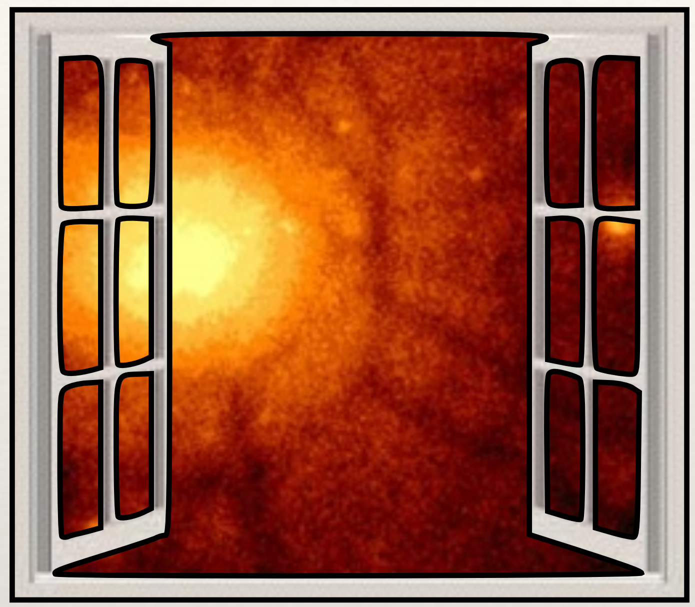
# ALPs and Galaxy cluster X-rays as a window to the dark sector



*M.C. David Marsh*

**Rudolph Peierls Centre for Theoretical Physics**
**University of Oxford**

**Mainz Theory Palaver, 20/1, 2015**

# Based on:

J. Conlon, *D.M.*, arXiv:1304.1804,

J. Conlon, *D.M.*, arXiv:1305.3603,

S. Angus, J. Conlon, *D.M.*, A, Powell, L. Witkowski, arXiv:1312.3947

M. Cicoli, J. Conlon, *D.M.*, M. Rummel, arXiv:1403.2370

*D.M.*, arXiv:1407.2501,

P. Alvarez, J. Conlon, F. Day, *D.M.*, M. Rummel, arXiv:1410.1867

# Outline:

1. Axion-like particles (ALPs)
2. Galaxy clusters as ALP converters
3. A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$
4. A Cosmic Axion Background and the cluster soft X-ray excess

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1. *Axion-like particles (ALPs)*
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# Axion-like particles (ALPs)

***What are they?***

ALPs are (pseudo)-Nambu-Goldstone bosons (PNGB) of an (explicitly) broken global symmetry.

*In field theory:*

If the vev of $\phi = ve^{ia}$ spontaneously breaks a global U(1) symmetry, the phase *a* will enjoy an exact shift-symmetry: $a \to a + \text{const}.$

If the U(1) symmetry is, in addition, explicitly broken, the field *a* obtains a potential and becomes a PNGB/ALP.

*Example:* $$\mathcal{L} \supset \frac{\alpha}{8\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} \, .$$

The QCD axion provides a beautiful solution to the strong CP-problem.

# Axion-like particles (ALPs)

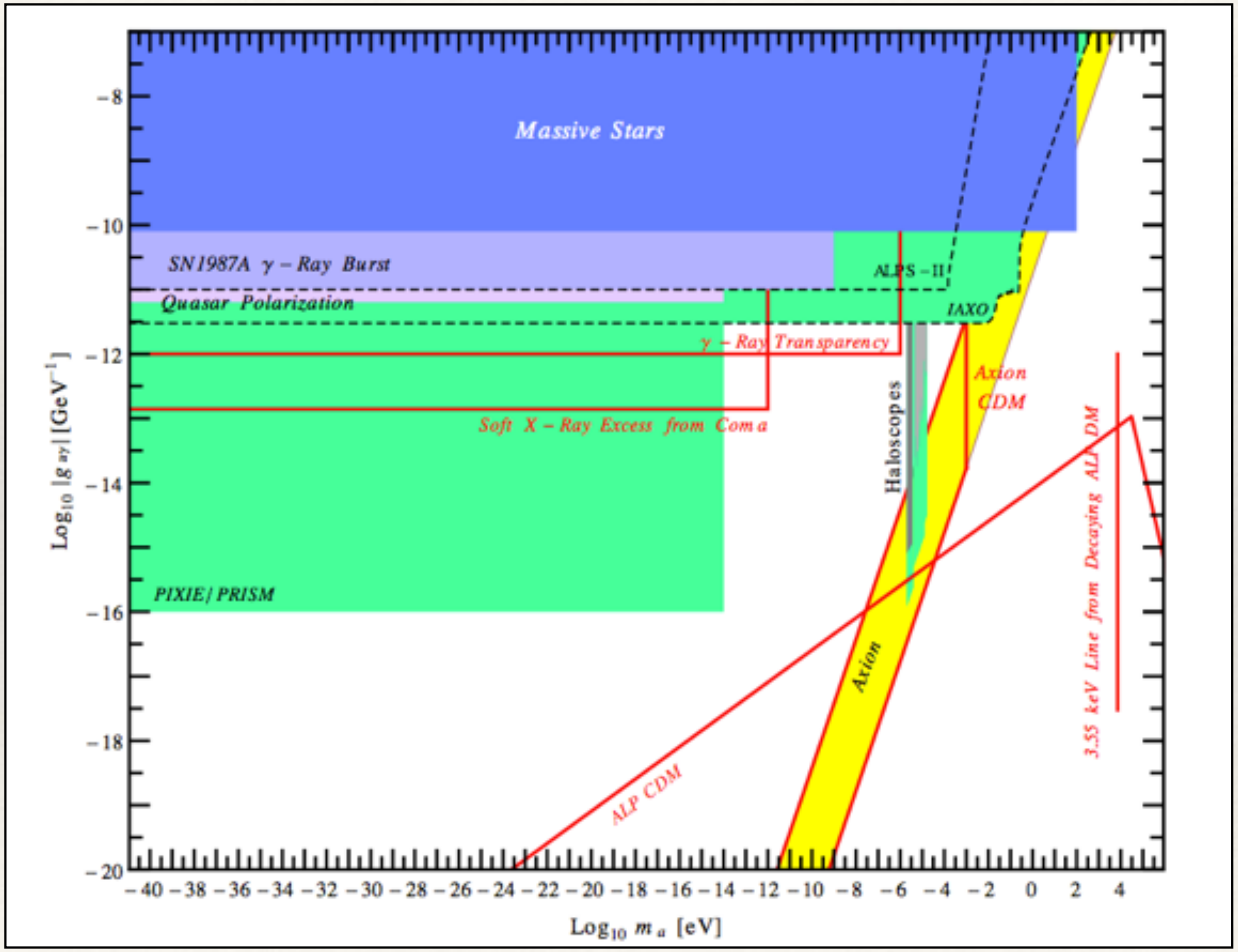
ALPs are highly interesting extensions of the Standard Model.

- ALPs are a common feature in compactifications of string theory.
- ALPs are highly versatile!
- Experimental progress does not rely on large colliders, but low-energy experiments can probe fundamental physics.
- Several hints have already been reported.

# Axion-like particles (ALPs)

The low-energy Lagrangian for an ALP is given by,

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{a}{4M} F_{\mu\nu}\tilde{F}^{\mu\nu} + c_{af}\frac{\partial_\mu a}{2M}\bar{\psi}_f \gamma^5 \gamma^\mu \psi_f \, .$$

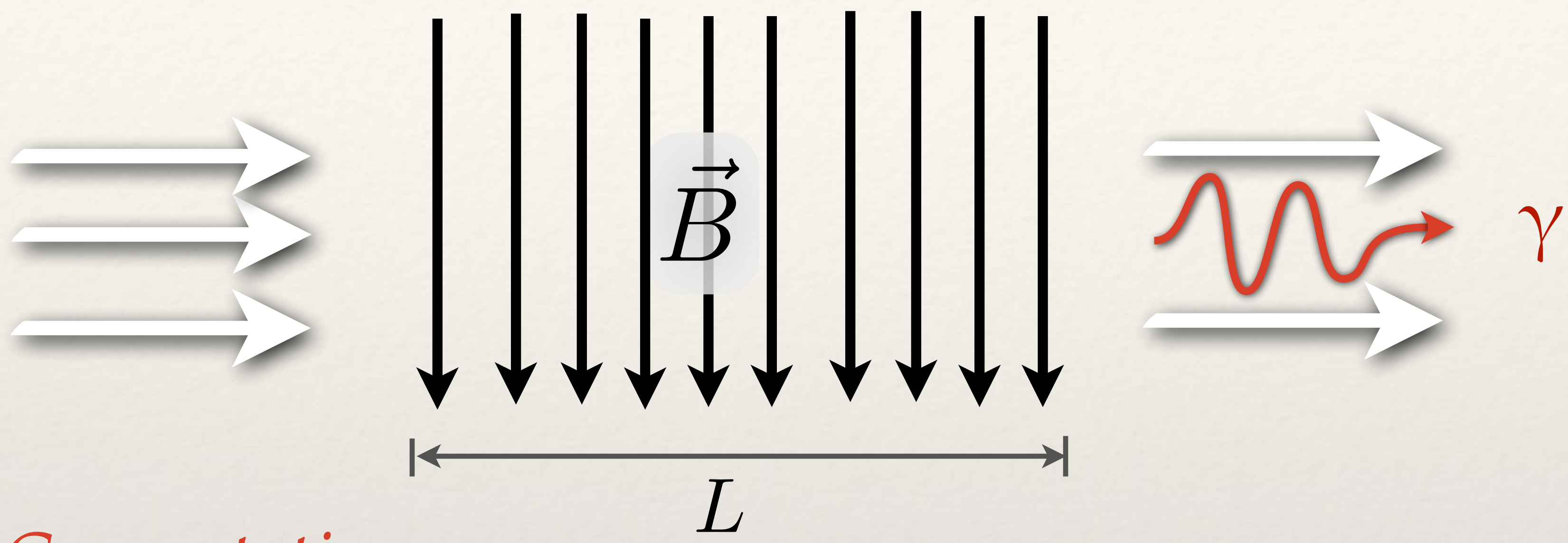



Dias et al.
arXiv:1403.5760

# Axion-like particles (ALPs)

ALP-photon conversion:

$$\frac{a}{M} F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{a}{M}\vec{E}\cdot\vec{B}\,.$$




*Computation:*

At the linearised level the three-level system is governed by a Schrödinger-like equation:

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & \Delta_\mathrm{F} & \Delta_{\gamma a x} \\ \Delta_\mathrm{F} & \Delta_\gamma & \Delta_{\gamma a y} \\ \Delta_{\gamma a x} & \Delta_{\gamma a y} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} \gamma_x \\ \gamma_y \\ a \end{pmatrix} = 0\,.$$

Sikivie '83

Here, $\Delta_\gamma = -\frac{\omega_{pl}^2}{2\omega}$, $\Delta_{\gamma a i} = B_i/2M$, $\Delta_a = -m_a^2/\omega$

# Axion-like particles (ALPs)

Conversion probability for a coherent magnetic field:

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos(2\theta)}\right) \to \frac{1}{4}\left(\frac{B_\perp L}{M}\right)^2 ,$$

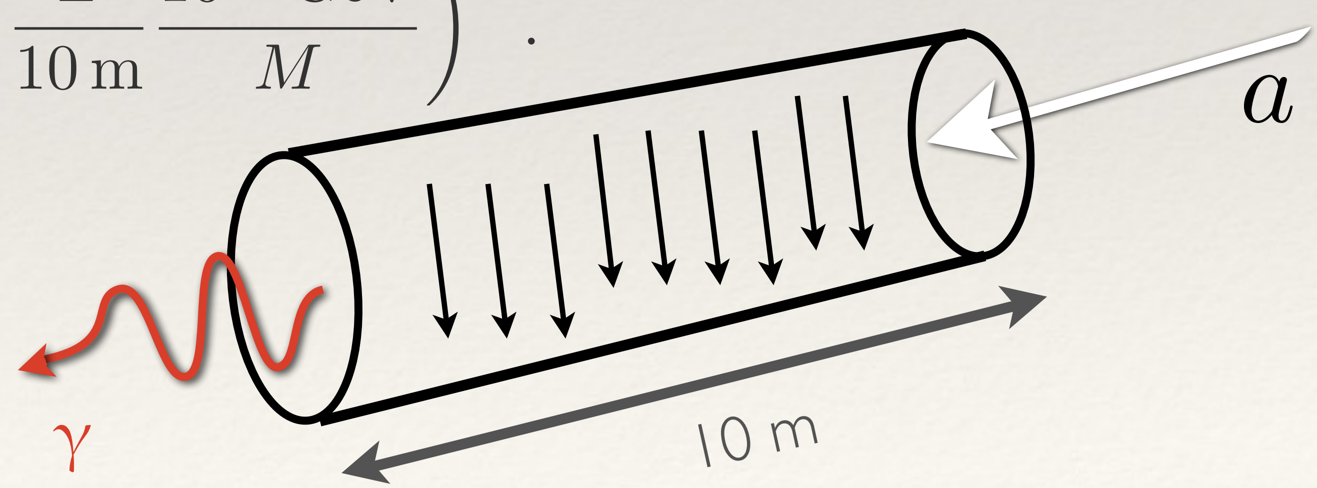
*"Small angle approximation"*

with $\theta \approx \frac{B_\perp \omega}{M(m_a^2 - \omega_{pl}^2)}$ and $\Delta = \frac{(m_a^2 - \omega_{pl}^2)L}{4\omega}$.

*Look for strong magnetic fields ($P \sim B^2$) coherent over large distances ($P \sim L^2$).*

*Example:* For CAST-like experiment:

$$P(a \to \gamma) \approx 2 \cdot 10^{-19} \cdot \left(\frac{B_\perp}{10\,\mathrm{T}}\frac{L}{10\,\mathrm{m}}\frac{10^{11}\,\mathrm{GeV}}{M}\right)^2 .$$



# Outline:

1. Axion-like particles (ALPs)
2. *Galaxy clusters as ALP converters*
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# Galaxy clusters as ALP converters

***What are they?***

Galaxy clusters are the largest gravitationally bound structures of the universe ($1 \lesssim R \lesssim 10$ Mpc, $10^{12} \lesssim M \lesssim 10^{15}\ M_{\odot}$), and consists of hundreds or thousands of galaxies.

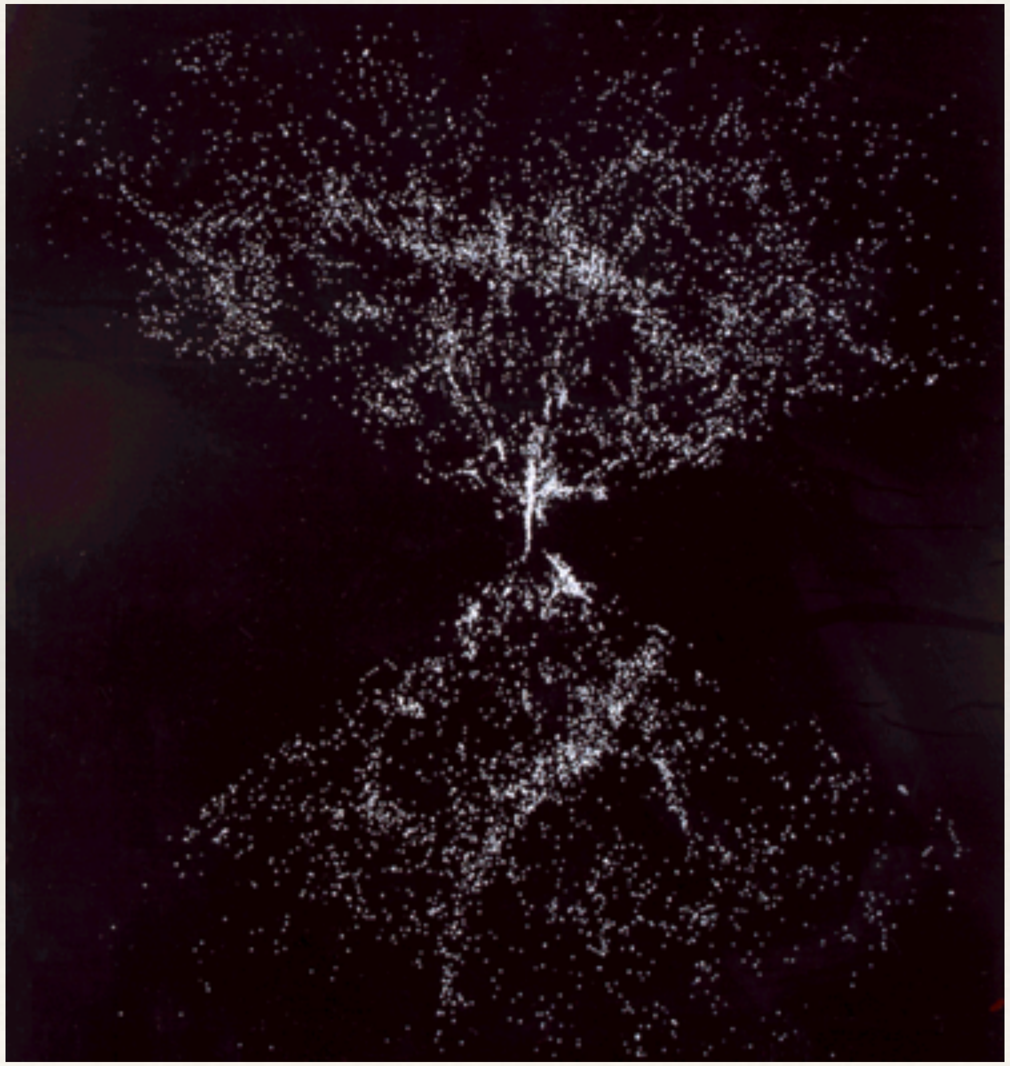

Image by Cfa.

