The Cluster Soft X-ray Excess from a Cosmic Axion Background

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Outline

- Review evidence for galaxy cluster soft X-ray excess
- Motivate a primordially generated axion-like particle background
- Show the soft excess in Coma can be explained by axion-photon conversion in the galaxy cluster magnetic field
- Discuss how conversions can give right morphology
- Compare simulations to observations of 3 more galaxy clusters

arXiv:1312.3947 [astro-ph.HE]
with Stephen Angus, Joseph P Conlon, MC David Marsh, Lukas T Witkowski

Cluster Soft Excess

- Hot intra-cluster medium emits thermally in hard X-rays via bremsstrahlung radiation.

- Intra-cluster medium: ionised gas thus hard X-ray regime contains many emission lines

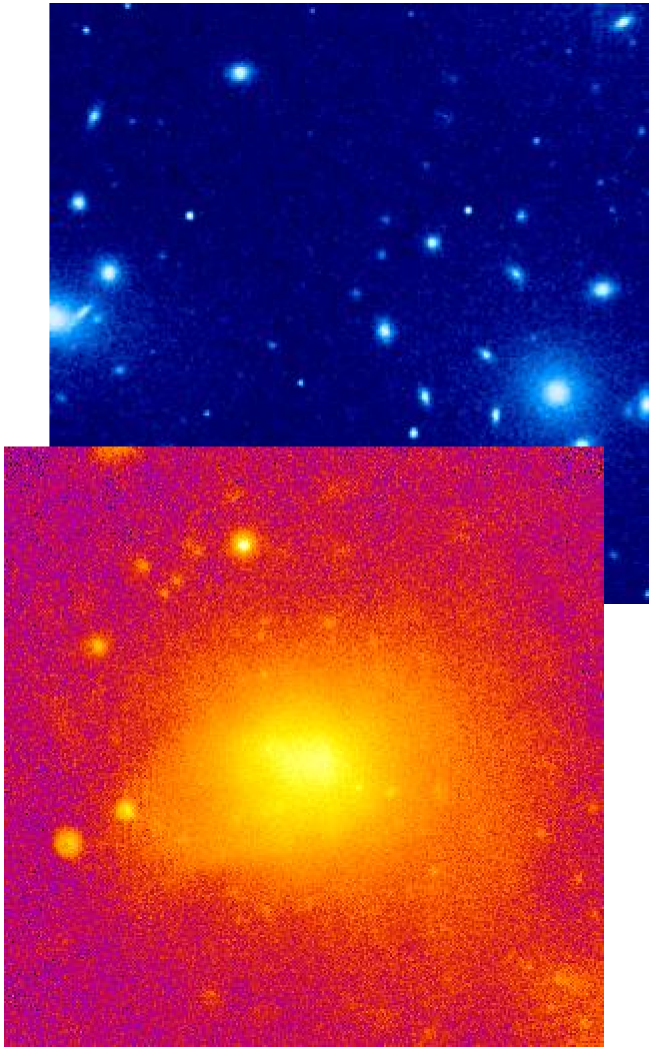
- Excess in the soft X-ray window ~0.2 keV seen in large number of galaxy clusters over the bremsstrahlung background

- Seen with EUVE, ROSAT satellites.

- Spectral resolution of above satellites poor at 0.2 keV.

- Observations with XMM-Newton inconclusive (better energy resolution, poorer background subtraction)

