The 3.5 keV Saga

Backgrounds, Observations, and Morphology

Eric Carlson

With Tesla Jeltema & Stefano Profumo

Based on:
1408.1699 (JP)
1411.1758 (CJP)

SCIPP
Santa Cruz Institute for Particle Physics

Workshop on Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics
Trieste, Italy April 13-17, 2015

Summary

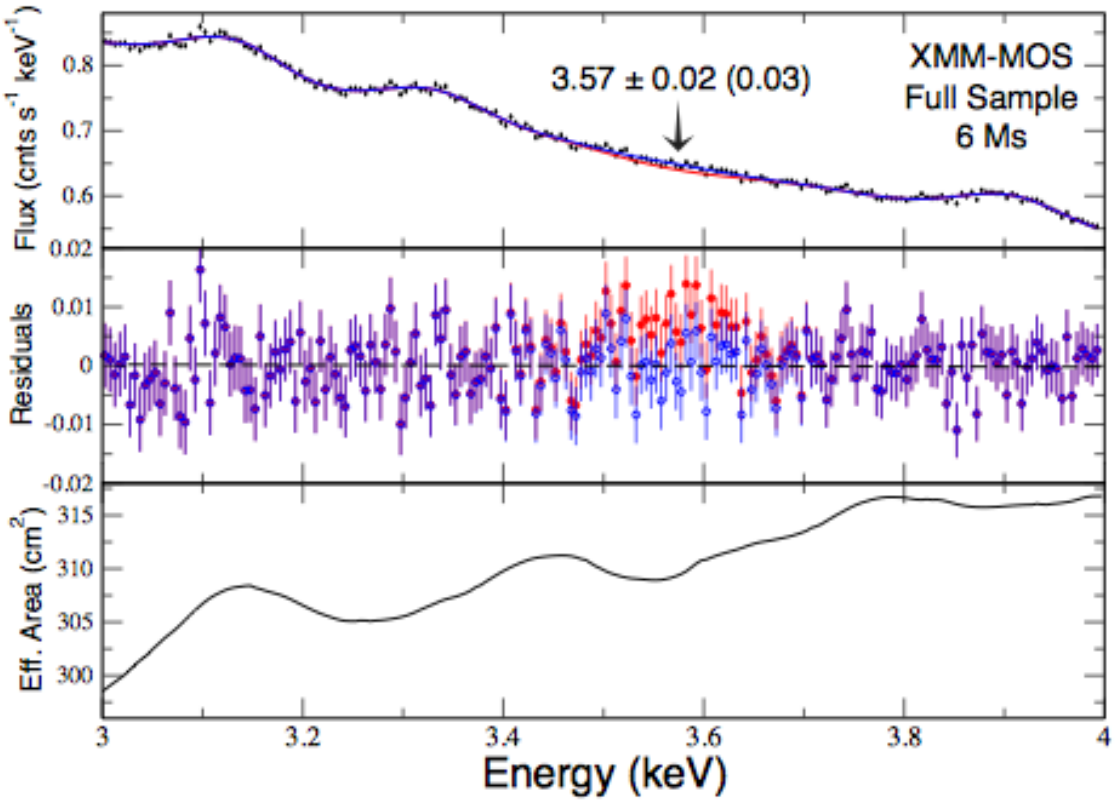
1. Status of the 3.5 keV X-ray line and Dark Matter
   - Evaluating the contribution of K-XVIII emission
   - Survey of detections in different objects and instruments

2. Morphology of the Galactic Center and Perseus at 3.5 keV
   - A template analysis: residuals, fits, and limits
   - Absorption effects
   - Cross-correlating the 3.5 keV line with other emission lines

3. Conclusions and Outlook

The 3.5 keV Line

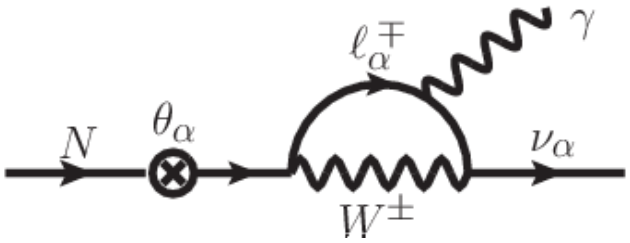
Bulbul et al (2014) - Stacked XMM observations of **galaxy cluster spectra** reveal an **unidentified X-ray line at ≈3.5 keV**



X-ray lines from Dark Matter

Sterile Neutrinos are well motivated DM candidate
(see preceding Merle & Boyarsky talks!)

- Small mixing with active neutrinos allows for radiative **decay**, producing **monochromatic γ**

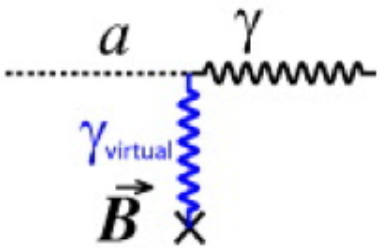


- Viable relic abundance production mechanism (Dodleson-Widrow '94)

- Potential link neutrino masses & baryogenesis

Axion-Like Particles (ALPs)

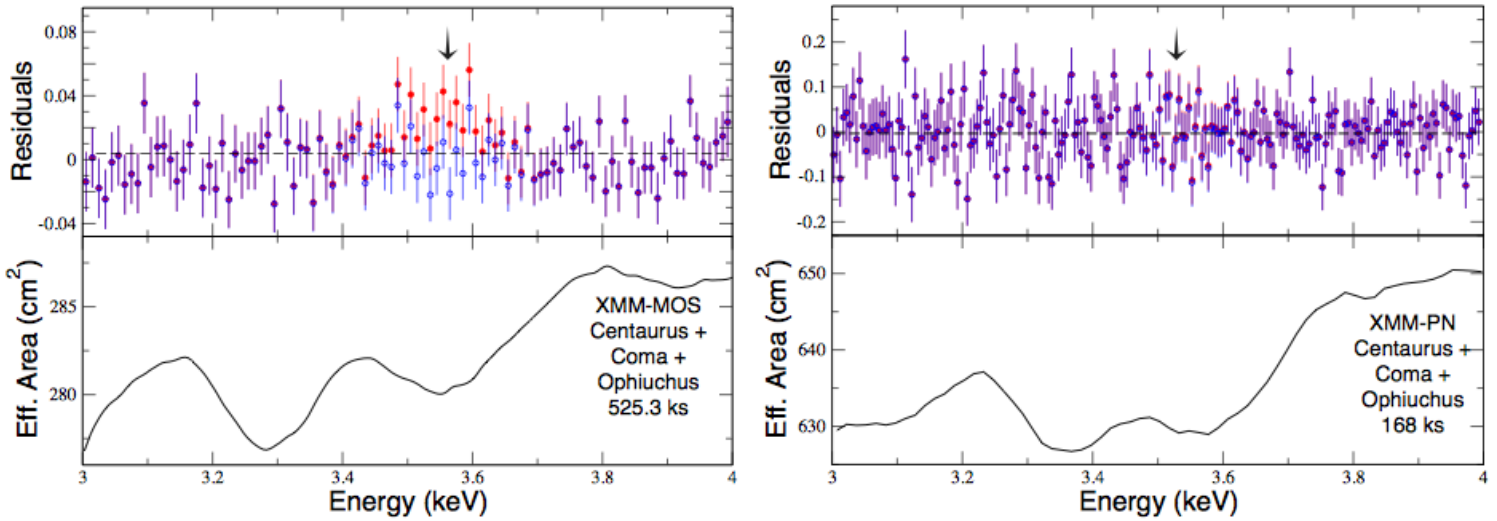
- **Primakoff effect produces line** with rate dependent on object's B-field strength and size
- Can possibly **reconcile different DM decay** rates in diff. objects



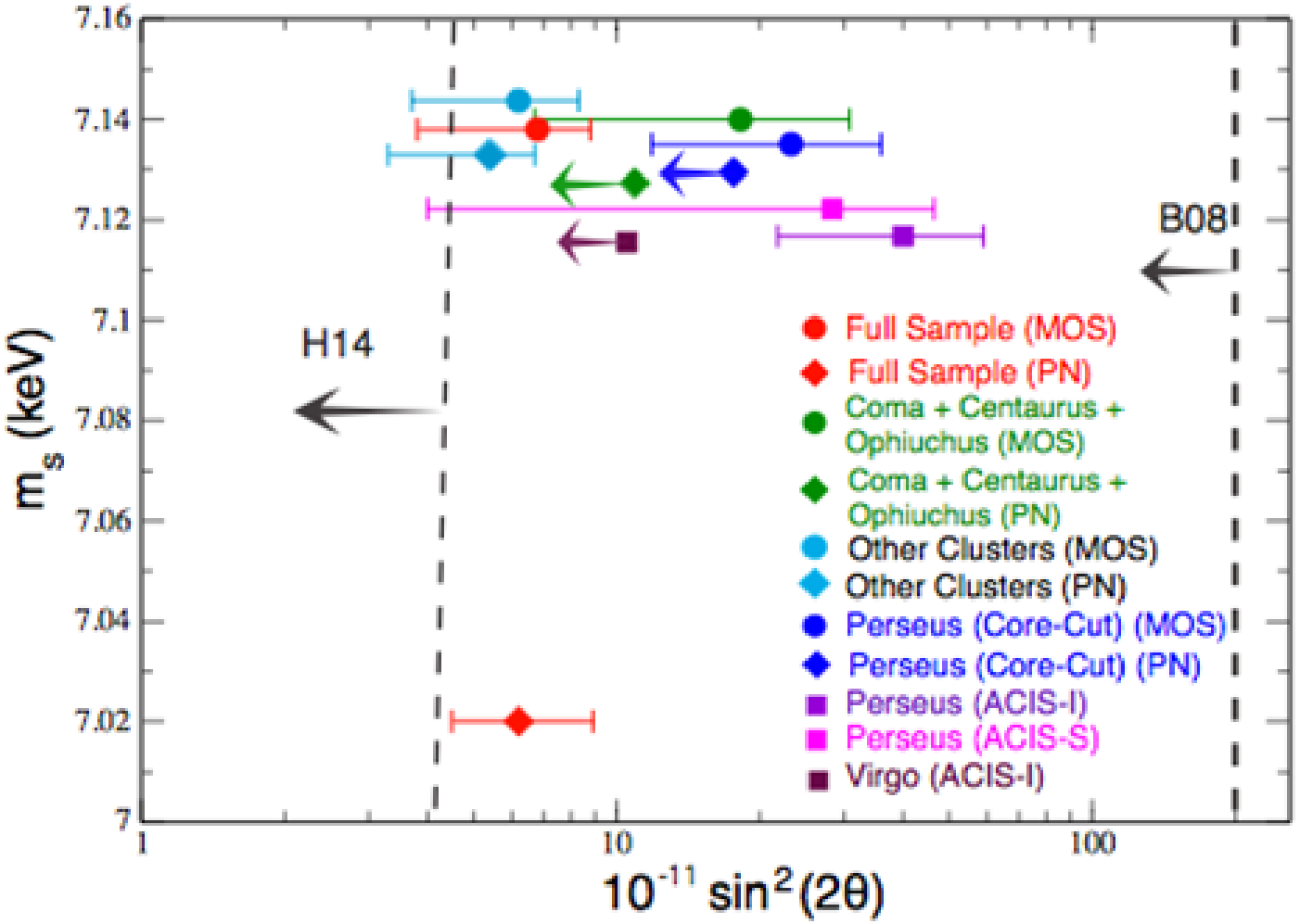
(see Talks by David Marsh, Andrew Powell, and e.g. Conlon et al 1406.5518, 1404.7741)

