Abundance and temperature of the outer hot circumgalactic medium

The SRG/eROSITA view of the soft X-ray background in the eFEDS field

G. Ponti\textsuperscript{1,2}, X. Zheng\textsuperscript{2}, N. Locatelli\textsuperscript{2}, S. Bianchi\textsuperscript{3}, Y. Zhang\textsuperscript{2}, K. Anastasopoulou\textsuperscript{1}, J. Comparat\textsuperscript{2}, K. Dennerl\textsuperscript{2}, M. Freyberg\textsuperscript{2}, F. Haberl\textsuperscript{2}, A. Merloni\textsuperscript{2}, T. H. Reiprich\textsuperscript{4}, M. Salvato\textsuperscript{2}, J. Sanders\textsuperscript{2}, M. Sasaki\textsuperscript{5}, A. Strong\textsuperscript{2}, and M. C. H. Yeung\textsuperscript{2}

1 INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate (LC), Italy
e-mail: gabrielle.ponti@inaf.it
2 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, 85748, Garching, Germany
3 Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, Via della Vasca Navale 84, 00146 Roma, Italy
4 Argelander-Institut für Astronomie (AIfA), Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
5 Roomex Observatory and ECAP, Universität Erlangen-Nürnberg, Sternwartstrasse 7, 96049 Bamberg, Germany

Received 10 May 2022 / Accepted 11 October 2022

ABSTRACT

Context. Despite their vital importance to understanding galaxy evolution and our own Galactic ecosystem, our knowledge of the physical properties of the hot X-ray emitting phase of the Milky Way is still inadequate. However, sensitive SRG/eROSITA large area surveys are now providing us with the long-sought data needed to mend this state of affairs.

Aims. Our aim is to constrain the properties of the Milky Way hot halo emission toward intermediate Galactic latitudes close to the Galactic anti-center.

Methods. We analyzed the spectral properties of the integrated soft X-ray emission observed by eROSITA in the relatively deep eFEDS field.

Results. We observe a flux of 12.6 and 5.1 \times 10^{-12}\text{ erg cm}^{-2}\text{ s}^{-1}\text{ deg}^{-2} in the total (0.3–2) and soft (0.3–0.6 keV) band. We measure the temperature and metal (oxygen) abundance of the hot circumgalactic medium (CGM) to be within $kT_{CGM} = 0.15-0.178$ keV and $Z_{CGM} = 0.052-0.072 Z_\odot$, depending on the contribution of solar wind charge exchange (SWCX). Slightly higher CGM abundances $Z_{CGM} = 0.05-0.10 Z_\odot$ are possible, considering the uncertain extrapolation of the extragalactic cosmic X-ray background (CXB) emission below $\sim1$ keV. To recover CGM abundances as high as $Z_{CGM} = 0.3 Z_\odot$, the presence of an additional component must be postulated, likely associated with the warm-hot intergalactic medium, providing $\sim 15-20\%$ of the flux in the soft X-ray band. We observe line widths of the CGM plasma smaller than $\Delta v \leq 500$ km s$^{-1}$.

The emission in the soft band is dominated ($\sim 47\%$) by the circumgalactic medium (CGM), whose contribution reduces to $\sim 30\%$ if heliospheric SWCX contributes at the level of $\sim 15\%$ also during solar minimum. The remaining flux is provided by the CXB ($\sim 33\%$) and the local hot bubble ($\sim 18\%$). Moreover, the eROSITA data require the presence of an additional component associated with the elusive Galactic corona plus a possible contribution from unresolved M dwarf stars. This component has a temperature of $kT \sim 0.4-0.7$ keV, a considerable ($\sim$ kiloparsec) scale height, and might be out of thermal equilibrium. It contributes $\sim 9\%$ to the total emission in the $0.6-2$ keV band, and is therefore a likely candidate to produce part of the unresolved CXB flux observed in X-ray ultra-deep fields. We also observe a significant contribution to the soft X-ray flux due to SWCX, during periods characterized by stronger solar wind activity, and causing the largest uncertainty on the determination of the CGM temperature.

Conclusions. We constrain temperature, emission measure, abundances, thermal state, and spectral shape of the outer hot CGM of the Milky Way.

Key words. X-rays: diffuse background – Galaxy: halo – local interstellar matter – Galaxy: abundances – ISM: structure – ISM: general

1. Introduction

We are living in a golden age for Galactic astrophysics. On the one hand, the Gaia satellite, together with large spectroscopic surveys are allowing us to understand the dynamics and composition of the stars of the Milky Way to a degree never reached before (Gaia Collaboration 2016, 2021; Majewski et al. 2017). On the other hand, the standard cosmological model dictates that the formation and evolution of Milky Way-like galaxies is governed by the elusive dark matter halo (White & Rees 1978; White & Frenk 1991; Dodelson & Efstathiou 2004; Mo et al. 2010). In particular, state-of-the-art cosmological simulations suggest that the dominant component of galactic baryons in the present-day Universe should reside in their halos, within the circumgalactic medium (CGM; Crain et al. 2010; Tumlinson et al. 2017; Bogdán et al. 2015; Kelly et al. 2021; Oppenheimer et al. 2020; Truong et al. 2020). Additionally, they predict that the growth and evolution of galaxies critically depend on the physics of the multi-phase interstellar medium (ISM) and CGM (Putman et al. 2012; Tumlinson et al. 2017; Naab & Ostriker 2017). In particular, the

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latter is expected to be dominated by its hotter component, which forms a rarefied plasma close to the virial temperature \( kT \sim 0.15\text{–}0.2\text{ keV} \) and extends to the virial radius \( R \sim 200 \text{ kpc} \). Therefore, this plasma is expected to form a diffuse emission component over the entire sky. Despite its vital importance, our knowledge of the hot Galactic plasma has yet to be attained.