→ Could be thermal or non-thermal

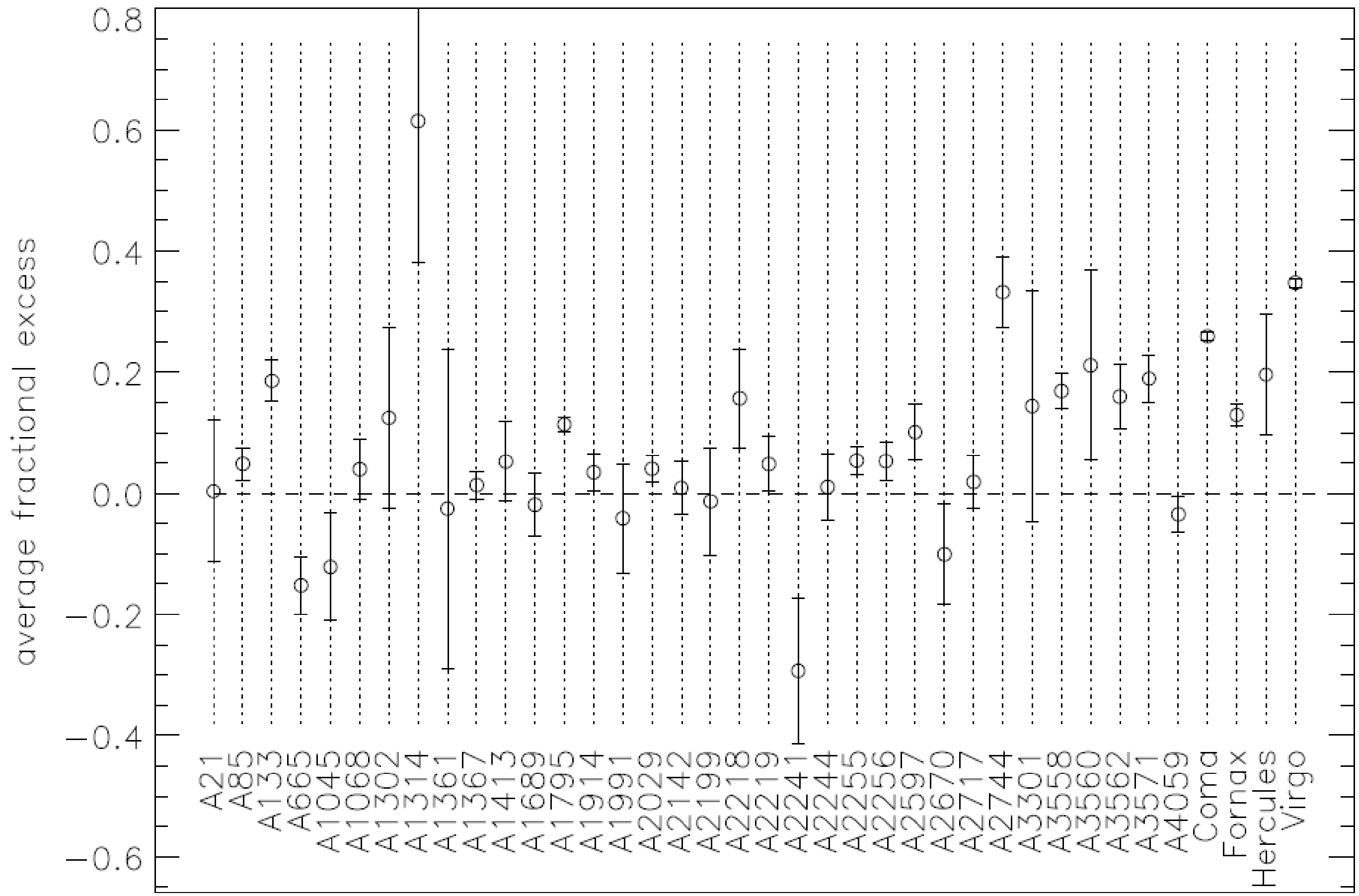


Observations

- Seen in ~30% of clusters in 38 cluster sample of Bonamente et al. (2002).
- Looked in 0.2-0.4 keV band
- Very high statistical significance in 5 clusters:

  Coma, Virgo, Fornax,
  A3558, A1795

- Excess seen preferentially at large radii



Bonamente et al., ApJ 576, 2002

Observations Summary

- Excess seen in 1/3 of galaxy clusters
- Observed in 0.2-0.4 keV “soft X-ray” band
- Seen with 2 satellites
- Little spectral information
- Review: Durret et al. (2008) 0801.0977 [astro-ph]

Cosmic Axion Background I

- String theory predicts many axion-like particles (ALPs, axions)
- Inflation displaces moduli and they oscillate around minimum as non-rel. matter.
  => moduli will dominate the energy density of universe after inflaton has decayed to rel. particles.
- Decay rates $\Gamma \propto \frac{m^3}{M_{Pl}^2}$ so lightest modulus will dominate the universe last, its decays reheat the SM
- Decays of modulus to light axions
  => rel. Cosmic ALP/Axion Background (CAB)

$$\rho_{\rm rad} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right)$$

- Contribute to dark radiation, of which there are hints

Planck: $N_{\rm eff} = 3.30 \pm 0.27$,
Planck + H_0: $N_{\rm eff} = 3.62 \pm 0.25$, arXiv:1303.5076 [astro-ph.CO]