Bulbul et al 2014

(i) Full 73 cluster Sample	line with **PN and MOS**
(ii) Persues	line with **MOS**, **no line with PN**
(iii) Coma+Cent+Oph	line with **MOS**, **no line with PN**
(iv) Full - (ii & iii)	line with **PN and MOS**
(v) Virgo	**No line**



Bulbul et al 2014



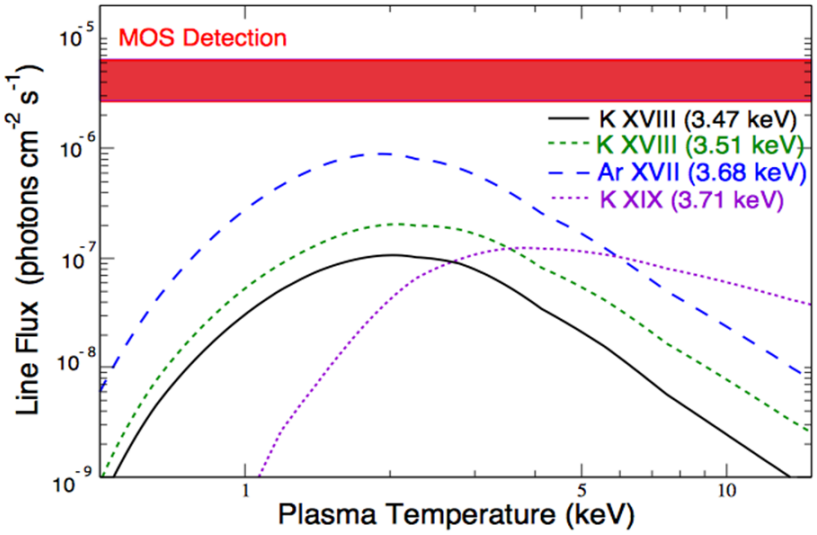
What are the Backgrounds?

Atomic transition lines are everywhere!

K-XVIII line at 3.47+3.51 keV + ArXVII at 3.68 keV
XMM Detectors have FWHM $\approx 100\ eV$

Flux estimate requires:
1. Relative abundances
2. Multi-temperature plasma model

- Fit 4 temperature model to line-free continuum
- Estimate K-XVIII flux using bright Ca and S lines
- Allow for factor of 0.1-3 times within solar abundances



Bulbul et al 2014

Bulbul et al finds maximal K-XVIII flux a **factor of $\sim$10 too low to explain 3.5 keV excess**

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*

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

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No monkeying around at MNRAS!

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

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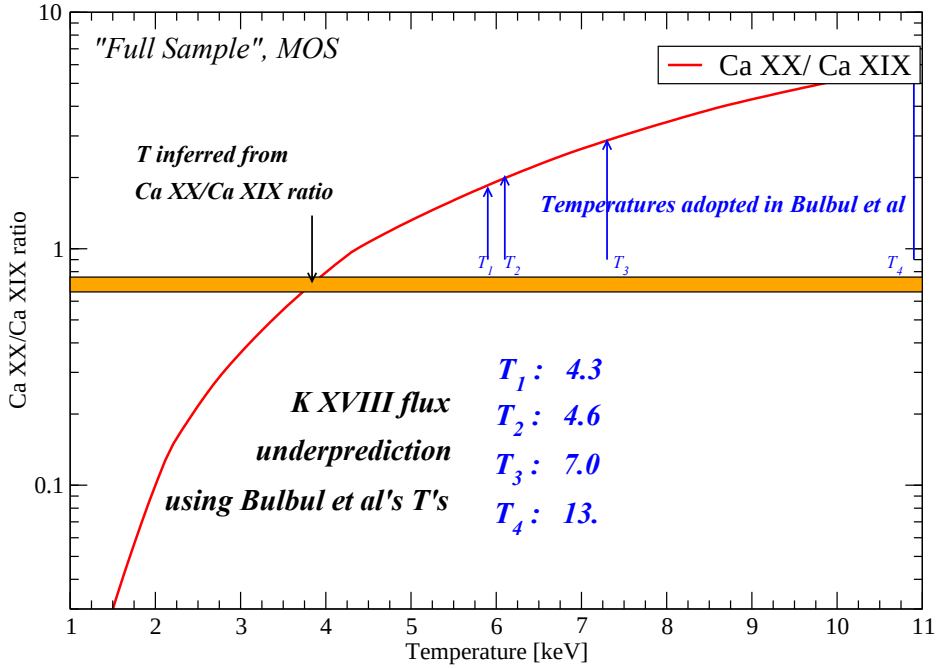
1. New analysis of XMM **Galactic Center** data: **discovery** of new line at 3.51 keV, compatible with K XVIII & DM
2. Re-analysis of XMM **M31** data: no significant line detected when BG power-law fit to ≈3-4 keV region.
3. Assess **systematics of lines strengths** for Galactic Center, M31, and, especially **clusters**: Claim Bulbul et al not conservative enough in K XVIII estimates based on CaXX/CaXIX line ratios.
4. **New in v2: 3.5 keV line detected in XMM obs. of Tycho SNR!** Nucleosynthesis in Type Ia SNe predicts K underabunant by factor 3-10. Maybe systematic for weak lines, maybe more K…

JP Claim: CaXX/CaXIX **line ratios indicate low temp (3.5 keV) plasma.** Bulbul et al fit higher temperatures and thus underestimate K-XVIII flux by at least factor 4



Bulbul et al**: Disagree + still need a line** unless **both** K-XVIII and Ar-XVII fluxes are much brighter than upper limits…

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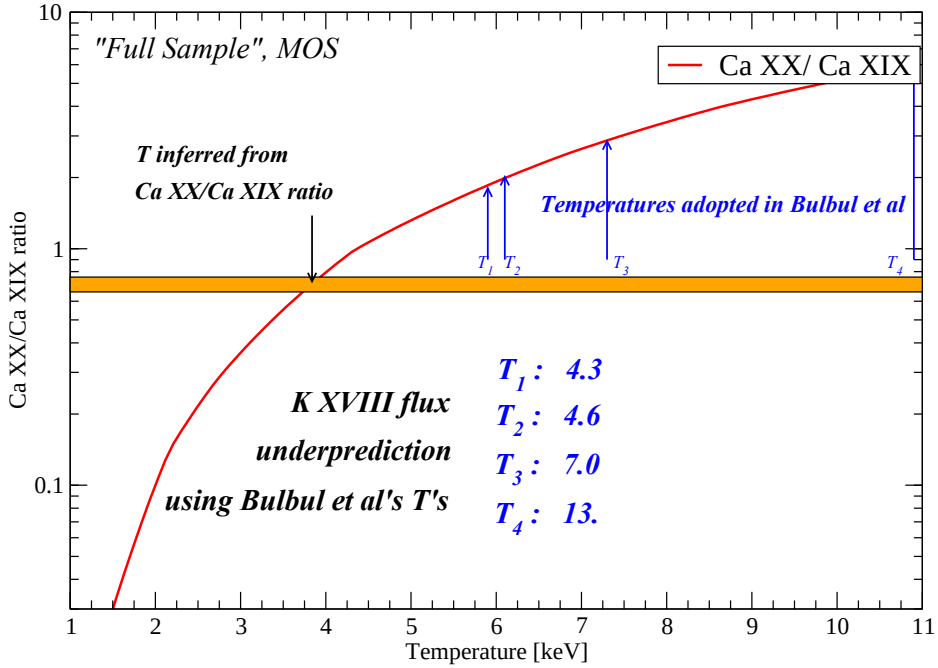


Bulbul et al**: Disagree + still need a line** unless **both** K-XVIII and Ar-XVII fluxes are much brighter than upper limits…

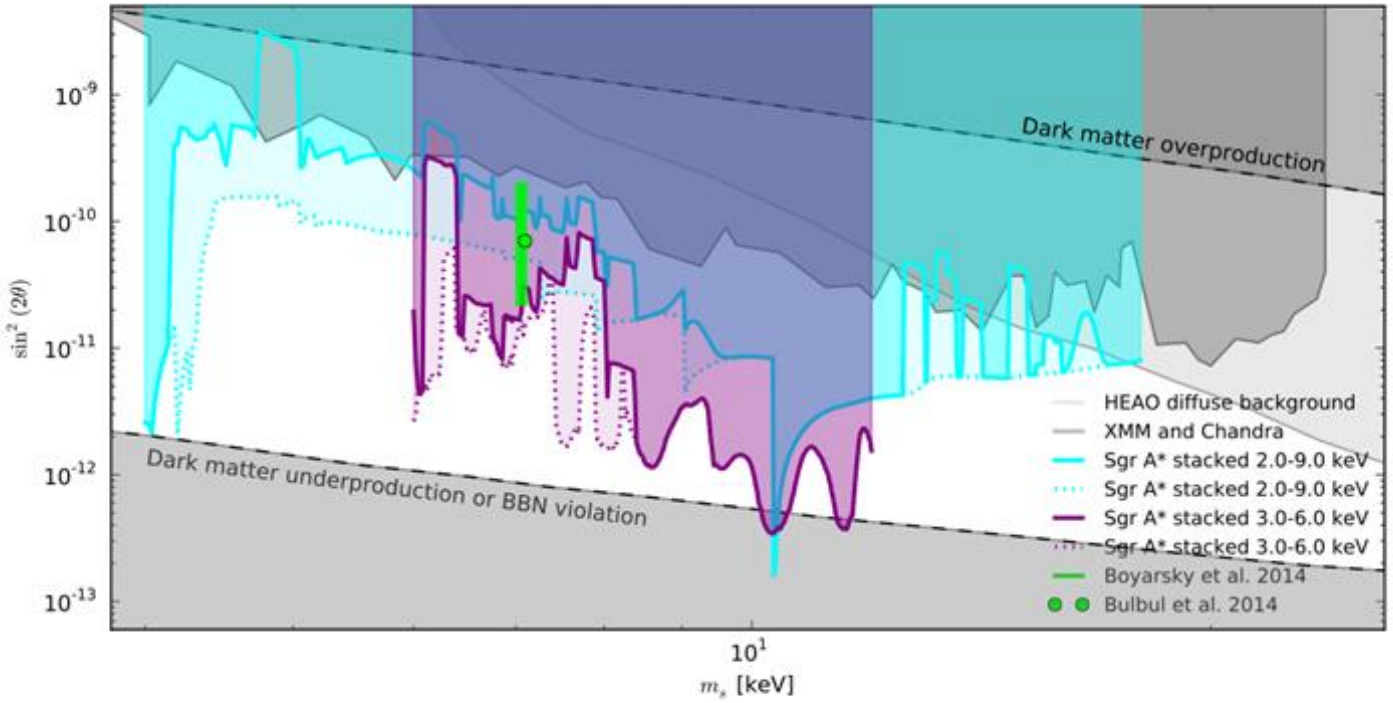
Stalemate!

