Status of the 3.5 keV line from X-ray observations: evidence for sterile neutrinos?

- **3.5 keV observation**: Franse's slides at HAP2015
- **Astro. origin: check the adjacent KXIX line?** Iakubovskyi, MNRAS 453, 4097 (2015)
- **3.5 keV already observed in solar flares**: Phillips et al., ApJ 809, 50 (2015)
- **A novel astro scenario (charge exchange)?** Gu et al., A&ALetter (arXiv:1511.06557)

Status of the 3.5 keV Line from X-Ray Observations of Galaxies and Clusters - Evidence for Sterile Neutrinos?

Jeroen Franse

Institutuut Lorentz & Leiden Observatory

HAP, Karlsruhe, Sept 21 2015

With
Alexey Boyarsky, Oleg Ruchayskiy, Dmytro Iakubovskyi, Esra Bulbul

DECAYING DARK MATTER

WIMPs

- Interaction strength at weak scale
- Correct Ω_{DM} for masses Gev – TeV
- Would have short lifetime
- Made stable with new physics

SUPERWIMPs

- Interaction strength weaker-than-weak
- Correct Ω_{DM} for masses of order keV
- Lifetime longer than age of universe
- Allowed to be decaying DM

DECAYING DM IN X-RAYS

For a keV-scale DM particle

$$\textit{Bosonic DM} \rightarrow \gamma + \gamma$$
$$\textit{Fermionic DM} \rightarrow \gamma + \nu$$

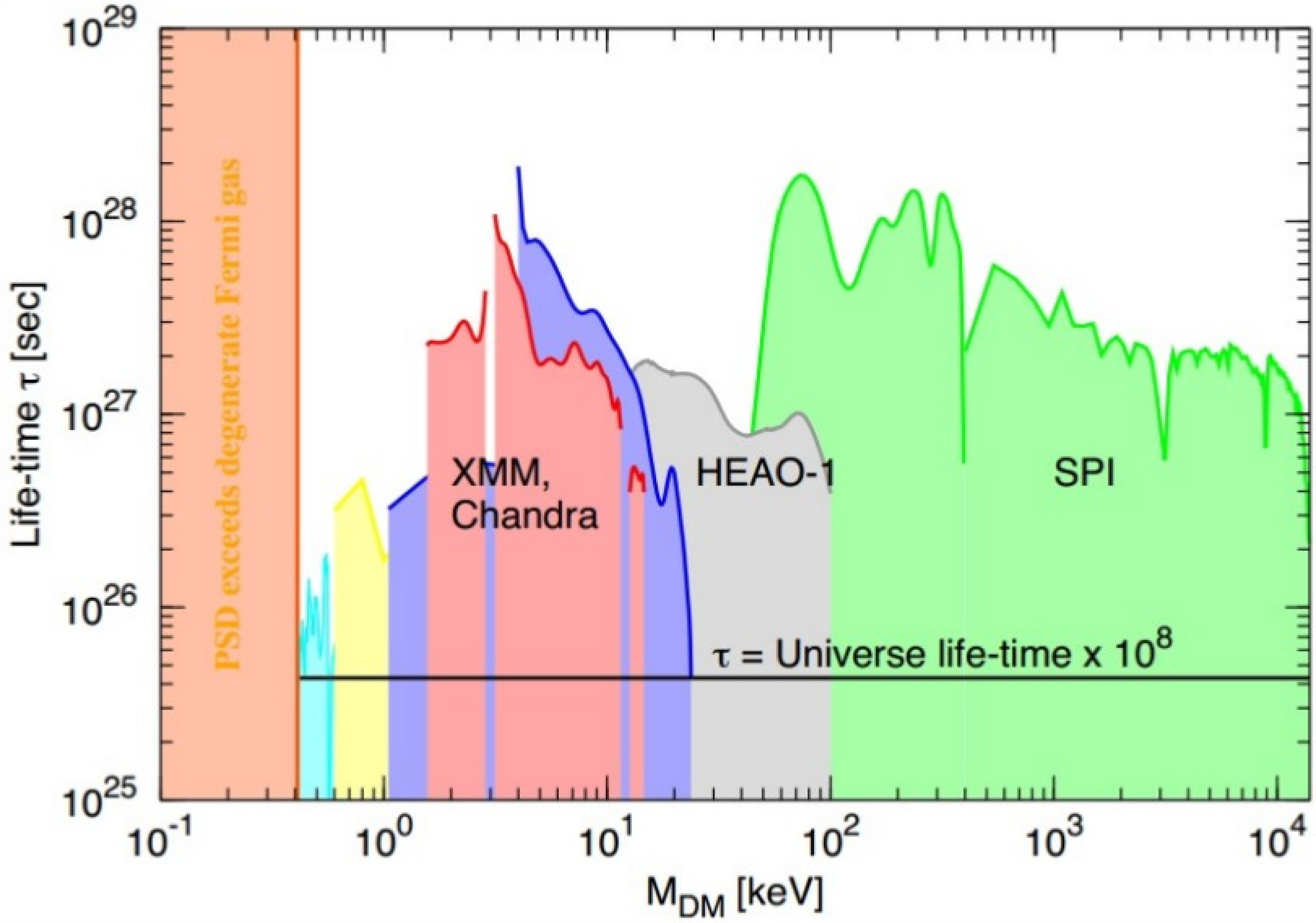
resulting in a ***monochromatic line*** with

$$E_\gamma = \frac{1}{2} m_{DM} c2$$

and velocity width

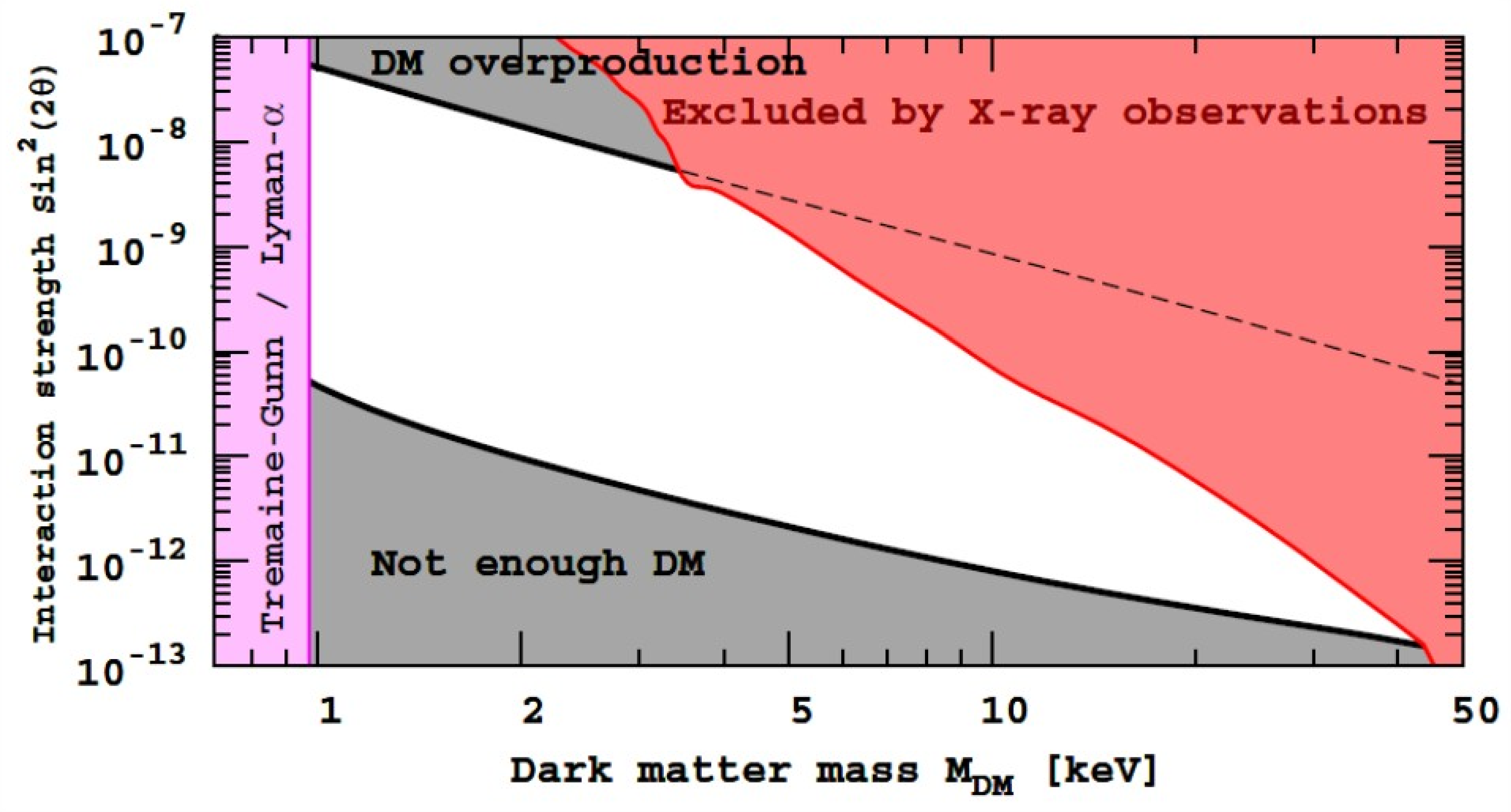
$$\frac{\Delta E}{E_\gamma} \sim \frac{v_{vir}}{c} \sim 10^{-4} - 10^{-2}$$