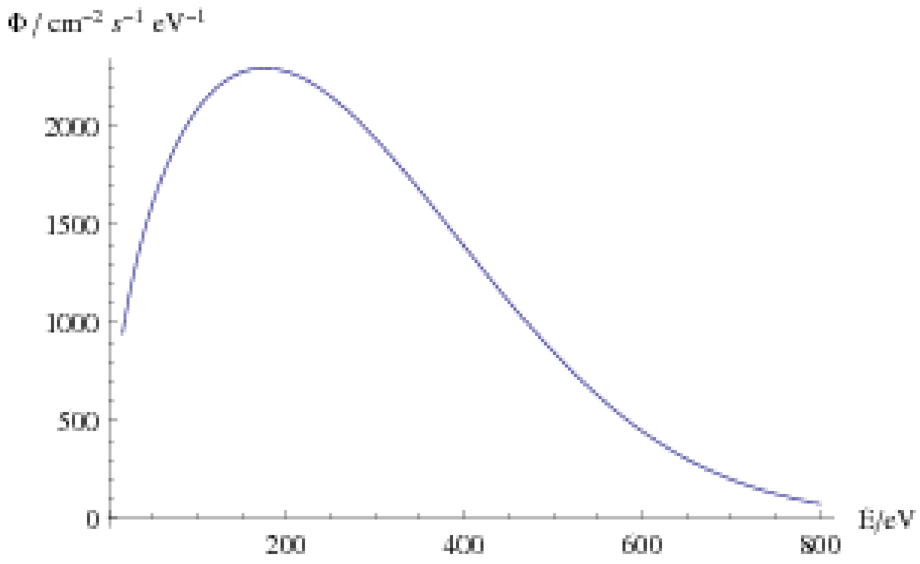
Cosmic Axion Background II

- Decay of modulus produces relativistic axions non-thermally $E_a = m_\Phi / 2$
- Axions do not thermalise and redshift as radiation to present day as isotropic and homogeneous CAB
- Energy is set as

$$\frac{E_{a,\rm now}}{T_{\gamma,\rm now}} \simeq \frac{E_{a,\rm init}}{T_{\gamma,\rm init}} \sim \left(\frac{M_{\rm P}}{m_\Phi}\right)^{1/2}$$

