Morphology of the Soft X-ray Excess in Galaxy Clusters from a Cosmic ALP Background

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A brief history of the soft X-ray excess

- First discovered in 1996 by Extreme Ultraviolet Explorer (EUVE).
- Excess of low-energy (soft) X-rays detected at $\sim 138\,\text{keV}$ in Virgo and Coma clusters.
- Consolidated by the ROSAT all-sky survey ($1990 - 1999$).
- ROSAT used position-sensitive proportional counters (PSPCs) with low internal backgrounds to scan energies $0.1 - 2.4\,\text{keV}$. Low resolution but large field of view: ideal for diffuse emission.
- Bonamente et al. (2002) used ROSAT data to study 38 clusters — found that soft excess X-ray emission is a generic feature.
- Next-generation experiments XMM-Newton, Chandra and Suzaku also studied the soft excess, but have small fields of view — suboptimal, as background subtraction is harder.

Soft X-ray excess from EUVE/ROSAT

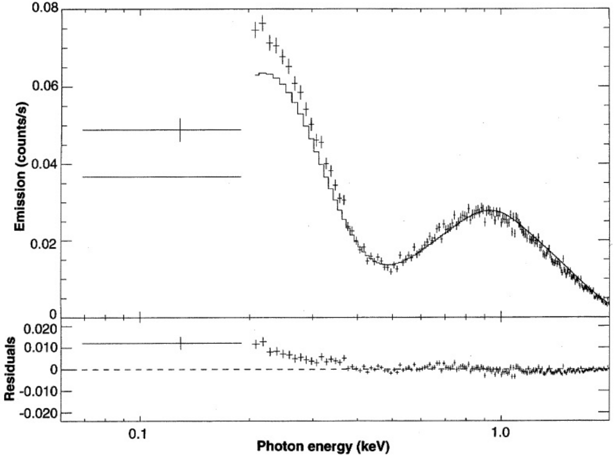

Fig. 2. Performance of the best fit MEKA single-temperature model (solid line) in a simultaneous fit to the EUVE DS and ROSAT PSPC data (the former is the first data point). The count rates correspond to those of the detected emission, and the residual is the difference between measured and model count rates.

Properties of the soft X-ray excess

Features of the soft excess:

- It is soft: predominantly seen in ROSAT R2 band ($E \lesssim 0.38\,\mathrm{keV}$).
- Present for both nearby and distant clusters ($z \sim 0.3$), but only observed for clusters away from the galactic plane, where $N_\mathrm{H} \lesssim 5 \times 10^{20}\,\mathrm{cm}^{-2}$.
- Preferentially found away from the cluster centre, at $r \gtrsim 150\,\mathrm{kpc}$.
- Extends far beyond the cluster core, up to $r \lesssim 5\,\mathrm{Mpc}$ (cluster size is typically $\sim 1\,\mathrm{Mpc}$).
- Background: thermal bremmstrahlung, weakest (at low energies) for high-temperature, low density clusters, e.g. Coma.

There are two main astrophysical explanations for the soft excess:

- Thermal bremmstrahlung from an additional “warm” gas component which is cooler than the hot ICM plasma;
  - but warm gas is unstable, cools much faster than cluster lifetime,
  - expect thermal emission lines (generally not observed).
- Inverse-Compton scattering of CMB photons off a non-thermal electron population;
  - but expect associated synchrotron (radio) emission, required B-field ($B_{\text{cluster}} \lesssim 1\,\mu$G) contradicts Faraday rotation (eg. $B_{\text{Coma}} \sim 5\,\mu$G),
  - also expect bremmstrahlung (γ-ray) emission — not observed,
  - excess extends to ~ 5 Mpc, beyond cluster — no electrons there?

- There are problems with astrophysical explanations of the excess.
- However, it is premature to say they are completely ruled out.
- Nevertheless it is worth considering alternative scenarios...

...dark radiation?

What is dark radiation?

- Dark radiation: hidden relativistic matter that contributes to the energy density of the universe.
- At CMB temperatures,

$$\rho_{\text{radiation}} = \rho_\gamma + \rho_\nu + \rho_{\text{hidden}} \,.$$

- Conventionally parametrised in terms of the "excess effective number of neutrino species", $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$:

$$\rho_{\text{radiation}} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right) \,.$$

NOTE: Not necessarily extra νs; N_{eff} can be non-integer valued!

