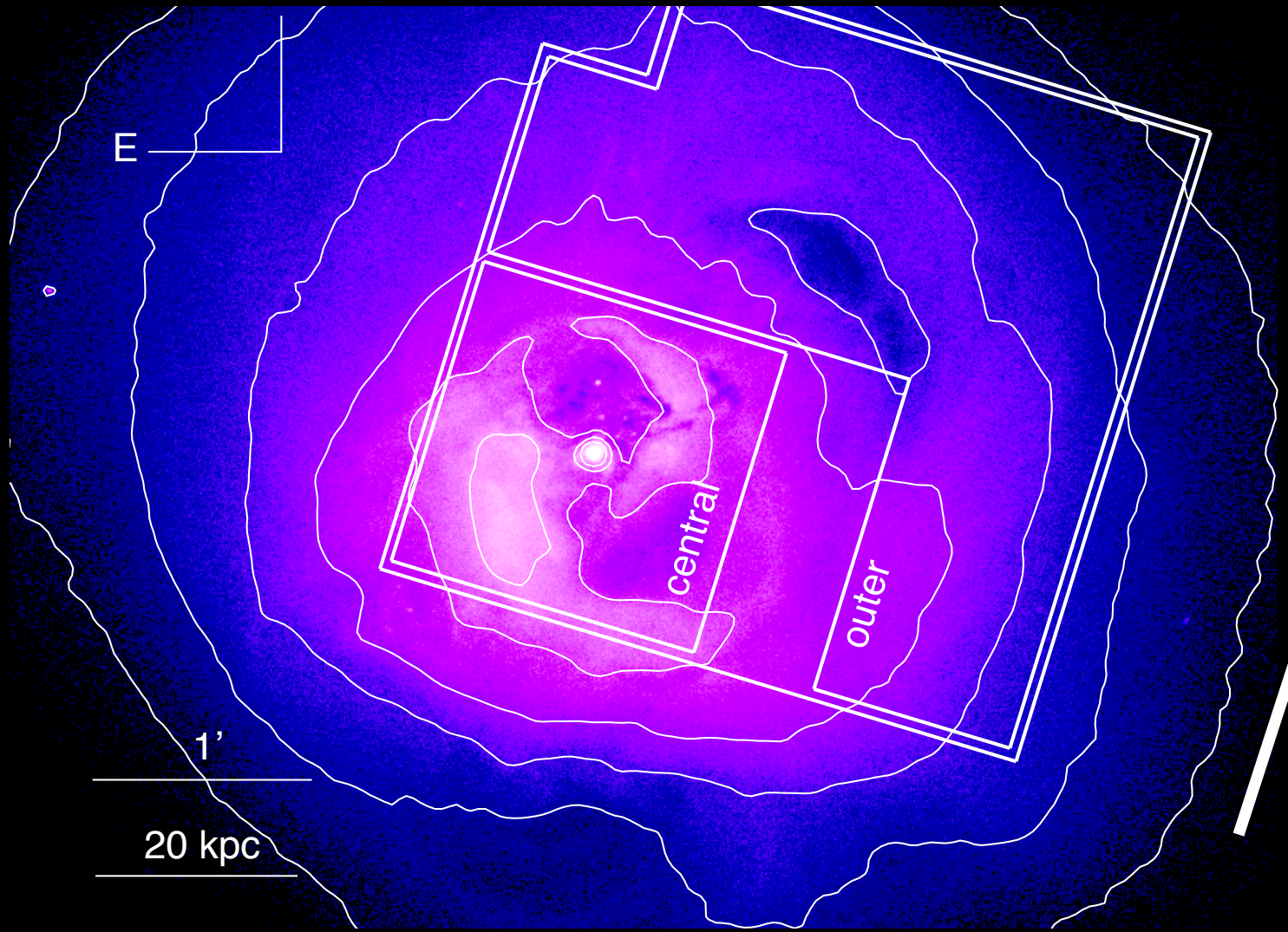




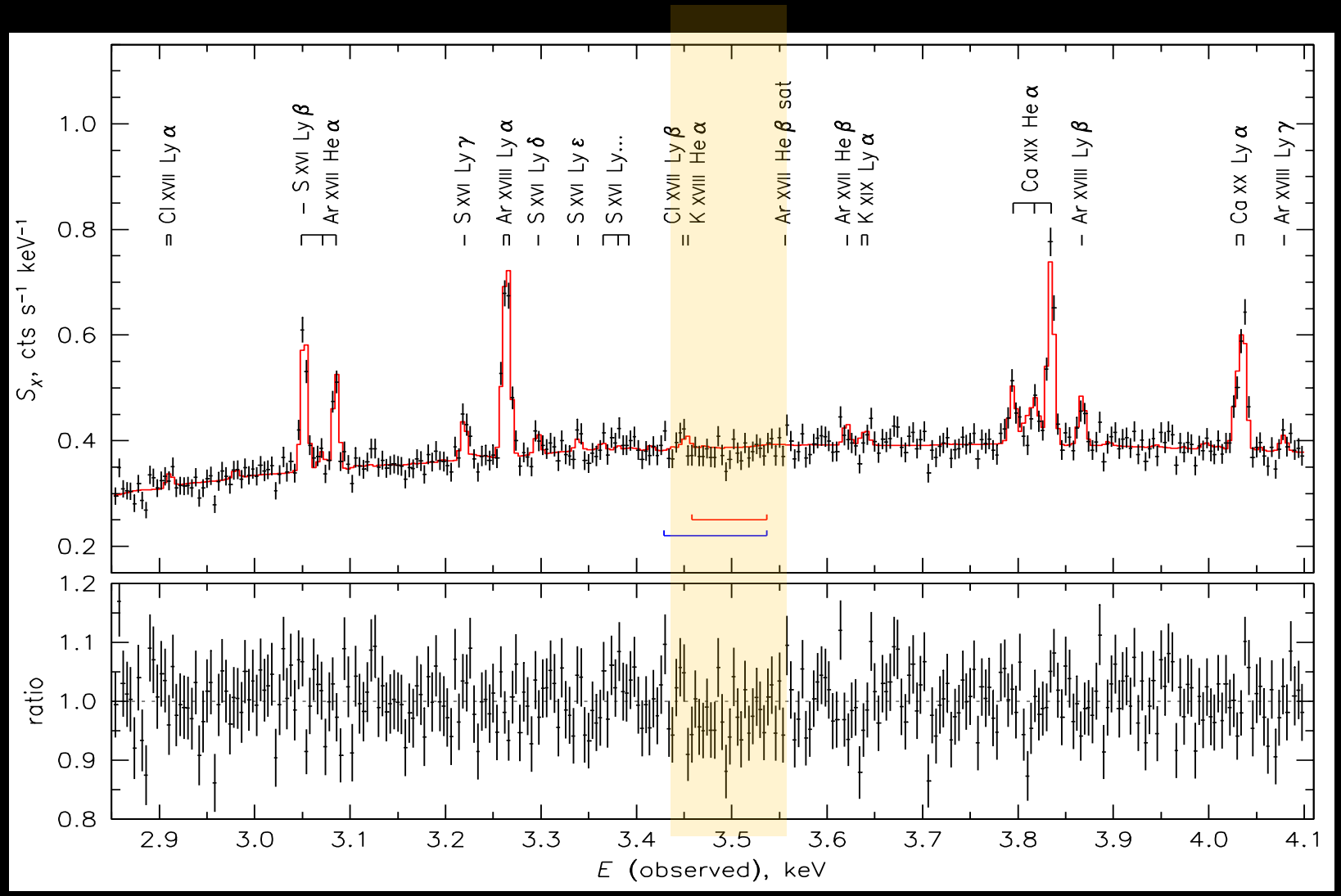
Cappelluti+2017

Hitomi Observations of the Perseus Cluster (200ks)