Meanwhile….

One can easily determine dark matter J-factors for other objects

The Galactic Center

In **GC**, **line detected in XMM data** (Jeltema & Profumo)
Not detected in shallower Chandra data, but abundance of K is left free here (Riemer-Sorensen)

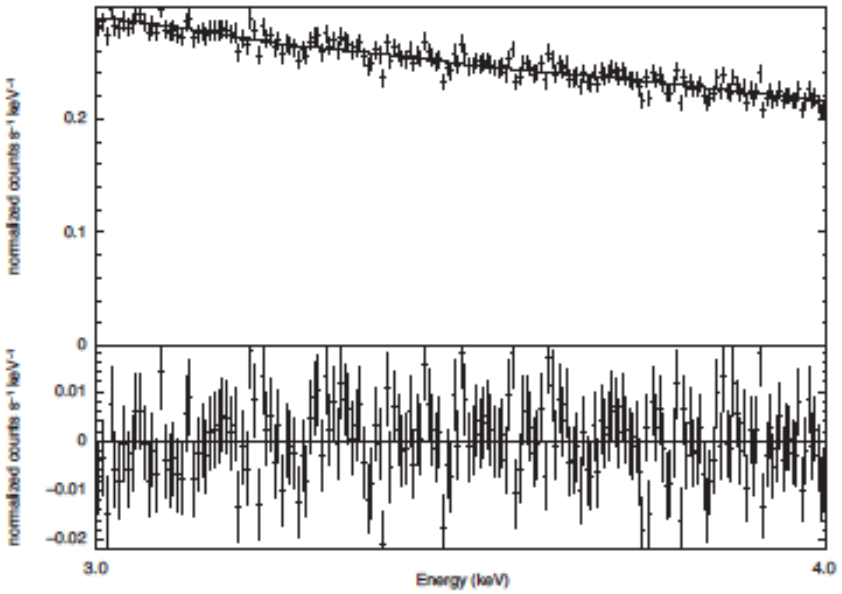


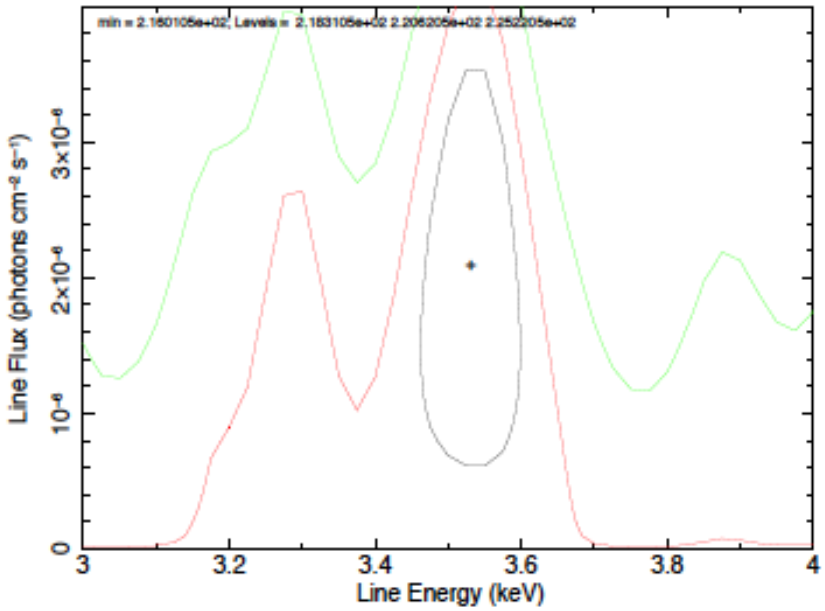
Reimer-Sorenson (1405.7943)

M31

- Detected by Boyarsky et al with PL background fit over 2-8 keV + some Gaussian lines
- Jeltema & Profumo only 1-2σ when BG power-law is locally fit to 3-4 keV range. Extending range leads to spurious residuals.

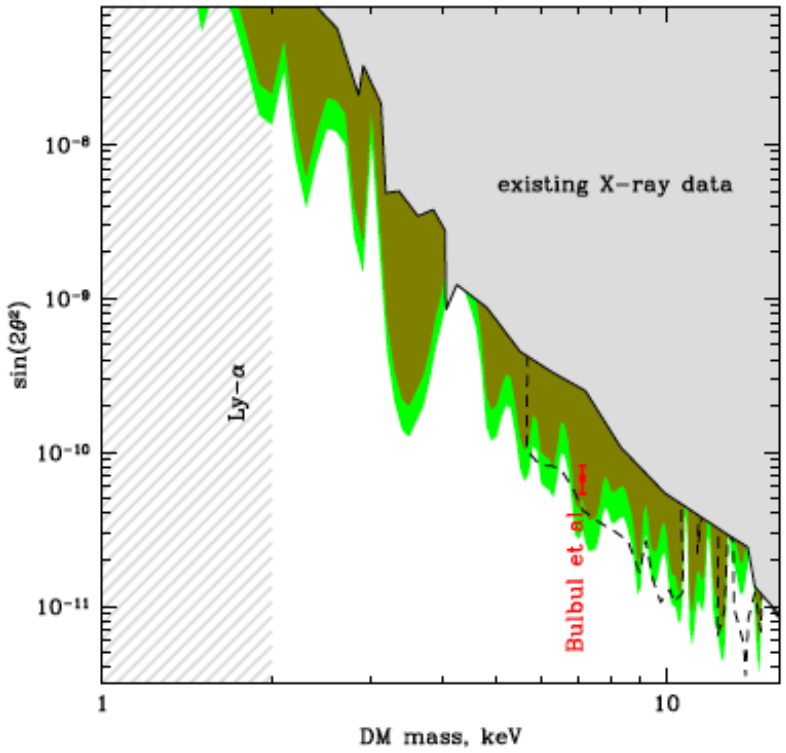
Jeltema & Profumo





Constraints on 3.55 keV line emission from stacked observations of dwarf spheroidal galaxies

D. Malyshev, A. Neronov, and D. Eckert
Department of Astronomy, University of Geneva, ch. d'Ecogia 16, CH-1290 Versoix, Switzerland



No line in dwarf galaxies rules out sterile neutrino interpretation of Bulbul at 4.6σ (Malyshev et al 1408.3531)

A *Suzaku* Search for Dark Matter Emission Lines in the X-ray Brightest Galaxy Clusters

O. Urban[1,2,3⋆], N. Werner[1,2], S. W. Allen[1,2,3], A. Simionescu[4],
J. S. Kaastra[5], L. E. Strigari[6]

- Detected in Perseus, not detected in Virgo, Coma, or Ophiucus
- Rules out DM interpretation of Perseus at ~2.6σ
- Perseus radial profile are inconsistent with standard DM decay
- Refitting Perseus with more thermal components eliminates need for line

Non-Detection of X-Ray Emission From Sterile Neutrinos in Stacked Galaxy Spectra

Michael E. Anderson[1⋆], Eugene Churazov[1,2], Joel N. Bregman[3]
[1] *Max-Planck Institute for Astrophysics, Garching bei Muenchen, Germany*
[2] *Space Research Institute (IKI), Profsoyuznaya 84/32, Moscow 117997, Russia*
[3] *Department of Astronomy, University of Michigan, Ann Arbor, MI, USA*

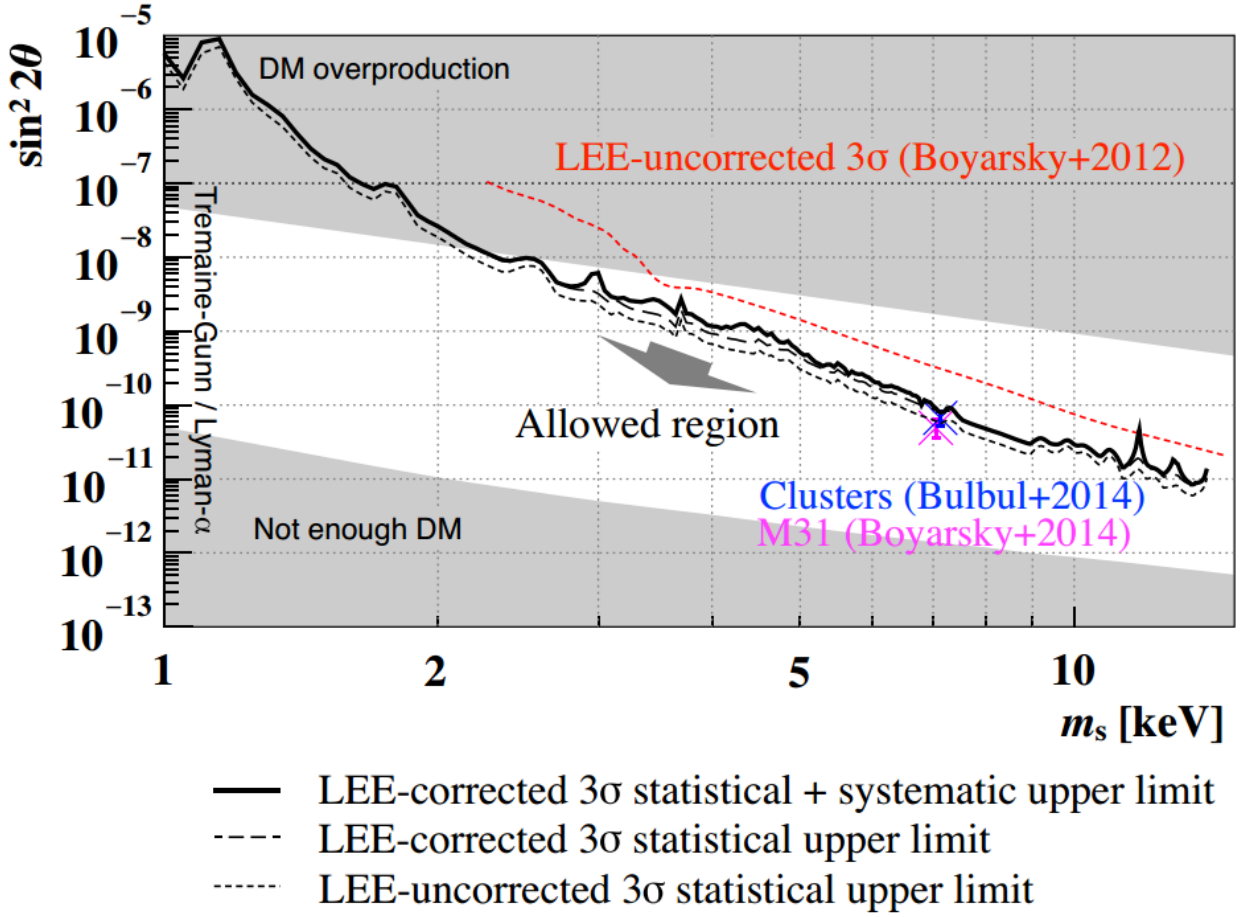
20 August 2014

Rules out Bulbul DM at 11.8 $(4.8)\sigma$ For XMM (Chandra)

ABSTRACT

We conduct a comprehensive search for X-ray emission lines from sterile neutrino dark matter, motivated by recent claims of unidentified emission lines in the stacked X-ray spectra of galaxy clusters and the centers of the Milky Way and M31. Since the claimed emission lines lie around 3.5 keV, we focus on galaxies and galaxy groups (masking the central regions), since these objects emit very little radiation above ~ 2 keV and offer a clean background against which to detect emission lines. We develop a formalism for maximizing the signal-to-noise of sterile neutrino emission lines by weighing each X-ray event according to the expected dark matter profile. In total, we examine 81 and 89 galaxies with Chandra and XMM-Newton respectively, totaling 15.0 and 14.6 Ms of integration time. We find no significant evidence of any emission lines, placing strong constraints on the mixing angle of sterile neutrinos with masses between 4.8-12.4 keV. In particular, if the 3.57 keV feature from Bulbul et al. (2014) were due to 7.1 keV sterile neutrino emission, we would have detected it at 4.4σ and 11.8σ in our two samples. Unlike previous constraints, our measurements do not depend on the model of the X-ray background or on the assumed logarithmic slope of the center of the dark matter profile.

