Soft X-ray excess from cosmic ALPs in magnetohydrodynamical cluster simulations

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Soft X-ray excess from EUVE/ROSAT

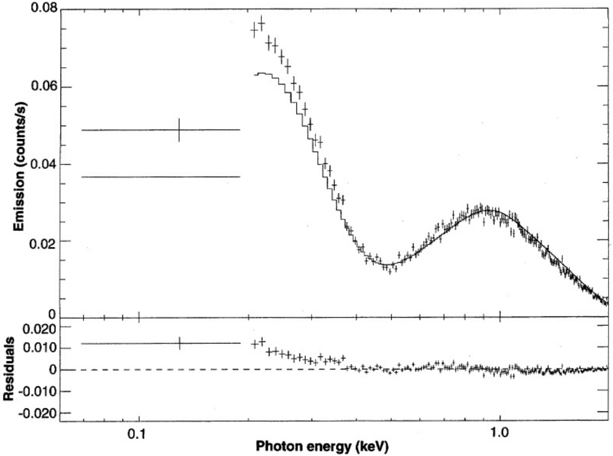


Fig. 2. Performance of the best fit MEKA single-temperature model (solid line) in a simultaneous fit to the EUVE DS and ROSAT PSPC data (the former is the first data point). The count rates correspond to those of the detected emission, and the residual is the difference between measured and model count 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 $N_H \lesssim 5 \times 10^{20}\,\mathrm{cm}^{-2}$.
- 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 cluster.

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 ($B_{\rm cluster} \lesssim 1\,\mu$G) contradicts Faraday rotation (eg. $B_{\rm Coma} \sim 5\,\mu$G),
  - also expect bremmstrahlung (γ-ray) emission — not observed,
  - excess extends to $\sim 5\,$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", $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$:

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

Experimental status:

- Planck TT+lowP+BAO results:

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

Moduli and reheating

String theory perspective:

- Generically $\mathcal{O}(100)$ gravitationally-coupled moduli (scalars), each with associated ALPs, many of which can remain massless.
- During inflation, moduli generically acquire 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, $N_{\rm eff}$;
  - ALP-photon conversion in galaxy cluster B-fields;
  - 3.5 keV line: DM $\to a \to \gamma$ in clusters/galaxies.

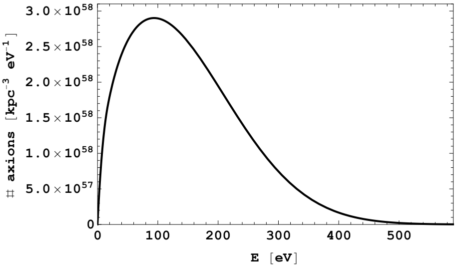


Figure: CAB, for $N_{\rm eff} = 3.62$.

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).
- 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 $m_{eff}^2 = m_a{}^2 - \omega_{pl}{}^2$.

- Interesting physics requires $\omega_{pl} \gtrsim m_a$; for simplicity we set $m_a = 0$.
- In the Coma cluster, $\theta \sim 10^{-5} \Rightarrow P(a \to \gamma) \simeq \theta^2 \sin^2(\Delta) \sim \frac{B_\perp^2}{M^2}$.

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",

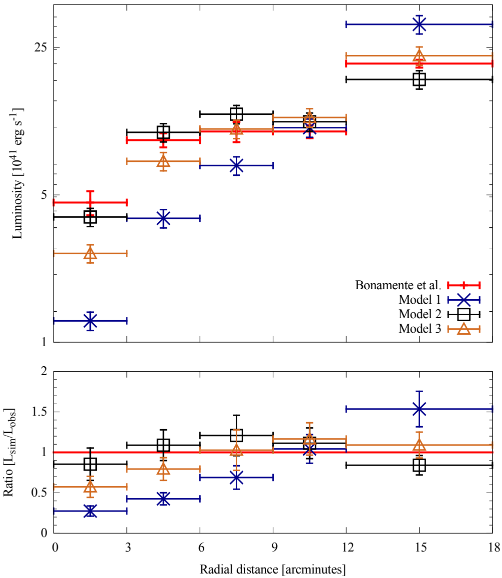
$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta} ,$$

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.

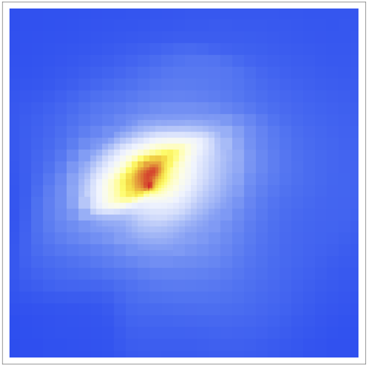
Results for Coma cluster — model comparison



- We simulated axion-photon conversion and compared the obtained luminosity vs radius with a 38-cluster survey (Bonamente et al., 2002).
- We considered 3 models:
  1. Turbulent B-field power spectrum ($n = 17/3$), $L \simeq 10$ kpc, fits RM data.
  2. Artificially tune B coherence $L \simeq 3$ kpc, poor fit to RMs.
  3. Flat power spectrum ($n = 4$), good fit to RM data.
- Matching observed luminosity in the C-band (200–400eV) 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 $\langle L\rangle_{\|} = \langle L\rangle_{\perp}$ for simplicity, but in a more realistic scenario $B_{\|}$ and $B_{\perp}$ may be correlated over different scales.



