A WHIM origin for the soft excess emission in the Coma cluster

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ABSTRACT
This paper provides a new analysis of ROSAT observations of the Coma cluster, to determine the amount of soft X-ray radiation in excess of the contribution from the hot intra–cluster medium. The re–analysis is made possible by a high–resolution study of the hot intra–cluster medium with the XMM–Newton and Planck telescopes out to the cluster’s virial radius. The analysis confirms the original findings of a strong excess of soft X-ray radiation, which is likely to be of thermal origin. We find quantitative agreement between the detected soft excess and the physical characteristics of warm–hot intergalactic medium (WHIM) filaments seen in hydrodynamical simulations. We conclude that the most plausible explanation for the soft excess is the presence of ~ 10 Mpc–long filaments at log \( T(K) \approx 6 \), with a baryon overdensity of ~ 300, converging towards the Coma cluster. This interpretation therefore provides support for the identification of the missing low–redshift baryons with WHIM filaments, as predicted by numerical simulations.

Key words: galaxies: clusters: individual: Coma cluster – galaxies: clusters: intracluster medium – cosmology: large–scale structure of the Universe

1 INTRODUCTION

Galaxy clusters are strong emitters of X-ray radiation, which originates from a diffuse intergalactic medium at temperatures of log \( T(K) \approx 7–8 \). The Coma cluster, also known as Abell 1656, is one of the best-studied clusters of galaxies in all energy bands from radio to X-rays. Its proximity (\( z = 0.0231 \); Struble & Rood 1999) and mass (\( M_{200} \approx 8.5 \times 10^{14} \, M_{\odot} \); Mirakhor & Walker 2020) make it an ideal target for many studies. X-ray observations have shown many spatial features of its intracluster medium, with a number of infalling substructures such as NGC 4839 (e.g. Neumann et al. 2001, 2003), signs of surface brightness fluctuations (e.g. Churazov et al. 2012), and variations of temperature (e.g. Watanabe et al. 1999; Simionescu et al. 2013). The Coma cluster also features a giant radio halo that extends over scales of about 1 Mpc, tracing the non-thermal Compton emission from relativistic electrons and large-scale magnetic fields. Furthermore, the Planck observation of the Coma cluster (Planck Collaboration et al. 2013) revealed at least two shock fronts in two separate locations around 40 arcmin to the south-east and west of the Coma center, which corresponds roughly to the outer edge of the giant radio halo. At the Coma redshift, one arcmin corresponds to a distance of 28 kpc, for a Hubble constant of \( H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \) and a standard ΛCDM cosmology with \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \).

The Coma cluster was one of two clusters where an excess of soft X–ray radiation, above the contribution from the hot intra–cluster medium (ICM), was originally detected by the EUVE mission (Lieu et al. 1996b,a; Bowyer et al. 1996). This excess of radiation, usually referred to as the cluster soft excess, was subsequently confirmed by ROSAT for the Coma cluster (Bonamente et al. 2003, 2009) and for several other nearby clusters (Bonamente et al. 2002, 2001a), and by several other X–ray instruments including XMM–Newton (e.g., Kaastra et al. 2003; Nevalainen et al. 2003, 2007) and BeppoSAX (Bonamente et al. 2001c). Some of the early EUVE measurements were subject to re–analyses that revised downward some of the soft excess fluxes (e.g. Bowyer et al. 1999), but there remain a preponderance of evidence that the cluster soft excess is a genuine astrophysical phenomenon.

The origin of this excess of soft X–ray radiation has not been determined conclusively, given the limited spectral resolution of the available X–ray spectrometers. Possible explanations include a non–thermal origin as inverse–Compton scattering of cluster cosmic rays with the thermal medium (e.g. Lieu et al. 1999; Bonamente et al. 2005), or a thermal origin as a sub–virial gas at million–Kelvin temperatures (e.g. Lieu et al. 1996b,a; Bonamente et al. 2003). The numerical simulations of Cheng et al. (2005) provided evidence that cluster may contain a halo of warm sub–virial baryons that can generate the soft excess emission, with a preferential distribution towards large radii, consistent with the distribution of the excess in many clusters, including Coma. The thermal origin of the soft excess is also consistent with the presence of sub–virial gas at the outskirts of clusters, where filaments of warm–hot intergalactic medium (WHIM) are expected to stretch between groups and clusters of galaxies. Such filaments are seen in a range of hydrodynamical simulations, from the early Cen & Ostriker (1999); Davé et al. (2001) results, to the more recent EAGLE (e.g. Schaye et al. 2015; Tuominen et al. 2021) and IllustrisTNG simulations (Martizzi et al. 2019; Galárraga–Espinosa et al. 2021).

The two major X–ray telescopes of the past decades, XMM–Newton and Chandra, have had a limited ability to further investigate and clarify the origin of the soft excess emission. This is given by the fact that the soft X–ray band of interest of their spatially–resolved spectrometers (photon energies below 1 keV) have low spectral reso-
lution, high background levels and known calibration issues (see, e.g. Bonamente & Nevalainen 2011), whereas ROSAT had a stable and well-calibrated 1/4 keV band (e.g. Snowden et al. 1994) with very low detector background, ideal for low surface-brightness soft X-ray emission. The eROSITA instrument (Meidinger et al. 2020) onboard the SRG mission has the potential to investigate this phenomenon, due to its wide field of view and soft X-ray response. It is therefore of interest to revisit the soft excess emission in one of the clusters with strongest signal, ahead of the analysis of eROSITA observations of Coma in search of the soft excess radiation, and possibly with future high spectral resolution instruments such as XRISM (XRISM Science Team 2020). An initial analysis of the eROSITA Coma data was presented by Churazov et al. (2021), with emphasis on the cluster’s spatial morphology that did not address the soft X-ray emission. Another eROSITA observation of a WHIM filament associated with the Abell 3391/3395 system by Reiprich et al. (2021) shows that its soft band can in fact detect the type of faint emission discussed in this paper.

This paper is structured as follows. Section 2 describes the ROSAT, XMM–Newton and Planck observations of Coma, Sect. 3 presents our method of re-analysis of the ROSAT data with the newer XMM–Newton/Planck temperatures, Sect. 4 provides the results and interpretation of the soft excess in the Coma cluster, and Sect. 5 presents our discussion and conclusions.

2 OBSERVATIONS OF THE COMA CLUSTER

This section presents the observations of the Coma cluster used to determine the soft excess fluxes. The ROSAT data of Bonamente et al. (2003) are used in conjunction with a more recent determination of the cluster temperatures by Mirakhor & Walker (2020).