Since its discovery, the study of the cosmic X-ray background (CXB) has been a major field of research (Giacconi et al. 1962). The CXB appears as a uniform X-ray glow over the entire sky, whose energy spectrum has been measured to be consistent with a power law with photon index of \( 1 \sim 1.45 \) in the \( 2\text{–}10\text{ keV} \) band, which then breaks to a steeper slope, therefore creating a peak in the energy spectrum at around \( \sim 30\text{ keV} \); the CXB then rolls over at higher energies (Marshall et al. 1980; Vecchi et al. 1999; Revnivtsev et al. 2003, 2005; De Luca & Molendi 2004; Hickox & Markevitch 2006; Kushino et al. 2002; Gilli et al. 2007). In particular, the advent of XMM-Newton and Chandra have allowed us to make giant leaps forward in our understanding of the CXB, thanks to an array of extragalactic surveys going from the ultra-deep (\( \sim 7\text{ Ms} \)) pencil beam exposures (Luo et al. 2017) to much larger area but shallower surveys (see Brandt & Yang 2022 for a review).

These extragalactic surveys reveal that the majority of the X-ray background above \( -0.5\text{ keV} \) is composed of a large number of faint distinct sources. They allowed us to resolve more than \( -80\% \) and \( -92\% \) of the CXB flux into discrete sources (i.e., active galactic nuclei, AGN; clusters of galaxies; groups; normal galaxies) in the \( 0.5\text{–}2 \) and \( 2\text{–}7\text{ keV} \) band, respectively (Luo et al. 2017; Brandt & Yang 2022). Instead, the X-ray background appears to be truly diffuse at the softest energies below \( -0.5\text{ keV} \).

In the 1990s, the all-sky ROSAT maps revolutionized our understanding of the X-ray background in the softer energy band (Snowden et al. 1991, 1994, 1995, 1997). In particular, the sensitive ROSAT images revealed that the soft X-ray background is highly inhomogeneous and fills the entire sky (Snowden et al. 1991, 1997). The ROSAT data allowed astronomers to disentangle the emission from the local hot bubble (LHB) from the Galactic-scale emission. The former component manifests itself as a hot \( (kT \sim 0.1\text{ keV}) \) bubble surrounding the Sun with a radius of \( \sim 200\text{ pc} \) (Liu et al. 2017; Zucker et al. 2022), therefore dominating the cosmic X-ray background (CXB) in the softest band \( (E < 0.2\text{ keV}; \text{Liu et al. 2017}) \). At energies in the range \( -0.2\text{–}0.6\text{ keV} \) the Galactic-scale emission dominates over the LHB and the CXB\(^1\). This Galactic component was interpreted as either a Galactic corona, which would be produced by a thickened disk with a scale height of a few kpc, or as the emission from the hot halo, extending out to the virial radius \( (r_v \sim 200\text{ kpc}) \). Unfortunately, the low energy resolution of the ROSAT cameras did not allow astronomers to disentangle the emission lines from the thermal continuum. Therefore, accurate measurements of the temperature and abundances of this Galactic component was not feasible. One of the major results of this work is the characterization of the physical properties (i.e., temperature, emission measure, abundances) of the Galactic component. Another result is demonstrating that the CGM\(^2\) and the Galactic corona components are both required by the eROSITA data. Finally, it is important that we verified that the steep continuum (which we associate with hot baryons in the warm-hot intergalactic medium) can contribute with a flux of less than \( -10^{-12}\text{ erg cm}^{-2}\text{ s}^{-1}\text{ deg}^{-2} \) in the \( 0.3\text{–}0.6\text{ keV} \) band, if the CGM abundances are high \( (Z_{\text{CGM}} \gg 0.1\ Z_{\odot}) \).

Over the last two decades, by accumulating hundreds of XMM-Newton and Suzaku observations, astronomers have tried to constrain the soft X-ray emission from the Milky Way (Henley et al. 2010; Henley & Shelton 2012, 2013, 2015; Miller & Bregman 2013, 2015; Miller et al. 2016; Yoshino et al. 2009; Nakashima et al. 2018). They have shown that the Galactic X-ray emission, outside of the Fermi bubbles, can be reproduced by either a beta model with \( kT \sim 0.2\text{ keV} \) and an extension of several hundred kpc (with abundances assumed to be \( Z_{\text{CGM}} = 0.3\ Z_{\odot}; \text{Miller et al. 2016; Bregman et al. 2018} \) or by an exponential atmosphere with a scale height of a few kiloparsec (Yao & Wang 2005, 2007; Yao et al. 2008; Wang et al. 2005; Wang 2009, 2010). Additionally, studies of absorption lines imprinted on the spectrum of a few dozen bright AGN and of the dispersion measure of fast radio bursts provide further observational evidence for the presence of either a hot halo around the Milky Way or an exponential atmosphere (Fang et al. 2015; Miller & Bregman 2015; Prochaska & Zheng 2019). Some of the most recent results include both components; however, they often find the halo component to be dominant (Bregman et al. 2018).

Very instructive is the comparison of what is observed in nearby galaxies. Surprisingly, deep observations of single normal galaxies have often failed to detect an X-ray halo extending to the virial radius, such as the one believed to be surrounding the Milky Way (Wang et al. 2001, 2003; Anderson & Bregman 2011; Anderson et al. 2016; Li & Wang 2013a,b; Li et al. 2017). The clearest detections of hot Galactic plasma were reported around edge-on massive spirals where the hot plasma is observed to form a thick atmosphere, like a corona, extending several kiloparsec above and below the disk (Anderson & Bregman 2011; Anderson et al. 2016; Wang et al. 2001, 2003). Only stacks of samples of galaxies allowed to reach the signal-to-noise ratio required to detect the hot halo beyond several tens of kiloparsec (Anderson et al. 2015; Li et al. 2018; Comparat et al. 2022).

In addition to the intrinsic challenges associated with the detection of such faint and extended galactic halos, an additional complication typically affects the soft X-ray band. It has been demonstrated that the process of charge exchange between the ionized particles of the solar wind with neutrals within the heliosphere can induce a time-variable component to the soft X-ray background, which can be significantly brighter than these galactic halos (Snowden et al. 2004; Kuntz 2019).

