The Cluster Soft Excess

A *possible* reservoir of baryons (and maybe dark matter) at the outskirts of galaxy clusters

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Outline

1) A brief history of the Cluster Soft Excess.

2) The outstanding case of the Coma cluster.

3) Thermal and non-thermal interpretations of the soft excess, including possible dark matter implications.

4) The future of the cluster soft excess with ASTRO-H.

1) A brief history of the Cluster Soft Excess

- Best history of the soft excess is in Angus et al. (2014)

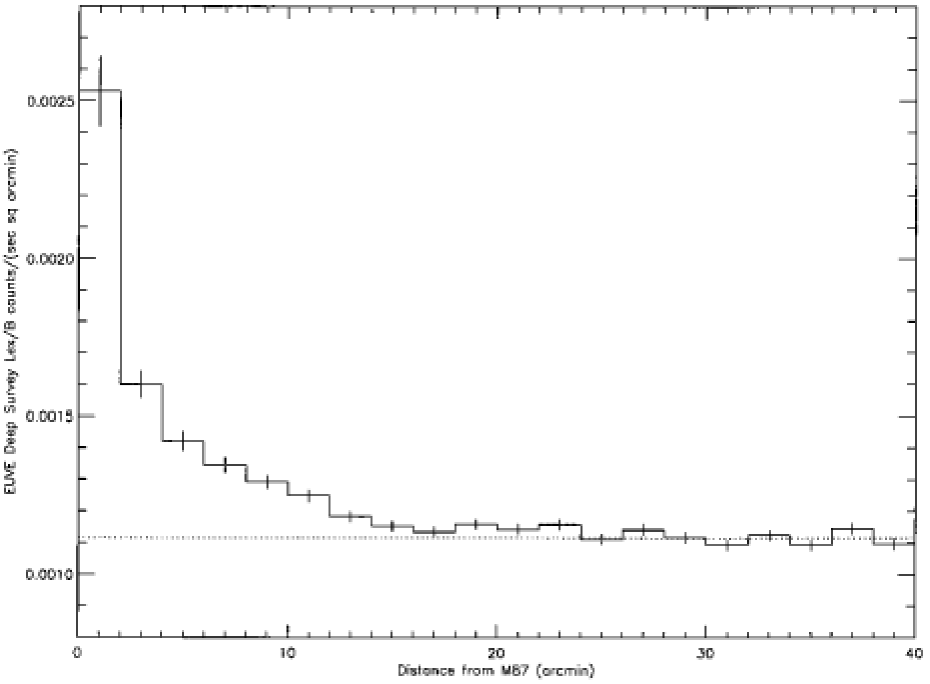


FIG. 1.—*EUVE* DS Lex/B filter count rates for concentric annuli centered at M87. Data from the innermost 2′ region are consistent with a point source. The region between 2′ and ~20′ corresponds to a diffuse excess (the EUV halo of M87). The background level is marked by a dotted line.

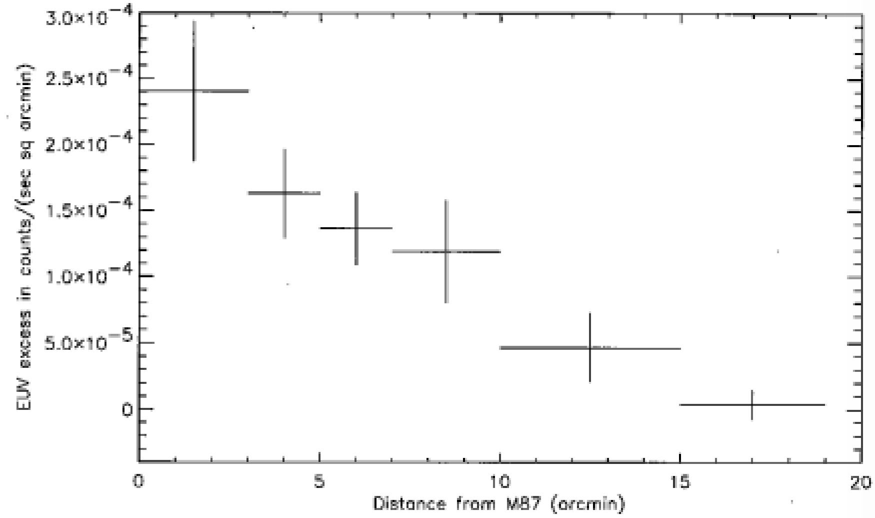


FIG. 3.—Radial profile of the surface brightness of "EUV excess," defined as the amount of diffuse emission within the DS Lex/B band above the best-fit single-temperature plasma model obtained by simultaneously fitting the DS data and the 0.18–2 keV PSPC data.

- Early detections of excess EUV radiation from Virgo and Coma clusters with the EUVE DS photometer (Lieu et al. 1996A, Lieu et al. 1996B, Bowyer et al. 1996)

- Much controversy about these detections:

  1. Background subtraction: issue resolved with in-situ measurements at short offset from the clusters (Bowyer et al. 1999; Bonamente et al. 2001)

  2. Use of accurate HI Galactic column densities (e.g., Arabadjis and Bregman 1999)

  3. Use of accurate He cross sections. He is the main absorber of ¼ keV photons, and there is a long history of revisions of those cross-sections. Most accurate measurements by Wilms, Allen and McCrary (2000) and Yan et al. (1998) confirm the Morrison & McCammon (1983, WABS) cross-sections, while Baluchinska-Church & McCammon (1992, PHABS) has higher He cross-sections.

- Ultimately the EUVE excesses were confirmed in a number of clusters, including Coma.

- Many detections with ROSAT, which is still to date the most suitable data to look for soft excess because of low background and wide field of view (e.g., Bonamente et al. 2002, 2003).

- Several detections with XMM, Suzaku and BeppoSAX (Nevalainen et al. 2003, 2007, Kaastra et al. 2003, Finoguenov et al. 2003, Werner et al. 2007, Kawaharada et al. 2010; but see Takei et al. 2008, Bregman et al. 2003)

2) The outstanding case of the Coma cluster

- In Bonamente et al. (2003) we have analyzed several pointed ROSAT observations of the Coma cluster, including in situ background

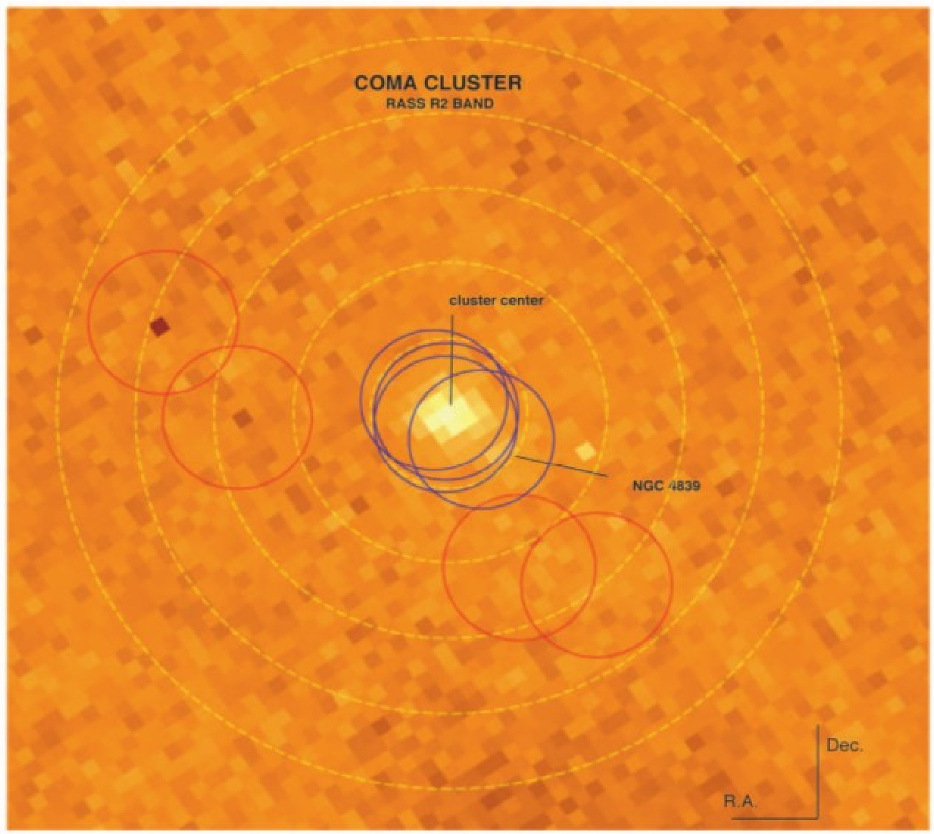


FIG. 2.—Location of *ROSAT* PSPC observations, overlaid on an RASS R2 band (0.15–0.3 keV) image of the diffuse emission of the Coma region. Dashed circles indicate distance from the cluster's center in intervals of 1°, blue circles represent the position of the pointed PSPC observations of Coma Cluster, and red circles are background observations.

