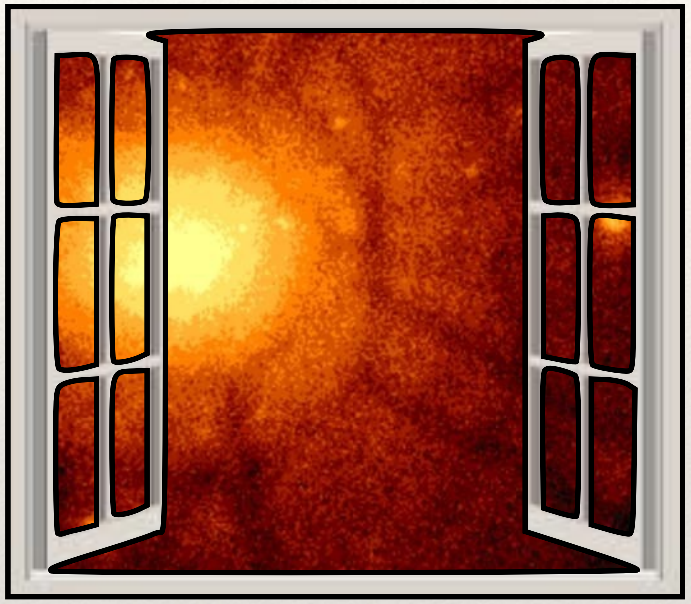
ALPs and Galaxy cluster X-rays as a window to the dark sector



M.C. David Marsh

Rudolph Peierls Centre for Theoretical Physics
University of Oxford

Workshop on off-the-beaten-track dark matter and
astrophysical probes of fundamental physics,
ICTP, Trieste, April 16, 2015

Based on:

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

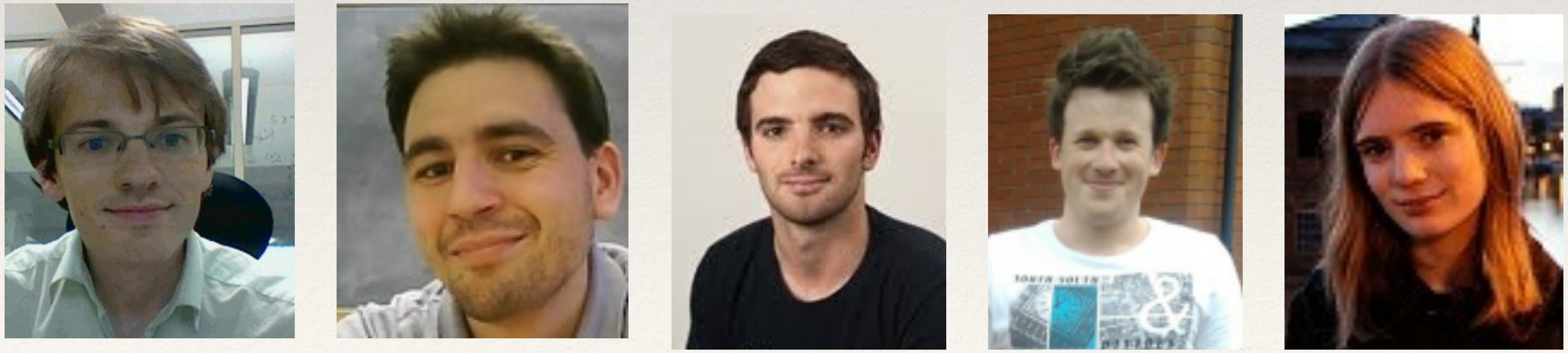
J. Conlon, *D.M.*, arXiv:1305.3603,

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



Principal message:

Galaxy clusters are *extremely efficient* at converting any population of light axion-like particles into photons.

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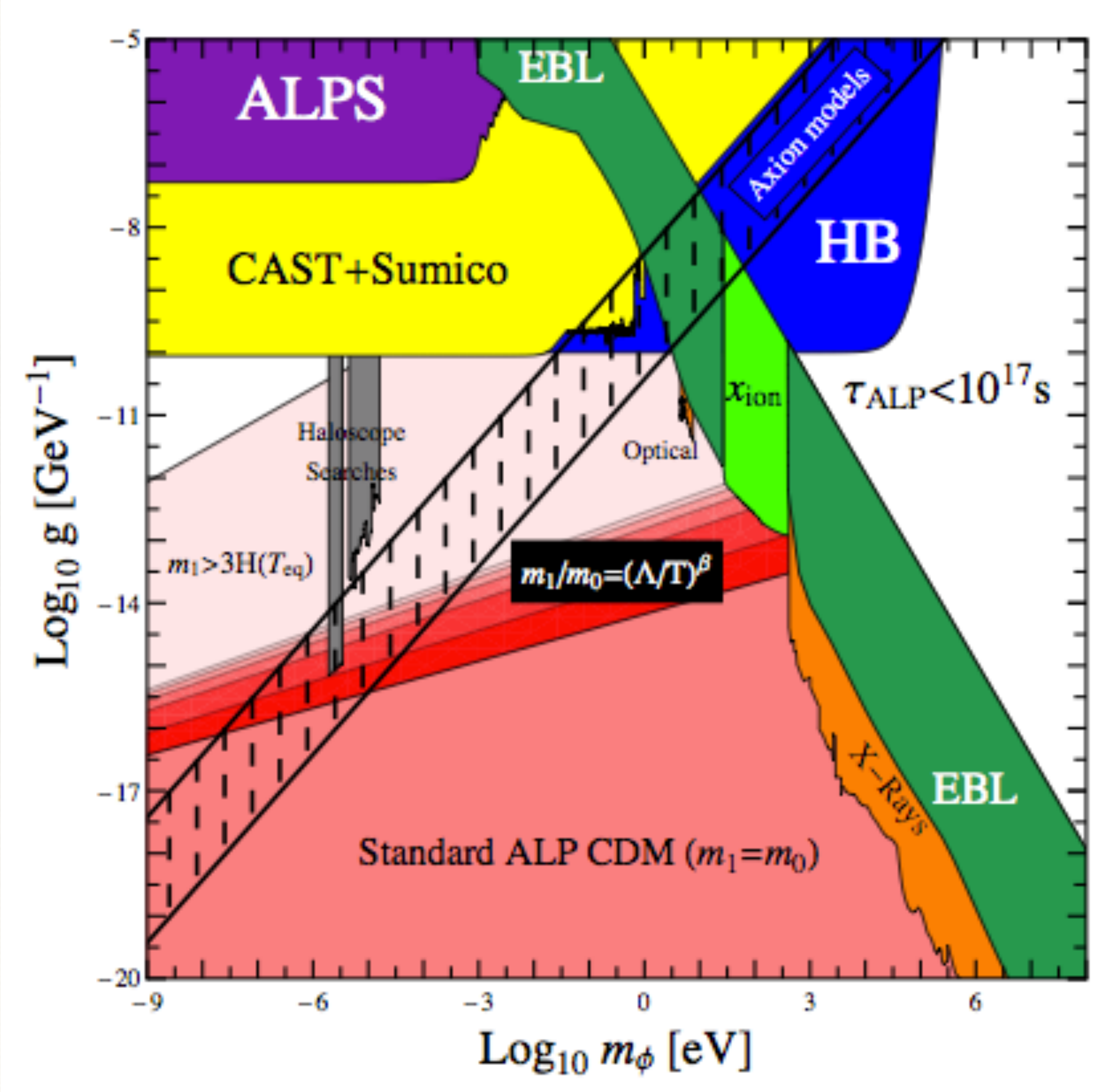
Galaxy clusters are *extremely efficient* at converting any population of light axion-like particles into photons.

The photons exhibit *distinct observational signatures* that well correlate with two unexplained features of the cluster X-ray spectrum.

Axion-like particles (ALPs)

ALPs have already been introduced 7 times at this conference. The low-energy effective theory is given by,

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



From Goodsell's talk.

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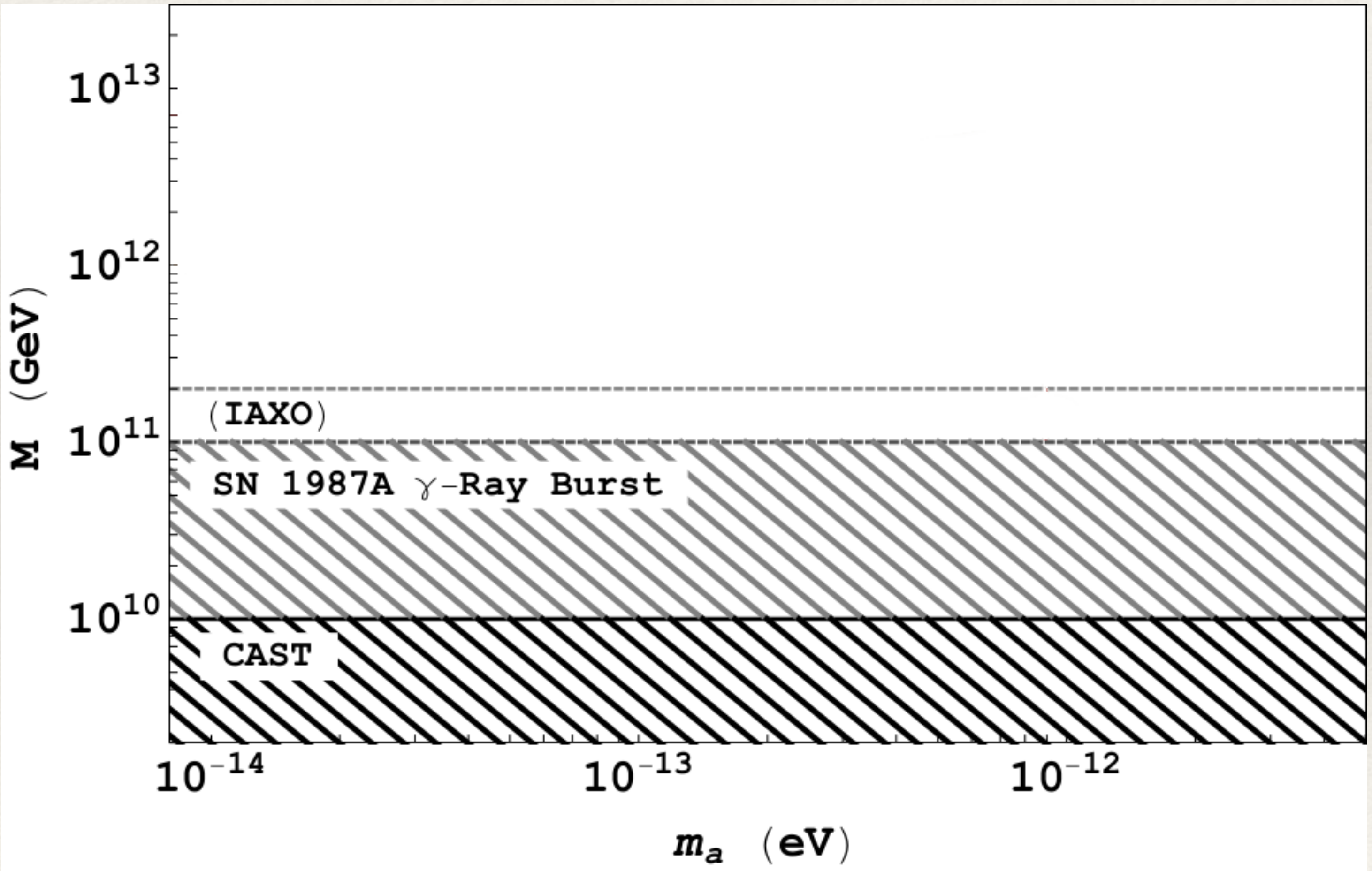

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Axion-like particles (ALPs)

ALP-photon conversion:

Sikivie ’83,
Raffelt,
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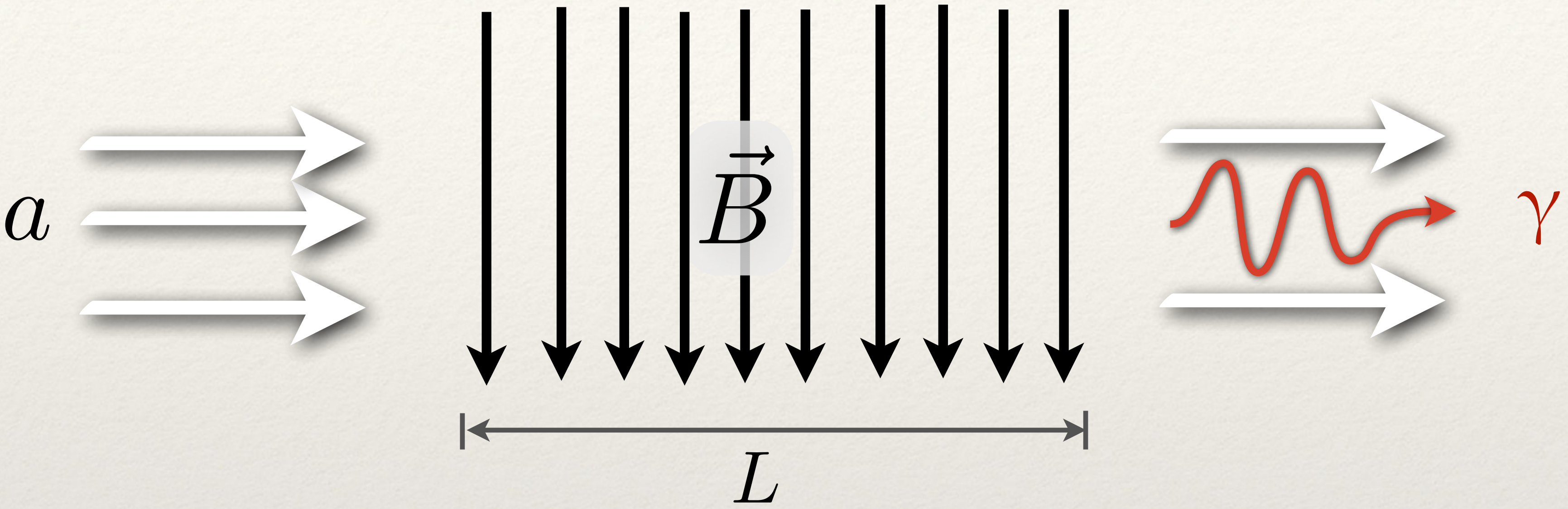

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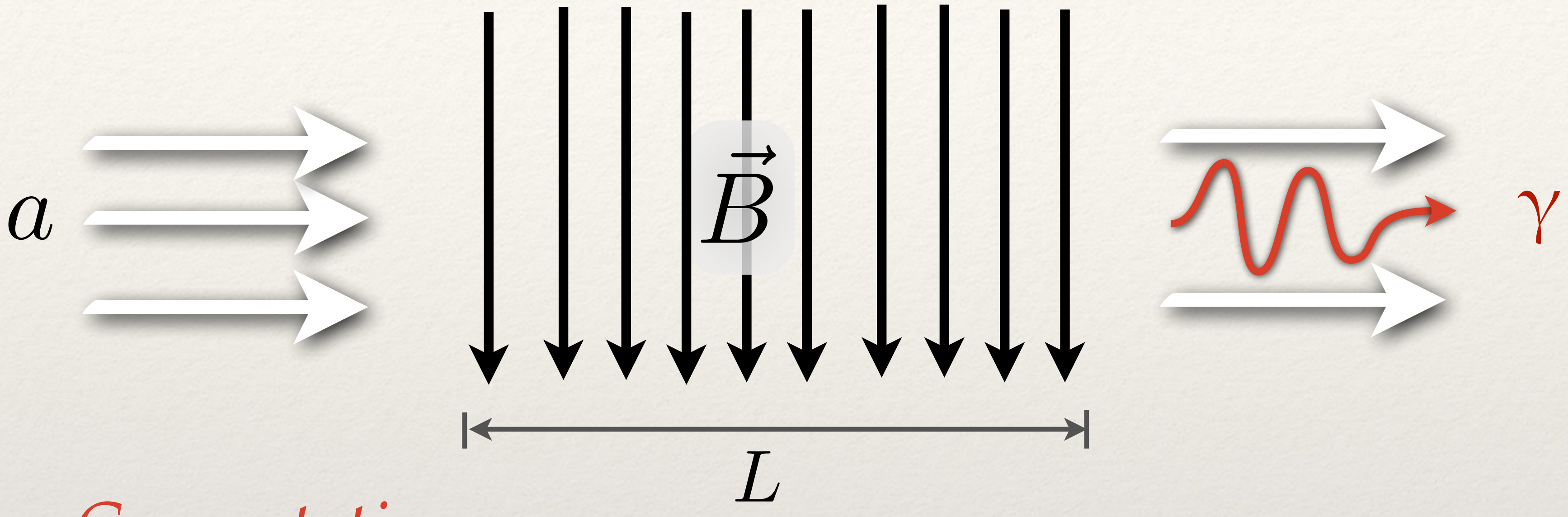

Computation:

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

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

Sikivie '83,
Raffelt,
Stodolsky '88.

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

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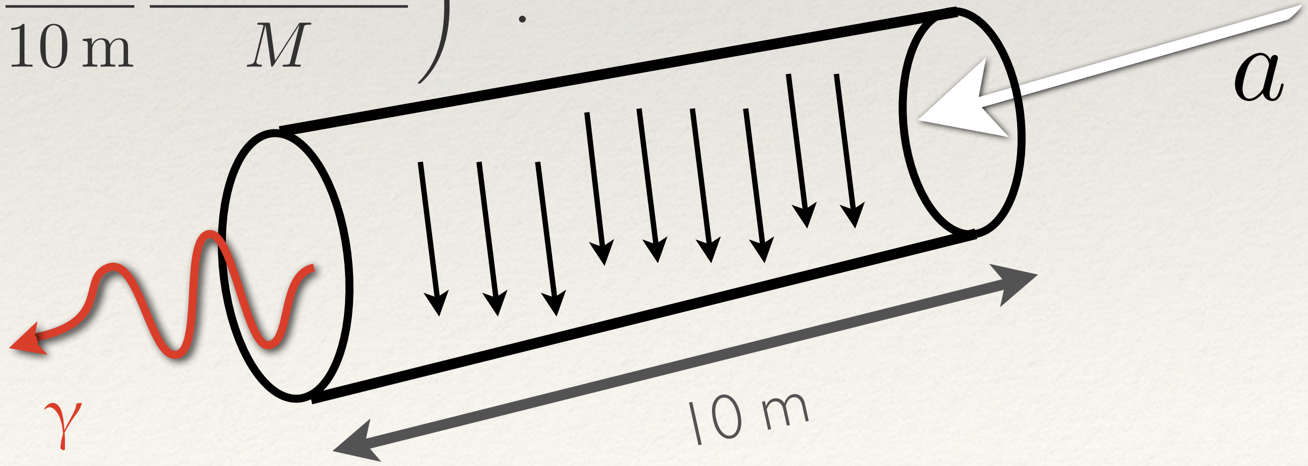
Look for strong magnetic fields (P~B²) coherent over large distances (P~L²).

Example: For CAST-like experiment:

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



Galaxy clusters as ALP converters

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 HST.

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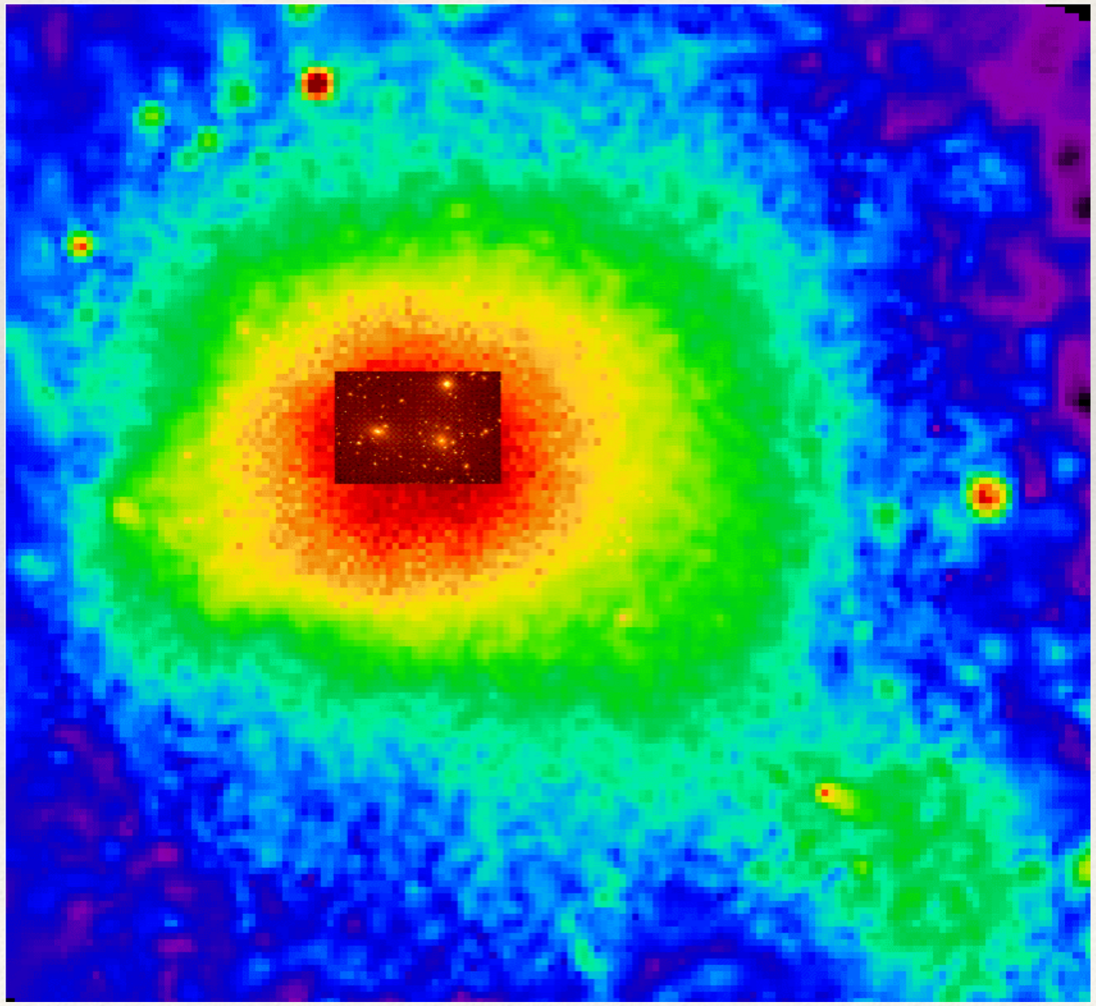

The Coma cluster, as seen by ROSAT.