DECAYING DM IN X-RAYS



Boyarsky; Ruchayskiy; Riemer-Sorenson; Abazajian; Watson; and more (2005-2010)

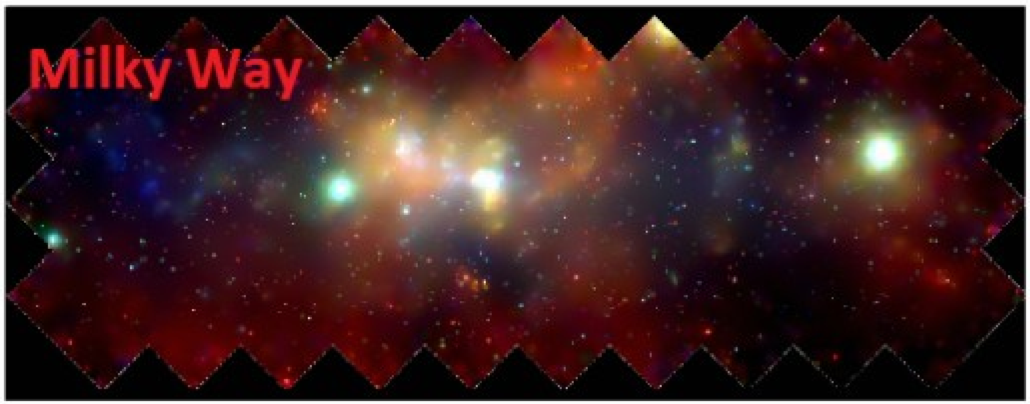
STERILE NEUTRINOS IN X-RAYS

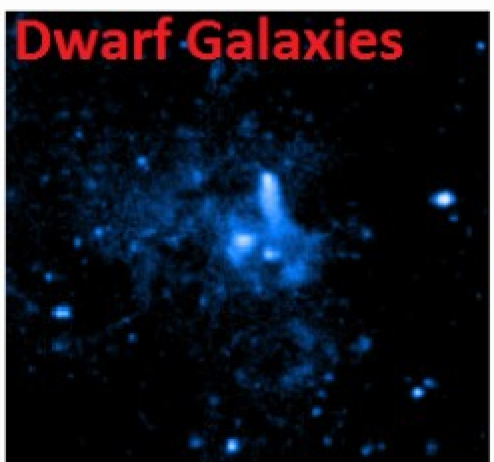


TARGET SOURCES

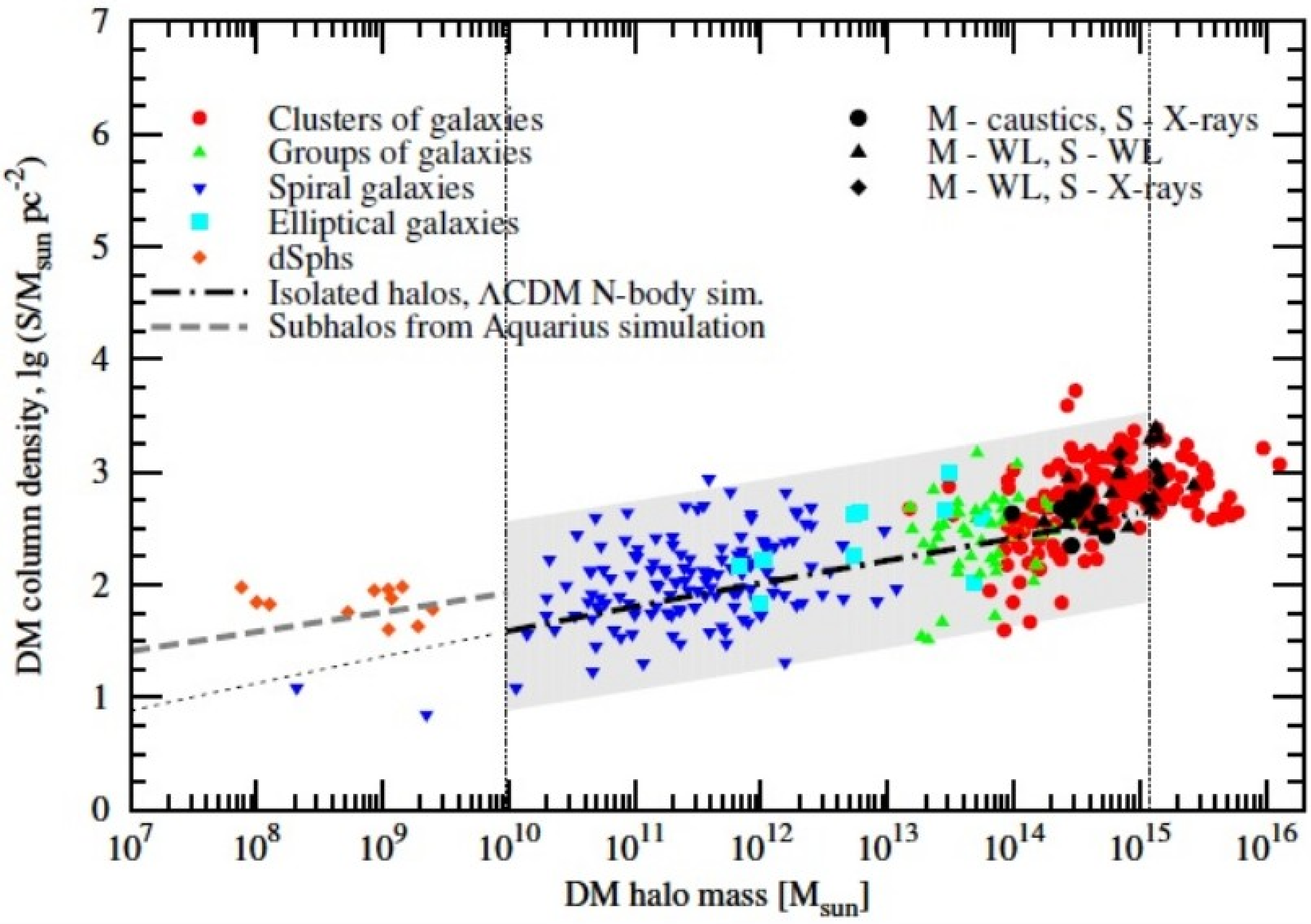
Good targets are dark matter dominated. Specifically, sources with high expected decay signal strength

$$\text{signal} \propto \text{DM mass in FoV / distance}^2$$





TARGET SOURCES



Boyarsky et al. 2006, 2009

DETECTIONS OF THE UNIDENTIFIED 3.5 KEV LINE

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

ESRA BULBUL[1,2], MAXIM MARKEVITCH[2], ADAM FOSTER[1], RANDALL K. SMITH[1] MICHAEL LOEWENSTEIN[2], AND SCOTT W. RANDALL[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