2.1 The ROSAT observations of Bonamente et al. (2003)

In Bonamente et al. (2003) we analyzed several pointed ROSAT PSPC observations out to a radial distance of ~1.5 degrees, from which we reported the presence of strong soft excess emission above the contribution from the hot ICM. One of the key limitations in the determination of the soft excess fluxes was the unavailability of high-resolution temperature maps for the hot ICM, given the narrow ROSAT bandpass (~0.2–2 keV). In our earlier ROSAT analysis, we obtained estimates of the hot ICM from a single-temperature fit to an optically-thin plasma emission model (MEKAL) in the 1-2 keV band. These estimates were then extrapolated to the neighboring soft X-ray bands R2–R4 (as defined in Snowden 1998, indicated as R2, ~0.2–1 keV) to determine the contribution from the hot ICM in that band. The ROSAT temperature profile from Bonamente et al. (2003) is reproduced in Table 1. The azimuthal coverage of the ROSAT data is complete out to 55 arcmin, and it is partial beyond it. A full azimuthal coverage of Coma was also available via the ROSAT All-Sky Survey data, which was analyzed in Bonamente et al. (2009) to confirm the presence of soft excess. Those short-exposure data however were only used for photometric purposes, and they are not considered in this paper.

2.2 Systematic errors associated with the ROSAT analysis

Prior to using the ROSAT soft X-ray fluxes with the XMM–Newton/Planck temperatures of Mirakhor & Walker (2020), it is useful to address certain sources of systematic errors associated with the Bonamente et al. (2003) analysis of the ROSAT data.

The soft X-ray fluxes in the R24 band, and especially in the softest 1/4 keV band (i.e., R2), are significantly modified by Galactic absorption. The column density of hydrogen towards Coma used in the Bonamente et al. (2003) paper was measured by Dickey & Lockman (1990) and Hartmann & Burton (1997), the latter part of the LAB survey (Kalberla et al. 2005). These measurements were complemented by an analysis of the IRAS data that confirmed a distribution with \( N_H = 0.9 \pm 0.1 \times 10^{20} \text{ cm}^{-2} \) within 5 degrees of the cluster’s center (see Figure 3 therein). A more recent measurement by the HI4PI survey (HI4PI Collaboration et al. 2016) confirms a smooth distribution of \( N_H \) towards Coma, with an average value of \( N_H = 0.9 \pm 0.1 \times 10^{20} \text{ cm}^{-2} \) towards the central degree of Coma, slightly rising to an average value of \( N_H = 1.1 \pm 0.1 \times 10^{20} \text{ cm}^{-2} \) within a radius of 3 degrees, consistent with the previous measurements within the statistical uncertainties. The soft excess fluxes measured by Bonamente et al. (2003) already include the systematic error corresponding to a possible \( \pm 1 \times 10^{19} \text{ cm}^{-2} \) uncertainty in the determination of the Galactic column density. Given that all available measurements towards the Coma cluster are statistically consistent with one another, no further source of systematic error is assessed in the re-analysis of the soft excess fluxes provided below in Sect. 3. Moreover, the cross-sections for the Galactic photoelectric absorption are those of Morrison & McCammon (1983) (\( \text{tbabs} \)), which are in agreement with those of Yan et al. (1998) and of the higher-resolution calculations Wilms et al. (2000) (\( \text{tbabs} \)). An extensive discussed of the photoelectric cross-sections for soft X-ray fluxes is provided in Bonamente et al. (2002) and Bonamente et al. (2001b).

The calibration and stability of the ROSAT PSPC detector are discussed in Snowden et al. (1994) and Snowden et al. (2001), including the calibration of the radial dependence of the detector efficiency with off-set angle. A study of the soft emission from white dwarfs and neutron stars by Beuermann et al. (2006) shows that the ROSAT PSPC soft X-ray fluxes are well calibrated within \( \pm 10 \% \), as also indicated by Snowden et al. (1995). Moreover, the Bonamente et al. (2003) analysis excluded the portions of the detector shadowed by the ‘wagon wheel’ structure used to house the filters, in correspondence of which the response of the PSPC is significantly reduced. The Beuermann et al. (2006) study also shows the overall good agreement between the Chandra HRC and ROSAT PSPC instruments, and Snowden (2002) finds a \( \pm 10 \% \) error in the cross-calibration among the Chandra, XMM and ROSAT imaging instruments. These results point to a stable and well-calibrated response for the PSPC, also when compared to other X-ray instruments. More importantly, an absolute calibration of the ROSAT and XMM–Newton fluxes is in fact not crucial for our analysis, since only the XMM–Newton/Planck temperatures (and not the fluxes or spectral normalizations) are applied to the ROSAT data.

Finally, the ROSAT PSPC detector was designed with a particle anti-coincidence shield that provides a \( \geq 99 \% \) rejection of particle background (Snowden et al. 1992; Plucinsky et al. 1993), thus making the particle background essentially unimportant for the majority of observations. The large field-of-view of ROSAT (approximately 1 degree in radius) makes it also possible to measure in situ background at the same time as the cluster observations, in order to control the time-variable components of the photon background, such as those

\( \text{phabs} \) cross-sections of He are believed to be less accurate than those of either Morrison & McCammon (1983) or Wilms et al. (2000), with a slightly lower value that would in fact lead to even larger soft excess fluxes.

1 The Balucinska-Church & McCammon (1992) (\( \text{phabs} \)) cross-sections of He are believed to be less accurate than those of either Morrison & McCammon (1983) or Wilms et al. (2000), with a slightly lower value that would in fact lead to even larger soft excess fluxes.
due by charge–exchange. Additional details on the reduction and background subtraction are provided in Bonamente et al. (2002).

2.3 The XMM–Newton/Planck observations of Mirakhor & Walker (2020)

Combining a large XMM–Newton mosaic with the Planck Sunyaev–Zeldovich effect observations of the Coma cluster, Mirakhor & Walker (2020) studied the thermodynamic properties of the Coma cluster in an azimuthally averaged profile and in 36 angular sectors out to the virial radius, with nearly full azimuthal coverage. They found that the temperature profiles in azimuthal sectors exhibit similar radial trends, with the temperature dropping from about 8.0 keV at the Coma core to about 3.0 keV in the outskirts. Beyond $r_{500}$, the temperature profiles, on average, tend to be flatter and do not drop with radius. Within a radius of 30 arcmin, there is a gradient in the gas temperature from the hotter region in the north-west to the colder region in the south-east, agreeing with previous measurements (e.g. Watanabe et al. 1999; Neumann et al. 2003). Along the less disturbed directions, Mirakhor & Walker (2020) found that the entropy measurements follow the power-law entropy profile predicted by non-radiative simulations for purely gravitational hierarchical structure formation. However, an entropy deficit is found in the outskirts along the south-west direction, where Coma connects to Abell 1367 through the cosmic web filament. This entropy deficit extends from 0.5$r_{200}$ out to the virial radius, consistent with what is expected from simulations of a filamentary gas streams that can penetrate deep into the cluster, bringing low-entropy gas into the cluster core.