Blank Sky (MW Halo)



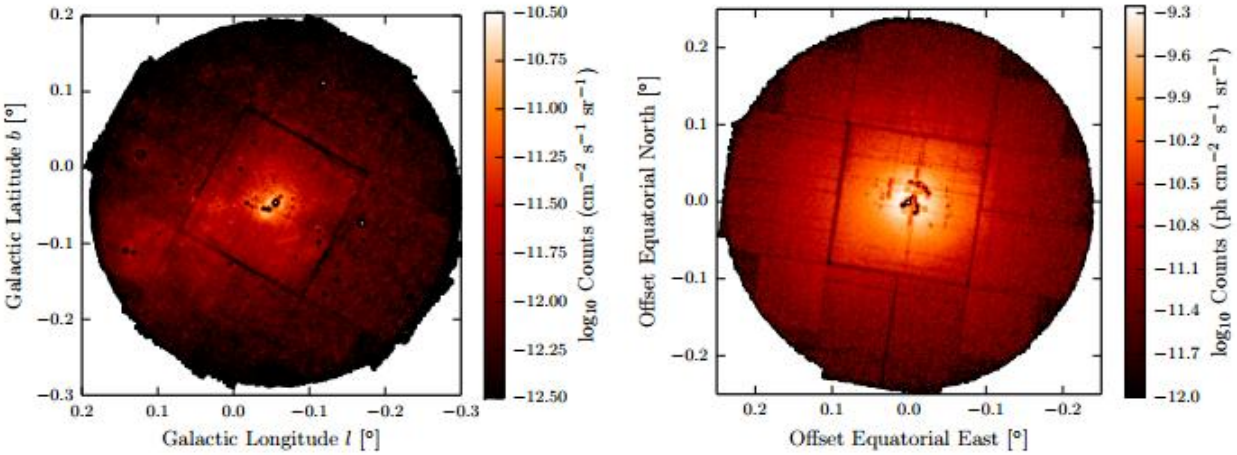
1504.02826

Not Convinced?

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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

Eric Carlson, Tesla Jeltema and Stefano Profumo

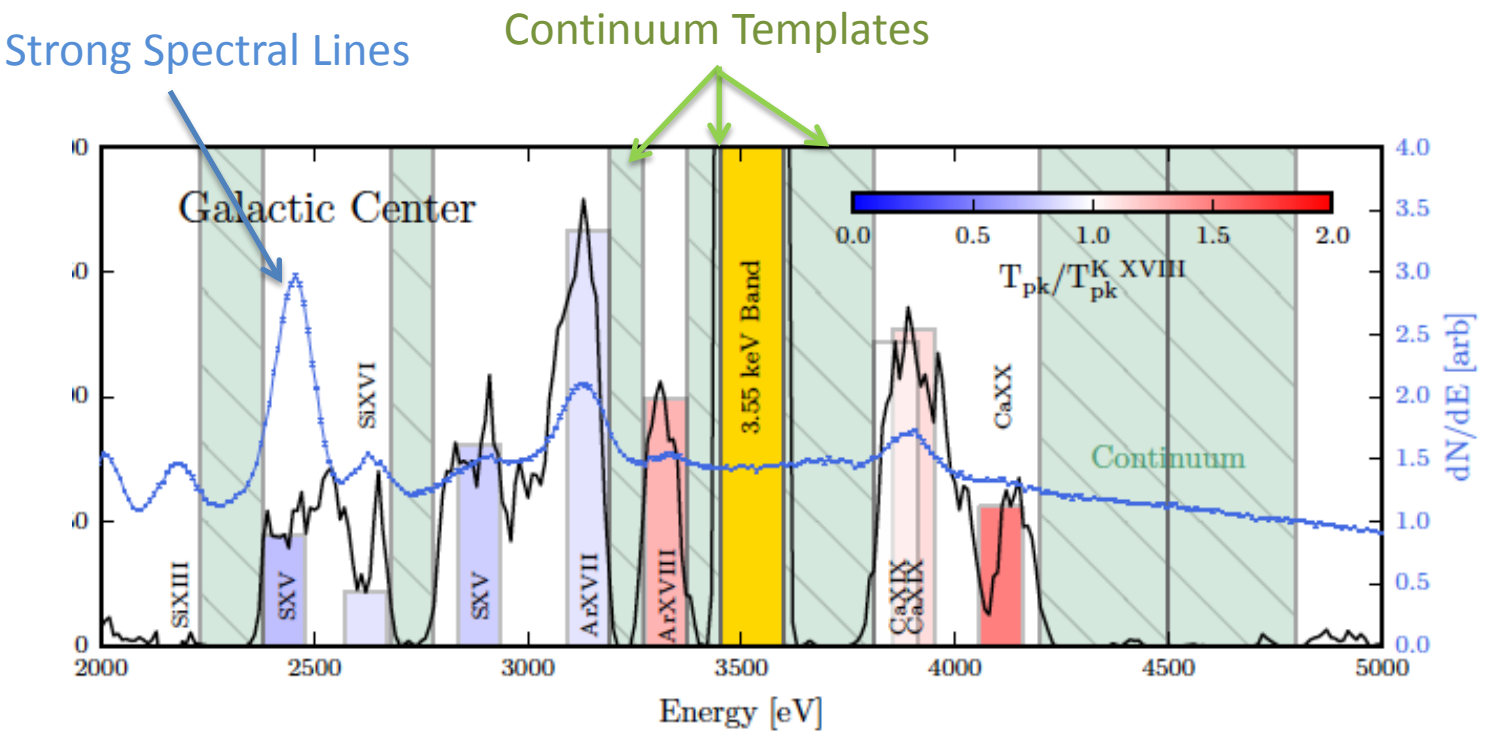


(a) Galactic center (b) Perseus cluster

arXiv: 1411.1758

Template Analysis

1. Spectral lines have a major advantage in indirect detection.
2. Isolate line energies (3.45-3.6 keV) and **compare directly to sideband** continuum emission. Data driven spatial templates.
3. Use a binned likelihood analysis to subtract continuum



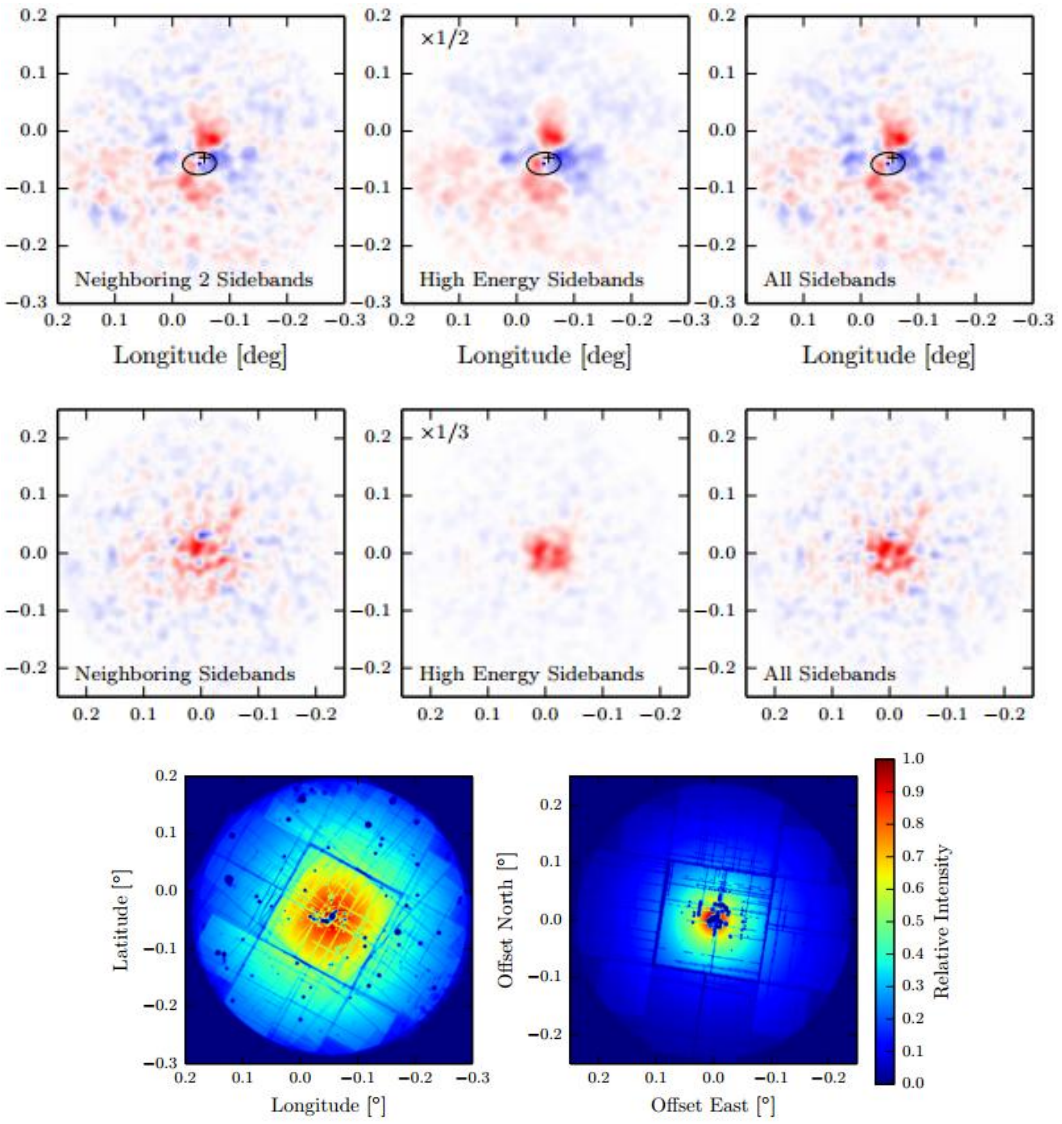
Residual Maps

Use **3 different continuum models** and subtract best fit from data.