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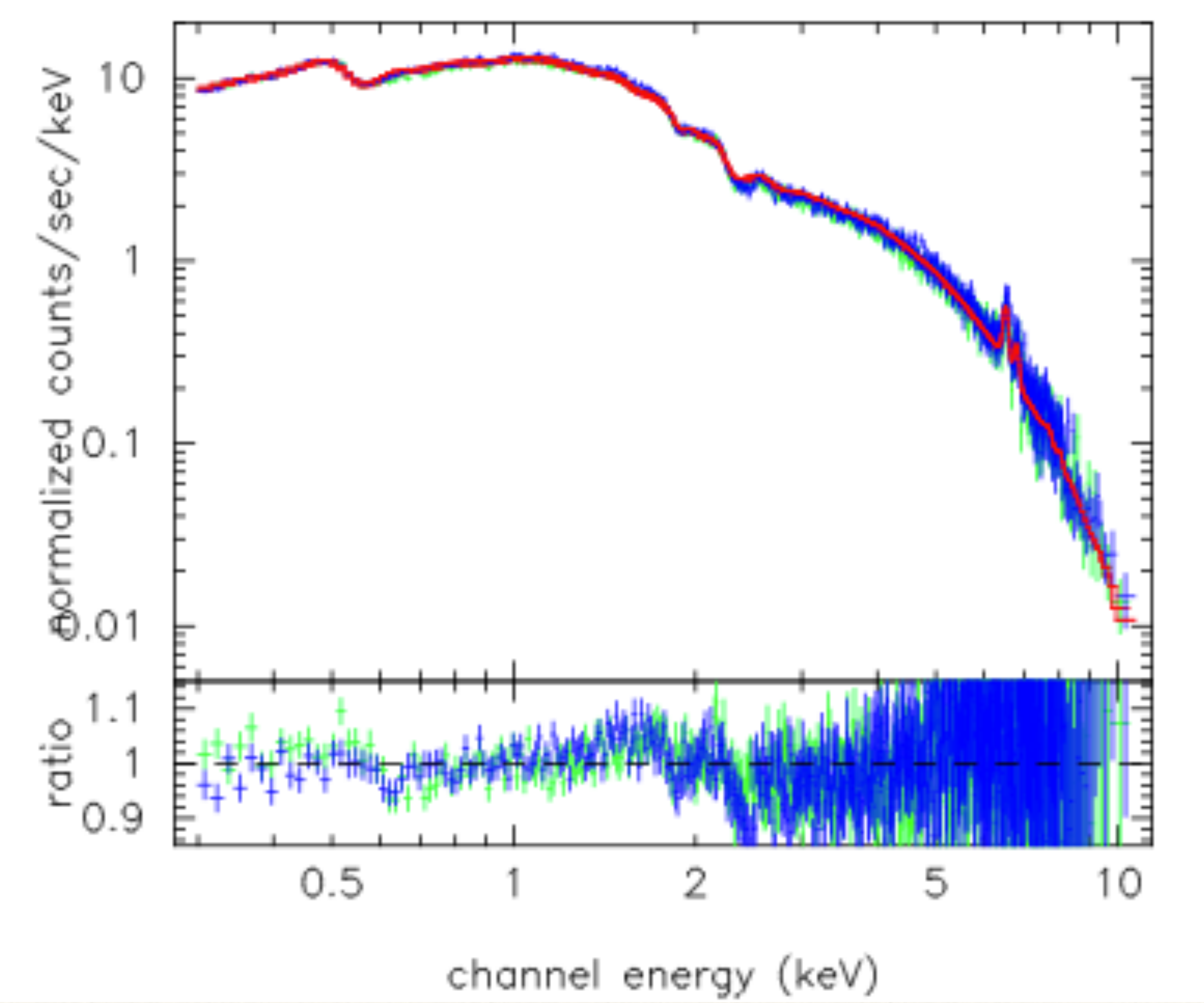


Thermal bremsstrahlung with $I(E) \propto g(E)$ exp[-c E], plus ion lines.

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

Galaxy clusters as ALP converters

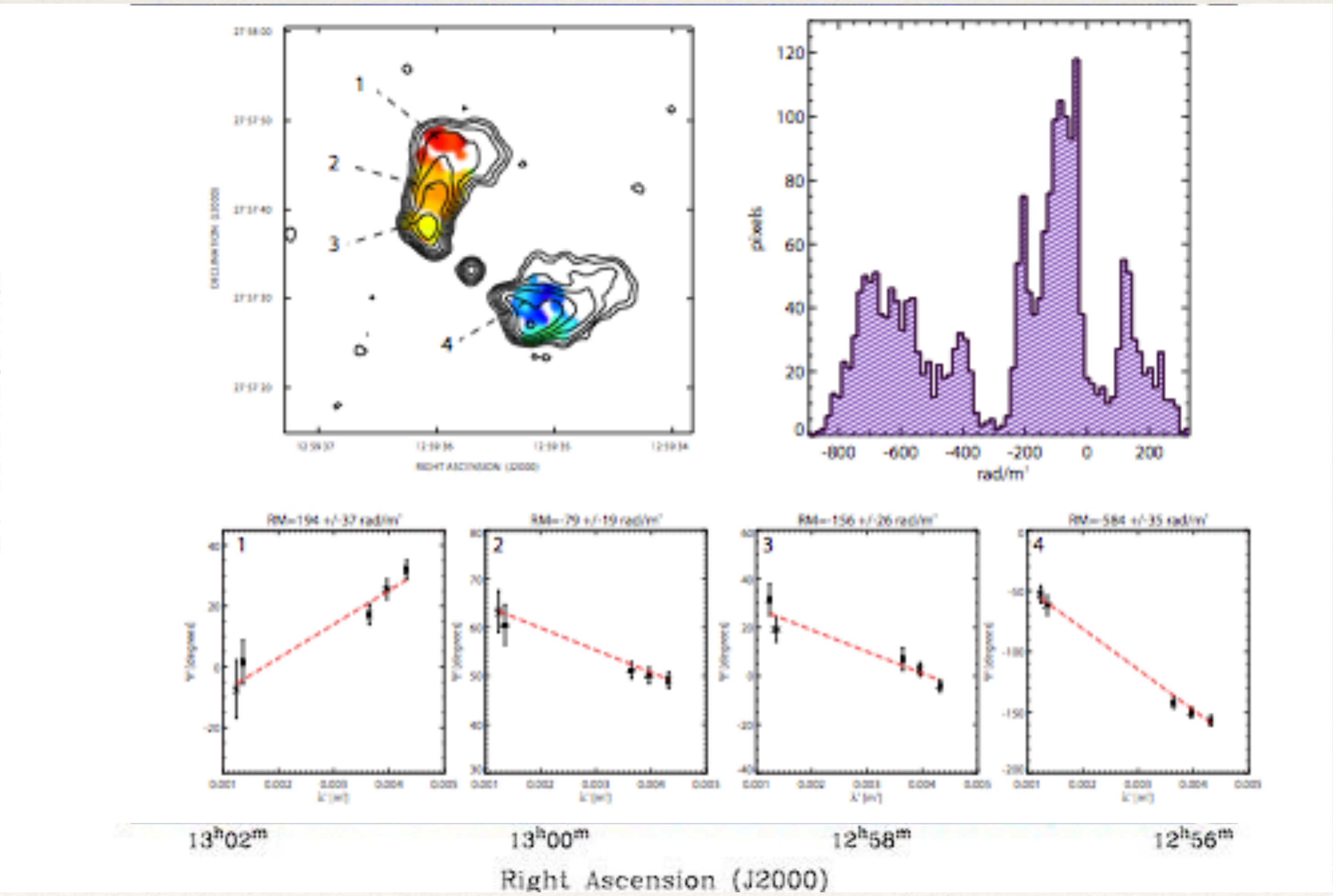
Clusters support magnetic fields with $\mathcal{O}(|B|)$=1-10 μG.

C.f. Bonafede's talk.

The birefringence of the magnetised plasma gives rise to *Faraday rotation* of polarised photons:

$$\Delta\theta \propto \lambda^2 \underbrace{\int n_e(l)\vec{B}\cdot d\vec{l}}_{RM}.$$

From Bonafede's thesis.



Galaxy clusters as ALP converters

Magnetic field model for the Coma cluster:

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

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

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

Bonafede et al., 2010.

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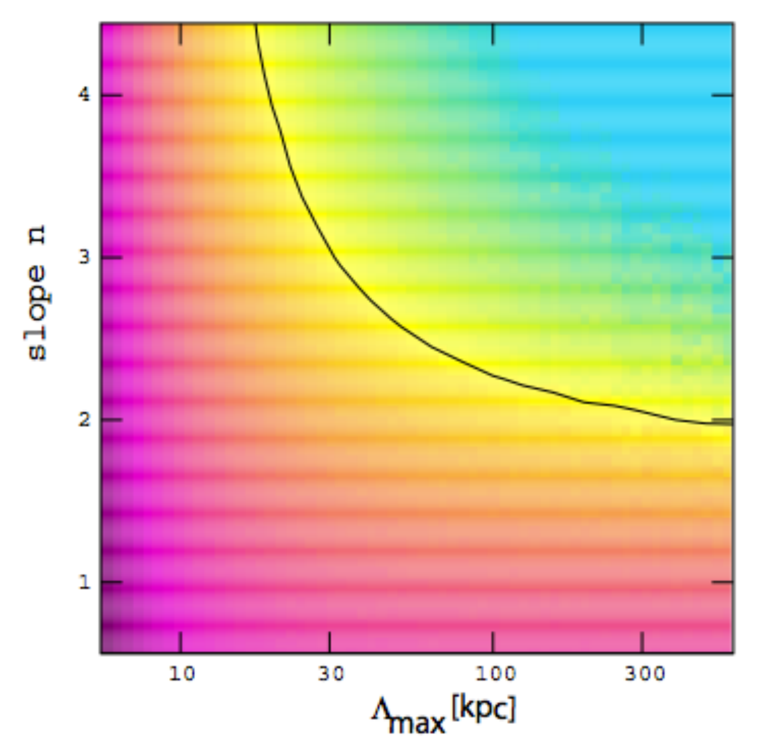

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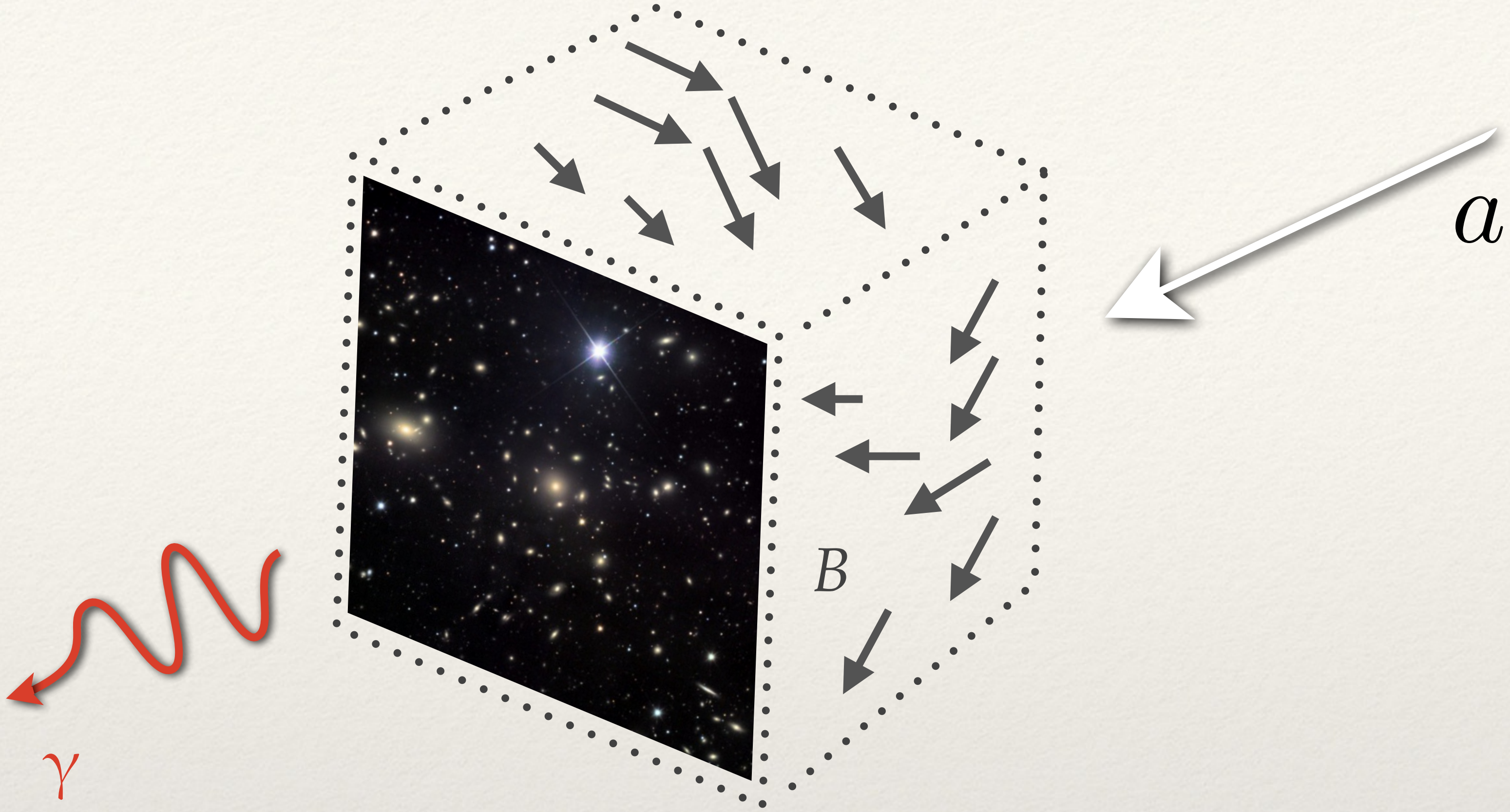
Baseline: $n=17/3$, $k_{\rm min}=2\pi/(34\ \text{kpc})$, $k_{\rm max}=2\pi/(3\ \text{kpc})$, $\eta=0.4\text{-}0.7$, and $B_0=3.9\text{-}5.4\ \mu\text{G}$.

Alternate model: $n=4$, $k_{\rm min}=2\pi/(100\ \text{kpc})$, $k_{\rm max}=2\pi/(2\ \text{kpc})$, $\eta=0.7$, and $B_0=5.4\ \mu\text{G}$.

Bonafede et al., 2010.

Galaxy clusters as ALP converters



Clusters source the conversion of light ALPs to photons with probabilities of order $P(a \longrightarrow \gamma) \sim O(1)$ for $M = 10^{11}$ GeV and $m_a < \omega_{pl} \approx 10^{-12}$ eV.

More massive ALPs generically have $P(a \longrightarrow \gamma) \sim (\omega_{pl}/m_a)^4$.

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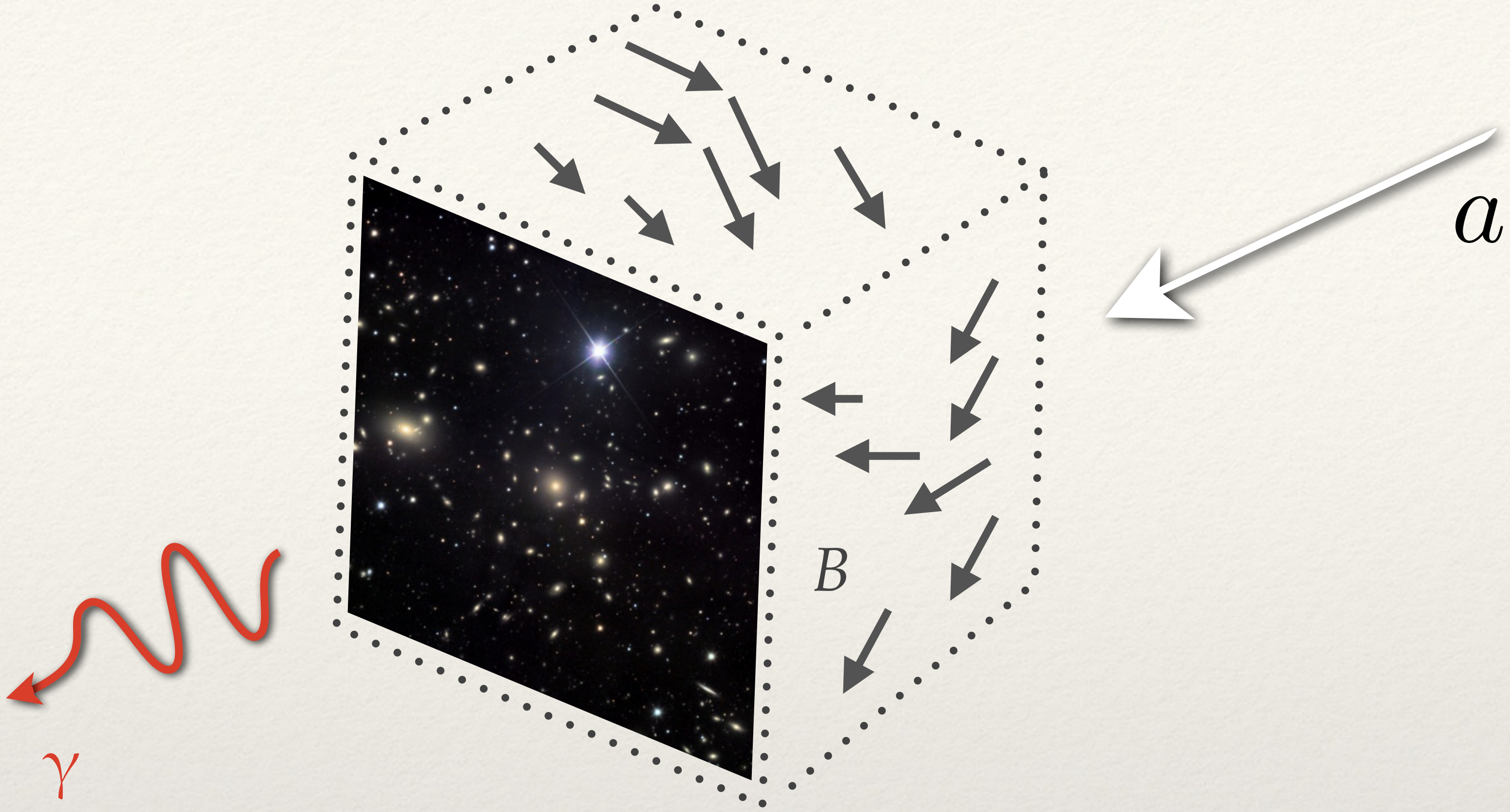

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Compare to: $P(a \to \gamma) \approx 2 \cdot 10^{-19} \cdot \left(\frac{B_\perp}{10\,\mathrm{T}} \frac{L}{10\,\mathrm{m}} \frac{10^{11}\,\mathrm{GeV}}{M} \right)^2 .$