These newer XMM–Newton/Planck measurements make it possible to re–analyze the ROSAT soft X–ray data in light of these more accurate ICM temperatures. Since the goal of this study is to determine the soft excess flux as measured by ROSAT, we use the averaged Mirakhor & Walker (2020) temperature measurements as the temperature value that applies to the ROSAT radial bins shown in Table 1. Such averaging procedure leads to the values reported in the rightmost column of Table 1. A comparison of the temperature measurements is also reported in Figure 1.

3 RE–ANALYSIS OF ROSAT SOFT EXCESS FLUXES WITH XMM–NEWTON/PLANCK TEMPERATURES

The soft excess flux is defined as the difference between the measured ROSAT PSPC R2–R4 band flux ($F_{24}$), covering approximately the 0.2–1 keV energy range (Snowden et al. 1994; Snowden 1998), and the flux in the same band predicted from the hot ICM as measured from the neighboring R5–R7 band (1–2 keV) and indicated as $P_{24}$, such that

$$E_{24} = F_{24} - P_{24}.$$  

The total measured ROSAT $F_{24}$ flux is independent of the temperature assumed for the hot ICM, while the $P_{24}$ prediction is sensitive to the spectral modelling, and primarily the temperature of the hot ICM. To determine the new soft excess fluxes using the XMM–Newton/Planck temperatures, it is therefore necessary to re–scale the predicted R24 band flux $P_{24}$ to account for the new XMM–Newton/Planck temperatures, as described in the following.

| Quadrant | Radius (arcmin) | PSPC $kT$ (keV) | EPIC $kT$ (keV) |
|----------|----------------|----------------|----------------|
| NW       | 10.0 ± 1.0     | 5.80 ± 0.40    | 7.50 ± 1.06    |
| NW       | 30.0 ± 1.0     | 2.60 ± 0.30    | 6.45 ± 0.71    |
| NW       | 47.5 ± 7.5     | 3.10 ± 2.00    | 4.11 ± 0.58    |
| NW       | 62.5 ± 7.5     | 3.50 ± 2.90    | 3.21 ± 0.72    |
| NE       | 10.0 ± 1.0     | 6.60 ± 0.60    | 8.17 ± 0.97    |
| NE       | 30.0 ± 1.0     | 4.30 ± 0.70    | 6.76 ± 0.69    |
| NE       | 47.5 ± 7.5     | 8.00 ± 4.00    | 4.52 ± 1.19    |
| SE       | 10.0 ± 1.0     | 6.80 ± 0.50    | 6.22 ± 1.02    |
| SE       | 30.0 ± 1.0     | 8.00 ± 2.60    | 5.86 ± 1.29    |
| SE       | 47.5 ± 7.5     | 3.60 ± 1.30    | 3.81 ± 0.73    |
| SW       | 10.0 ± 1.0     | 13.60 ± 2.50   | 5.54 ± 0.92    |
| SW       | 30.0 ± 1.0     | 7.80 ± 1.70    | 5.56 ± 0.84    |
| SW       | 47.5 ± 7.5     | 3.50 ± 0.70    | 3.20 ± 0.73    |
| SW       | 62.5 ± 7.5     | 2.30 ± 0.70    | 2.48 ± 0.48    |
| SW       | 80.0 ± 1.0     | 2.90 ± 0.70    | 2.78 ± 0.28    |

Figure 1. Comparison of ROSAT and XMM–Newton/Planck temperatures in the Coma cluster. The blue datapoints correspond to the quadrants in Table 1, in black are the last 5 datapoints with the azimuthal averages.

3.1 Determination of soft–band predictions using XMM–Newton/Planck temperatures

A few steps are required to rescale the soft excess fluxes to account for the more accurate XMM–Newton/Planck temperatures. First, the emission integral $I$ of a spectrum is proportional to the square of the

| ROSAT soft excess in Coma | 3 |
|-------------------------|---|
| Table 1. Comparison of XMM–Newton/Planck and ROSAT temperatures. ROSAT temperatures are reproduced from Bonamente et al. (2003) .

| Quadrant | Radius (arcmin) | PSPC $kT$ (keV) | EPIC $kT$ (keV) |
|----------|----------------|----------------|----------------|
| NW       | 10.0 ± 1.0     | 5.80 ± 0.40    | 7.50 ± 1.06    |
| NW       | 30.0 ± 1.0     | 2.60 ± 0.30    | 6.45 ± 0.71    |
| NW       | 47.5 ± 7.5     | 3.10 ± 2.00    | 4.11 ± 0.58    |
| NW       | 62.5 ± 7.5     | 3.50 ± 2.90    | 3.21 ± 0.72    |
| NE       | 10.0 ± 1.0     | 6.60 ± 0.60    | 8.17 ± 0.97    |
| NE       | 30.0 ± 1.0     | 4.30 ± 0.70    | 6.76 ± 0.69    |
| NE       | 47.5 ± 7.5     | 8.00 ± 4.00    | 4.52 ± 1.19    |
| SE       | 10.0 ± 1.0     | 6.80 ± 0.50    | 6.22 ± 1.02    |
| SE       | 30.0 ± 1.0     | 8.00 ± 2.60    | 5.86 ± 1.29    |
| SE       | 47.5 ± 7.5     | 3.60 ± 1.30    | 3.81 ± 0.73    |
| SW       | 10.0 ± 1.0     | 13.60 ± 2.50   | 5.54 ± 0.92    |
| SW       | 30.0 ± 1.0     | 7.80 ± 1.70    | 5.56 ± 0.84    |
| SW       | 47.5 ± 7.5     | 3.50 ± 0.70    | 3.20 ± 0.73    |
| SW       | 62.5 ± 7.5     | 2.30 ± 0.70    | 2.48 ± 0.48    |
| SW       | 80.0 ± 1.0     | 2.90 ± 0.70    | 2.78 ± 0.28    |
plasma density $n_e^2$ as

$$ I = \int n_e^2 dV \propto \frac{K}{\Lambda(kT, A)}, \quad (1) $$

and it is proportional to the normalization constant $K$ of the thermal model and the emissivity or cooling function $\Lambda(kT, A)$ of the plasma. For this analysis, $I$ indicates the hot ICM emission integral as determined from the the 1-2 keV ROSAT spectral fits using the MEKAL code, (Mewe et al. 1985, 1986; Kaastra 1992). These fits were also used to determine the prediction $P_{24}$ by the same model in the lower–energy R24 band.