7% of the time required for the detection of the 3.5 keV line

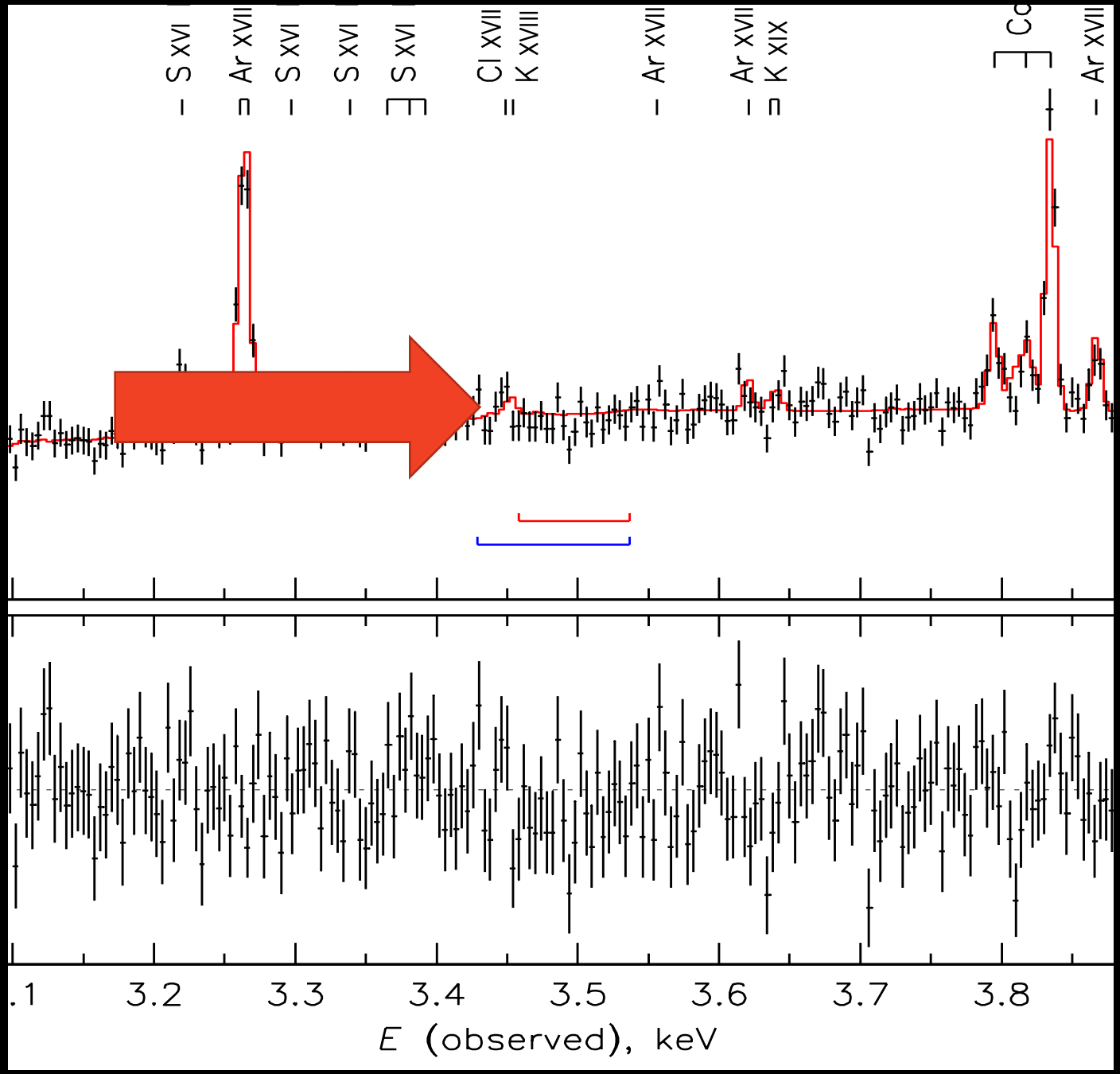


Hitomi 3-4 keV Band



- Broad instrumental dip near 3.5 keV
- Potassium is sub-solar

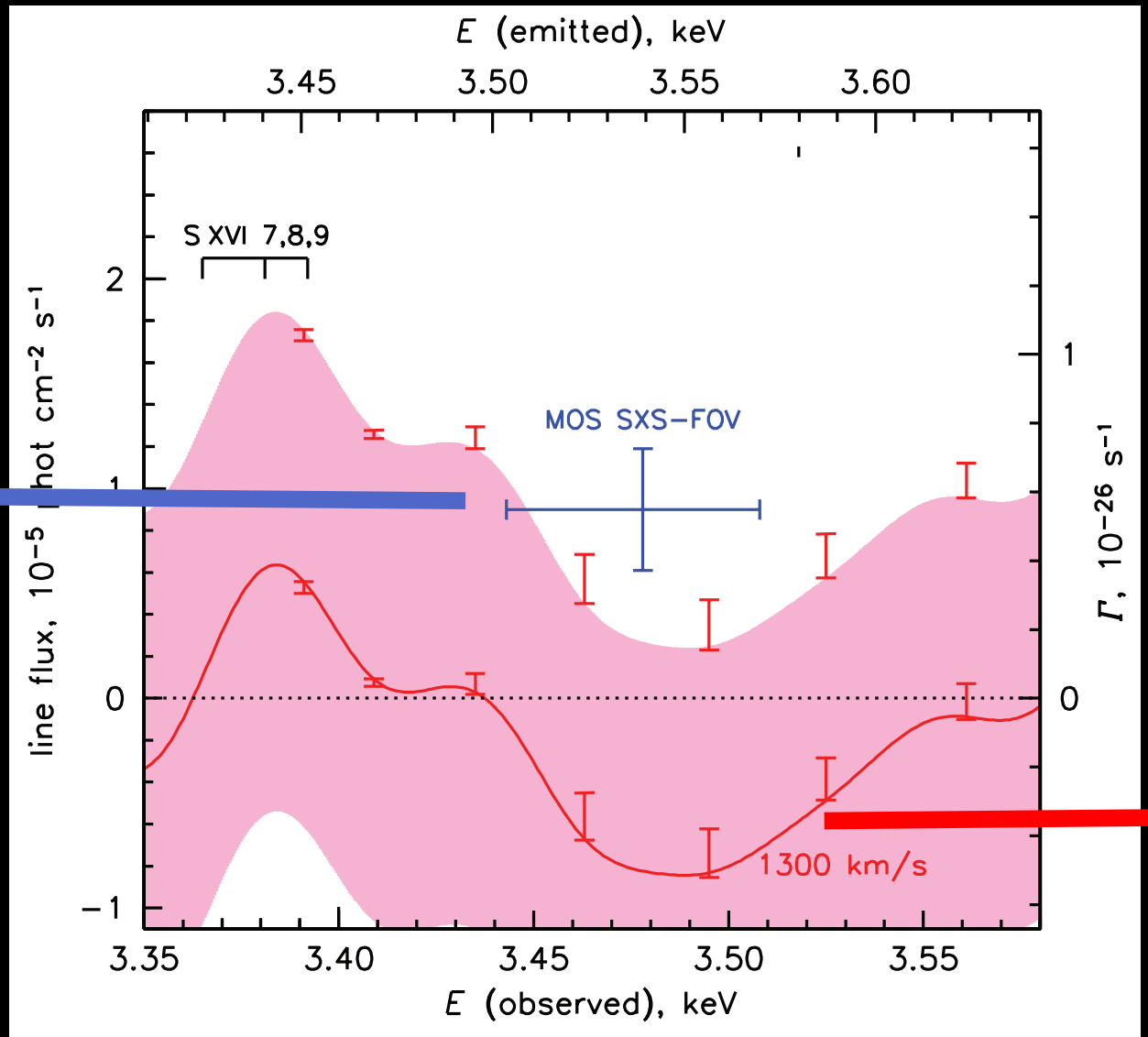
Hitomi Collaboration, 2017


S XVI
Ar XVIII
S XVI
S XVI
S XVI
Cl XVII
K XVIII
Ar XVIII
Ar XVIII
K XIX
Ar XVIII
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
E (observed), keV