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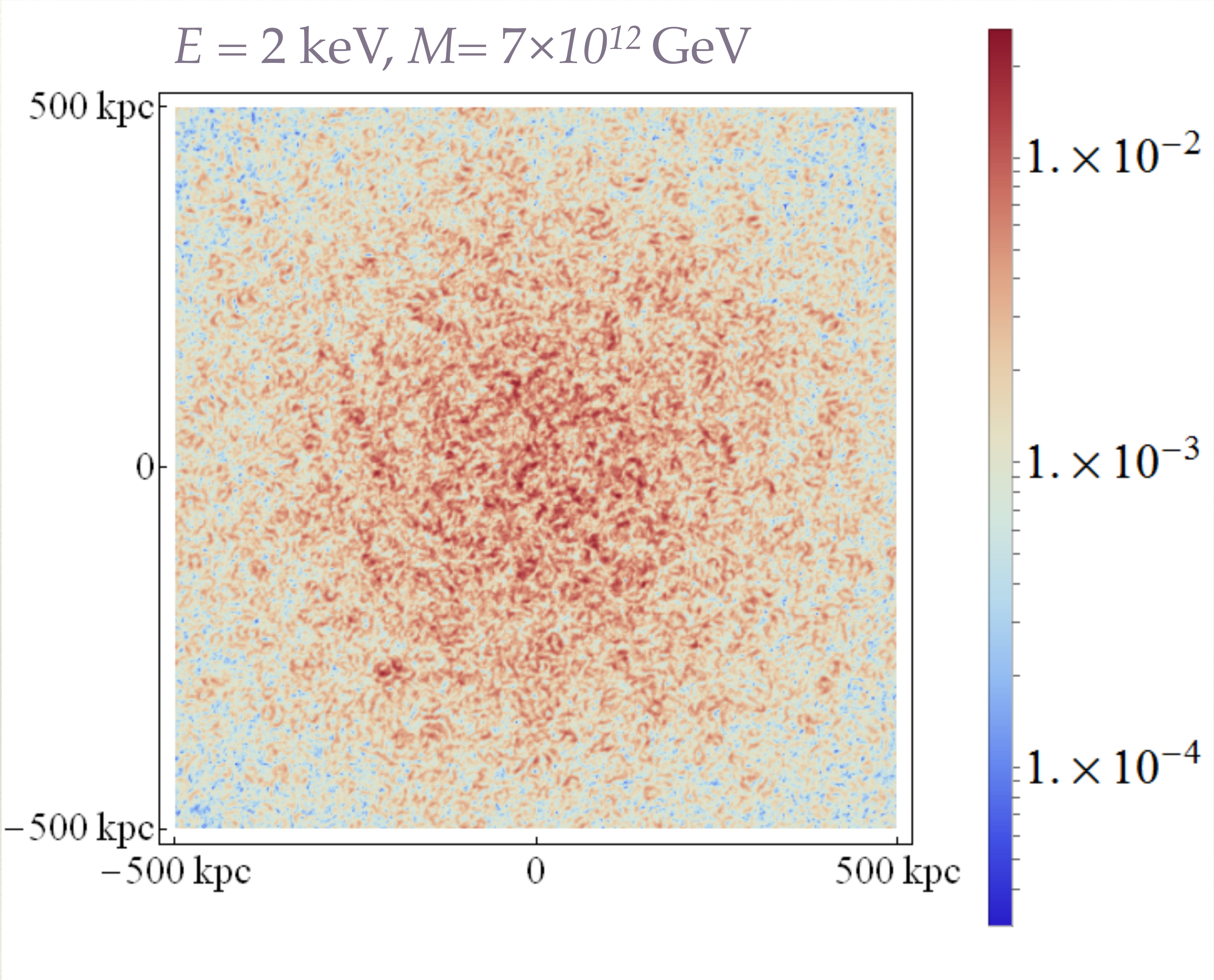
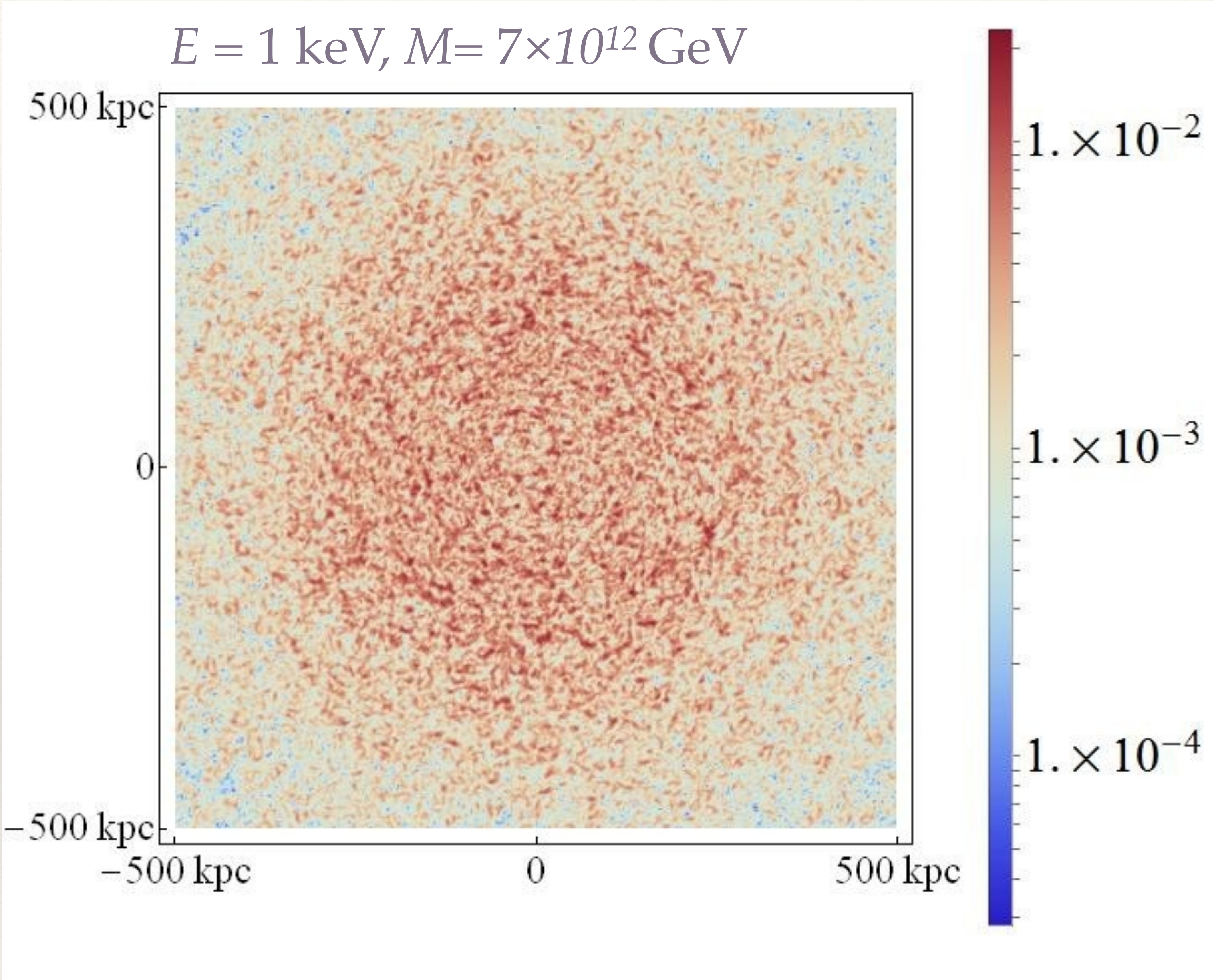


Angus, Conlon, *D.M.*, Powell, Witkowski, ’13.

Galaxy clusters as ALP converters



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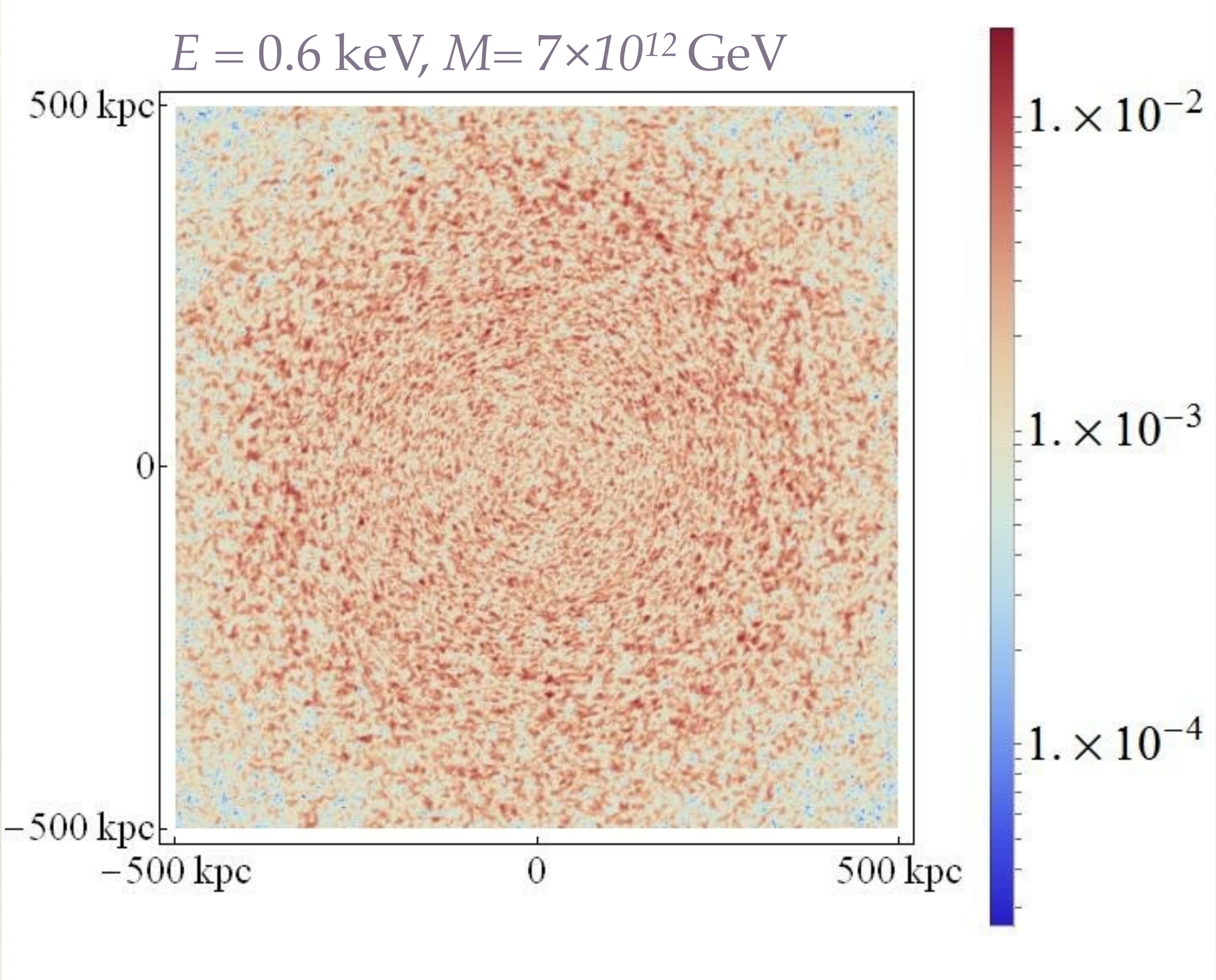

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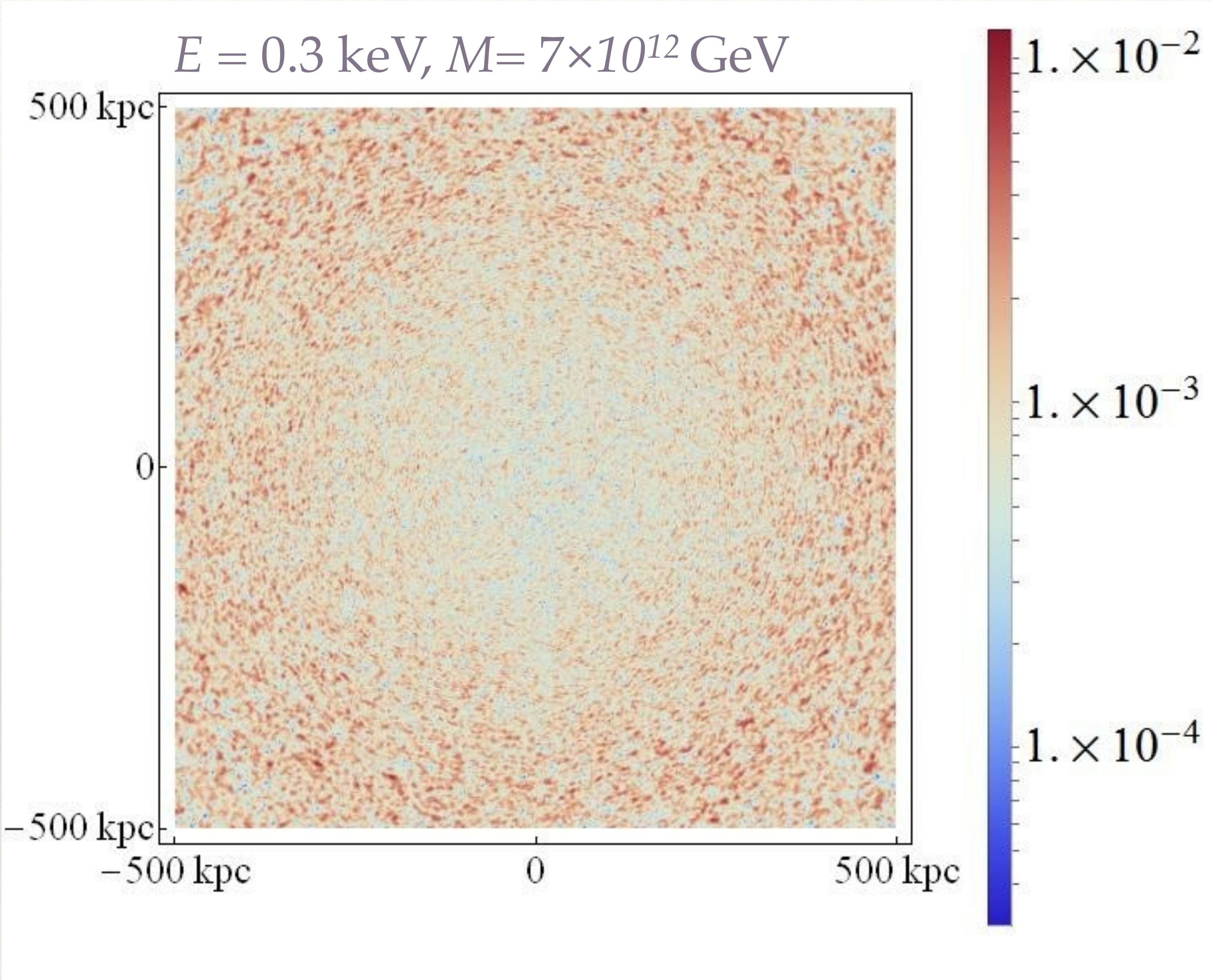

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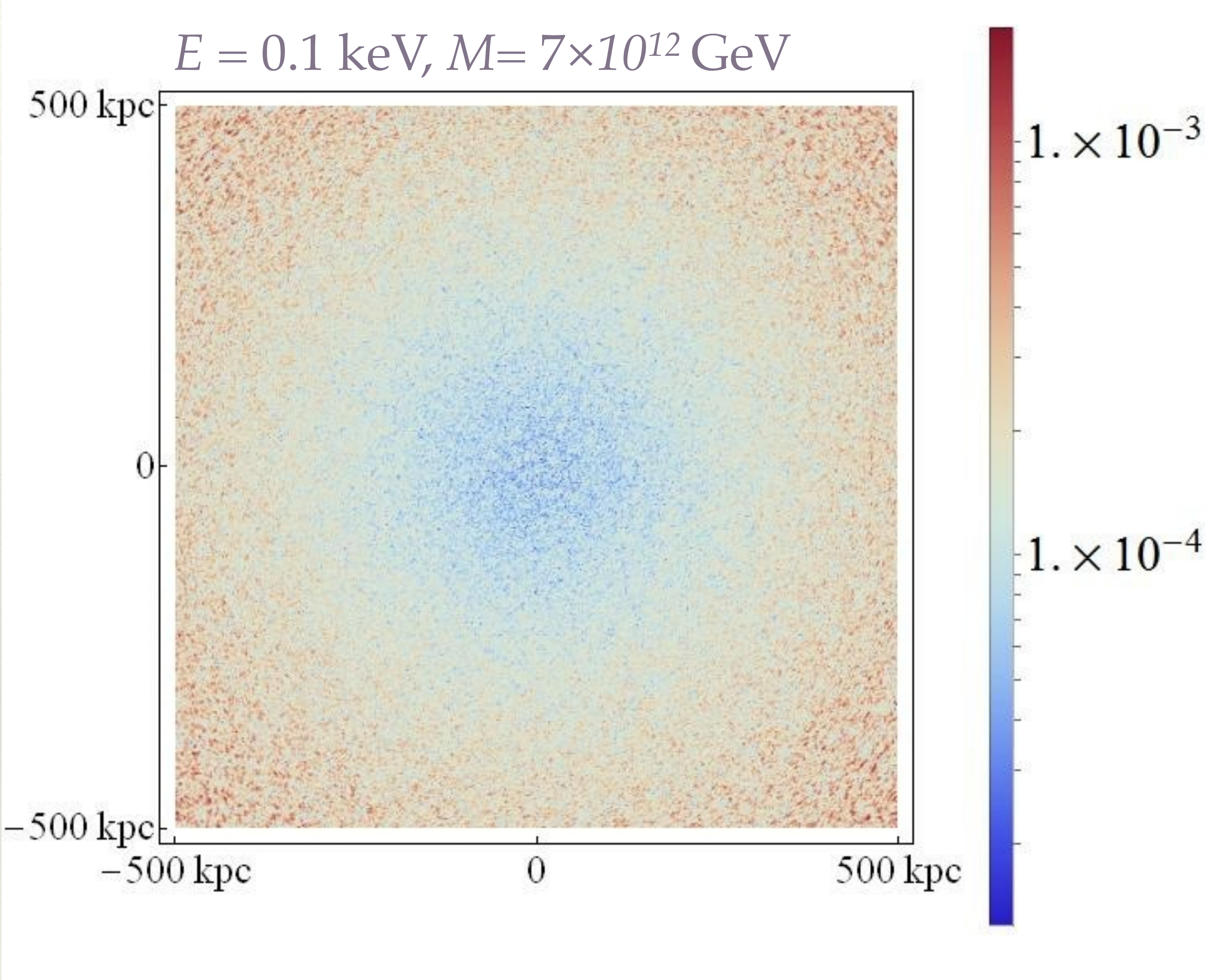

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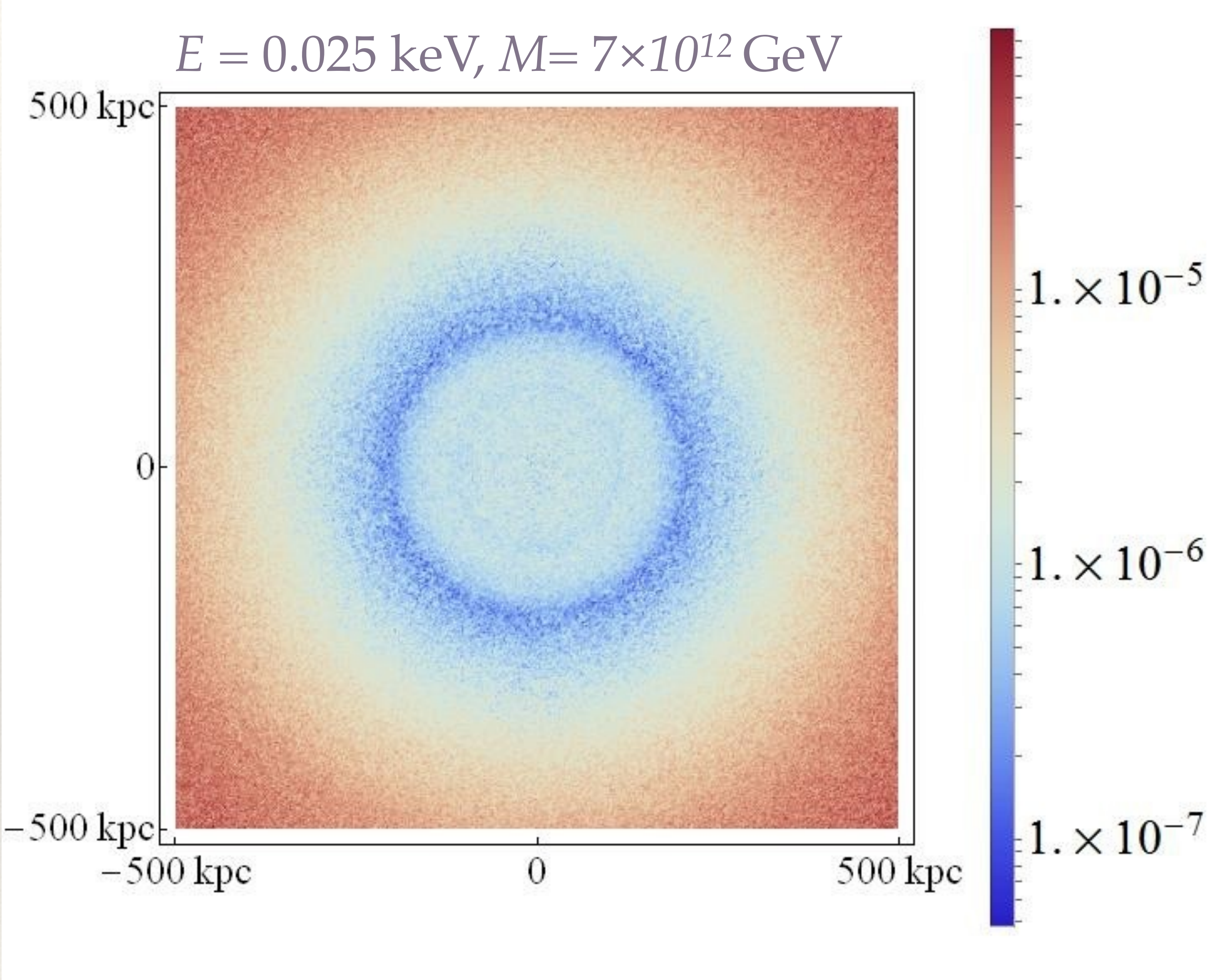

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Where would such ALPs come from?

Galaxy clusters as ALP converters

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Where would such ALPs come from?

The decay of any heavier particle that couples to it, e.g. through:

1. Dark matter decaying to ALPs.

2. ALPs being produced at reheating.

1. Dark Matter decaying into ALPs:

The nature of dark matter is not known, and effective field theory is useful in parametrising the possible couplings.

Example 1: Sterile neutrino dark matter

Operator: $\mathcal{L} \supset \frac{\partial_\mu a}{\Lambda} \bar{\psi} \gamma^\mu \gamma_5 \nu$

Process: $\nu_s \rightarrow \nu + a$

Rate: $\Gamma_{\psi \to \nu a} = \frac{1}{16\pi} \frac{m_\psi^3}{\Lambda^2}$,

Example 2: Moduli (scalar) dark matter

Operator: $\mathcal{L} \supset \frac{\Phi}{\Lambda} \frac{1}{2} \partial_\mu a \partial^\mu a$,

Process: $\Phi \rightarrow a\, a$,

Rate: $\Gamma_{\Phi \to aa} = \frac{1}{128\pi} \frac{m_\Phi^3}{\Lambda^2}$.

1. Dark Matter decaying into ALPs:

The photon flux for DM → ALP → γ is then given by,

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

stronger signal for
strong magnetic field

c.f. to standard, decaying sterile neutrino flux:

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

Can DM → ALP → γ explain the claimed observations of a 3.55 keV line from clusters?

The 3.55 keV line

The observational status of the unidentified X-ray line at ~3.55 keV was reviewed yesterday by Bulbul, and discussed by Boyarsky and Carlson.