With more than three million photons in the soft X-ray band, the eROSITA (Predehl et al. 2021) Final Equatorial Depth Survey (eFEDS) provides us with an unprecedented possibility to study the characteristics of the soft X-ray background (Snowden et al. 1997). The survey, defined during the eROSITA performance verification phase, comprises about 142 square

\(^1\) Hereafter, to avoid confusion, we refer to the extragalactic component of the X-ray background with the term CXB, clearly separating it from the other constituents that become more relevant in the soft X-ray band. We also consider models for the CXB which have a larger flux in the soft band (CXBs) and larger flux in the hard band (CXBh; see Sect. 6.2 for details).

\(^2\) Within a galaxy the CGM would comprise both the coronal component, the halo, and other possible constituents. Throughout this work, we use the term “CGM” (and not “halo”) to refer to all the contributions apart from the hotter Galactic corona. It is likely that the halo emission constitutes the dominant part of what we call CGM; however, we prefer to avoid using the term halo because we still have to probe whether this component has a density distribution consistent with a halo component or whether this emission has a significant fraction produced by a warm corona.
degrees, observed to a uniform depth of $\sim 2.2$ ks in 2019 (Brunner et al. 2022), and re-observed as part of the ongoing all-sky survey program in 2020 and 2021.

2. Dataset and data reduction

We use both the public eROSITA data from the eFEDS field collected during the performance verification (sometimes abbreviated as PV) phase, which we refer to as $e_0$, and the data from the same region accumulated during the first three passes of the all sky survey, which we refer to as $e_1$, $e_2$, and $e_3$, respectively. We refer to the sum of the data from the first two passes as $e_12$ (see our Fig. 1; Brunner et al. 2022).

The eFEDS field covers $\sim 142$ square degrees, extending from Galactic latitude $l$ from $\sim 220^\circ$ to $\sim 235^\circ$ and from Galactic longitude $b$ from $\sim 20^\circ$ to $\sim 40^\circ$ (see Fig. 1). To avoid possible complications occurring at the edges of the eFEDS region, we focus our analysis on the rectangular cyan region shown in Fig. 1, which spans 107.5 square degrees on the sky. A similar surface brightness and color is observed both within the eFEDS field and in regions away from the Galactic plane and away from the Galactic center (Fig. 1). This suggests that the diffuse X-ray emission from the eFEDS field is likely characteristic of the diffuse emission away from the Galactic plane and center. Therefore, it represents an excellent field to study the emission from the soft X-ray background, which is not impacted by the Galactic outflow (Sofue 2000; Bland-Hawthorn & Cohen 2003; Su et al. 2010; Ponti et al. 2019, 2021; Predehl et al. 2020).

In this work we consider the total emission from this region, including point sources, extended sources, diffuse emission, and background.

We investigated the temporal evolution of the particle background during the eROSITA observations of the eFEDS field and we found, in $e_3$, an instance (possibly associated with a coronal mass ejection) where the particle background is enhanced by $\sim 80\%$ and $\sim 30\%$ in the 2.3–4.5 and 0.3–1.4 keV bands, respectively. Such events are observed during $e_0$, $e_1$, or $e_2$. In particular, Fig. B.1 shows the comparison between the $e_12$ spectrum applying the filtering for background flares (with the FLAREGTI tool) and not. The consistency between these spectra corroborates that important background flares do not affect the $e_12$ spectrum; therefore, they do not have an effect on the results obtained here.

The eFEDS field was observed with an exposure depth of approximately $\sim 2.2$ ks during the PV phase ($e_0$), and for about $\sim 250$ s during each of the three all-sky surveys. The eFEDS field was scanned by eROSITA during the following periods: 3–9 November 2019 during $e_0$; 30 April–14 May 2020 during $e_1$; 1–14 November 2020 during $e_2$; and 3–15 May 2021 during $e_3$. We reduced the data with the eSASS Software version 947 (Brunner et al. 2022). In particular, we utilized the user release eSASSusers_201009 from October 2020, which has significant improvements in the energy calibrations of each camera (Dennerl et al. 2020). We considered only single and double events.

To avoid contamination from light leak (Predehl et al. 2021), which affects the cameras TM5 and TM7, we used only the “on-chip” filter cameras: TM1, TM2, TM3, TM4, and TM6.

We fit all spectra with the XSPEC software (Arnaud 1996) version 12.11.1. Uncertainties are reported at the 1σ confidence level for one interesting parameter unless stated otherwise. We used the $\chi^2$ statistics to fit separately the different TM cameras aboard eROSITA (although tying all parameters of the model reproducing the emission from the sky); however, we show the combined spectra and residuals for display purposes only. We assume the Lodders (2003) abundances and Verner et al. (1996) cross sections, unless stated otherwise.

3. Absorption

We estimated the column density of Galactic neutral material from the HI4PI data cube (HI4PI Collaboration 2016). We divided the $\sim 107.5$ square degrees of the eFEDS field that we analyzed into pixels of 11.7 square arcminutes (0.00325 square degrees) and recorded the average column density in the HI4PI map within these pixels. By approximating the observed distribution with a log-normal, we measured a mean column density of neutral hydrogen of $\log(N_H / \text{cm}^{-2}) = 20.51$ and standard deviation $\sigma = 0.117$. Hereafter, following Locatelli et al. (2022), we reproduce the effects of the observed distribution of the neutral absorption column densities by employing the disnt model.

4. Impact of the instrumental background

Figure 2 shows the total emission from the eFEDS field, including all point and extended sources, diffuse emission from the sky, and instrumental background. Thanks to the analysis of the filter wheel closed data, the eROSITA team developed a model of the instrumental background for each camera aboard eROSITA. These models are shown as dotted lines in Fig. 2 (see also Fraternali 2017). At energies above $\sim 0.5--1$ keV, the instrumental background is dominated by a flat power law with a photon index close to $\Gamma = 0$, plus a series of emission lines that are induced by interactions of particles with the detectors and other components of the satellite. At energies below $\sim 0.5$ keV, an increase in

$^3$ Similarly, $e_{123}$ refers to the sum of the first three passes, and so on.
the background level is observed as a consequence of electronic
noise (see the steep power-law shape dominating at low energy).

