

STATUS OF THE 3.5 KEV LINE FROM X-RAY OBSERVATIONS OF GALAXIES AND CLUSTERS - EVIDENCE FOR STERILE NEUTRINOS?

Jeroen Franse

Instituut Lorentz & Leiden Observatory

HAP, Karlsruhe, Sept 21 2015

With

Alexey Boyarsky, Oleg Ruchayskiy, Dmytro Iakubovskiy, 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

$$\text{Bosonic DM} \rightarrow \gamma + \gamma$$

$$\text{Fermionic DM} \rightarrow \gamma + \nu$$

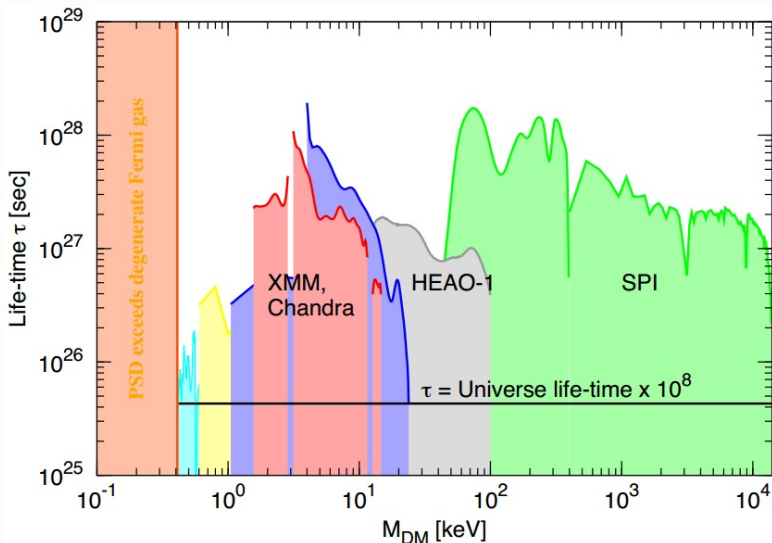
resulting in a **monochromatic line** with

$$E_\gamma = \frac{1}{2} m_{\text{DM}} c^2$$

and velocity width

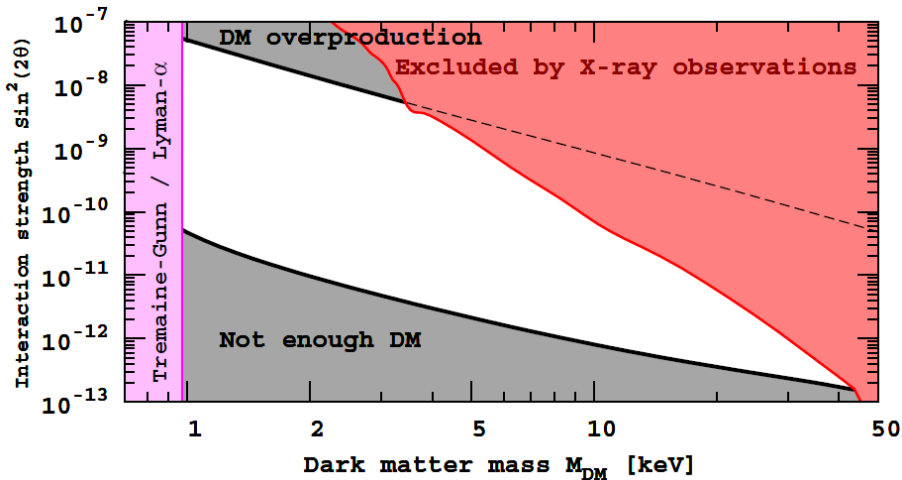
$$\frac{\Delta E}{E_\gamma} \sim \frac{v_{\text{vir}}}{c} \sim 10^{-4} - 10^{-2}$$

DECAYING DM IN X-RAYS

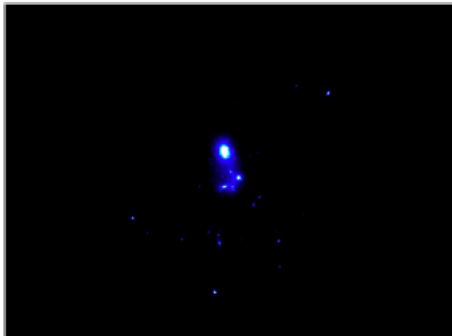
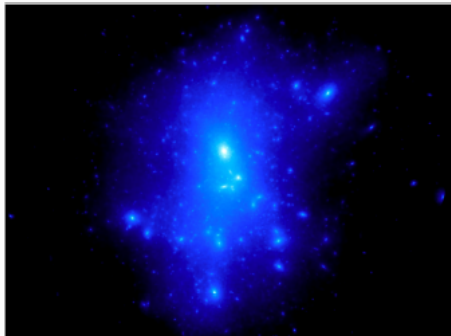