SUBMITTED TO APJ, 2014 FEBRUARY 10
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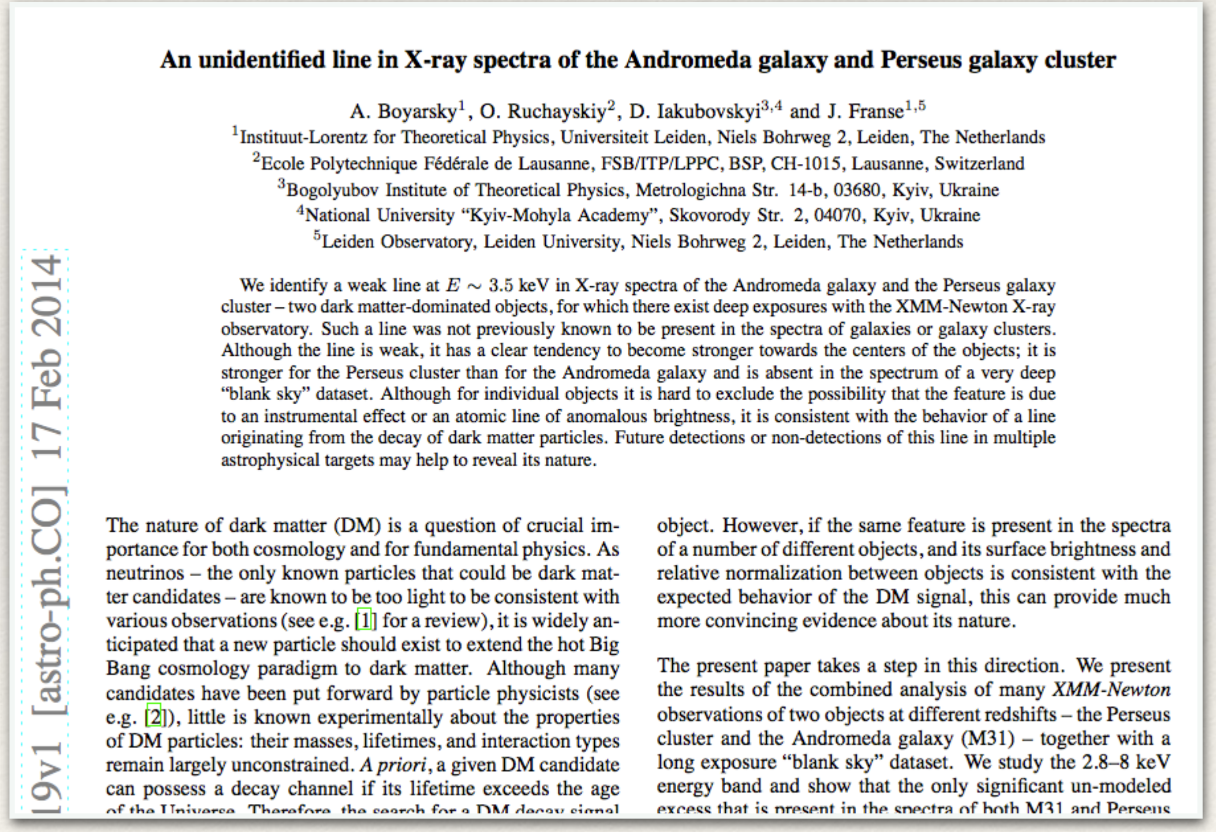
DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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

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 ~ 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



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
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[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

The 3.55 keV line

The observational status of the unidentified X-ray line at ~3.55 keV was reviewed yesterday by Bulbul, and discussed by Boyarsky and Carlson.

The 3.55 keV line: estimated statistical 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. ‘14

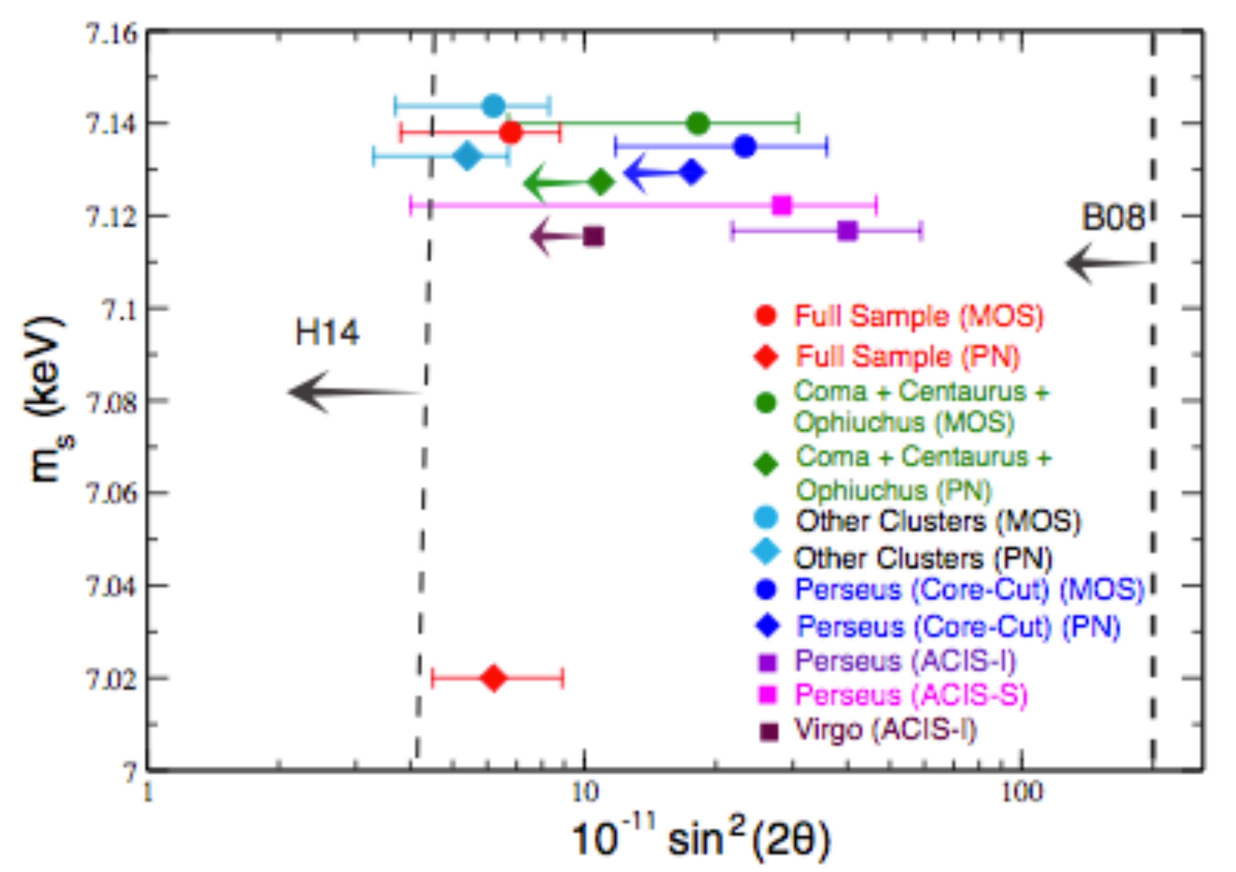
Boyarsky et al. ‘14

The 3.55 keV line: sterile neutrino interpretation

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, $\sin^2(2\theta)$:

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



Bulbul et al. '14

The 3.55 keV line: sterile neutrino interpretation

Issues with the decaying sterile neutrino 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. ‘14

The 3.55 keV line: subsequent results

Urban et al. ‘14,
Tamura et al ‘14,
Bulbul’s talk.

- *Suzaku data of Perseus*: line observed by Urban et al, not found by Tamura et al, but found by Bulbul et al.

Malyshev et al.
arXiv:1408.3531

- *No evidence* for the line in stacked XMM-Newton spectra of *dwarf spheroidal galaxies*, claimed exclusion of the sterile neutrino explanation at 4.6σ.

Anderson et al.
arXiv:1408.4115

- *Non-detection* of the line in stacked XMM-Newton (and Chandra) spectra of outskirts of 89 (81) *galaxies*, claimed exclusion of the sterile neutrino explanation at 11.8σ (4.4σ).

Riemer-Sörensen ’14, Boyarsky et al. ’14, Jeltema, Profumo ’14, Carlson’s talk.

- *Galactic centre*: controversy regarding existence of and correct interpretation of observed line.
- *M31*: controversy regarding the significance of observed line.

The 3.55 keV line:

Bulbul’s talk,
Boyarsky’s talk.

The line in clusters will be tested by stacked Suzaku data, and resolved by long Astro-H observations of Perseus. The existence of a line in the dwarf spheroidal Draco is currently being tested.

The 3.55 keV line:

Bulbul's talk,
Boyarsky's talk.

The line in clusters will be tested by stacked Suzaku data, and resolved by long Astro-H observations of Perseus. The existence of a line in the dwarf spheroidal Draco is currently being tested.

Still, *standard decaying dark matter scenario does not fit the already reported data well*:

- 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.
- No evidence for the line in *stacked galaxies*.
- No line from *dwarf spheroidals*.

The 3.55 keV line: *DM→ ALP→ γ.*

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

Signal can be explained for *M* ≲ 5×10^{15} GeV. This scenario has *distinct observational signatures*:

- Conversion probability from ALP to photon is *much larger in clusters* (where *R* ~ *1* Mpc) than galaxies (where *R~30* kpc).
- *Nearby clusters* particularly good targets as FOV covers central region in which the magnetic field is strongest.
- *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

The 3.55 keV line: $DM \rightarrow ALP \rightarrow \gamma$.

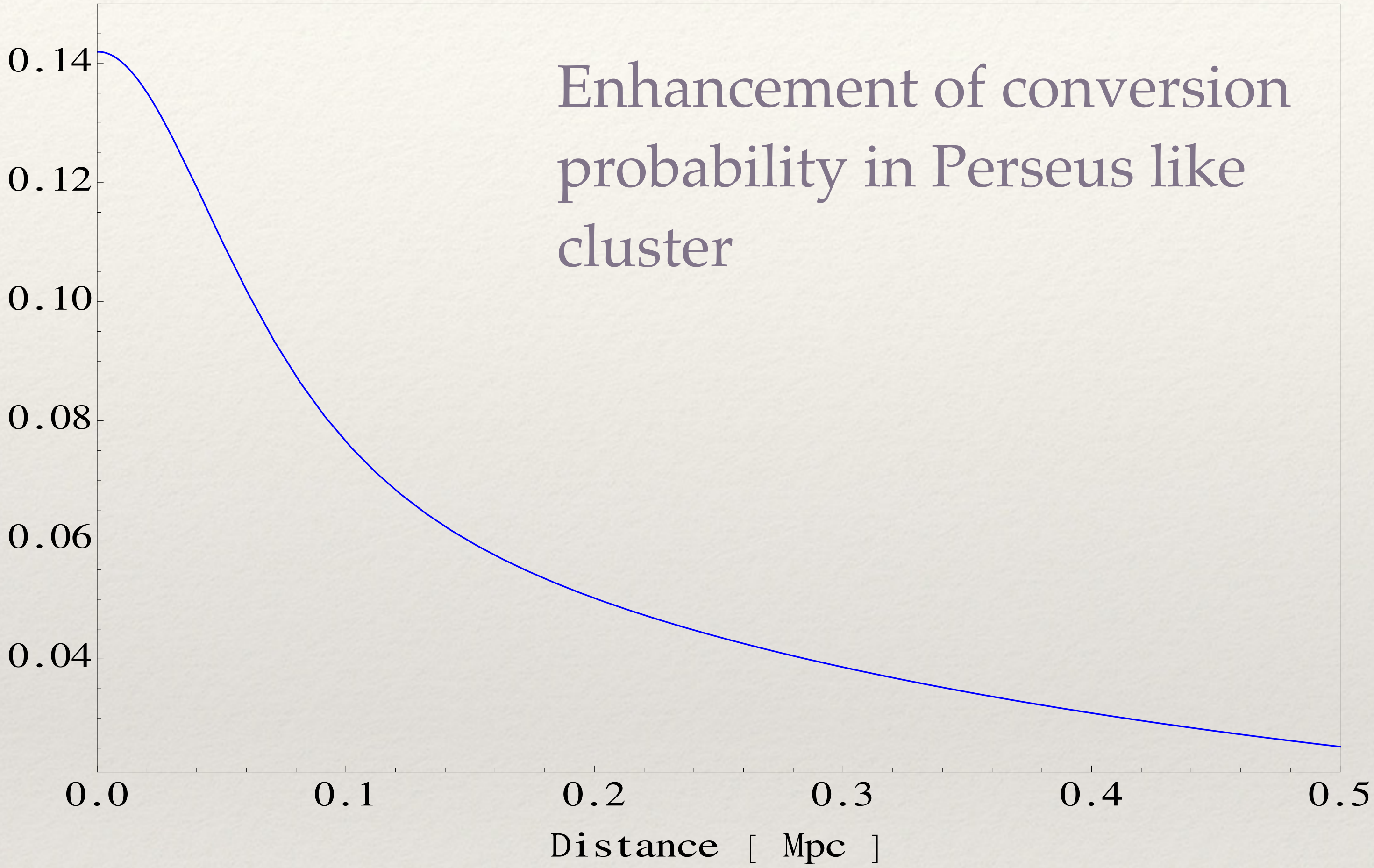
Predictions:

- *No signal* is expected from dwarf spheroidal galaxies, (including Draco).
- *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

The 3.55 keV line: *DM* → *ALP* → γ.

Morphology of signal

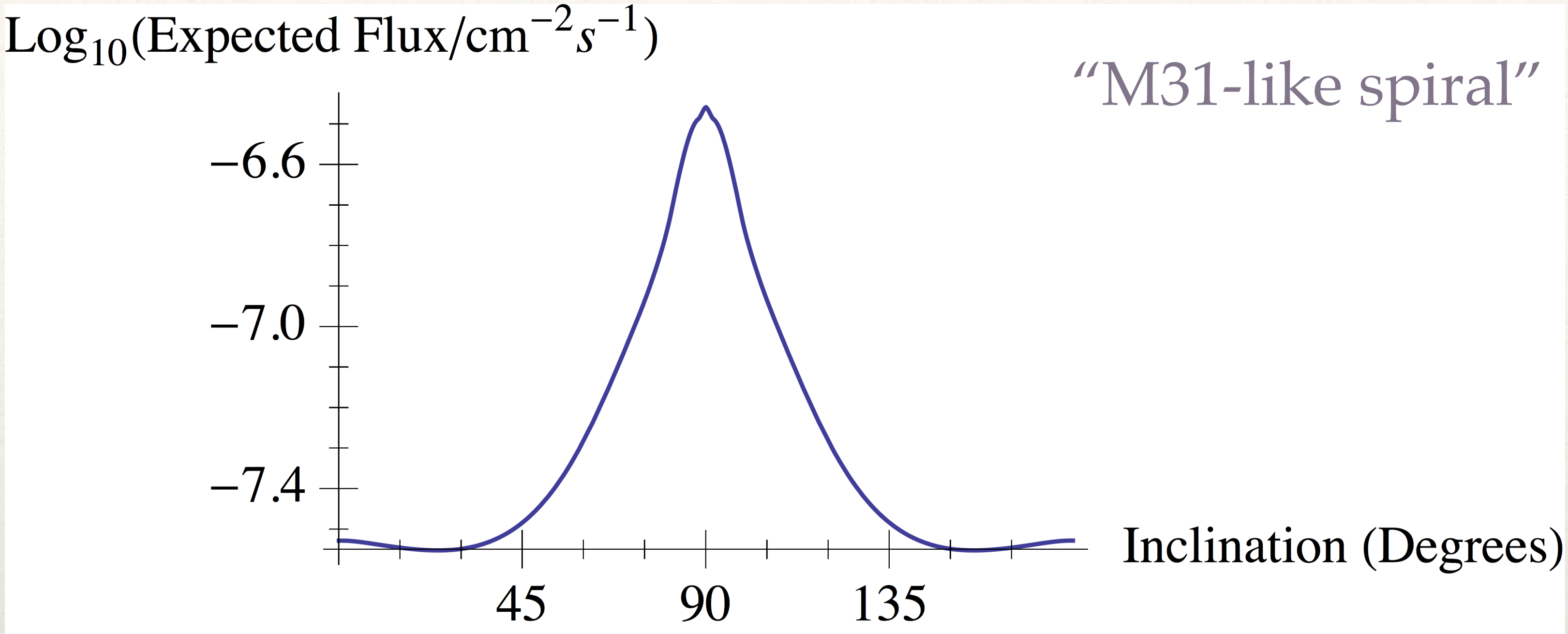


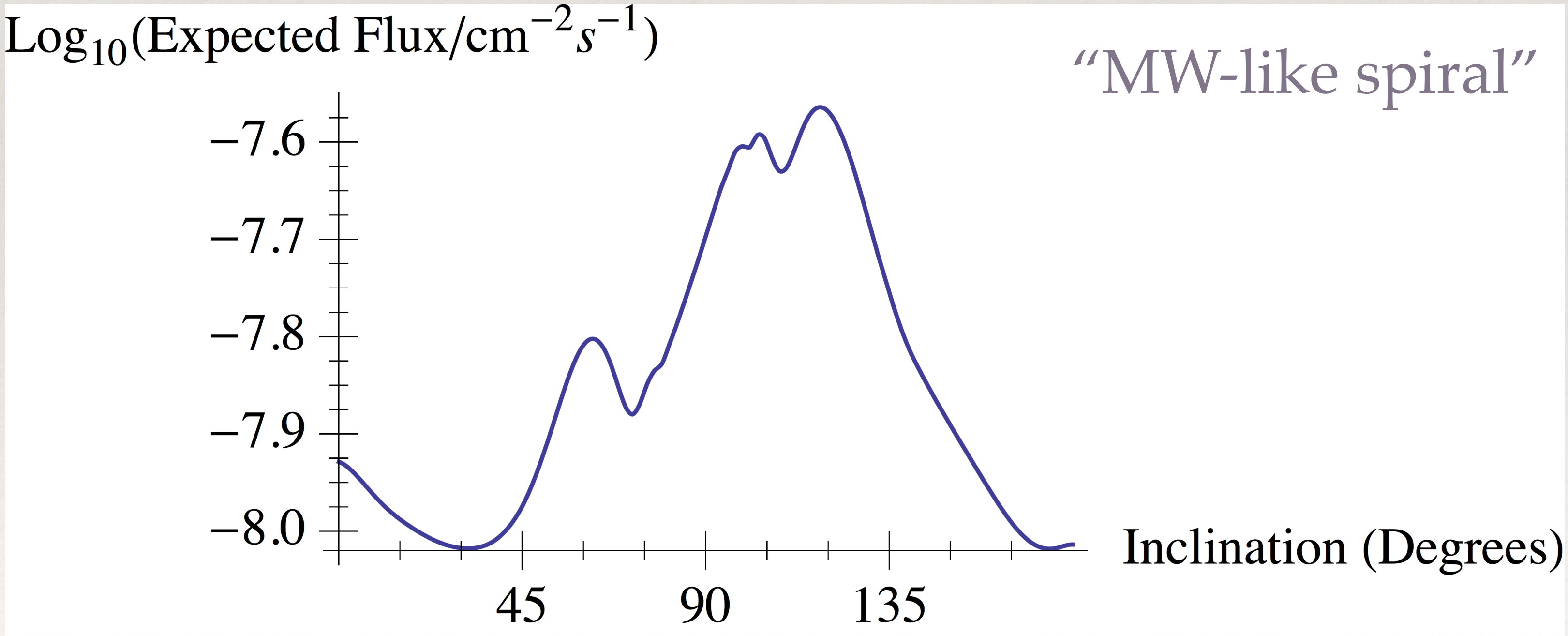
Enhancement of conversion probability in Perseus like cluster

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

The 3.55 keV line: $DM \rightarrow ALP \rightarrow \gamma$.

Signal from other galaxies?