- Strong soft excess emission detected out to 1.5 degrees, or 2.6 Mpc (Ho=72 km/s/Mpc)
- It is not possible to explain the emission with variation of Galactic HI column density absorption
- Thermal model for the excess emission emission (kT=0.2 keV plasma) preferred over non-thermal (power-law) model

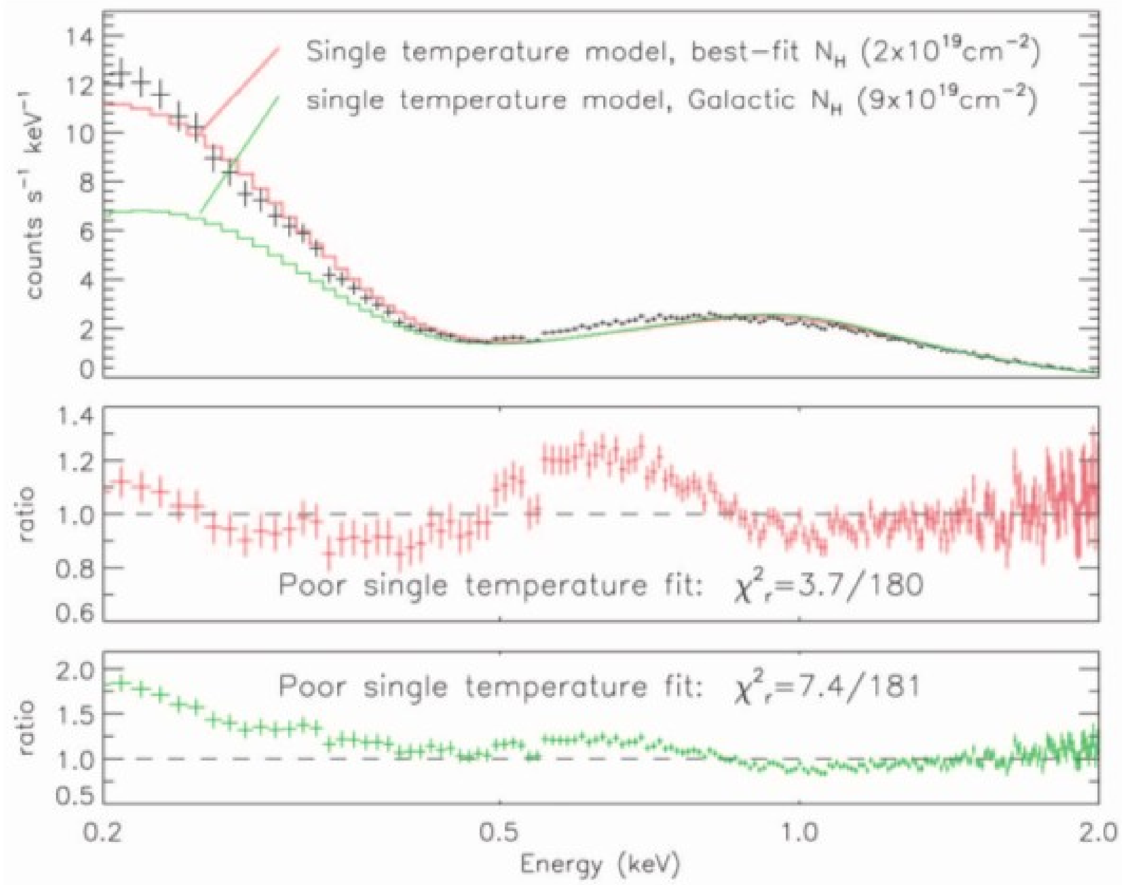


FIG. 4.—*ROSAT* PSPC spectrum of the 20′–40′ region around the center of the Coma Cluster, fitted to a single-temperature model with variable N_H (*red*) and with Galactic N_H (*green*).

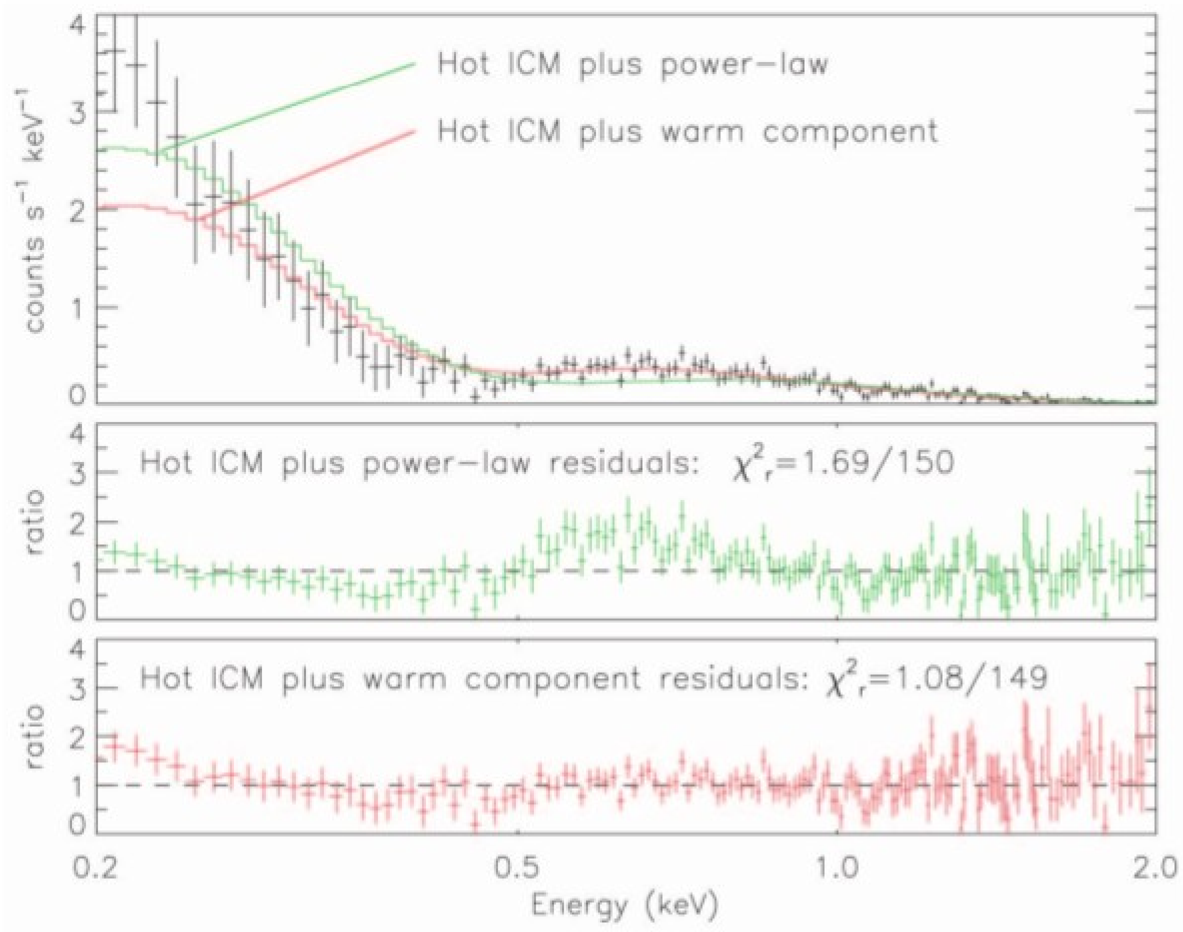


FIG. 6.—*ROSAT* PSPC spectrum of the 55′–70′ northeastern quadrant. In green is the hot ICM plus power-law model (§ 4.4), in red the hot ICM model plus a low-energy thermal component (§ 4.5).