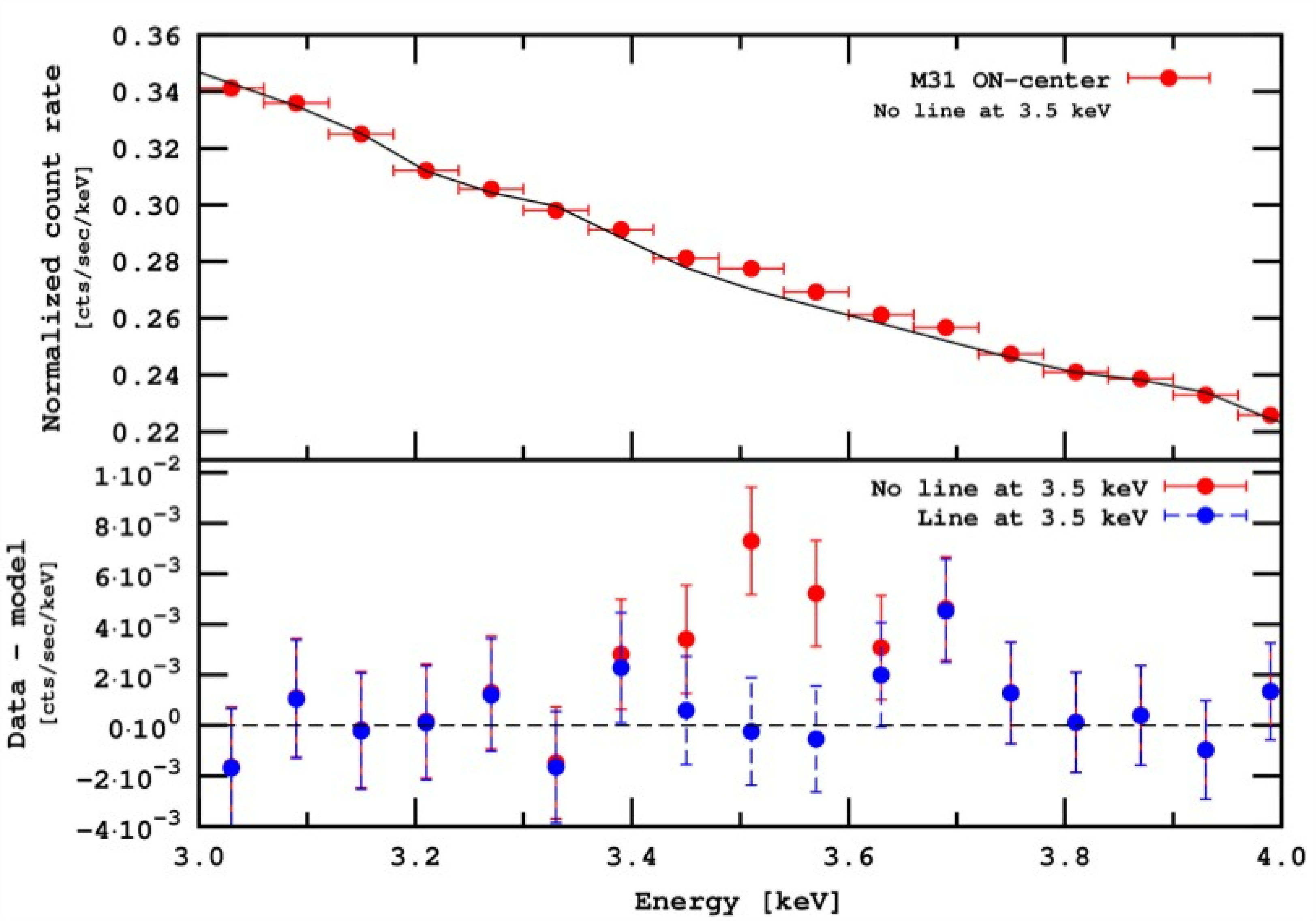
ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

PRL (2014) [1402.4119]

DETECTION AT ∼3.55 KEV IN ANDROMEDA (M31)



Boyarsky et al. 2014a [1402.4119]

Detections of the Unidentified 3.5 keV Line

Boyarsky et al. 2014a [1402.4119]

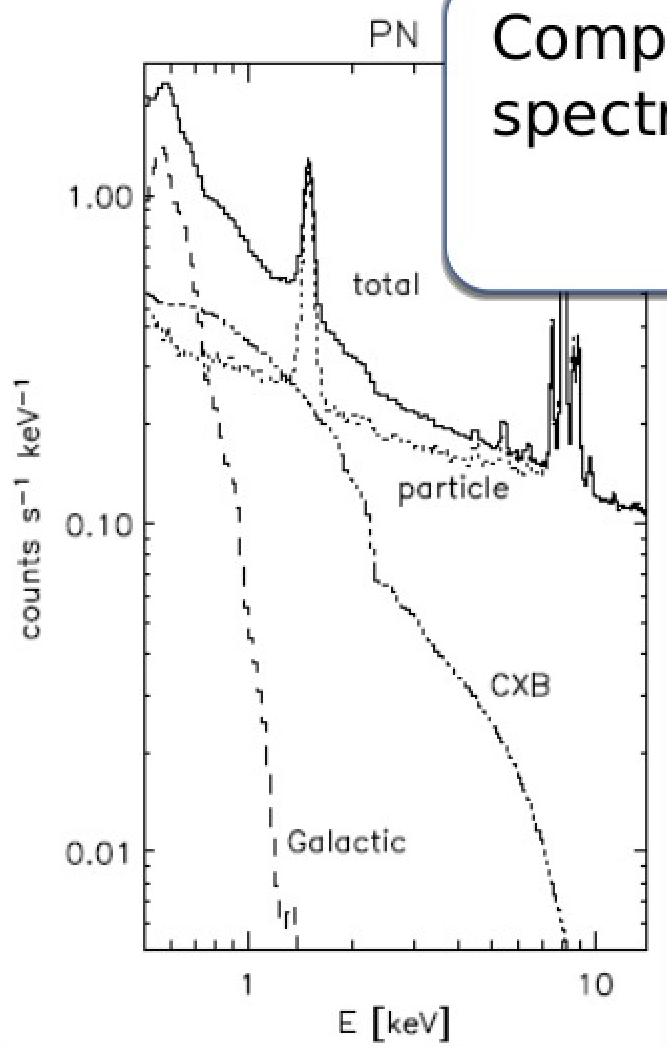
M31 galaxy	XMM-Newton, center & outskirts	4.4σ
Perseus cluster	XMM-Newton, outskirts only	

Bulbul et al. 2014 [1402.2301]

73 clusters	XMM-Newton (MOS & PN), centers only, up to $z = 0.4$	5σ & 4σ
Perseus cluster	Chandra, center only	3.5σ

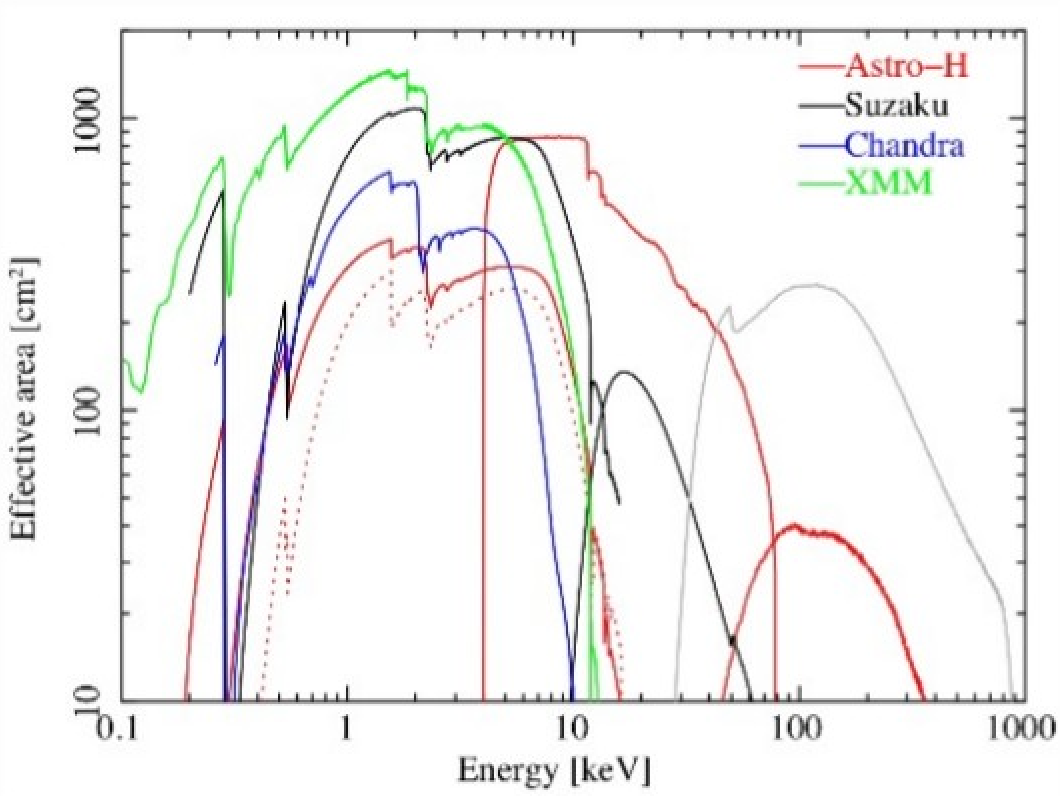
Estimated global significance $\sim$**6.6**σ