Hitomi Constraints on the 3.5 keV Line

Hitomi Collaboration, 2017

XMM-Newton Detection in the Hitomi FOV



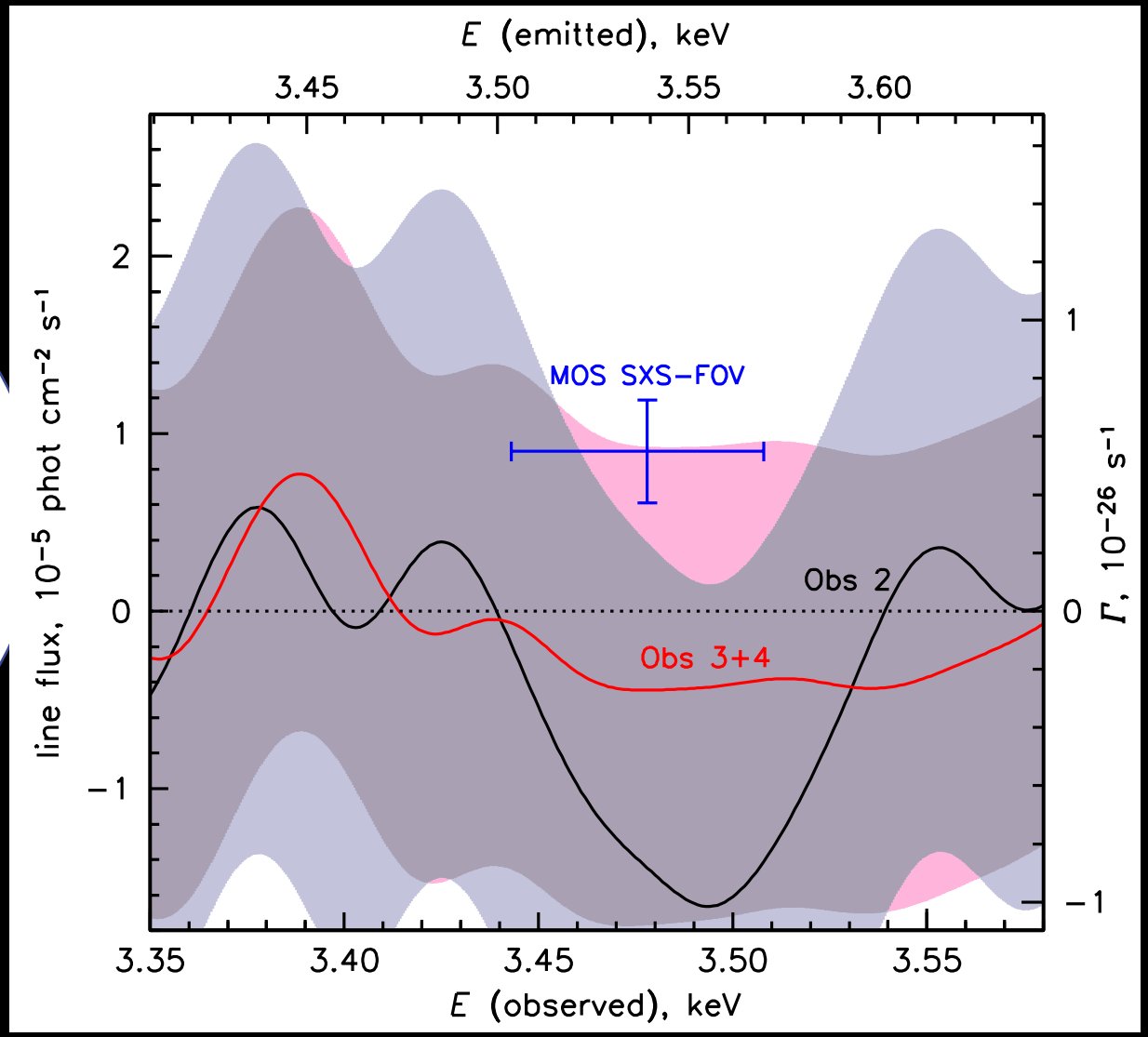
Best-fit DM line

Dividing the Hitomi Observations

Obs 2

Obs 3+4

are a week apart



Hitomi Collaboration, 2017

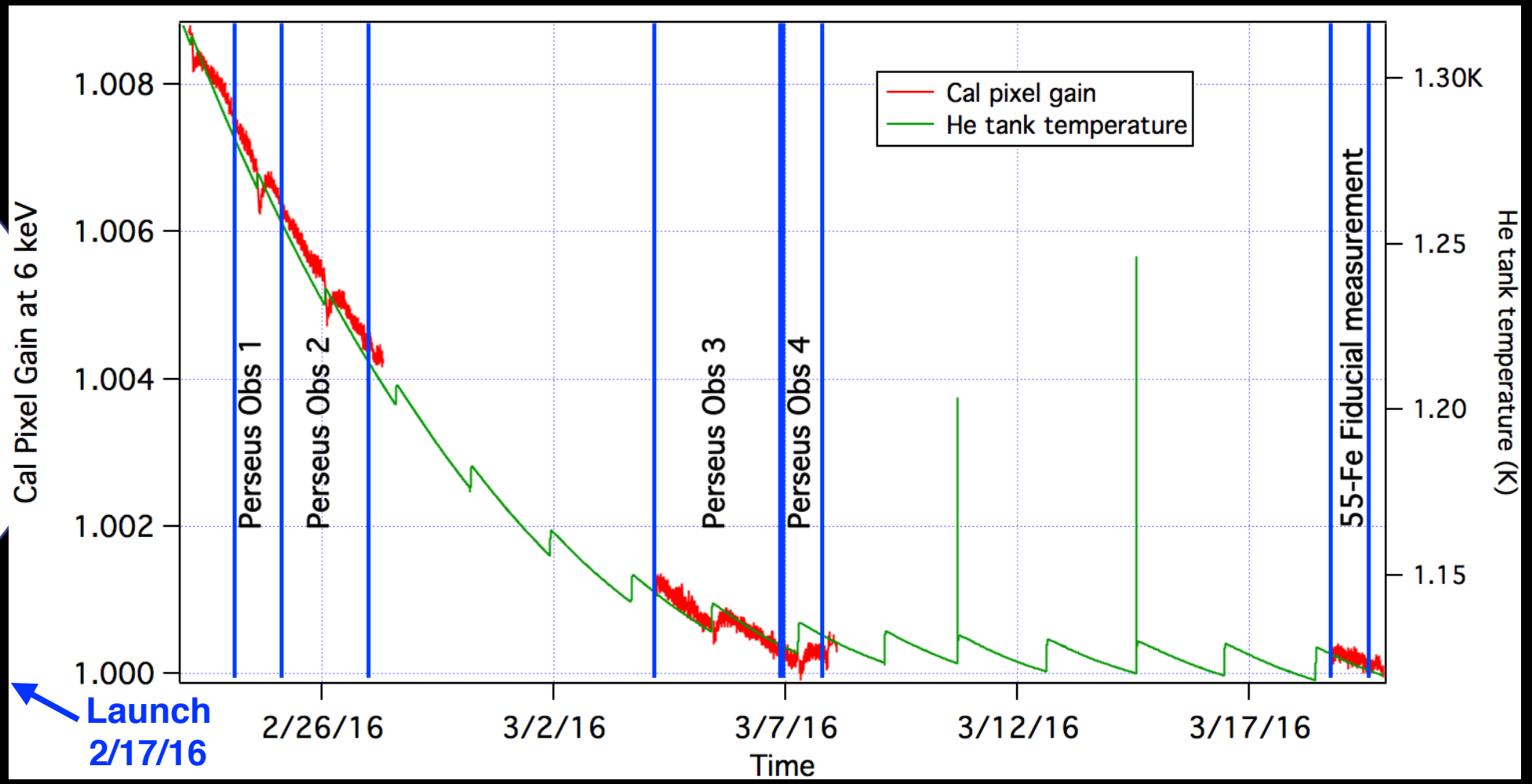
Broad Instrumental Dip in Observation 2

Obs 2

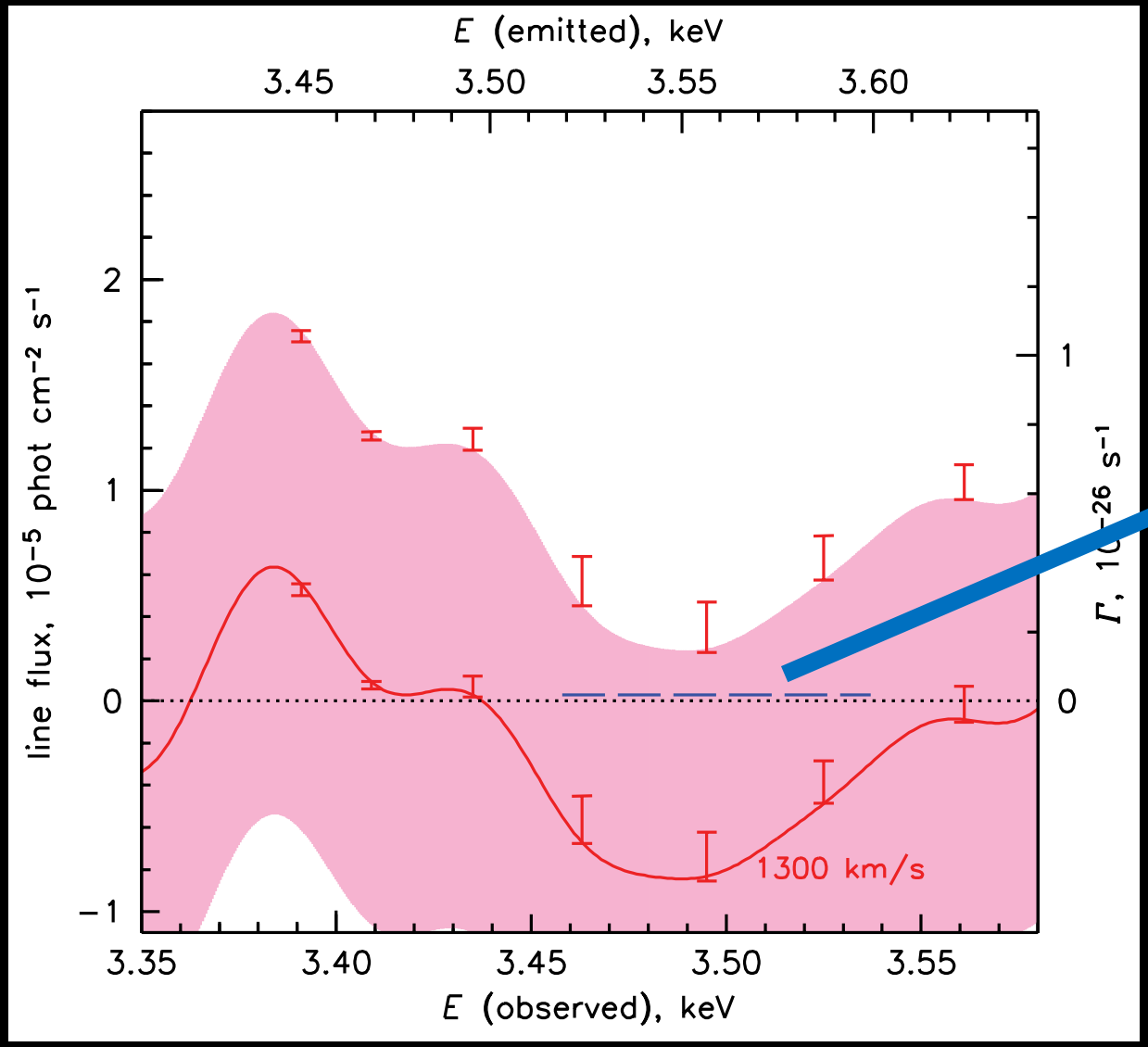
Obs 3+4

are a week

apart



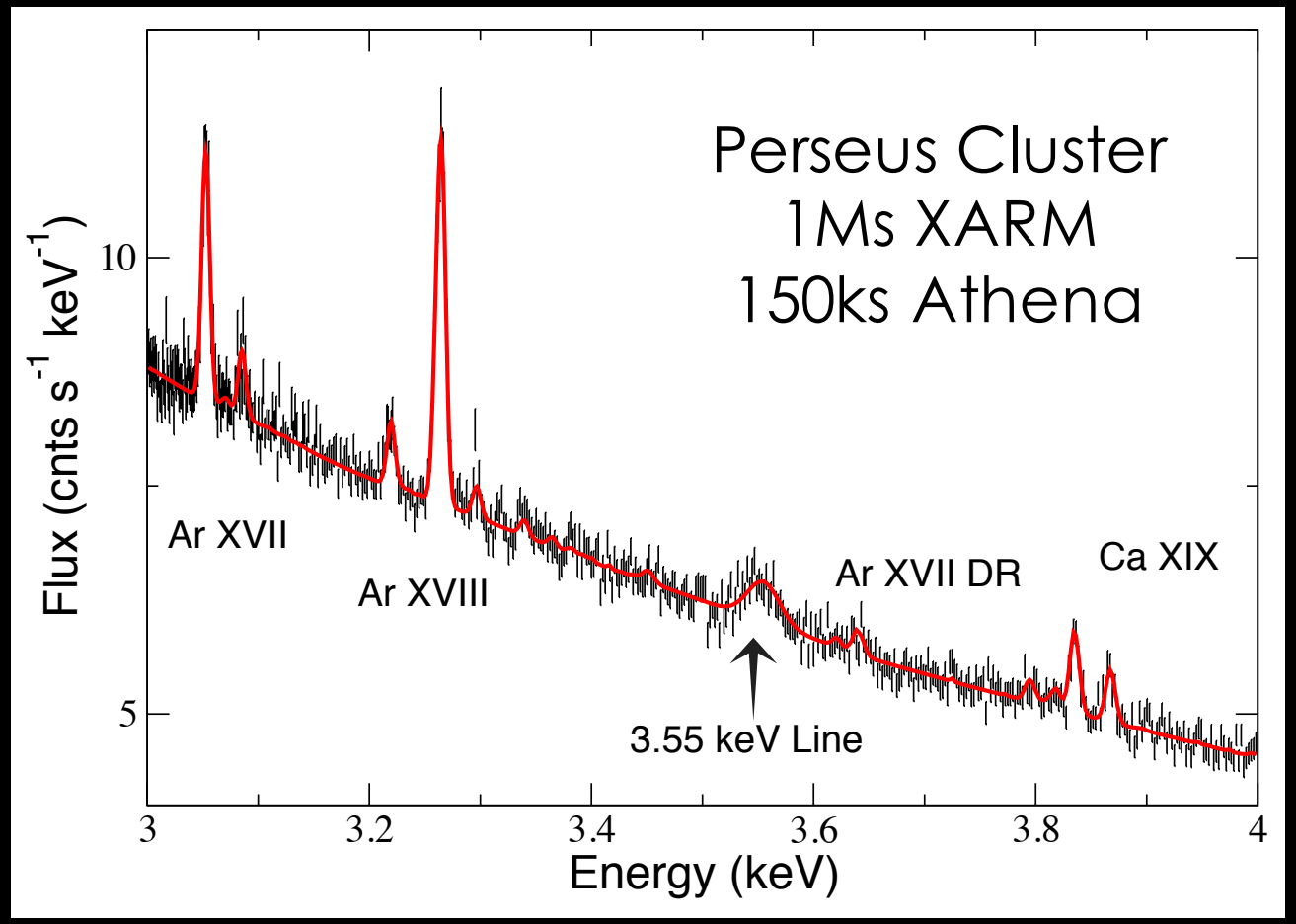
Hitomi Constraints are Consistent!



3.5 keV line flux from a sample excluding Perseus

Hitomi Collaboration, 2017

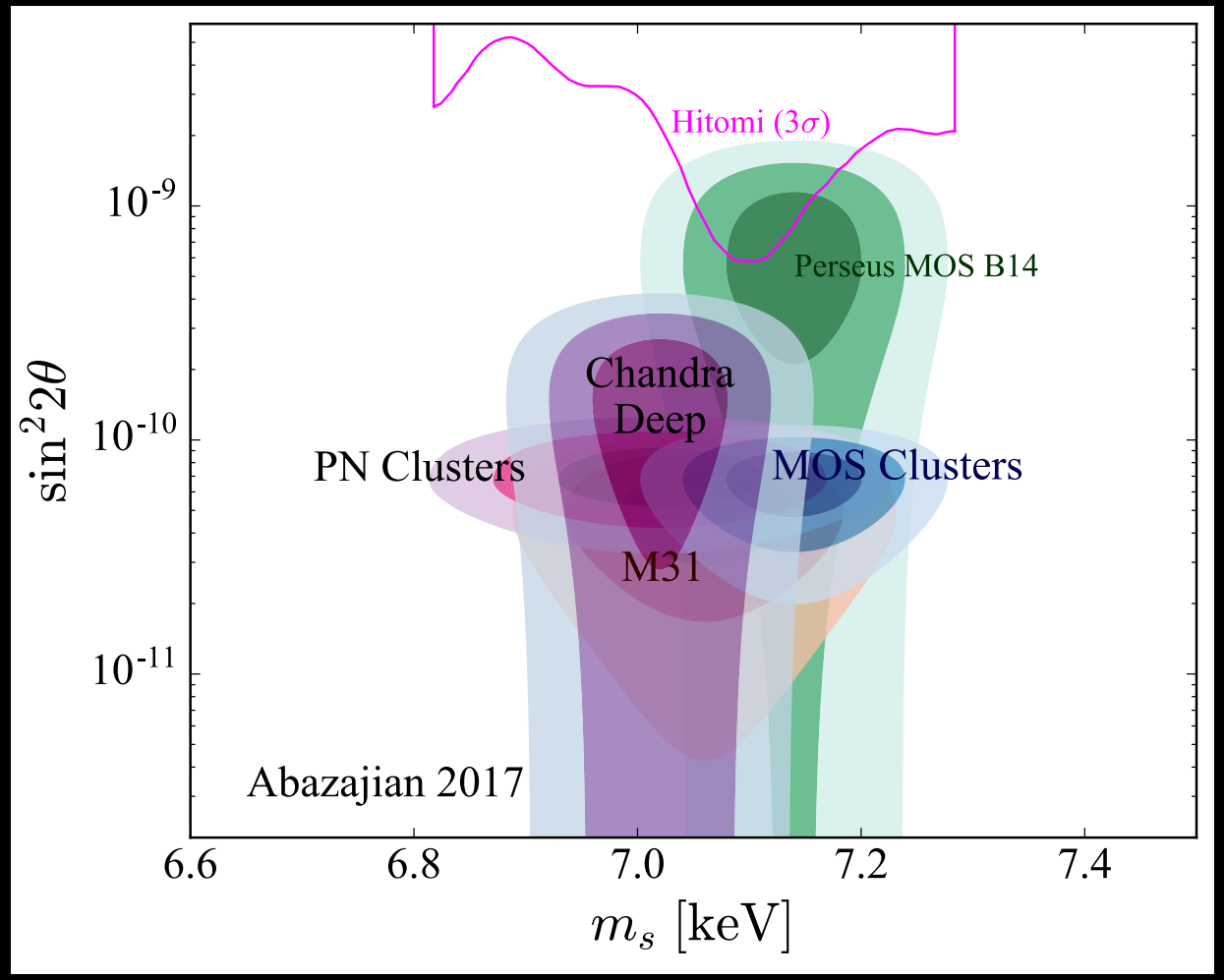
What is Next for Warm Dark Matter Searches in the X-ray Band?



- XARM/Athena XIFU Observations to test the 3.5 keV line in clusters
- See Ranjan Laha's talk for testing the Galactic Center signal with Micro-X

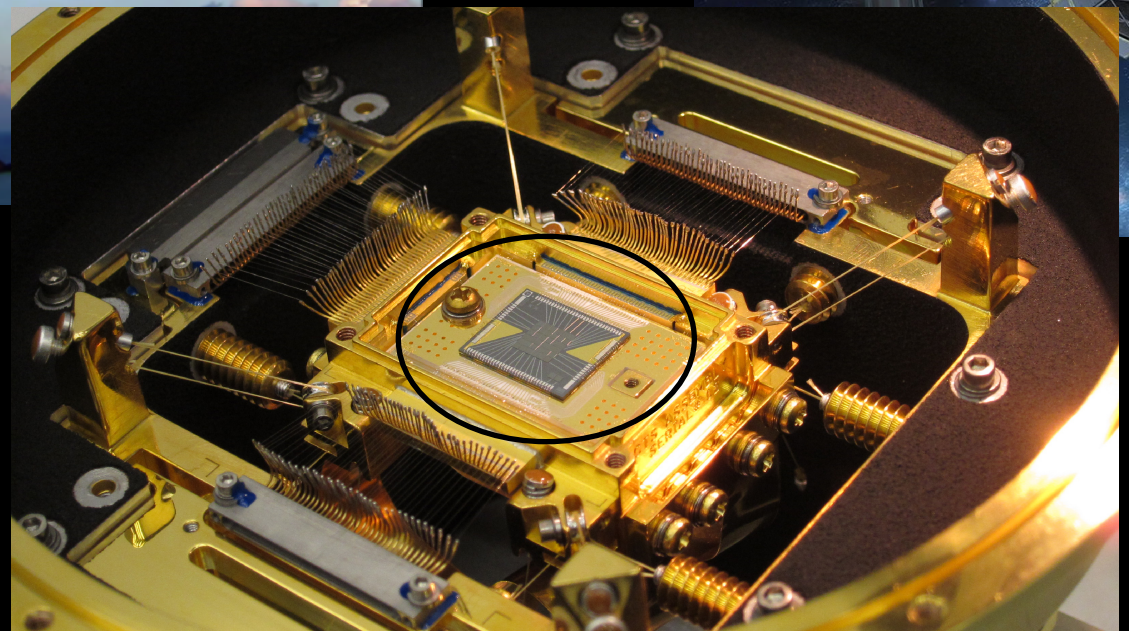
Summary

- Most of the astrophysical including potassium has been eliminated
- Upper limits provided by the Hitomi observations are consistent with decaying dark matter model



Abazajian 2017

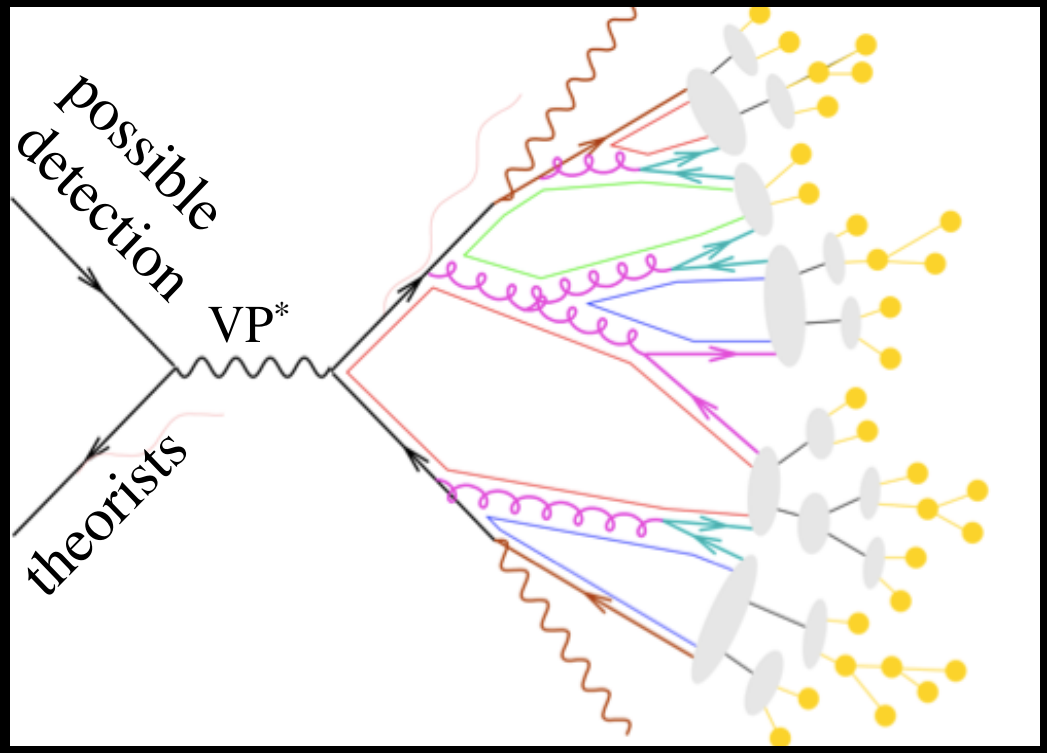
Hitomi (Launched 2/17/2016)



Spectrometer (calorimeter) has 20 times better resolution!