- Mass budget depends on the geometry of the emitting gas
  - If the gas is within the volume of the cluster, Mwarm/Mhot=0.75
  - If the gas is in filaments with density 1e-4 cm-3, then Mwarm/Mhot=3!!

- It is necessary to point out that no current instrument has reliably detected emission lines from warm gas in Coma (or any other cluster):

  - The ROSAT PSPC camera does not have sufficient spectral resolution.
  - The XMM spectrometer has better resolution, and Kaastra et al. (2003, see Figure) had a tentative detection of OVII emission lines in a few clusters.
  - These lines were not confirmed by Suzaku (Werner 2007, Takei 2008).

- The ROSAT data prefer a 0.2 keV model for the soft excess with a 1-10 % Solar abundance of heavy elements.

There are strong azimuthal variations in the amount of soft excess emission.

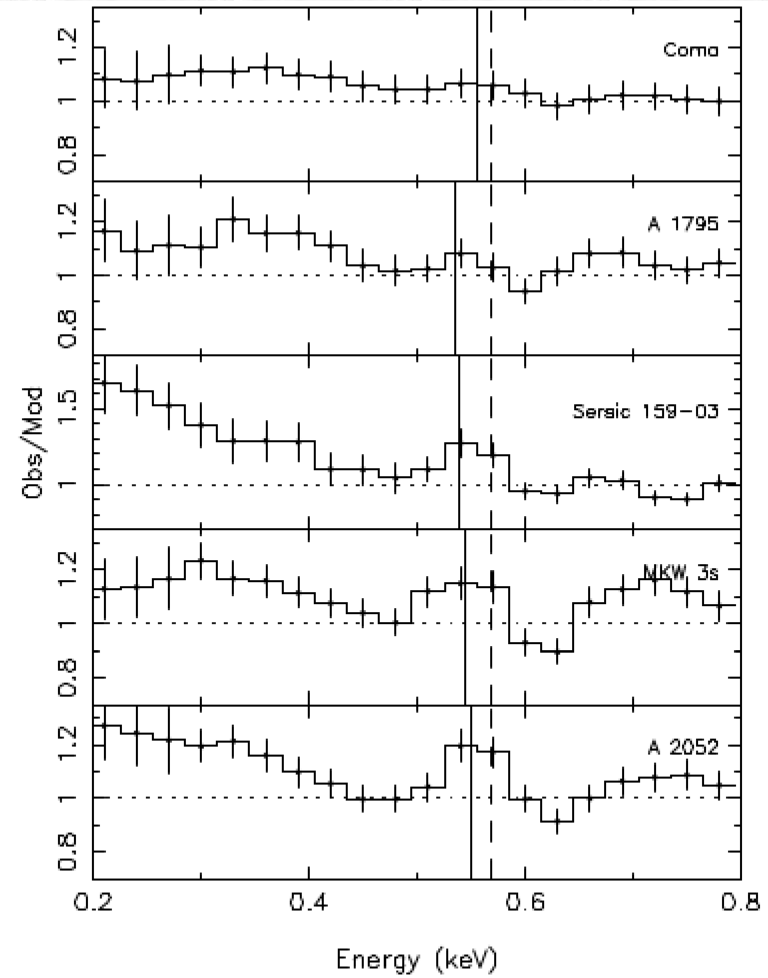


Fig. 6. Fit residuals with respect to the two temperature model for the outer 4–12′ part of five clusters. We have included the systematic background error in the fit, but have excluded it in this plot. We indicate in each panel the position of the O vii triplet in the cluster rest-frame by a solid line and in our Galaxy's rest frame by a dashed line at 0.569 keV (21.80 Å). The fit residuals for all instruments (MOS, pn) are combined. The instrumental resolution at 0.5 keV is ~60 eV (*FWHM*). A similar plot but now for the 0.5–4.0′ range is shown as Fig. 7.

- Further proof of the soft excess in Coma is provided by the ROSAT All-Sky Survey data analyzed by Bonamente et al. (2009).
- The1/4 keV R2 band has a much more extended radial profile of the surface brightness than the harder R7 band.

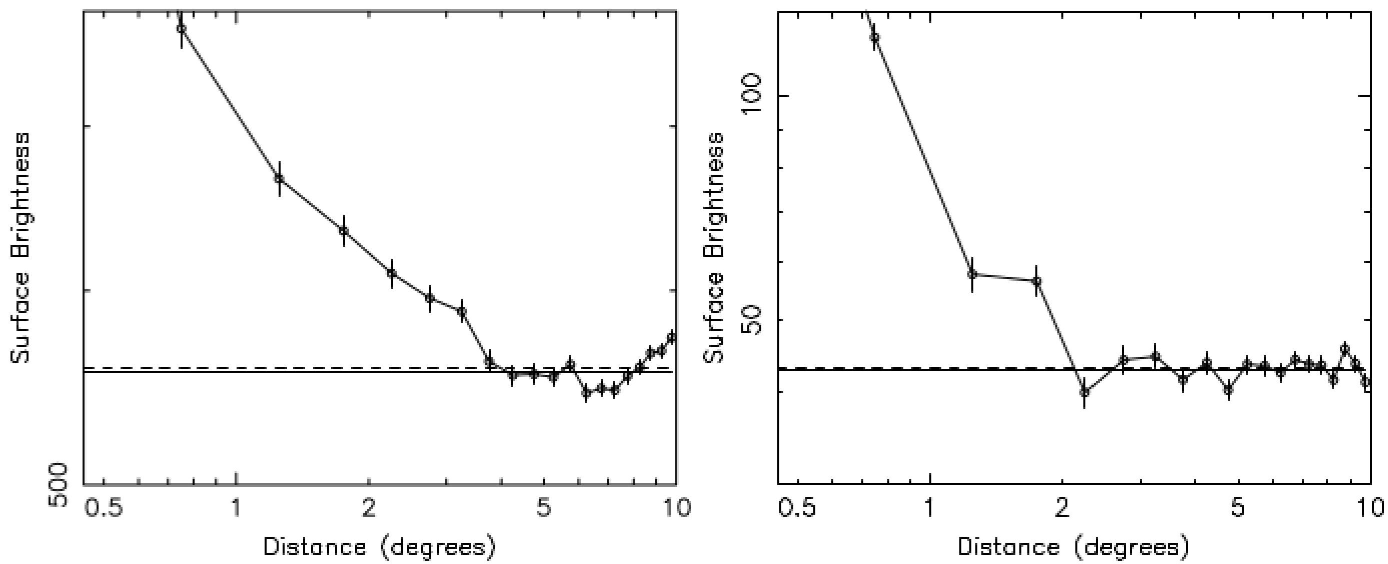


Figure 2. Radial profiles of the diffuse emission near Coma in R2 (*a*) and R7 band (*b*). Units of the surface brightness are 10^{-6} PSPC counts s^{-1} $arcmin^{-2}$.