In turn, the measured flux in the 1-2 keV band is also proportional to the emission integral, given that detector characteristics such as extraction region size, calibration, and efficiency remain constant for a given spectrum, as the temperature of the hot ICM is varied. We therefore found a simple empirical relationship between the ratio of the predicted R24 band flux, and the emission integral and the temperature, as

$$ \log \frac{P_{24}}{I} = a + b \log kT. \quad (2) $$

This relationship applies with different best–fit values $a$ and $b$ for different regions, since the efficiency of the ROSAT detector is a function of the radial distance from the on–axis position. The high accuracy of these relationships can be evinced from Figure 2, where each point corresponds to the results (i.e., emission integral, prediction in R24 band, and temperature) of a spectral fit to the Bonamente et al. (2003) PSPC spectra.

The relationship (2) can be equivalently rewritten as a function of ratios between quantities,

$$ \log \frac{P_{24,\text{new}}}{P_{24}} = \log \frac{I_{\text{new}}}{I} + b \log \frac{kT_{\text{new}}}{kT}. \quad (3) $$

where ‘new’ refers to the values with the modified temperature. Notice that the parameter $a$ of (2) is not necessary for (3), since the latter uses logarithmic ratios. Equation 3 is used to find the new $P_{24}$ prediction without the need to fit again the ROSAT spectra, but instead using directly the results provided in Bonamente et al. (2003).

Moreover, this equation gives us an opportunity to study analytically the impact of temperature changes in the hot ICM on the soft excess fluxes, and it provides the basis for error propagation. The emission integral $I$ in the 1-2 keV band is assumed to be due primarily to the hot ICM. This assumption is justified by the exponential cutoff of the bremsstrahlung emission from the warm phase at photon energies $\epsilon > kT_w$, whereas the Bonamente et al. (2003) analysis indicates typical warm gas temperatures well below 1 keV. The spectral resolution of the PSPC detector has a FWHM of ~0.4 keV at 1 keV photon energies (or a standard deviation of ~0.17 keV). This implies that, e.g., even photons at 0.75 keV from the high–energy tail of a warm plasma will only have small ($\pm 5\%$) probability of being redistributed into the 1-2 keV band.

In (3) the emission integral (and similarly density and mass) will change with the temperature because of the temperature–dependence of the emissivity of the plasma. This dependence is approximately described by the consideration that the surface brightness is

$$ S_x \propto \int \Lambda(kT, A) n_e^2 dV \propto kT^{-1/2} e^{-E/kT} n_e^2 = \text{const}, $$

accounting for the fact that the bulk of the main–band X–ray emission is from thermal bremsstrahlung, and that the measured surface brightness $S_x$ or flux is the invariant. With $E = 0.2–1$ keV the energy of the soft X–ray photons in the narrow band of concern, and with $kT \geq 2$ keV the hot plasma temperature of Coma, the dependence of the emission integral on the temperature is approximately $n_e^2 \propto kT^{1/2}$.

As a result, when a new temperature is introduced in the analysis of the ROSAT data, the emission integral must be accordingly modified as

$$ \frac{I_{\text{new}}}{I} = \left( \frac{n_{e,\text{new}}}{n_e} \right)^2 = \left( \frac{kT_{\text{new}}}{kT} \right)^{1/2}. \quad (4) $$

This means that if ROSAT temperatures are revised upwards, so are the corresponding emission integrals.

Finally, use of (3) and (4) lead to the sought–after change in the predicted fluxes in the R24 band,

$$ \frac{P_{24,\text{new}}}{P_{24}} = \left( \frac{kT_{\text{new}}}{kT} \right)^{b+1/2} \quad (5) $$

which, for small changes in $kT$, (5) is approximately

$$ \Delta P_{24} \approx \left( b + \frac{1}{2} \right) \frac{\Delta kT}{kT} \quad (\text{small changes}) $$

Notice that $b \approx -0.4$ according to the results shown in Figure 2, and therefore the change in the predicted flux is only a very mild function of the temperature assumed for the hot ICM. This finding alone is sufficient to show that even moderately large changes in the assumed temperatures, $\Delta kT/kT \leq 1$, lead to changes in the predicted R24 band fluxes, and therefore soft excess fluxes, at the level of $\pm 10\%$. This is due to two opposing effects, e.g., an increase in the emission integral as $kT$ is modified upwards according to (4), followed by a reduction in the predicted flux (at constant $I$) as a function of temperature, according to (3).

3.2 The soft excess flux in ROSAT with XMM–Newton/Planck temperatures and error analysis

The result of re–scaling the predicted soft X–ray fluxes according to Sect. 3.1 are presented in Table 2 and Figure 3, where the fractional soft excess flux is defined as

$$ \eta = \frac{F_{24} - P_{24}}{P_{24}} \quad (6) $$
in the same manner as in Bonamente et al. (2003). Figure 4 also shows the distribution of the soft excess fluxes as a function of radial distance from the center of the Coma cluster, using the same \( \eta \) values as in Figure 3.

Uncertainties in the new R24 band predictions and in the fractional soft excess fluxes are obtained through standard error propagation formulas (e.g., see Chapter 5 of Bonamente 2022). According to (5), the standard error in \( z = P_{24,\text{new}} \) is given by

\[
\sigma_{z}^{2} = \frac{1}{2 + b} \left( \sigma_{x}^{2} + \sigma_{y}^{2} \right)^{2}
\]

where \( x = kT \) and \( y = kT_{\text{new}} \) are the ROSAT and XMM–Newton/Planck temperatures of Table 1, respectively. Likewise, the error in the fractional soft excess fluxes according to (6) is given by

\[
\sigma_{\eta}^{2} = \left( \frac{F}{P} \right)^{2} \left( \frac{\sigma_{F}^{2}}{F^{2}} + \frac{\sigma_{P}^{2}}{P^{2}} \right)
\]

where \( F \) is the measured ROSAT R24 band flux, which remained constant throughout the analysis, and \( P \) is the predicted flux in that band, indicated as respectively \( P_{24} \) for the ROSAT temperatures, and \( P_{24,\text{new}} \) for the XMM–Newton/Planck temperatures. The results of Table 2 illustrate that the weak dependence of the hot ICM–predicted soft X-ray fluxes \( P_{24} \) on temperature, according to (5), leads to only small changes in soft excess fluxes between the cases of ROSAT or XMM–Newton/Planck temperatures.