Boyarsky; Ruchayskiy; Riemer-Sorenson; Abazajian; Watson; and more (2005-2010)

STERILE NEUTRINOS IN X-RAYS



TARGET SOURCES



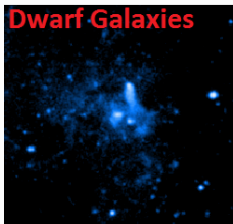
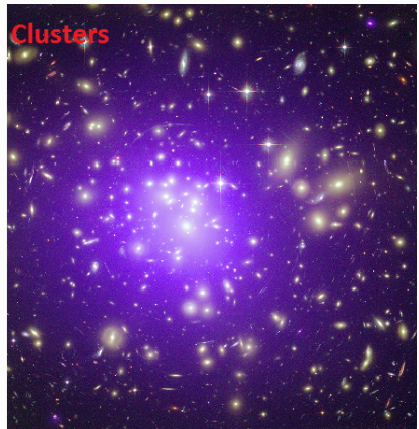
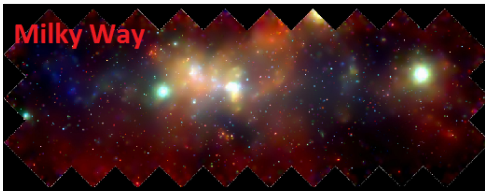
Decay is not as sensitive to density as ***annihilation***,
giving more freedom in source selection

simulation from B. Moore

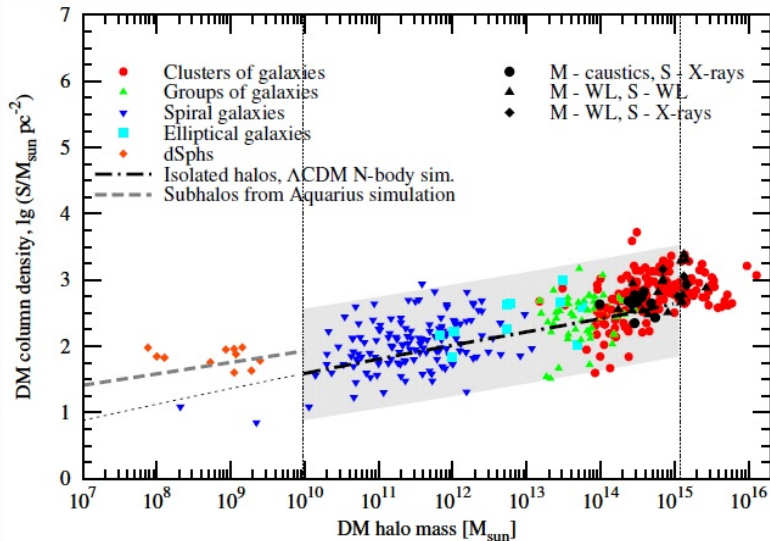
TARGET SOURCES

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

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



TARGET SOURCES



Boyarsky et al. 2006, 2009



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

ESRA BULBUL^{1,2}, MAXIM MARKEVITCH², ADAM FOSTER¹, RANDALL K. SMITH¹ MICHAEL LOEWENSTEIN², AND SCOTT W. RANDALL¹

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. Boyarsky¹, O. Ruchayskiy², D. Iakubovskiy^{3,4} and J. Franse^{1,5}

¹Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands

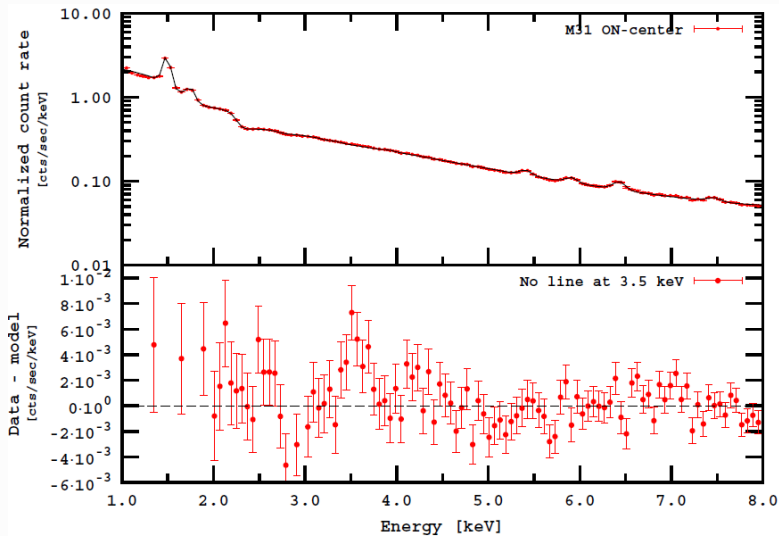
²Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

³Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine

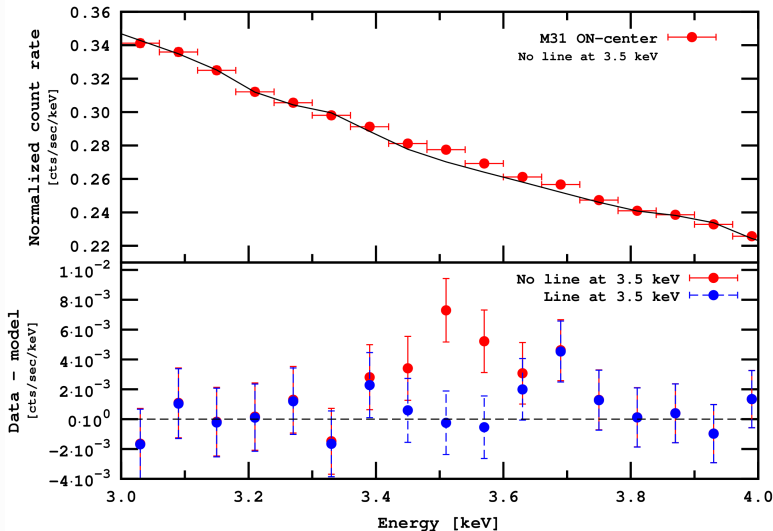
⁴National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine

⁵Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

PRL (2014) [1402.4119]

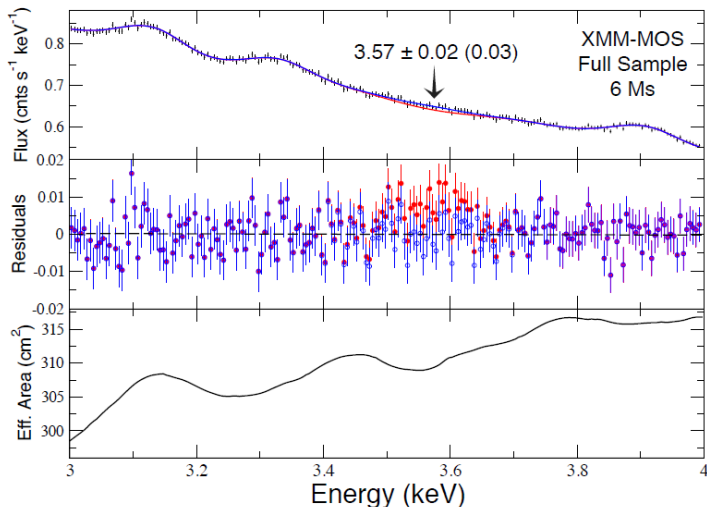
DETECTION AT ~ 3.55 keV IN ANDROMEDA (M31)

Boyarsky et al. 2014a [1402.4119]

DETECTION AT ~ 3.55 keV IN ANDROMEDA (M31)

Bovaryskiy et al. 2014a [1402.4119]

DETECTION IN CLUSTER STACK (BULBUL ET AL.)



Bulbul et al. 2014

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]

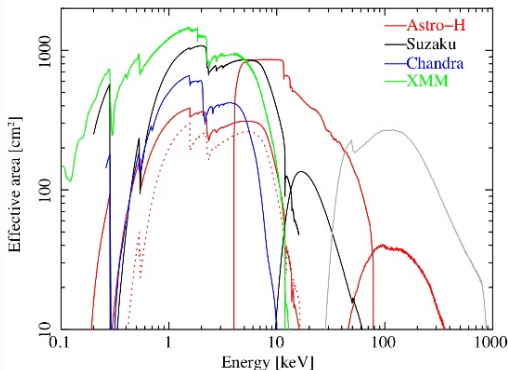
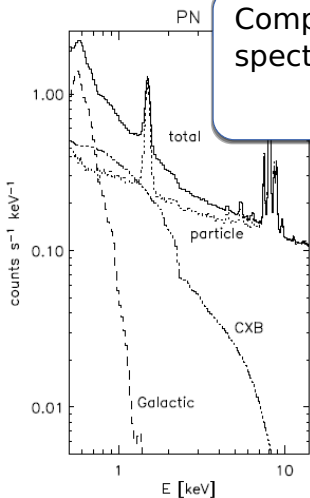
73 clusters	XMM-Newton (MOS & PN), centers only, up to $z = 0.4$	5σ & 4σ
Perseus cluster	Chandra, center only	3.5σ