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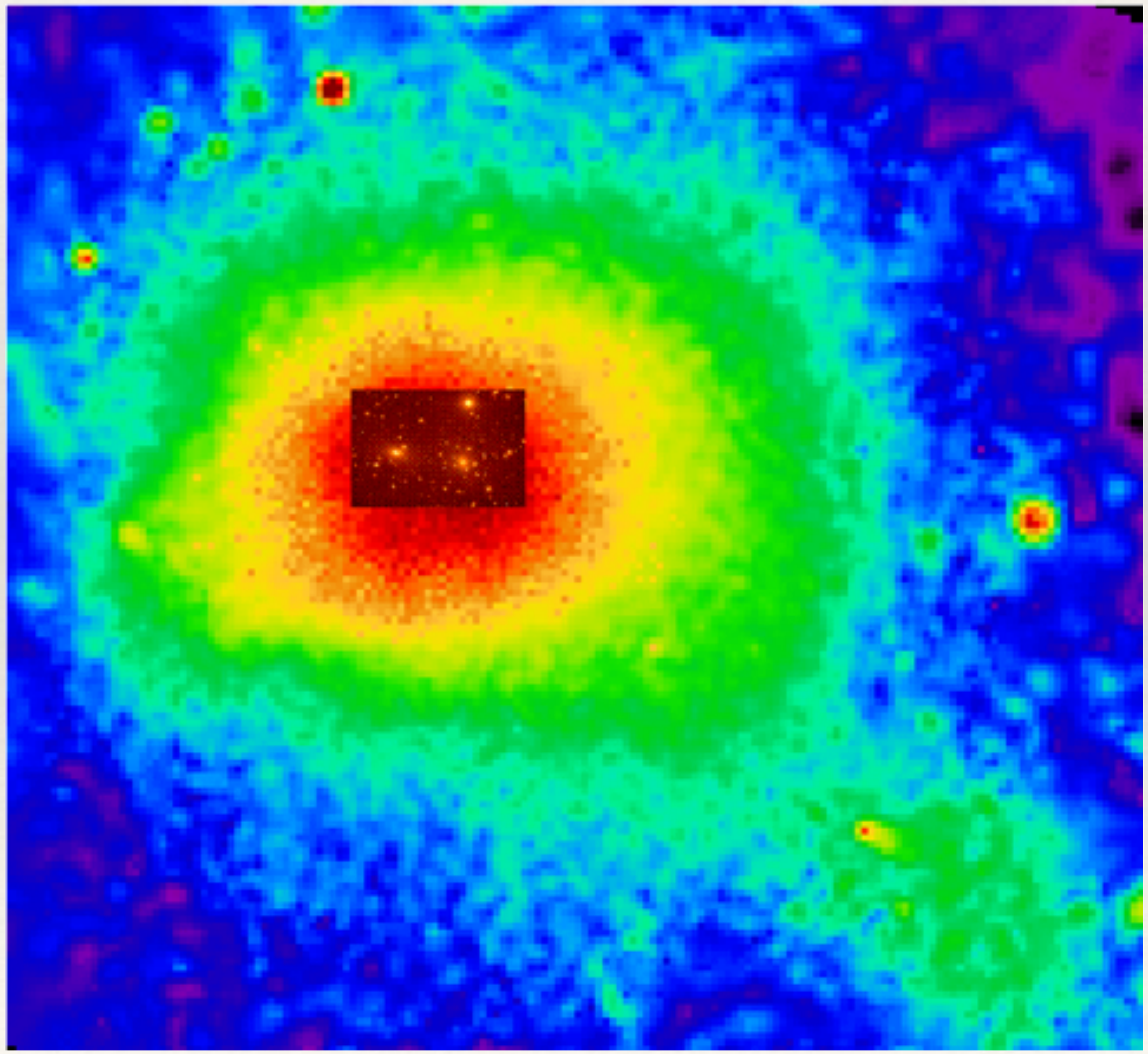
The Coma cluster, as seen by HST.

# Galaxy clusters as ALP converters

***What are they?***

Galaxy clusters are dark matter dominated (90% in mass), and is permeated by hot gas with keV temperatures (9% in mass).



The Coma cluster, as seen by ROSAT.

# Galaxy clusters as ALP converters

***What are they?***

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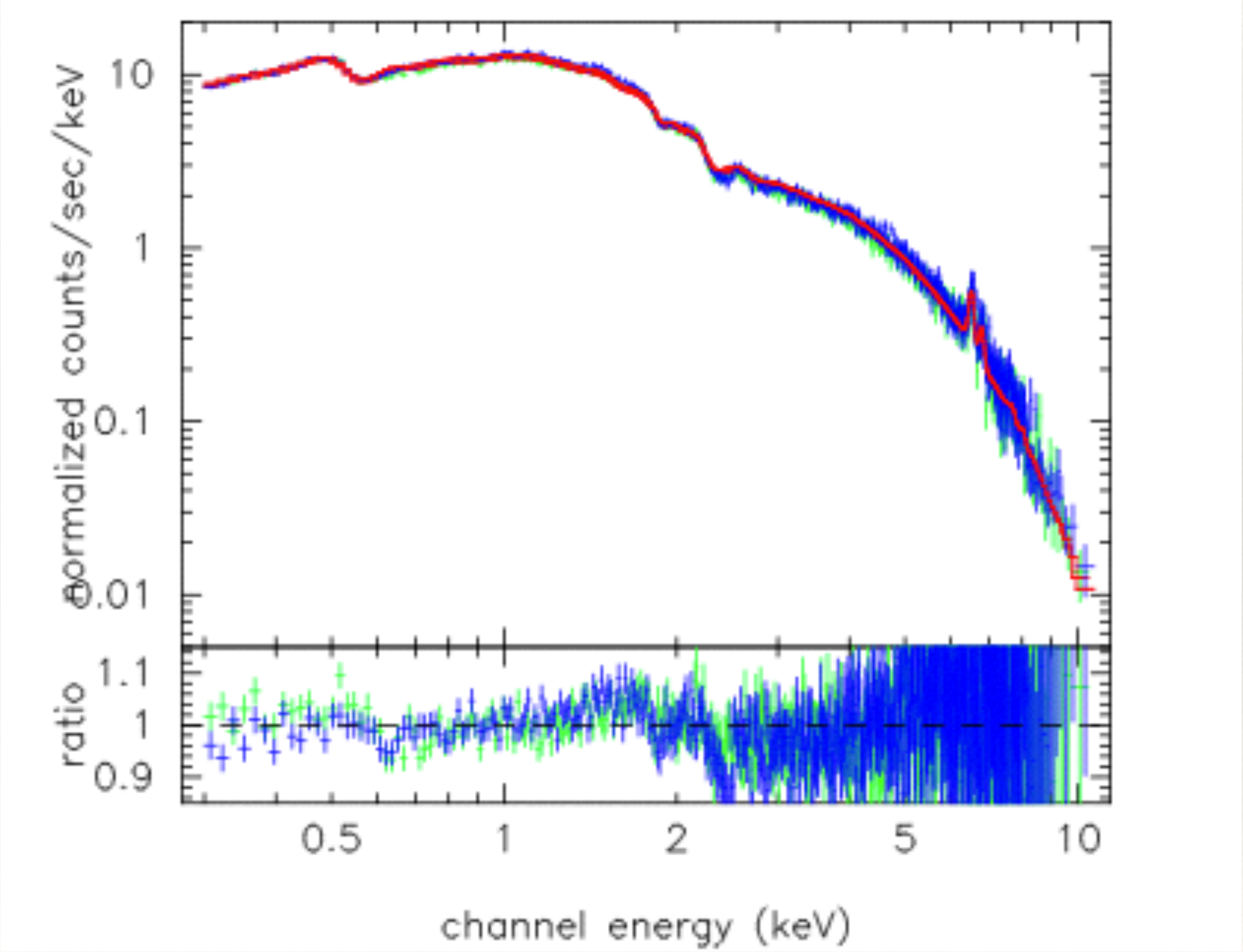



Thermal bremsstrahlung with $I(E) \propto g(E)$ exp[-c E], plus ion lines.

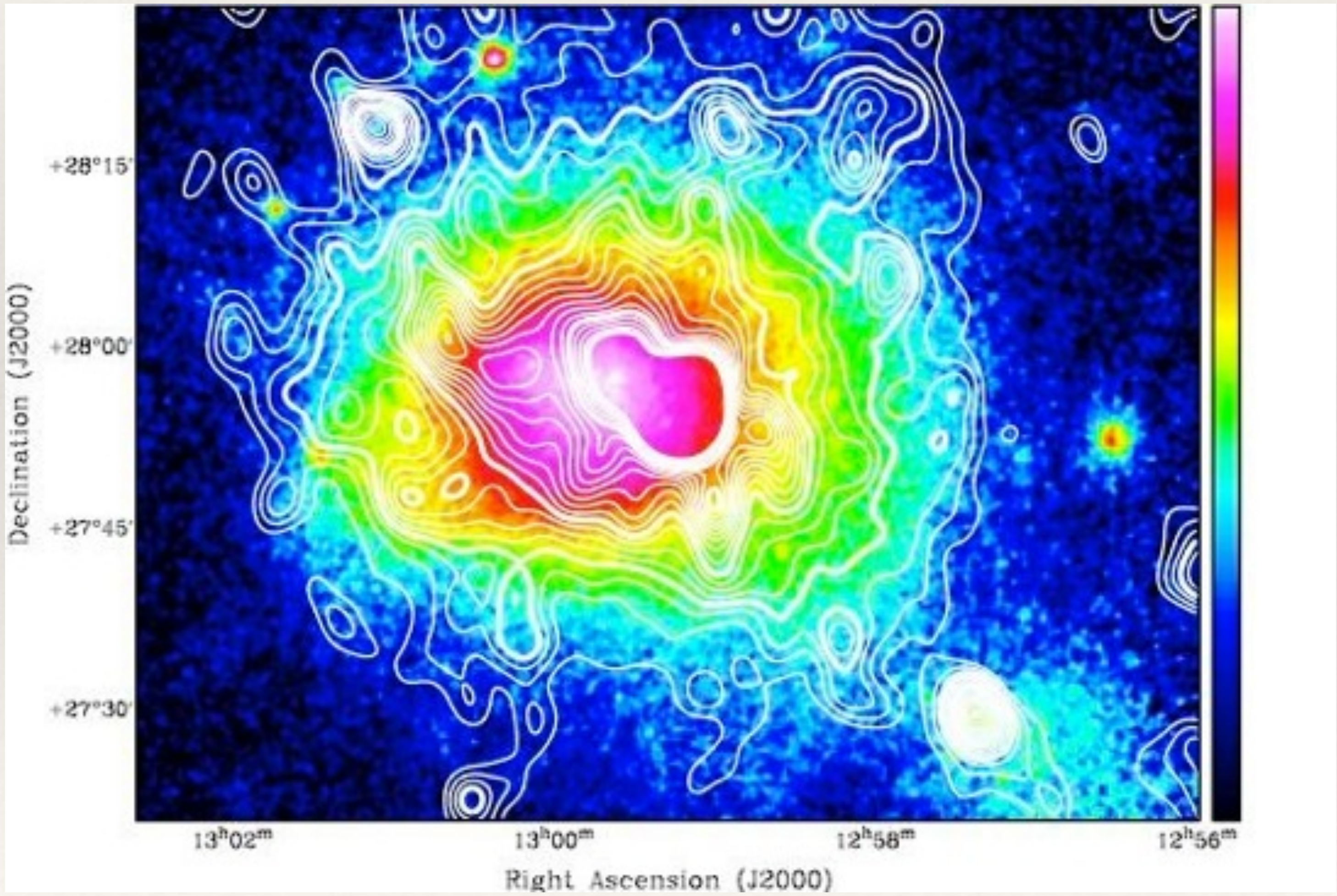
XMM-Newton (MOS1 & MOS2) spectrum for central region of Coma. Arnaud et al., 2001.

# Galaxy clusters as ALP converters

### *Magnetic fields in galaxy clusters*

Clusters support magnetic fields with $\mathcal{O}(|B|)=1\text{-}10\ \mu G$.

Radio halos arise from synchrotron radiation of a population of relativistic electrons.




Coma radio halo.

# Galaxy clusters as ALP converters

***Magnetic fields in galaxy clusters***

Clusters support magnetic fields with $\mathcal{O}(|B|)=1\text{-}10\ \mu G$.

Radio halos arise from synchrotron radiation of a population of relativistic electrons.

For the Coma cluster, the level of synchrotron emission from the radio halo (and non-observation of IC-CMB hard X-rays), gives $\langle |B| \rangle > 0.2\ \mu\text{G}$.

Coma radio halo.

# Galaxy clusters as ALP converters

## *Magnetic fields in galaxy clusters*

Clusters support magnetic fields with $\mathcal{O}(|B|)$=1-10 $\mu$G.

The birefringence of the magnetised plasma gives rise to Faraday rotation of polarised photons: $\Delta\theta \propto \lambda^2 \int n_e(l)\vec{B}\cdot d\vec{l}\,.$

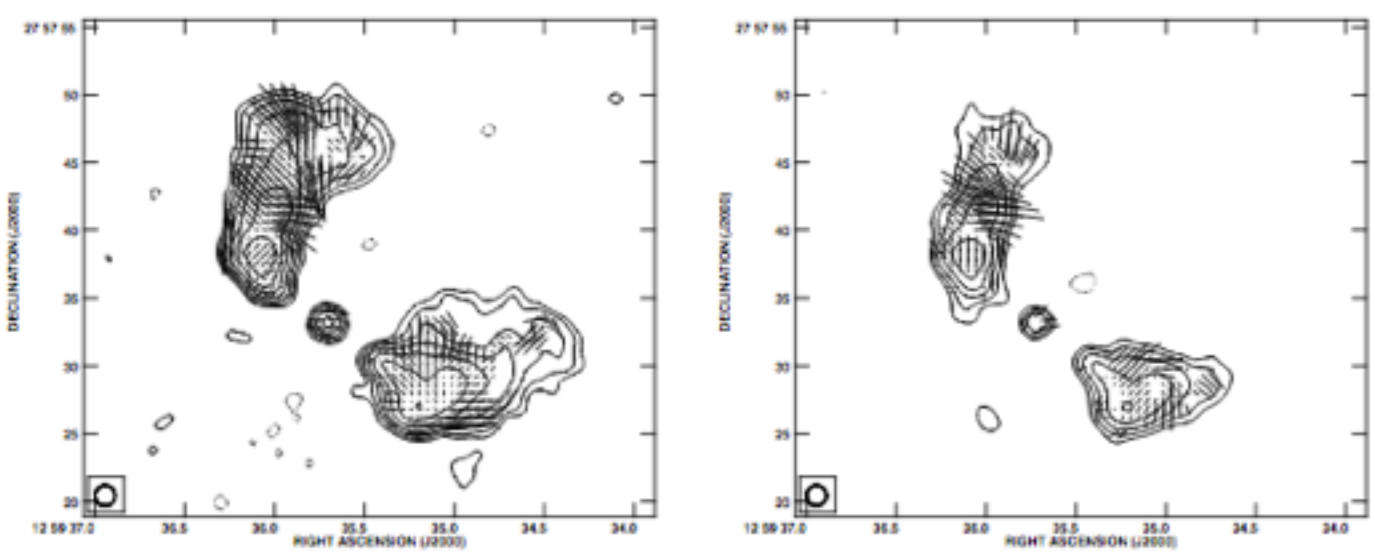


Figure 3.2: Source 5C4.85. Total intensity radio contours and polarization vectors at 4.535 GHz (left) and 8.465 GHz (right). The bottom contour corresponds to a $3\sigma$ noise level, contours are then spaced by a factor of 2. E vectors are superimposed: the orientation indicates the direction of the E field, while the line length is proportional to the fractional polarization intensity (1″ corresponding to 10%).

Radio image of a source in Coma, taken from Bonafede's thesis.

# Galaxy clusters as ALP converters

## *Magnetic fields in galaxy clusters*

Clusters support magnetic fields with $\mathcal{O}(|B|)$=1-10 $\mu$G.

The birefringence of the magnetised plasma gives rise to Faraday rotation of polarised photons: $\Delta\theta \propto \lambda^2 \underbrace{\int n_e(l)\vec{B}\cdot d\vec{l}}_{RM}$.

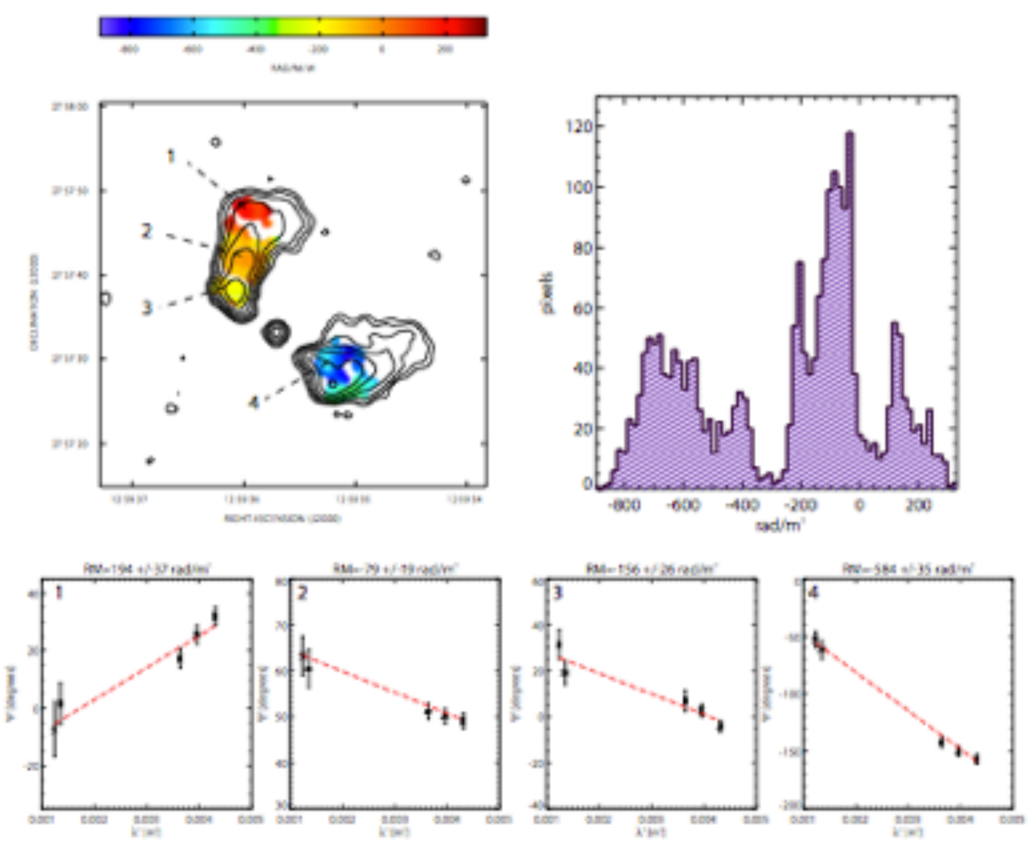



Figure 3.9: **5C4.85:** *Top left:* The *RM* fit is shown in color along with total intensity radio contours 4.935 GHz. The bottom contour correspond to the 3$\sigma$ noise level and contours are then spaced by a factor of 2. *Top right* distribution histogram of the *RM* values. *Bottom:* fits of polarization angle versus $\lambda^2$ in four representative pixels.

Radio image of a source in Coma, taken from Bonafede's thesis.

# Galaxy clusters as ALP converters

***Magnetic fields in galaxy clusters***

Magnetic field model for Coma:

1. $\langle|\tilde{A}_k|^2\rangle \sim k^{-n}\,,\; k_{\rm min} \leq k \leq k_{\rm max}\,.$
2. $\vec{\tilde{B}}_{\rm gen.} := i\vec{k} \times \vec{\tilde{A}}(k)\,.$

$$\vec{B}_{\rm tot.} := \mathcal{C}B_0 \left(\frac{n_e(r)}{n_e(0)}\right)^{\eta} \vec{B}_{\rm gen.}\,.$$

The parameters $n$, $k_{min}$, $k_{max}$, $\eta$, and $B_0$ may then be constrained by comparing the observed distribution of RMs from a set of radio sources to simulated mock RMs.

*Baseline:* $n$=17/3, $k_{min}$=2π/(34 kpc), $k_{max}$=2π/(3 kpc), $\eta$=0.4-0.7, and $B_0$=3.9-5.4 μG.