Origin

- No known plausible atomic lines at this energy!
- Astrophysical Origin (K XVIII, Ar XVII DR, charge exchange)
- Simple decaying Dark Matter
- Others ALPs, fluorescent DM, XDM



> 300 Citation since published

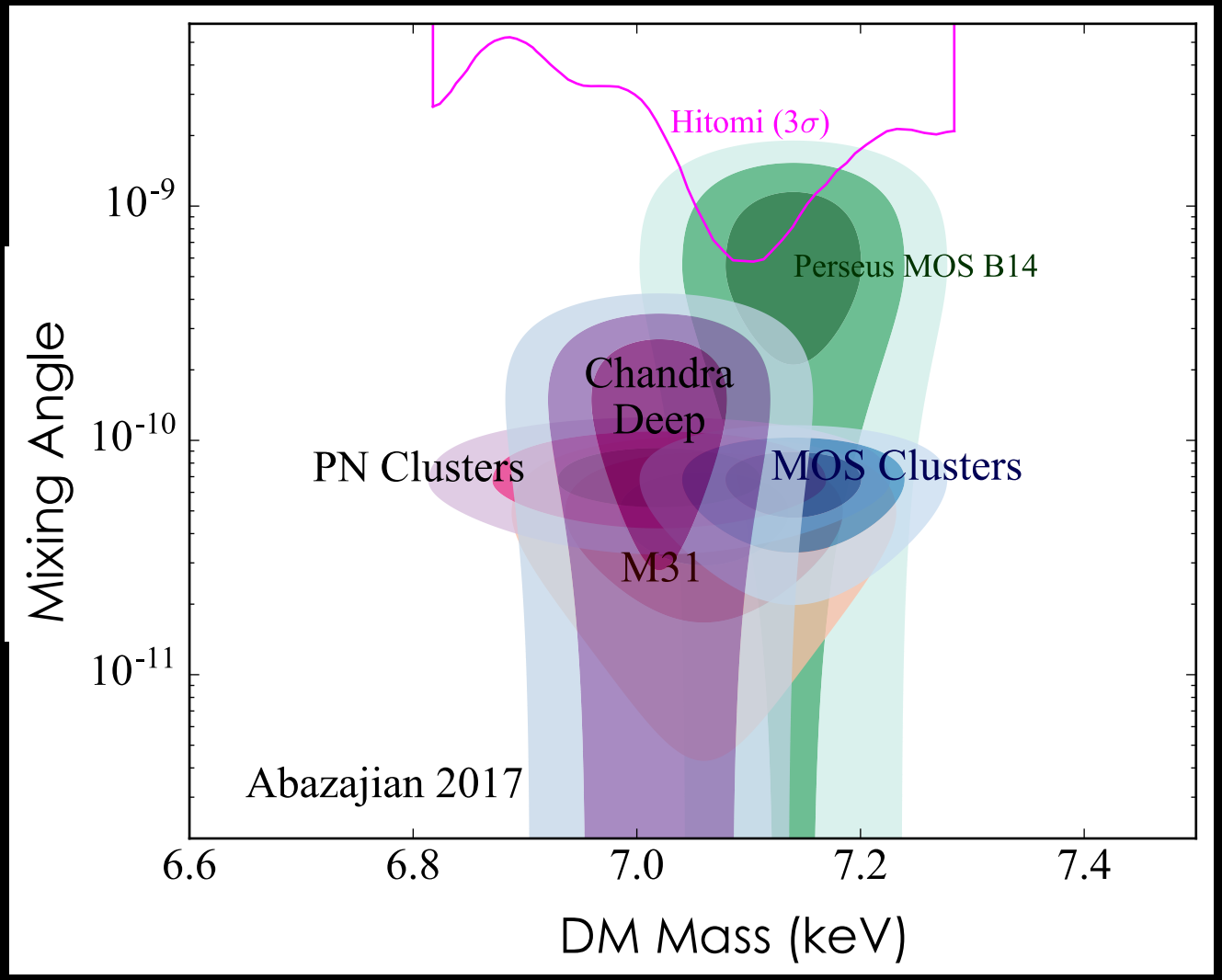
Hitomi Constraints are Consistent!

Stacked Clusters

M31

Perseus XMM

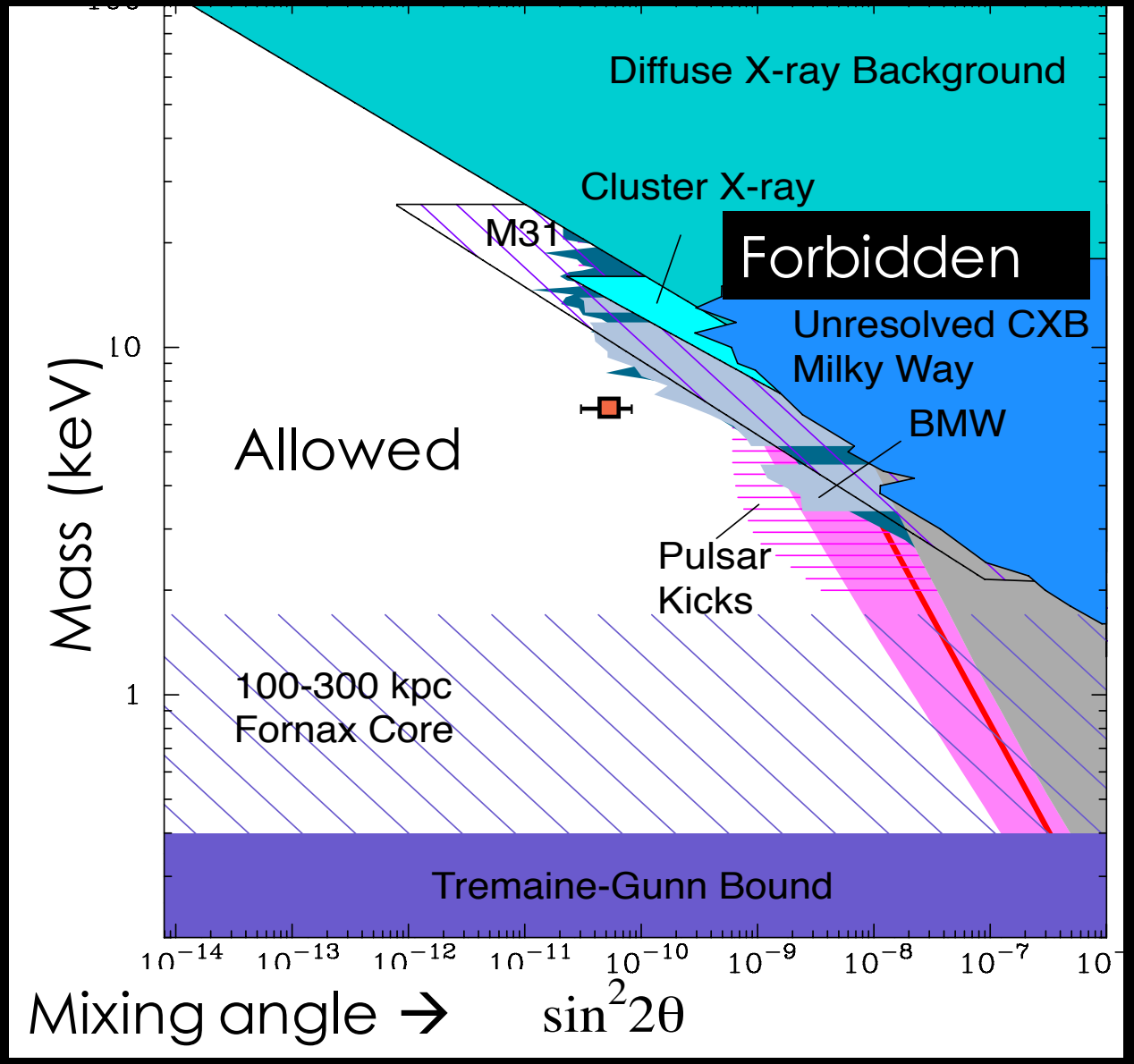
Chandra Deep Fields



3σ Constraints From Hitomi

Abazajian 2017

Comparison with Upper Limits in the Literature



Abazajian 2009

Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla Jeltema[1⋆] and Stefano Profumo[1†]
[1]*Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*

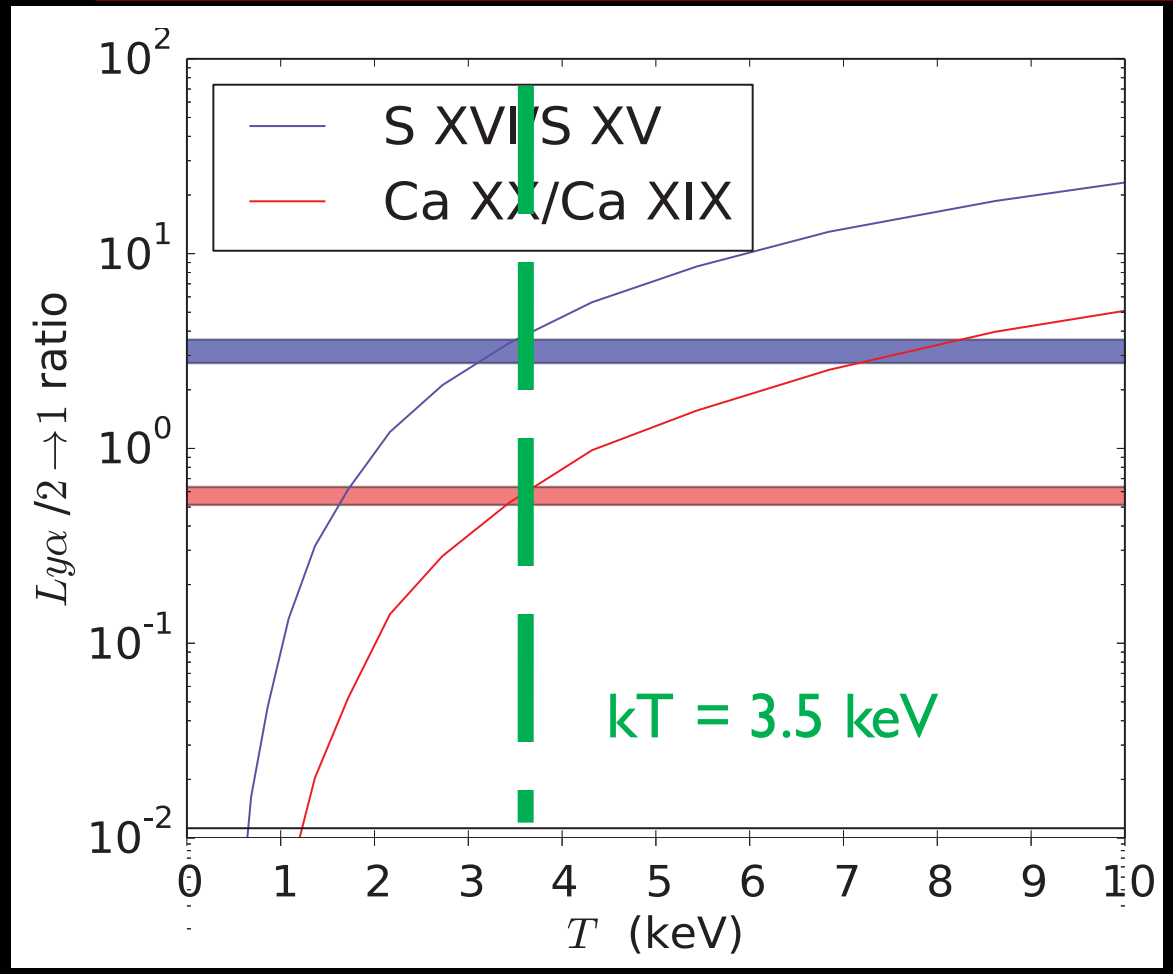
Claims:

- Various line ratios indicate wide and inconsistent plasma temperatures
- can't restrict the temperature range and use other lines to predict the K XVIII flux
- there may be a very cool component which will produce a much brighter K line
- Possible contribution of Cl XVII at 3.51 keV not included

COMMENT ON "DARK MATTER SEARCHES GOING BANANAS: THE CONTRIBUTION OF POTASSIUM (AND CHLORINE) TO THE 3.5 KEV LINE"

Esra Bulbul (1), Maxim Markevitch (2), Adam R. Foster (1), Randall K. Smith (1), Michael Loewenstein (2), Scott W. Randall (1)
(1) Harvard-Smithsonian Center for Astrophysics, (2) NASA/GSFC

Draft version September 16, 2014



- The line ratio temperatures in JP are inconsistent because JP used incorrect atomic data — in fact, different ratios are in agreement.