~EUV/Soft X-ray band for

$$m_\Phi \sim 10^6 \text{ GeV}$$



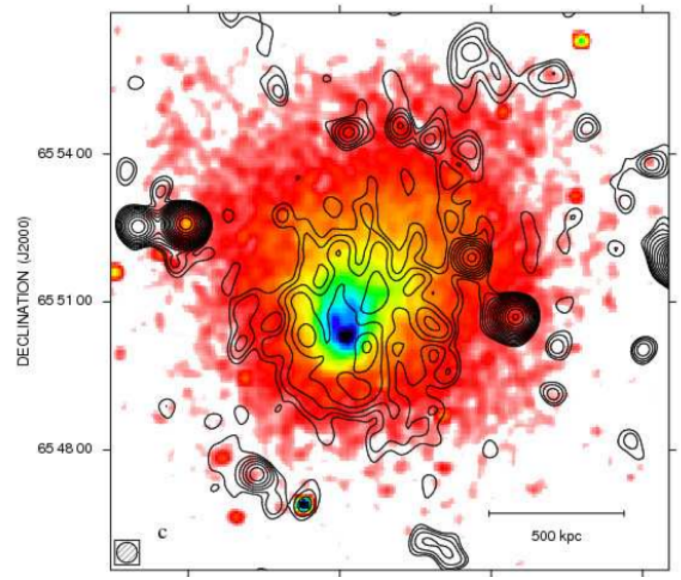
Conlon and Marsh:1304.1804

- CAB energy unknown parameter

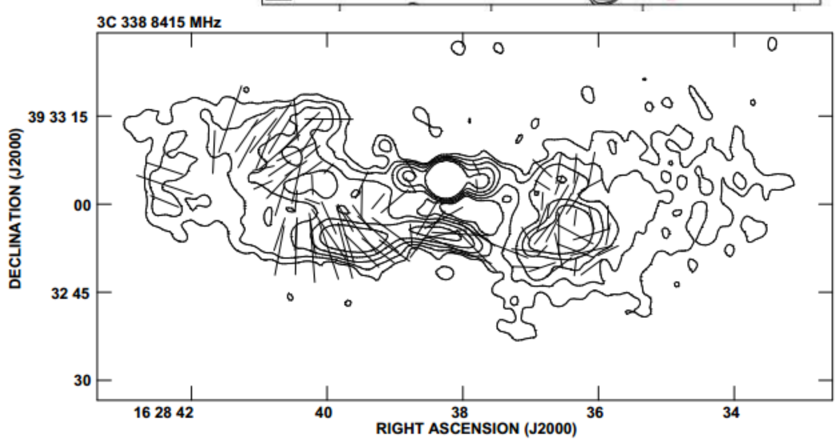
Axion-Photon Conversion

- Axion-photon conversion via lagrangian: $$\mathcal{L} \supset \frac{1}{8M} a F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{1}{M} a \vec{E} \cdot \vec{B}$$
- Most stringent bounds on M for massless ALPS from SN1987a γ ray burst $$M > 1 \times 10^{11} \text{ GeV}$$ Brockway, Carlson, Raffelt (1996) Grifols, Masso, Toldra (1996)
- Probability to convert over one domain is $$P(a \to \gamma) = \sin^2 2\theta \ \sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$
- With: $\theta \sim \frac{B_\perp \omega}{M n_e}$, $\Delta \sim \frac{n_e L}{\omega}$
- Where we set $m_a = 0$, but holds for $$m_a \ll \omega_{pl} = \sqrt{\frac{4\pi n_e e^2}{m_e}} \approx 10^{-12} \text{ eV}$$

Magnetic Fields in Clusters



- Field observations
  - synchrotron radio emission
  - Faraday rotation



- Constrain magnetic field by making various model assumptions

  => equipartition
  => faraday rot. with fixed magnetic field cells
  => gaussian random field

Murgia et al. (2004)
Govoni et al. (2006)
Bonafede et al. (2010)
Vacca et al.(2010)
Vacca et al. (2012)

Typical fields **1-5 μG** (10-25 μG for cool core) coherent over lengths **1-100 kpc**

Luminosity

- Probability to convert over one domain is

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

- With: $\theta \sim \dfrac{B_\perp \omega}{M n_e}$, $\Delta \sim \dfrac{n_e L}{\omega}$

- "Small angle approximation":

$$P(a \to \gamma) = \frac{1}{4} \left(\frac{BL}{M} \right)^2$$

- Over 1 Mpc of cluster:

$$P(a \to \gamma) = 9.3 \times 10^{-4} \left(\frac{B}{2\ \mu\mathrm{G}} \frac{10^{13}\ \mathrm{GeV}}{M} \right)^2 \left(\frac{L}{10\ \mathrm{kpc}} \right)$$

- Corresponding Luminosity comparable to soft excess in Coma

$$\mathcal{L} \sim 10^{42} - 10^{43}\ \mathrm{erg\ s^{-1}}$$

Morphology

- Two regimes ($\theta \sim \frac{B_\perp \omega}{M n_e}$ always small)

$$\Delta \sim \frac{n_e L}{\omega}$$

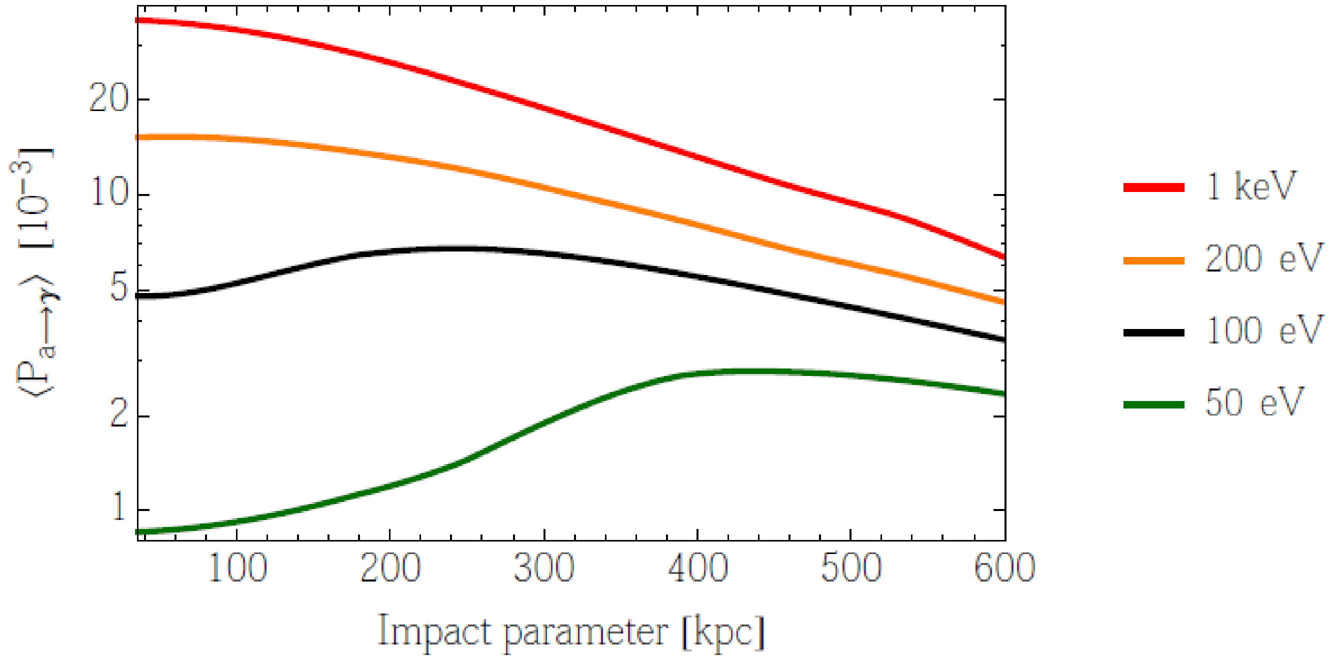
Large Δ: $$P \sim \frac{\omega^2}{M^2}\left(\frac{B_\perp(r)}{n_e(r)}\right)^2$$