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

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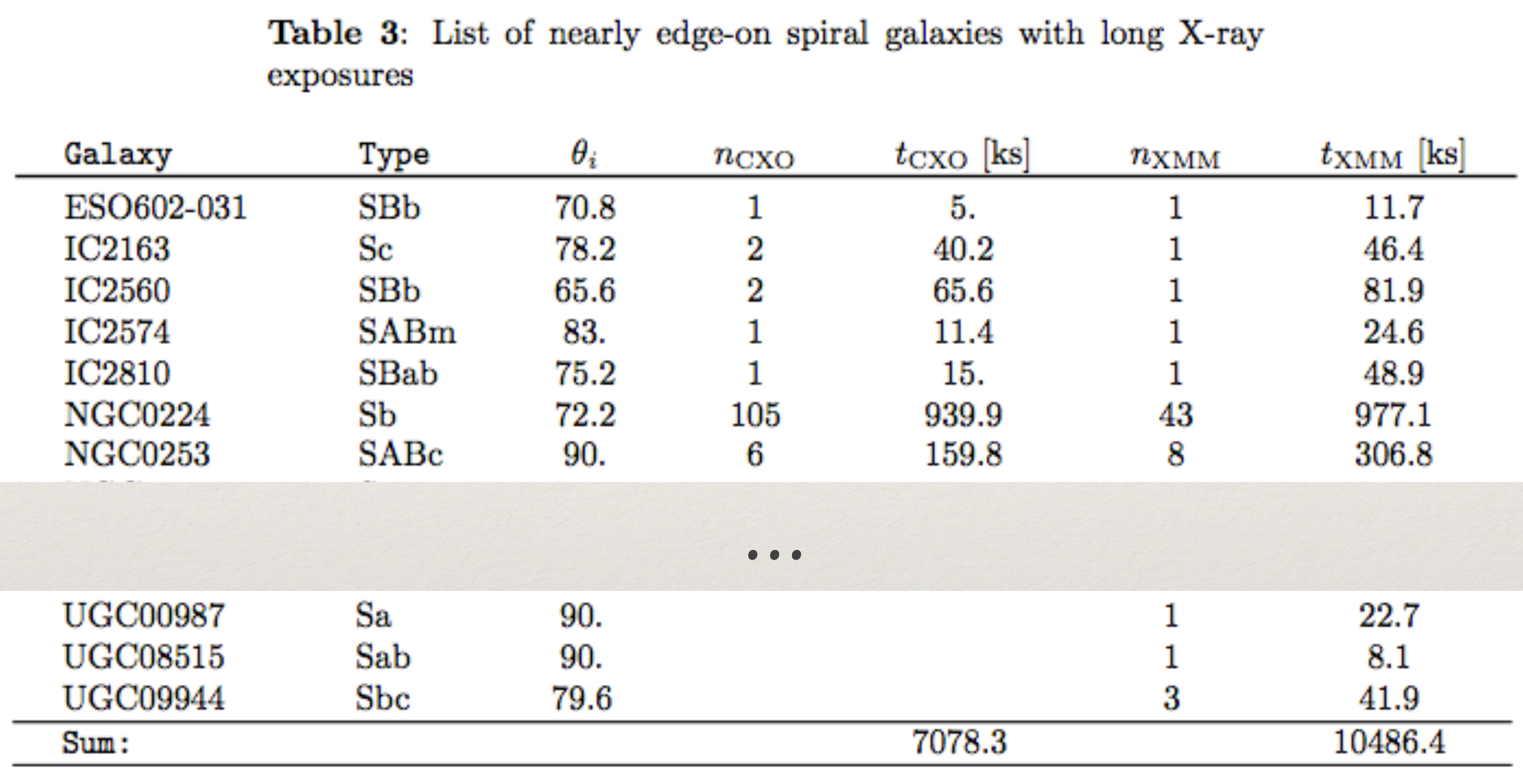


Table 3: List of nearly edge-on spiral galaxies with long X-ray exposures

Galaxy	Type	θ_i	n_{CXO}	t_{CXO} [ks]	n_{XMM}	t_{XMM} [ks]
ESO602-031	SBb	70.8	1	5.	1	11.7
IC2163	Sc	78.2	2	40.2	1	46.4
IC2560	SBb	65.6	2	65.6	1	81.9
IC2574	SABm	83.	1	11.4	1	24.6
IC2810	SBab	75.2	1	15.	1	48.9
NGC0224	Sb	72.2	105	939.9	43	977.1
NGC0253	SABc	90.	6	159.8	8	306.8
…						
UGC00987	Sa	90.			1	22.7
UGC08515	Sab	90.			1	8.1
UGC09944	Sbc	79.6			3	41.9
Sum:				7078.3		10486.4

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

7 and *10* Ms of raw exposure on a set of nearby close to edge-on spiral galaxies for *Chandra* and *XMM*.

2. ALPs from reheating: motivation

Reheating may be driven by a massive scalar ϕ that decays into Standard Model particles. In string theory, ϕ is a modulus that couples with Planck mass suppressed couplings.

In general, ϕ may also decay into light particles that may be too weakly coupled to ever thermalise, such as ALPs.

Such ALPs would be more energetic than CMB photons by a factor of $(M_{\rm Pl}/m_\phi)^{1/2}$, and would constitute a *'Cosmic Axion Background'* (CAB) that contributes to 'dark radiation'.

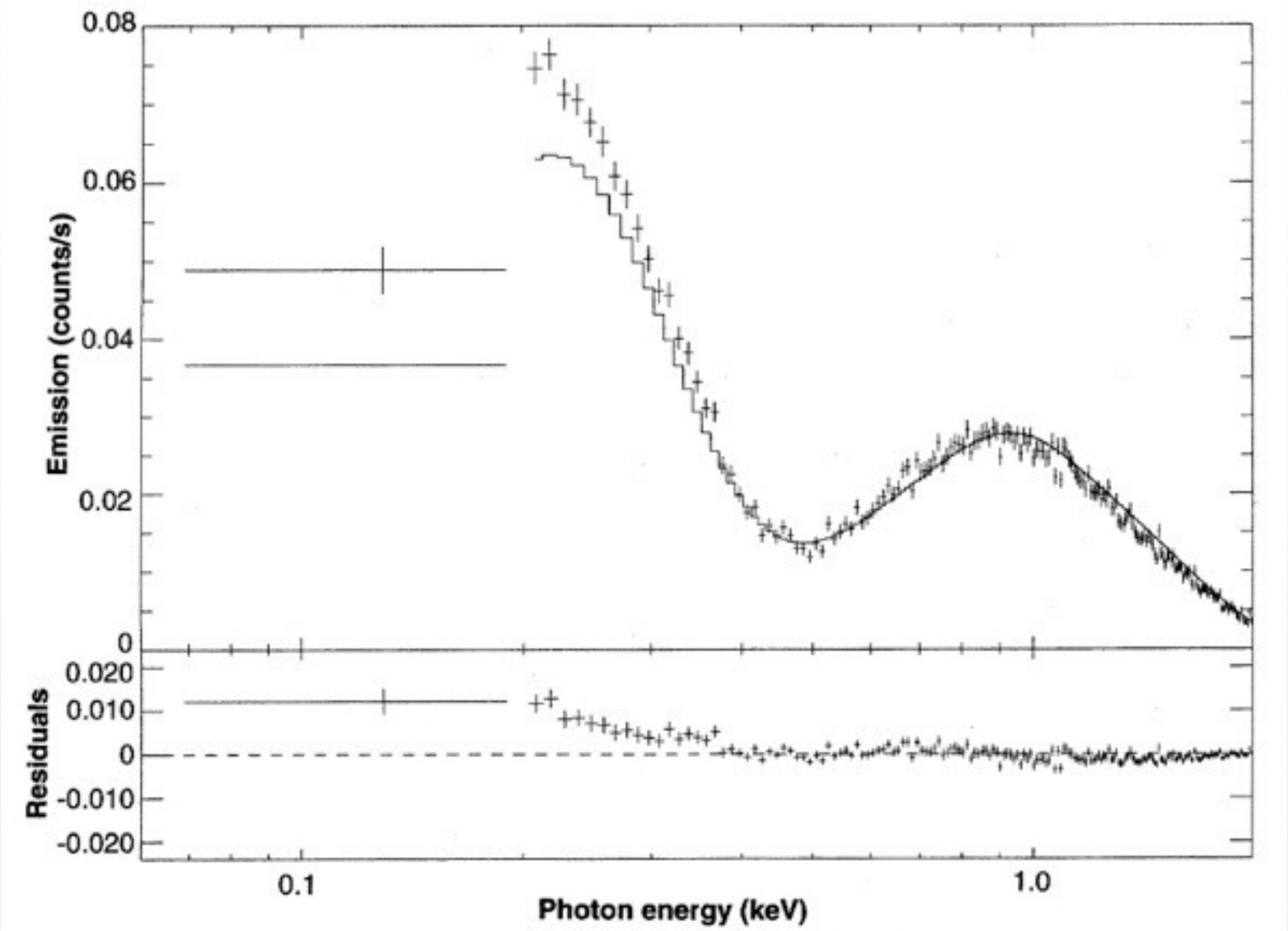
For $m_\phi \approx 10^6$ GeV, the present-day energy would be $E \sim O(0.1\text{-}1~\text{keV})$.

Conlon, *D.M.*, '13.

Clusters could make such a background visible in the soft X-ray spectrum through ALP-photon conversion.

2. ALPs from reheating: the soft X-ray excess

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.

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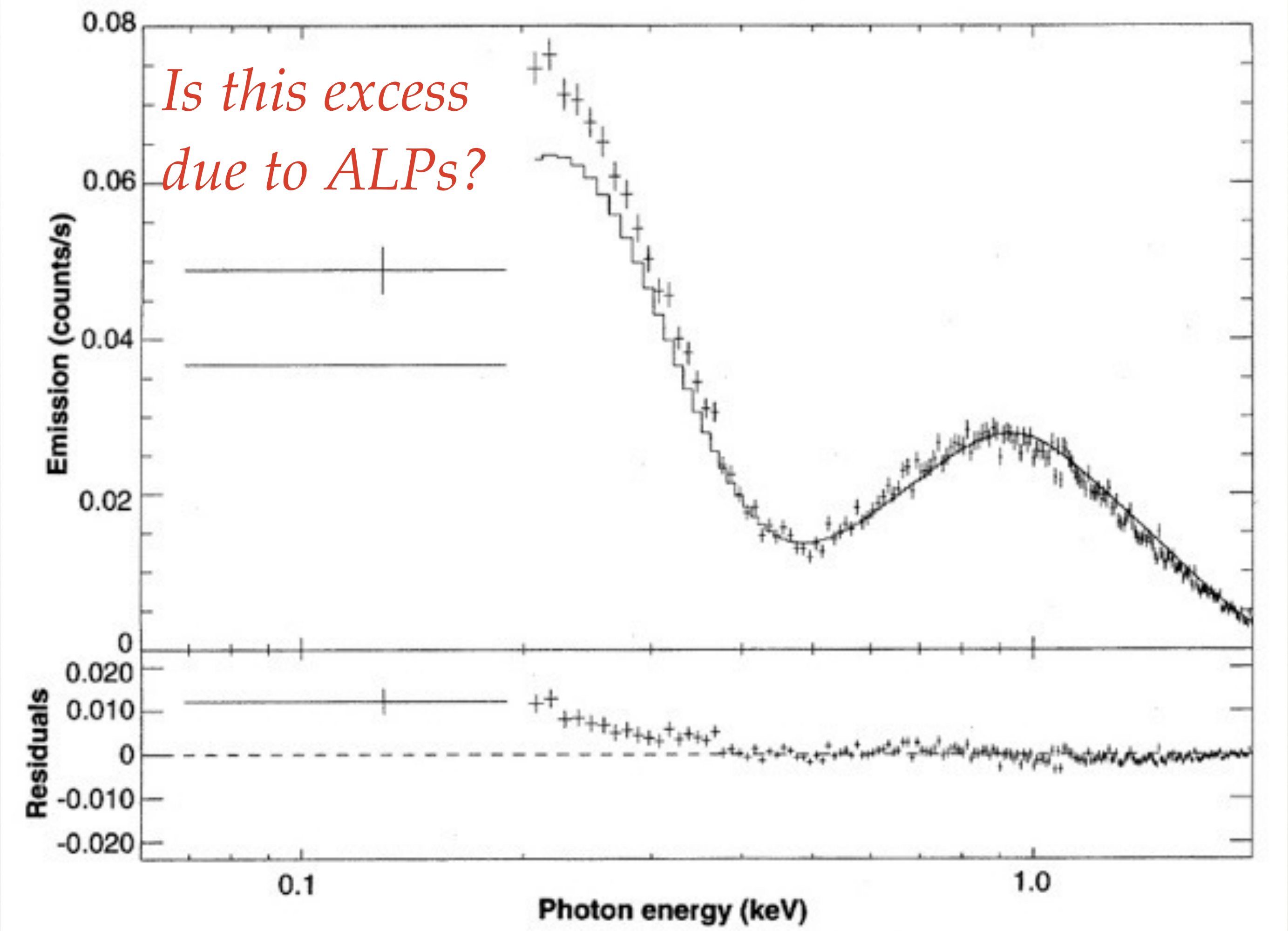


Is this excess due to ALPs?

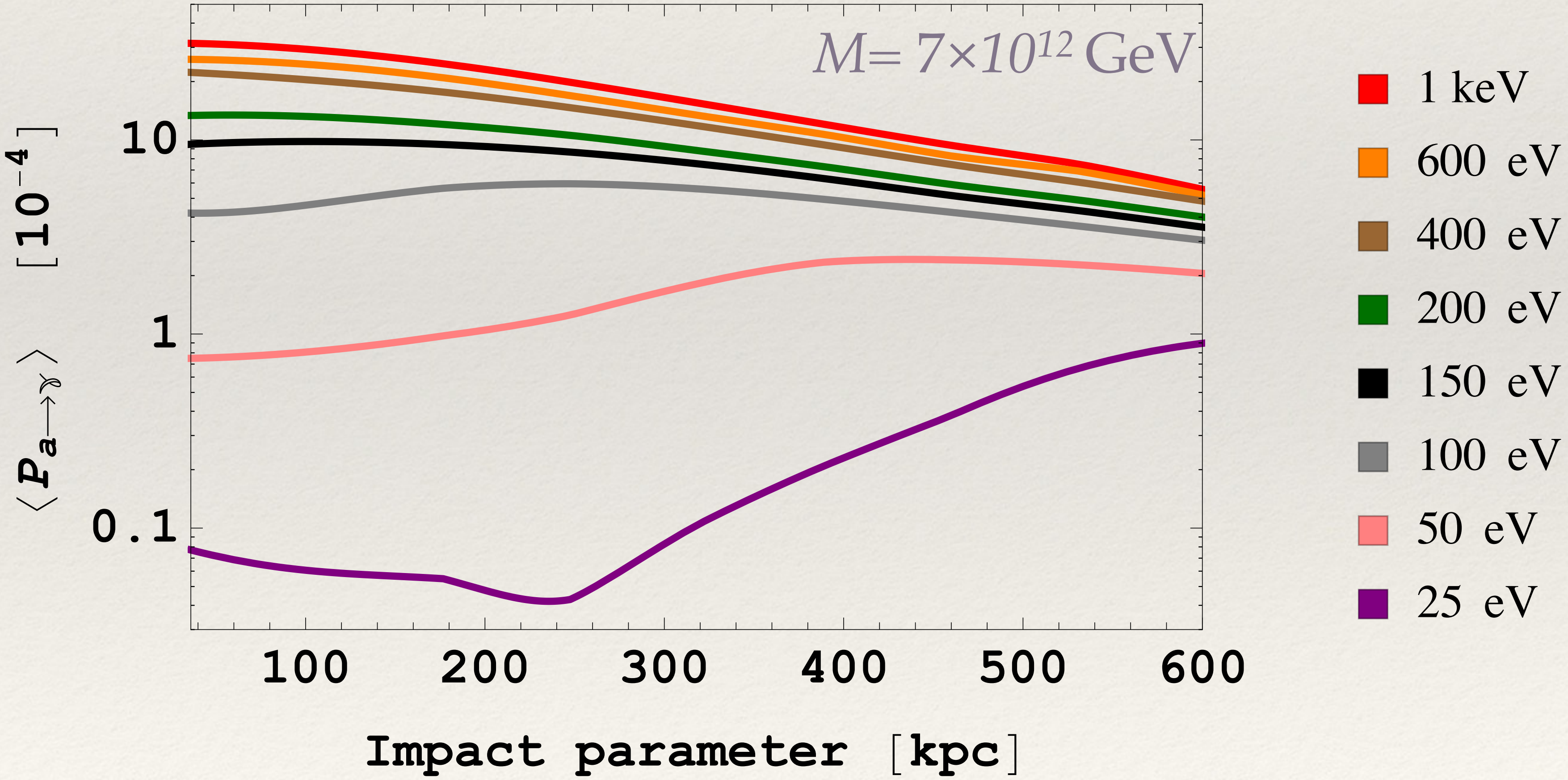
EUVE on Virgo from Liu et al. '96.

2. ALPs from reheating: the 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.

Powell's talk.

Test with the models for the Coma clusters.



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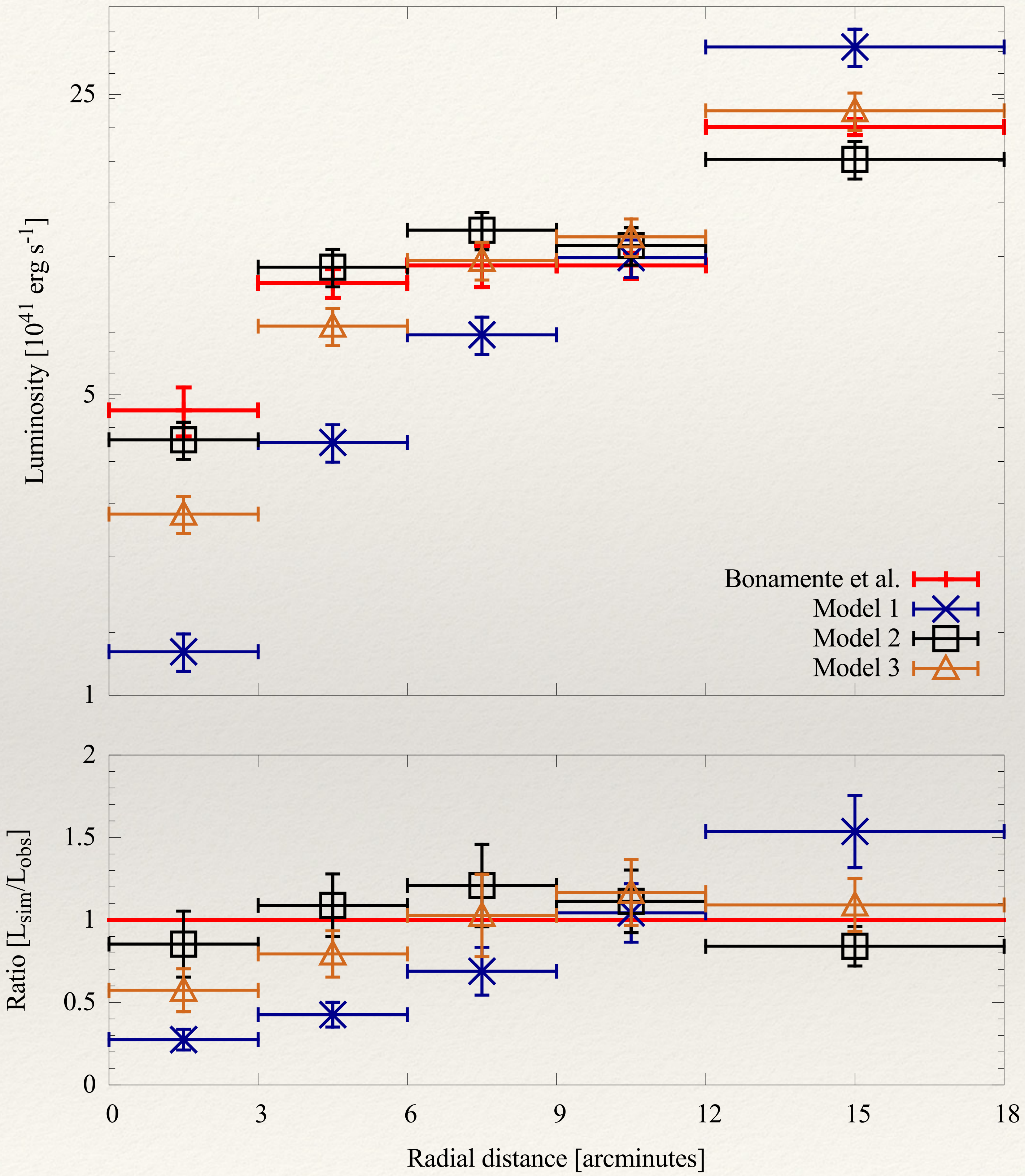

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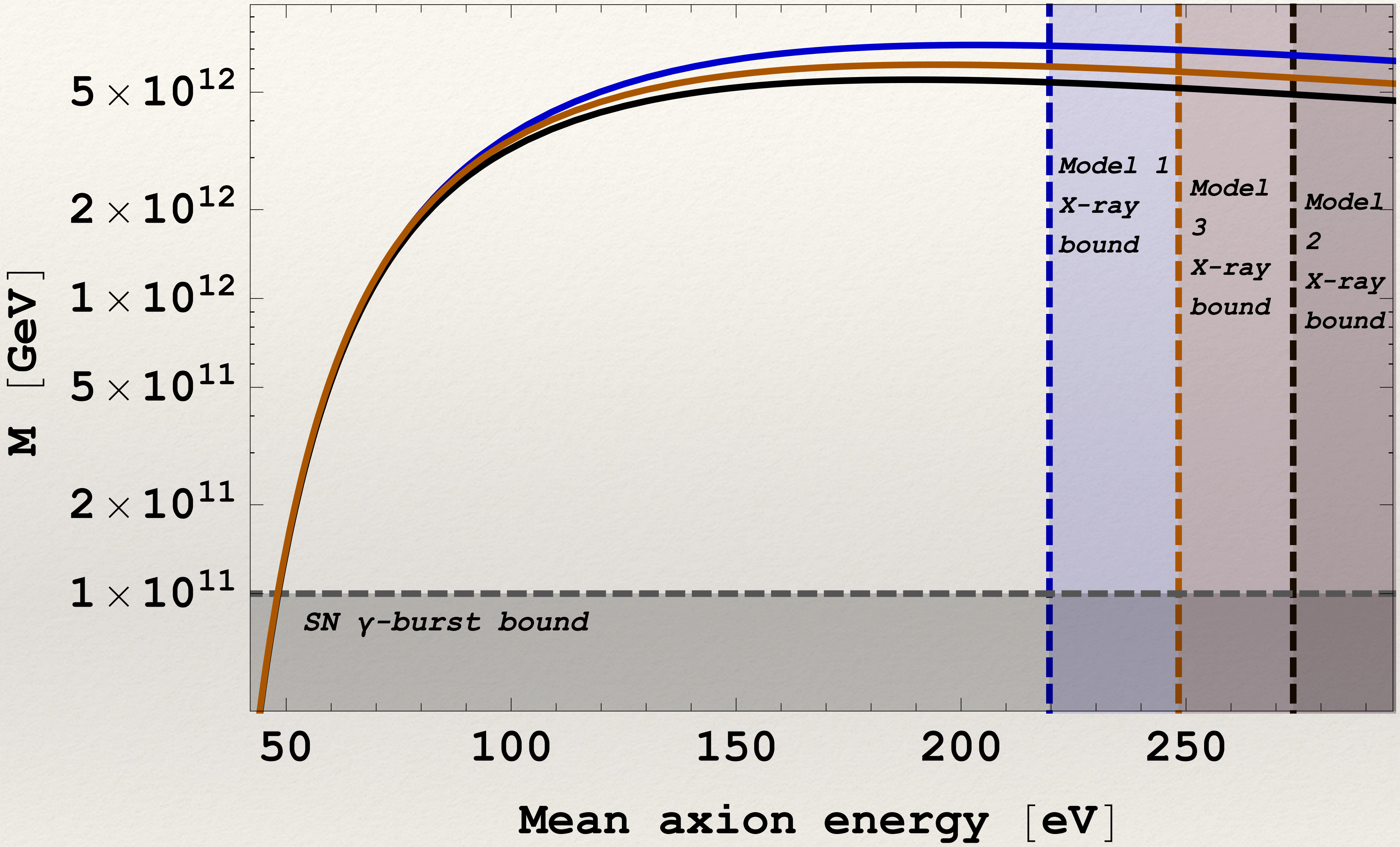