Galactic Center: Quadrapolar structure. DM is azimuthally symmetric...

Perseus Cluster: Residual emission traces cool core.. Radial profile does not match DM

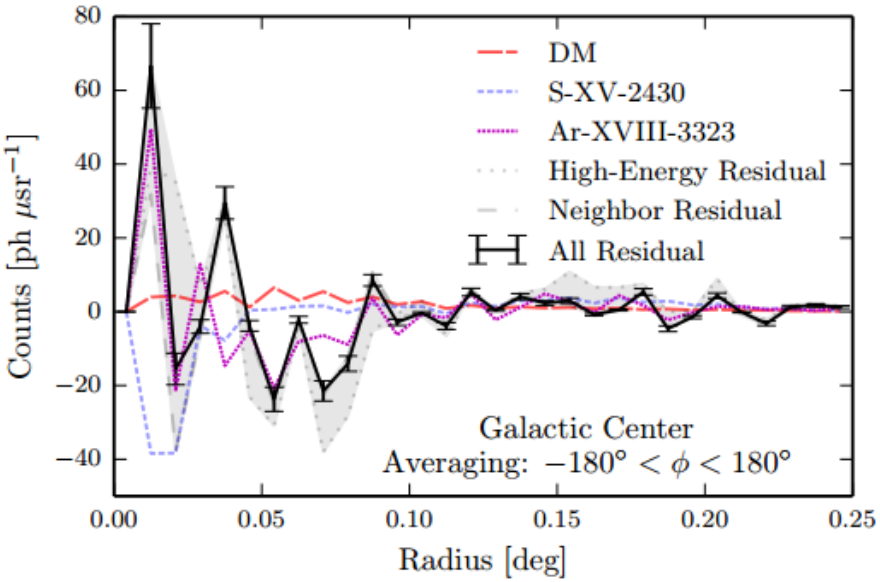
Decaying DM templates after exposure and point source masking

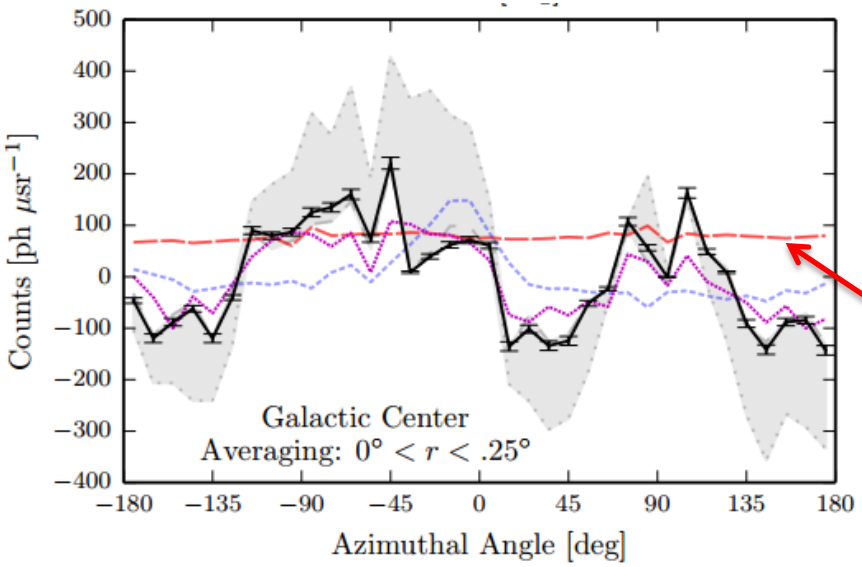


GC Radial Profiles

Radial profiles averaged azimuthally

- DM is much flatter radially than what is observed





Azimuthal profiles averaged radially

- DM is azimuthally symmetric
- 3.5 keV line is Quadrapolar

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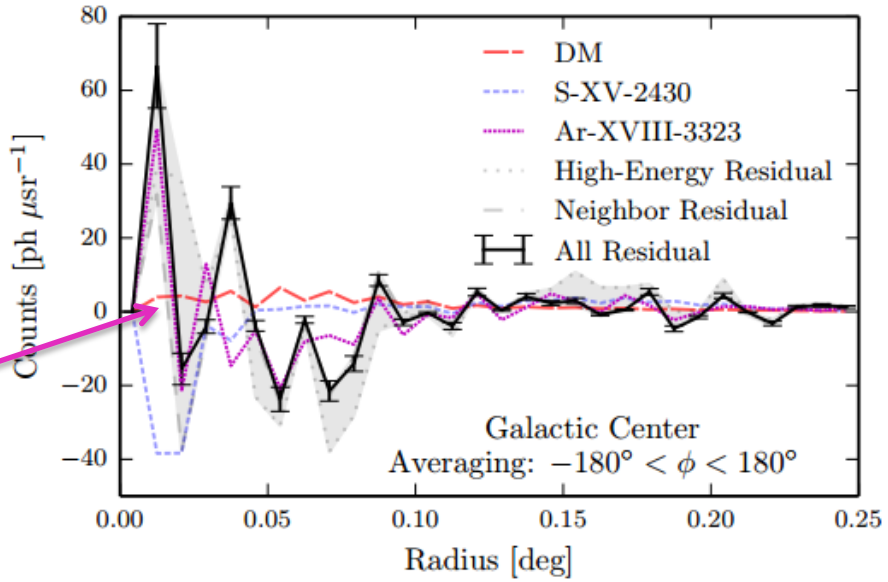
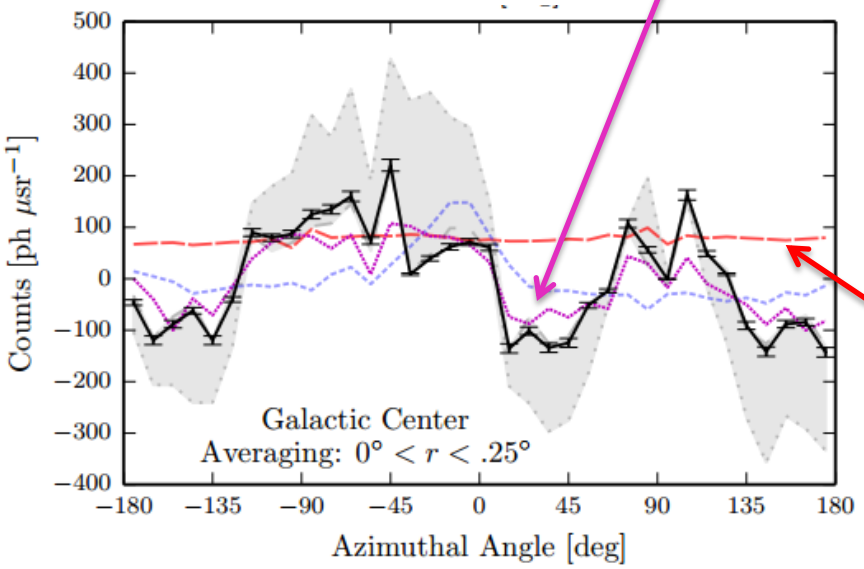


3.5 keV band is well traced by typical medium T line in radially and azimuthally



Azimuthal profiles averaged radially

- DM is azimuthally symmetric
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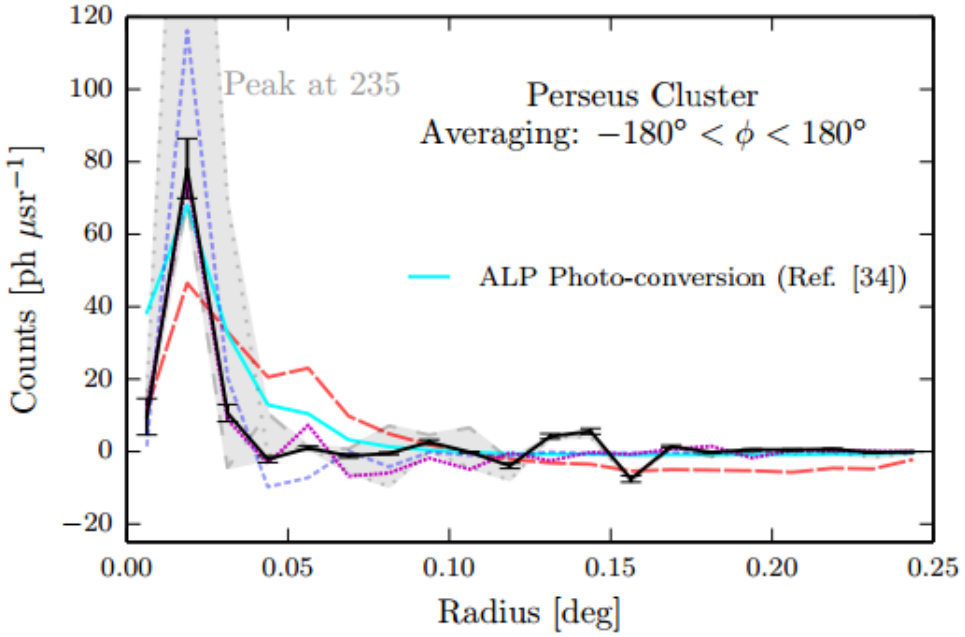
Perseus Radial Profiles

DM too flat again. 3.5 keV band traces the cool-core of Perseus along with other lines at similar temperature.



Steepest ALP profiles are perfectly viable.
ALPs cannot explain the GC signal (which is ok!)
Signal Depends critically on B-field (See papers by Conlon et al)

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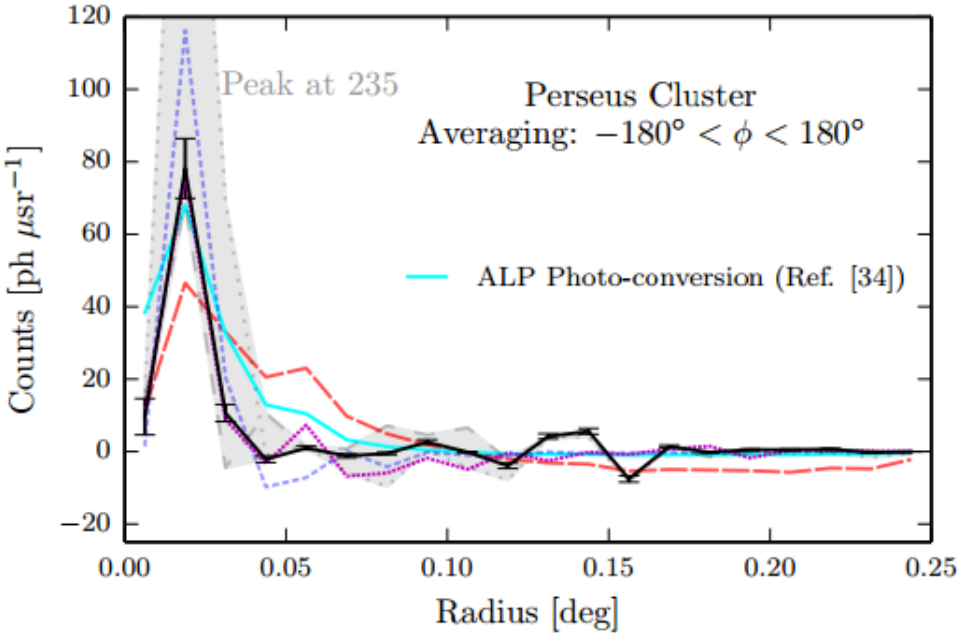