Small Δ: $$P \sim \frac{L^2}{M^2} B_\perp(r)^2$$

- n_e decreasing function of radius => Δ will always become small at some radius

- Point at which Δ become small:

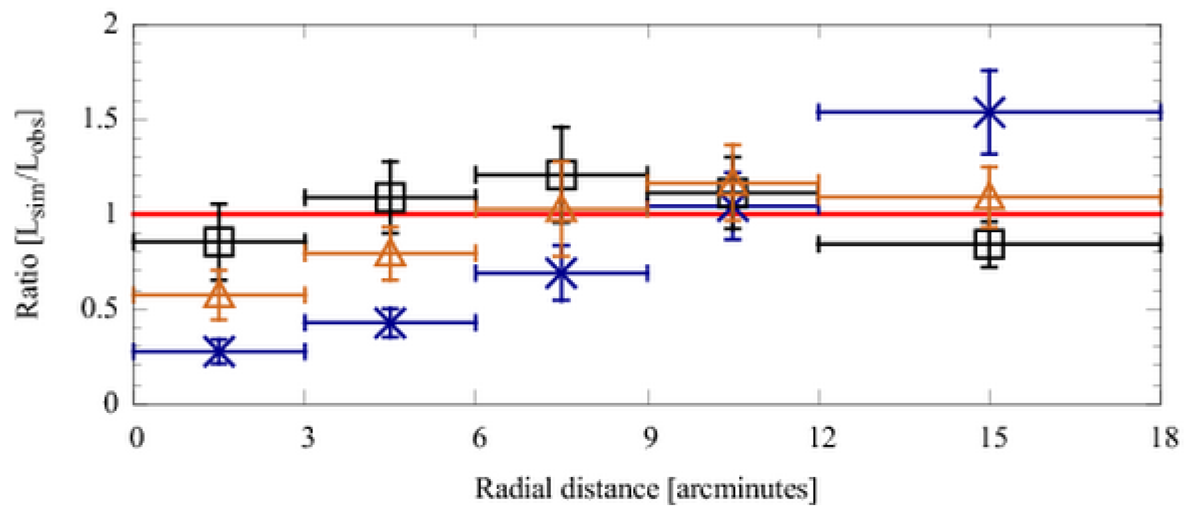
  function of axion energy and coherence lengths L