Why dark radiation?

General considerations:

- Simple and natural extension of ΛCDM — if DM, why not DR?
- No a-priori reason why $N_{\rm eff} = 3.046$ (eg. not symmetry-protected).

String theory perspective:

- Generically $\mathcal{O}(100)$ gravitationally-coupled moduli (scalars), each with associated ALPs, many of which can remain massless.
- After inflation, universe reheated by decays of the lightest moduli.
- Any non-zero branching ratio to light hidden states sources DR. Harder to argue why dark radiation should *not* exist! (Conversely, if $N_{\rm eff} = 3.046$, string theory models must explain why.)

Experimental status:

- Planck TT+lowP+BAO results:

  $N_{\rm eff} = 3.15 \pm 0.23$ (arXiv:1502.01589, Planck Collaboration).
- Small DR contribution possible (up to $\Delta N_{\rm eff} \lesssim 0.3$ at 1σ).

Reheating

What happens after inflation?

- Any gravitationally-coupled scalar particles (eg. moduli in string theory) have generically acquired large non-zero VEVs.
- Begin to oscillate coherently about their final vacuum.
- Redshift as matter, $\rho_M \sim a^{-3}$; any radiation redshifts as $\rho_R \sim a^{-4}$.
- Moduli come to dominate the energy density of the universe; reheating is driven by the last modulus to decay.
- Final modulus Φ decays into visible and hidden-sector particles, with comparable decay rates, $\Gamma \sim m_\Phi^3 / M_P^2$.
- Decays to visible sector induce reheating at a temperature

$$T_{rh} \sim \frac{m_\Phi^{3/2}}{M_P^{1/2}} \sim 1\,\text{GeV} \left(\frac{m_\Phi}{10^6\,\text{GeV}} \right)^{3/2} .$$

Cosmic ALP Background

- Decay to axion-like particles (ALPs) can occur via the interaction

$$\mathcal{L} \supset \frac{2}{\sqrt{6}M_P} \Phi \partial_\mu a \partial^\mu a \,.$$

- This produces pairs of ALPs, each with energies $E_a = m_\Phi / 2$.
- These ALPs are highly relativistic and stream freely.

- Present day: would form a Cosmic ALP Background 1305.3603 (Conlon, Marsh).
- Can test CAB hypothesis via:
  - CMB, N_{eff};
  - ALP-photon conversion in galaxy cluster B-fields;
  - 3.5 keV line: DM $\rightarrow a \rightarrow \gamma$ in clusters/galaxies.

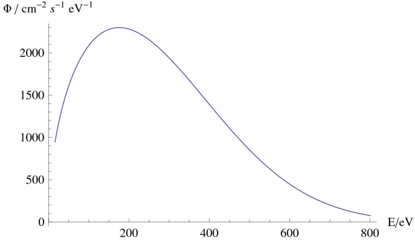

Figure: CAB, for $N_{\mathrm{eff}} = 3.62$.

ALP-photon conversion

- ALPs mix with photons via the term

$$\mathcal{L} \supset \frac{1}{4M} a F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{1}{M} a \vec{E} \cdot \vec{B} \,.$$

- In the presence of a magnetic field, ALPs convert into photons (in a process analogous to neutrino oscillations).
- Typically this interaction is very weak, but can produce an observable effect over the scale of a galaxy cluster (eg. Coma).
- Linearised wave equation for the coupled ALP-photon system:

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z \right) \begin{pmatrix} |\gamma_\perp\rangle \\ |\gamma_\parallel\rangle \\ |a\rangle \end{pmatrix} = 0 \,,$$

where $\Delta_\gamma = -{\omega_{\mathrm{pl}}}^2/2\omega$, $\Delta_{\gamma ai} = B_i/2M$ and $\Delta_a = -{m_a}^2/\omega$.

Propagation over a single coherent domain

- Conversion probability for propagation through a homogeneous magnetic field in a domain of size L:

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right) ,$$

where $\tan 2\theta = \frac{2B_\perp \omega}{M m_{eff}^2}$, $\Delta = \frac{m_{eff}^2 L}{4\omega}$ and $m_{eff}^2 = {m_a}^2 - {\omega_{pl}}^2$.