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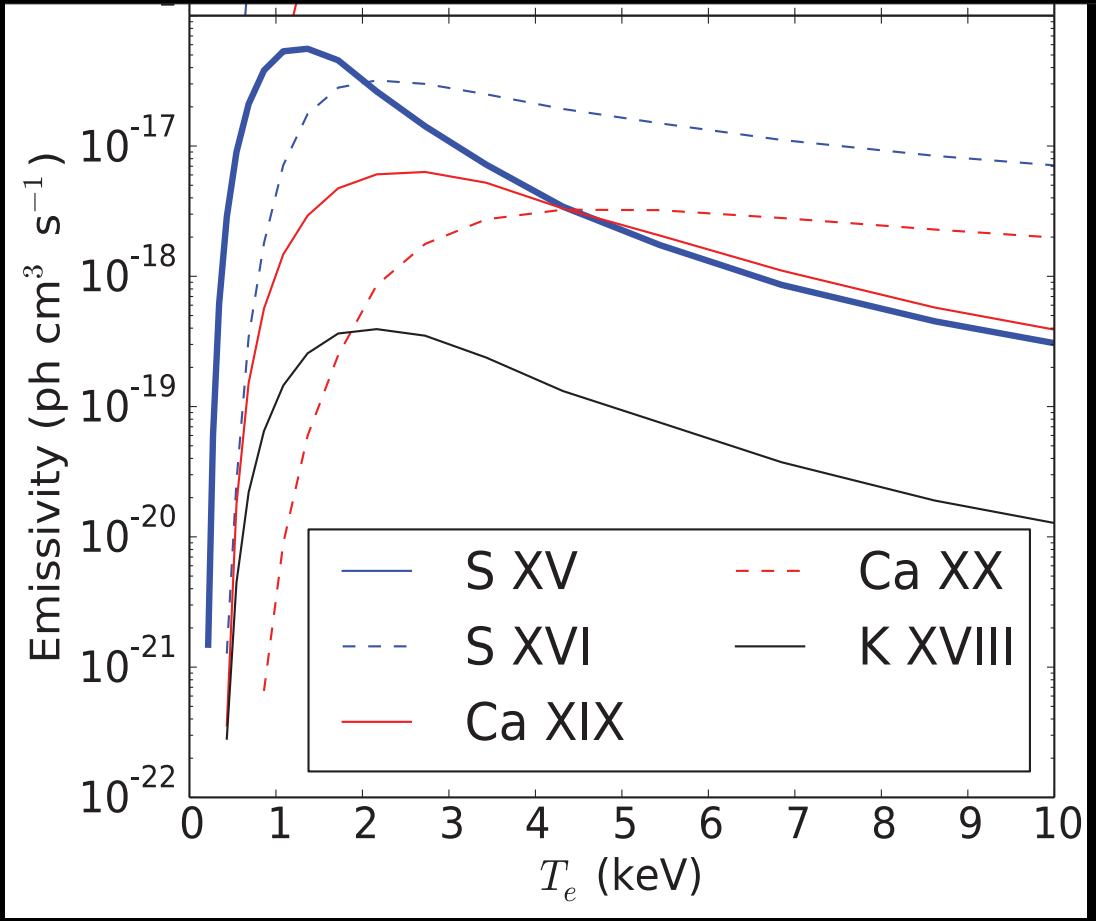

- S XV peaks at $T \sim 1$ keV.
- The S line ratio indicates absence of significant quantities of such gas even in the Perseus cool core (as well as in other subsamples).

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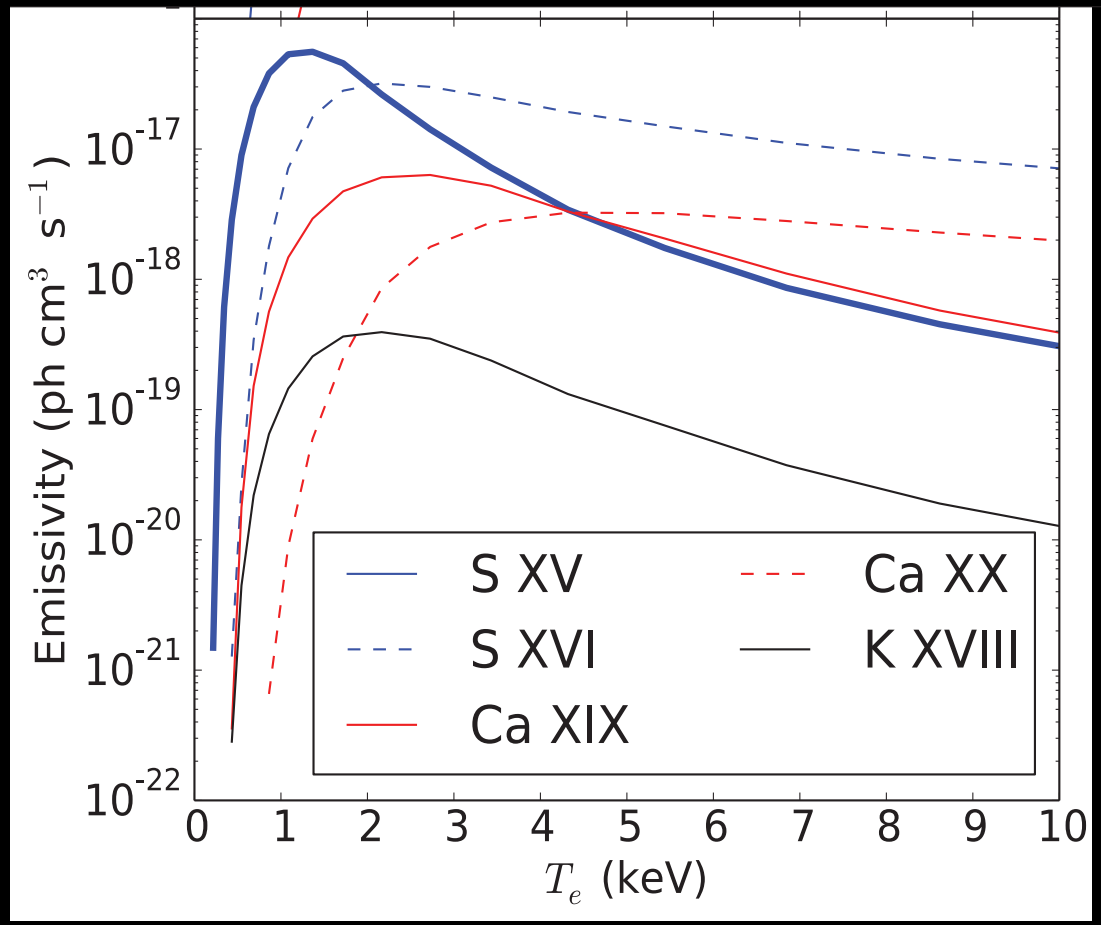


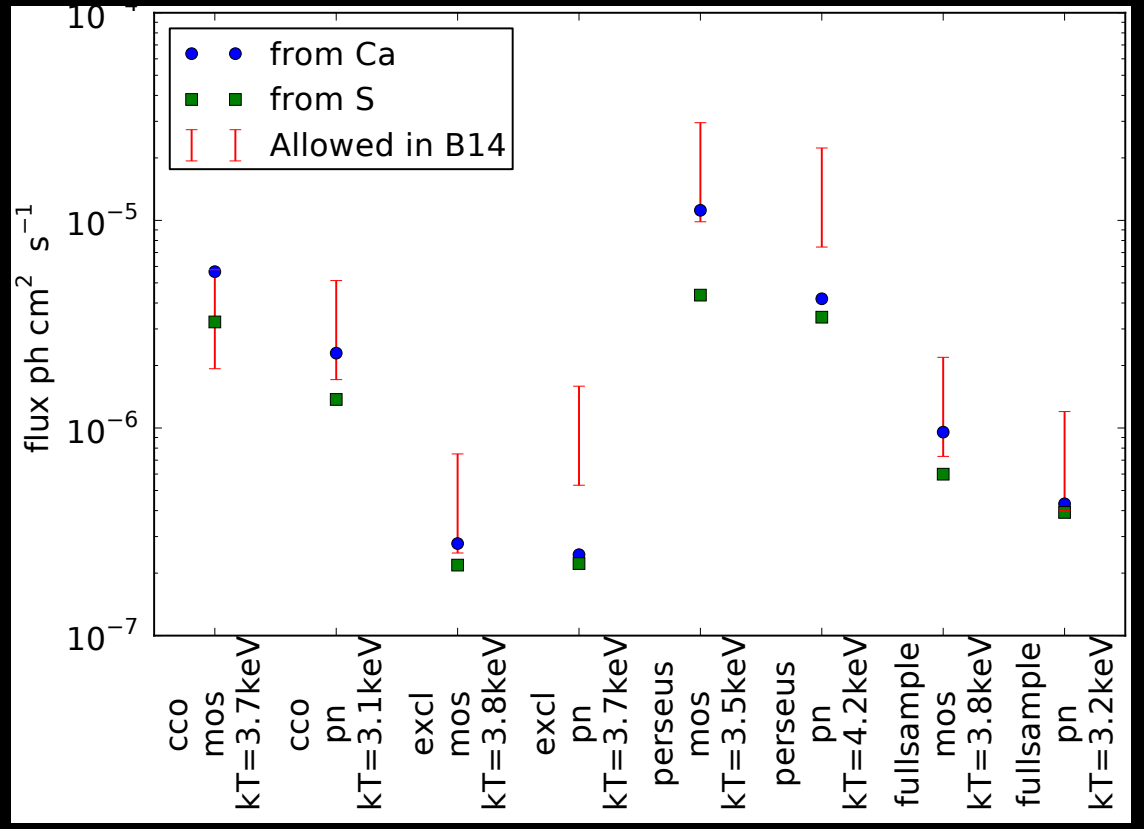
- S XV peaks at $T \sim 1$ keV.
- The S line ratio indicates absence of significant quantities of such gas even in the Perseus cool core (as well as in other subsamples).
- Six times brighter Cl XVII Ly-σ at 2.96 keV was not detected

Discovery of a 3.5 keV line in the Galactic Center and a Critical Look at the Origin of the Line Across Astronomical Targets

Tesla Jeltema[1⋆] and Stefano Profumo[1†]
[1]*Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*

- Claim: Ca Line ratios indicate ~1 keV plasma?

- A further mistake in the Ca line ratio to temperature conversion in v2 of the J&P paper ...