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

SOME NOTES ON X-RAY ASTRONOMY

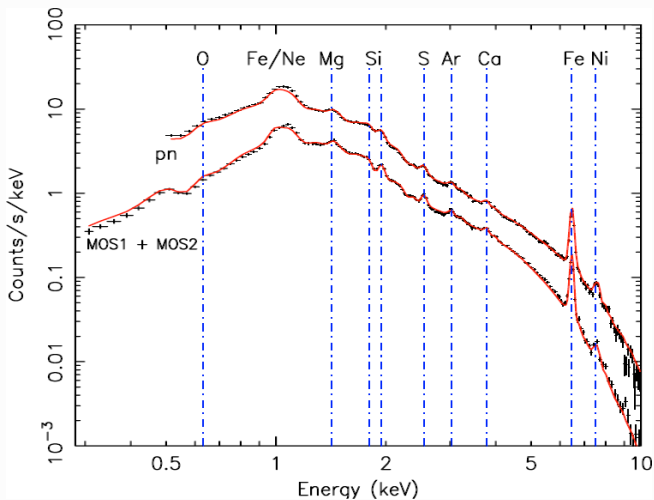
Complicated *instrumental* (particle-induced) spectral and spatial features

Non-trivial telescope *response*



Lumb et al. 2005

ATOMIC LINES IN HOT PLASMA



Typical cluster spectrum

Werner et al. 2006

ATOMIC LINES IN HOT PLASMA

Various elements are synthesized in stars and expelled during supernovae or stellar winds.

- Abundances ***vary with environment***
- Abundances have ***large*** theoretical and observational ***uncertainties***

Atoms are excited in high temperature plasmas and emit characteristic lines.

Intensity depends on

- Plasma ***temperature***
- Element ***abundance***

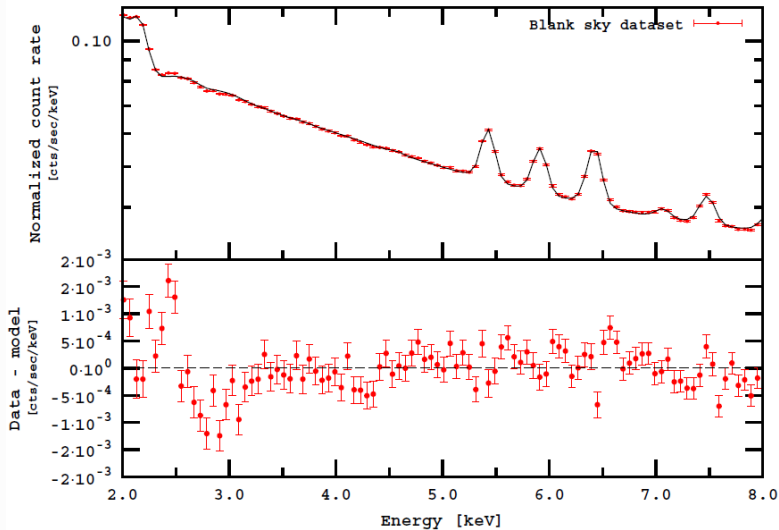
INSTRUMENTAL ORIGIN?



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

BLANK-SKY SPECTRUM

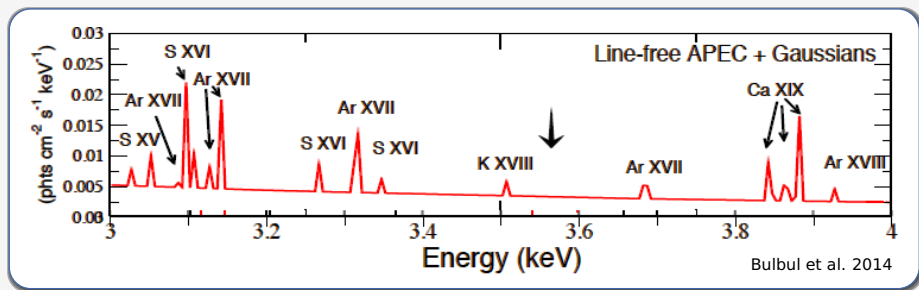


Boyarsky et al. 2014a [1402.4119]

ATOMIC LINE?



Unlikely: can not explain consistently all observations

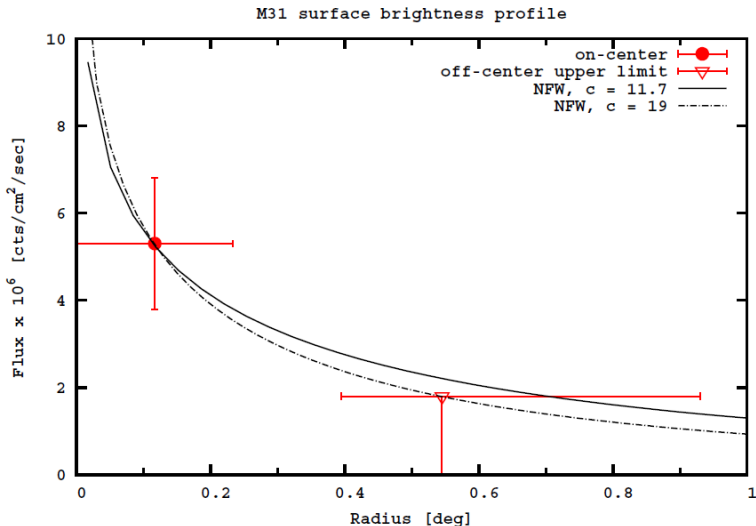


M31 line is **stronger** than other atomic emission
 CLUSTERS need **anomalous line ratios** of a factor $\sim 20 - 30$

DARK MATTER DECAY?