3) Thermal and non-thermal interpretation of the soft excess

- Thermal interpretation of soft excess by sub-virial gas may follow different scenarios:

1. Diffuse warm gas in contact with hot ICM gas. Issues for its feasibility are the <u>thermal conductivity</u> (which depends on B fields) and <u>pressure balance</u>. It is unlikely that pressure imbalance can be kept beyond a sound-crossing time, which is a fraction of the Hubble time in clusters.
2. <u>High-density, low entropy warm gas 'clumps'</u>, as successfully proposed by Cheng et al. (2005) using numerical simulations. This scenario can reproduce the typical soft excess in many clusters from Bonamente et al. (2002)

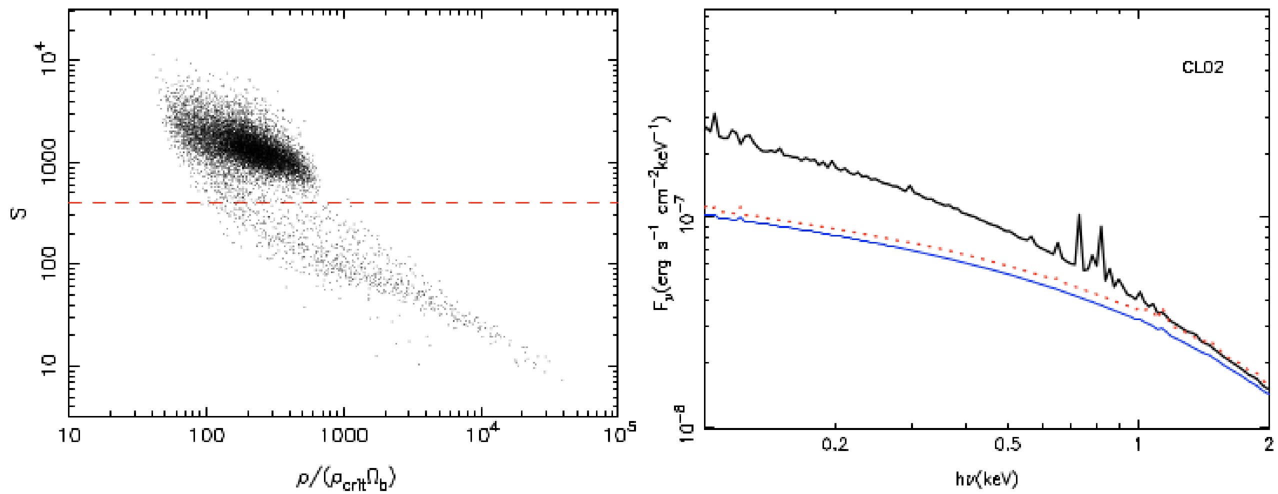


Fig. 4. Tracing the gas particles responsible for the soft excess in the CL02 cluster. *Left panel*: the phase diagram shows entropy vs. density for the gas particles at a projected distance from the cluster center $0.4 < R/R_{vir} < 0.7$. *Right panel*: the synthetic spectrum of CL02 (thick line) compared with that expected from the hot ICM one (dotted curve) and with the synthetic one obtained by excluding from the computations all the gas particles with entropy $S < 400$ keV cm^2 (horizontal dashed line in the left panel).

3. Diffuse WHIM-type gas that may be accreting from cosmological filaments, as in the Cen & Ostriker (1998) model. Thi scenario was tested by Mittaz et al. (2004), and found that typical WHIM filaments don't have enough density to produce the observed emission.
4. Electrons and ions may not in thermal equilibrium near the virial accretion shock region, as proposed by Prokhorov (2008). Protons are hotter because they are heated more efficiently by the shock (carry the bulk of kinetic energy), and electrons are colder. These cooler electrons in a shell around the virial radius can give rise to EUV radiation

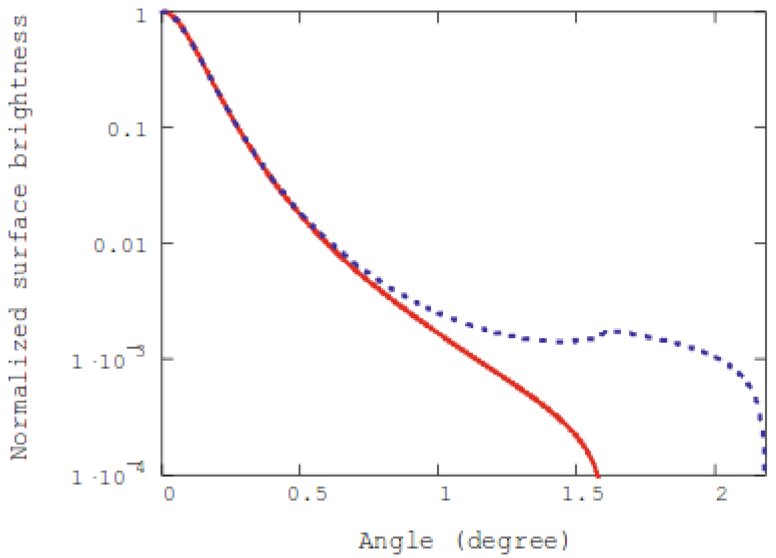


Fig. 4. Normalized surface brightness for the Coma cluster: the hot gas (solid line), the hot gas + the baryonic shell (dashed line).

- Non-thermal interpretations:

  1. Inverse Compton scattering of CMB radiation off of relativistic electrons (Lorentz factor of few 100) in clusters, as proposed by Sarazin & Lieu (1998).These particles survive IC losses for approximately a Hubble time, and have ~10% of the energy of the hot ICM.

  2. Possible connection with the hard excess (i.e., Fusco-Femiano et al. 1999), which would be generated by much more energetic relativistic electrons.

$$\frac{E_{\rm CR}}{E_{\rm gas}} = 0.085 \left(\frac{L_{\rm EUV}}{10^{45}\ {\rm ergs\ s^{-1}}}\right)\left(\frac{\langle\gamma\rangle}{300}\right)^{-1} \times \left(\frac{M_{\rm gas}}{10^{14}\ M_\odot}\right)^{-1}\left(\frac{T}{7\times 10^{7}\ {\rm K}}\right)^{-1}$$

$$t_{\rm IC} = \frac{\gamma m_e c^2}{\frac{4}{3}\sigma_{\rm T} c \gamma^2 U_{\rm CMB}} = 7.7\times 10^{9}\left(\frac{\gamma}{300}\right)^{-1}\ {\rm yr.}$$

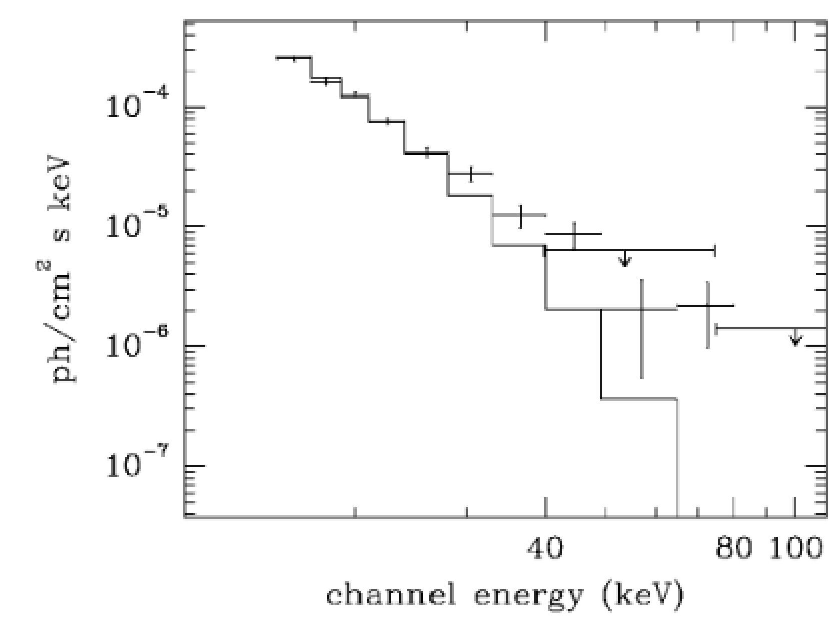


FIG. 1.—PDS data. The continuous line represents the best fit with a thermal component at the average cluster gas temperature of 8.21 keV (Hughes et al. 1993). The upper limits refer to the OSSE experiment (Rephaeli et al. 1994).