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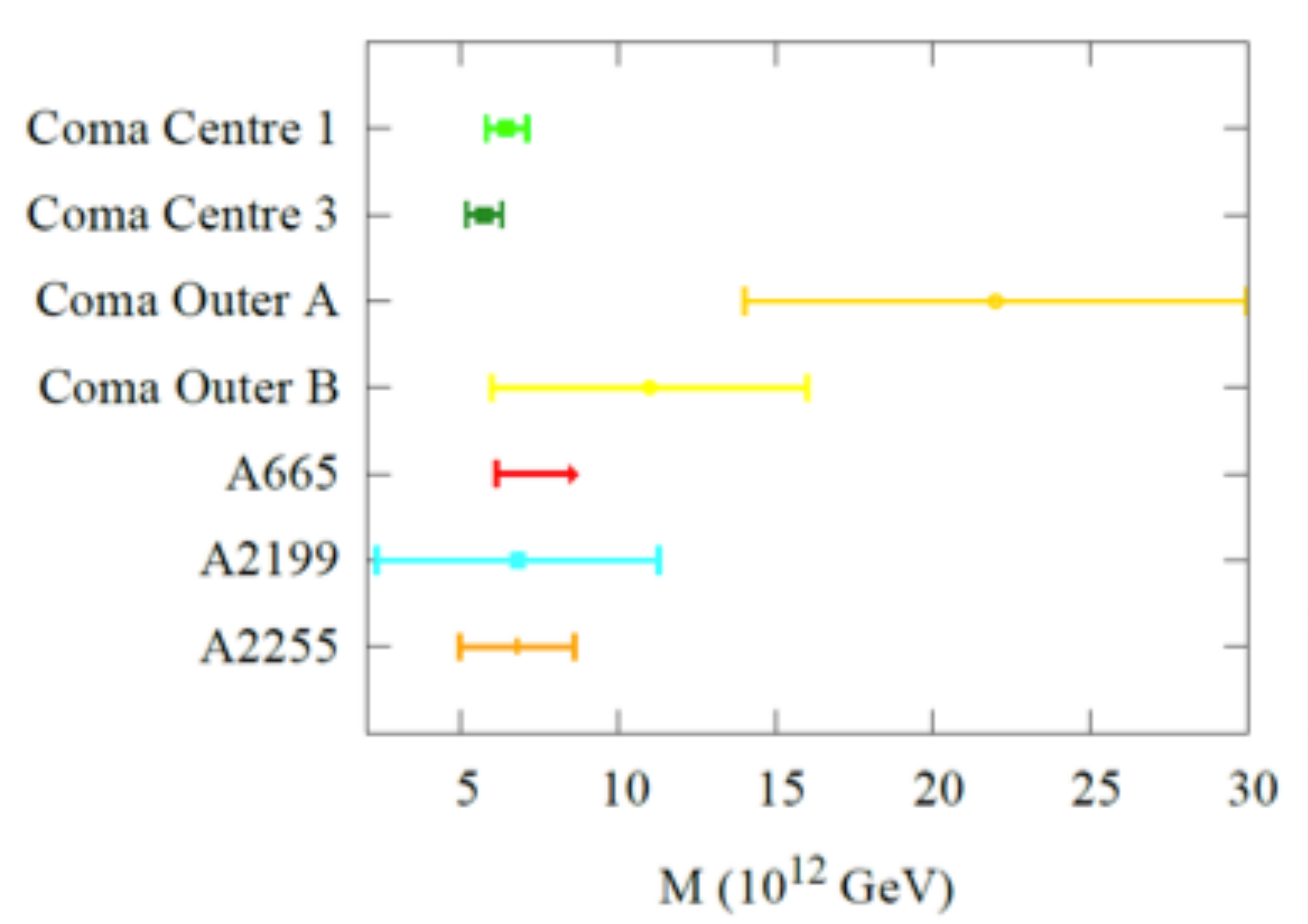

Powell
arXiv:1411.4172

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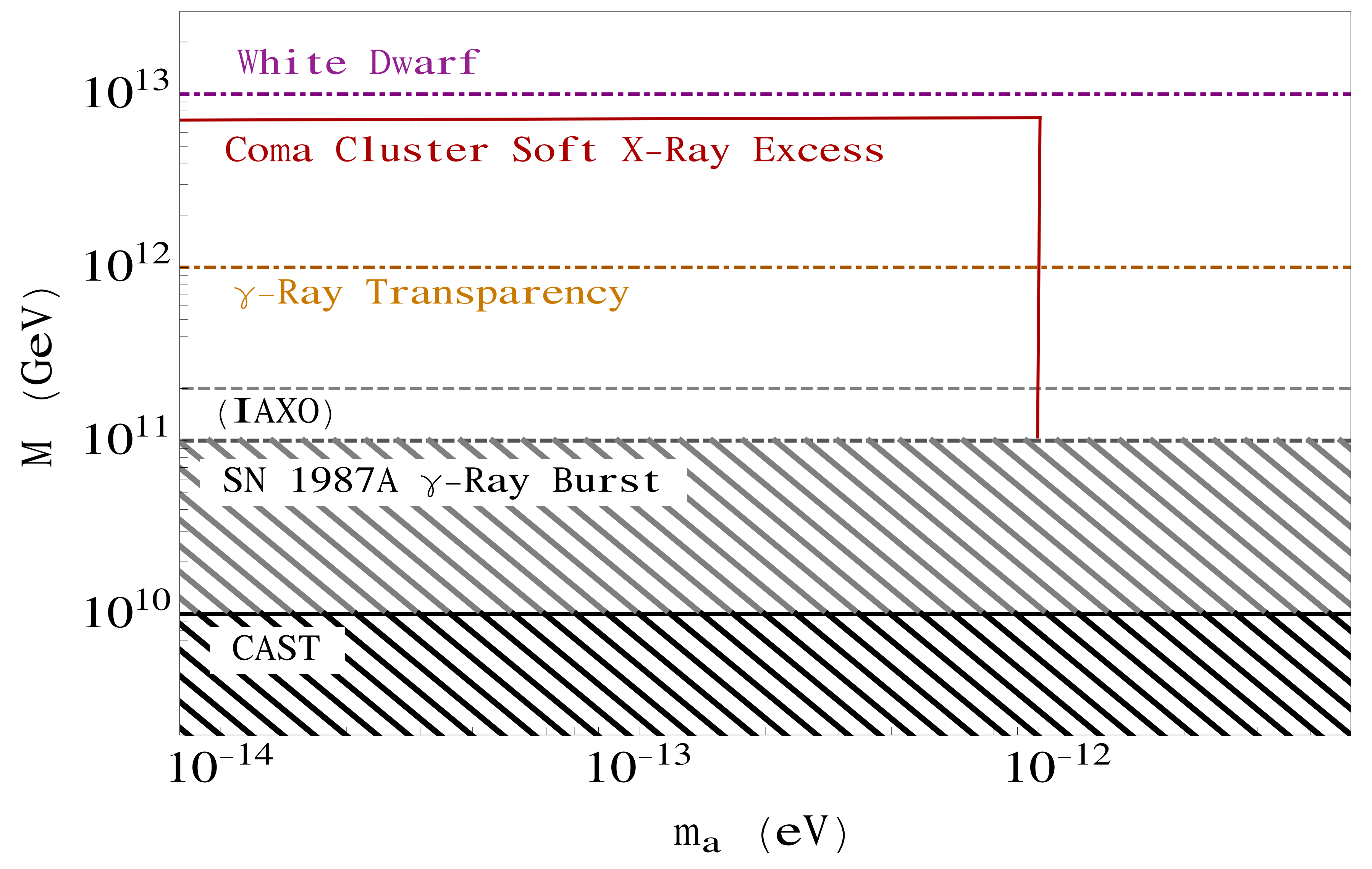


Principal message:

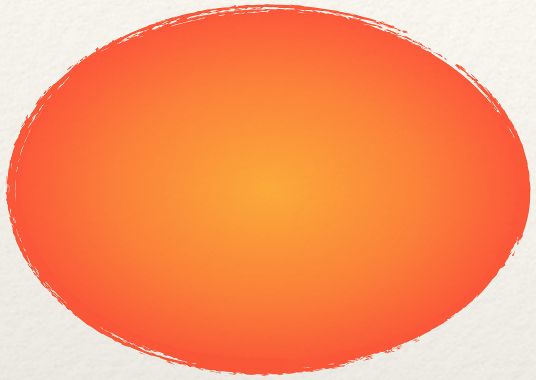
Galaxy clusters are *extremely efficient* at converting any population of light axion-like particles into photons.

The photons exhibit *distinct observational signatures* that well correlate with two unexplained features of the cluster X-ray spectrum: ***i)*** the reported unidentified *3.55 keV line*, ***ii)*** the long-standing *cluster soft X-ray excess*.

Extra slides

Other explanations for the soft X-ray excess

Other explanations for the soft X-ray excess



Thermal model:

Default suggestion at time of detection, currently disfavoured as main explanation.

Problems:

- The gas would *cool too rapidly*:

$$pV = nRT$$

Other explanations for the soft X-ray excess

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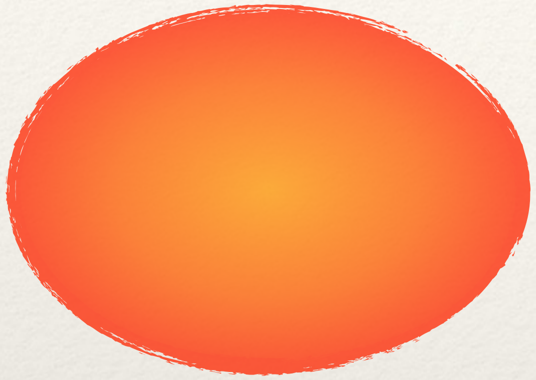


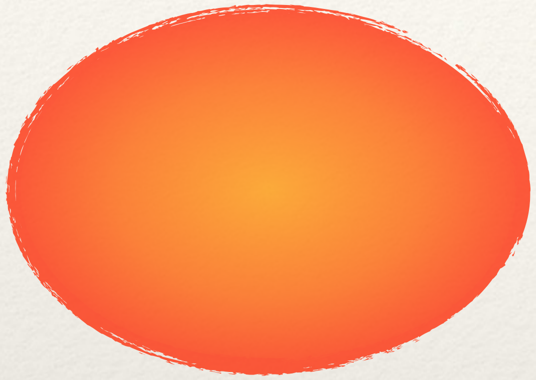
Problems:

- The gas would *cool too rapidly*:

Same for
hot & warm gas

$$\underline{pV} = nRT$$

Other explanations for the soft X-ray excess



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Smaller for warm gas

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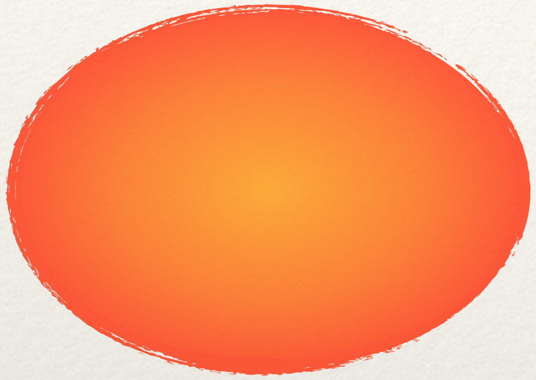

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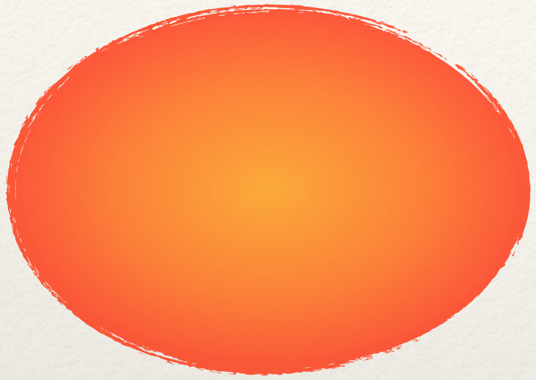

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Larger for warm gas

$$t^{(\text{warm})}_{\text{cooling}} \sim n^{-2}_{(\text{warm})} \approx 10^{-4} n^{-2}_{(\text{hot})} \sim 10^{8}\ \text{yrs} \ll \tau^{(\text{cluster dyn.})}\,.$$

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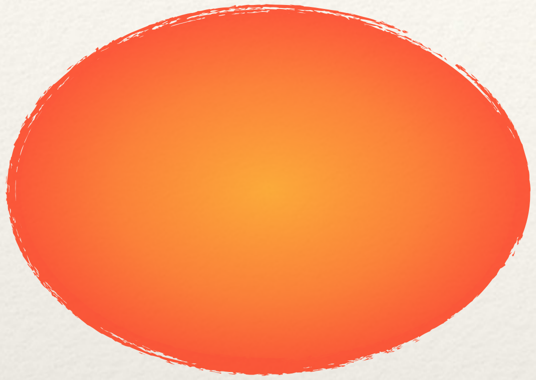

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- It would give rise to *unobserved emission lines*.

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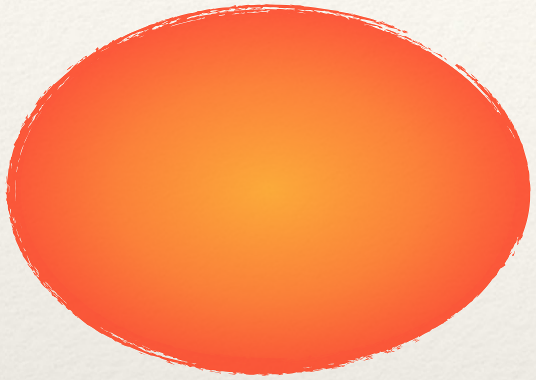

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Problems:

- The gas would *cool too rapidly*:

$$\underline{pV} = \underline{\underline{n}}R\underline{T}$$

Same for hot & warm gas

Larger for warm gas

Smaller for warm gas

$$t^{(\rm warm)}_{\rm cooling} \sim n^{-2}_{(\rm warm)} \approx 10^{-4} n^{-2}_{(\rm hot)} \sim 10^8 \text{ yrs} \ll \tau^{(\rm cluster\ dyn.)} \, .$$

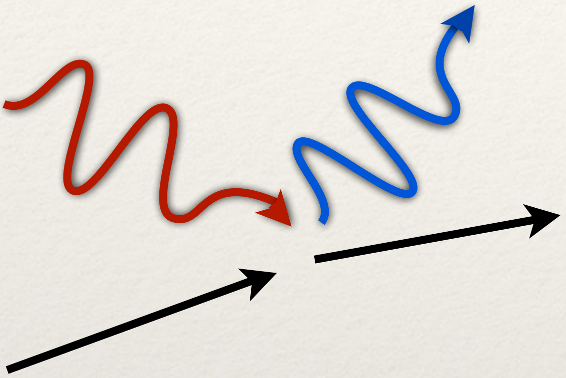
- It would give rise to *unobserved emission lines*.

Still, suggested to be possible explanation of excess at large radii.

Other explanations for the soft X-ray excess

Non-thermal model:
Inverse Compton Scattering of CMB photons off non-thermal gas:

$$E_{\rm scattered} \sim \gamma^2 E_{\rm CMB} \, .$$



Hwang 1997,
Bowyer *et al* 2004,
Sarazin 1999,
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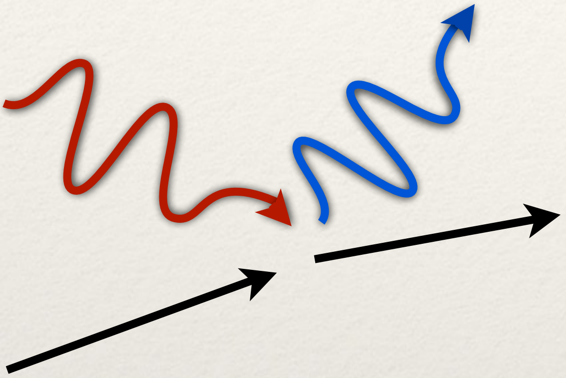

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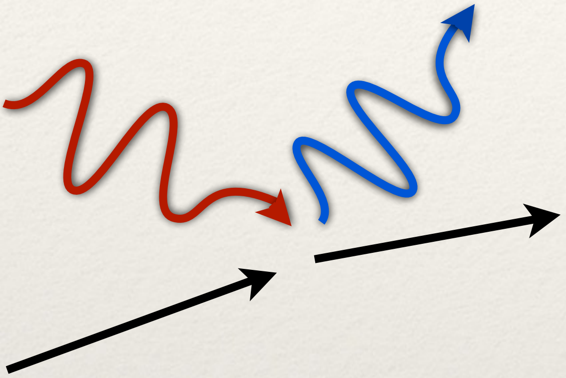

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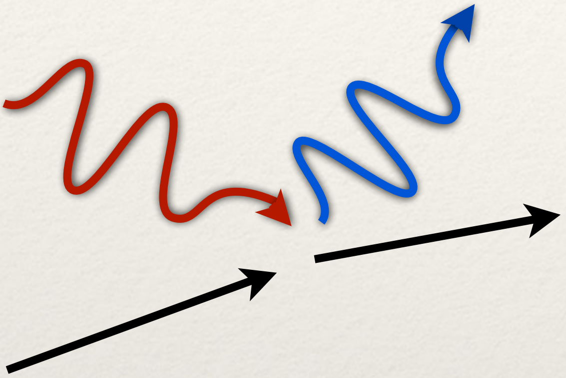
~200 eV

~ 10^{-3} eV

$\gamma \sim 500$



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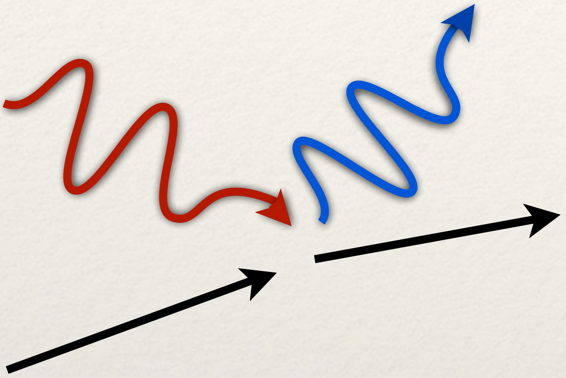

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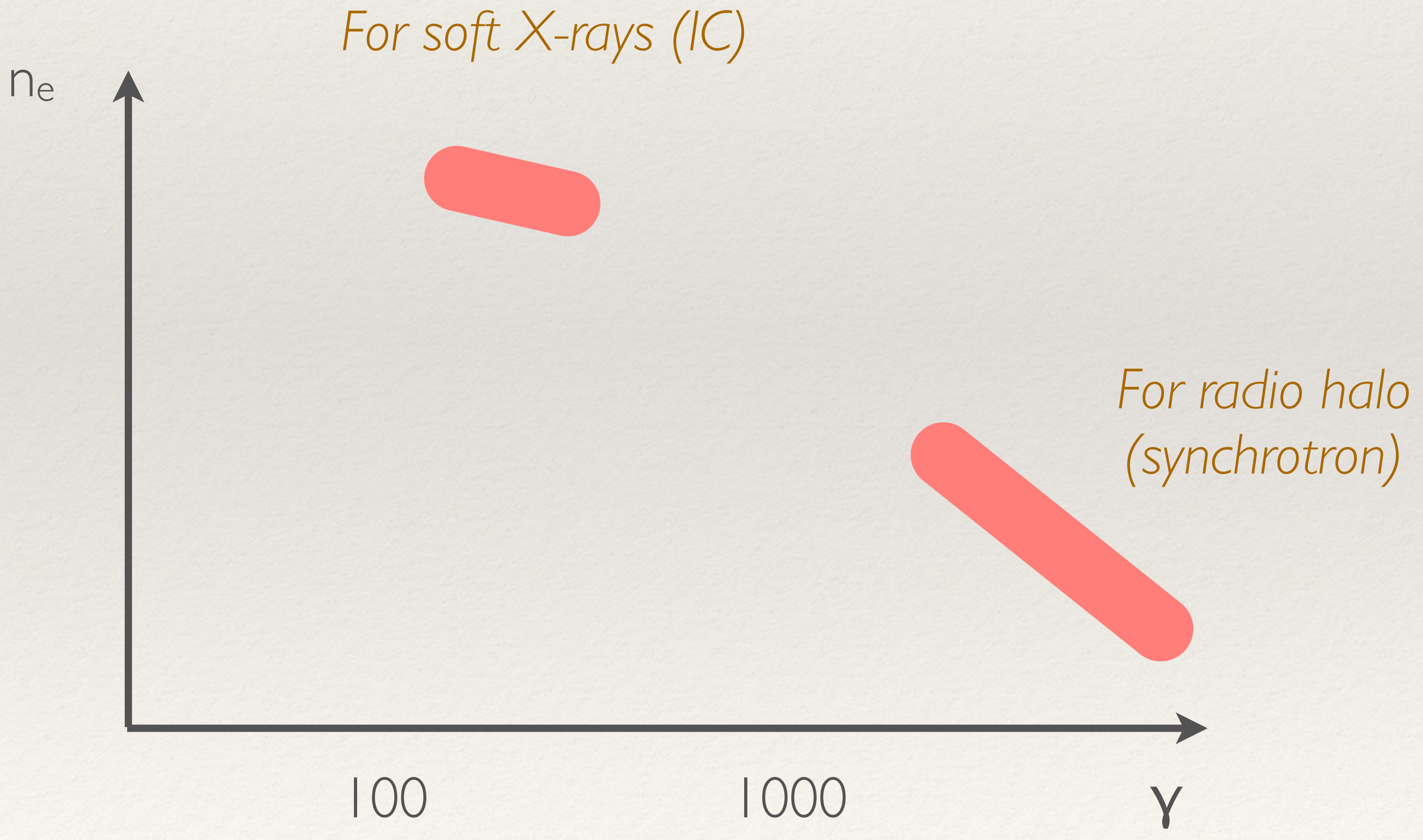