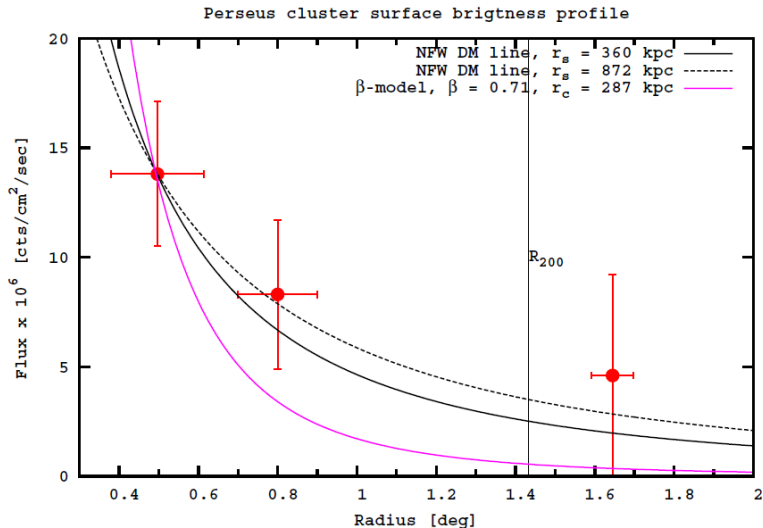
The line flux should be proportional to mass / distance²



DARK MATTER DECAY?

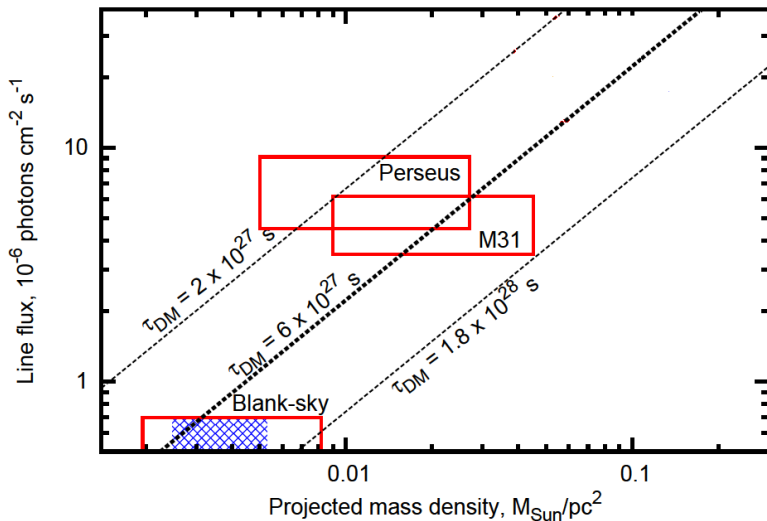


The line flux should be proportional to mass / distance²

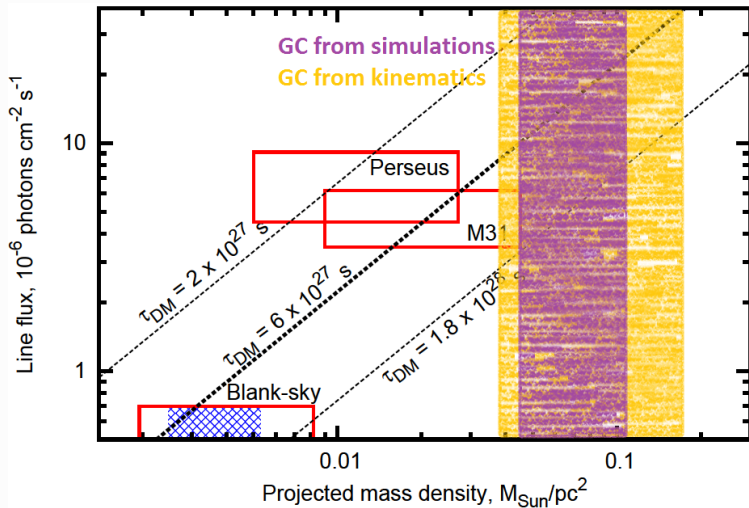


DARK MATTER DECAY?