The small effect of the hot ICM temperature on soft excess fluxes also indicates that any multi–phase structure along the sightline (i.e., in a given annular region) is unlikely to have a significant effect on our results. We therefore regard the best–fit temperature in an given region as the average temperature along the sightline, and do not include systematic errors associated with possible multi–temperature gas.

Both the original ROSAT and the newer XMM–Newton/Planck results assumed a significantly sub–solar abundance of Z > 2 elements. In particular, at large radii the ROSAT data were analyzed with a MEKAL model with \( A = 0.2 \) Solar abundances, and the XMM–Newton/Planck data with a APEC thermal model with \( A = 0.3 \) Solar abundances. To address the effect of uncertainties in our knowledge of the chemical abundance of the hot ICM in Coma, we calculated the spectral intensity of an optically–thin thermal spectrum in collisional equilibrium, for temperatures in the range \( kT = 2 – 8 \text{ keV} \), which are typical of the Coma cluster. Figure 5 shows the spectral intensity of the optically–thin APEC emission model (Smith et al. 2001), which is a higher–resolution replacement for the MEKAL model. 2 At a temperature of \( kT = 2 \text{ keV} \), the total spectral intensity of an optically–thin APEC plasma with Solar abundances of \( Z > 2 \) elements (e.g., according to Anders & Grevesse 1989) is 7.56 \( \times 10^{-15} \) photons cm\(^{-2} \) s\(^{-1} \), with 24.7\% of the total intensity provided by line emission. At a temperature of \( kT = 8 \text{ keV} \), these lines provide only 11.2\% of the intensity, consistent with an increased dominance of continuum emission at higher temperatures, where most of the ICM is fully ionized. These calculations clearly indicate that small changes in the metal abundance (e.g., of order \( \Delta A = 0.1 \)), only contribute to a small (~ 1 – 2\%) change in the plasma emissivity, and in the associated prediction of the R24 band fluxes from an hot ICM at these temperatures. To account for our uncertainty in the chemical abundances in the Coma hot plasma, we introduce a systematic error of ±2\% in \( P_{24,\text{new}} \) to the calculation of the errors in the fractional soft excess fluxes. These errors are included in the \( \eta_{\text{new}} \) column of Table 2.

4 CONFIRMATION OF STRONG SOFT EXCESS EMISSION IN COMA AND ITS ASTROPHYSICAL IMPLICATIONS

The results of Table 2 show that the soft excess emission is detected with high statistical significance (≥ 3\( \sigma \)) in all regions at \( r \geq 20\text{ arcmin} \), as also shown in Figure 4. The excess becomes stronger, relative to the emission of the hot ICM, at large radial distances from the center of the Coma cluster. Use of the more accurate XMM–Newton/Planck temperatures, and an allowance for systematic errors associated with the metal abundances, therefore confirms the results of Lieu et al. (1996a) and of Bonamente et al. (2003, 2009) of strong soft excess emission from Coma.

Although the spectral resolution of the soft excess emission in the 0.2–1 keV band is limited, the previous ROSAT analysis suggested that a thermal origin for the soft excess, as modelled via a single–temperature additional thermal component, is to be preferred to a non–thermal origin, as modelled with a power–law component. It is therefore instructive to follow the thermal interpretation for the soft excess signal and estimate the inferred warm gas masses. The ROSAT spectral modelling of the soft excess indicated a warm gas temperature of \( \log T(K) \approx 6 – 6.5 \), with a metal abundance \( A \leq 0.3 \), in all regions. These conditions are also consistent with a significant fraction of the warm–hot intergalactic medium (WHIM) that is predicted in large–scale filaments that converge towards clusters (e.g. Wijers et al. 2019; Tuominen et al. 2021). From these observations, it is not possible to determine whether the putative warm gas is within the cluster, or whether it is seen in projection onto the cluster. We therefore follow both scenarios to provide an estimate of the mass that could be responsible for this signal in Sects. 4.1 and 4.2, and we draw our conclusion from these estimates in Sect. 4.3.

4.1 Mass estimates for warm intra–cluster gas

The soft excess emission can in principle originate from warm, sub–virial intra–cluster gas. In this scenario, the warm gas would likely be clumpy (i.e., with a volume filling factor \( f < 1 \)), as discussed in Sect. 3 of Bonamente et al. 2001a), in order to maintain local pressure equilibrium with the hotter ICM. For the calculations of this section we assume no clumping (\( f = 1 \)), and comment on how the results would be modified in the presence of clumping at the end of the section.

For each quadrant, the soft excess flux \( S_{24} = F_{24} – P_{24} \) is first re–scaled according to the new XMM–Newton/Planck temperatures, according to the method of Sect. 3. This flux is proportional to the emission integral \( I_{\text{em}} \) of the warm gas, with the characteristics reported in Table 3 of Bonamente et al. (2003) (viz., the emission integral, temperature and abundance of the warm gas model). Accordingly, the measured emission integrals of the warm gas are rescaled in proportion to their change in \( S_{24} \) for the new temperatures of the hot gas.

Moreover, we examined the possibility that the warm gas temperatures may vary from the best–fit values of the ROSAT analysis, given the limited spectral resolution of PSPC. To this end, we used the ATOMDB data for the APEC thermal model to determine the changes in the warm gas emissivity as a function of both the temperature and abundance. Unlike the case of the hot gas at \( \log T(K) \geq 7 \) (see

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2 The APEC model is accessible via the ATOMDB project, which also provides the PyAtomDB software at https://atomdb.readthedocs.io/en/master/index.html.
Table 2. Soft excess fluxes using the new XMM–Newton/Planck temperatures. $P_{24}$ are the original predicted fluxes from Bonamente et al. (2003) (the small errors are ignored), $\Delta P_{24}$ is the change based on the temperature change $\Delta kT$ between the new XMM–Newton/Planck temperature and the old ROSAT temperatures, and $\eta$ are the fractional soft excess fluxes.