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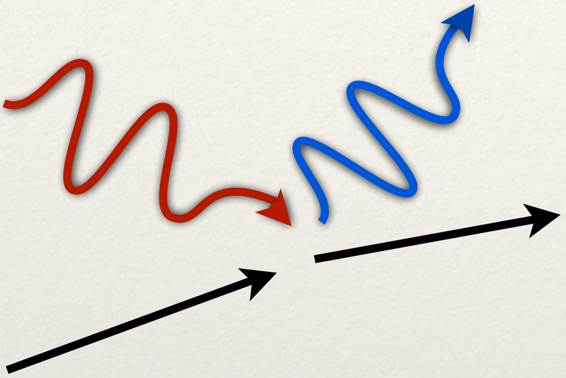

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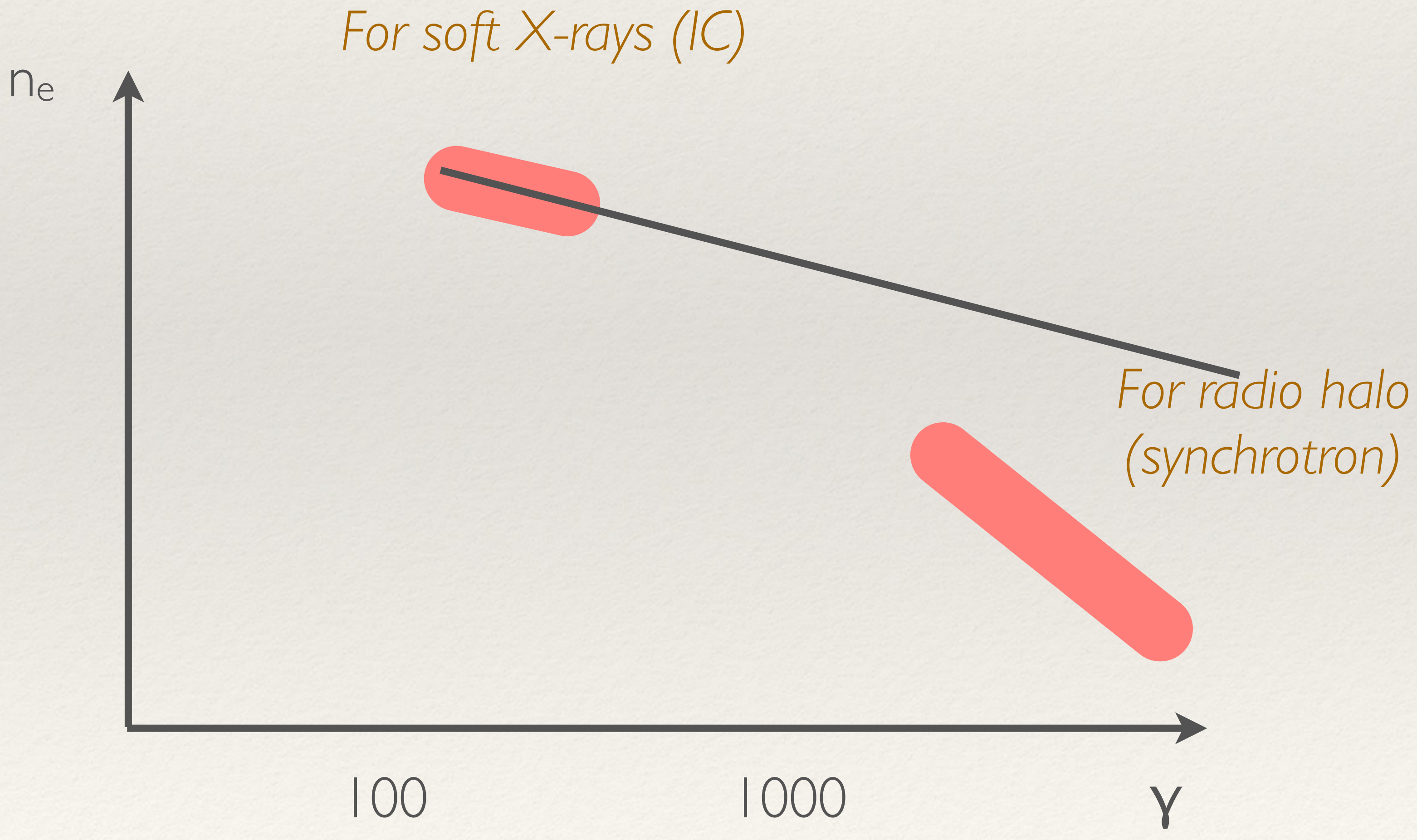

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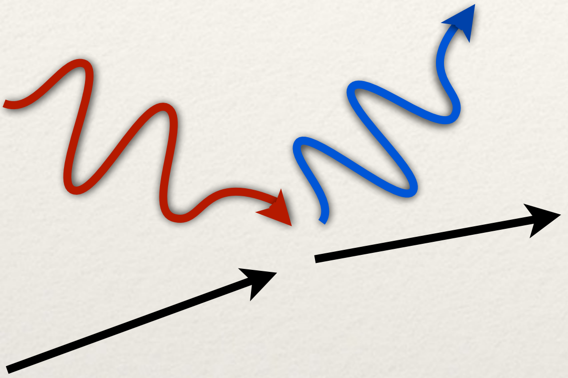

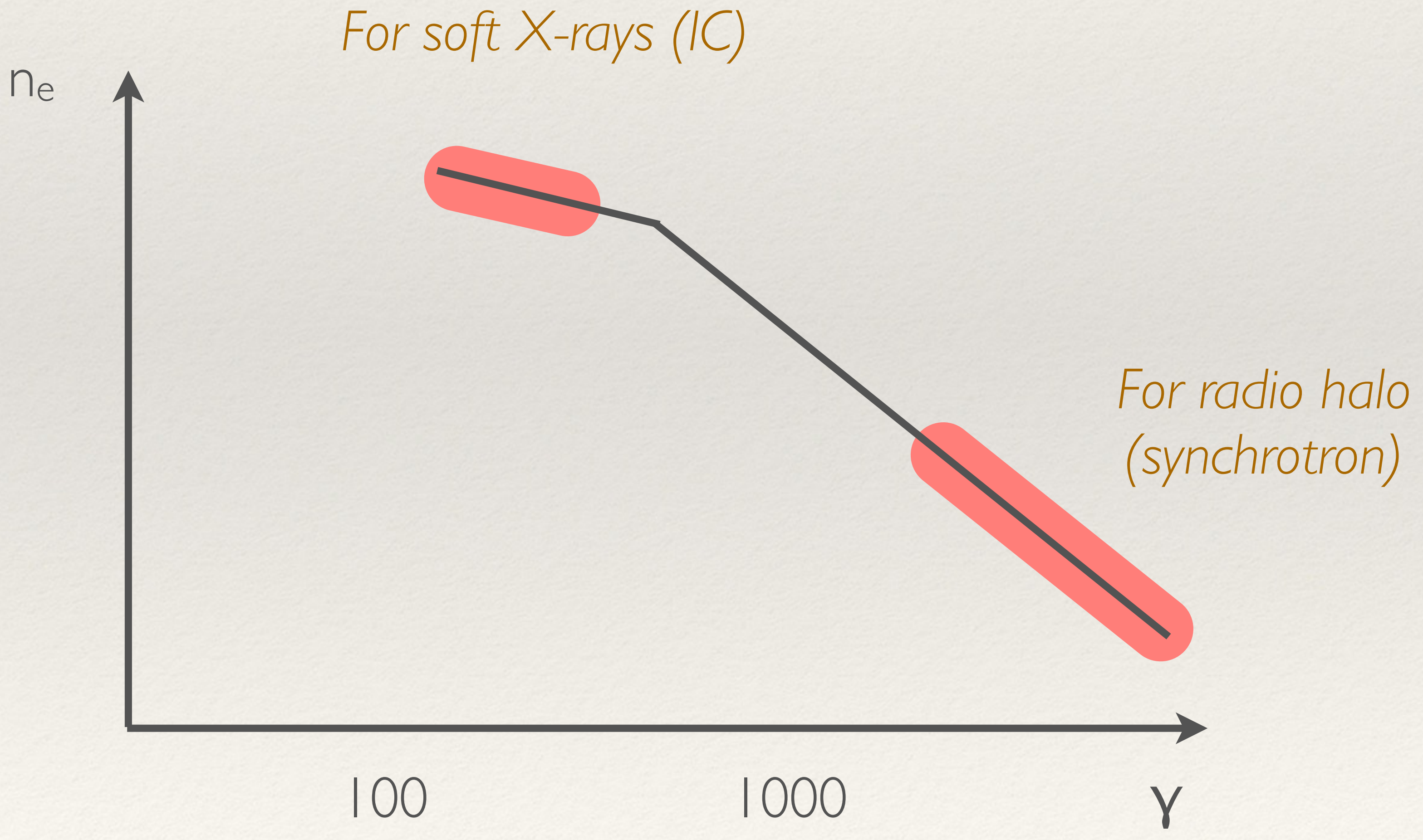

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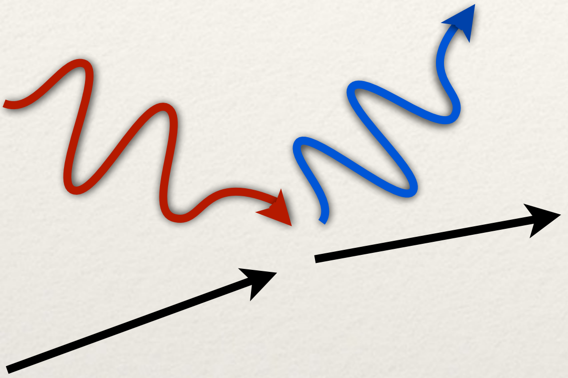

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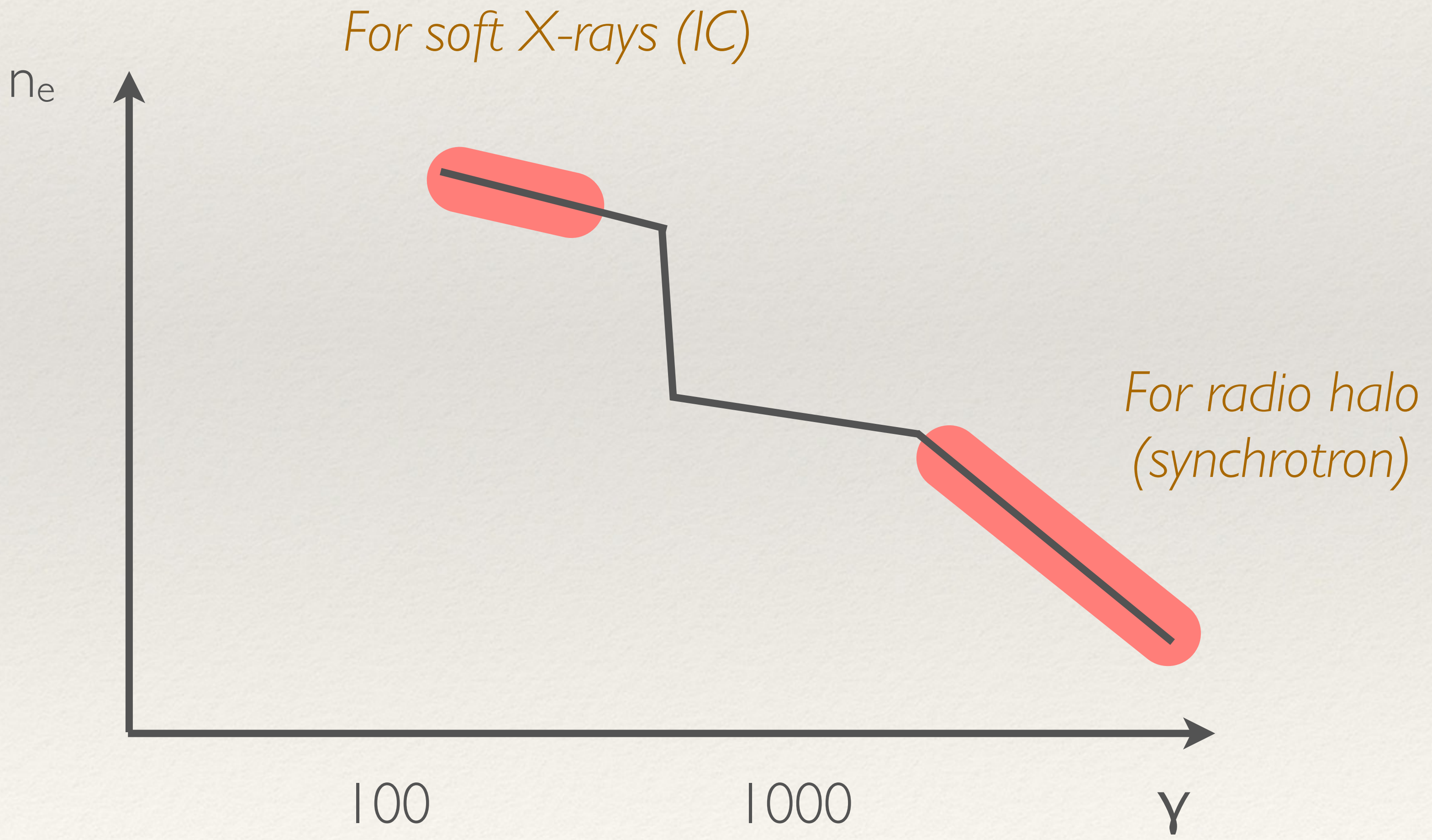

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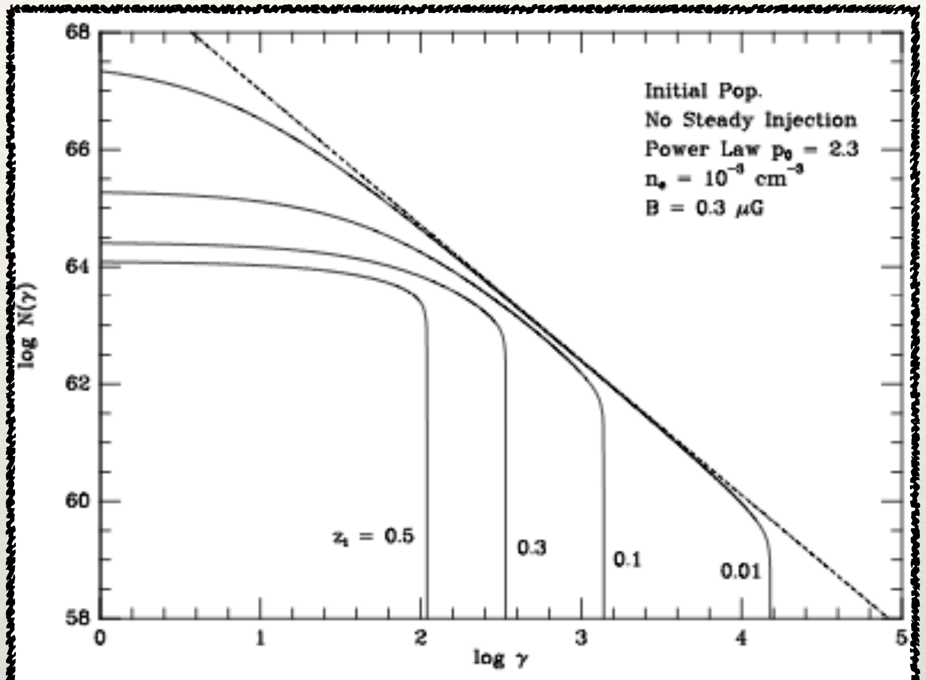

Fig. 3. The present day relativistic electron populations in models with no current particle acceleration (e.g., no subcluster merger at present). An initial population of electrons, which is shown as a dashed line, was introduced into the cluster at a redshift of $z_i = 0.01, 0.1, 0.3$, and 0.5.

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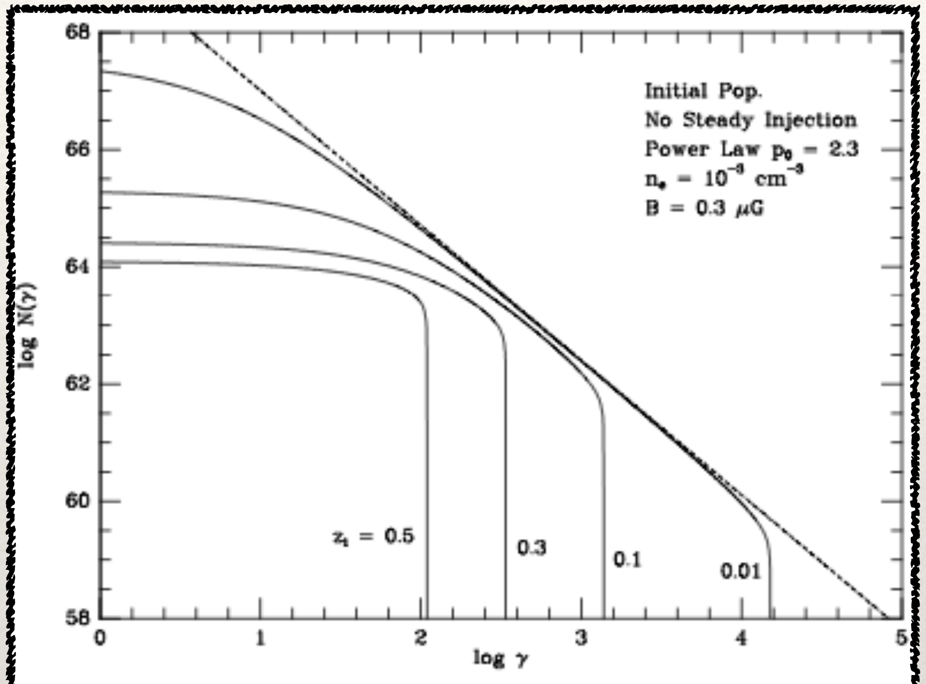

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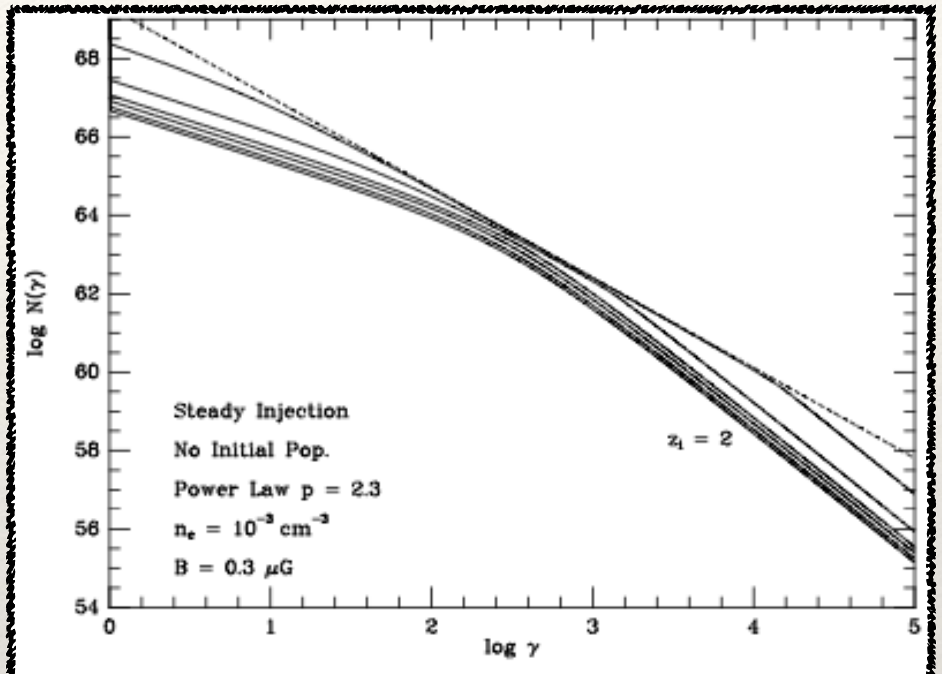
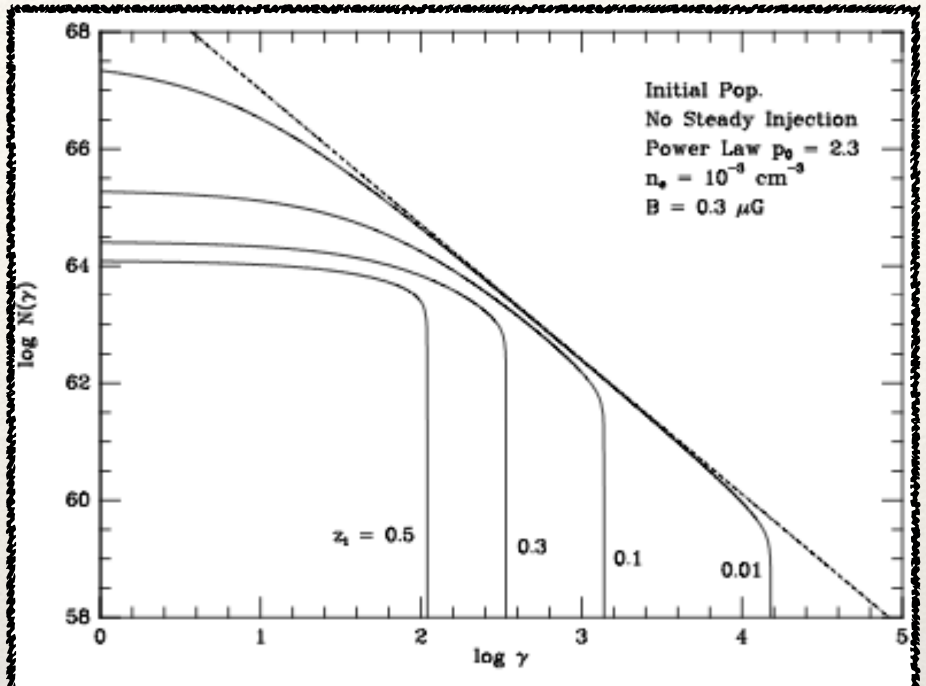


Fig. 4. The present day relativistic electron populations in a series of models with ongoing particle acceleration, perhaps due to a cluster merger shock. he solid curves show models for clusters which started at redshifts of $z_i =$ 2, 1, 0.5, 0.3, 0.1, and 0.01 (bottom to top). The short-dashed curve gives the total power-law spectrum of all of the injected particle over the cluster lifetime.