SOME NOTES ON X-RAY ASTRONOMY



Complicated ***instrumental*** (particle-induced) spectral and spatial features

Non-trivial telescope ***response***



Lumb et al. 2005

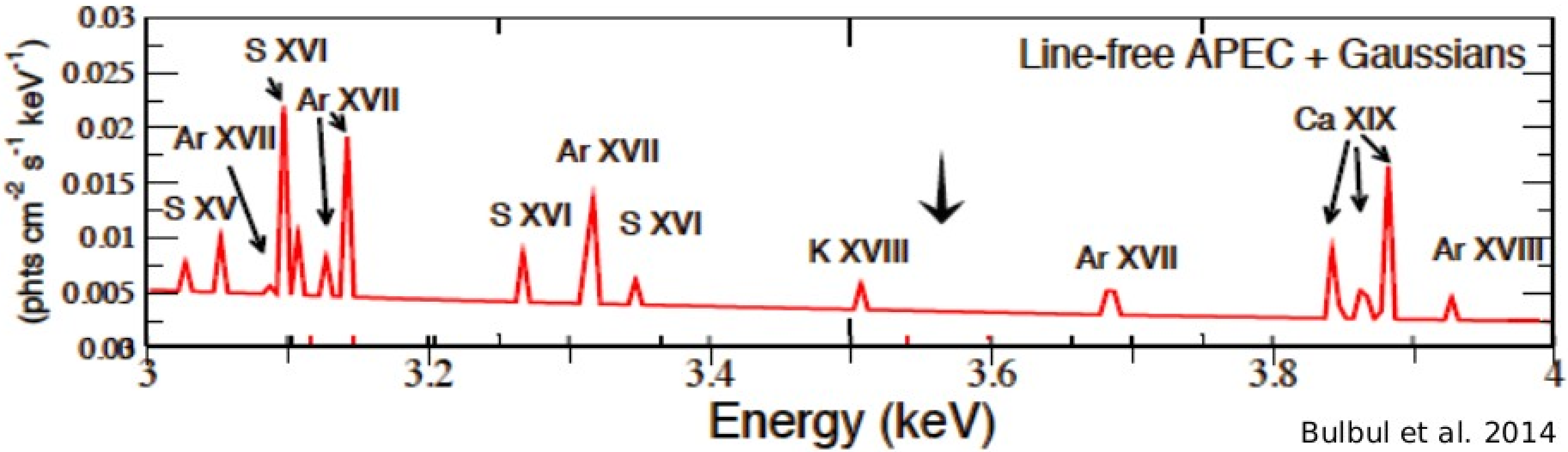
INSTRUMENTAL ORIGIN?

Instrumental origin unlikely

1. Detected in 4 different detectors
   - XMM-Newton MOS and PN detectors
   - Chandra ACIS-S, ACIS-I
2. Line redshifts correctly with sources
   - Clusters stacked in object restframe (Bulbul et al)
   - Line in Perseus redshifted correctly at $\sim 2\sigma$
3. Not detected in blank sky dataset
   - 16 Msec of 'empty' sky

ATOMIC LINE?