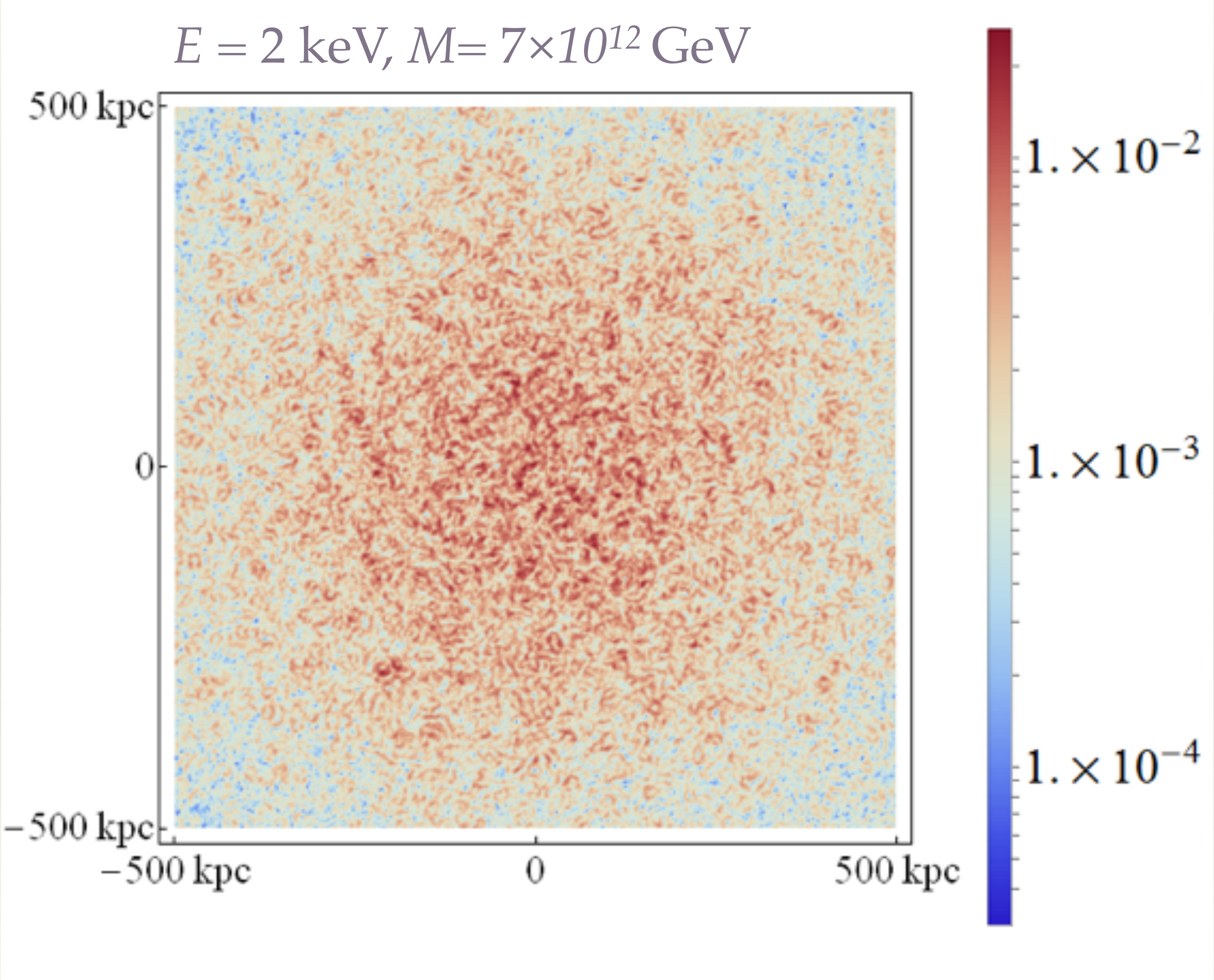
*Alternate model:* $n$=4, $k_{min}$=2π/(100 kpc), $k_{max}$=2π/(2 kpc), $\eta$=0.7, and $B_0$=5.4 μG.

Bonafede et al., 2010.

# Galaxy clusters as ALP converters

***Galaxy clusters are efficient ALP converters***

The kpc coherence lengths of the magnetic field leads to conversion probabilities $P(a \longrightarrow \gamma) \sim 10^{-3}$- $10^{-2}$.




Angus, Conlon, *D.M.*, Powell, Witkowski, ’13.

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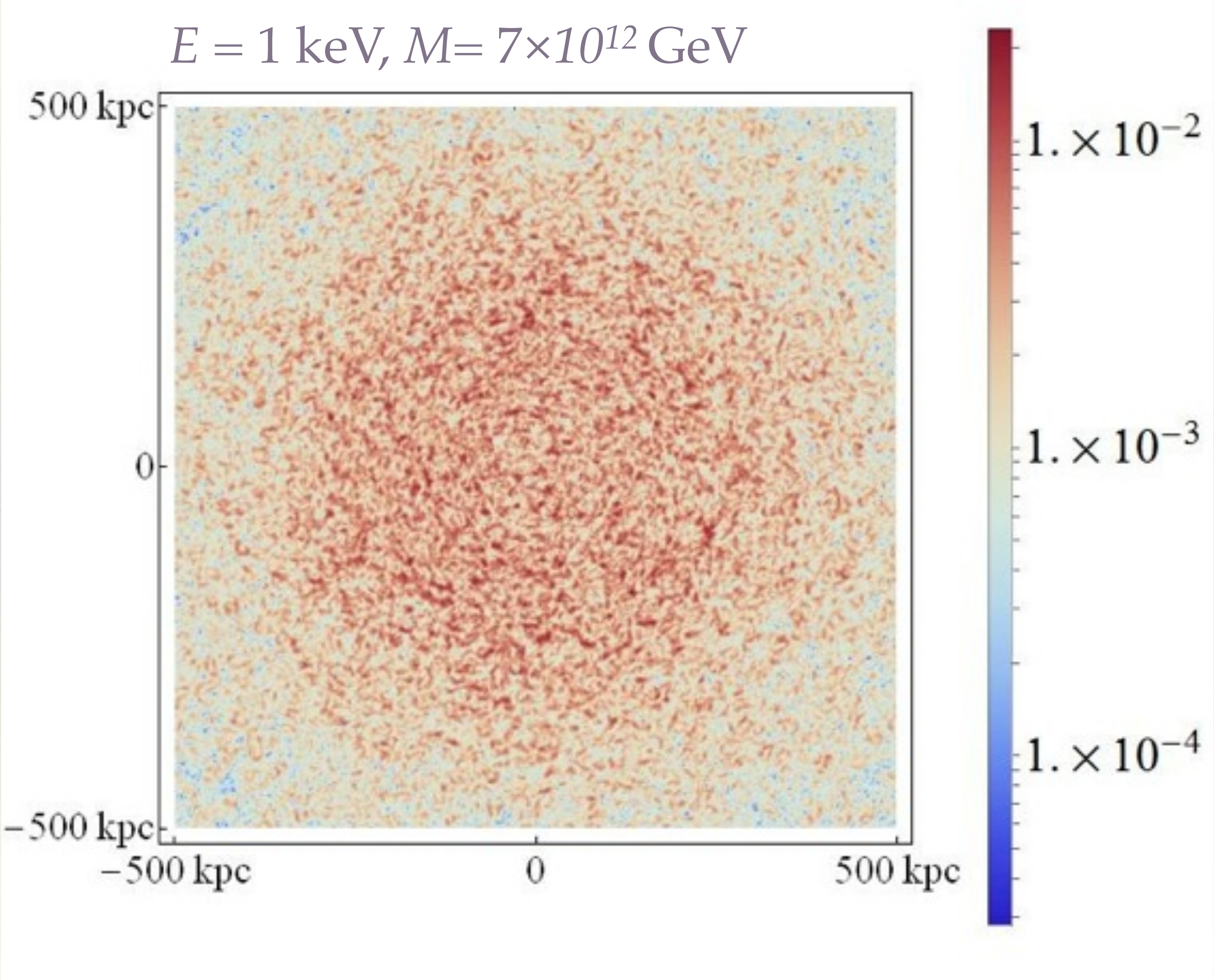


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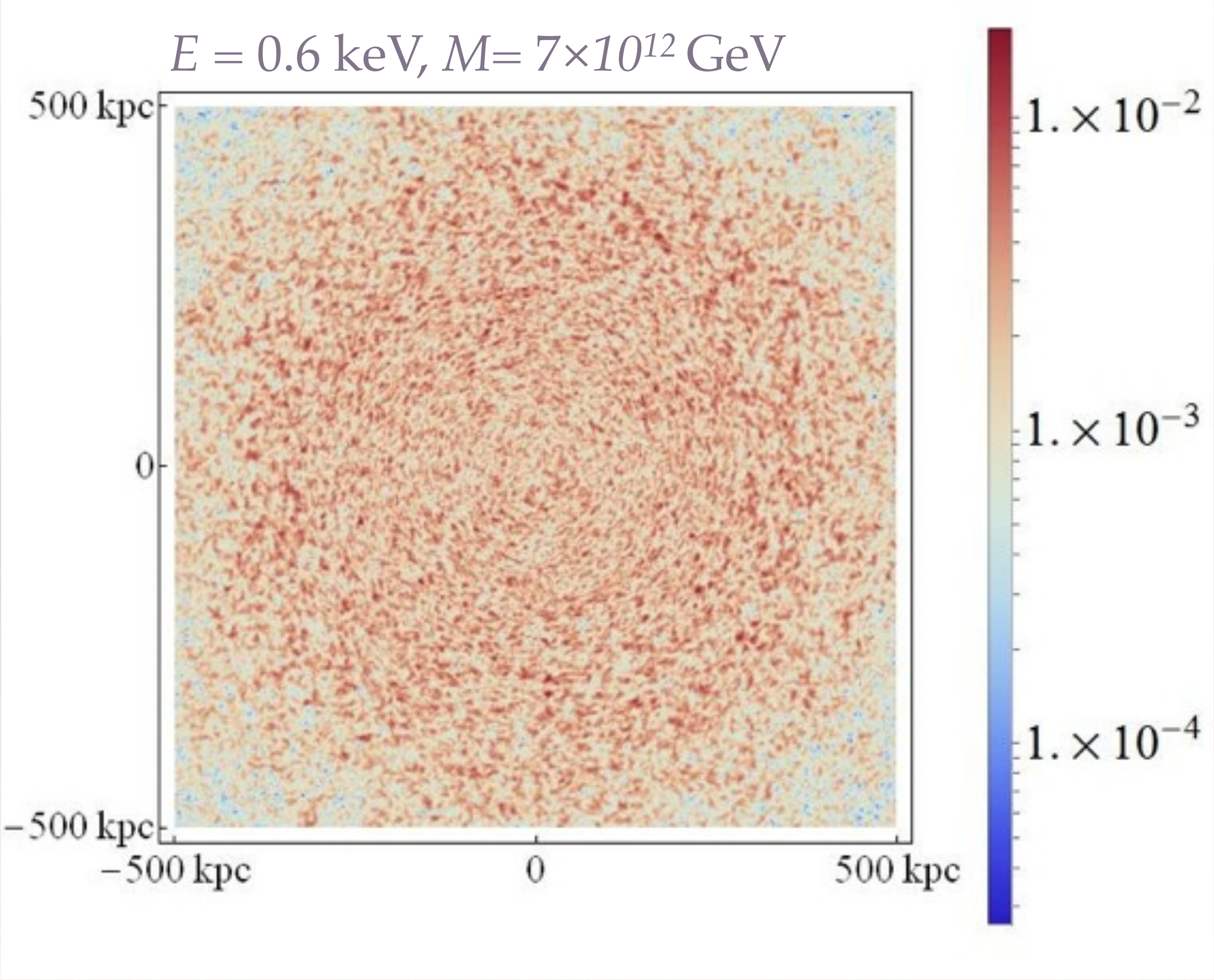


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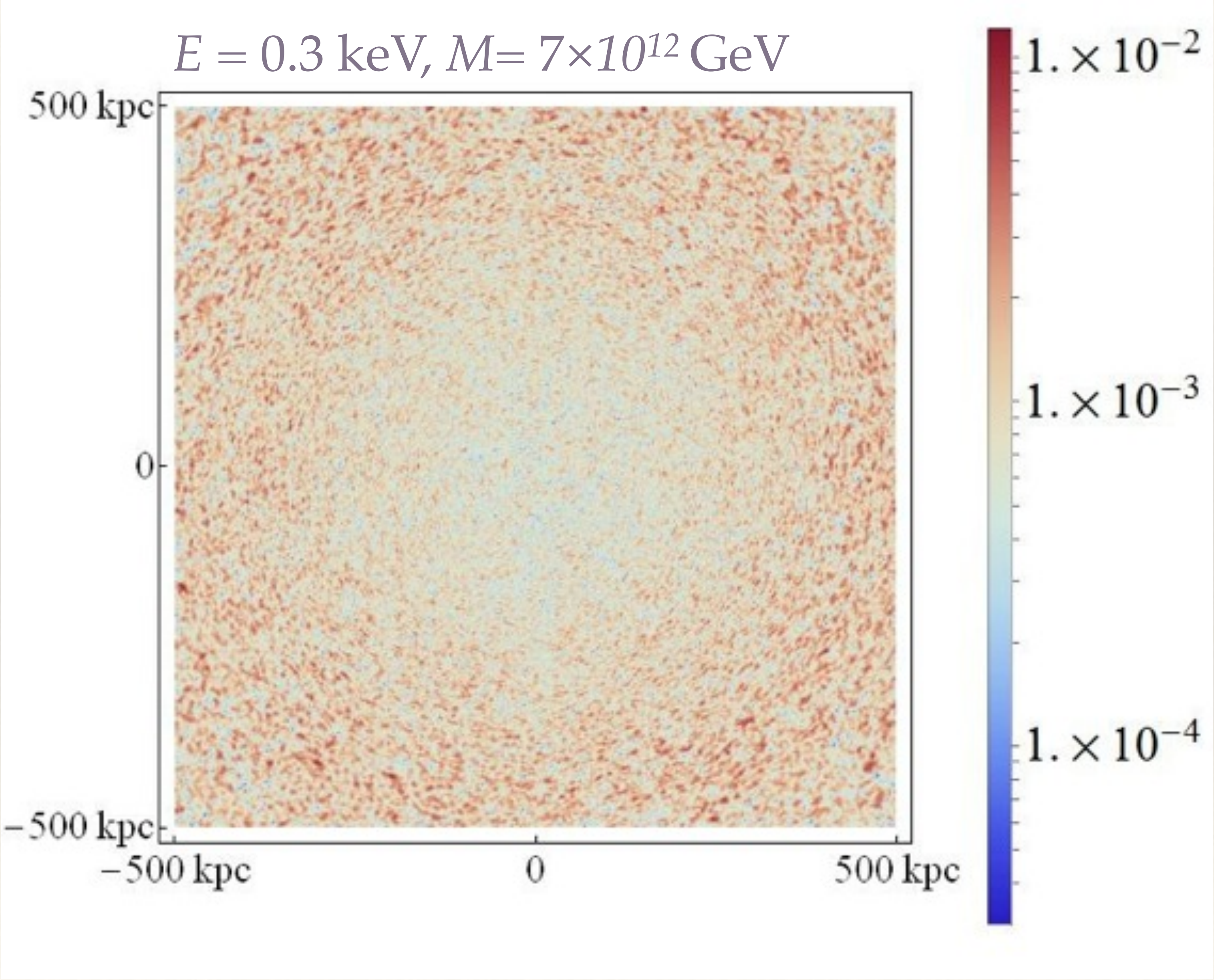


Angus, Conlon, *D.M.*, Powell, Witkowski, '13.

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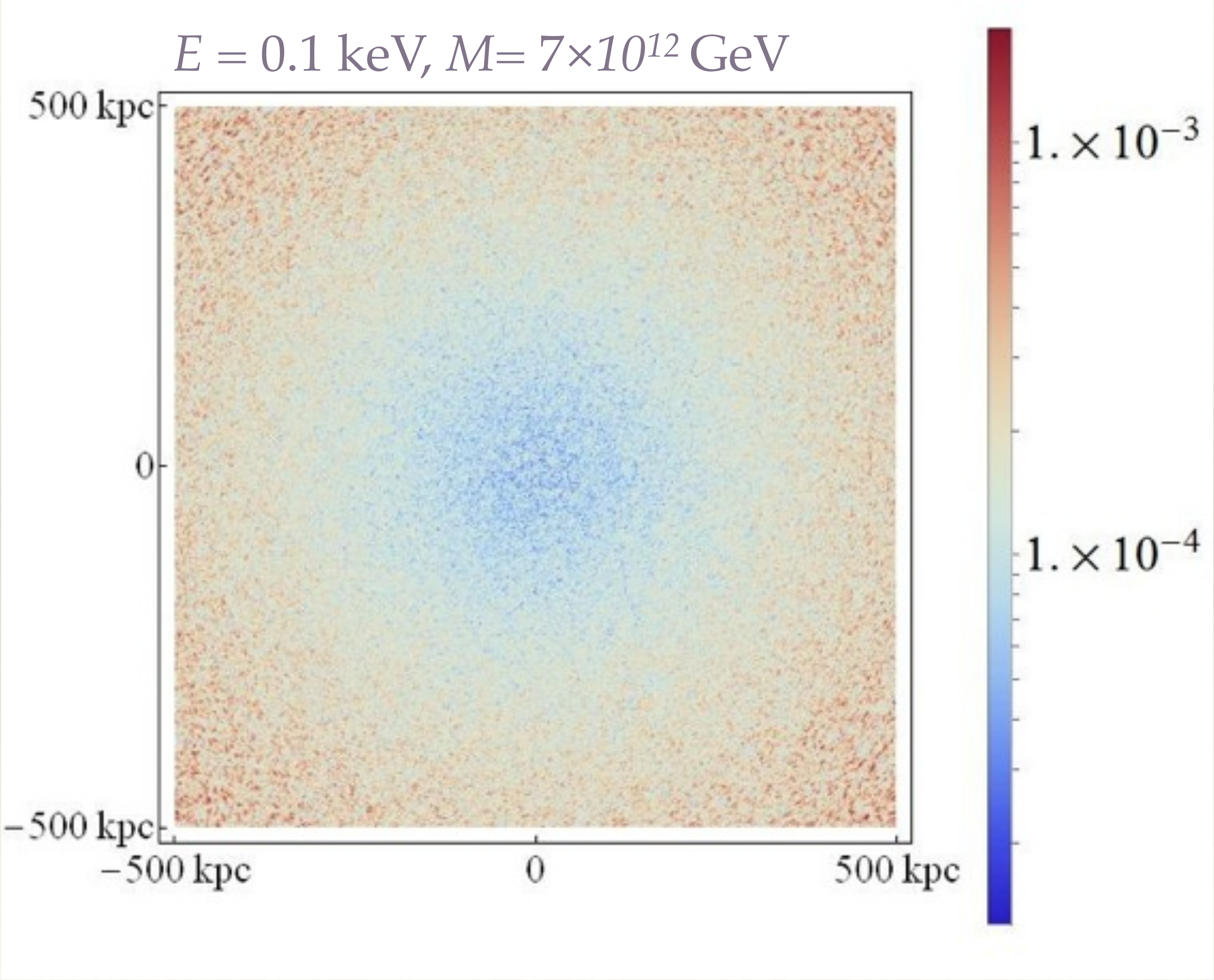


Angus, Conlon, *D.M.*, Powell, Witkowski, ’13.