We observe that the instrumental background dominates over the
effect below \( E \lesssim 0.25 \text{ keV} \) and above \( E \gtrsim 1.5 \text{ keV} \) (Fig. 2). We first perform a fit of the spectrum of
each camera over the entire energy range from 0.2 to 3 keV. We
use a different instrumental background model for each camera,
as specified by the eROSITA team (Fraternali 2017). For each
camera, all the parameters of the instrumental background model
are fixed, apart from a normalization factor which is adjusted, to
the value necessary to fit the data above 2 keV, where the back-
ground is almost a factor of \( \sim 5 \) stronger than the emission
from the sky\(^5\). Then, for each camera, we fix the normalization
of the internal background model to the observed best fit param-
eter and subsequently leave it fixed to that value. We note that this
technique is able to adjust for the variations in the rate of par-
ticles inducing hard X-ray emission; however, it is not suitable
for determining the noise component below 0.25 keV, which is
caused by different effects, and thus not strictly correlated with
the high energy background. We observe large residuals below
\( \sim 0.3 \text{ keV} \) (Fig. 2). Therefore, considering the still limited knowl-
dge of the instrumental background and its evolution with time,
we decided to fit the spectrum only within 0.3 and 1.4 keV to
reduce the impact of the possible variations in the instrumental
background on our best fit models.

5. Solar wind charge exchange (SWCX)

The interaction of the ionized particles of the solar wind with
the flow of neutral ISM that constantly passes through the helio-
sphere produces diffuse soft X-ray emission by charge exchange

\(^5\) This is a consequence of the drop in effective area above \( \sim 2 \text{ keV} \).

(Snowden et al. 2004; Kuntz 2019). The brightness of this component is expected and observed to be modulated by the
properties of the solar wind, and therefore to be variable over
time. Thanks to the scanning strategy of eROSITA, we can probe
all these timescales, and thus verify the impact of any variable
components on the observed emission.

5.1. Variations induced by SWCX

The black, red, green, and blue data in the left panel of Fig. 3
show the total X-ray emission (including point sources, extended
sources, diffuse emission, and background) as observed by
eROSITA in the eFEDS field during e1, e2, e3, and e0 (the PV
phase observations), respectively\(^6\). The diffuse emission has a
low value and it is constant during e1 and e2. The data points
of the e1 and e2 spectra are consistent with each other over the
\( \sim 0.3–1.4 \text{ keV} \) energy band (Fig. 3). On the other hand, enhanced
emission is observed between \( \sim 0.3–0.7 \text{ keV} \) during e3 and e0. In
particular, the peak flux of the O VII line increases from \( \sim 2.6 \) to
\( \sim 3.3 \text{ ph s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \), corresponding to an increase of \( \sim 25\% \)
during e3 (see inset of Fig. 3). For this reason, hereafter we
consider primarily the data taken during e1 and e2.

To determine the total O VII and O VIII line intensities
observed during e12, we fitted the e12 spectrum, within a narrow
energy band (0.45–0.75 keV), with an absorbed power
law and two narrow Gaussian lines plus the instrumental back-
ground\(^7\). We obtain best fit intensities for the O VII and
O VIII of \( I_{\text{O VII}} = 3.1 \pm 0.1 \text{ ph s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \) and \( I_{\text{O VIII}} = 0.28 \pm 0.03 \text{ ph s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \), respectively.

5.2. Constraining SWCX from the difference spectrum

The right panel of Fig. 3 shows the spectrum of the variable
component obtained from the difference of the spectrum observed
during e3 minus that observed during e1. In this way, all constant
components are subtracted, leaving only the variable emission.

We fit the difference spectrum with a solar wind charge
exchange model (ACX2 model in XSPEC, which is part of the
ATOMDB package; Smith et al. 2012; Foster et al. 2020). We
assume solar abundances\(^8\) and single recombination\(^9\). Addition-
ally, we assume a collision speed velocity of 450 km \( \text{s}^{-1} \), in order to
reflect the solar wind speed; however, we tried two different
implementations of this velocity. The first attempt assumes that
450 km \( \text{s}^{-1} \) corresponds to the center of mass velocity, while
the second trial assumes that it corresponds to the donor ion veloci-
ity. The right panel of Fig. 3 shows that an acceptable fit can be
obtained with the first attempt (black line), while the second trial
leaves unacceptable residuals. Therefore, hereafter we assume
a collision speed velocity of 450 km \( \text{s}^{-1} \), corresponding to the
center of mass velocity.

\(^6\) Hereafter we refer to the total emission as “diffuse”. This is justified
by the fact that the diffuse emission dominates over all other contribu-
tions on the large scales considered here. We observe that, within the
\( \sim 0.3–2 \text{ keV} \) band, on scales of a fraction of a square degree or larger,
the total emission is dominated by the diffuse component (including
true diffuse hot plasma components as well as the integrated emission
from point sources, such as the CXB and the Galactic ridge emission).

\(^7\) The absorption is fixed to the values discussed in Sect. 4, while the
background to the values discussed in Sect. 4.

\(^8\) The ACX2 model assumes the Anders & Grevesse (1989) abundances.

\(^9\) We also assume the acx model number four; for more details on
this assumption, see the model documentation at: https://acx2.
readthedocs.io/en/latest/
The black line shows the best fit model, while the red line shows a different implementation of the same model. An enhancement at the energies of the soft X-ray emission lines is observed during e3, compared with e1 and e2. This enhancement is characterized by a spectral shape characteristic of the emission induced by SWCX. A similar enhancement is observed during e0. The inset shows an enlargement of the spectra around the O vii line where the enhancement is most evident.

**Fig. 3.** Left panel: Diffuse X-ray emission as observed by eROSITA in the eFEDS field during e1, e2, e3, and e0 (eRASS1, eRASS2, eRASS3, and PV phase observations) in black, red, green, and blue, respectively (the emission from different TMs is combined for display purposes). An enhancement in the energies of the soft X-ray emission lines is observed during e3, compared with e1 and e2. This enhancement is characterized by a spectral shape characteristic of the emission induced by SWCX. A similar enhancement is observed during e0. The inset shows an enlargement of the spectra around the O vii line where the enhancement is most evident. Right panel: Spectrum of the variable diffuse emission component fitted with a model for the SWCX. The black line shows the best fit model, while the red line shows a different implementation of the same model.