| Quadrant | Radius (arcmin) | $\frac{\Delta kT}{kT}$ | $P_{24}$ (c s$^{-1}$) | $\Delta P_{24}$ (c s$^{-1}$) | $\eta$ | $\eta_{new}$ |
|----------|----------------|------------------|-----------------|-----------------|------|-------------|
| NE       | 10.0 ± 10.0    | 0.29             | 1.810           | 0.038 ± 0.044   | 0.122 ± 0.034 | 0.099 ± 0.063 |
| NE       | 30.0 ± 10.0    | 1.48             | 0.345           | 0.026 ± 0.009   | 0.536 ± 0.053 | 0.429 ± 0.085 |
| NE       | 47.5 ± 7.5     | 0.33             | 0.095           | 0.002 ± 0.010   | 2.789 ± 0.332 | 2.705 ± 0.559 |
| NE       | 62.5 ± 7.5     | -0.08            | 0.137           | -0.001 ± 0.018  | 2.650 ± 0.454 | 2.675 ± 0.732 |
| NW       | 10.0 ± 10.0    | 0.24             | 1.700           | 0.029 ± 0.039   | 0.094 ± 0.035 | 0.076 ± 0.063 |
| NW       | 30.0 ± 10.0    | 0.57             | 0.500           | 0.018 ± 0.015   | 0.370 ± 0.054 | 0.321 ± 0.089 |
| NW       | 47.5 ± 7.5     | -0.44            | 0.180           | -0.008 ± 0.015  | 2.778 ± 0.207 | 2.954 ± 0.482 |
| SE       | 10.0 ± 10.0    | -0.09            | 2.180           | -0.015 ± 0.058  | 0.110 ± 0.034 | 0.118 ± 0.068 |
| SE       | 30.0 ± 10.0    | -0.27            | 0.420           | -0.010 ± 0.024  | 0.505 ± 0.104 | 0.543 ± 0.173 |
| SE       | 47.5 ± 7.5     | 0.06             | 0.091           | 0.000 ± 0.006   | 3.176 ± 0.997 | 3.157 ± 1.103 |
| SW       | 10.0 ± 10.0    | -0.59            | 2.000           | -0.139 ± 0.069  | 0.135 ± 0.055 | 0.220 ± 0.103 |
| SW       | 30.0 ± 10.0    | -0.29            | 0.714           | -0.019 ± 0.028  | 0.310 ± 0.075 | 0.345 ± 0.122 |
| SW       | 47.5 ± 7.5     | -0.09            | 0.380           | -0.003 ± 0.017  | 0.763 ± 0.086 | 0.776 ± 0.154 |
| SW       | 62.5 ± 7.5     | 0.08             | 0.160           | 0.001 ± 0.009   | 1.188 ± 0.131 | 1.174 ± 0.214 |
| SW       | 80.0 ± 10.0    | -0.04            | 0.121           | -0.000 ± 0.005  | 1.769 ± 0.231 | 1.778 ± 0.307 |

Figure 3. Distribution of fractional soft excess fluxes as a function of plasma temperature. For comparison, lighter–color datapoints represent the results using the original Bonamente et al. (2003) temperatures.
Figure 4. Distribution of fractional soft excess fluxes as a function of radial distance from the center of the Coma cluster. Lighter–color datapoints represent the results using the original Bonamente et al. (2003) temperatures. Datapoints at the same radius were slightly shifted for clarity.

Figure 5. Spectral intensity of an APEC optically–thin thermal spectrum in collisional ionization equilibrium at two characteristic hot ICM temperatures. Continuum emission is the dominant mechanisms at these temperatures, with line emission becoming more significant at lower temperatures.

The emissivity of warm gas at log $T(K) = 6 - 7$ depends strongly on metal abundances, since there is a much larger contribution from line emission than at higher temperatures, where most of the ions are fully ionized, in collisional ionization equilibrium (e.g. Mazzotta et al. 1998). The warm gas emission integrals were therefore also rescaled in proportion to the change in the emissivity of the warm plasma according to (1), for a few representative abundances and temperatures of the warm gas (log $T(K) = 6, 7$ and $A = 0.1, 1$).

In each spectral region, the ratio of warm–to–hot gas mass is given by

$$\frac{M_{w,i}}{M_{h,i}} = \frac{n_{w,i} V_i}{n_{h,i} V_i} = \left( \frac{I_{w,i}}{I_{h,i}} \right)^{1/2}$$

where $V_i$ is the volume of the representative region, $n_i$ indicates average density, $I_h$ is the emission integral of the hot plasma, and $I_w$ that of the warm plasma, the latter being rescaled for different choices of the warm gas temperature and abundance according to (1) as described above. We used this relationship to calculate the warm gas mass in each annular region covered by the Mirakhor & Walker (2020) analysis (see their Figure 7), using the ratio of emission integrals of the warm–to–hot gas from the ROSAT data. Since the XMM–Newton/Planck masses were reported on a finer angular resolution than the ROSAT soft excess fluxes, the ratios according to (7) were constant for a few of the XMM–Newton/Planck differential mass bins. Uncertainties in the warm gas masses are obtained by a standard error propagation based on (7), where for simplicity the smaller uncertainties of the emission integrals of the hot phase were ignored.

The results of the estimates are shown in Figure 6, where in blue are two estimates obtained for log $T(K) = 7$ and metal abundances of respectively 10% and 100% Solar, and in green two similar estimates for a lower temperature of log $T(K) = 6$. As expected, the estimated gas masses are strong function of both the temperature and abundances assumed for the warm gas. For a metal abundance of 0.1 Solar, the emissivity in the 0.2-1 keV band is $1.1 \times 10^{-24}$ erg cm$^{-3}$ s$^{-1}$ at log $T(K) = 6$, increasing approximately four times to $4.7 \times 10^{-24}$ erg cm$^{-3}$ s$^{-1}$ at log $T(K) = 7$. 

[$\text{MNRAS 000, 1–11 (2022)}$]
10^{-24}\text{ erg cm}^{-3}\text{ s}^{-1} at a temperature of log T(K) = 7. This increase in emissivity corresponds to a nearly two–fold decrease in estimated gas masses, consistent with the comparison between the blue light and light green mass profiles in Fig. 6. Similar considerations apply to the comparison of warm gas mass estimates for the same temperature, but for varying metal abundances.

The main result from the intra–cluster warm gas interpretation of Fig. 6 is that the warm gas mass inferred from the soft excess fluxes are comparable to that of the hot gas, and they are strongly dependent on the uncertain physical conditions of the warm gas. It is also clear that, consistent with the increasing fraction of soft excess fluxes towards large radii, the putative warm gas becomes dominant towards the cluster’s virial radius. The intra–cluster warm gas masses would be reduced according to $M \propto \sqrt{T}$ in the presence of clumping (f < 1), since the emitting gas would be denser, and the X–ray emission is proportional to the square of the density (e.g. Bonamente et al. 2001a).