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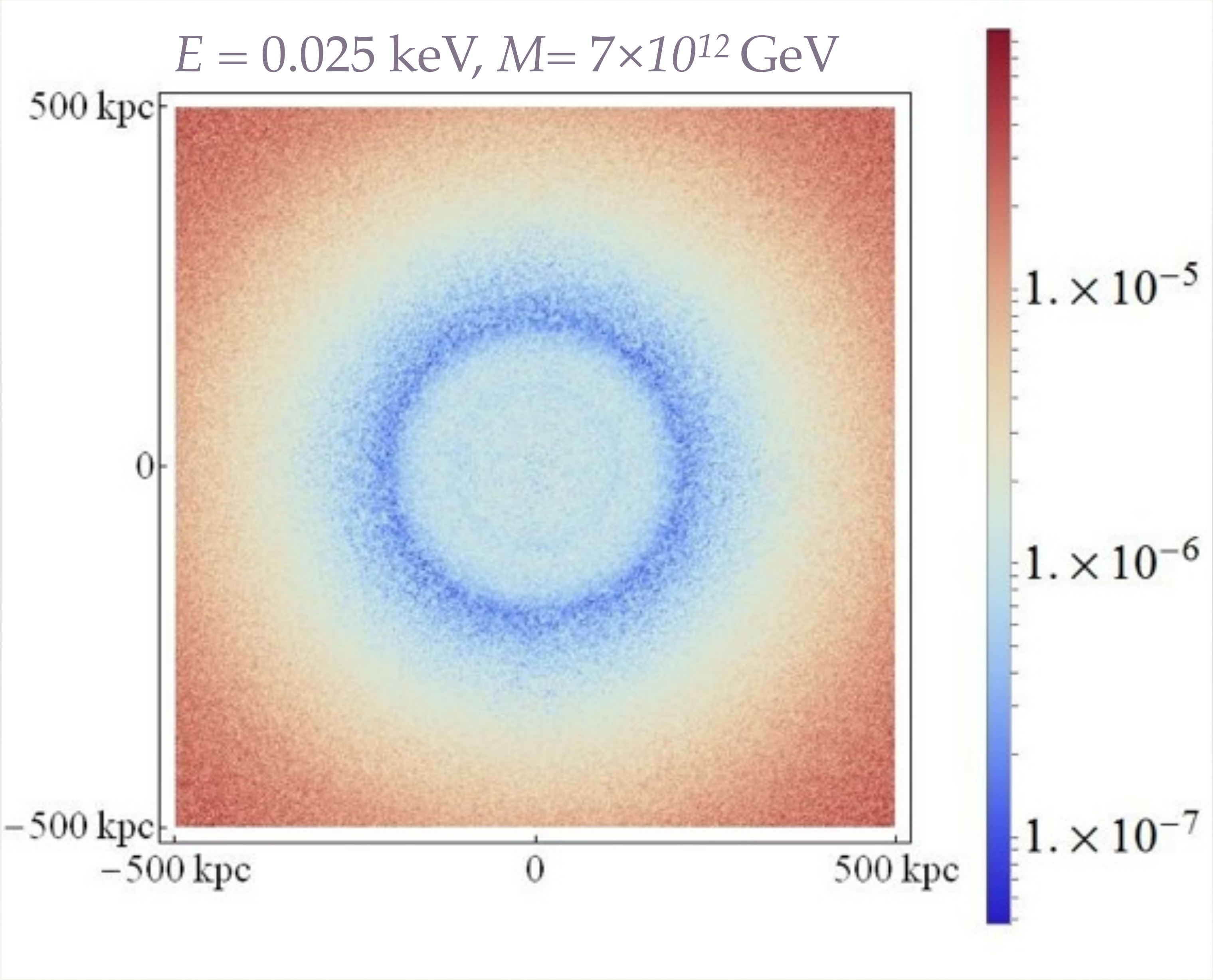
The kpc coherence lengths of the magnetic field leads to conversion probabilities $P(a \longrightarrow \gamma) \sim 10^{-3}$- $10^{-2}$ for $m_a \ll 10^{-12}$ eV.




Angus, Conlon, *D.M.*, Powell, Witkowski, '13.

# Galaxy clusters as ALP converters

***Galaxy clusters are efficient ALP converters***

The kpc coherence lengths of the magnetic field leads to conversion probabilities $P(a \longrightarrow \gamma) \sim 10^{-3} - 10^{-2}$ for $m_a \ll 10^{-12}$ eV.

*If light ALPs are produced in significant numbers by any mechanism, galaxy clusters are ideal targets to search for them.*

Angus, Conlon, *D.M.*, Powell, Witkowski, '13.

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# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***Cast:***

XMM-Newton: MOS, PN

Chandra: ACIS-I, ACIS-S


Suzaku

ASTRO-H

(

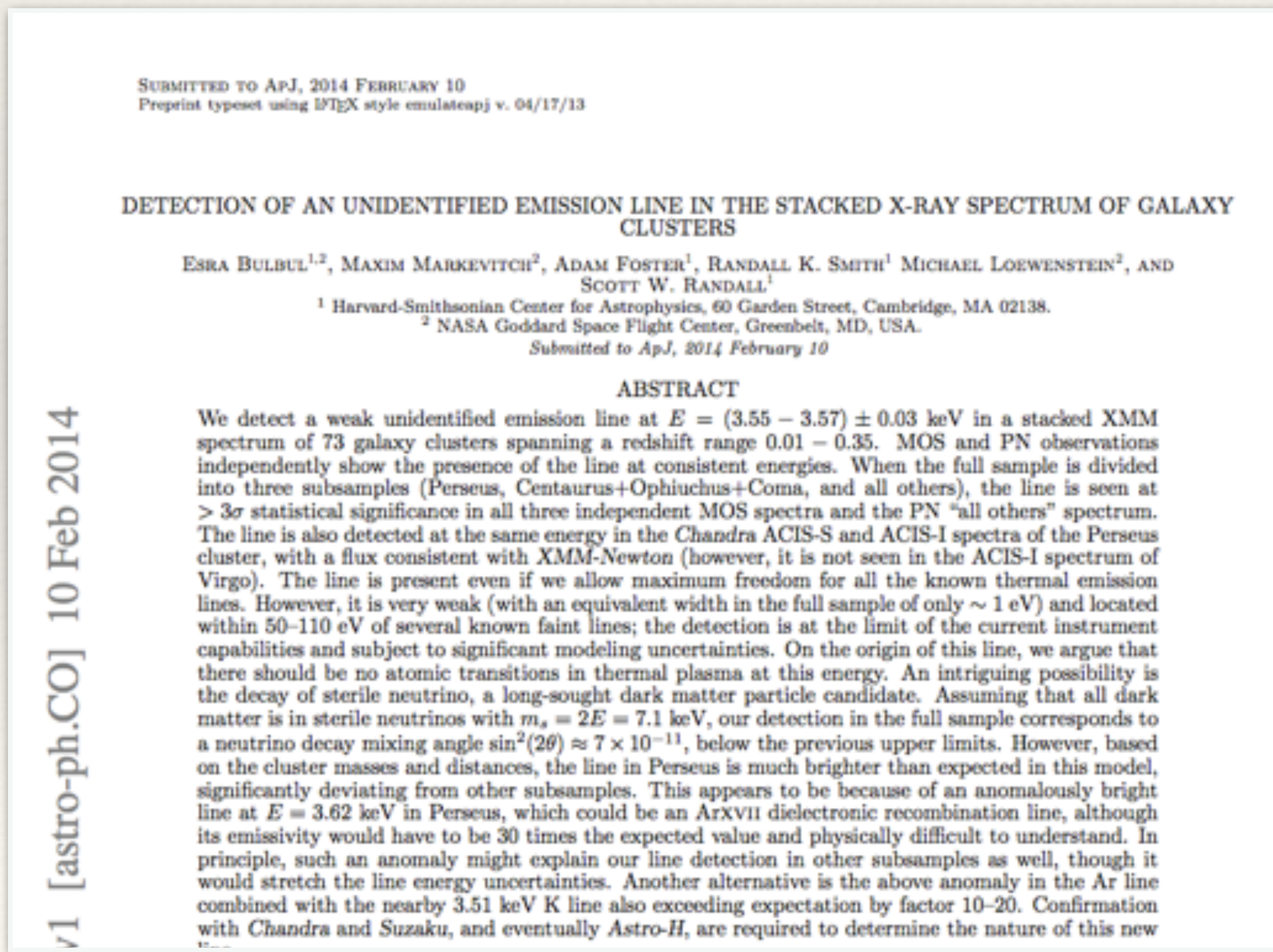
)

ROSAT

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

### *The '3.5 keV line'*

In February 2014, two papers appeared that through independent analysis of X-ray spectra from clusters (and Andromeda (M31)) claimed the detection of an unidentified emission line at $E \approx 3.5$ keV.



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Preprint typeset using LATEX style emulateapj v. 04/17/13

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

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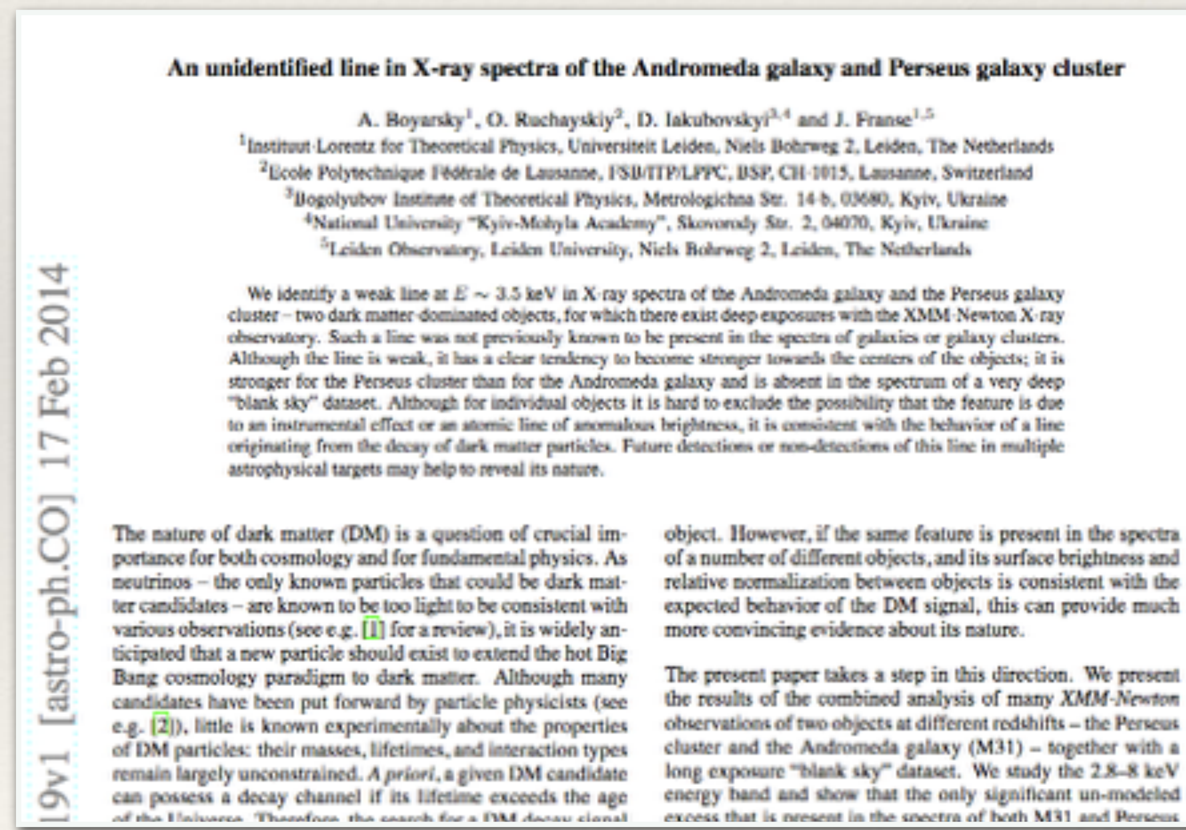
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
*Submitted to ApJ, 2014 February 10*

ABSTRACT

We detect a weak unidentified emission line at $E = (3.55 - 3.57) \pm 0.03$ keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01 − 0.35. MOS and PN observations independently show the presence of the line at consistent energies. 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. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only $\sim 1$ eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, 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 in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the 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. In principle, such an anomaly might explain our line detection in other subsamples as well, though it would stretch the line energy uncertainties. Another alternative is the above anomaly in the Ar line combined with the nearby 3.51 keV K line also exceeding expectation by factor 10–20. Confirmation with *Chandra* and *Suzaku*, and eventually *Astro-H*, are required to determine the nature of this new

v1 [astro-ph.CO] 10 Feb 2014



**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]
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[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

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

The nature of dark matter (DM) is a question of crucial importance for both cosmology and for fundamental physics. As neutrinos – the only known particles that could be dark matter candidates – are known to be too light to be consistent with various observations (see e.g. [1] for a review), it is widely anticipated that a new particle should exist to extend the hot Big Bang cosmology paradigm to dark matter. Although many candidates have been put forward by particle physicists (see e.g. [2]), little is known experimentally about the properties of DM particles: their masses, lifetimes, and interaction types remain largely unconstrained. *A priori*, a given DM candidate can possess a decay channel if its lifetime exceeds the age of the Universe. Therefore the search for a DM decay signal

object. However, if the same feature is present in the spectra of a number of different objects, and its surface brightness and relative normalization between objects is consistent with the expected behavior of the DM signal, this can provide much more convincing evidence about its nature.

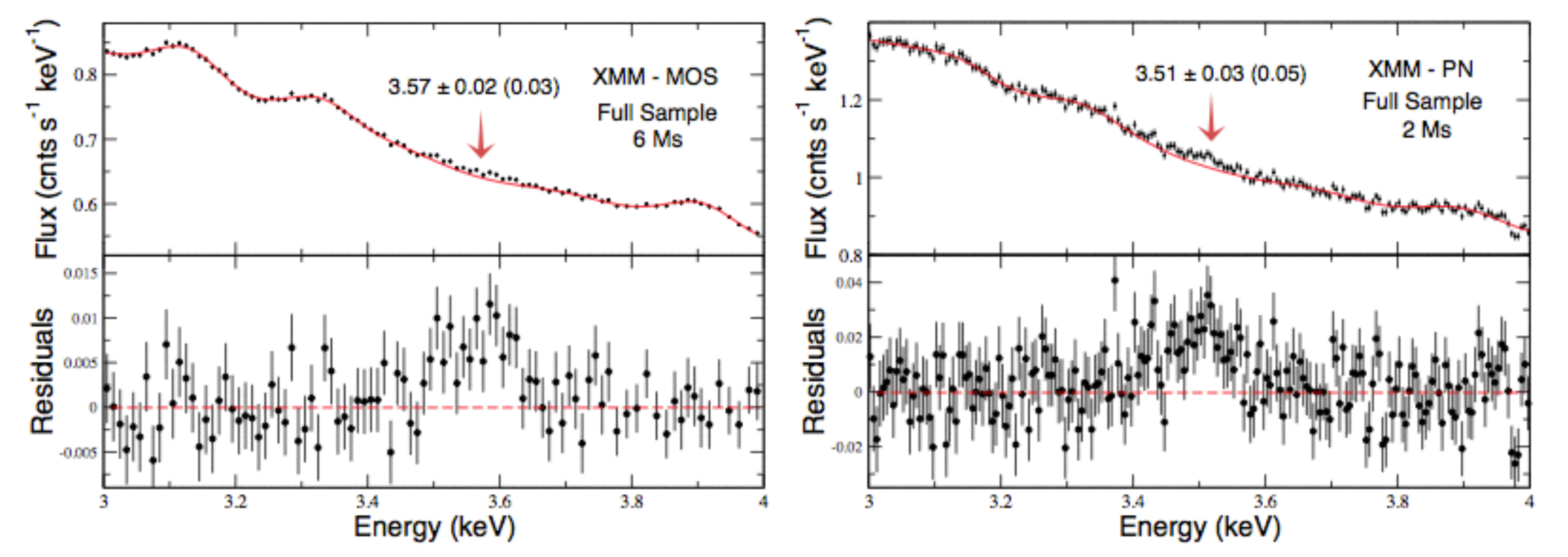
The present paper takes a step in this direction. We present the results of the combined analysis of many *XMM-Newton* observations of two objects at different redshifts – the Perseus cluster and the Andromeda galaxy (M31) – together with a long exposure "blank sky" dataset. We study the 2.8–8 keV energy band and show that the only significant un-modeled excess that is present in the spectra of both M31 and Perseus

19v1 [astro-ph.CO] 17 Feb 2014

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

**Bulbul et al., 1402.2301**

- An unidentified emission line at $E$=3.55-3.57 keV was found in a *stacked sample of 73 galaxy clusters* in both MOS and PN spectra of XMM-Newton.



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- An unidentified emission line at $E$=3.55-3.57 keV was found in a *stacked sample of 73 galaxy clusters* in both MOS and PN spectra of *XMM-Newton*.
- The line was further found in *three subsamples* (Perseus, Coma+Ophiuchus+Centaurus, all others) by MOS, and in “all others” by PN.
- The line in Perseus was also found separately in ACIS-I and ACIS-S *Chandra* data.

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

**Boyarsky et al., 1402.4119**

- An unidentified emission line at $E \approx 3.5$ keV was found in *XMM-Newton* MOS and PN spectra of *M31*, and the *outskirts of Perseus*. No line was found in *"blank sky"* observations.

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

## *Estimated significance*

| Target [detector] | $\Delta\chi$ |
|---|---|
| Perseus [MOS] | 15.7 [1] |
| Coma+Centaurus+Ophiuchus [MOS] | 17.1 [1] |
| "All others" (69 clusters) [MOS] | 16.5 [1] |
| "All others" (69 clusters) [PN] | 15.8 [1] |
| Perseus [ACIS-I] | 11.8 [2] |
| Perseus [ACIS-S] | 6.2 [1] |
| Perseus outskirts [MOS] | 9.1 [2] |
| Perseus outskirts [PN] | 8.0 [2] |
| Andromeda (M31) [MOS] | 13.0 [2] |

Bulbul et al.

Boyarsky et al.

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

***Origin?***

- Stacking diminishes the systematic detector uncertainties. Data from two satellites and 5 detectors used.
- An Potassium ion (K XVIII) transition line at 3.51 keV is in the correct energy range, but the flux needs to be ~30 times larger than conservative estimates to match the flux in clusters. Also, galaxies don't have an ICM.
- Dark matter decay or annihilation? Tantalising, but does it work?

*"As intriguing as the dark matter interpretation of our new line is, we should emphasize the significant systematic uncertainties affecting the line energy and flux in addition to the quoted statistical errors"*

Bulbul et al.

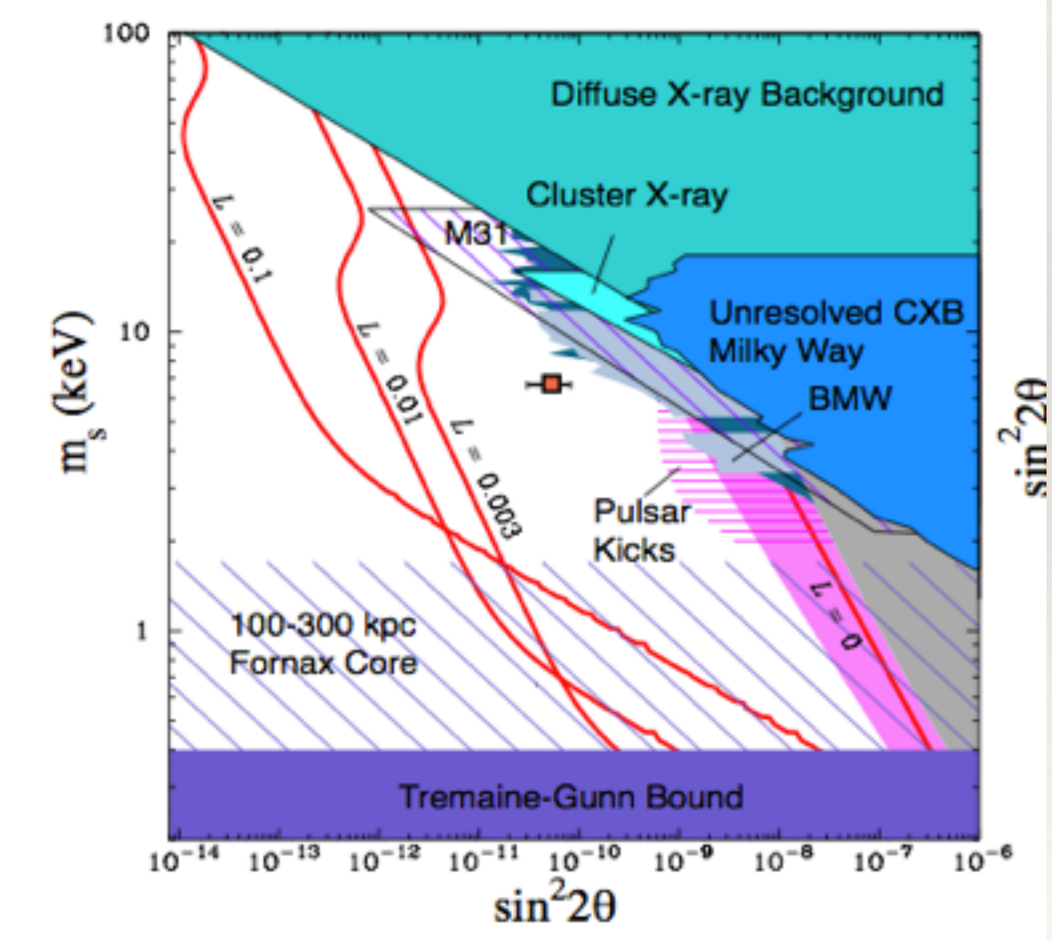
# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***X-rays from the decay of sterile neutrinos***

Sterile neutrino dark matter with $m_s$=7 keV may produce a 3.5 keV X-ray line by the (one-loop) decay $\nu_s \rightarrow \nu+\gamma$.