### Table 1

| Energy (keV) | eRASS1 | eRASS2 | eRASS3 | eRASS3 − eRASS1 |
|-------------|--------|--------|--------|-----------------|
| 0.5         | 1.5    | 2      | 2.5    | 3               |
| 0.55        | 1.5    | 2      | 2.5    | 3               |
| 0.6         | 1.5    | 2      | 2.5    | 3               |

**Notes.** The first column (kT) lists the plasma temperature, in units of keV. The second column (F<sub>He0</sub>) is the fraction of neutral helium (relative to the total neutral population, assumed to be H and He) in the plasma. The third column is the flux of the acx2 component in the 0.4–0.6 keV band, over the eFEDS region, in units of 10^−11 erg cm^−2 s^−1 deg^−2. Columns 5 and 6 give the χ^2 and the degrees of freedom.

The best fit plasma temperature of the ionized component and the fraction of neutral helium are kT = 0.136 ± 0.007 keV and F<sub>He0</sub> > 0.2, with a normalization of 0.25 ± 0.09, corresponding to an average flux of 7.4 × 10^−11 erg cm^−2 s^−1 over the eFEDS area in the 0.4–0.6 keV band, which correspond to 6.9 × 10^−13 erg cm^−2 s^−1 deg^−2 (χ^2 = 168.4 for 161 d.o.f.; see Table 1). On the one hand, we note that such values are consistent with this emission being produced by solar wind charge exchange. On the other hand, we note that the spectrum is composed of the variable component only (missing the emission from the constant component); therefore, it is most likely that the best fit values are biased, hampering us from going into a deeper investigation of this effect in this work.

5.4. SWCX emission during e12

Our analysis demonstrates that SWCX is present during e0 and e3, while it still remains to be demonstrated whether SWCX is present also during e1 and e2. Theoretical arguments suggest that this component must also be present at solar minimum, although at a lower level.

Currently, various attempts are in progress to establish the contribution to the total emission due to SWCX during e1 and e2.

− Through a preliminary investigation of the evolution in time of the SWCX component, Dennerl et al. (in prep.) are estimating a count rate in the 0.4–0.6 keV band of −0.068, −0.074, and −0.16 ph s^−1 cm^−2 within the eFEDS field during e1, e2, and e3, respectively. These estimates are consistent with the flux of the SWCX component observed by analyzing the e3 minus e1 spectrum (with a count rate of 0.09 ph s^−1 cm^−2 and flux (6.9 ± 1.5) × 10^−13 erg cm^−2 s^−1 deg^−2 in the 0.4–0.6 keV band; see Table 1). Assuming the SWCX spectrum observed in Sect. 5.2, these values correspond to a flux of −1.2 ph s^−1 cm^−2 sr^−1 in the O vii line during e12.

5.3. Spatial distribution of the excess emission and association with heliospheric SWCX

We investigated the map in the 0.5–0.6 keV band of the emission observed during e3, which is characterized by a more intense solar wind. From the map accumulated during e3, we subtracted the emission in the same band accumulated during e12. The difference map is consistent with a constant excess over the entire region. This confirms that the SWCX emission is associated with an increased glow over the entire eFEDS region (see Ponti et al. 2023), indicating that the excess of SWCX emission occurs on timescales longer than ∼6 days, which is the time it took to scan the eFEDS region.

This behavior appears to be remarkably different from the variability pattern observed in XMM-Newton and Chandra data, where the variations induced by SWCX occur on timescales of hours or days. It is likely that the high Earth orbit of XMM-Newton and Chandra make them more sensitive to the rapidly variable SWCX emission occurring at the edge of the Earth’s magnetosphere (Snowden et al. 2004; Kuntz 2019), while for the orbit around L2 of eROSITA this component is missing, so that eROSITA is sensitive to the more slowly varying heliospheric component of the SWCX emission (Kuntz 2019; Dennerl et al., in prep.).
– Through the study of the nearby Ophiuchus dark cloud, Yeung et al. (2023) are preliminarily estimating the flux of the SWCX component observed by eROSITA. Yeung et al. (2023) observe a flux of \( F_{\text{SWCX}} = (2.1 \pm 0.6) \times 10^{-13} \) and \( F_{\text{SWCX}} = (6.1 \pm 0.7) \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{deg}^{-2} \) in the 0.4–0.6 keV band toward the Ophiuchus cloud during e1 and e2, respectively. These estimates are \( \sim 1.7 \) times lower than the previous values, and they might be the consequence of the different lines of sight or of the different times of observation\(^\text{10}\). Alternatively, they might reflect the intrinsic uncertainty in determining the intensity of the SWCX component. Considering the different SWCX model assumed by Yeung et al. (2023), the above 0.4–0.6 keV surface brightness translates into a flux of \( \lesssim 1.0 \text{ph s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \) in the O VII line during e12.

– Qu et al. (2022) have studied the temporal variation of the O VII and O VIII flux, as observed by XMM-Newton, over one solar cycle. They found a significant variation induced by the heliospheric SWCX component, which shows a minimum close to the solar minimum. In particular, they estimated the true Galactic O VII and O VIII emission lines to have mean values on the order of \( \sim 5.4 \) and \( \sim 1.7 \) ph s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\), respectively. We note that such values are about a factor of \( \sim 1.7 \) and \( \sim 6 \) times higher than the line intensities toward the eFEDS field. This is in line with the fact that we are looking toward a line of sight away from the Galactic outflow, and corroborates the fact that in the e12 spectrum the effects of SWCX are minimal. Additionally, we note that the O VII flux measured by Qu et al. (2022) close to solar minimum are consistent with being entirely due to the Galactic O VII emission. This suggests, therefore, a negligible contribution due to heliospheric SWCX during solar minimum, such as during e12.