Hwang 1997,
Bowyer *et al* 2004,
Sarazin 1999,
Atoyan *et al* 1999.

Other explanations for the soft X-ray excess

Non-thermal model:



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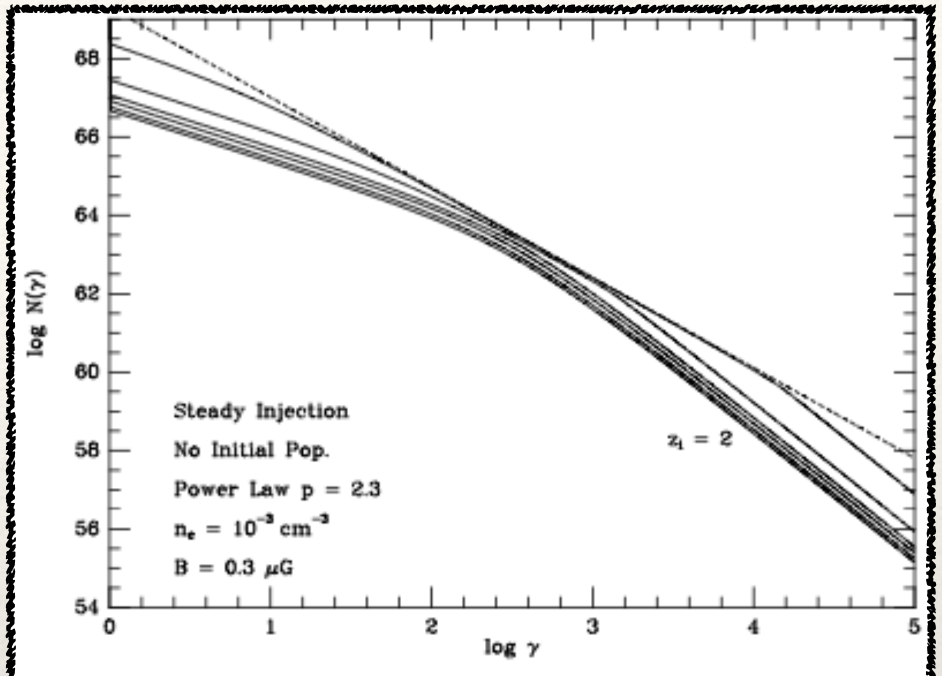

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Fine-tuned IC:

For Coma: $t_{injection} \sim 1.0\text{-}1.4 * 10^9$ yrs.

In addition: small injection even in recent past to produce CR's for radio halo.

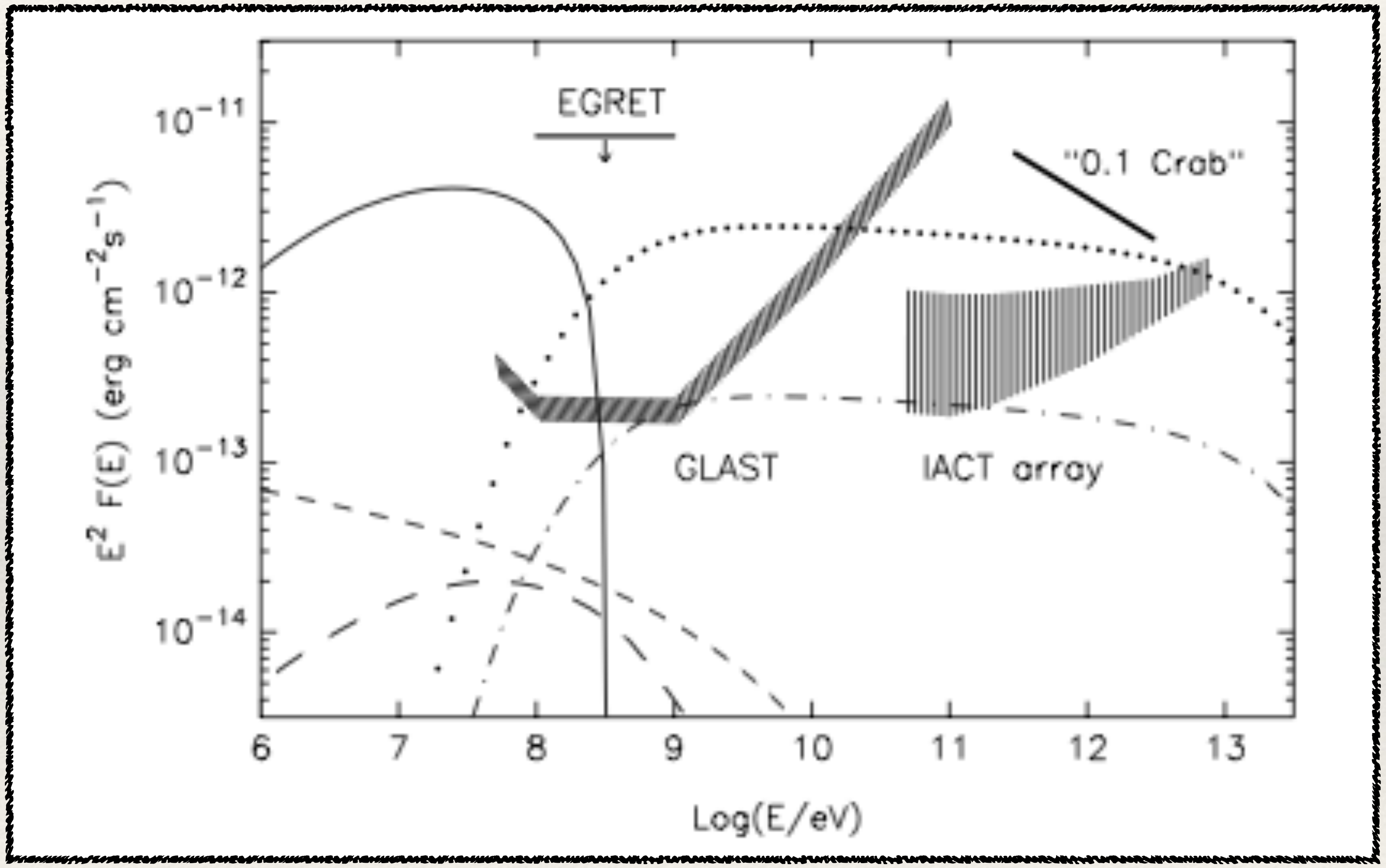
Hwang 1997,
Bowyer *et al* 2004,
Sarazin 1999,
Atoyan *et al* 1999.

Other explanations for the soft X-ray excess

Non-thermal model:

Additional constraint: associated bremsstrahlung:

Coma: predicted gamma-ray flux of ~ $2*10^{-8}$ cm^{-2} s^{-1}.



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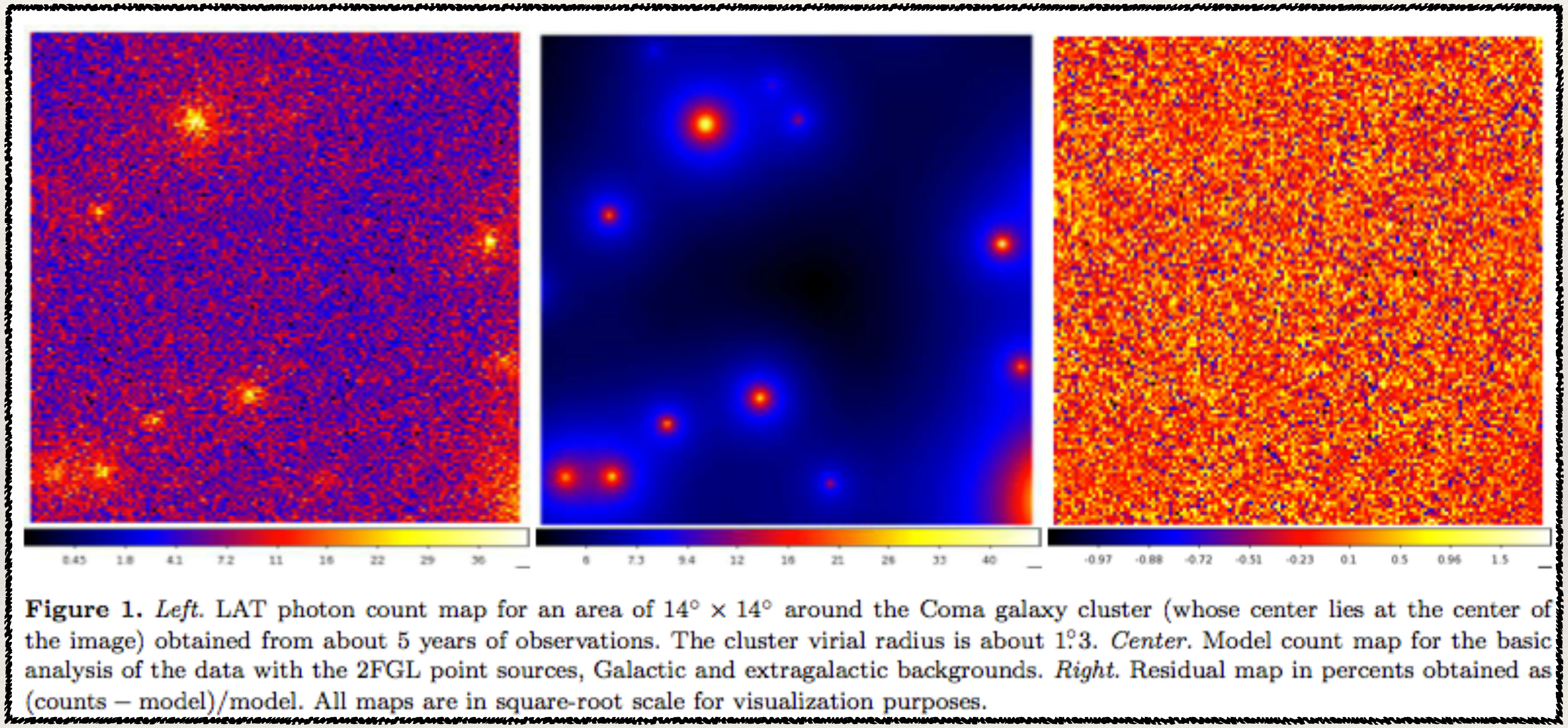

Figure 1. *Left*. LAT photon count map for an area of 14° × 14° around the Coma galaxy cluster (whose center lies at the center of the image) obtained from about 5 years of observations. The cluster virial radius is about 1°.3. *Center*. Model count map for the basic analysis of the data with the 2FGL point sources, Galactic and extragalactic backgrounds. *Right*. Residual map in percents obtained as (counts − model)/model. All maps are in square-root scale for visualization purposes.

Zandanel, Ando, 2013.

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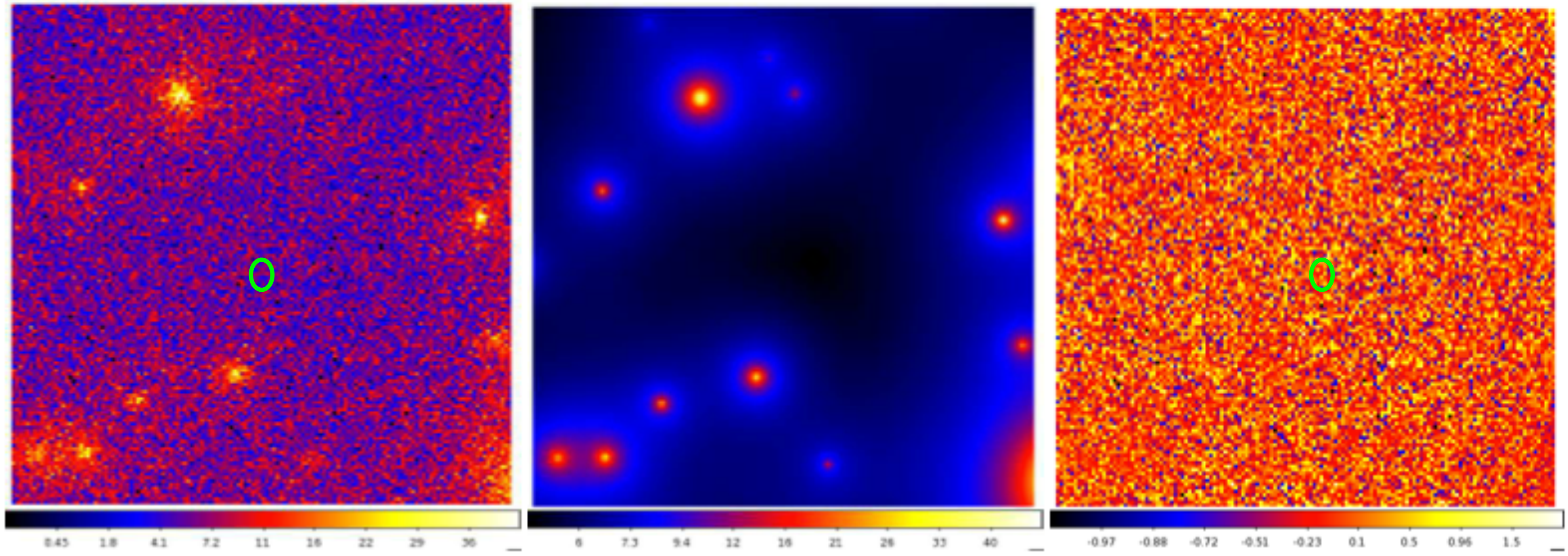

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Sarazin 1999.

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* $\rightarrow \gamma$.

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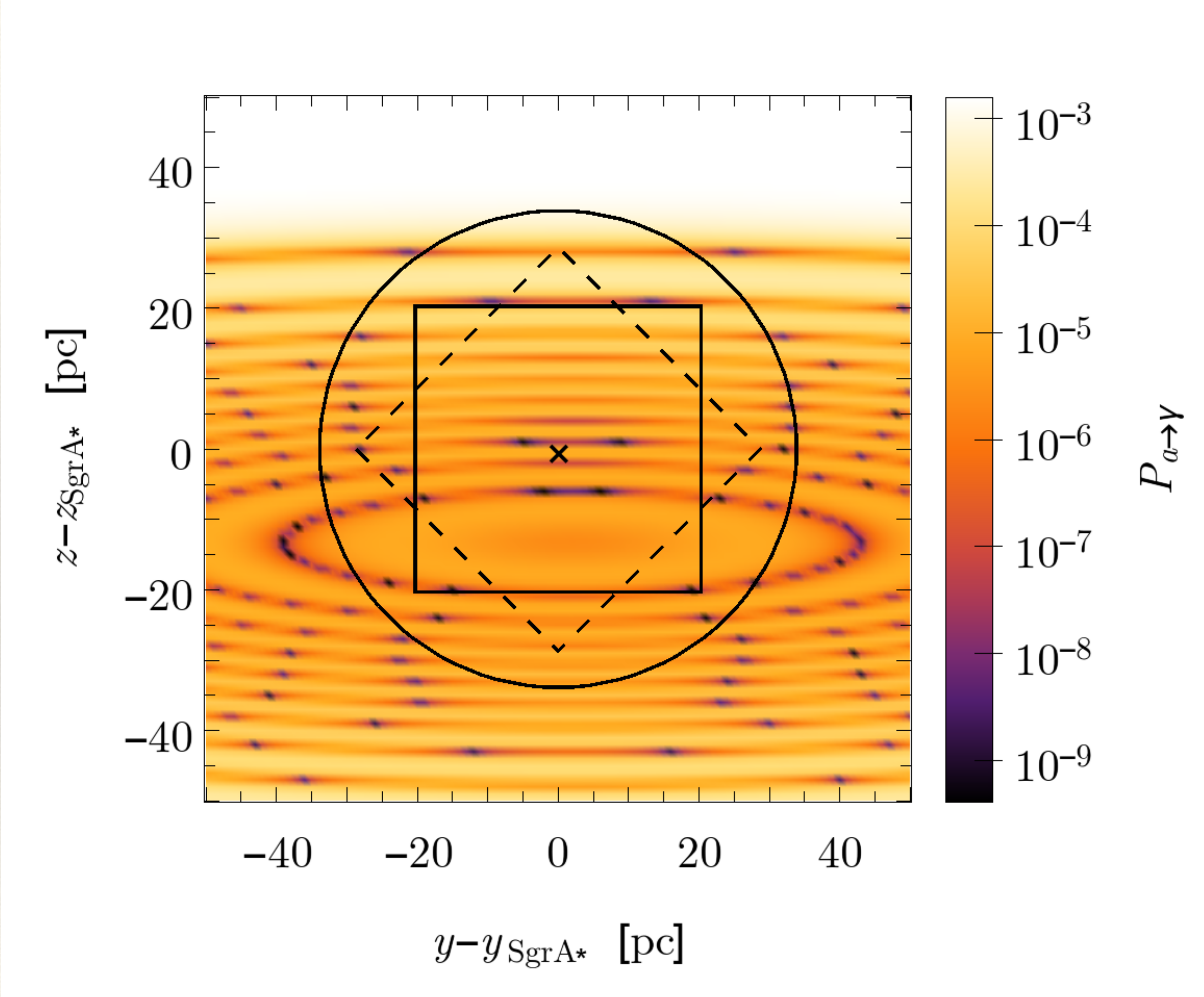
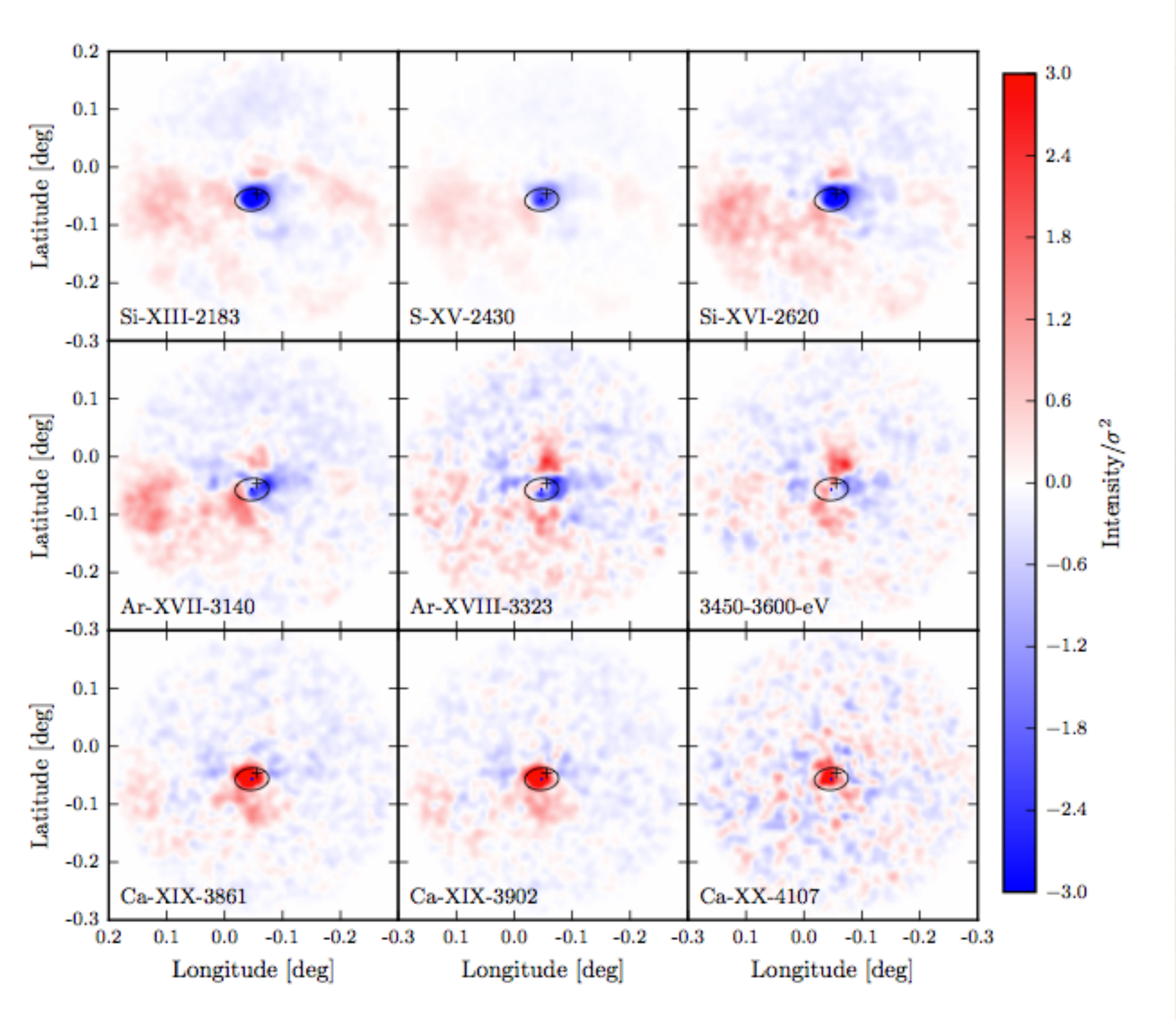
Alvarez, Conlon, Day, D.M., Rummel arXiv:1410.1867



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

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.