This finding is corroborated by Suzaku measurements of radial profile. (Urban et al 2014)

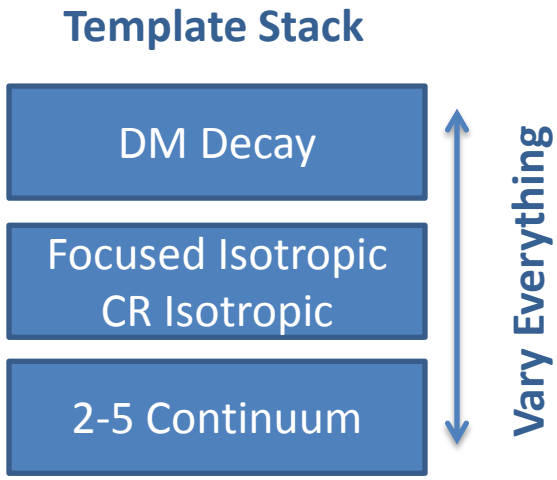
Steepest ALP profiles are perfectly viable.
ALPs cannot explain the GC signal (which is ok!)
Signal Depends critically on B-field (See papers by Conlon et al)

But Eric, The 3.5 keV flux is very weak. This residual might be mismodeling of the continuum.

Fair point! We test this…

- Allowing all templates to float, we add a decaying DM template and find **strictly $\mathbf{TS = -2\Delta log(L) = 0}$ improvement for both Perseus and Galactic center for any continuum model or halo profile** (tried Burkert, Einasto, & NFW).

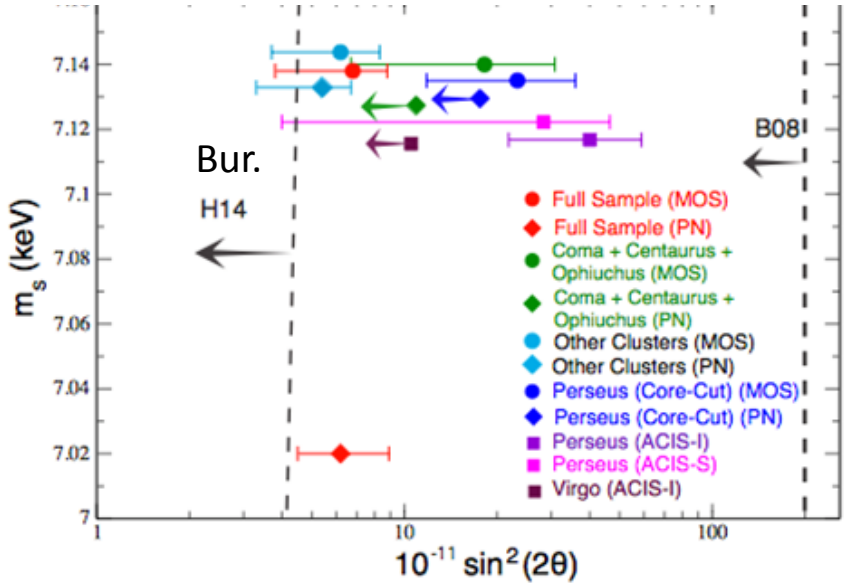
- Additional Tests… **Consider variations on DM template**: Halo location, inner profile slope, scale radius, remove isotropic templates, mask<5', mask r>5'.
  (Also no preference for annihilating profile)



Derived limits from **only** morphology

(Completely independent of spectral limits)

Target	Template Set	Profile	$\mathcal{J}$ (10^{18} GeV cm^{-2})	τ (10^{28} s)	$\sin^2(2\theta)$
GC	All+Lines	NFW	6.8	>3.7	$< 1.1 \times 10^{-11}$
GC	All+Lines	Ein	8.2	>5.9	$< 7.0 \times 10^{-12}$
GC	All+Lines	Bur	1.9	>1.3	$< 3.3 \times 10^{-11}$
Perseus	All	NFW	1.4	>.55	$< 7.5 \times 10^{-10}$
Perseus	All+Lines	NFW	1.4	>.03	$< 1.5 \times 10^{-9}$



Derived limits from **only** morphology

(Completely independent of spectral limits)

- Most conservative DM halo profile still rules out a sterile neutrino interpretation (any decaying DM) at high confidence
- **Most stringent limits to date on 3.5 keV decaying DM!**
- Perseus limits are not competitive

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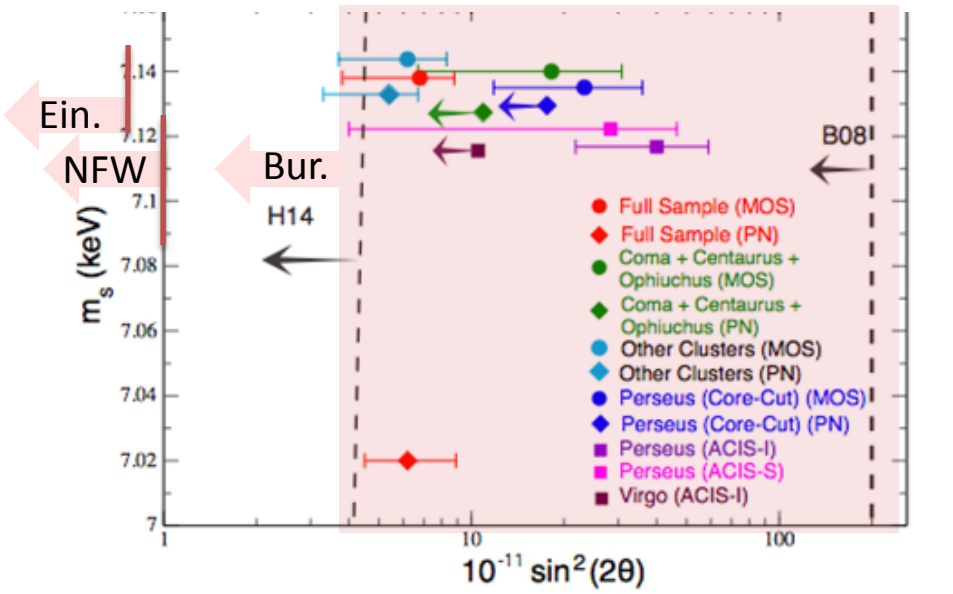
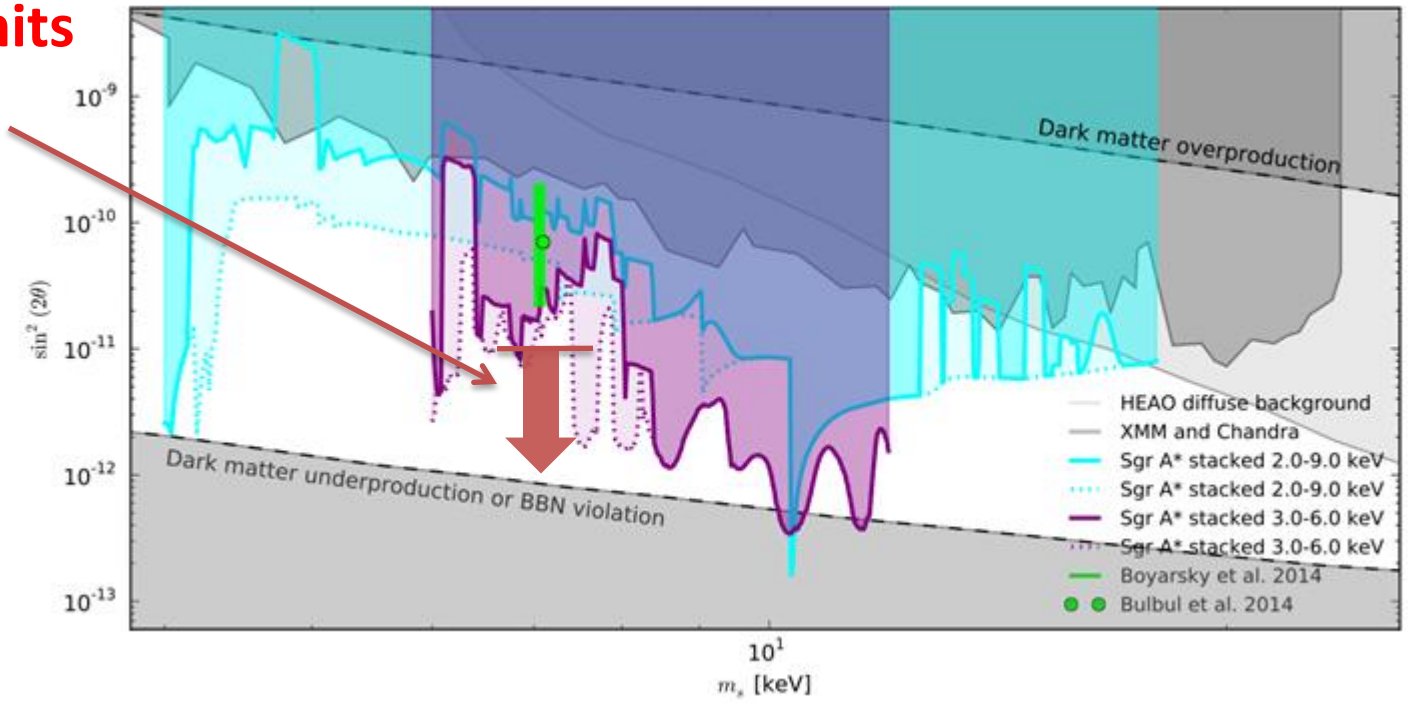


Morphological limits also have advantage where strong spectral lines are present!

Working on extending X-ray limits to additional energies

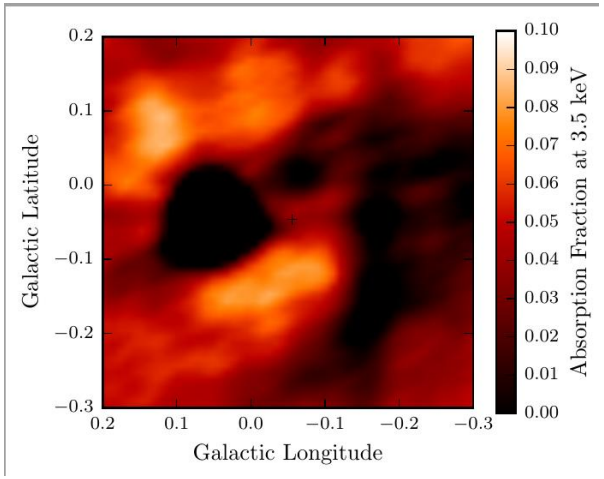
Our GC limits for NFW



Reimer-Sorenson (1405.7943)

Absorption in GC?