Unlikely: can not explain consistently all observations



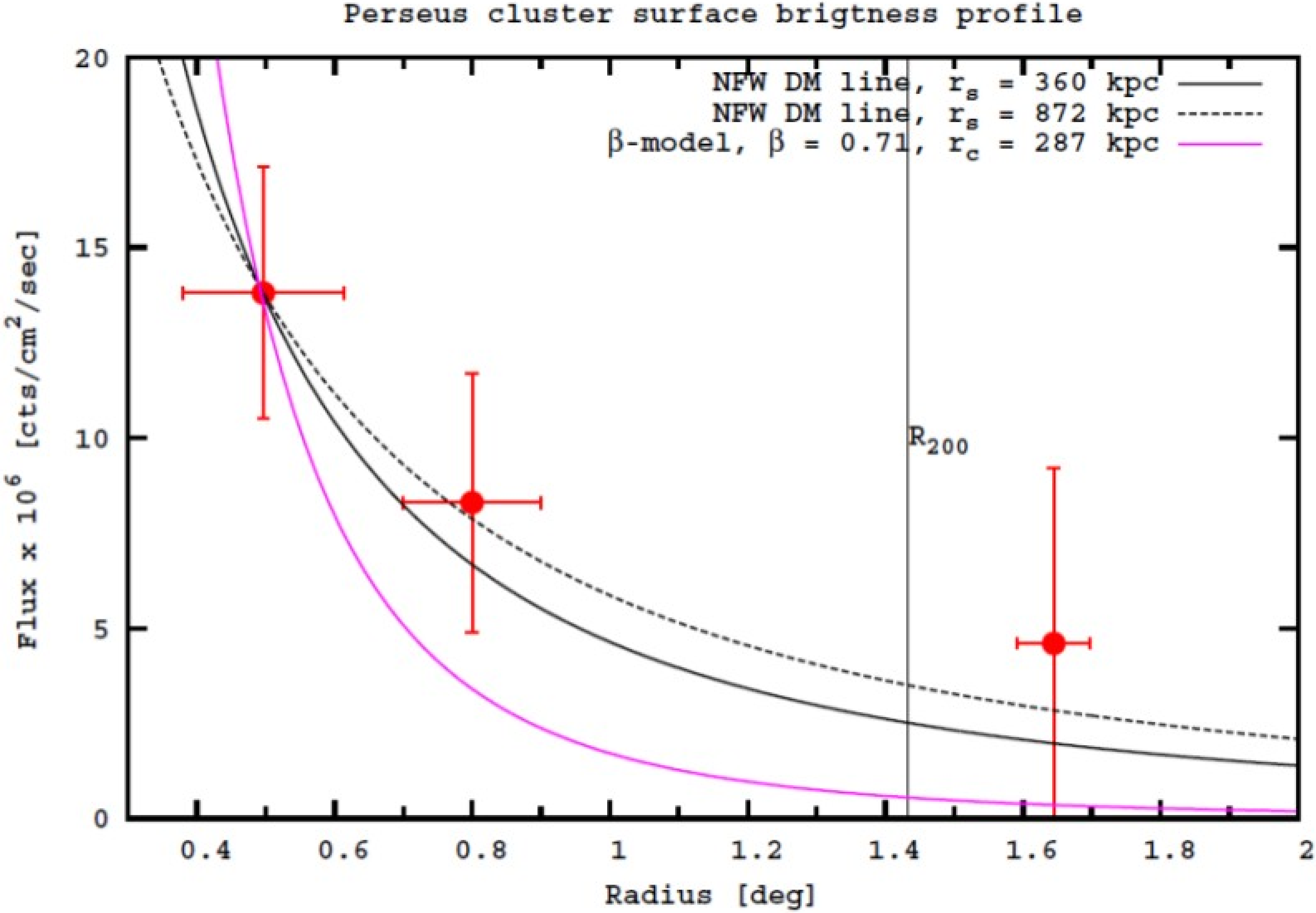
Bulbul et al. 2014

M31 line is stronger than other atomic emission

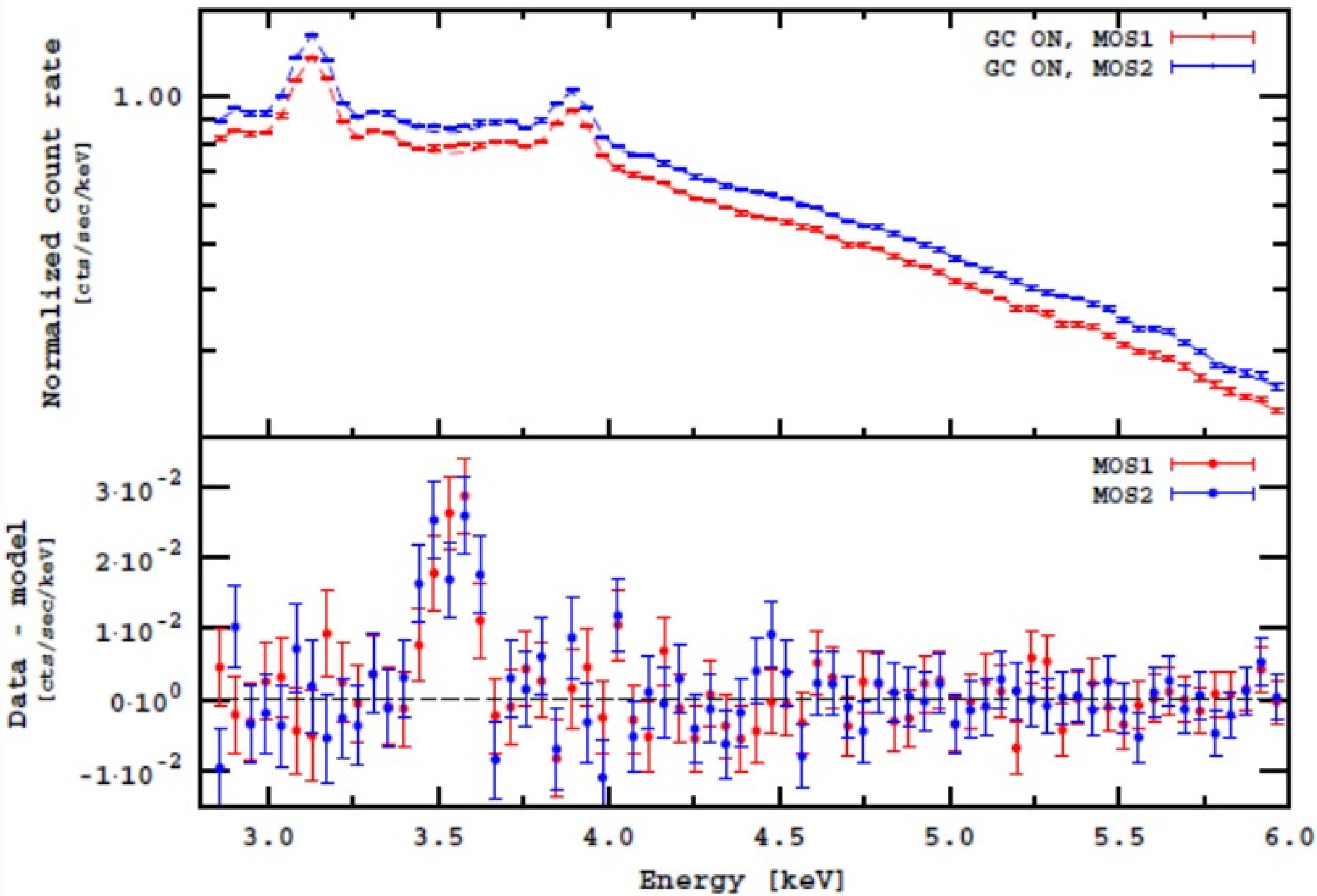
CLUSTERS need anomalous line ratios of a factor $\sim 20-30$

DARK MATTER DECAY?

The line flux should be proportional to mass / distance^2



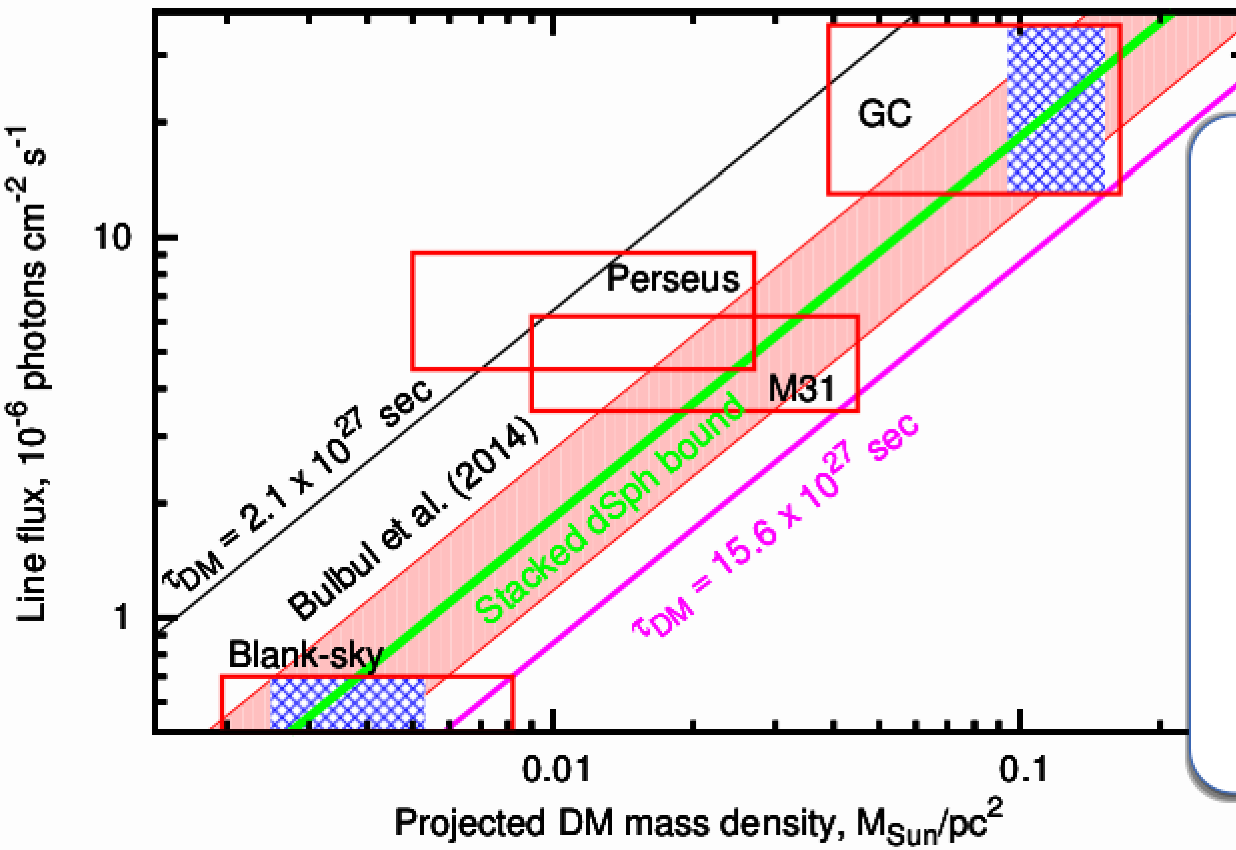
GALACTIC CENTER



Boyarsky et al. 2014b [1408.4388]

Dwarf Galaxies

- Nearby, dark matter dominated object
- Well-known DM content (Geringer-Sameth+ 2014)
- Very gas-poor (***do not expect any atomic lines***)



Malyshev, Neronov & Eckert [1408.3531]

Stacked analysis of all XMM archival dwarf data.

$$\tau > 10^{27}$$

Perseus with Suzaku

Two papers using the ***same*** data

Urban et al. [1411.0050]

The ~ 3.55 keV line is detected in the center, but seems too strong compared to non-detections in other Suzaku clusters.