3. <u>Conversion of Axions into EUV/Soft X-ray photons</u>. Much attention has been devoted to the association of the soft excess with the conversion of a cosmic axion background (CAB) into EUV photons via magnetic field coupling (Conlon et al. 2013, Angus et al. 2014, Kraljiic et al. 2015, Powell et al. 2015, Carvajial et al. 2015). Predictions of the theory are:

- Soft excess depends on the configuration of the magnetic field;
- Soft excess is independent of the temperature and mass of the hot gas in clusters.

Angus et al. (2014) have performed complex simulations of the conversion of CAB into soft photons, which easily reproduce the observed Coma excess

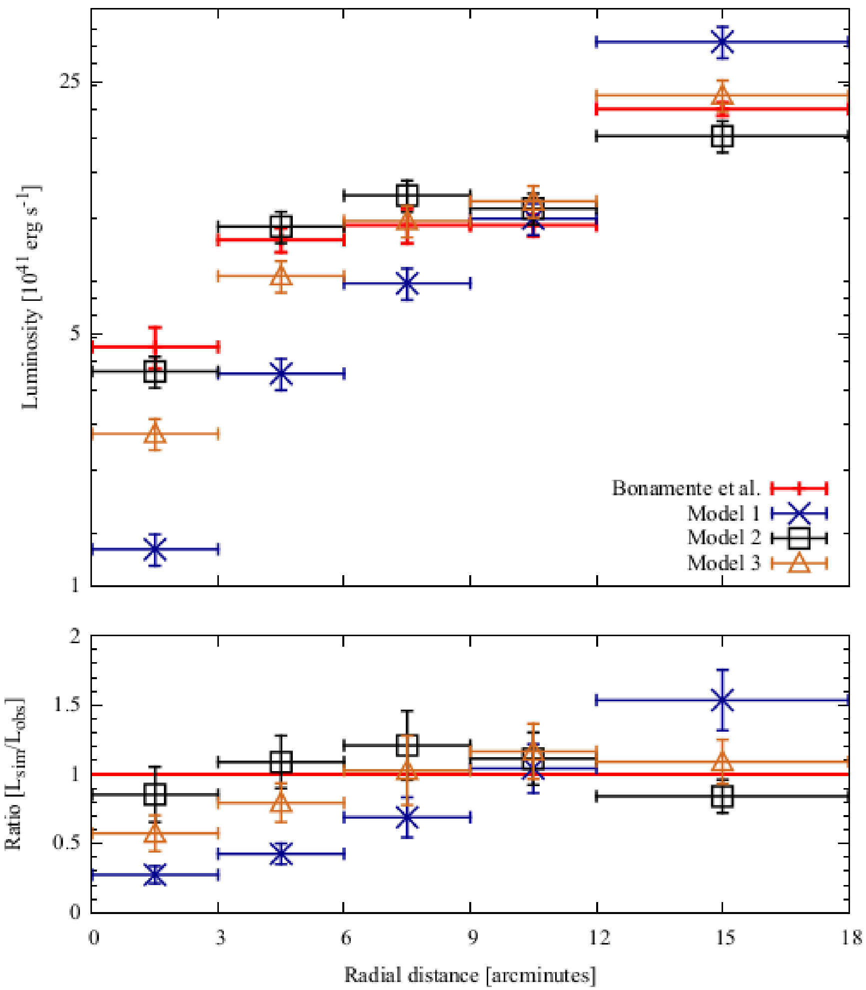


Figure 9. Luminosity comparison for the different models compared to the 'thermal' excess data. For $\Delta N_{eff} = 0.5$ and $\langle E_{CAB} \rangle = 150$ eV, normalisation of the integrated luminosities gives $M = 6.5 \times 10^{12}$, 5.2×10^{12} and 5.7×10^{12} GeV for Models 1 ($\eta = 0.7$), 2, and 3 respectively.

4) The future of the soft excess with Astro-H

- To date there is no conclusive evidence on the nature of the soft excess.

- Major advances will be made by Astro-H, with its non-dispersive soft X-ray spectrometer (SXS) with micro-calorimeter detectors. Main features:

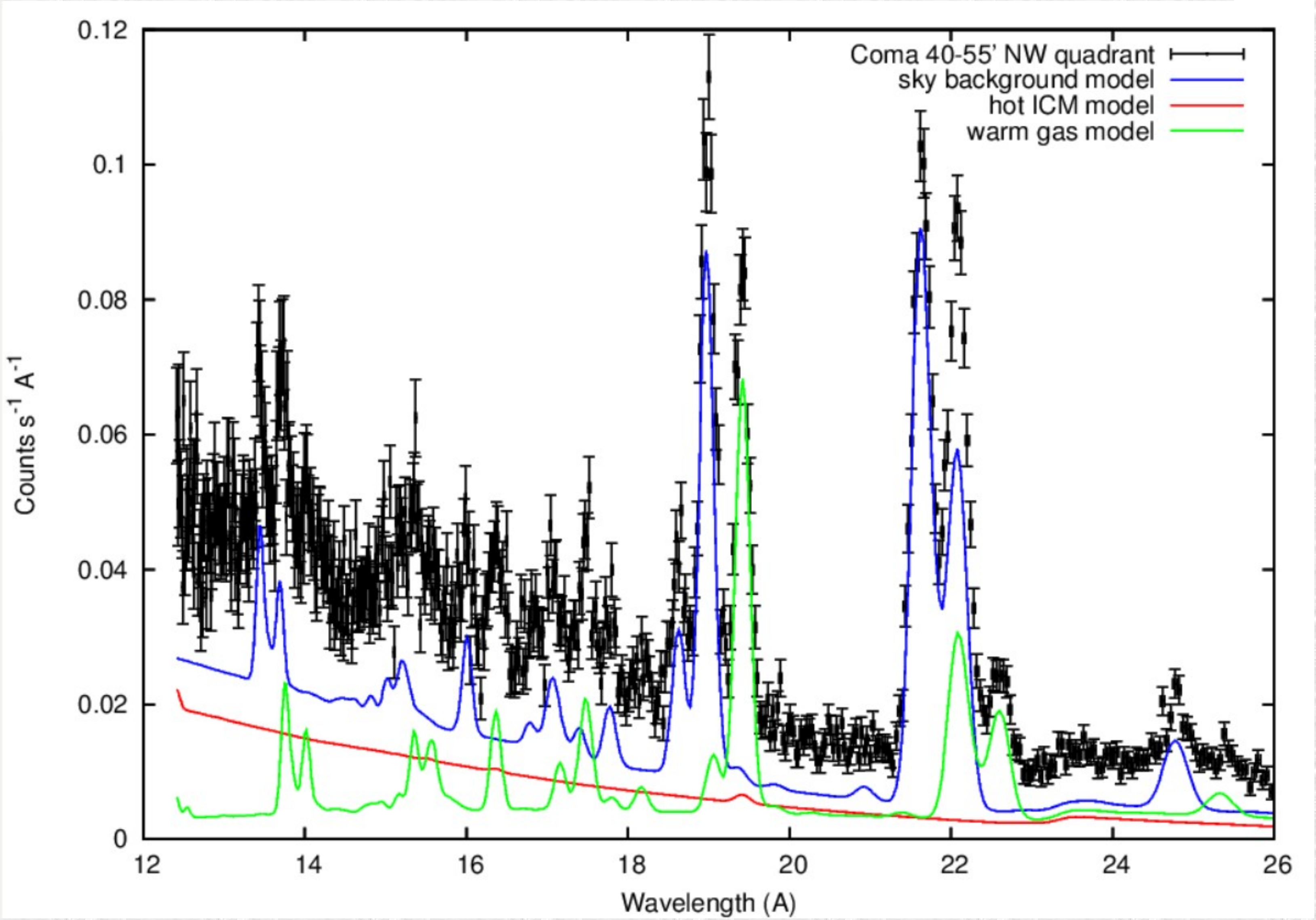
  - 5-7 eV resolution at 0.3-12 keV
  - 0.5 arcmin angular resolution
  - 2.85x2.85 sq. arcmin field of view (small, compared to ROSAT and other instruments)
  - Effective area at 1 keV of 200 cm^2
  - “Low” background (Suzaku-type) compared to XMM or Chandra.