4.2 Warm gas mass estimates for a WHIM origin of the soft excess

To investigate whether the soft excess emission could originate from WHIM filaments projected towards Coma, Figure 7 provides the radial profile of the surface brightness of the soft excess. For this profile, the excess flux $F_{24} - F_{14}$, rescaled for the XMM–Newton/Planck temperatures, was divided by the area of the extraction region, accounting for excluded regions (e.g. point sources excluded from the field of view, and partial coverage of the annuli or quadrants). The results show that the surface brightness is rather constant with radius, providing general consistency with a simple model where approximately uniform–density WHIM filaments are seen in projection towards the cluster. While WHIM filaments are expected to have gradients in their WHIM density (see, e.g. Tuominen et al. 2021), these gradients are much milder than those of the hot ICM gas density, which typically vary from the center to the virial radius of a cluster by more than two orders of magnitude.

If the soft excess originates from WHIM filaments projected onto Coma, it is possible to estimate the length and mass associated with the filaments, as a function of the filament density. The estimate is based upon the relationship that applies to each spectral extraction region

$$I_w = \int n^2 dV \approx \pi^2_{WHIM} \cdot (L_{WHIM} \times A),$$

where $I_w$ is the measured emission integral of the warm gas, $A$ is the area, $L_{WHIM}$ is the length of the filament, and $n_{WHIM}$ is a characteristic density for the WHIM that needs to be assumed a priori. Gas in a dense WHIM filament is expected to feature baryon overdensities

$$\delta_\rho = \frac{n_b - \bar{n}_b}{\bar{n}_b} \sim 30 - 300,$$

where $\bar{n}_b = 4.2 \times 10^{-31} \text{ g cm}^{-3} = 2.6 \times 10^{-7} \text{ H atoms cm}^{-3}$ is the mean baryon density of the universe, for the standard ΛCDM Planck cosmology (Tuominen et al. 2021; Holt et al. 2022; Planck Collaboration et al. 2014, 2016). According to (8), all ROSAT regions can be interpreted with a WHIM origin of the soft excess, where filaments have characteristic lengths in the range

$$L_{WHIM} = (4.5 - 33.3) \times \left(\frac{n_{WHIM}}{7.8 \times 10^{-5} \text{ cm}^{-3}}\right)^{-2} \text{ Mpc},$$

where $n_{WHIM} = 7.8 \times 10^{-5} \text{ cm}^{-3}$ corresponds to $\delta_\rho = 300$, for an average length of

$$L_{WHIM} = 15.5 \pm 9.1 \times \left(\frac{n_{WHIM}}{7.8 \times 10^{-5} \text{ cm}^{-3}}\right)^{-2} \text{ Mpc}.$$ 

These lengths are generally consistent with WHIM filaments seen in EAGLE simulations (e.g. Wijers et al. 2019; Tuominen et al. 2021; Holt et al. 2022), and the region–to–region scatter can be attributed to mild gradients in the WHIM density and to the geometry of the filaments. For these estimates, we assumed the original emission integrals for the warm phase as reported in Bonamente et al. (2003), without any rescaling by temperature and abundance as was done in Sect. 4.1 for the intra–cluster interpretation of the soft excess. Any such rescaling would result in changes to these estimates by a factor of few, according to (1) and (8), and hence leave all considerations provided in this section largely unchanged. Notice that, if the filaments where to have a significantly lower density, e.g., $\delta_\rho = 30$, the filament length estimates according to (8) would be significantly larger, i.e., by a factor ×100. Such filament lengths would be at odds with our current understanding of the large–scale filamentary structures. Our data therefore suggest that WHIM filaments towards Coma are indeed on the high–density end of the range expected based on the EAGLE numerical simulations.

Following this WHIM interpretation with $\delta_\rho = 300$ filaments, the warm gas mass in the ROSAT regions is estimated as

$$M_{WHIM} = 2.2 \pm 0.2 \times 10^{14} \left(\frac{n_{WHIM}}{7.8 \times 10^{-5} \text{ cm}^{-3}}\right)^{-1} M_\odot,$$

where the inverse dependence on the assumed WHIM density derives from the inverse proportionality between filaments lengths and the square of the density, according to (8), and the error is the statistical uncertainty associated with the measured emission integrals of the warm gas. This mass estimate does not include any region not explicitly covered by the ROSAT observations, and therefore is to be considered as a strict lower limit, especially given that the coverage at large radii is very sparse. In this paper we do not attempt to correct for the partial coverage of the ROSAT observations, which would lead to an increase of these mass estimates possibly by a factor of few times.

This mass estimate is generally consistent with the EAGLE simulation results of Tuominen et al. (2021) and Holt et al. (2022), where in a $100^3 \text{ Mpc}^3$ volume there is a total mass of $2.2 \times 10^{15} M_\odot$ in several WHIM filaments in the temperature range log T(K) = 5–7, as identified by the Bisous method (Stoica et al. 2007). Our observations of the soft excess emission in the Coma cluster are therefore consistent with a WHIM origin, where WHIM filaments with density, temperature and size of the kind seen in the EAGLE simulations, are responsible for the excess of soft X–ray radiation detected by ROSAT.

4.3 Intra–cluster vs. WHIM origin of the excess

The intra–cluster origin of the soft excess was investigated in the hydrodynamical simulations of Cheng et al. (2005). Their results indicated that an excess of soft X–ray radiation can originate from low–entropy, high–density cooler gas within the virial radius of the cluster. Within this scenario, the gas responsible for the soft excess is inhomogenous or clumpy (as also discussed in Sect. 4.1), as opposed to the more diffuse and homogeneous nature for the hotter, lower–entropy hot ICM. Such clumpiness implies that mass estimates based on a diffuse gas (as those in Sect. 4.1) would be overestimated by a
Figure 6. Estimated masses in the warm phase of the intracluster medium, according to the soft excess flux in the Coma cluster, for different choices of the temperature and abundance of the warm gas. Confidence bands are at the 1σ level. Hatched areas indicate the range of warm gas masses for two representative temperatures, when the metal abundances vary from 10% to 100% Solar.