We take the differences between these preliminary estimates of the normalization of the SWCX component during e12 as a measure of the current uncertainty on its contribution, which goes from a negligible fraction to a flux of \( \sim 1.2 \text{ph s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \) in the O VII line.

6. Definition of the initial model

In this section we spell out all the ingredients that compose the initial model of the spectrum and that we consider in the following fits.

To minimize the contribution of the emission from SWCX, we fit the e12 spectra alone. Even though the e0 spectrum has a better signal-to-noise ratio, the large and not-well-tracked fluctuations of the flux of the various ions composing the solar wind would induce significant systematic uncertainties to the best fit of e0 and e3.

6.1. SWCX

We assume that the emission from SWCX is subdominant during e12. This is corroborated by the observation that i) the spectra observed during e1 and e2 are consistent with each other; ii) the energy of the O VII triplet is shifted toward the resonant line (Sect. 8.1); and iii) the lines and continuum are consistent with being produced by an optically thin thermal plasma. SWCX is expected to be intrinsically time-variable (as a consequence of the variability of the solar wind, among other effects; Dennerl et al., in prep.); it is characterized by O VII triplets dominated by the forbidden line and has a continuum different from a bremsstrahlung; therefore, it is unlikely to provide a dominant contribution during e1 and e2.

On the other hand, to quantify how our ignorance on the flux of the SWCX component during e12 propagates into our best fit results, we performed two sets of fits. One where we assume that the SWCX emission can be completely neglected. The second one assumes a SWCX component with an intensity as large as estimated by Dennerl et al. (in prep.), and therefore corresponding to a flux of \( (6.9 \pm 1.5) \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) deg\(^{-2}\) in the 0.4–0.6 keV band and a spectral shape constrained by the e3-e1 difference spectrum (Table 1; Sect. 5.2).

6.2. Cosmic X-ray background (CXB)

The integrated emission from the cosmic X-ray background, as measured by different X-ray instruments is shown in Fig. 4 (figure from Gilli et al. 2007)\(^\text{11}\). Over the \( \sim 1 \) to \( \sim 10 \) keV energy range, the CXB can be described with a simple absorbed power-law model (POWERLAW model in XSPEC) with photon index fixed to \( \Gamma = 1.45 \) and a normalization of \( \sim 10.5 \text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at 1 keV (see red dotted line in Fig. 4)\(^\text{12}\). We refer to this model component as CXBh. Additionally, considering its extragalactic nature, we assume that the CXB is absorbed by the full column density of Galactic absorption. Detailed studies with Chandra, XMM-Newton, ROSAT, and other X-ray instruments have resolved more than \( \sim 95 \% \) of this component into point sources (AGN) and galaxy clusters, in the 2–8 keV energy range (Hasinger et al. 1993; Hickox & Markevitch 2006; Revnivtsev et al. 2003; Liu et al. 2017). We note that the CXB normalization of \( \sim 10.5 \text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at 1 keV for a photon index of \( \Gamma = 1.45 \) corresponds to a normalization of \( \sim 0.34 \text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at 1 keV within the eFEDS field of \( \sim 107.5 \text{square degrees} \). Unless otherwise stated, we leave the normalization of the CXB component to be free in the fits and we verify a posteriori whether the normalization of the CXB is within the range allowed by the cosmic variance.

We note that the CXB synthesis models also containing the contribution from groups and clusters suggest that there might be a steepening of the CXB slope at energies below \( \sim 1 \) keV (Gilli et al. 2007). To reproduce this steepening we considered a double broken power-law model, which is assumed to be identical to the simple power-law model above 1.2 keV, but producing a higher flux at lower energies (black dashed line in Fig. 4). The double broken power law has a photon index of \( \Gamma_1 = 1.9 \) below 0.4 keV, then \( \Gamma_2 = 1.6 \) between 0.4 and 1.2 keV, and then \( \Gamma_3 = 1.45 \) above 1.2 keV, with a normalization of \( 8.2 \text{photons cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at 1 keV (corresponding to 0.269 photons cm\(^{-2}\) cm\(^{-1}\) at 1 keV over the eFEDS area). This appears as the most realistic representation of the constraints on the CXB accumulated to date (Gilli et al. 2007), and therefore we use this component (which we refer to as CXB) in all our fits, unless stated otherwise.

We also note that the observed data show a large scatter below \( \sim 1 \) keV (Fig. 4). Therefore, we define a third model, which is still in rough agreement with the observational data and maximizes the emission in the soft X-ray band (see blue dashed line in Fig. 4). The model has a double broken power-law shape

\(^{10}\) eROSITA scans through the Ophiuchus cloud region about one month before the eFEDS field.

\(^{11}\) The y-axis in Fig. 4 reports the values \( E \times F(E) \), where \( F(E) \) shows the flux as a function of energy: \( F(E) = E \times N_{\text{phot}}(E) \), where \( N_{\text{phot}}(E) \) is the number of photons as a function of energy in units of \( \text{c}^{-1} \text{sr}^{-1} \text{keV}^{-1} \).

\(^{12}\) Fluctuations around the average normalization of the CXB are expected to be observed as a consequence of the cosmic variance.
Fig. 4. Cosmic X-ray background spectrum observed by different instruments (see legend at top left) (from Gilli et al. 2007). The solid lines show the predicted contribution from the different components. The black, blue, red, and magenta lines show the emission from Compton-thick, obscured Compton-thin, unobscured AGN, and total AGN plus galaxy cluster emission, respectively. The red dashed line shows the simplified CXB model often assumed in the literature, composed of a power-law shape with photon index $\Gamma = 1.45$ and normalization of 10.5 photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ at 1 keV (referred to as CXBh in this work). In particular, this model fails to properly reproduce the constraints on the cosmic X-ray background emission below $\sim 1$ keV (referred to as CXB in this work). It is composed of a power law with photon index of $\Gamma_1 = 1.96$ below 0.6 keV, then $\Gamma_2 = 1.75$ between 0.6 and 1.2 keV, and then $\Gamma_3 = 1.45$ above 1.2 keV, with a normalization of 8.5 photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ at 1 keV (black dashed line in Fig. 4). We refer to this model as CXBs and we employ it (alongside CXBh) in Sect. 8 in order to understand how our assumptions on the CXB might systematically impact our results.