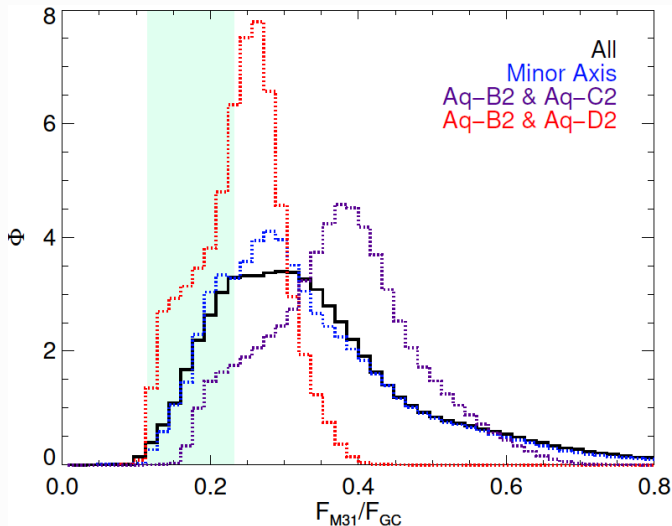
The line flux should be proportional to mass / distance²



Expect large signal from GC \rightarrow “easy” cross-check

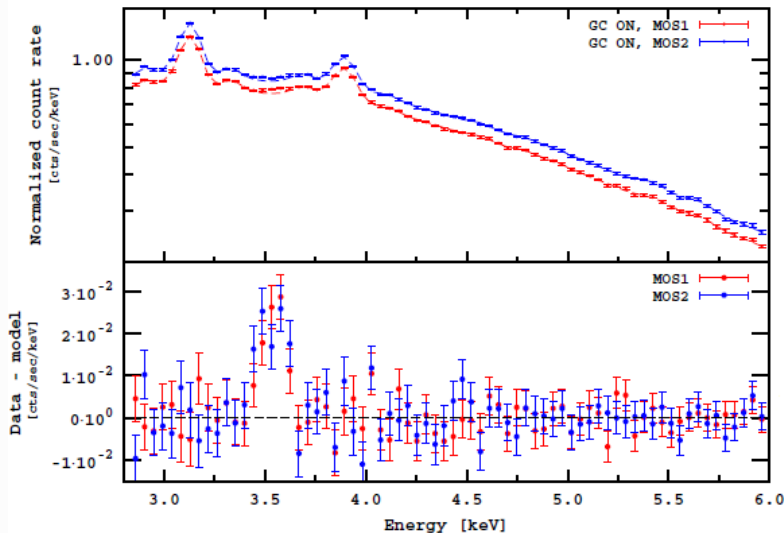


GALACTIC CENTER VS. M31 SIMULATIONS



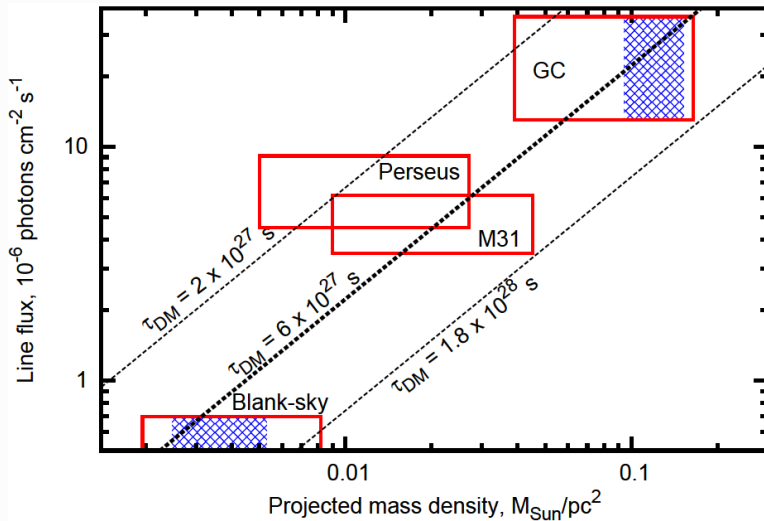
Lovell et al. 2014 [1411.0311]

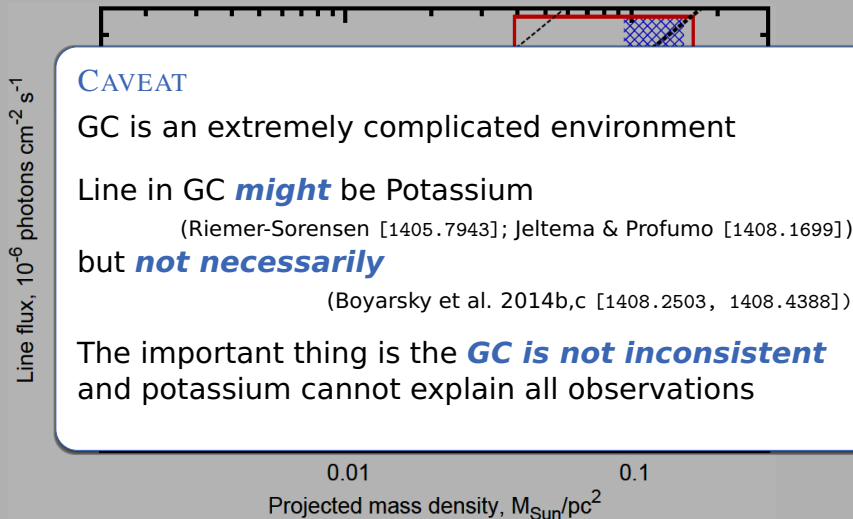
GALACTIC CENTER



Boyersky et al. 2014b [1408.4388]