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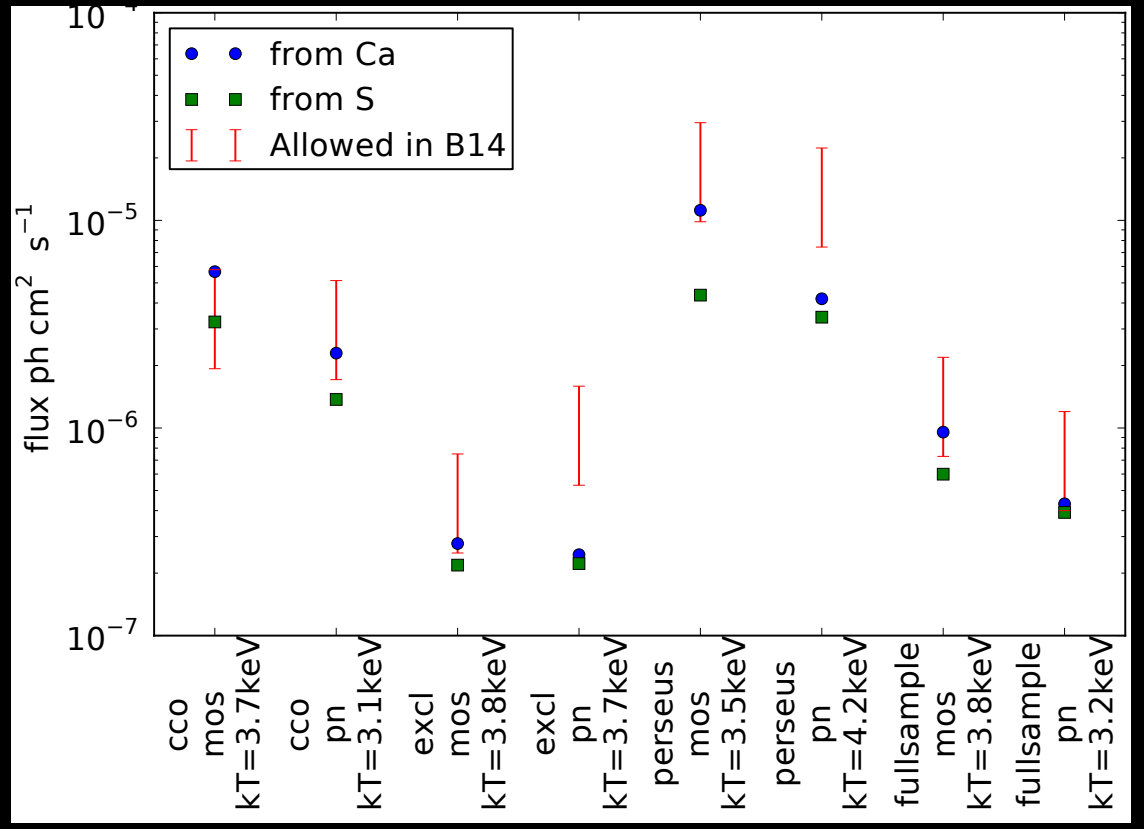
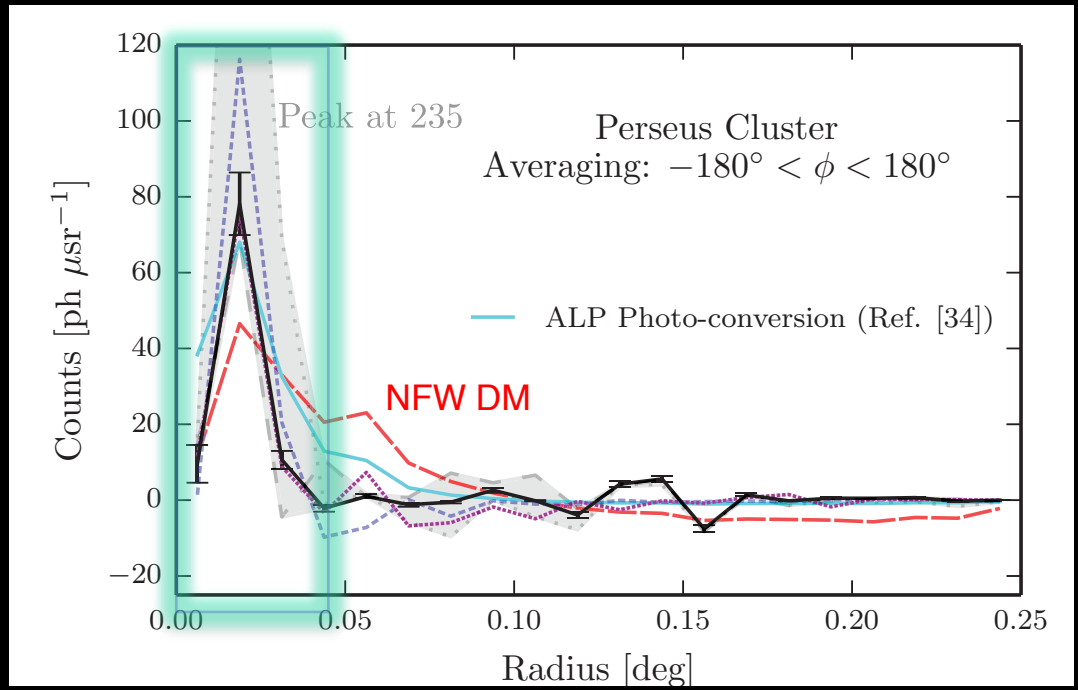


Where do the 3.5 keV photons come from? A morphological study of the Galactic Center and of Perseus

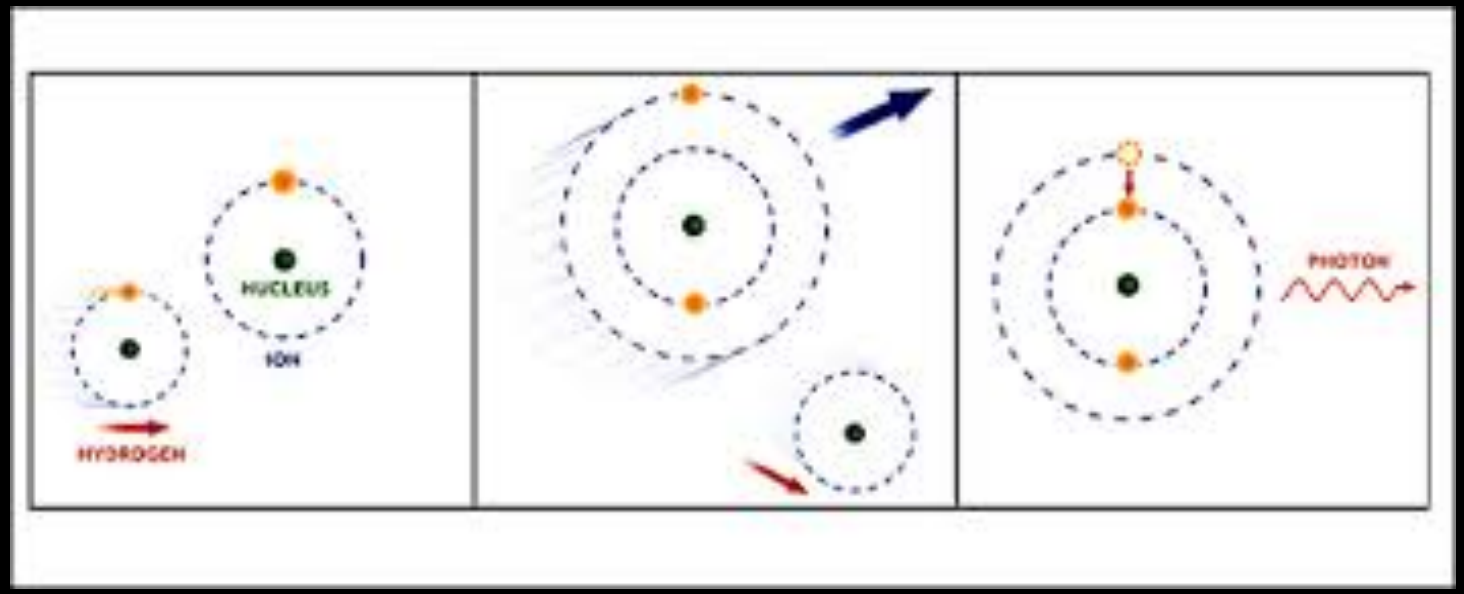
Eric Carlson,[a,b] **Tesla Jeltema,**[a,b] **Stefano Profumo**[a,b]

- 3.55 keV line is ~ 1% of continuum, so any errors of continuum > few % will result in mapping the astrophysical continuum
- The line from the whole Perseus cluster is detected at 3σ significance
- small error bars on the profile cannot represent the line signal

R=3'



Charge Exchange

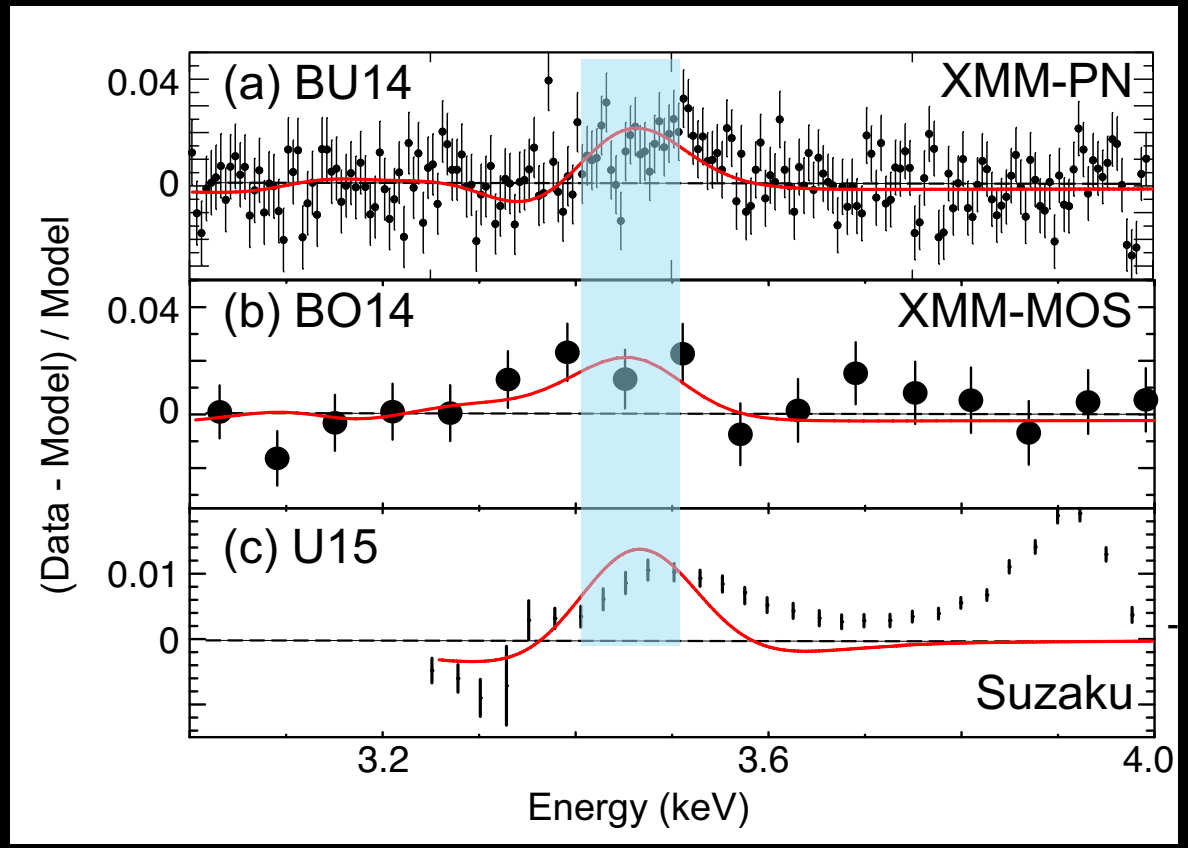


A novel scenario for the possible X-ray line feature at ~3.5 keV:

Charge exchange with bare sulfur ions

Liyi Gu[1], Jelle Kaastra[1,2], A. J. J. Raassen[1,3], P. D. Mullen[4], R. S. Cumbee[4], D. Lyons[4], and P. C. Stancil[4]

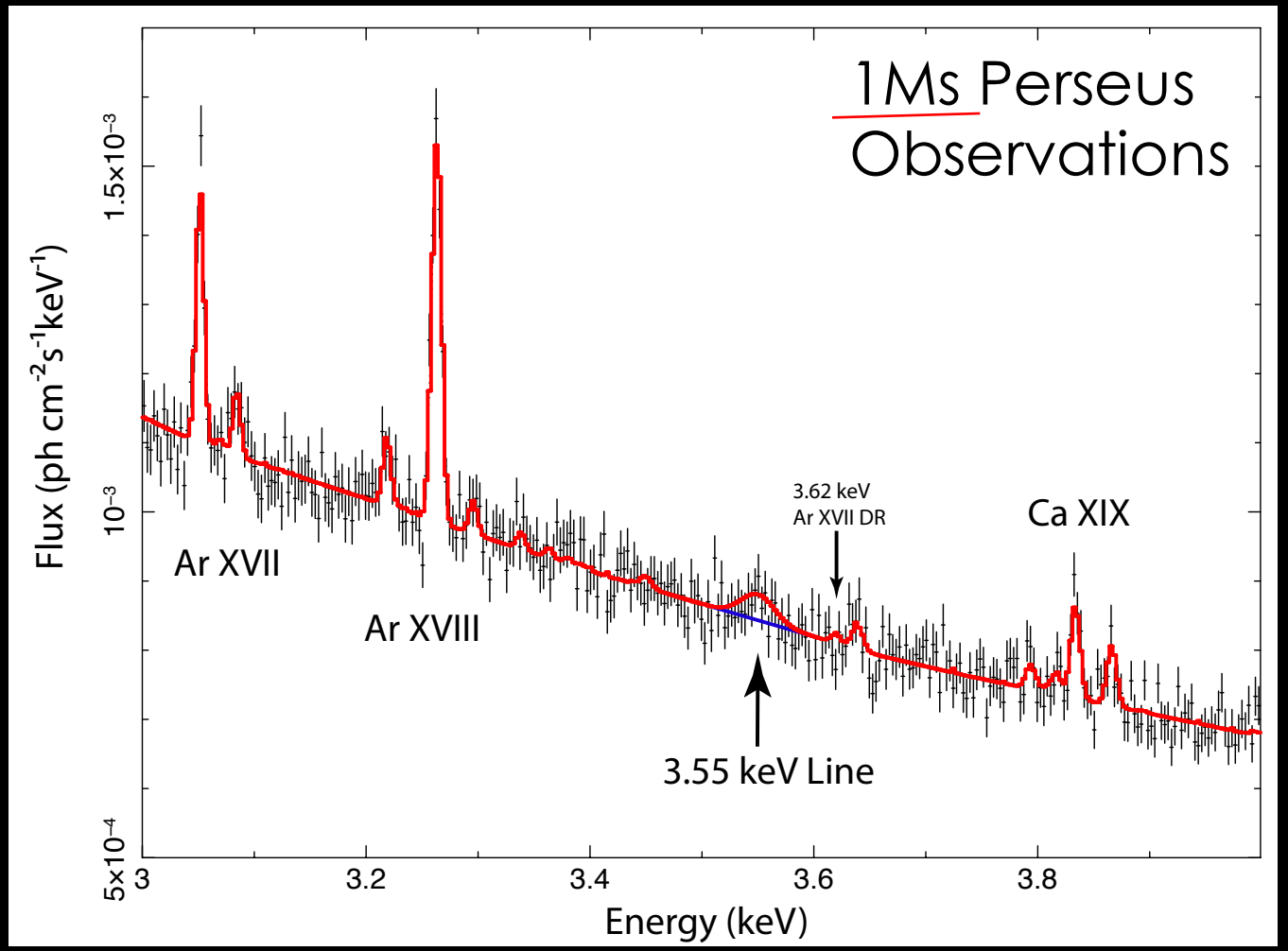
- charge exchange (CX) between bare sulfur and neutral hydrogen interacting with a relative velocity of ~ 200 km/s.
- S XVI CX Line is located at 3.44 keV