- Definitions:
  - ω is the ALP energy (also the energy of the converted X-ray);
  - ω_{pl} is the plasma frequency of the ICM, $\omega_{pl} = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \sim \sqrt{n_e}$;
  - $B_\perp$ is the magnetic field component transverse to propagation;
  - M is the inverse ALP-photon coupling;
  - m_a is the ALP mass.

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where $\tan 2\theta = \frac{2B_\perp \omega}{M m_{eff}^2}$, $\Delta = \frac{m_{eff}^2 L}{4\omega}$ and $m_{eff}^2 = m_a{}^2 - \omega_{pl}{}^2$.

- Interesting physics requires $\omega_{\rm pl} \gtrsim m_a$; for simplicity we set $m_a = 0$.
- E.g. in the Coma cluster, $\theta \sim 10^{-5}$ so the small-θ approximation is always valid, giving $P(a \to \gamma) \simeq \theta^2 \sin^2(\Delta)$, with $\theta \simeq \frac{B_\perp \omega}{M \omega_{\rm pl}{}^2}$.
- Hence even averaged over many domains, $\langle P(a \to \gamma) \rangle \sim M^{-2}$.
- We will make use of this fact later!

Simple magnetic field model

- In arXiv:1312.3947 (SA, Conlon, Marsh, Powell, Witkowski) we simulated the Coma magnetic field as a multi-scale, tangled field with Gaussian statistics and power spectrum $P(k) \propto k^{-n+4}$, that fits Rotation Measure (RM) observations (Murgia et al., 2004).
- The intracluster medium (ICM) density in the central region of the Coma cluster is well-described by a "β-model",

$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta} ,$$

with $n_0 = 3.44 \times 10^{-3}\,\mathrm{cm}^{-3}$, $r_c = 291\,\mathrm{kpc}$, and $\beta = 0.75$.
- Assume magnetic field magnitude follows a related distribution,

$$B(r) = B_0 \left(\frac{n_e(r)}{n_0}\right)^{\eta} ,$$

where η is another parameter of the model.

Results

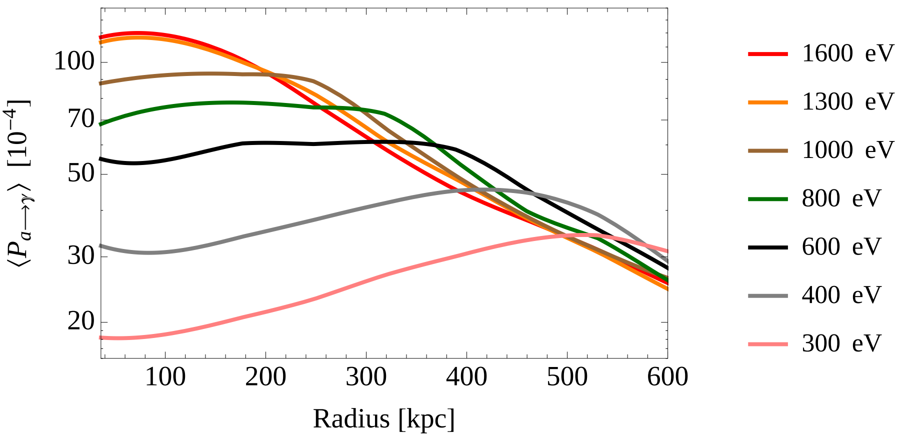


Figure: Conversion probabilities as a function of radius, with $\eta = 0.5$, $B_0 = 4.7\,\mu$G, $\Lambda_{\text{min}} = 2$ kpc, $\Lambda_{\text{max}} = 34$ kpc, $n = 17/3$ and $M = 5 \cdot 10^{12}$ GeV.

Results for Coma cluster — models considered

We compared the luminosity at given radii with data presented in a 38-cluster survey (Bonamente et al., 2002).