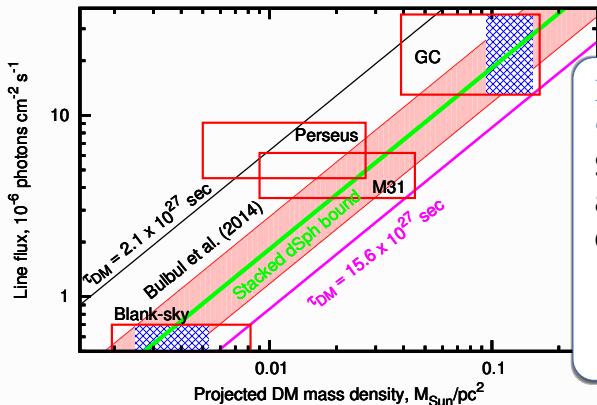
GALACTIC CENTER





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.

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

DARK MATTER DISTRIBUTIONS MATTER!



ANDERSON, CHURAZOV & BREGMAN [1408.4115]

Large stacks of galaxy outskirts.

For strong assumptions on the DM distributions, decaying DM interpretation would be excluded.

CARLSON, JELTEMA & PROFUMO [1411.1758]

Sophisticated morphological study of GC and Perseus.
Spherical DM distributions do not match ~ 3.55 keV emission.

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.

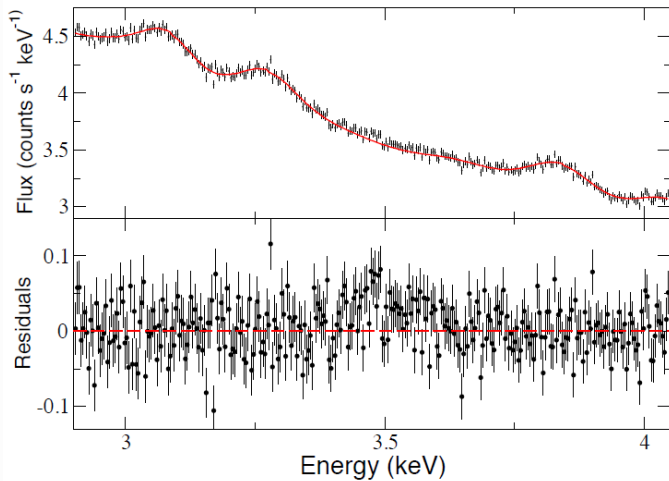
TAMURA ET AL. [1412.1869]

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

MORE PERSEUS WITH SUZAKU (SOON)



Preliminary 1 Ms with *Suzaku*, 3σ detection in the center



Fransé, Bulbul et al. (in prep)