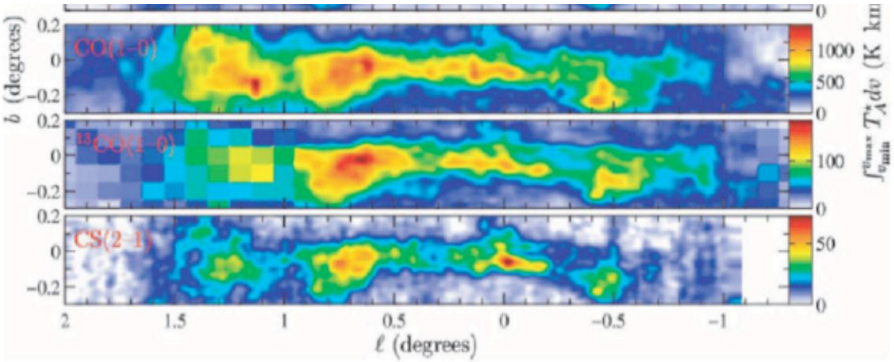
- Optical depth $\propto E^{-3}$
- Quadrupolar shape enhanced from ATCA HI column density template.
- Maximal absorption is <10%, typically only a few percent
- **Limits are unchanged** when including absorption modeling!



Absorption template based on ATCA GC survey + Wilms et al (2000)

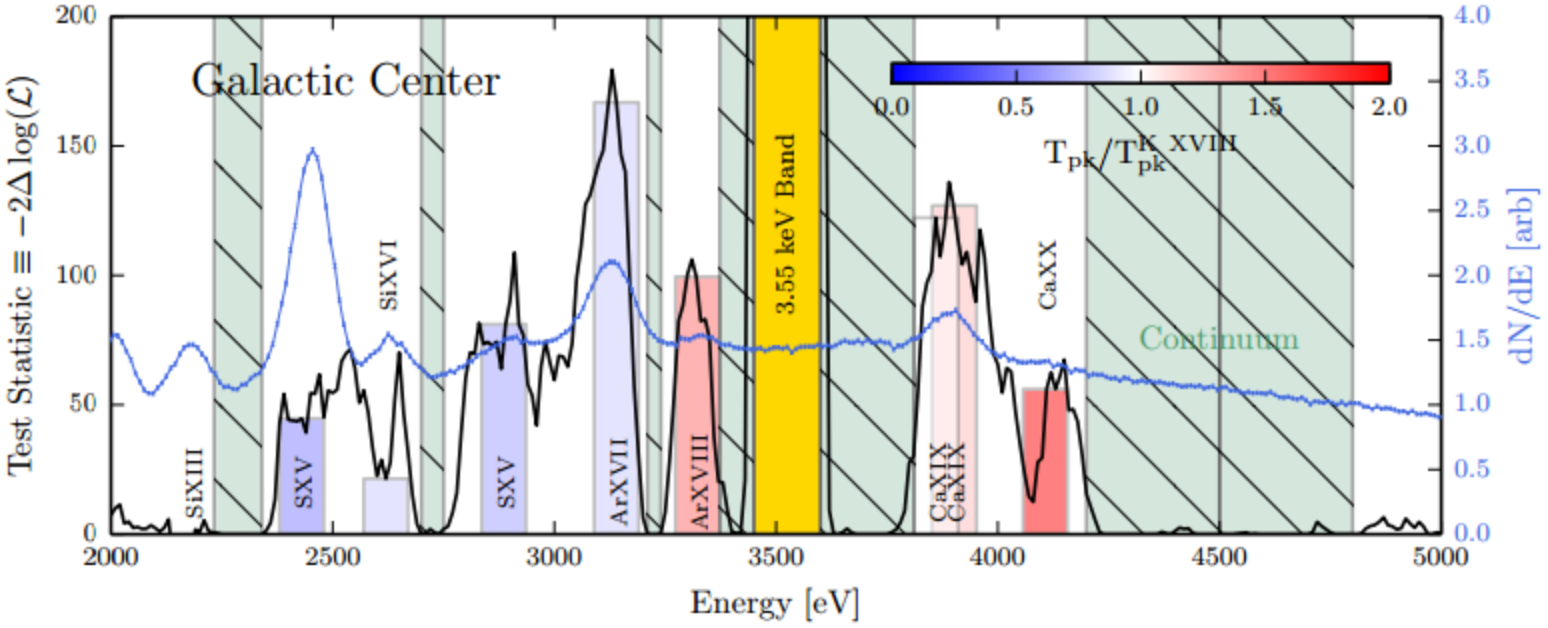
- H_2 optical depth at 3.5 keV

$$\tau \approx 10^{-5} \frac{N_{H_2}}{10^{20}\mathrm{cm}^{-2}}$$



Xiao et al (2006)

Cross-Correlations with Other Lines

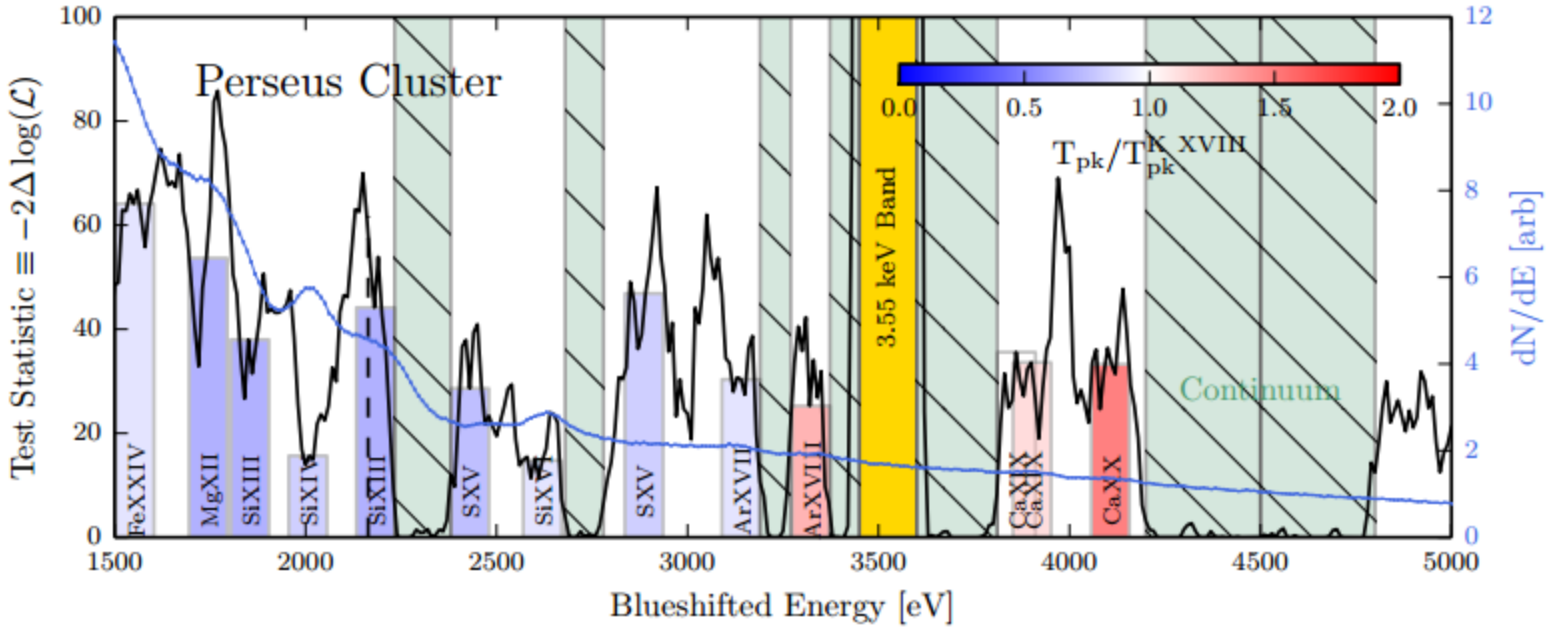


Compare the likelihood of a continuum only fit with that of the continuum plus a narrow 50 eV-wide “sliding window” template which is scanned from 2-5 keV

Emission correlated with the 3.55 keV residual shows up as positive values of black line

Adding an emission line template very significantly improves fit while un-modeled continuum does not.

Cross-Correlations with Other Lines



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3.5 keV Line Conclusions

- Spectrally, inconsistent flux across objects, make a radiatively decaying dark matter interpretation almost impossible to reconcile.

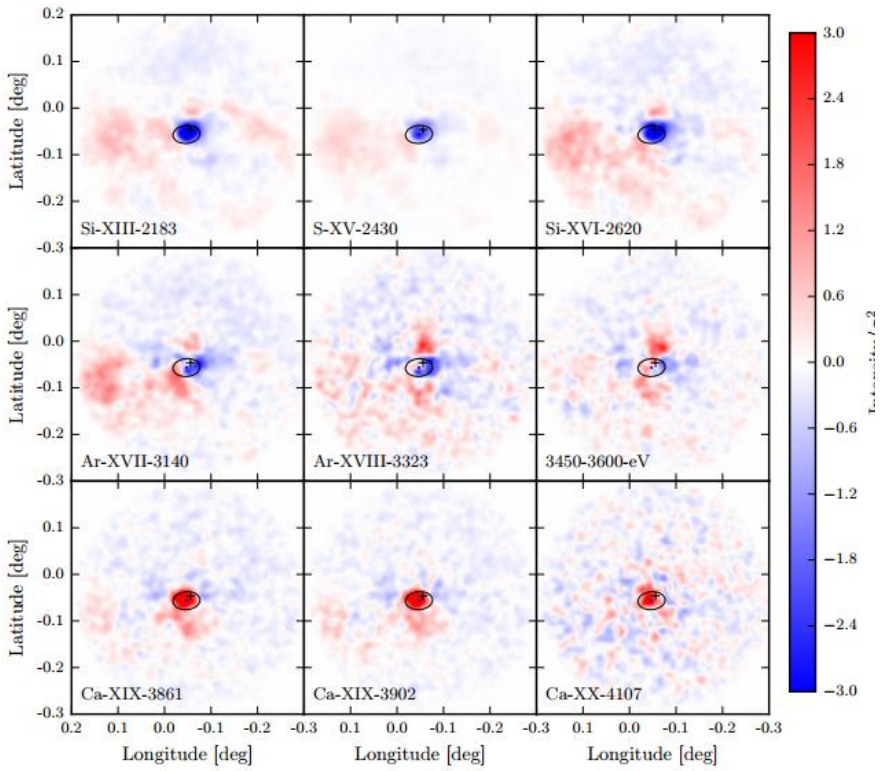
- ALPs ok in Perseus, cannot be responsible for GC line.