Tamura et al. [1412.1869]

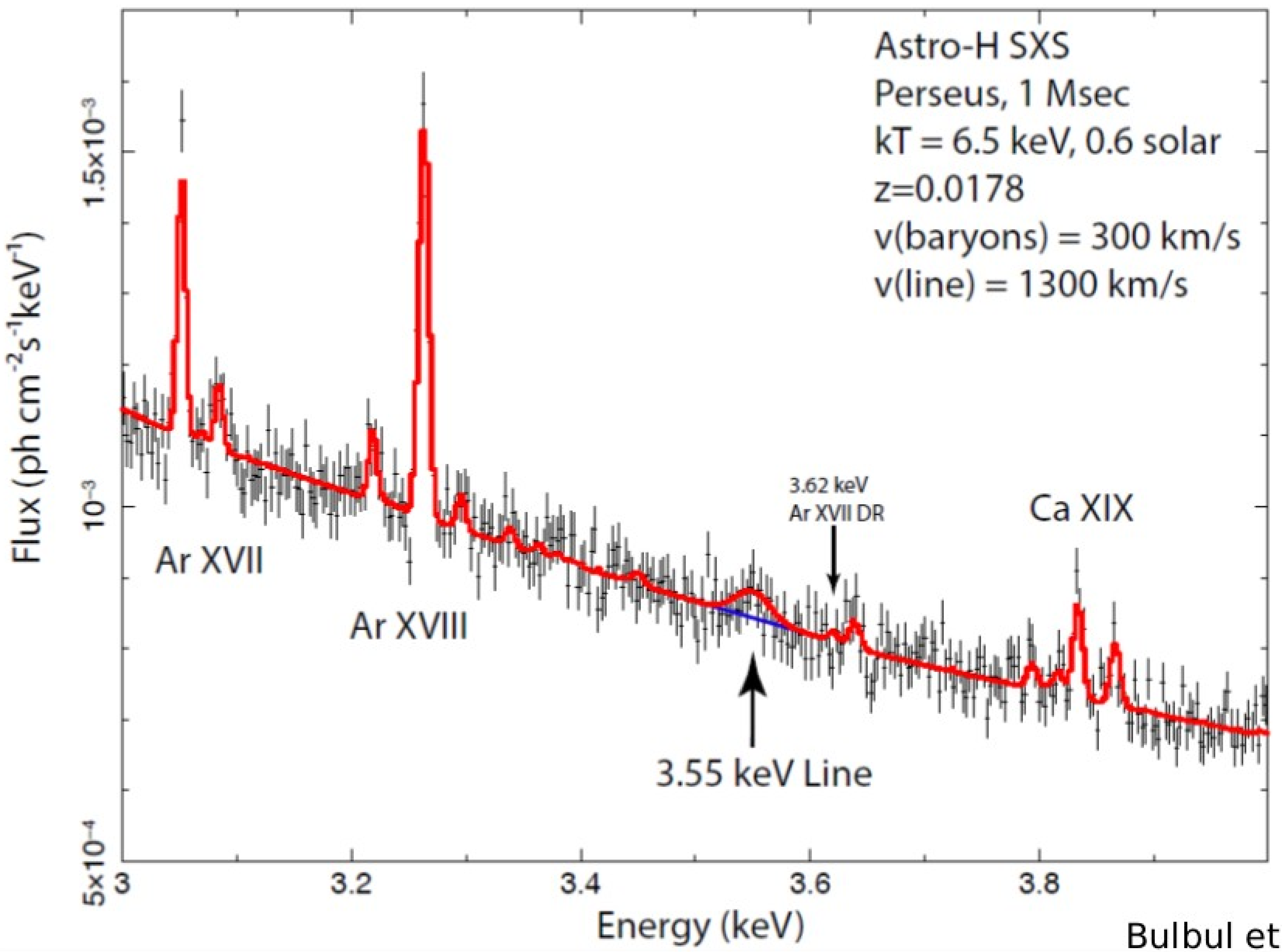
No detection of the ~ 3.55 keV line reported; does not comment on Urban et al.

Imminent: Lots of Draco

We have been ***awarded 1.4 Ms*** of XMM observations of the Draco dwarf galaxy this year

- Highest expected signal of all dwarf galaxies (Geringer-Sameth+ 2014, Lovell+ 2014)
- Very gas-poor (***do not expect any atomic lines***)
- We will be able to **confirm or deny the DM origin** of the 3.5 keV line somewhere **in 2016**.

Future: Astro-H



Bulbul et al.(2014)

- **Astro. origin: check the adjacent KXIX line?** Iakubovskyi, MNRAS 453, 4097 (2015)
- **3.5 keV already observed in solar flares**: Phillips et al., ApJ 809, 50 (2015)
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The line flux for a multitemperature APEC (Smith et al. 2001) model with electron temperatures $T_{e,i}$ is

$$F\,[\mathrm{ph\ cm^{-2}\ s^{-1}}] \equiv 10^{14} \sum_i \left[\epsilon(T_{e,i})\, A_i\, N_i\right], \quad (1)$$

where $\epsilon(T_{e,i})$ is the line emissivity (in $\mathrm{cm^3\ s^{-1}}$), A_i is the abundance of the line-emitting element (with respect to the Solar values adopted in Anders & Grevesse 1989),

$$N_i = \frac{10^{-14}}{4\pi D_A^2 (1+z)^2} \int n_e n_H \mathrm{d}V$$

Assuming the abundances of all components to be the same ($A_i^{(\mathrm{ref})} = A^{(\mathrm{ref})}$, $A_i^{(\mathrm{new})} = A^{(\mathrm{new})}$), we obtain the more convenient expression used in Bulbul et al. (2014a,b) and Jeltema & Profumo (2014, 2015), namely

$$F^{(\mathrm{new})} = F^{(\mathrm{ref})} \frac{A^{(\mathrm{new})}}{A^{(\mathrm{ref})}} \frac{\sum_i \left[\epsilon^{(\mathrm{new})}(T_{e,i})\, N_i\right]}{\sum_i \left[\epsilon^{(\mathrm{ref})}(T_{e,i})\, N_i\right]}. \quad (5)$$

The predicted line flux $F^{(\mathrm{new})}$ depends linearly on the potassium-to-metal abundance ratio $A^{(\mathrm{new})}/A^{(\mathrm{ref})}$, which is not measured directly

Following Bulbul et al. (2014b) and Jeltema & Profumo (2014), we avoid the above-mentioned uncertainty by studying the emission lines of *the same* element, so that $A^{(\mathrm{new})} \equiv A^{(\mathrm{ref})}$ and (4) simplifies:

$$F^{(\mathrm{new})} = F^{(\mathrm{ref})} \frac{\sum_i \left[\epsilon^{(\mathrm{new})}(T_{e,i})\, N_i\right]}{\sum_i \left[\epsilon^{(\mathrm{ref})}(T_{e,i})\, N_i\right]}. \quad (6)$$

To calculate line emissivities, we used the astrophysical atomic emission line data base AtomDB (Foster et al. 2014). The lat-

In order to account for the finite energy resolution of imaging spectrometers, we broadened each emission line with a Gaussian shape:

$$f(E) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right),$$

where E_0 is the line position, σ is the energy dispersion [note that for the Gaussian line, full width at half-maximum (FWHM) is defined

Table 1. Emission lines for the 3.4–3.8 and 4.1–4.5 keV ranges from the AtomDB v3.0.2 data base. Level transitions are in AtomDB format. The Potassium lines are marked bold for clarity. The range of T_e shows when the emissivity of a given line is $>10^{-20}$ ph cm^3 s^{-1}. $T_{e,max}$ and ϵ_{max} indicate the temperature at which the maximal emissivity of the line is reached, and the maximal value of the line emissivity; $\epsilon_{2.16}$ and $\epsilon_{4.32}$ are the line emissivities at $T_e = 2.16$ and 4.32 keV.

Position [eV]	Ion	Transition	T_e range [keV]	$T_{e,max}$ [keV]	$\epsilon_{max}/\epsilon_{2.16}/\epsilon_{4.32}$ [10^{-20} ph cm^3 s^{-1}]
3423.78	S XVI	38 → 1	1.08–10.8	2.16	6.8/6.8/3.9
3424.84	S XVI	39 → 1	1.08–21.6	2.16	13.8/13.8/9.4
3440.48	S XVI	51 → 1	1.37–8.62	2.16	3.9/3.9/2.2
3440.52	S XVI	52 → 1	1.08–13.7	2.16	8.7/8.7/6.0
3443.61	Cl XVI	31 → 1	1.08–2.72	1.72	3.0/2.4/—
3451.92	S XVI	66 → 1	1.37–6.84	2.16	2.9/2.9/1.9
3451.95	S XVI	67 → 1	1.37–10.8	2.16	5.1/5.1/3.4
3460.11	S XVI	83 → 1	1.72–5.44	2.16	2.1/2.1/1.4
3460.13	S XVI	84 → 1	1.37–6.84	2.16	3.0/3.0/2.0
3475.04	**K XVIII**	**2 → 1**	**0.862–5.44**	**2.16**	**11.8/11.8/3.5**