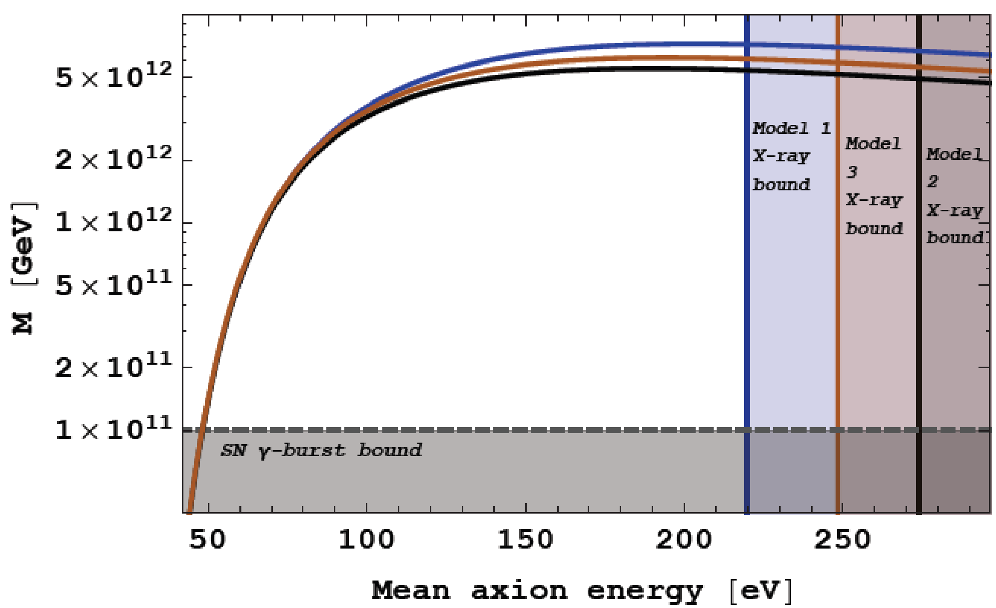
Recap

- Soft Excess in 1/3 of galaxy clusters in 200-400 eV region.
- Cosmic Axion Background formed by decays of scalar field into massless axions
- For scalar masses $m_\Phi \sim 10^6\ \mathrm{GeV}$, axions have energy ~200 eV
- Axion/photon conversion in cluster magnetic field can explain excess
- Morphology and size will vary from cluster to cluster depending on details of magnetic field
- Study individual clusters to explain observed/lack of soft excess

Results - Coma



- Degeneracies/uncertainties on field model
- Luminosites dependent on ΔN_{eff} set to 0.5 here



- Axion energy unknown
- Bounded such that it does not overproduce higher energy > 400 eV photons

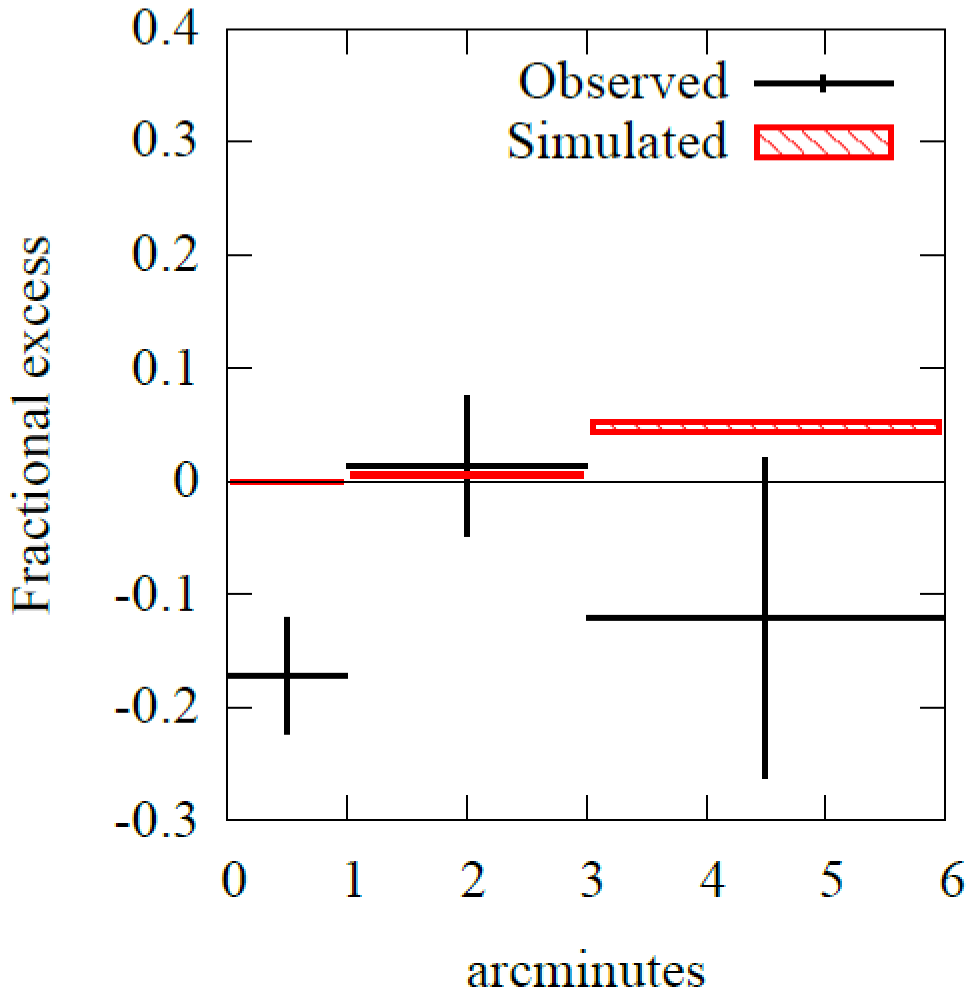
Angus, Conlon, Marsh, AP, Witkowski
arXiv:1312.3947