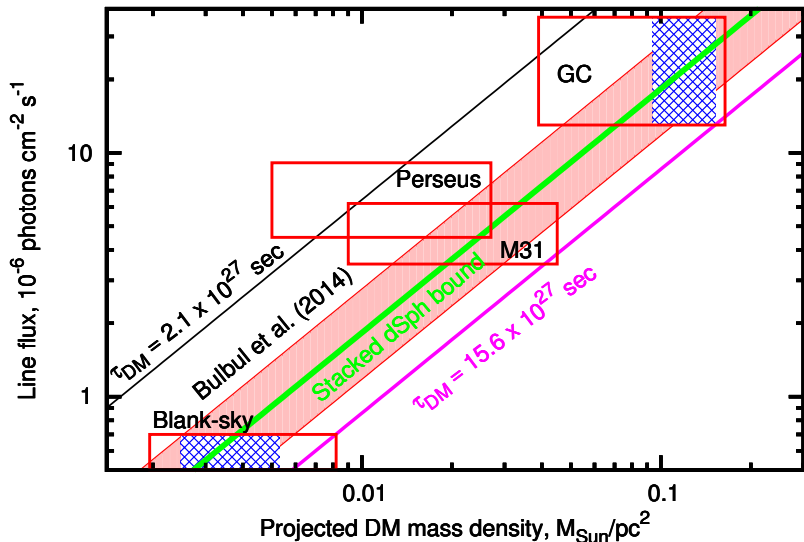
IMMINENT: LOTS OF DRACO



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

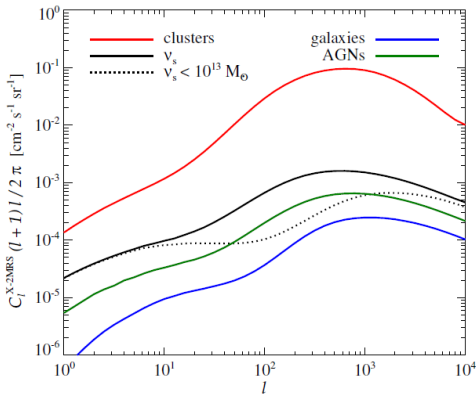
- Highest expected signal of all dwarf galaxies (Geringer-Sameth+ 2014, Lovell+ 2014)
- Very gas-poor (**do not expect any atomic lines**)
- We will be able to **confirm or deny the DM origin** of the 3.5 keV line somewhere **in 2016**.

DRACO dSPH OBSERVATION PROJECTIONS



Angular cross-correlation measurable with eRosita

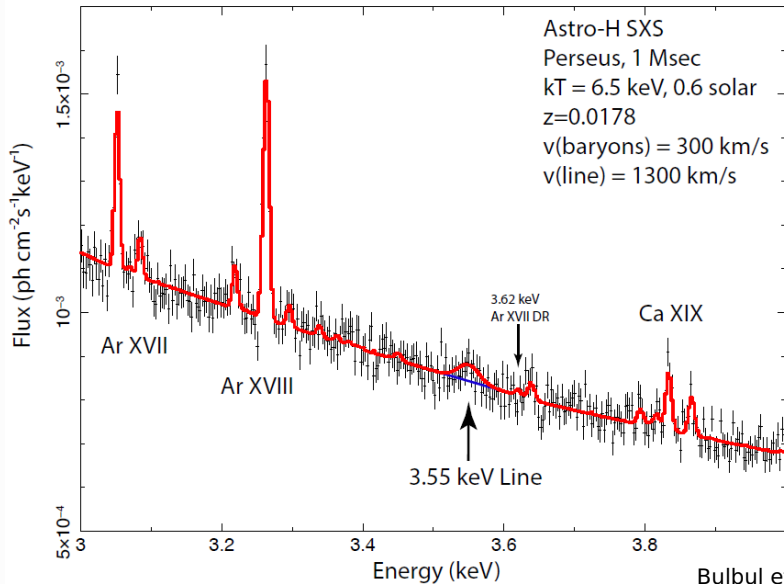
Zandanel et al. 2015 [1505.07829]



Correlations in spectral, spatial and redshift space

Franse (in prep.)

FUTURE: ASTRO-H



Bulbul et al.(2014)

MIGHT BE STERILE ν , MIGHT BE...

The 3.5 keV X-ray line from decaying **gravitino** dark matter. **Axino** dark matter in light of an anomalous X-ray line. The Quest for an Intermediate-Scale Accidental **Axion** and Further **ALPs**. keV Photon Emission from Light **Nonthermal Dark Matter**. X-ray lines from R-parity violating decays of keV **sparticles**. Neutrino masses, leptogenesis, and **sterile neutrino** dark matter. A Dark Matter Progenitor: **Light Vector Boson Decay** into (Sterile) Neutrinos. A 3.55 keV Photon Line and its Morphology from a 3.55 keV ALP Line. 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model. X-ray line signal from decaying **axino** warm dark matter. The 3.5 keV X-ray line signal from **decaying moduli** with low cutoff scale. X-ray line signal from 7 keV **axino** dark matter decay. Can a **millicharged dark matter** particle emit an observable gamma-ray line?. Effective field theory and keV lines from dark matter. Resonantly-Produced 7 keV **Sterile Neutrino Dark Matter** Models and the Properties of Milky Way Satellites. Cluster X-ray line at 3.5 keV from axion-like dark matter. Axion Hilltop Inflation in Supergravity. A 3.55 keV hint for decaying axion-like particle dark matter. The 7 keV axion dark matter and the X-ray line signal. An X-Ray Line from **eXciting Dark Matter**. 7 keV **sterile neutrino dark matter** from split flavor mechanism. **FIMP** Miracle of Sterile Neutrino Dark Matter by Scale Invariance. **Non-abelian Dark Matter** Solutions for Galactic Gamma-ray Excess and Perseus 3.5 keV X-ray Line. 3.5 keV X-ray Line Signal from Dark Matter Decay in **Local $U(1)_{B-L}$ Extension of Zee-Babu Model**. **SIMPLE** Dark Matter: Self-Interactions and keV Lines. Exploring X-Ray Lines as **Scotogenic** Signals. **Hidden axion dark matter** decaying through mixing with QCD axion ...

SUMMARY