Figure 7. Surface brightness of the soft excess in each of the ROSAT regions. The soft excess fluxes $F_{24} - P_{24}$ were divided by the area of each region (quadrant or annulus).
factor equal to the degree of clumpiness of the gas, defined as
\[ C = \frac{n_1}{n_2} \leq \frac{1}{f} \geq 1, \]
where the volume of the emitting gas is \( V_E = f \times V \), with \( V \) the physical volume of the spectral region and \( f \leq 1 \) the volume filling factor. Cheng et al. (2005) also found that the amount of soft excess of Coma cannot be readily interpreted as intra–cluster clumpy warm gas, which was seen in lower amounts than those required to explain the Coma excess. The excess emission seen in other clusters, e.g., in the sample studied by Bonamente et al. (2002), was at a lower level, and one that is more consistent with the Cheng et al. (2005) simulations.

Another problem with the intra–cluster warm gas scenario is that such gas would have a short cooling time, raising the issue of its maintenance over a cosmological time (e.g. Bonamente et al. 2001a).

Large–scale hydrodynamical simulations from EAGLE, on the other hand, feature WHIM filaments that can directly explain the soft excess emission in the Coma cluster. In this scenario, filaments with \( 10 \leq 20 \) Mpc length, a temperature of \( \log T(K) \sim 6 \) and an average baryon overdensity \( \delta_B \sim 300 \), provide a natural interpretation for the excess of soft X–ray radiation, which is seen in projection against the cluster, as described above in Sect. 4.2. A similar picture also emerges from the IllustrisTNG simulations (see, e.g. Martizzi et al. 2019; Galárraga-Espinosa et al. 2021), where warm WHIM gas is also preferentially found at large projected distances from the cluster core (Goun et al. 2022).

Additional observational evidence of a WHIM origin for the soft excess in Coma is provided by the spatial distribution of the hot gas and by the measurements of the gas mass fraction and entropy profiles by Mirakhhor & Walker (2020). In fact, along the south–western quadrant where Coma connects with Abell 1367, there is a well–known enhancement of X–ray brightness accompanied by a gas mass fraction that is significantly above the cosmic mean, also featuring a decrease in entropy (see bottom–right panels of Figs. 11 and 13 of Mirakhhor & Walker 2020). As shown in Figs. 3–4 and in Fig. 7, this quadrant also has significant soft excess emission that extends beyond Coma’s virial radius. A natural interpretation of the higher–than–cosmic gas mass fraction from the XMM–Newton/Planck data is that there is an especially hot filament between Coma and Abell 1367, with significant emission both in the main and in the soft X–ray bands. Such filament, when projected against the more spherically–symmetrical distribution of the cluster hot gas and its underlying dark matter potential, could explain the overall higher gas mass fraction in that quadrant. In other azimuthal directions where the gas mass fraction reaches the cosmic value near the virial radius (see other panels of Fig. 13 of Mirakhhor & Walker 2020), the soft X–ray excess is plausibly provided by WHIM filaments at lower temperatures that emit primarily in the soft X–ray band, and thus providing little or no contribution to the gas mass fraction. The presence of these filaments is also consistent with the predictions of numerical simulations by Zinger et al. (2016), where low–entropy WHIM filaments are seen to penetrate deep into the cluster interior. If the soft excess had originated from an intra–cluster gas instead, its large mass implications (see Fig. 6) would further increase the gas mass fraction in all quadrants to significantly higher–than–cosmic values, especially in the south–western quadrant, thus exacerbating the discrepancy between the gas mass fraction and the cosmological ratio of baryons to total matter.

The concurrence of (a) quantitative agreement between the estimated temperature, mass and filament lengths inferred from the observed soft excess with the predictions from numerical simulations of the WHIM, and (b) difficulties in the interpretation of the soft excess as intra–cluster gas, especially in terms of the gas mass fraction, leads to the conclusion that the most likely origin for the cluster soft excess is a WHIM origin.

5 DISCUSSION AND CONCLUSIONS

The availability of high–resolution X–ray measurements of Coma’s temperature profile by XMM–Newton and Planck (Mirakhhor & Walker 2020) have provided confirmation of the presence of strong soft excess emission associated with the cluster. The soft excess was detected in ROSAT data (Bonamente et al. 2003), and it is consistent with a thermal origin from warm gas at sub–virial temperatures, \( \log T(K) \leq 7 \). A similar excess of soft X–ray radiation above the contribution from the hot ICM is present in several other clusters (e.g. Bonamente et al. 2002), but the size, distance and brightness of Coma provide a unique opportunity for the investigation of this phenomenon. In particular, we have investigated two possible origins for the radiation: an intra–cluster origin, where the warm gas co–exists with the hot gas, and a WHIM origin, where the gas is located in filaments that converge towards the cluster. The agreement between expected properties of the WHIM and those inferred from the soft excess, and the difficulties in the interpretation of the excess as warm intra–cluster gas, lead to the conclusion that the most likely interpretation for the soft excess is emission from WHIM filaments that converge towards the massive Coma cluster.

There have been a wealth of observational efforts towards the direct detection of WHIM filaments. The more commonly used methods include the stacking of SZE signal (e.g. de Graaff et al. 2019; Tanimura et al. 2019) and the direct detection of its X–ray emission (e.g. Kull & Böhringer 1999; Eckert et al. 2015; Scharf et al. 2000; Werner et al. 2008; Zappacosta et al. 2005), in addition to the indirect method to identify WHIM filaments via X–ray (e.g. Bonamente et al. 2016; Nicastro et al. 2018) or FUV absorption lines (e.g. Danforth et al. 2016; Tilton et al. 2012). The soft excess phenomenon, demonstrated with high statistical significance in this paper for the Coma cluster, provides a unique way to overcome some of the limitations of the other direct methods of detection of the WHIM. In fact, WHIM filaments are expected to be denser when seen – in projection – within a cluster’s virial radius, and therefore with stronger X–ray emission than when seen beyond that radius (e.g., as in the case of Eckert et al. 2015), or for filaments that are not associated with massive clusters (e.g., in de Graaff et al. 2019).

It remains an open question whether the WHIM can solve the missing baryons problem, i.e., the observation that a significant portion (approximately 1/2) of the low–redshift baryons have not been identified yet (e.g. Danforth et al. 2016). Both numerical simulations and observations are converging on a consensus that WHIM baryons in filaments are sufficient to bridge the missing baryons gap. The ultimate confirmation of the resolution of this problem can only be provided observationally, and the current results are certainly encouraging, but based only on a small sampling of the local universe, as in the cases of Nicastro et al. (2018) and Eckert et al. (2015). The cluster soft excess phenomenon offers a unique opportunity to observe a large sample of nearby clusters with current and future missions featuring stable and well–calibrated soft X–ray response, such as eROSITA, in order to conclusively solve this problem.