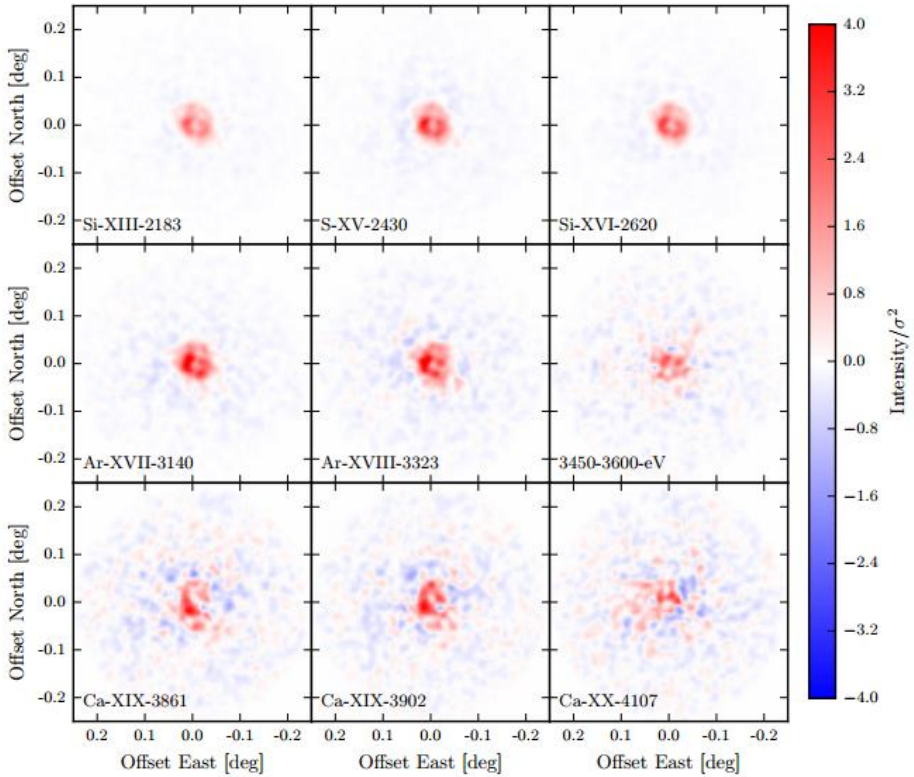
- **Morphologically, the GC signal is completely inconsistent with DM**, and 3.5 keV correlates strongly with nearby atomic transition lines. Perseus is less definitive, but seems to correlate to cool core.

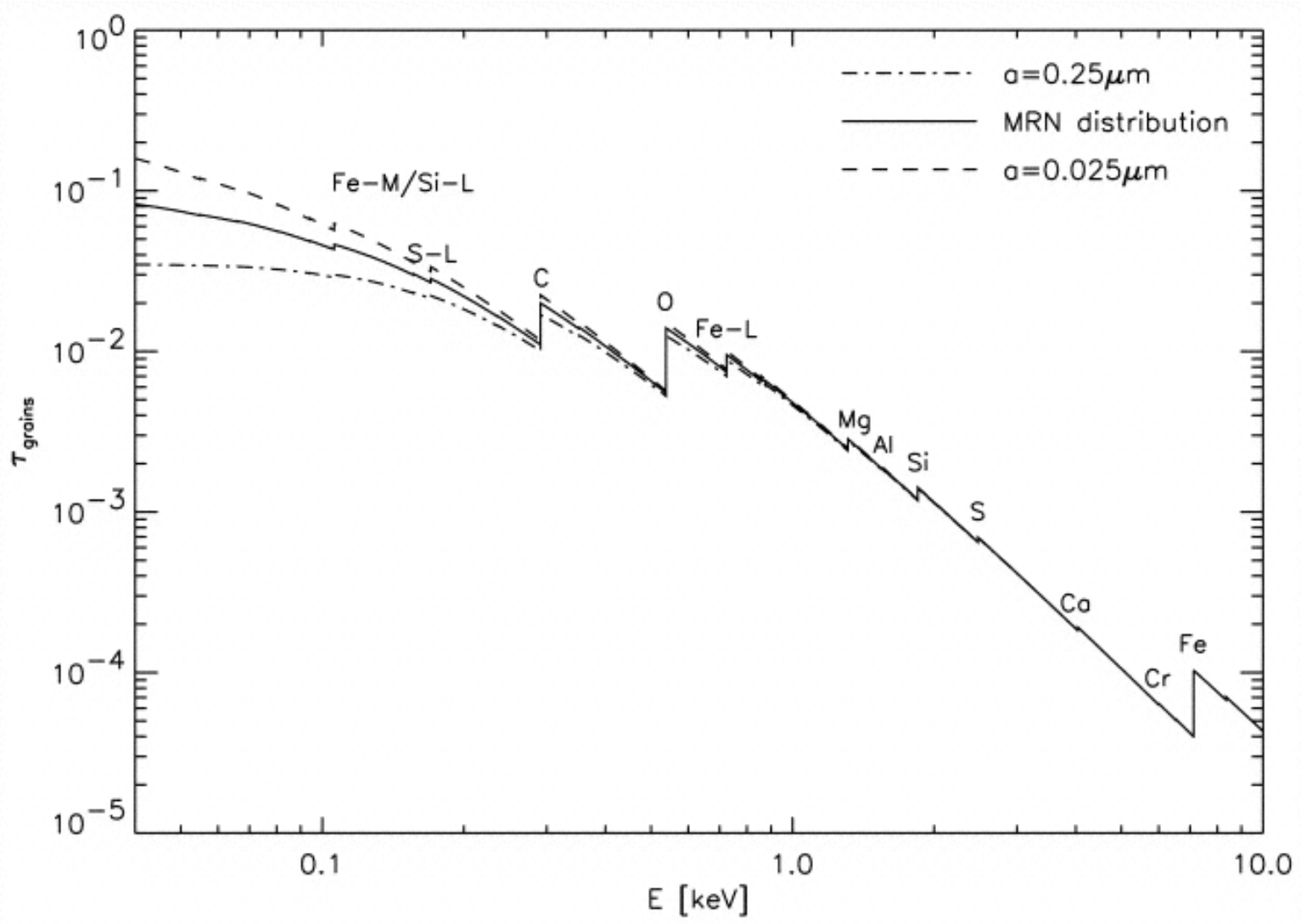
- Morphological limits provide **most stringent and independent constraints at 3.5 keV**. And provide advantage when overlapping bright background lines.

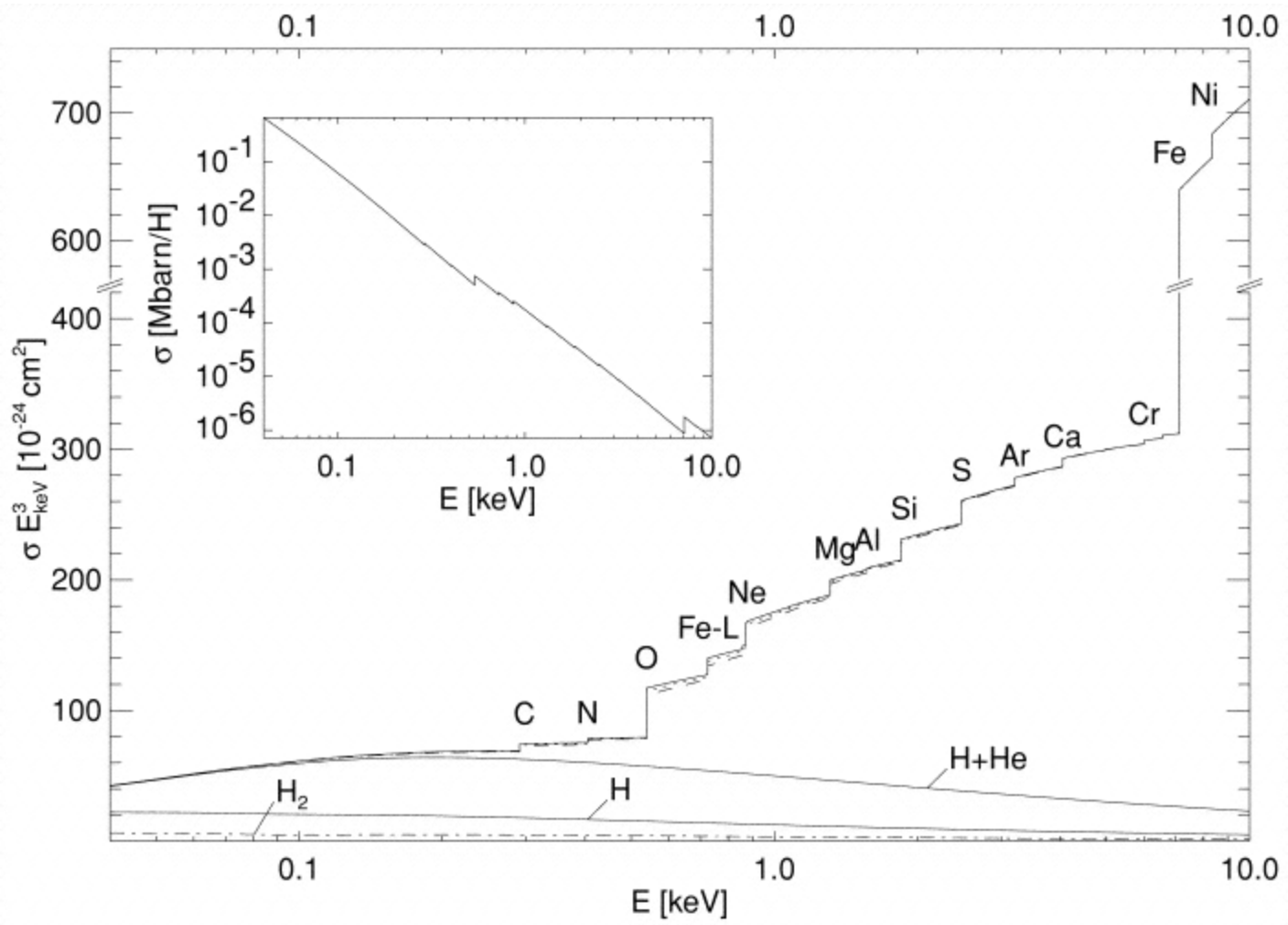
- ASTRO-H will provide spectral resolution to give final word.

Auxillary Slides


Si-XIII-2183
S-XV-2430
Si-XVI-2620
Ar-XVII-3140
Ar-XVIII-3323
3450-3600-eV
Ca-XIX-3861
Ca-XIX-3902
Ca-XX-4107
Latitude [deg]
Longitude [deg]


Si-XIII-2183
S-XV-2430
Si-XVI-2620
Ar-XVII-3140
Ar-XVIII-3323
3450-3600-eV
Ca-XIX-3861
Ca-XIX-3902
Ca-XX-4107
Offset North [deg]
Offset East [deg]
Intensity/σ^2


a=0.25μm
MRN distribution
a=0.025μm
Fe–M/Si–L
S–L
C
O
Fe–L
Mg
Al
Si
S
Ca
Fe
Cr
τ_{grains}
E [keV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.1
1.0
10.0


0.1
1.0
10.0
700
600
400
300
200
100
σ E³keV [10⁻²⁴ cm²]
σ [Mbarn/H]
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
E [keV]
Ni
Fe
Cr
Ca
Ar
S
Si
Al
Mg
Ne
Fe-L
O
C
N
H+He
H
H₂