6.3. Local hot bubble

The Sun is located within a bubble of hot plasma with a temperature of $kT \sim 0.1$ keV and an extension of $\sim 10^2$ parsec, which fills the local cavity (therefore it is unabsorbed in the X-ray band). This bubble is typically called the local hot bubble (LHB), (Cox & Snowden 1986; Snowden & Schmitt 1990; Galeazzi et al. 2014; Liu et al. 2017). Following the work of Liu et al. 2017, we assume that the emission from the LHB is well reproduced by the hot plasma component in thermal equilibrium (APEC model in XSPEC) with a temperature of $kT = 0.097$ keV. Additionally, we assume that this component is unabsorbed, being located within only a few $10^2$ parsec from the Sun. Finally, we assume that it has solar abundance. From Fig. 6 of Liu et al. (2017), we estimate the average emission measure associated with the LHB in the eFEDS field, which results to be 0.00266 cm$^{-6}$ pc. The APEC normalization $N_{\text{spec}}$ is defined as

$$N_{\text{spec}} = 10^{-14} / (4\pi D_A^2) \times \int n_e n_H dV,$$

where $n_e$ and $n_H$ are the electron and hydrogen densities (in cm$^{-3}$), respectively, V is the volume (cm$^{-3}$) and $D_A$ is the angular diameter distance (in cm; see Xspec User Manual13). This can be written as $N_{\text{spec}} = 10^{-14} \int n_e n_H x dV = 10^{-14} \frac{\dot{A}}{4\pi D_A^2} \int n_e n_H x dV$, where $\dot{A}$ is the area of the section of the volume $\perp$ perpendicular to the line of sight and whose extension along the line of sight is $l$, and 0 is the subtended solid angle (in units of steradian). Considering the projected area on the sky of the eFEDS field, which is $\sim$107.5 square degrees, corresponding to 0.0327 sr, this becomes $N_{\text{spec}} = 10^{-14} \frac{0.0327 \times 3.09 \times 10^{14} \times EM \text{(pc cm$^{-6}$)}}{4\pi} \sim 80 \times EM \text{(pc cm$^{-6}$)}. Hereafter, we convert all best fit APEC normalizations from Xspec into $N_{\text{spec}}$ (pc cm$^{-6}$). As for the CXB, we leave the normalization of the LHB free to vary and we check a posteriori whether its value agrees with that observed by ROSAT (Liu et al. 2017).

6.4. Circumgalactic medium

Finally, we assume that the emission from the circumgalactic medium is composed of hot plasma in thermal equilibrium (APEC model in XSPEC).

7. Detection of the elusive Galactic corona

We start our investigation by fitting the eFEDS spectrum with three components: two thermal components (APEC models in XSPEC) of which one for the LHB (red line in Fig. 5) and one for the CGM (blue line in Fig. 5) and a double broken power law for the CXB (magenta line in Fig. 5), in addition to the instrumental background (black line in Fig. 5 and Table A1) and, when specified, the SWCX emission (cyan line in the right panels of Fig. 5). We note that, as a consequence of our assumptions, the spectral shape of the LHB and the CXB are fixed, and therefore only their normalizations are allowed to vary in the fit.

We first investigated the effects of assuming different sets of abundances (see Appendix A) and decided to assume the solar abundances measured by Lodders (2003).

7.1. Signature of the Galactic corona: What is the contribution from faint dwarf M stars?

Regardless of the assumed abundances and whether we include or not the SWCX component, the top panels of Fig. 5 show large residuals at the energy of the O VIII line and between $\sim 0.7$ and 1 keV. The spectrum shows a hump between $\sim 0.7$ and $\sim 1$ keV that cannot be fit by the power-law shape of the CXB (Fig. 5).

To reproduce this hump the continuum of the CGM component would need to have a temperature in excess of $kT \geq 0.2$ keV. On the other hand, the O VIII / O VIII line ratio forces the best fit temperature to be lower than $\sim 0.2$ keV. The result of this tension is displayed by the very bad residuals in the top panels of Fig. 5.

Such bad residuals represent incontrovertible evidence that an additional element is required to reproduce the eROSITA data. Therefore, we add to the model a second thermal component to fit the emission from the Galactic corona. We initially assume the Galactic corona to be collisionally ionized, in thermal equilibrium, and optically thin. Therefore, we assume that it can be described by an APEC model in XSPEC. We further assume the metal abundance within the Galactic corona to be relatively high (based on the belief that the plasma might be deeply

13 https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/ XspecManual.html

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related with fountains and outflows from the interstellar medium in the plane of the Milky Way), and therefore we assume solar abundances for this component (Shapiro & Field 1976; Spitzer 1990; Bregman 1980; Fraternali 2017)\(^\text{14}\).

A very significant improvement of the fit is observed by the addition of the spectral component describing the emission of the Galactic corona, which correspond to \(\Delta kT = 175.3\) and \(\Delta kT = 107.6\) for the addition of two free parameters in the case of negligible and high SWCX contribution, respectively (see Table 2). The model comprising the Galactic corona, in addition to the three other components, now reproduces the bulk spectral features in the soft X-ray spectrum (see Fig. 5). The best fit temperature of the Galactic corona is \(kT = 0.70-0.75\) keV, which is significantly higher than that of the CMG and somewhat lower but in line with what is typically observed along the Galactic plane (and at the Galactic center) and attributed to the hot phase of the interstellar medium (e.g., \(kT \sim 1\) keV; Ponti et al. 2013 and references therein).