Line in the stacked MOS observations

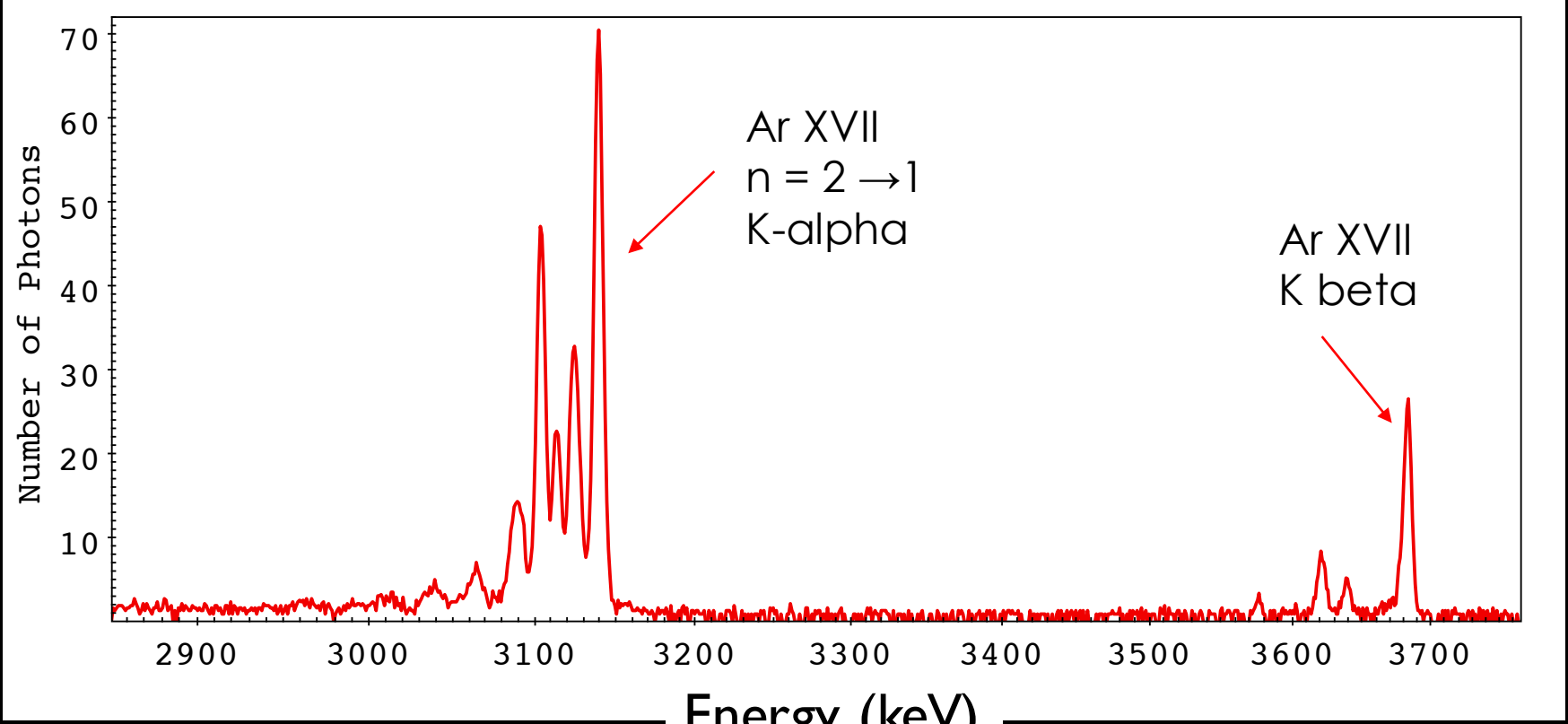
Future: Observations with Hitomi re-flight

Hitomi re-flight launch 2021

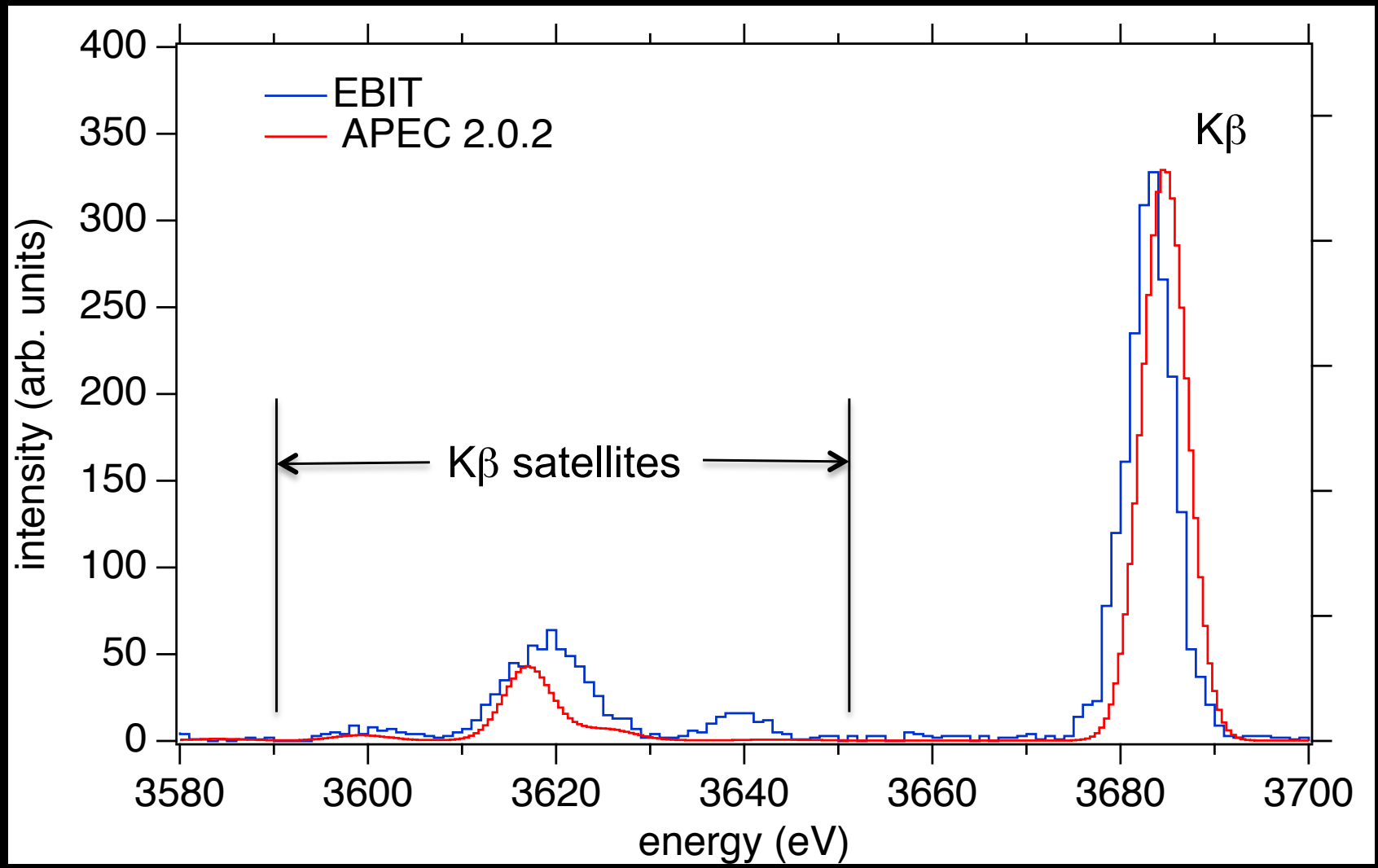


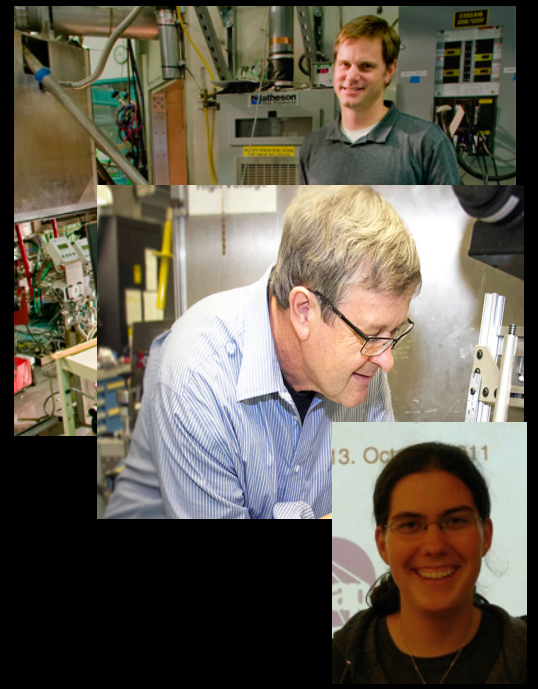
EBIT Experiments to Test the Astrophysical Origin

- LLNL EBIT/ECS experiment for measuring Ar XVII an K XVIII transitions



EBIT Argon Experiment

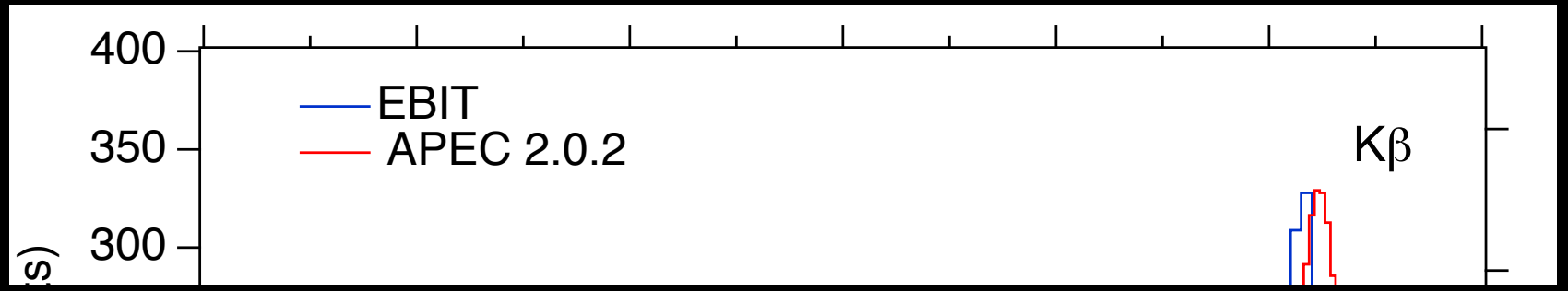




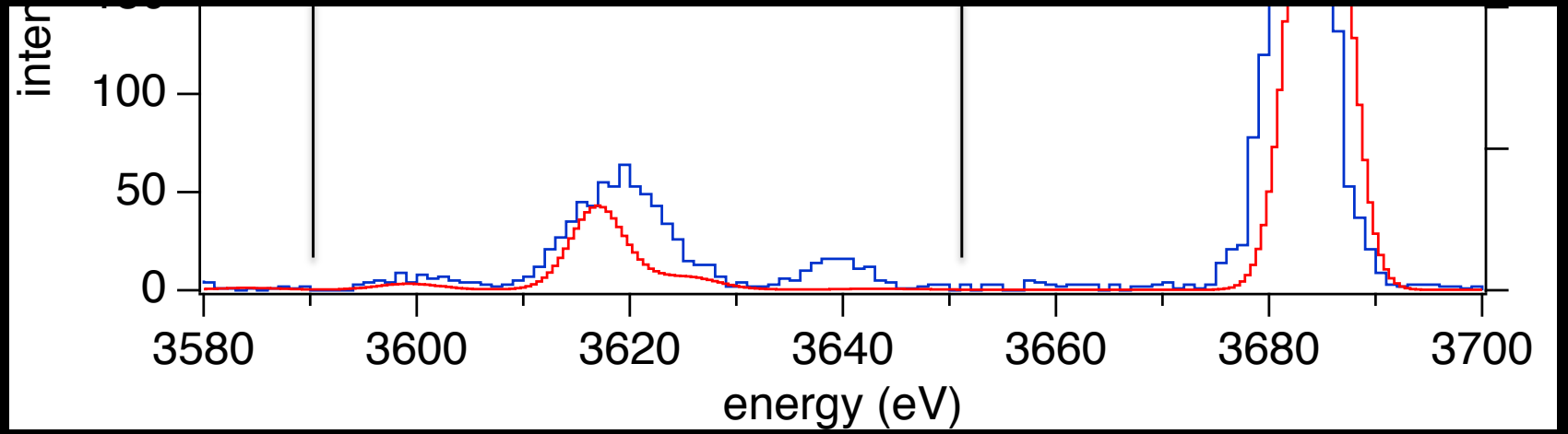
Greg Brown, Natalie Hell, and Peter Beiersdorfer