The decay rate is set by the mixing angle, $\sin^2(2\theta)$:

$$\Gamma = 1.38 \cdot 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2(2\theta)}{10^{-7}}\right)\left(\frac{m_s}{7.1\ \mathrm{keV}}\right)^5 .$$

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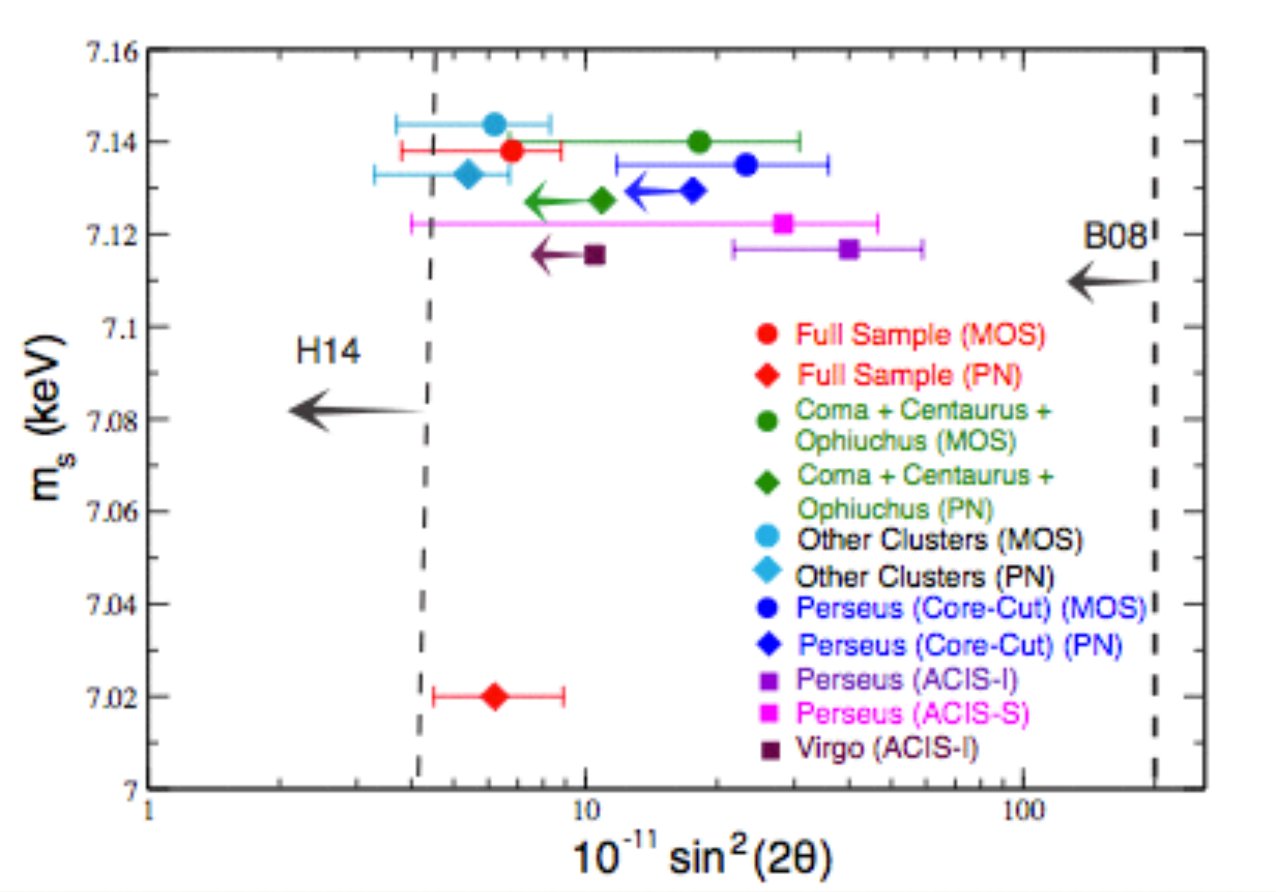
The decay rate is set by the mixing angle, $\sin^2(2\theta)$:

$$\Gamma = 1.38 \cdot 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2(2\theta)}{10^{-7}}\right)\left(\frac{m_s}{7.1\ \mathrm{keV}}\right)^5 .$$




Bulbul et al.

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***X-rays from the decay of sterile neutrinos***

Sterile neutrino dark matter with $m_s$=7 keV may produce a 3.5 keV X-ray line by the (one-loop) decay $\nu_s \rightarrow \nu+\gamma$.

The decay rate is set by the mixing angle, $\sin^2(2\theta)$:

$$\Gamma = 1.38 \cdot 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2(2\theta)}{10^{-7}}\right)\left(\frac{m_s}{7.1\ \mathrm{keV}}\right)^5 .$$

Issues with the dark matter explanation:

- The line in Perseus is *much stronger* than expected.
- In Perseus, a large fraction of the flux comes from the *cool core* (central 20 kpc).
- In the Coma+Ophiuchus+Centaurus sample, the cool core cluster again give a very large contribution.

Bulbul et al.

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***Subsequent results and controversy, I***

Malyshev et al.
arXiv:1408.3531

- *No evidence* for the line in stacked XMM-Newton spectra of *dwarf spheroidal galaxies*, excluding the sterile neutrino explanation at $4.6\sigma$.

Anderson et al.
arXiv:1408.4115

- *Non-detection* of the line in stacked XMM-Newton (and Chandra) spectra of outskirts of 89 (81) *galaxies*, thus excluding the sterile neutrino explanation at $11.8\sigma$ ($4.4\sigma$).

Urban et al.
arXiv:1411.0050

- Detection of line in *Suzaku data of Perseus*, but with radial decay inconsistent with sterile neutrino explanation. If correct, a line should have also been seen in Coma, Virgo and Ophiuchus.

Tamura et al.
arXiv:1412.1869

- No line found in *Suzaku data of Perseus*, in apparent contradiction with the previous point.

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***Subsequent results and controversy, II***

Riemer-Sörensen arXiv:1405.7943

- *No clear evidence* of the presence of the line in *Chandra* data of the galactic centre.

Boyarsky et al. arXiv:1408.2503, Jeltema, Profumo arXiv:1408.1699

- *Detection of a line in XMM-Newton* data of the galactic centre, but astrophysical origin cannot be excluded. Line flux larger than upper bound from the point above. *J&P:* excludes dark matter origin of cluster excess.

Jeltema, Profumo arXiv:1408.1699

Boyarsky et al. arXiv:1408.4388

Jeltema, Profumo arXiv:1411.1759

- Controversy about the line in *M31*. *J&P:* line is just $1\sigma$, and most likely astrophysical. *Boyarsky et al.:* this is just because inappropriately small fitting interval was used that inflates error bars. *J&P:* when fitting a broader energy band, spurious residuals appear at 3.5 keV.

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***Subsequent results and controversy, III***

- Controversy about the line in *clusters*. *J&P:* re-evaluate evidence for line, and find that when uncertainties in abundances and expected flux from various lines are taken into account, and a contribution from Cl XVII added, no conclusive excess emission remains. *Bulbul et al.:* J&P use incorrect atomic data and use inconsistent spectroscopic models. Cl XVII contribution is ruled out based on non-observed other transitions. No inconsistency when correct data is used. *J&P:* Cl contribution was in any case subdominant. Wrong atomic data was used, but this doesn't affect conclusions. Conclusions were correct, and the modelling by Bulbul et al. is inconsistent.

Jeltema, Profumo arXiv:1408.1699

Bulbul et al., arXiv:1409.4143

Jeltema, Profumo arXiv:1411.1759

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

***Subsequent results and controversy, IV***

Resonaances blog

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***Conclusions:***

An unidentified line at 3.5 keV has been found independently by several groups using detectors on three different satellites. It's unlikely to be an instrumental effect.

Attempts to explain the line by Potassium ion lines are controversial. Future satellites will be able to resolve the line (e.g. Astro-H, launch 2015/2016) and settle the issue.

Here, I will entertain the possibility that the cluster line is not a systematic effect. The line from MW centre may be atomic in nature.

Still, *standard decaying dark matter does not fit the data* (line strength and morphology in Perseus, Ophiuchus, no signal from dwarf spheroidals or galaxies).

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

***DM → ALP:***

Here, I will consider a scenario in which the dark matter decay includes an ALP in the final state.

*Example 1:* Sterile neutrino dark matter

Sterile neutrinos have more decay modes than $\nu_s \to \nu + \gamma$ and may also couple to ALPs:

$$\mathcal{L} \supset \frac{\partial_\mu a}{\Lambda} \bar{\psi} \gamma^\mu \gamma_5 \nu \qquad \Gamma_{\psi \to \nu a} = \frac{1}{16\pi} \frac{m_\psi^3}{\Lambda^2} \,,$$

*Example 2:* Moduli dark matter

*7.1* keV scalar dark matter may decay into two ALPs

$$\mathcal{L} \supset \frac{\Phi}{\Lambda} \frac{1}{2} \partial_\mu a \partial^\mu a \,, \qquad \Gamma_{\Phi \to aa} = \frac{1}{128\pi} \frac{m_\Phi^3}{\Lambda^2} \,.$$

# A galaxy cluster 3.5 keV line from *DM→ALP→ γ*.

***X-ray flux:***

DM→ALP → γ:

$$\mathcal{F}_{\psi\to\nu\gamma} = \frac{\Gamma_{\mathrm{DM}\to a}}{4\pi}\int_{\mathrm{FOV}}\varrho\,\mathrm{d}\varrho\,\mathrm{d}\phi\int_{\mathrm{l.o.s.}}\frac{\rho_{\mathrm{DM}}(l,\varrho,\phi)}{m_{\mathrm{DM}}}\underline{P_{a\to\gamma}(l,\varrho,\phi)}\,\mathrm{d}l,$$

c.f. to standard sterile neutrino flux:

$$\mathcal{F}_{\psi\to\nu\gamma} = \frac{\Gamma_{\psi\to\nu\gamma}}{4\pi}\int_{\mathrm{FOV}}\varrho\,\mathrm{d}\varrho\,\mathrm{d}\phi\int_{\mathrm{l.o.s.}}\frac{\rho_{\mathrm{DM}}(l,\varrho,\phi)}{m_{\psi}}\mathrm{d}l\,.$$

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

***Properties of $DM \rightarrow ALP \rightarrow \gamma$:***

While the signal in any scenario in which dark matter decays to photons:

- Conversion probability from ALP to photon is *much larger in clusters* (where $R \sim 1$ Mpc) than galaxies (where $R \sim 30$ kpc).
- *Nearby clusters* particularly good targets as FOV covers central region with strong magnetic field.
- *Cool-core clusters* (e.g. Perseus) are special because they have large central magnetic fields.
- M31 is special as it's a nearby spiral that is close to edge-on with an *unusually large coherent magnetic field*.

Cicoli, Conlon, *D.M.*, Rummel arXiv:1403.2370

Conlon, Day arXiv:1404.7741

# A galaxy cluster 3.5 keV line from *DM → ALP → γ*.

***Predictions of DM → ALP → γ:***

- *No signal* is expected from dwarf spheroidal galaxies.
- *No signal* is expected from a random sample of galaxies and galaxy outskirts.
- Nearby edge-on spirals are the best candidates to observe the line in galaxies.

Cicoli, Conlon, *D.M.*, Rummel arXiv:1403.2370

*Observations (recall):*

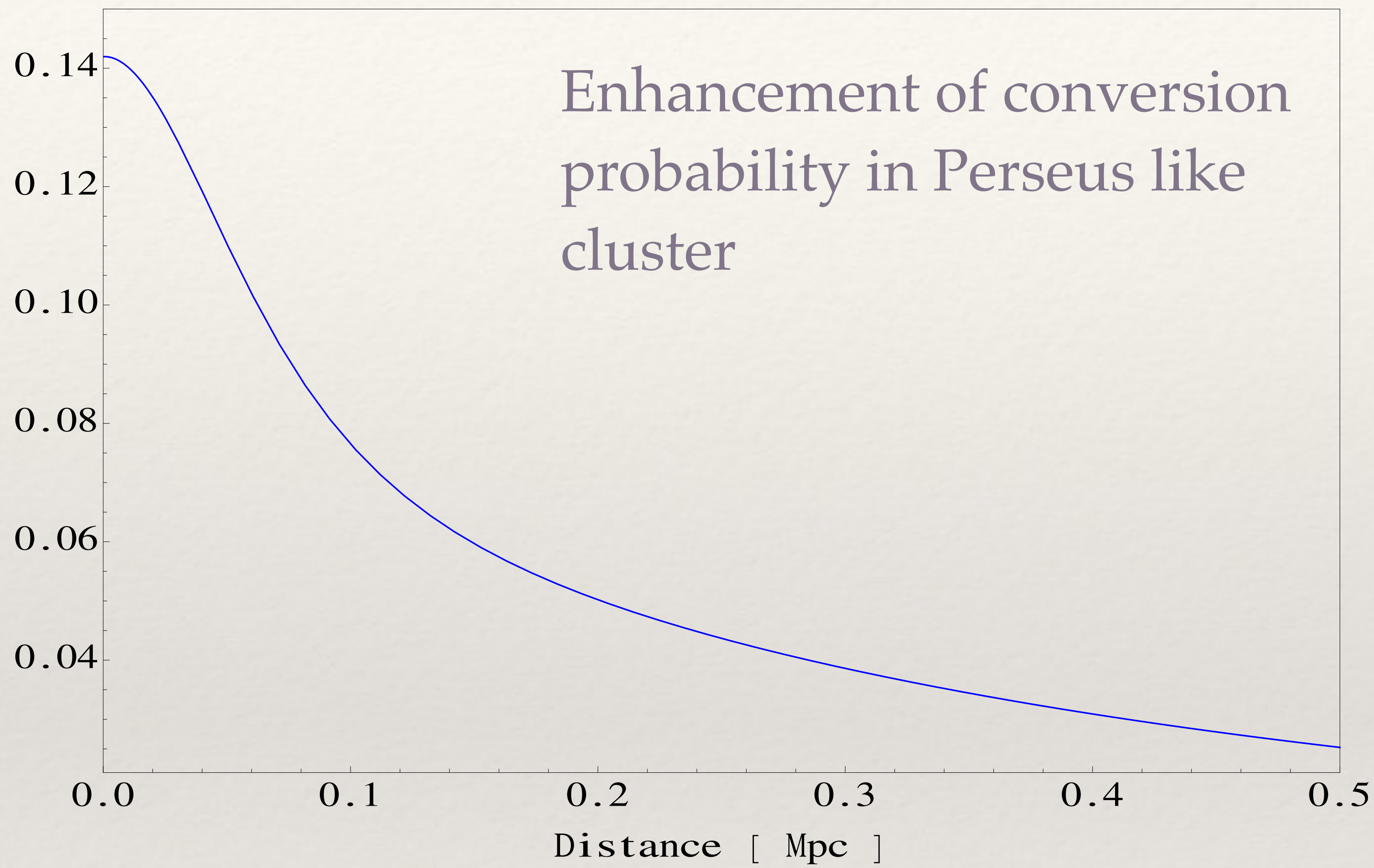
- *No evidence* for the line in stacked XMM-Newton spectra of *dwarf spheroidal galaxies*, excluding the sterile neutrino explanation at *4.6*σ.
- *Non-detection* of the line in stacked XMM-Newton (and Chandra) spectra of outskirts of 89 (81) *galaxies*, thus excluding the sterile neutrino explanation at *11.8*σ (*4.4*σ).

Malyshev et al. arXiv:1408.3531

Anderson et al. arXiv:1408.4115

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

**Morphology of signal**




Cicoli, Conlon, *D.M.*, Rummel arXiv:1403.2370

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

**Signal from the Milky Way?**

Conlon, Day
arXiv:1404.7741

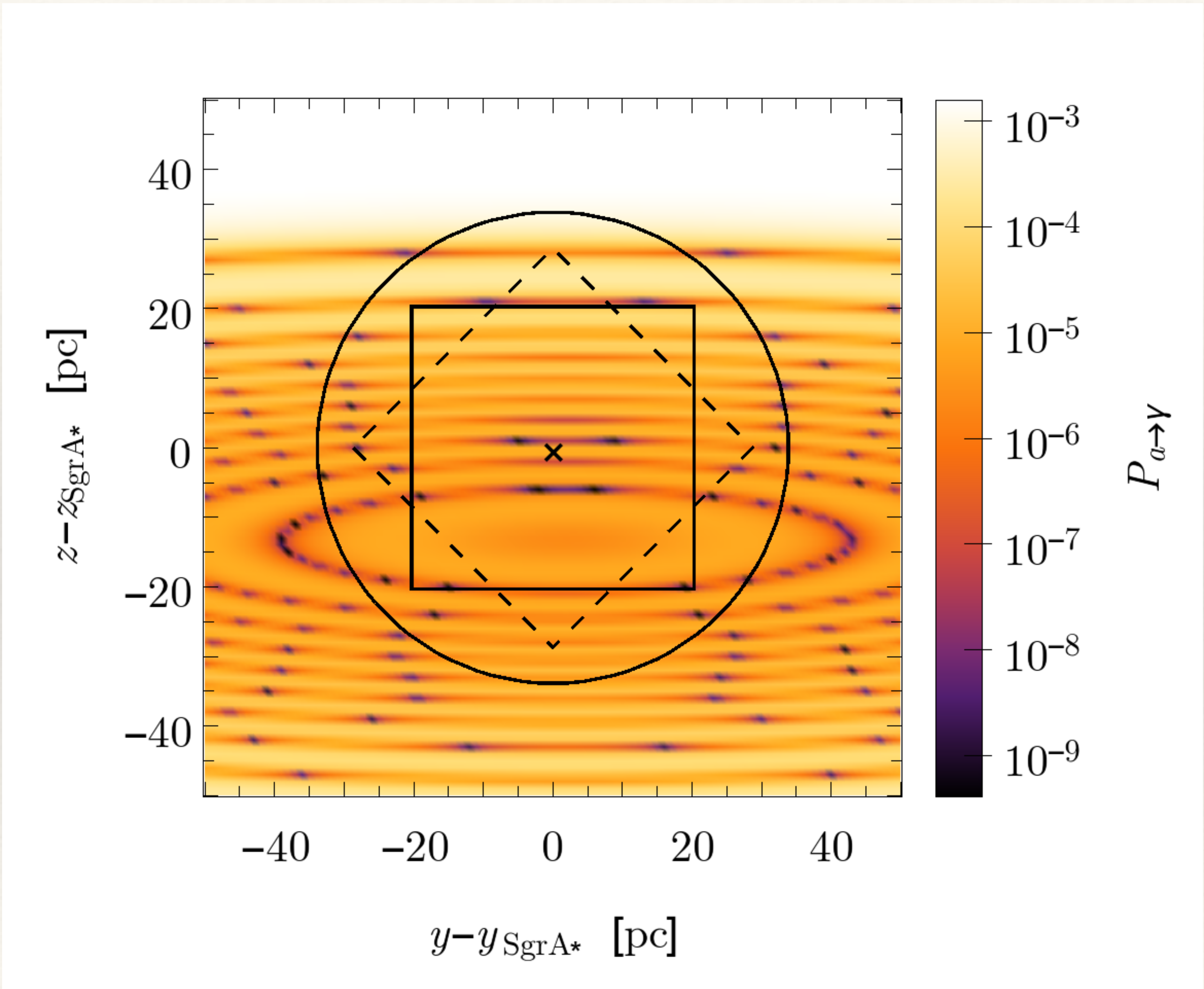
- From the bulk of the MW, the signal is unobservable small.