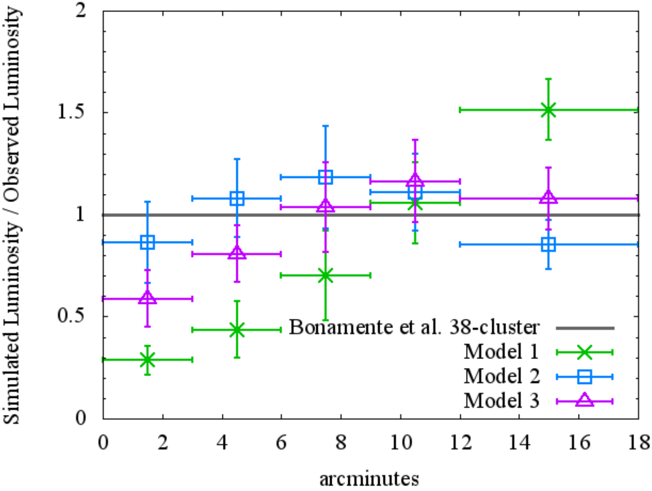
- **Model 1:** Baseline model. Uses magnetic field coherence lengths between $\Lambda_{\mathrm{min}} = 2\,\mathrm{kpc}$ and $\Lambda_{\mathrm{max}} = 34\,\mathrm{kpc}$, a Kolmogorov power spectrum $n = 17/3$, $\eta = 0.4 - 0.7$, and $B_0 = 3.9 - 5.4\,\mu\mathrm{G}$.
- **Model 2:** Decrease Λ_{max} to 5 kpc, which does not fit Faraday RM data. In addition, use $\eta = 0.7$ and $B_0 = 5.4\,\mu\mathrm{G}$.
- **Model 3:** Flat power spectrum ($n = 4$). To fit RM data we need to compensate by increasing Λ_{max} to 100 kpc. $\eta = 0.7$; $B_0 = 5.4\,\mu\mathrm{G}$.

The results were normalised such that $\Delta N_{\mathrm{eff}} = 0.5$ and the total luminosity in the “C-band” (200 – 400 eV) within 500 kpc equals the total observed luminosity quoted by Bonamente et al. (2002),

$$\mathcal{L}_{\mathrm{total}} = 1.31 \cdot 10^{43}\,\mathrm{erg\,s^{-1}}\,.$$

This allows us to predict the ALP-photon coupling M for each model.

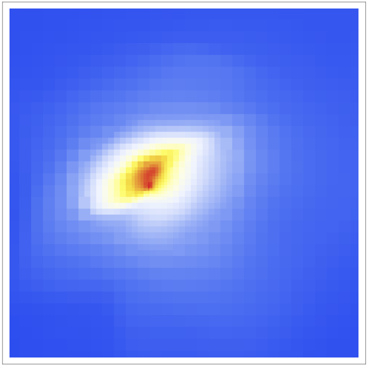
Model comparison



Furthermore, matching observed luminosity requires $M \sim 10^{13}$ GeV.

MHD simulations of cluster formation

- The parameter values that best fit Faraday RMs tend to under-produce X-rays on smaller scales.
- Loophole: Faraday RMs observe $B_{\|}$; axion-photon conversion probability depends only on $B_{\perp}$.
- Previous model assumed $\langle \Lambda \rangle_{\|} = \langle \Lambda \rangle_{\perp}$ for simplicity, but in a more realistic scenario $B_{\|}$ and $B_{\perp}$ may be correlated over different scales.



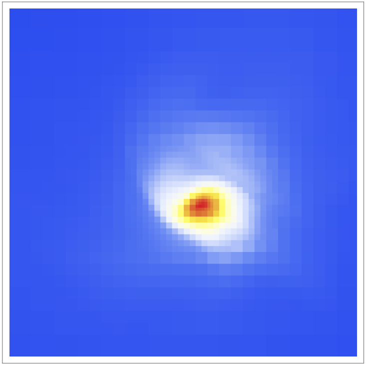
Sample ICM density map.

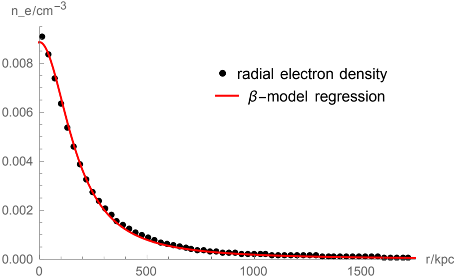
Therefore:

Consider ALP conversion to photons in anisotropic galaxy cluster magnetic fields generated by magnetohydrodynamical simulations.