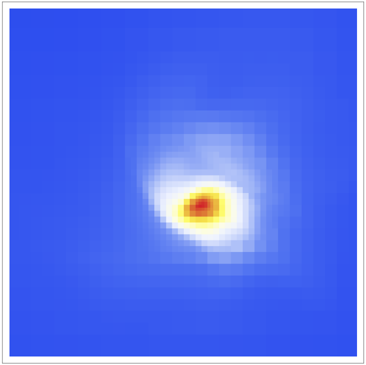
Sample ICM density map.

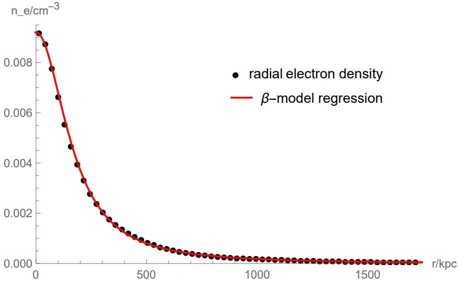
Therefore:

Consider ALP-photon conversion in anisotropic cluster magnetic fields from magnetohydrodynamical simulations. 1612.0xxxx (SA, Shin)

Input data: electron density

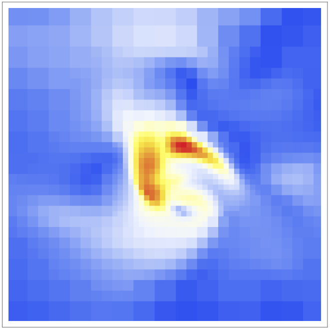
- Input data: ICM densities and magnetic fields for four galaxy clusters that were generated by a magnetohydrodynamical simulation (http://www.horizon-simulation.org/).
- For each cluster, the electron density is a good fit to a β-model; for example, for one cluster:





Best-fit: $n_0 = 9.21 \cdot 10^{-3}\,\mathrm{cm}^{-3}$, $r_c = 180\,\mathrm{kpc}$, and $\beta = 0.75$.

Input data: magnetic fields

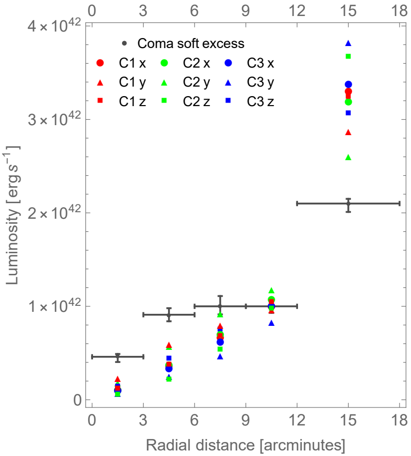


- However, the magnetic field data generally does not follow the "η-model" profile of the Coma cluster ($B \propto n^{\eta}$).
- Typically B is too large away from the center to be a good fit to Faraday RMs. This will be reflected in our results for ALP-photon conversion.

- Additional problem: in the raw simulation data, $B_0 \sim 10^{-11}$ G $\Rightarrow$ need to keep same profile, but scale the overall magnitude.
- This is valid due to the small-θ approximation (recall $\theta \propto B_\perp / M$). Here θ is small before and after (and during) rescaling.
- Furthermore, we already know that the observed B_0 is consistent with the CAB hypothesis! Here we only care about morphology.

Results

Consider ALP propagation through three simulated clusters in various directions — for simplicity, propagate along coordinate axes.



- Observed luminosity in radial annuli along the *x*,*y* and *z* directions (C1 $=$ cluster 1, etc).
- Note: Coma used as benchmark only; NOT directly comparable.

General features:

- excess typically underproduced in center/overproduced in outskirts;
- in each cluster, significant dependence on direction of propagation through the cluster.

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 excess matches data if the magnetic field has more power on smaller scales than suggested by Faraday rotation.

Outlook for CAB conversion in MHD models:

- Simulated electron density provides a good fit to a β-model.
- Simulated magnetic field is large so needs to be rescaled, and it is often dominant on larger scales than supported by observations.
- Luminosity can have significant variance along different directions.
- Further simulations would need to reproduce RM observations in order to test quantitatively whether the tension between the simulated and observed morphology can be resolved.