Results – A665

PRELIMINARY

- Soft excess not observed in A665.
- Consistent with our simulations for

$$M \gtrsim 10^{12}\ \mathrm{GeV}$$

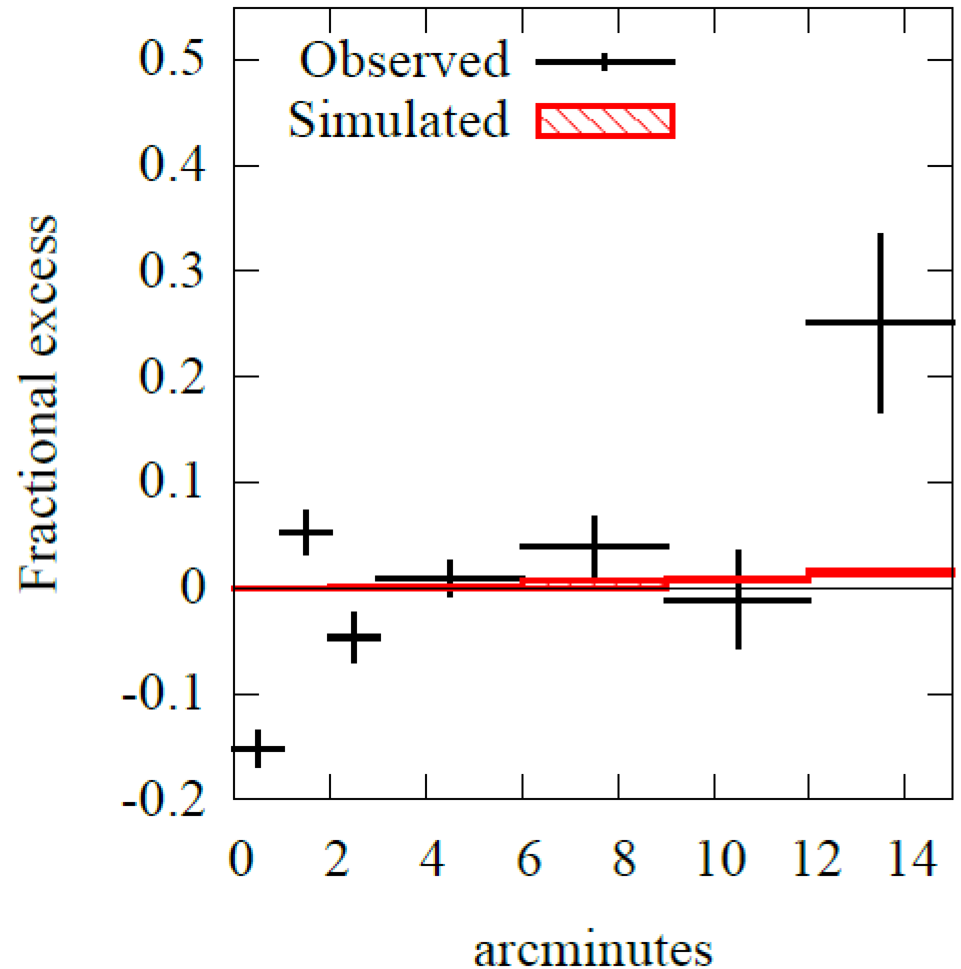


Results – A2199

PRELIMINARY

- Limited evidence for soft excess in A2199
- Simulation predicts no observable soft excess for