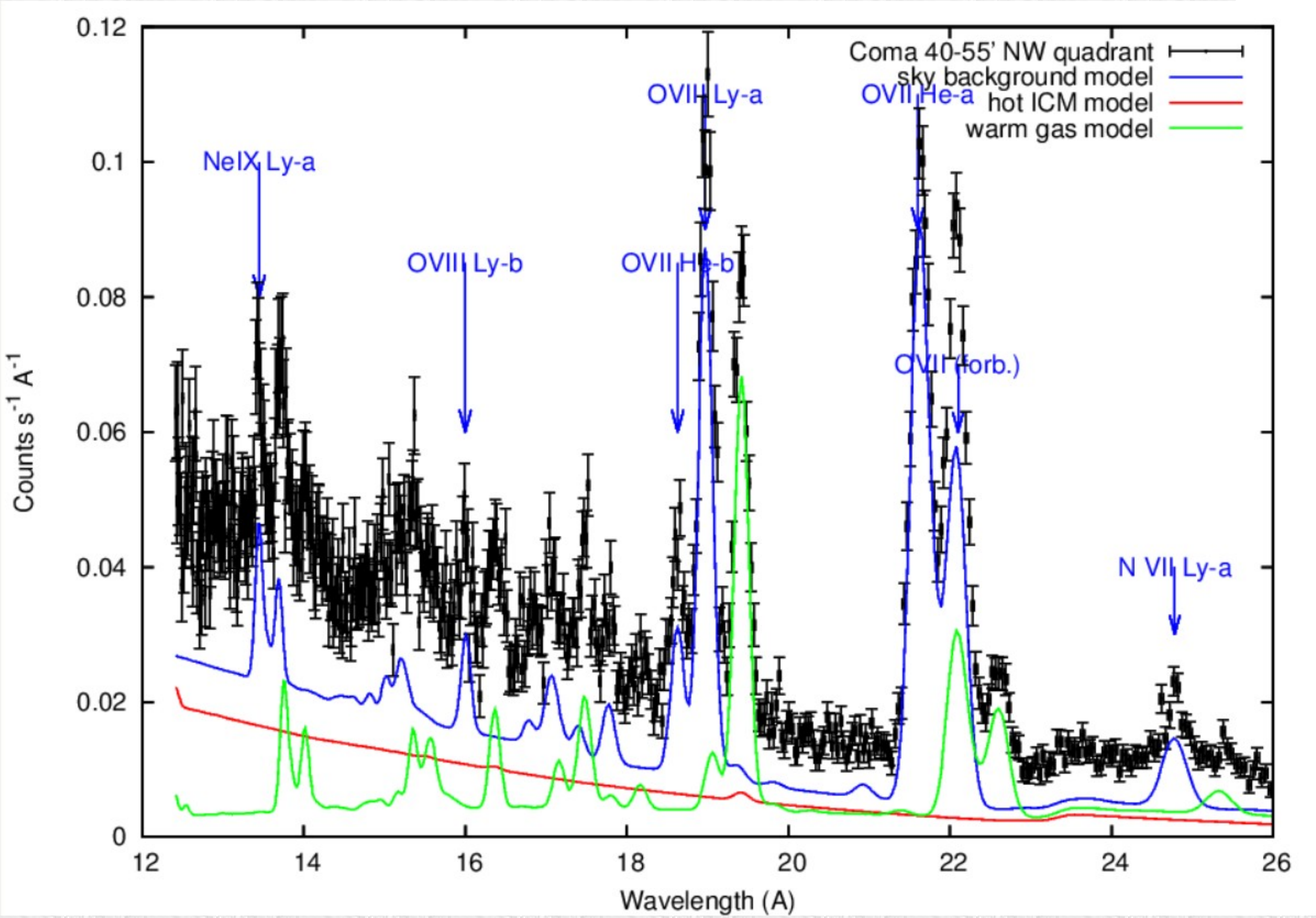
- We performed a 100 ks simulation of the soft excess with Coma in NW quadrant of the 40-55 arcmin annulus, from Bonamente et al. (2003):

  - 0.2 keV emitting gas
  - A=0.03 (3% Solar) abundance of heavy elements

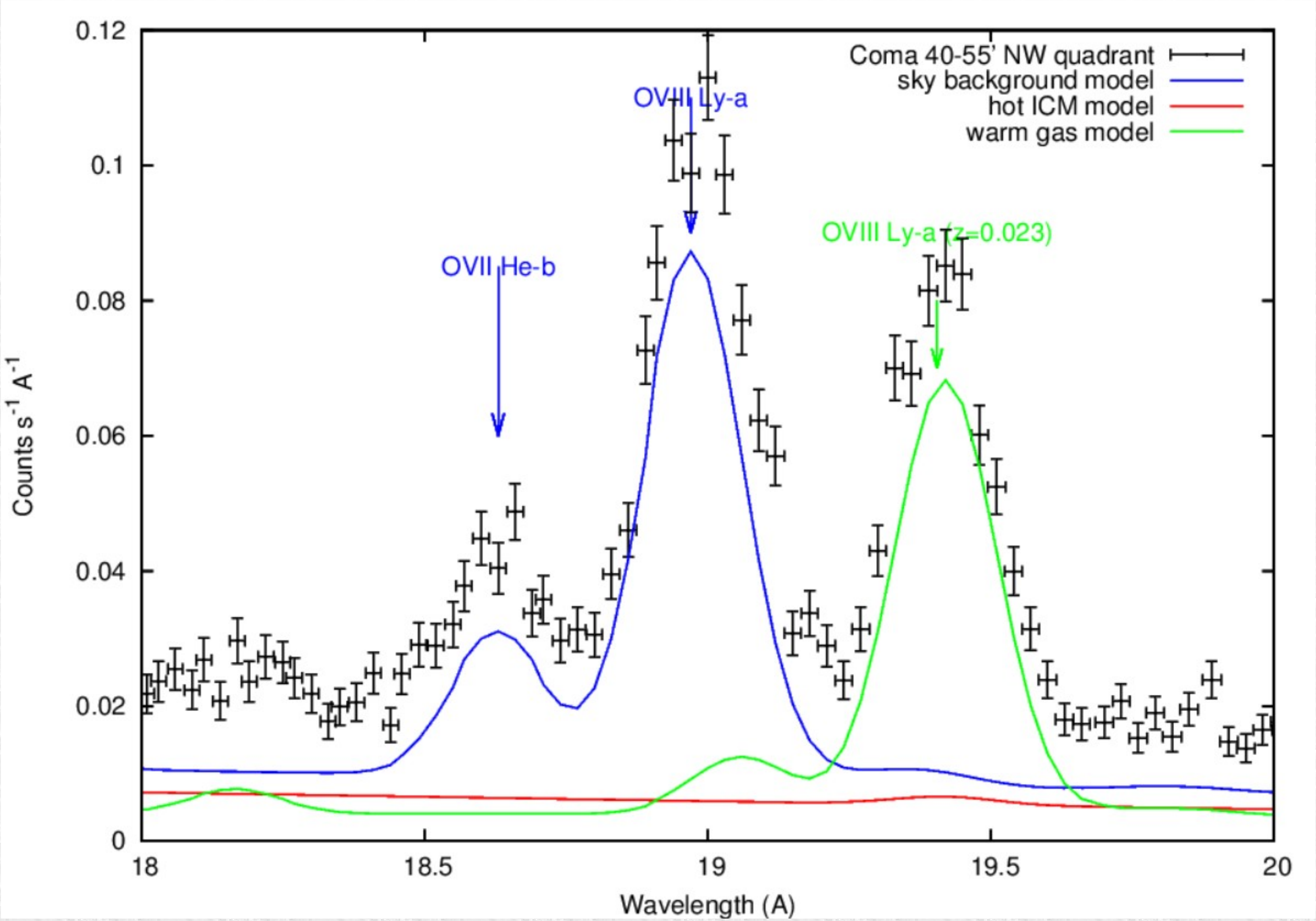
  (These soft excess parameters agree with the XMM results of Finoguenov et al. 2003)