Alvarez, Conlon, Day, *D.M.*, Rummel
arXiv:1410.1867

- The magnetic field in the central region of the Milky Way is not known, and estimates differ by two orders of magnitude. The $DM \rightarrow ALP \rightarrow \gamma$ scenario only give an observable signal for the highest estimates of the magnetic field, and if so, may suggest an explanation to why the line is seen in *XMM-Newton* data but not *Chandra*.

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

## Signal from the Milky Way?

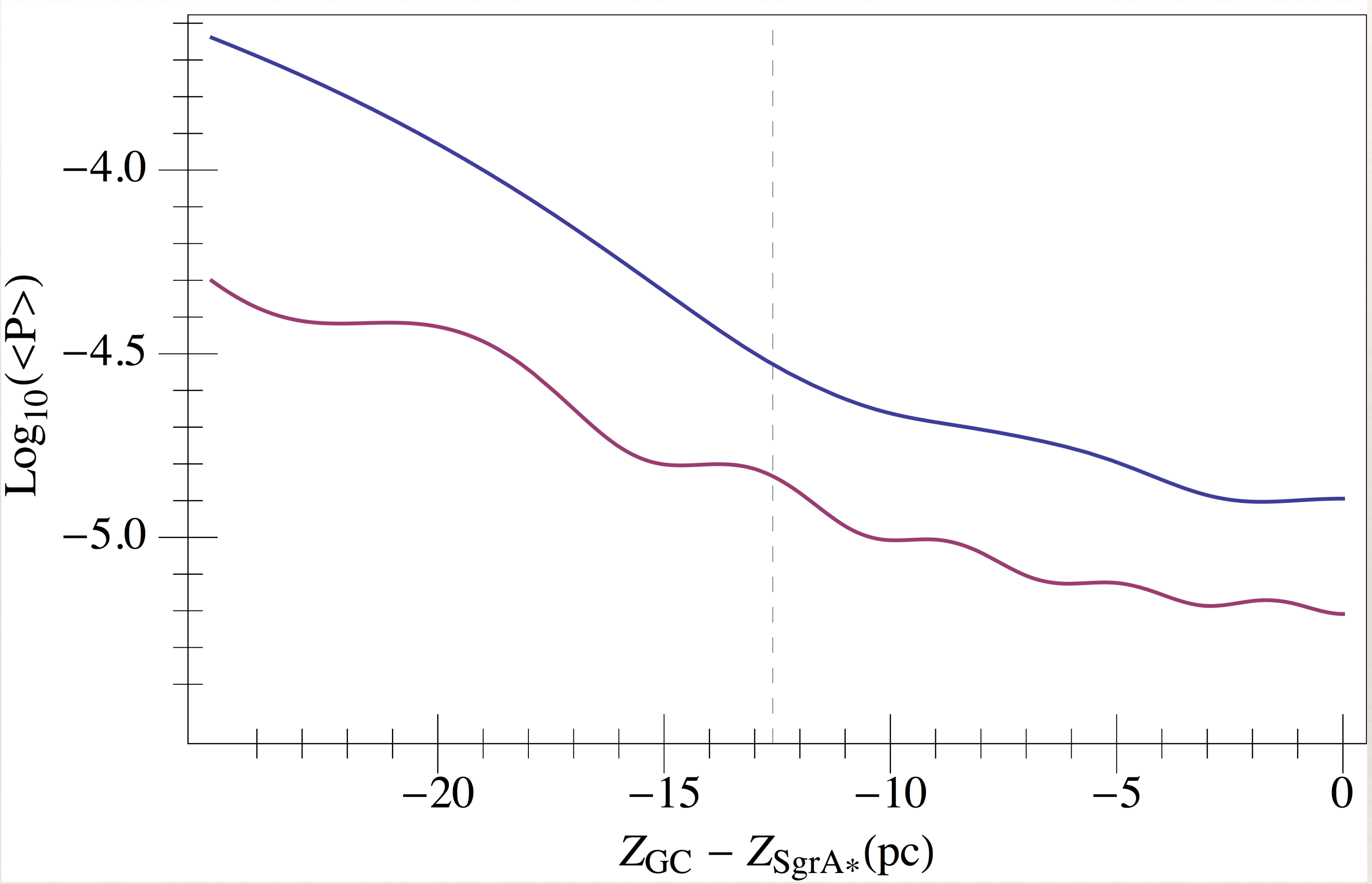



Alvarez, Conlon, Day, *D.M.*, Rummel arXiv:1410.1867

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

## Signal from the Milky Way?

Alvarez, Conlon, Day, *D.M.*, Rummel arXiv:1410.1867

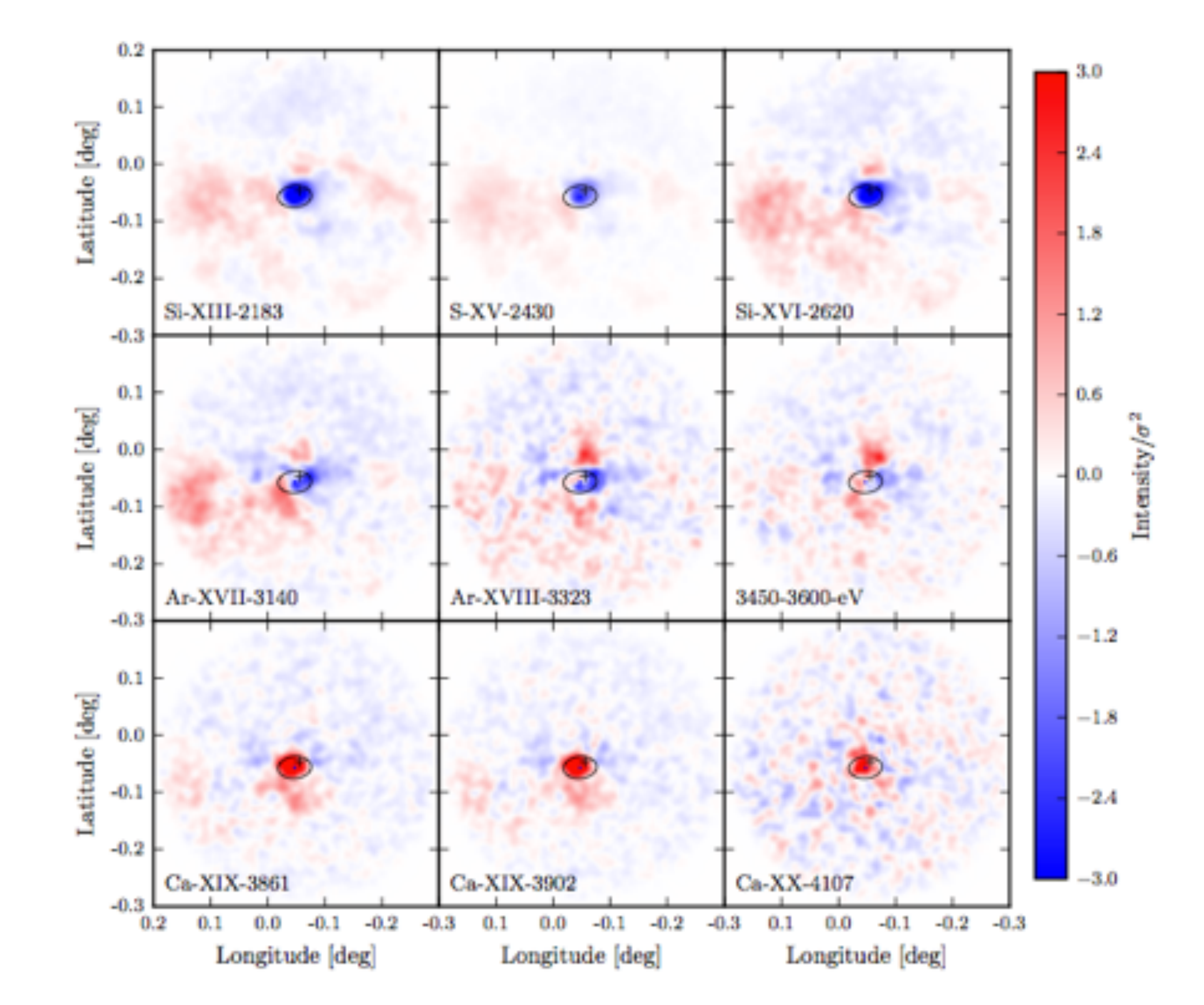


# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

**Signal from the Milky Way? *J&P+Carlson's take:***

The morphology of the 3.5 keV signal in the centre of the MW is distinct from that expected from decaying dark matter, or the scenario discussed in this talk.

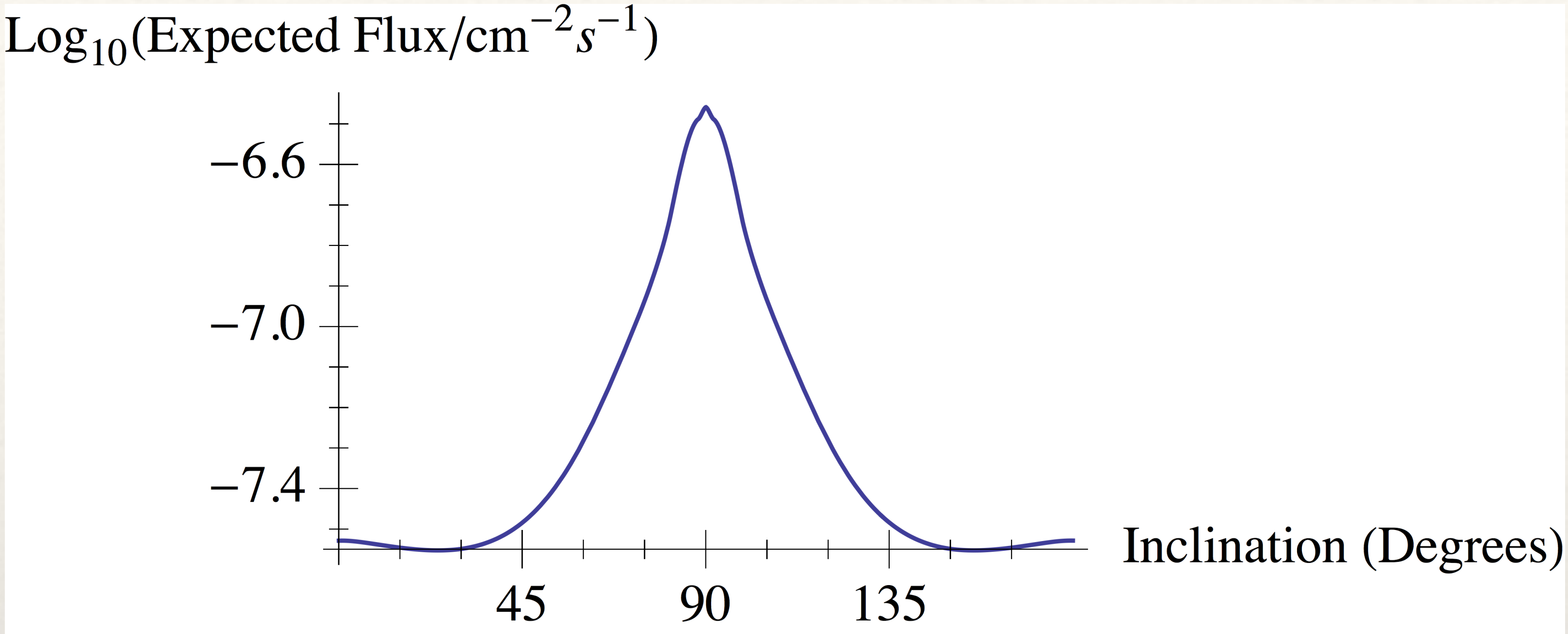
Carlson, Jeltema, Profumo arXiv:1411.1758

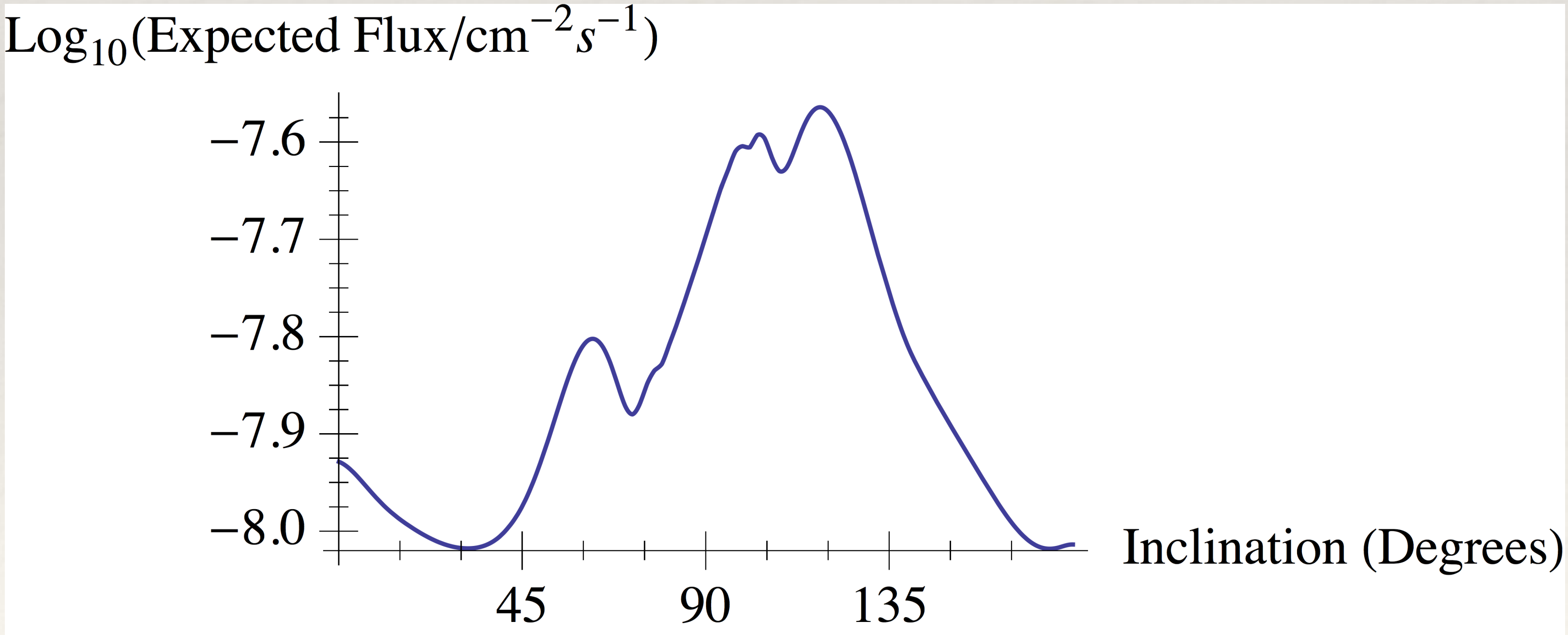



*But again expected to be controversial (X-ray absorption not taken into account).*

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

## Signal from other galaxies?




Alvarez, Conlon, Day, *D.M.*, Rummel
arXiv:1410.1867

# A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$.

## Signal from other galaxies?

**Table 3:** List of nearly edge-on spiral galaxies with long X-ray exposures

| Galaxy | Type | $\theta_i$ | $n_{\rm CXO}$ | $t_{\rm CXO}$ [ks] | $n_{\rm XMM}$ | $t_{\rm XMM}$ [ks] |
|---|---|---|---|---|---|---|
| ESO602-031 | SBb | 70.8 | 1 | 5.0 | 2 | 20.9 |
| IC2163 | Sc | 78.2 | 2 | 40.2 | 1 | 14.9 |
| IC2560 | SBb | 65.6 | 2 | 65.6 | 3 | 64.9 |
| IC2574 | SABm | 83.0 | 1 | 11.4 | 2 | 61.0 |
| IC2810 | SBab | 75.2 | 1 | 15.0 | 5 | 331.0 |
| NGC0224 | Sb | 72.2 | 105 | 939.9 | 1 | 96.3 |
| NGC0253 | SABc | 90.0 | 6 | 159.8 | 1 | 14.8 |
| NGC0520 | Sa | 75.7 | 1 | 50.0 | 8 | 371.0 |
| NGC0625 | SBm | 90.0 | 1 | 61.1 | 3 | 130.0 |
| NGC0660 | Sa | 78.7 | 4 | 58.2 | 2 | 151.6 |

*Continued on next page*

Alvarez, Conlon, Day, D.M., Rummel arXiv:1410.1867

*7* and *8.5* Ms of raw exposure on a set of nearby close to edge-on spiral galaxies for *Chandra* and *XMM*.

# A galaxy cluster 3.5 keV line from $DM \to ALP \to \gamma$.

More observational papers are expected to appear:

- Bulbul et al., using *Suzaku* and *Chandra* data.
- Boyarsky et al., looking at A520 (the "train wreck").