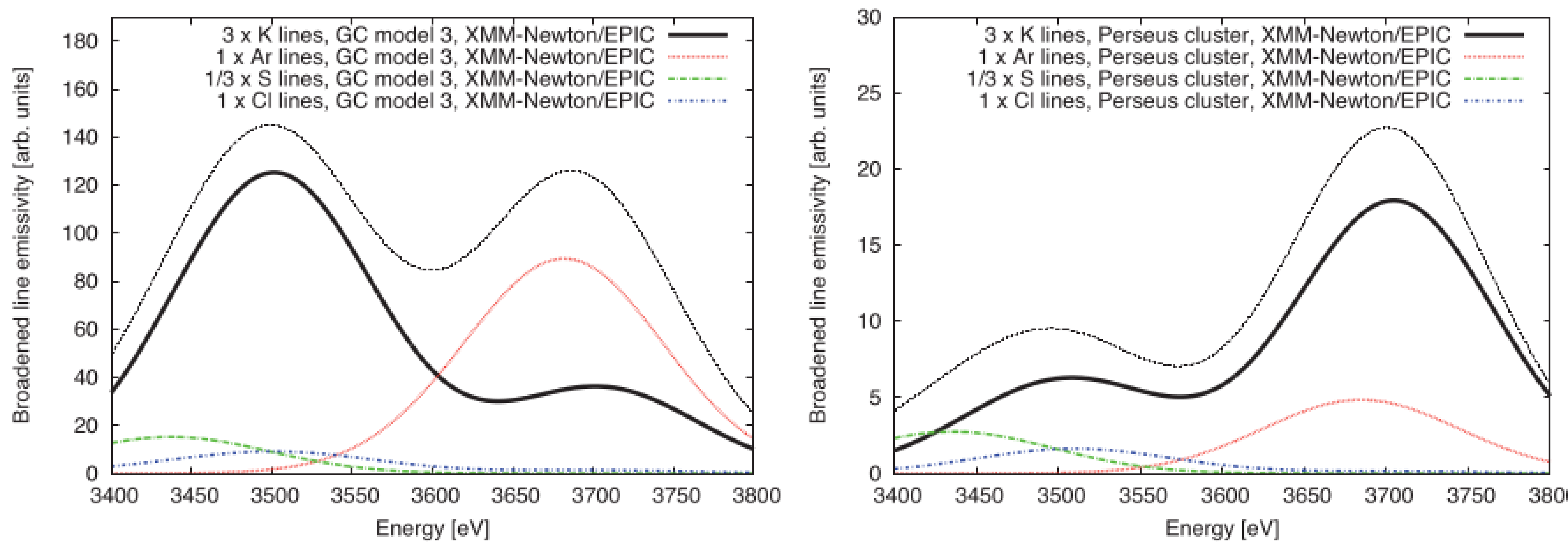

Figure 2. Left: Line emissivities broadened with $\sigma_{XMM} = 60$ eV as a function of energy for the three-component model of Jeltema & Profumo (2015) of the Galactic Centre. The relative S, Ar, Cl and K abundances are set to 1/3 : 1 : 1 : 3 (see section 2.2 of Jeltema & Profumo 2015). The thin dashed line shows the total emissivity. Right: Broadened line emissivities as a function of energy for the best-fitting two-component model of the Perseus cluster given by Bulbul et al. (2014a). The relative element abundances in Solar units given by Anders & Grevesse (1989) are the same as in the left panel.

Table 1. Emission lines for the 3.4–3.8 and 4.1–4.5 keV ranges from the AtomDB v3.0.2 data base. Level transitions are in AtomDB format. The Potassium lines are marked bold for clarity. The range of T_e shows when the emissivity of a given line is $>10^{-20}$ ph cm^3 s^{-1}. $T_{e,max}$ and ϵ_{max} indicate the temperature at which the maximal emissivity of the line is reached, and the maximal value of the line emissivity; $\epsilon_{2.16}$ and $\epsilon_{4.32}$ are the line emissivities at $T_e = 2.16$ and 4.32 keV.

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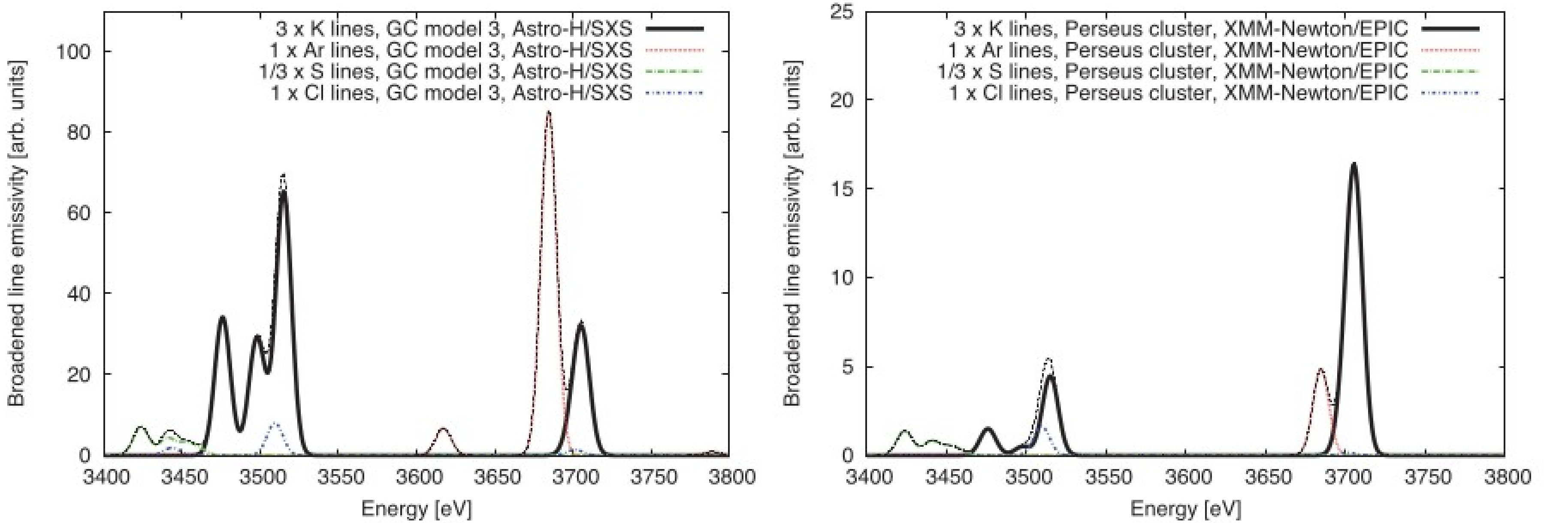


Figure 3. As Fig. 2, but broadened with *Astro-H*/SXS or *Micro-X* energy resolution $\sigma_{SXS} = 5$ eV (see text).

ABSTRACT

It is currently unclear whether the new line at $\sim$3.5 keV, recently detected in various samples of galaxy clusters, the Andromeda galaxy and the central part of our Galaxy, is caused by potassium emission lines. By using the latest astrophysical atomic emission line data base, AtomDB v. 3.0.2, we show that the most promising method to check its potassium origin directly will be the study of the K XIX emission line complex at $\sim$3.7 keV using forthcoming X-ray imaging spectrometers such as the Soft X-ray spectometer onboard the *Astro-H* mission or the microcalorimeter onboard the *Micro-X* sounding rocket experiment. In order to further reduce the remaining (factor of $\sim$3–5) uncertainty of the 3.7/3.5 keV ratio, more precise modelling should be performed, including the removal of significant spatial inhomogeneities, a detailed treatment of background components, and the extension of the modelled energy range.