• Simulation results (requires many pointings to cover the necessary area)



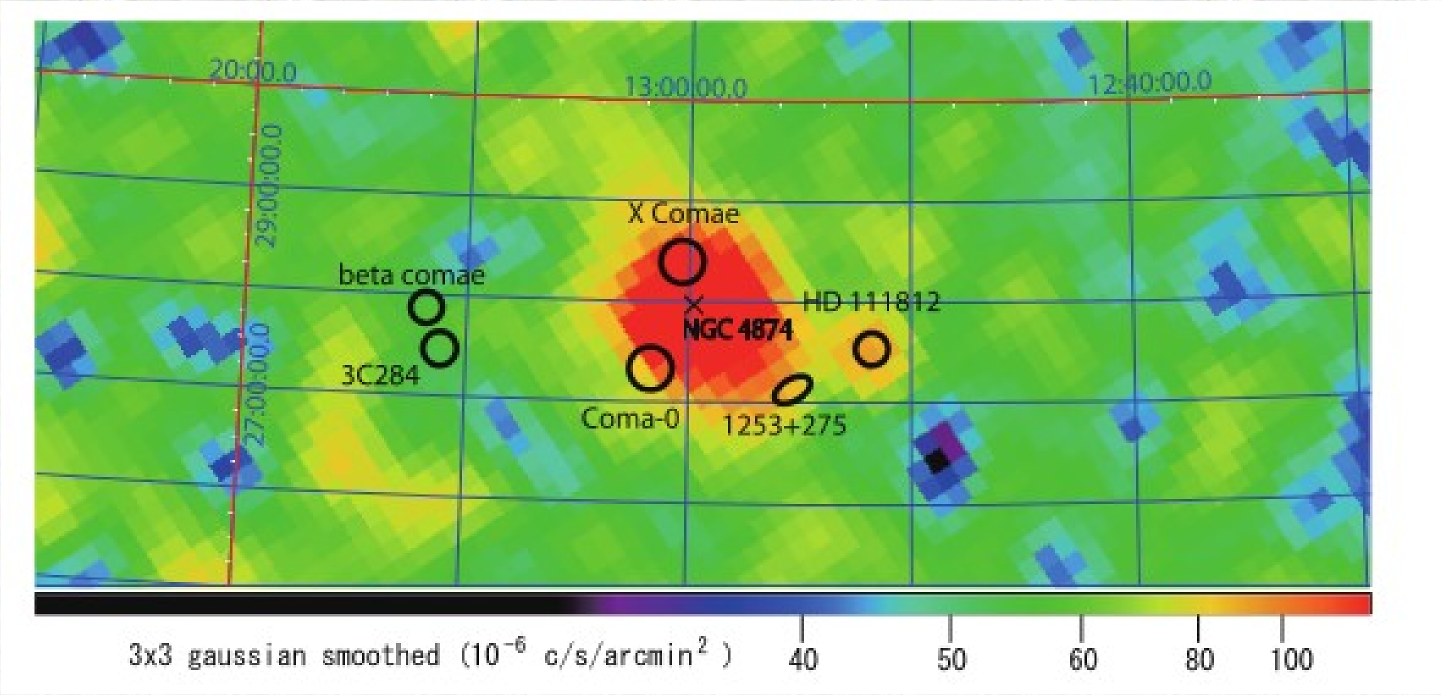


Coma 40-55' NW quadrant
sky background model
hot ICM model
warm gas model
NeIX Ly-a
OVIII Ly-b
OVII He-b
OVIII Ly-a
OVII He-a
OVII (forb.)
N VII Ly-a
Counts s^{-1} A^{-1}
Wavelength (A)
0
0.02
0.04
0.06
0.08
0.1
0.12
12
14
16
18
20
22
24
26



- It is clear that Astro-H will be able to tell if there are emission lines associated with the soft excess and therefore put the final word on the dispute between thermal and non-thermal interpretation of the excess. <u>Requires > 1Ms investment with Astro-H</u>

- But there is more: X Comae (z=0.091) in the background of the Coma cluster (z=0.023) can be used for absorption line spectroscopy.
- Takei et al. (2007) analyzed almost 500 ks of XMM RGS data (grating spectroscopy) and reported a tentative detection of Ne IX absorption lines in X Comae at the Coma cluster redshift.
- They also report a possible Ne IX emission lines in the CCD-resolution data, above the background which features the same line (indistinguishable in redshift at the CCD resolution)



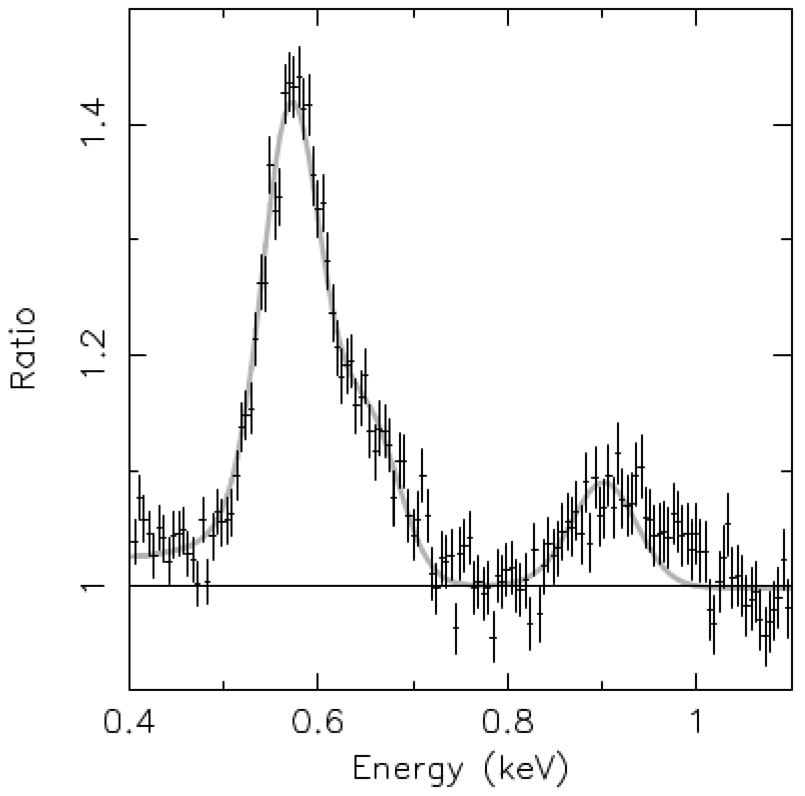


FIG. 8.—EPIC pn spectrum from the entire X Com field. Plotted is the ratio of the data to the smooth continuum with parameters in Table 7. The gray line is a fit of three narrow-width Gaussians to the residuals. The centers of the lower energy Gaussians are fixed to O VII and O VIII at zero redshift, and that of the higher energy Gaussian is fixed to Ne IX at the Coma redshift.