$$M > 2 \times 10^{12}\ \text{GeV}$$

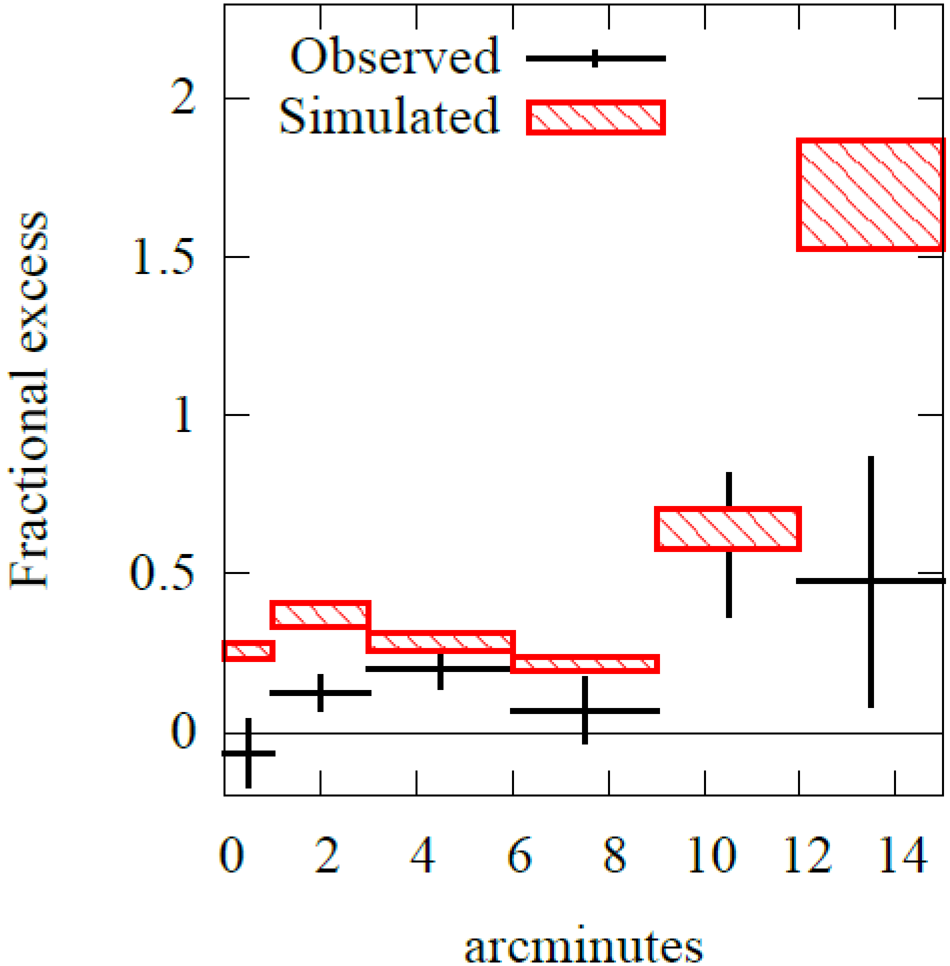


Results – A2255

PRELIMINARY

- Evidence for soft excess as low radii
- Large radii has low Signal to background thus excess uncertain
- Can easily produce excess at low radii for

$$M \sim 7 \times 10^{12}\ \mathrm{GeV}$$



Summary

- A soft X-ray excess has been observed in a 1/3 of clusters in 200-400 eV channel

- A Cosmic Axion Background is a generic prediction of string theory

- Conversion of CAB can easily reproduce excess in Coma, with correct morphology

- Region to fit the Coma excess overlaps with hints from γ-ray transparency of universe and some of space will be probed by IAXO

- Simulations consistent with observations of A665, A2199 and A2255.

- To do: larger statistical study of galaxy clusters?
  more realistic magnetic field model?

Explanations

- **Warm ICM Component:** Soft excess is the thermal emission of a second, colder component to the intra-cluster gas

  Problem: 1) ideal gas law => higher electron densities in cool gas
  => larger cooling rates

  $$\tau_{cooling} \sim 6 \times 10^9 \left(\frac{10^{-3}\ \mathrm{cm}^{-3}}{n_{gas}} \right)\ \mathrm{years}$$

  2) no lines detected in excess

- **WHIM:** Warm gas at outskirts of cluster
  Simulations predict most of baryons in filamentary warm-hot intergalactic medium
  => thermal emission produces soft excess

  Problem: emission too faint?

- **Inverse Compton Scattering:** Relativistic electrons off CMB
  Rel. electrons known to exist due to radio synchrotron emission in magnetic fields from clusters

  Problem: 1) can't explain both with same electrons, B fields too large
  2) lack of associated gamma emission from relativistic protons etc

Magnetic Field Model

- Magnetic field model of Murgia et al., A&A**424** (2004)

- Simulate stochastic, multi-scale, gaussian random field, with power spectrum

$$|B_k|^2 \sim k^{-n+2}$$

- Limit modes to $\frac{2\pi}{\Lambda_{max}} \leq k \leq \frac{2\pi}{\Lambda_{min}}$

- Modulate field such that $B(r) = B_0 \left(\frac{n_e(r)}{n_0} \right)^\eta$

- Parameters have been constrained by fitting to Faraday rot. maps or radio halo images

- Field produced on large 2000^3 grid, axion-photon wavefunction numerically 'propagated' from one grid point to next.