- **Astro. origin: check the adjacent KXIX line?** Iakubovskyi, MNRAS 453, 4097 (2015)
- **3.5 keV already observed in solar flares**: Phillips et al., ApJ 809, 50 (2015)
- **A novel astro scenario (charge exchange)?** Gu et al., A&ALetter (arXiv:1511.06557)

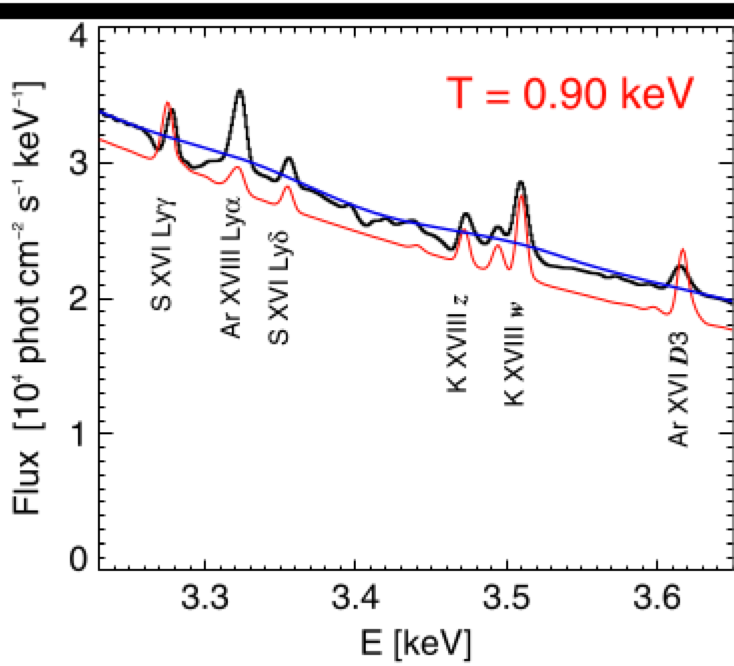
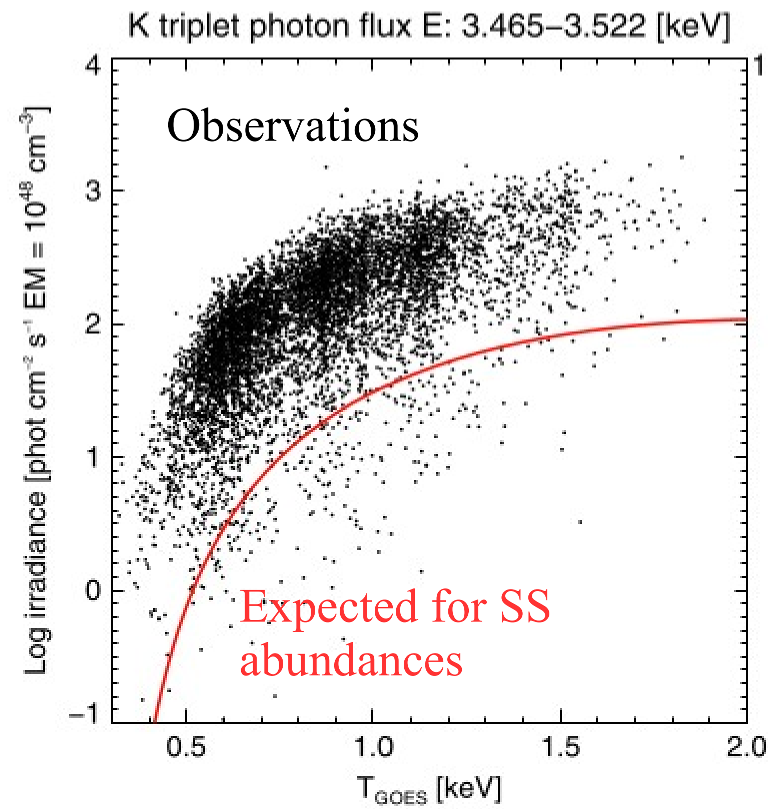


Figure 1. Thick black curve: summed RESIK spectrum for the entire data set (9295 spectra taken during 101 solar flares) in the channel 1 energy range (3.23–3.65 keV). The average temperature for this spectrum, estimated by the closest fit of a CHIANTI spectrum to the observed, is 0.90 keV (10.5 MK), somewhat higher than the averaged value of T_{GOES} (0.82 keV). Principal line features are identified by ion labels; more detailed information of lines occurring in this range are given in Table 1. Blue curve: RESIK spectrum convolved with a Gaussian profile with FWHM of 100 eV to match the resolution of the *XMM-Newton* detectors. Red curve: Theoretical spectrum from CHIANTI with temperature equal to 0.90 keV. Abundances from the CHIANTI "coronal–ext" (Feldman 1992) abundance set are assumed.



Reminder from previous slides:

line is stronger than other atomic emission

need anomalous line ratios of a factor $\sim 20-30$

→ *from solar observations ~ 10*

emitters. Here it is pointed out that the K XVIII lines have been observed in numerous solar flare spectra at high spectral resolution with the RESIK crystal spectrometer and also appear in *Chandra* HETG spectra of the coronally active star σ Gem. In addition, the solar flare spectra at least indicate a mean coronal potassium abundance, which is a factor between 9 and 11 higher than the solar photospheric abundance. This fact, together with the low statistical quality of the *XMM-Newton* spectra, completely account for the ~3.5 keV feature and there is therefore no need to invoke a sterile neutrino interpretation of the observed line feature at ~3.5 keV.

- **Astro. origin: check the adjacent KXIX line?** Iakubovskyi, MNRAS 453, 4097 (2015)
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- **A novel astro scenario (charge exchange)?** Gu et al., A&ALetter (arXiv:1511.06557)

We propose a novel scenario that the 3.5 keV ULF can be explained to some extent by charge exchange (hereafter CX) processes between hot cosmic plasma and cold neutral gas. Astronomical CX X-rays were first discovered in near-Earth comets (Lisse et al. 1996) and now the related detections have been expanded to various types of objects, from neighboring planets to distant galaxy clusters (see the review by Dennerl et al. 2010). A qualitative discussion on the possible CX lines near 3.5 keV was presented in BU14. Compared to their model, our new plasma code, as described in detail in Gu et al. (2015), is expected to produce more realistic line emissivities. Our code incorporates the velocity-dependent cross-section data with resolved final states based on the most up-to-date theoretical calculations.

al. 1996),[1] to calculate X-ray emission due to charge exchange. The flux is given by

$$F = \frac{1}{4\pi D_{\rm l}^2} \int n_{\rm I} n_{\rm N} \upsilon \sigma_{\rm I,N}(\upsilon, n, l, S) dV, \quad (1)$$

where $D_{\rm l}$ is the luminosity distance of the object, $n_{\rm I}$ and $n_{\rm N}$ are the densities of ionized and neutral media, respectively, υ is the collisional velocity, $\sigma_{\rm I,N}$ is the charge exchange cross section, and V is the interaction volume. The cross section is usually in

Based on our own calculation, we propose a new emission line near 3.5 keV from charge exchange between bare sulfur ions and neutral hydrogen atoms. The CX line center is close to that of the ULF reported by BU14, BO14, U15, and Iakubovskyi et al. (2015). Next, we examine whether or not the CX line is responsible for the ULF. This immediately poses three questions to be addressed. (i) Assuming the ULF is indeed created by CX, what is the origin of the CX emission? (ii) Are the properties (e.g., flux and central energy) of the predicted CX line consistent with the ULF observation? And (iii) why, given that CX lines are expected for many ions, is only the S XVI feature detected? Below we examine these issues one by one.

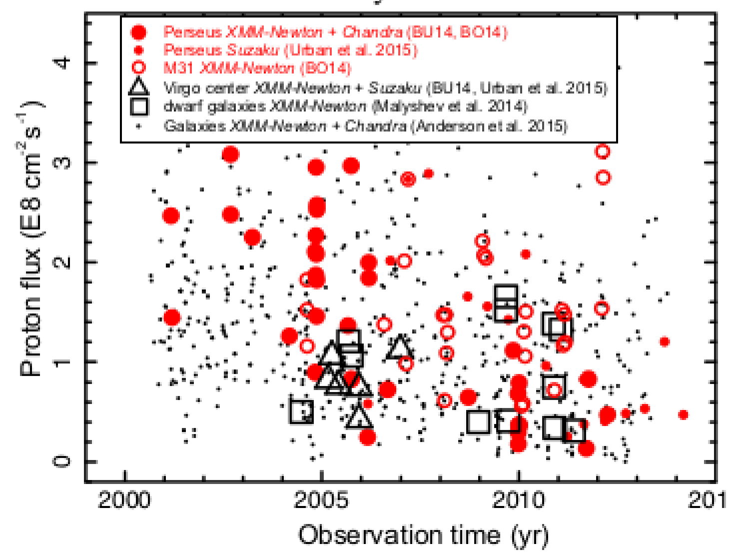

Fig. 3. Solar wind proton flux, taken from the ACE SWEPAM, at periods of X-ray observations of the Perseus cluster, Virgo cluster center, M31, and two samples of dwarf galaxies and normal galaxies. The ULF detection and nondetection cases were plotted in red and black, respec-

scenario, the observed 3.5 keV line flux in clusters can be naturally explained by an interaction in an effective volume of ~1 $\rm kpc^3$ between a ~3 keV temperature plasma and cold dense clouds moving at a few hundred km $\rm s^{-1}$. The S XVI lines at ~3.5 keV also provide a unique diagnostic of the charge exchange phenomenon in hot cosmic plasmas.