Bulbul & Smith+2017, in prep

EBIT Argon Experiment

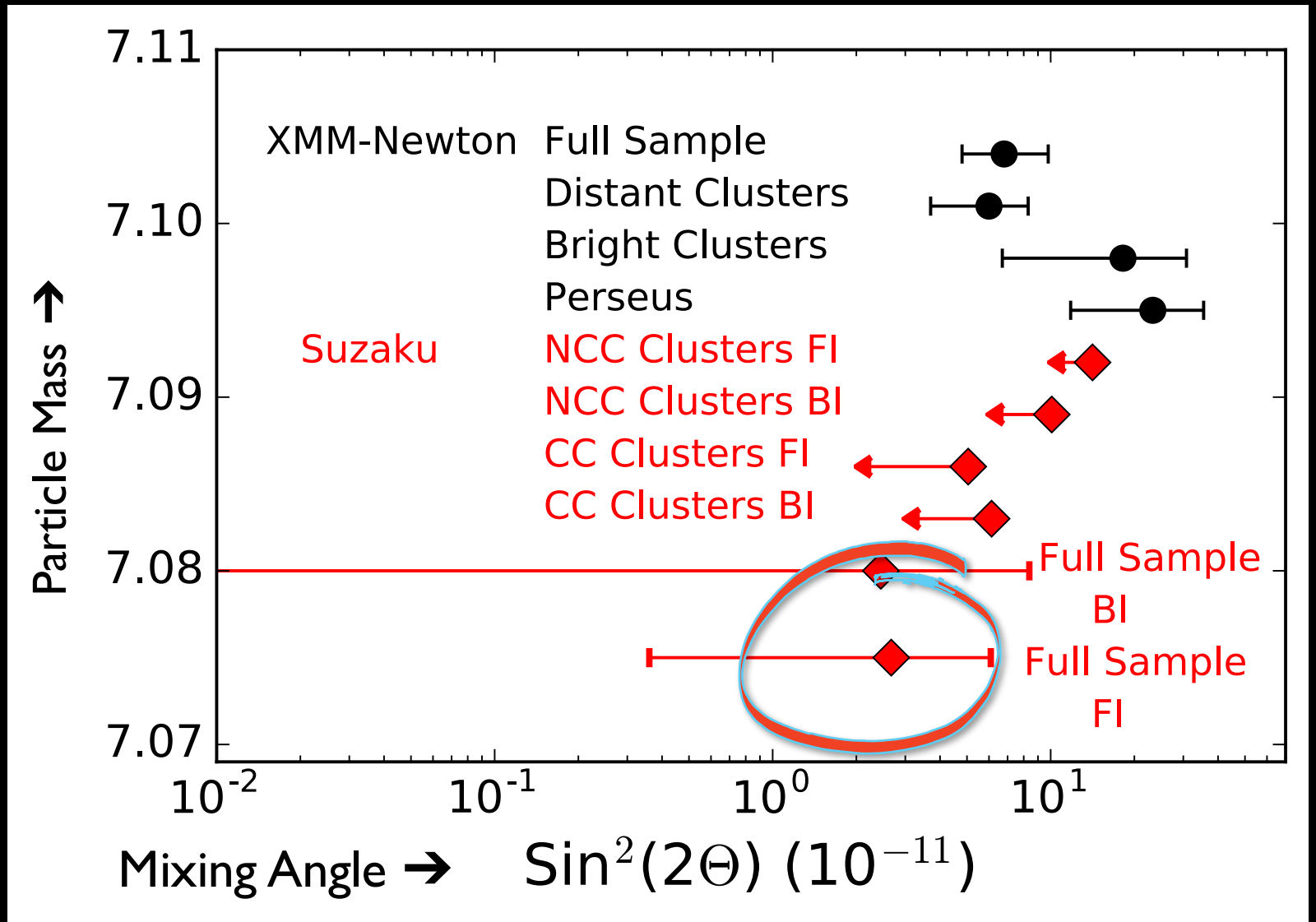


APEC is not off by factor of 30!



Bulbul+2017, in prep

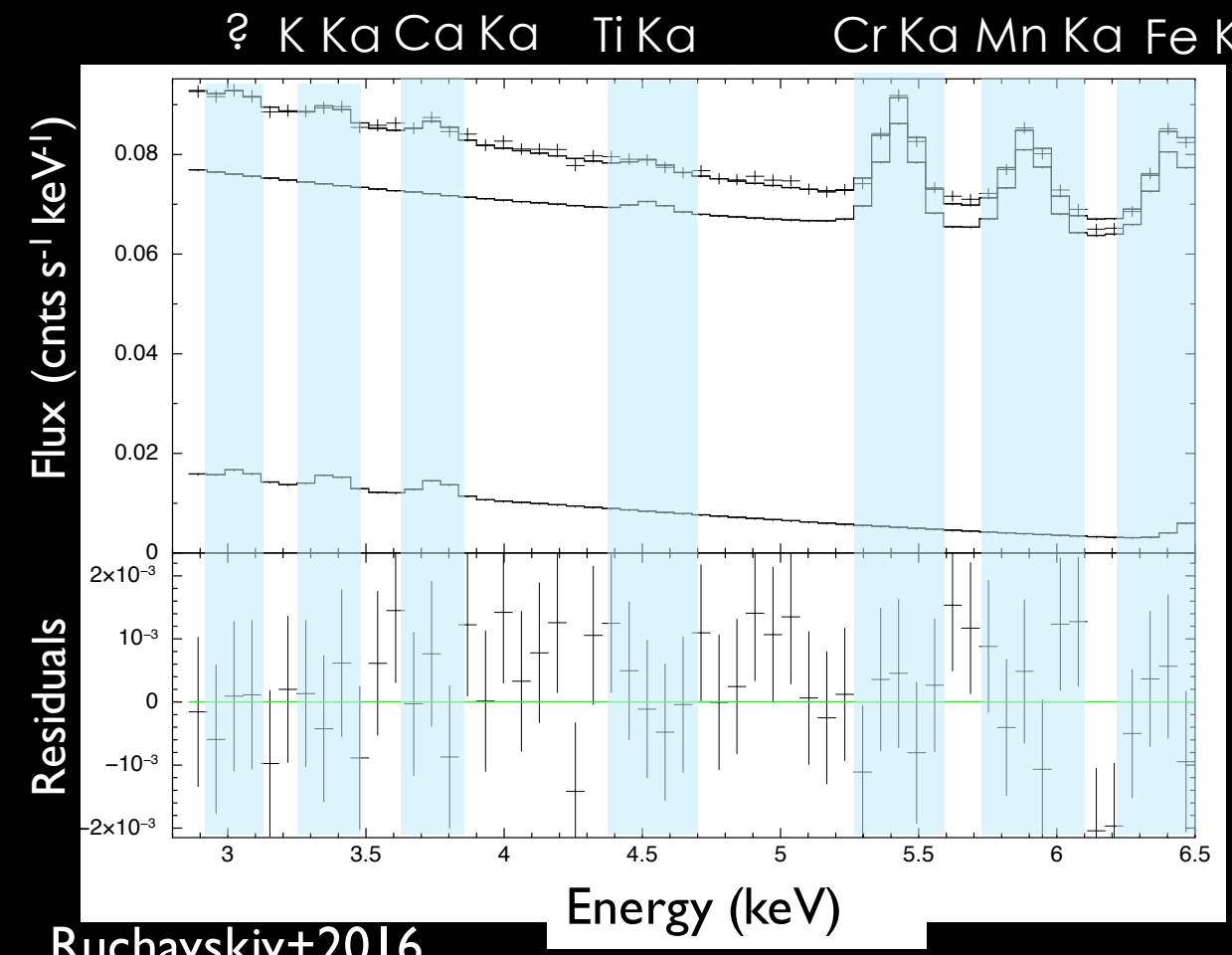
Stacked Suzaku Observations
0.01 < z < 0.45



Bulbul+2016b

Deep XMM Observations of Draco rule out at the 99% Confidence Level a Dark Matter Decay Origin for the 3.5 keV Line

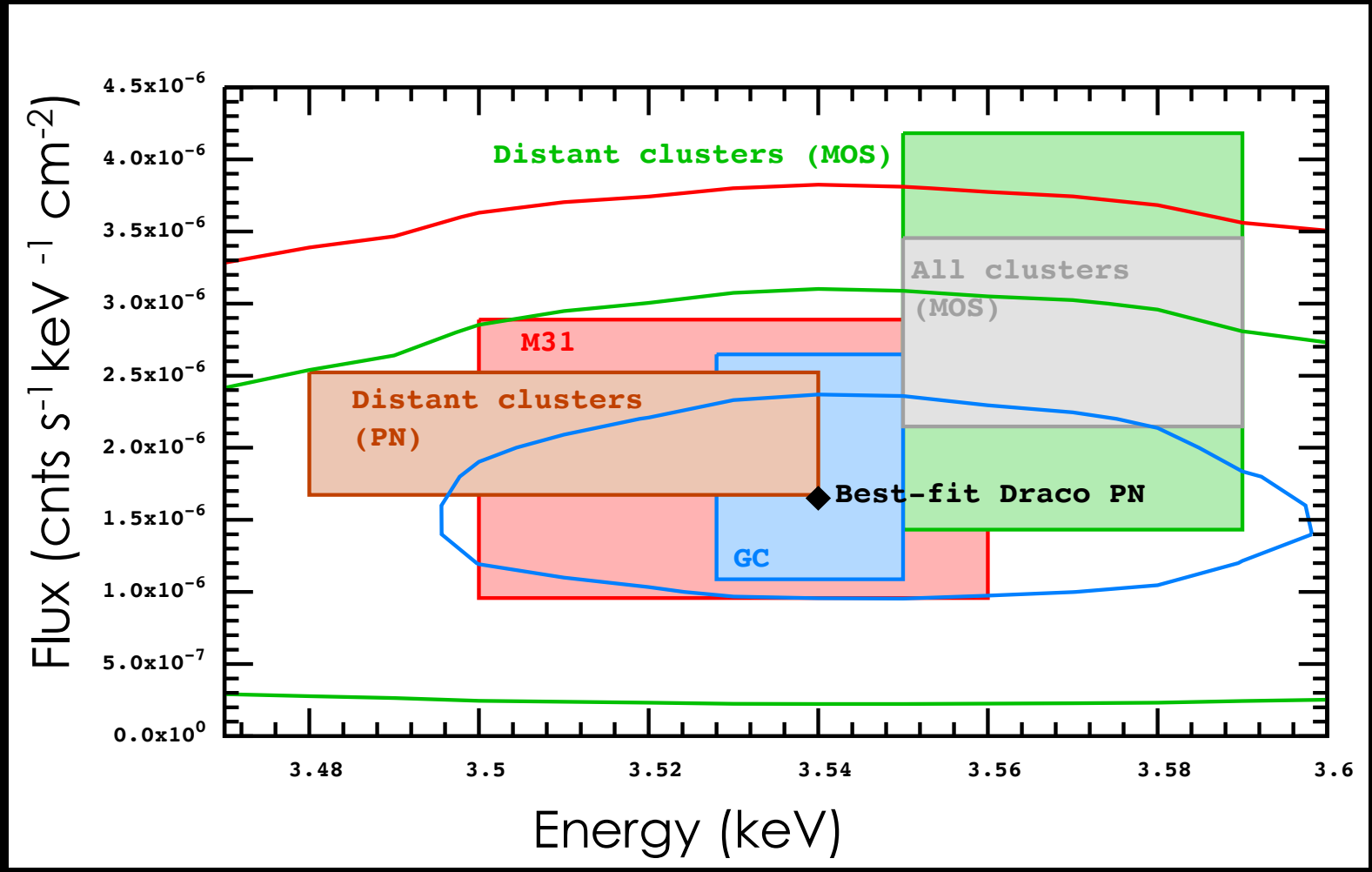
Tesla Jeltema[1]* and Stefano Profumo[1]†
[1]*Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*



Ruchayskiy+2016

- Band is very crowded with instrumental lines
- Any inaccuracies in the modeling would produce artificially high continuum
- Instrumental lines are not included in the J&P 2016

Dwarf Spheroidal Draco



Ruchayskiy,..& Bulbul+2016