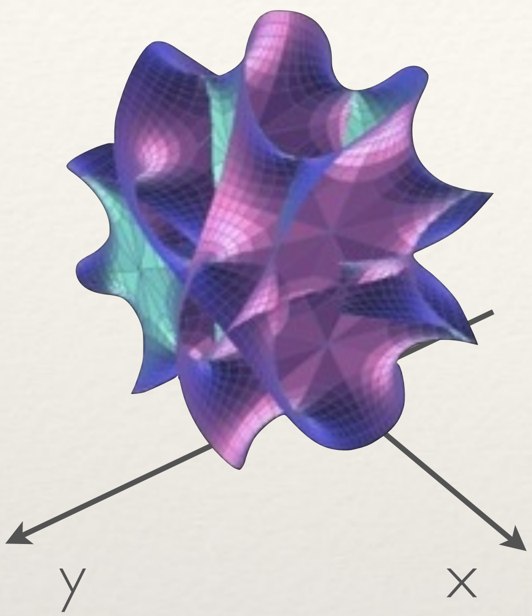
# Outline:

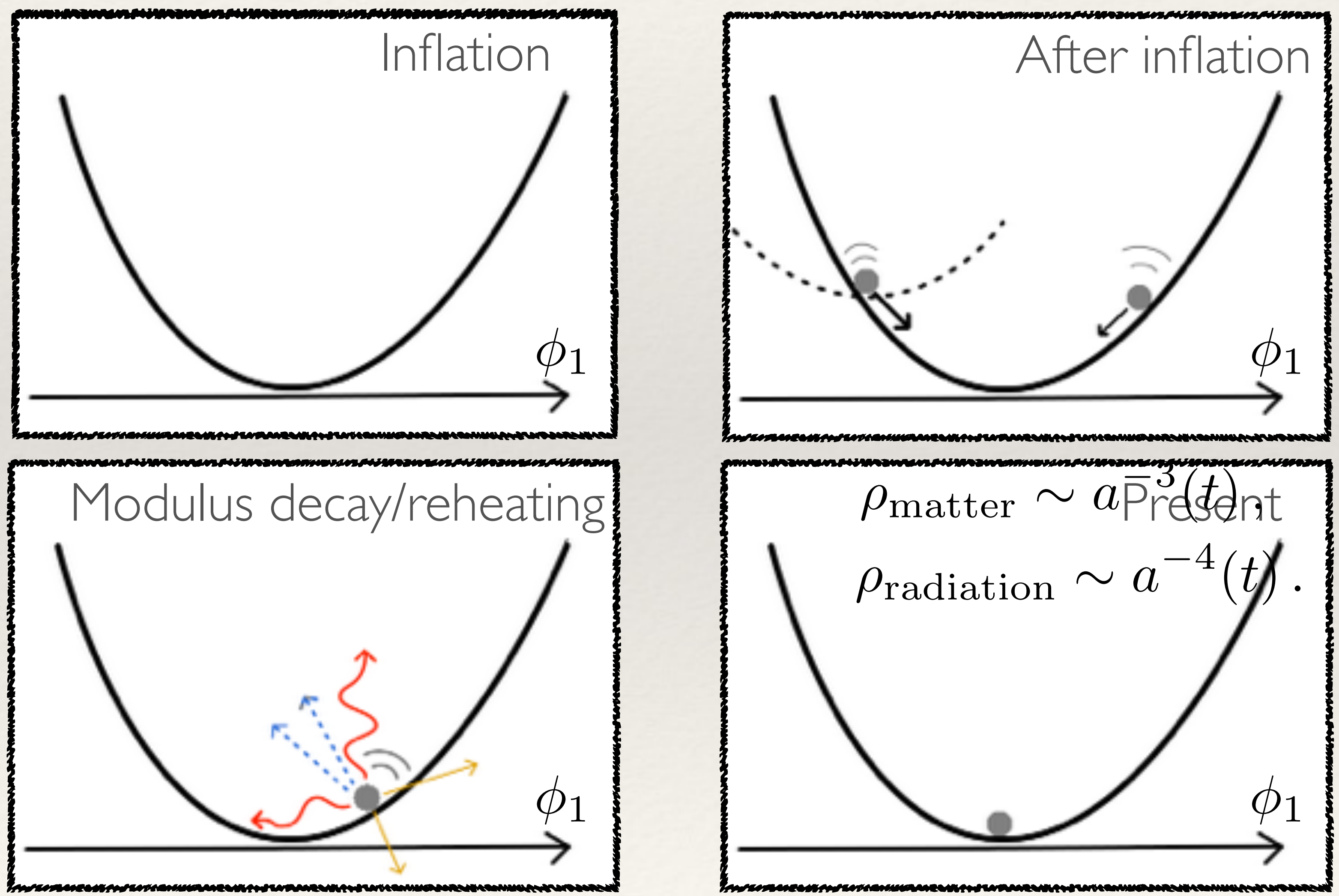
1. Axion-like particles (ALPs)
2. Galaxy clusters as ALP converters
3. A galaxy cluster 3.5 keV line from $DM \rightarrow ALP \rightarrow \gamma$
4. *A Cosmic Axion Background and the cluster soft X-ray excess*

# A Cosmic Axion Background and the cluster soft X-ray excess

## *Motivation:* Moduli decay into ALPs

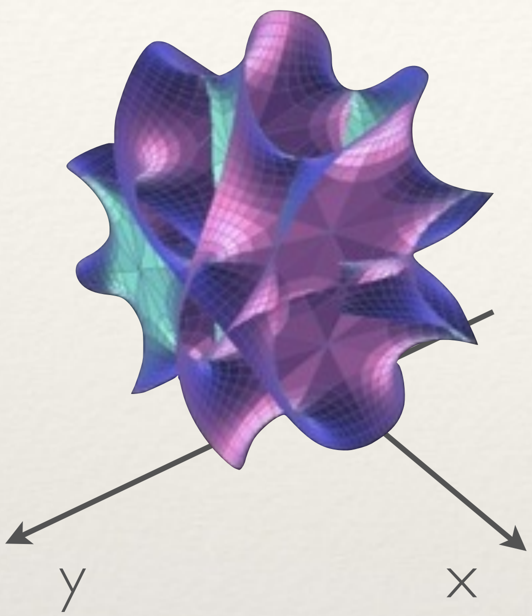
The low-energy spectrum of stabilised compactifications of string theory include massive scalar fields that couple with Planck mass suppressed couplings (moduli).



# A Cosmic Axion Background and the cluster soft X-ray excess

***Motivation:*** **Moduli decay into ALPs**




The decay of the lightest modulus drives reheating, but very weakly coupled fields never thermalise.

*Thermal bath:*

$$T_{rh} \sim \left(3H^2_{decay}M^2_{Pl}\right)^{1/4} \sim \left(3M^2_{Pl}/\tau^2_{\phi}\right)^{1/4} \sim \frac{m_\phi^{3/2}}{M_{Pl}^{1/2}}$$

$$\sim 0.6 \text{ GeV} \left(\frac{m_\phi}{10^6 \text{ GeV}}\right)^{3/2},$$

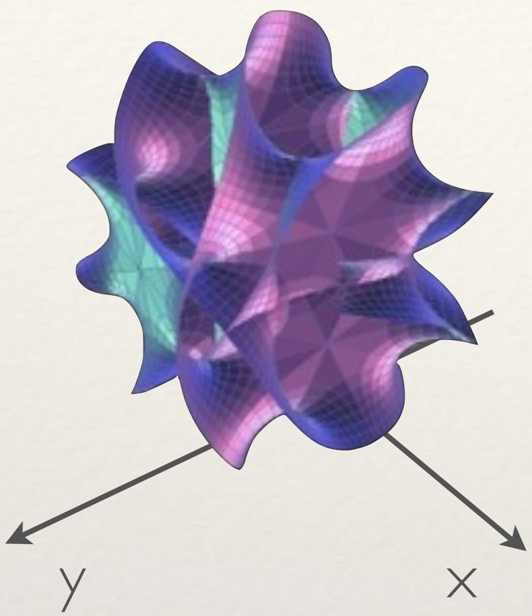
*Weakly coupled particles (ALPs, hidden photons):*

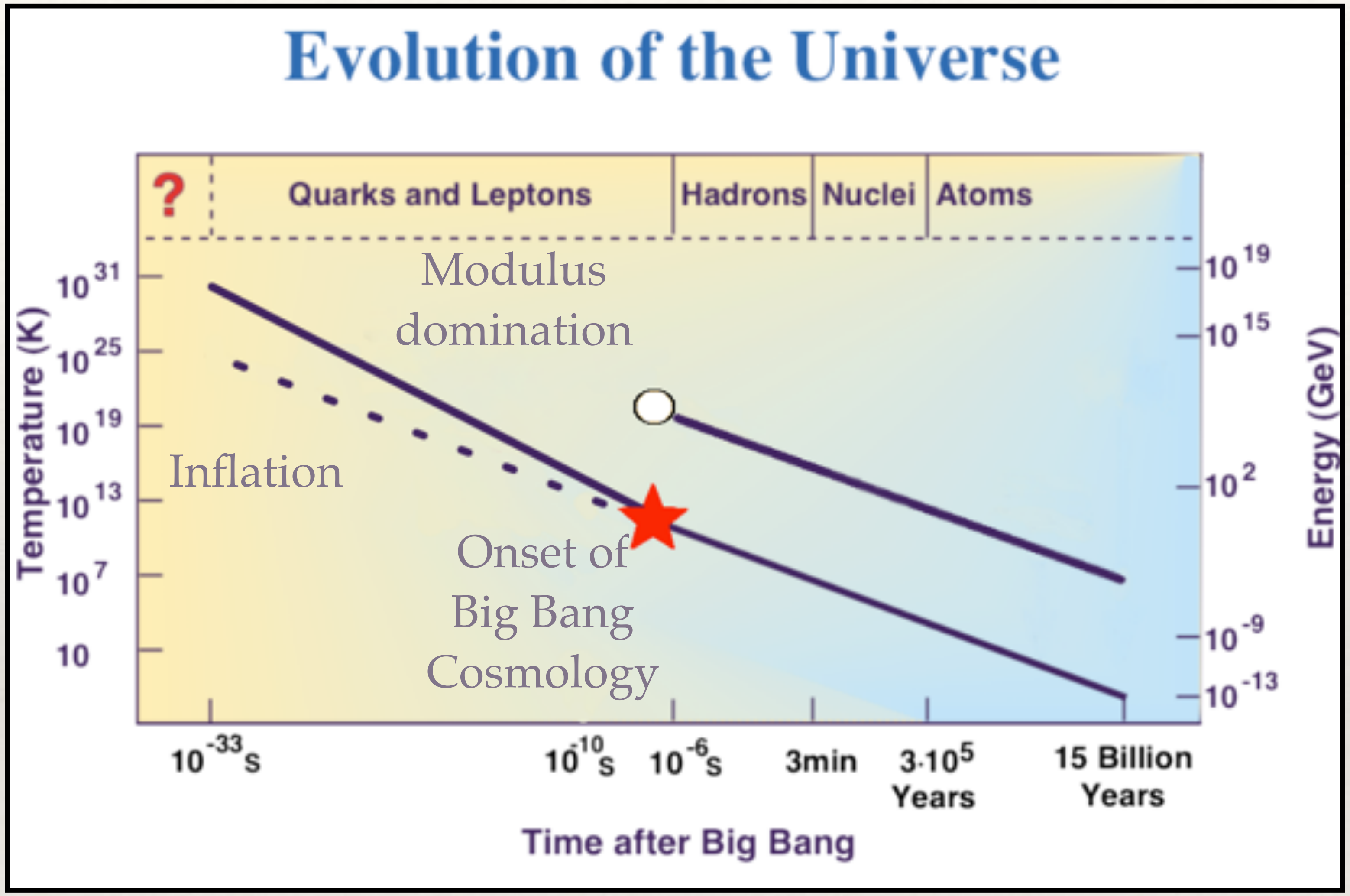
$$E_a^{(0)} = m_{\phi_1}/2 \gg T_{rh} \, ,$$

Moduli decay into light, weakly coupled hidden sector fields (e.g. *axion-like particles*, hidden photons) produce *dark radiation* with present energies $E \sim O(0.1\text{-}1 \text{ keV})$.

# A Cosmic Axion Background and the cluster soft X-ray excess

## *Motivation:* A Cosmic Axion Background (CAB)



# A Cosmic Axion Background and the cluster soft X-ray excess

***Constraints on dark radiation***

1. BBN: $\Delta N_{eff} > 0$ increases expansion rate at BBN and increase the primordial abundance of $^4$He.
2. CMB: $\Delta N_{eff} > 0$ effectively enhances the Silk damping of high-l multipoles.

# A Cosmic Axion Background and the cluster soft X-ray excess

## *Constraints on dark radiation*

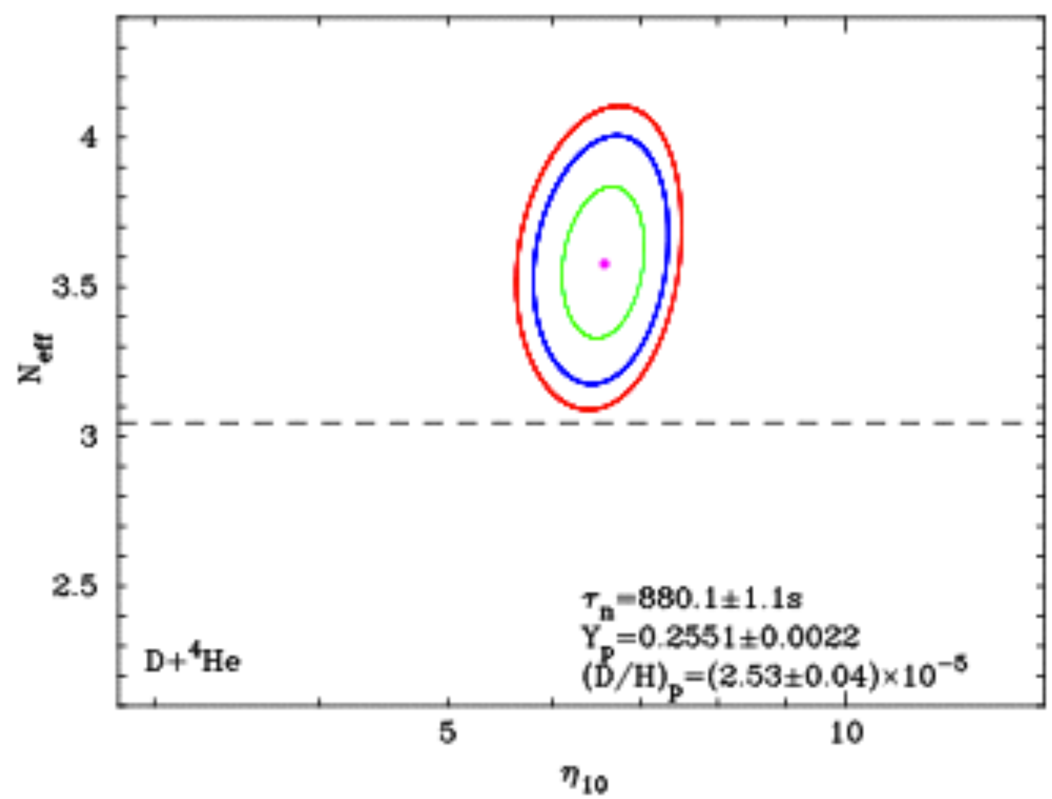



**Figure 11.** Joint fits to the baryon-to-photon number ratio, $\eta_{10}$=$10^{10}\eta$, and the effective number of light neutrino species $N_{eff}$, using a $\chi^2$ analysis with the code developed by Fiorentini et al. (1998) and Lisi et al. (1999). The primordial value of the He abundance has been set to $Y_p$ = 0.2551 (Fig. 9) and that of $(D/H)_p$ is taken from Cooke et al. (2014). The neutron lifetime is taken to be $\tau_n$ = 880.1 ± 1.1s (Beringer et al. 2012). The filled circle corresponds to $\chi^2 = \chi^2_{min} = 0$. Ellipses from the inside out correspond respectively to confidence levels of 68.3% ($\chi^2 - \chi^2_{min}$ = 2.30), 95.4% ($\chi^2 - \chi^2_{min}$ = 6.17) and 99.0% ($\chi^2 - \chi^2_{min}$ = 9.21). The SBBN value $N_{eff}$ = 3.046 is shown with a dashed line.

Izotov et al.
arXiv:1408.6953

# A Cosmic Axion Background and the cluster soft X-ray excess

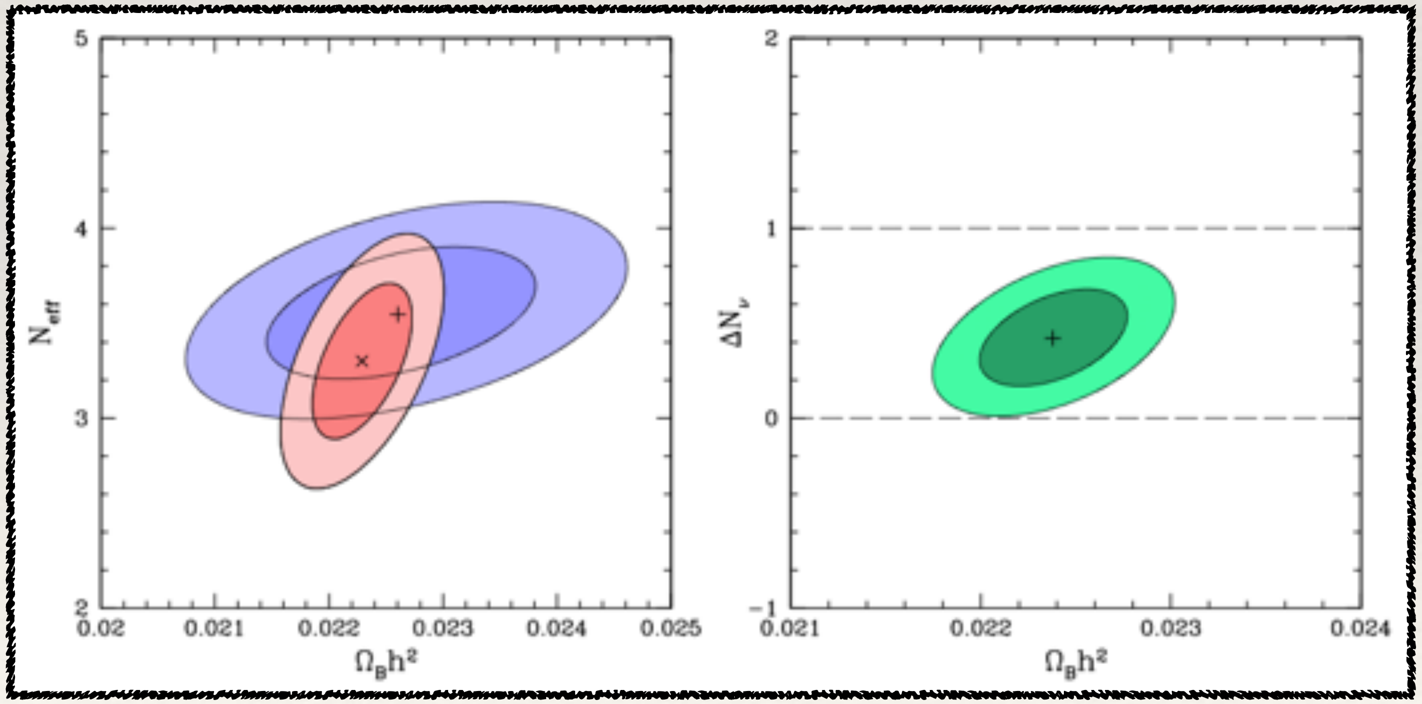
***Constraints on dark radiation***

Planck: $\Delta N_{eff}$

*Planck+WMAP-pol+ high-l+BAO:* $0.26 \pm 0.27\,,$

*Planck+WMAP-pol+ high-l+BAO +H₀:* $0.48 \pm 0.25\,.$

Planck+BBN:



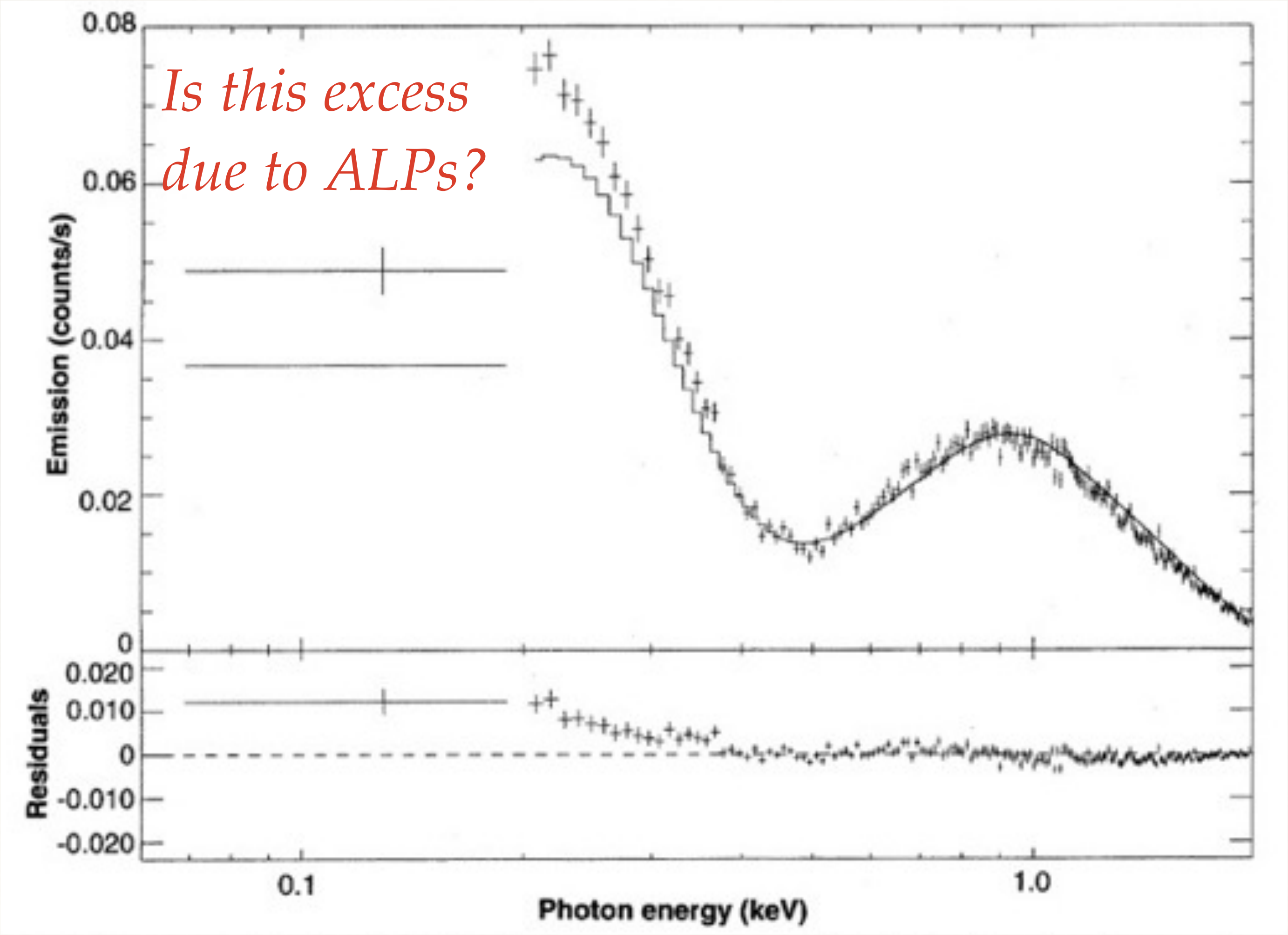

$0.40 \pm 0.16\,.$

Planck collab. ’13,
Nollet, Steigman, ’13.

# A Cosmic Axion Background and the cluster soft X-ray excess

A CAB could be visible through ALP-photon conversion in clusters, and would result in an additional source of soft X-rays.

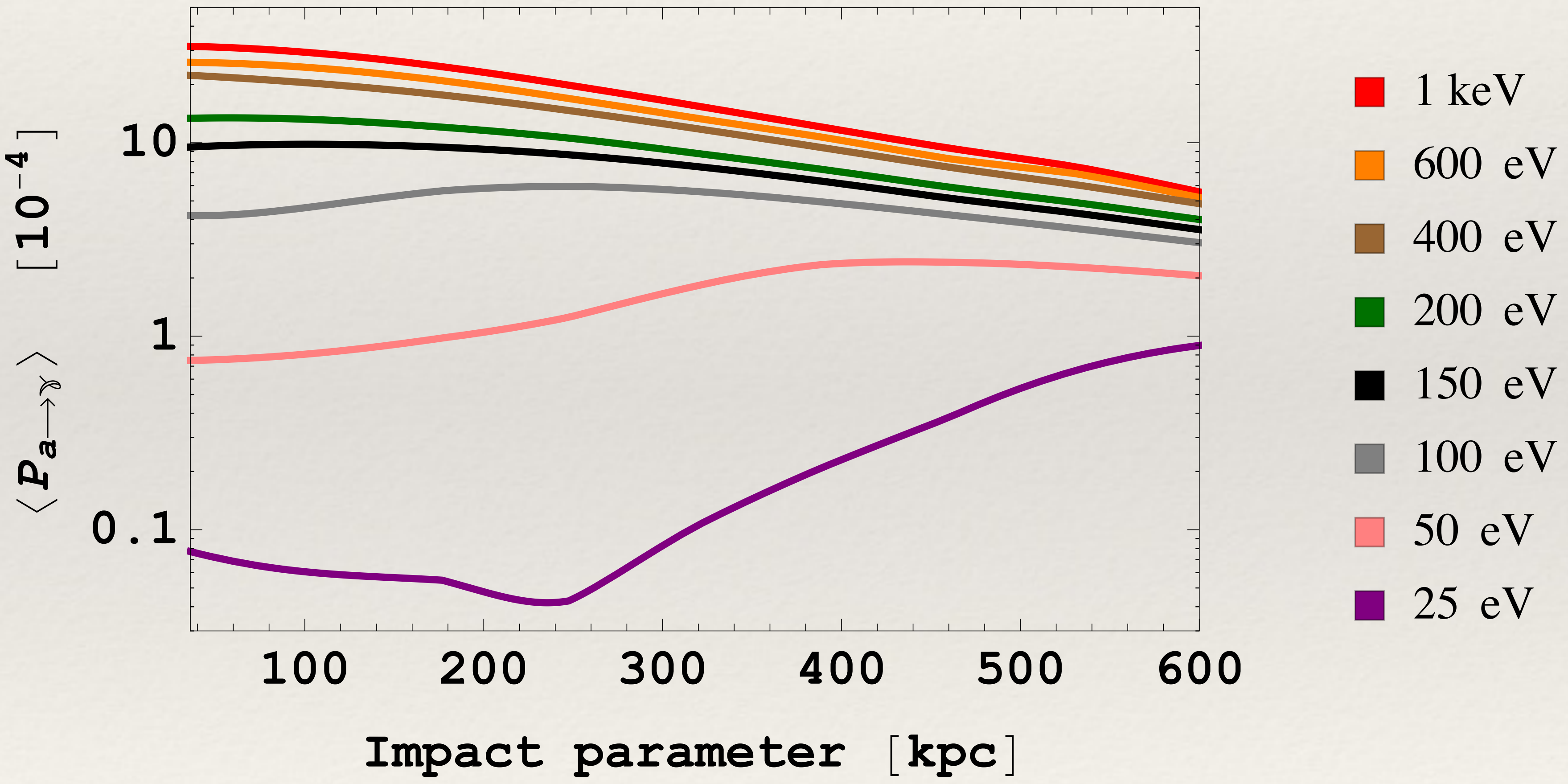
Intriguingly, an *excess of soft X-rays* from galaxy clusters have been reported in a large number of clusters since 1996.



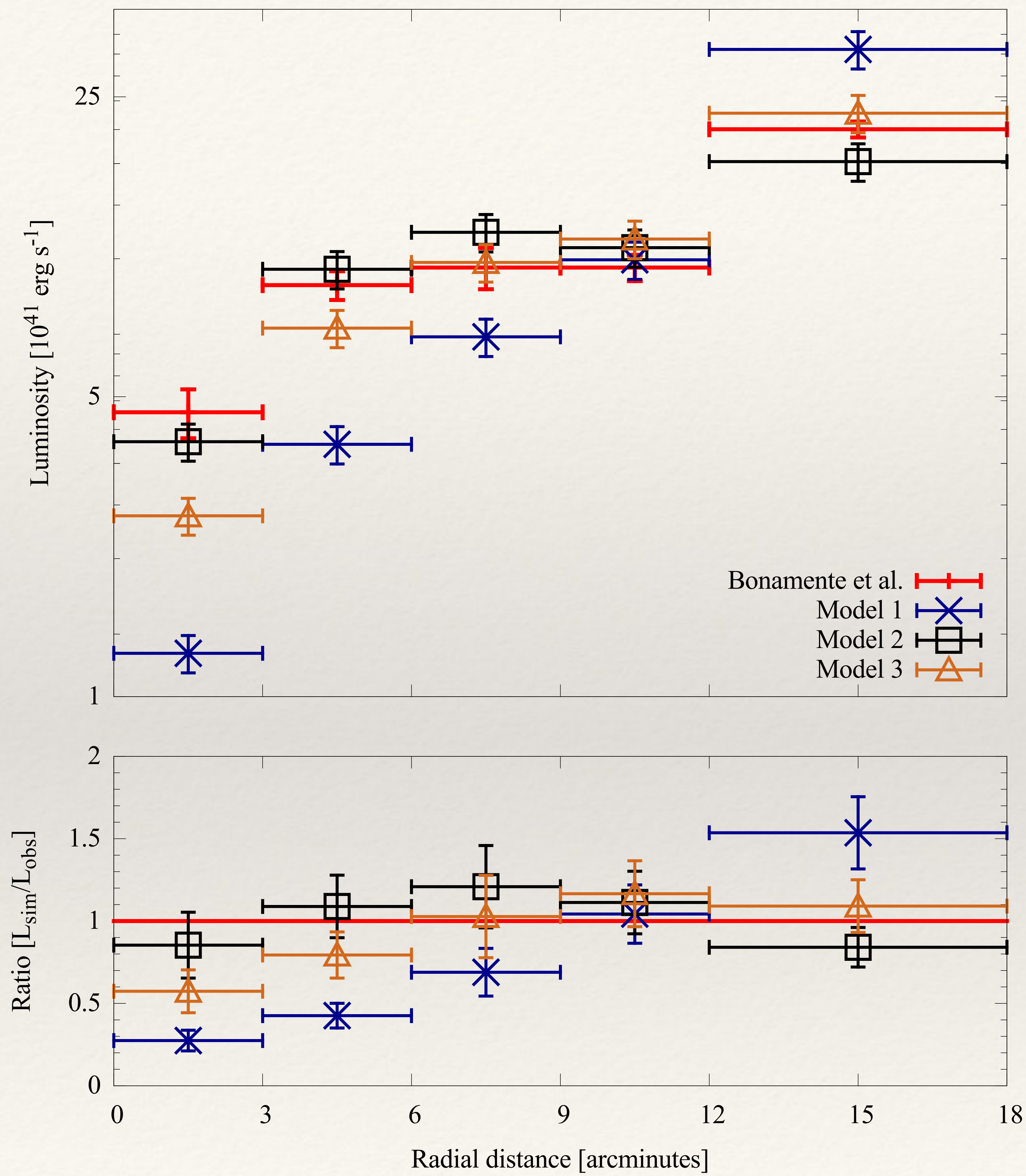

EUVE on Virgo from Liu et al. ’96.

# A Cosmic Axion Background and the cluster soft X-ray excess

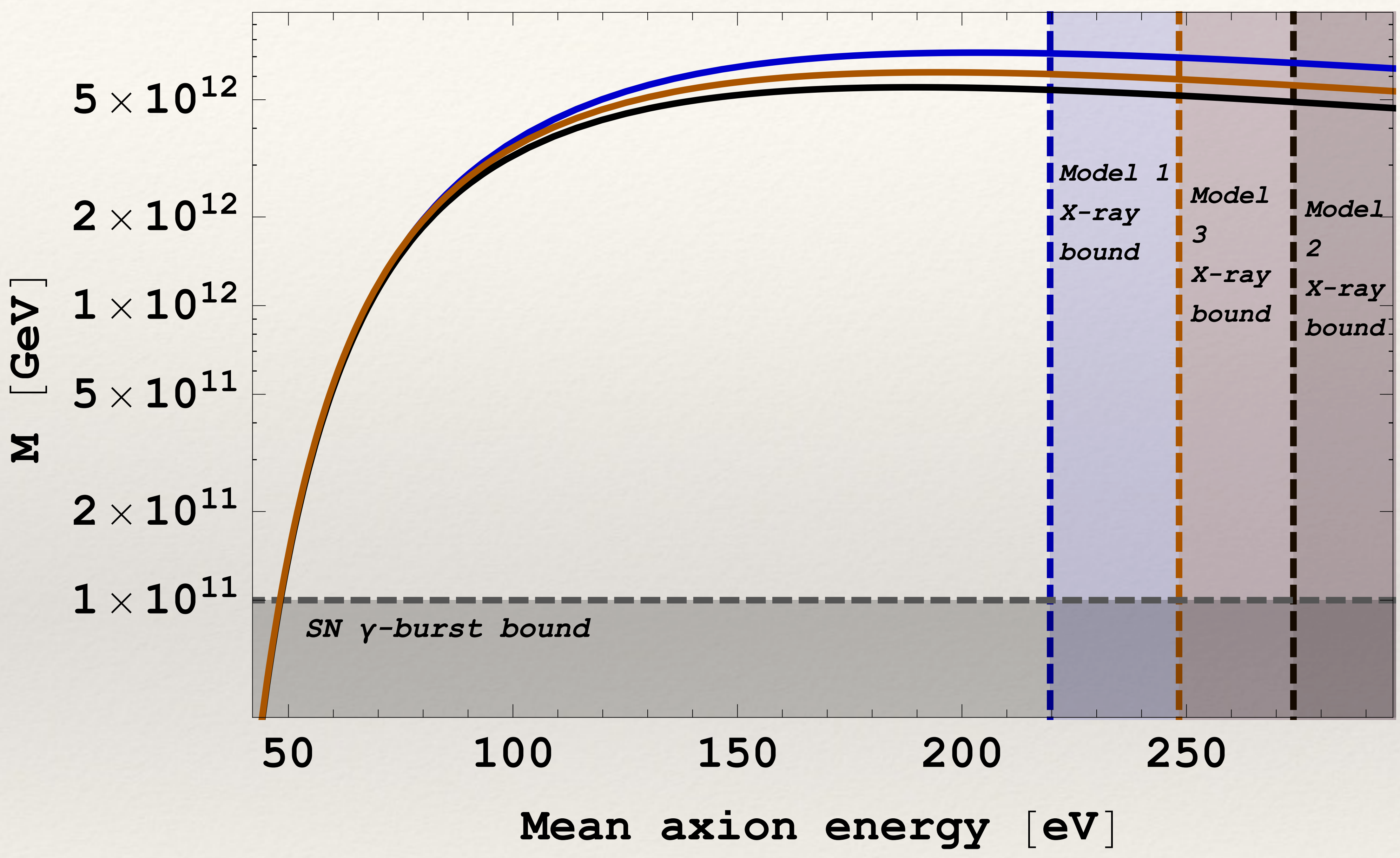
A CAB explanation of the soft X-ray excess gives distinct predictions for the morphology of the soft X-ray excess, if the electron density and magnetic field is known. *Test with the models for the Coma clusters.*



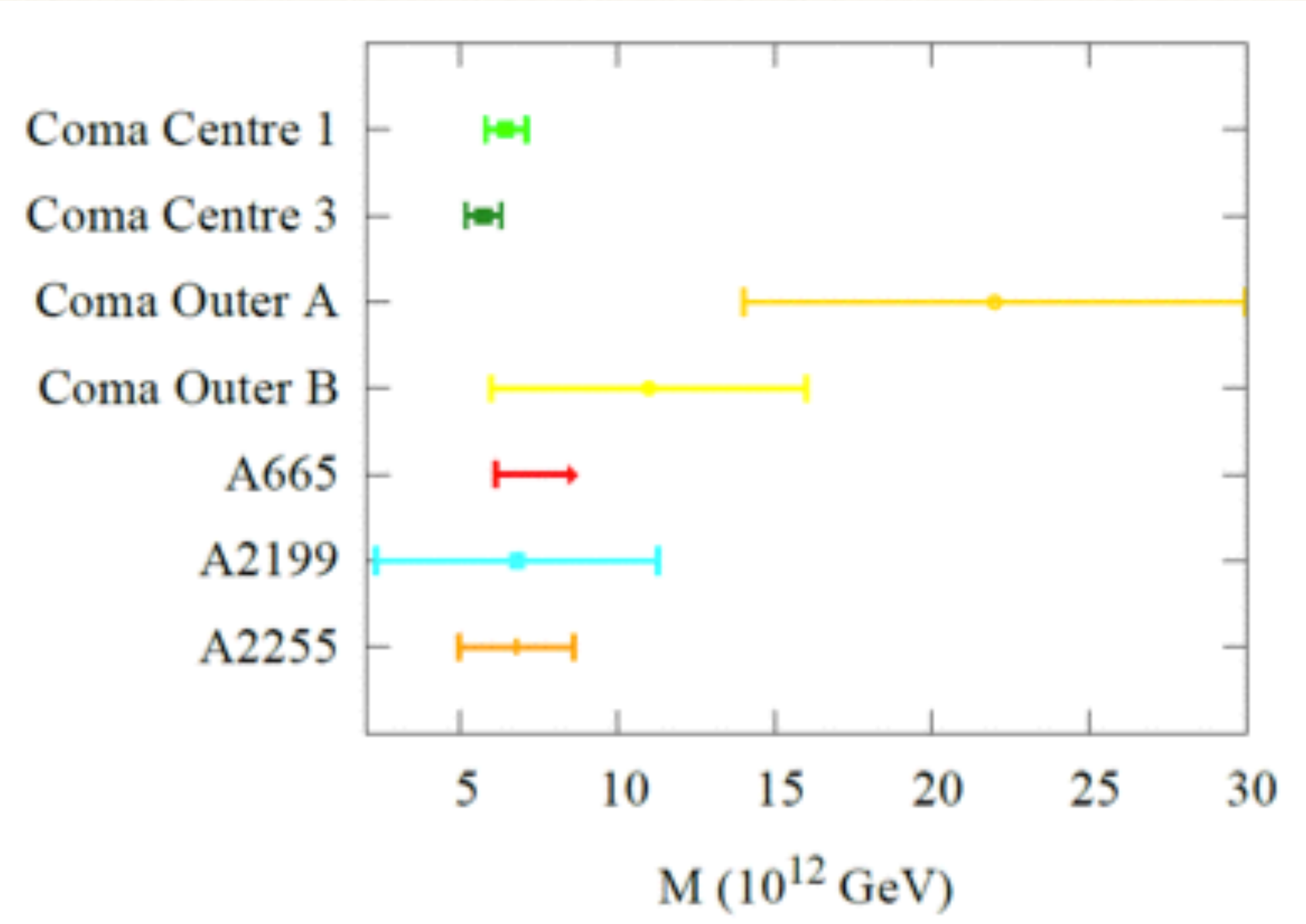
# A Cosmic Axion Background and the cluster soft X-ray excess



# A Cosmic Axion Background and the cluster soft X-ray excess



# A Cosmic Axion Background and the cluster soft X-ray excess




Powell
arXiv:1411.4172

# Conclusions

- Galaxy clusters are highly *efficient converters* of very light axion-like particles, with *O(1)* conversion probabilities for $M = 10^{11}$ GeV.
- *Key morphological properties* of the 3.5 keV signal from clusters and M31 are well-described by a model in which dark matter decays to an ALP, that subsequently convert into an X-ray photon. This is a predictive scenario that will be tested against observations.
- Large classes of string theory compactifications suggest the existence of a *cosmic ALP background*, which may explain the *cluster soft X-ray excess*.