- Top (EPIC): background plus warm gas emission above the continuum in the Coma cluster CCD spectrum
- Right (RGS): possible Ne IX absorption line in the grating spectrum of X Comae

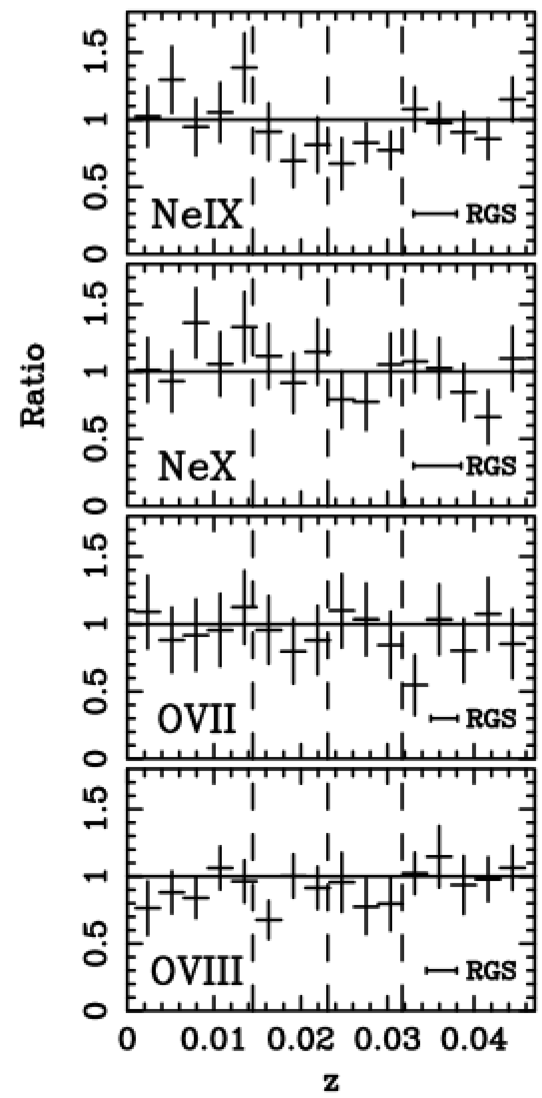
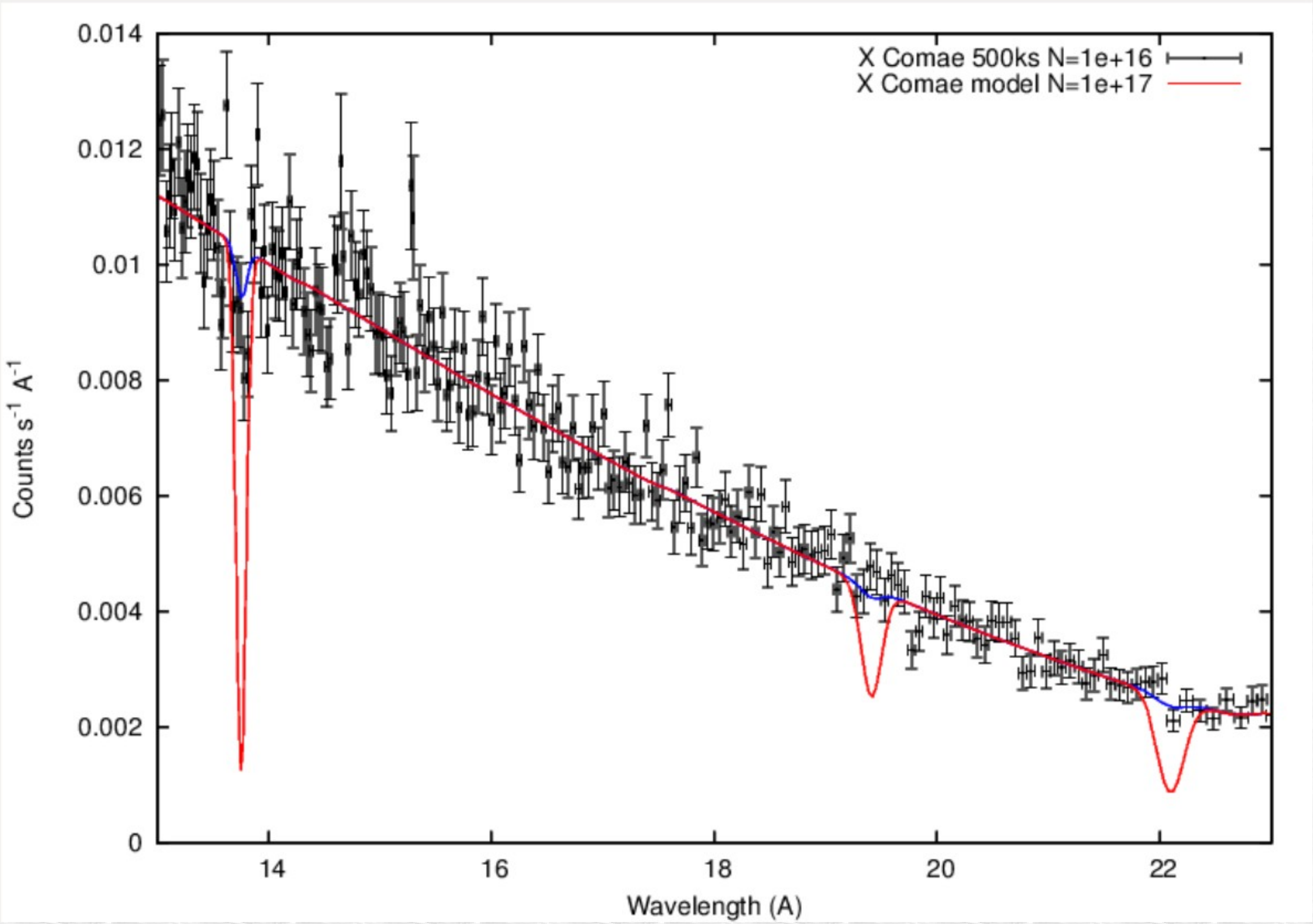


FIG. 3.—Ratios of the data to the continuum model (as defined in eq. [1]) vs. z for Ne IX, Ne X, O VII, and O VIII (*from top to bottom*). Vertical dashed lines indicate z_{Coma} and $z_{Coma} \pm 2.5\sigma_{gal}$. The average RGS1 and RGS2 instrumental resolution of 0.067 Å (FWHM) corresponds to a redshift resolution of 0.0050, 0.0055, 0.0031, and 0.0035 (*from top to bottom*), which is indicated as a horizontal line at the lower right of each panel.

- We simulated a 500 ks spectrum of X Comae in quiescence, as in the Takei et al. (2007) observations.
- Assume column densities of log N (cm^{-2}) = 16 or 17 for OVII, OVII and Ne IX, to study feasibility of detection of absorption lines with Astro-H. The soft excess emission is compatible with log N > 16 for these ions at the X Comae distance.



- It is clear that log N > 16 will be detected with a moderate investment of Astro-H resources.

Conclusions

- Soft excess emission from galaxy clusters is a possible reservoir of warm baryons. Current X-ray missions favor thermal over non-thermal interpretation, but no conclusive evidence from emission or absorption lines yet.
- It is possible that the soft excess is non-thermal in origin. A exciting possibility is the radiation from the interaction of a cosmic axion background (CAB) with magnetic fields in clusters. In that case the soft excess would have dark matter implications.
- The thermal nature of the excess is likely, but not confirmed yet.
- Astro-H has the ability to provide conclusive evidence, both in emission and in absorption against background AGN's. It will require Ms-class observations.