Input data: electron density

- Input data: ICM densities and magnetic fields for four galaxy clusters that were generated by a magnetohydrodynamical simulation (http://www.horizon-simulation.org/).
- For each cluster, the electron density is a good fit to a β-model; for example, for Cluster 3:

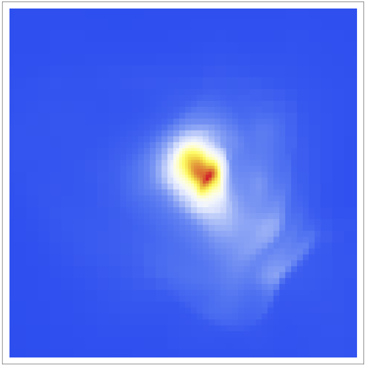


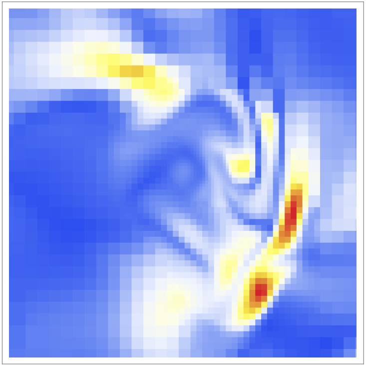


Best-fit: $n_0 = 8.86 \cdot 10^{-3}\,\text{cm}^{-3}$, $r_c = 182\,\text{kpc}$, and $\beta = 0.75$.

Input data: magnetic fields

- However, in all but one case, the magnetic field data does not follow the "η-model" profile of the Coma cluster ($B \propto n^\eta$).
- Here are cross-section images of the electron density (left) and magnetic field magnitude (right) for Cluster 4:



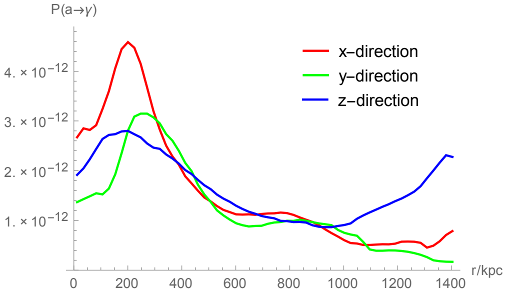


Input data: magnetic fields

- Only for Cluster 3 at $r \gtrsim 500\,\mathrm{kpc}$ is an η-model relationship obtained, with $\eta \sim 0.5$.
- Additional problem: in the raw simulation data, $B_0 \sim 10^{-11}$ G!
- However, this issue can be circumvented with an assumption: keep same profile, but scale the overall magnitude.
- This is valid due to the small-θ approximation (recall $\theta \propto B_\perp / M$). Hence artificially re-scaling B everywhere by the same factor is equivalent to a (fake) rescaling of M.
- Furthermore, we already know that the observed B_0 is consistent with the CAB hypothesis! Here we only care about morphology.
- Nevertheless, it is a strong assumption that the rescaled magnetic field could be produced by the simulation.

Preliminary results

- Consider ALP propagation through Cluster 3 in different directions — for simplicity, propagate along coordinate axes.
- Conversion morphology example ($\omega = 200\,\text{eV}$):



- **Goal:** study dependence of morphology on B-field correlation length;
- test across different energies to see if MHD-generated B-field data can improve the fit to the observed excess.

…work in progress!

Summary and Outlook

- The soft X-ray excess from galaxy clusters is a long-standing astrophysical puzzle. Cosmic ALP Background conversion may explain this excess.
- For the Coma cluster, the predicted morphology of the soft X-ray spectrum matches observations if the magnetic field has more power on small scales than suggested by Faraday rotation.
- Anisotropic magnetic fields generated by MHD simulations may be able to resolve this tension.

Outlook for CAB conversion in MHD models:

- B-field profile does not fit observations, except in specific cases.
- Some variance in conversion morphology with propagation direction. . . connected with B-field correlation scale?
- Still need full results at different energies to compare directly with soft excess data for clusters (in progress!).