Along the Galactic disk a thermal component with a temperature of \(kT \sim 0.7\) keV, therefore with characteristics similar to the Galactic corona, has been observed in Suzaku data and it has been attributed to the cumulative emission due to faint dwarf M stars (Masui et al. 2009). Additionally, observations with X-ray quantum calorimeters aboard sounding rockets achieved measurements of the soft X-ray emission with unprecedented spectral resolution from four large locations within field of view of \(\sim 1\) sr (McCammon et al. 2002, 2008; Wulf et al. 2019). Wulf et al. (2019) detected a spectral feature at \(E \sim 0.9\) keV that can be fitted with a hot emission component \((kT \sim 0.7\) keV\), in addition to the CMG, the LHB, and the SWCX emission, in the two fields crossing the Galactic plane, while such emission was absent at high Galactic latitudes. In Masui et al. (2009), the authors attributed such emission to the contribution of faint dwarf M stars. From the M dwarf model in Wulf et al. (2019), we estimate a contribution from M dwarfs toward the direction of the Galactic center, according to the model proposed by Wulf et al. (2019).

However, we note that the uncertainty on the knowledge of the scale height of the Galactic disk can induce significant scatter in the predicted contribution due to stars. More recent models of the mass distribution and gravitational potential of the Milky Way refine the disk scale height assumed by Wulf et al. (2019), therefore predicting a different contribution due to stars at the relatively high Galactic latitudes characteristic of the eFEDS field. Although this will be the subject of a future investigation that carefully addresses this point, we note that the observation of super-virial plasma in absorption toward some bright AGN (Das et al. 2019a, 2021) corroborates the presence of truly diffuse Galactic hot coronal plasma.

For these reasons, hereafter we associate the hot emission toward the eFEDS field to the Galactic corona; however, we note that a fraction of this emission is most likely due to stars. Soon, by connecting the improved mass distributions of the Milky Way with the advances in our knowledge of the X-ray emission from stars allowed by eROSITA, it will be possible to obtain much improved understanding of the contribution by stars to the overall observed hot plasma emission.

\(^{14}\)We performed all the fits shown in this paper also assuming a metal abundance of 0.7 solar, obtaining statistically equivalent results. The only parameter in the fit that was significantly affected by the change in assumed abundances was the normalization (emission measure) of the coronal component.

Table 2. Best fit parameters obtained by fitting the eFEDS e12 spectrum with different models.

| SPECTRUM e12 | LHB-CGM-CXB | LHB-CGM-Coro-CXB | Shift | LHB-CGM-Coro-CXB | LHB-CGM-Coro2-CXB |
|-------------|-------------|-----------------|-------|-----------------|------------------|
| N_{LHB}     | 5.4 ± 0.5   | 5.7 ± 0.4       | 3.7 ± 0.4 | 4.0 ± 0.4       | 3.4 ± 0.5       |
| N_{CXB}     | 0.300 ± 0.002 | 0.292 ± 0.003   | 0.276 ± 0.003 | 0.274 ± 0.003   | 0.275 ± 0.003   |
| kT_{CGM}    | 0.190 ± 0.005 | 0.240 ± 0.006   | 0.166 ± 0.003 | 0.191 ± 0.006   | 0.162 ± 0.003   |
| Z_{CGM}     | 0.085 ± 0.007 | 0.12 ± 0.02     | 0.069 ± 0.005 | 0.064 ± 0.007   | 0.067 ± 0.004   |
| N_{CGM}     | 27 ± 4      | 11 ± 1          | 46 ± 4   | 26 ± 4          | 49 ± 4          |
| kT_{Coro}   | 0.70 ± 0.03 | 0.75 ± 0.03     | 0.69 ± 0.03 | 0.71 ± 0.03     | 0.49 ± 0.09     |
| \(\chi^2\)  | 1129.8      | 1097.9          | 954.5   | 990.3           | 926.8           |
| d.o.f.      | 815         | 815             | 813     | 813             | 808             |

Notes. LHB, CGM, CXB, Coro, Coro2, SWCX, and shift stand for the local hot bubble, circumgalactic medium, coronal emission in and out of thermal equilibrium, solar wind charge exchange, and shift of the energy scales, respectively. Each column shows the best fit parameters obtained for each model. Each adjacent pair of columns shows the best fit results with the same model, under the assumption of either negligible (left) or thermal equilibrium, solar wind charge exchange, and shift of the energy scales, respectively. Each column shows the best fit parameters obtained for each model. Each adjacent pair of columns shows the best fit results with the same model, under the assumption of either negligible (left) or high SWCX (right) contribution. \(N_{LHB}, N_{CGM},\) and \(N_{Coro}\) show the normalizations of the local hot bubble, circumgalactic medium, and coronal components, respectively, in units of \(10^{10}\) pc cm\(^{-3}\). \(N_{CXB}\) shows the normalization of the CXB component in units of photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV. \(kT_{CGM}\) and \(kT_{Coro}\) show the temperatures of the circumgalactic medium and coronal components in keV. \(\tau\) shows the ionization timescales of the coronal plasma in units of \(10^{10}\) s cm\(^{-3}\).
Fig. 5. **Top left panel**: Diffuse emission as observed by eROSITA within the eFEDS field during e12, fitted with a three-component model (LHB-CGM-CXB in Table 2). The red, blue, magenta, and black solid lines show the contribution from the local hot bubble, circumgalactic medium, cosmic X-ray background, and instrumental background, respectively. The dotted lines show the various contributions to the instrumental background. **Top right panel**: Same as top left panel, once the contribution from SWCX is added to the model (LHB-CGM-CXB-SWCX). The cyan line shows the contribution due to SWCX. **Central left panel**: The addition of the emission from the Galactic corona (solid green) significantly improves the fit (LHB-CGM-Coro-CXB). However, significant positive residuals (at the position of the vertical dashed lines) remain at the energy of the blue wing of the very prominent O\,VII emission line as well as negative residuals on its red wing. **Central right panel**: Same as central left panel, with the addition of the SWCX component (LHB-CGM-Coro-SWCX model). **Bottom left panel**: The addition of a significantly different energy shift applied to the best fit model of each camera reduces the residuals around the O\,VII emission line (shift-LHB-CGM-Coro-CXB). **Bottom right panel**: Same as bottom left panel, with the addition of the SWCX component (shift-LHB-CGM-CXB-SWCX model).

To investigate the origin of these residuals, we fitted the spectrum with a parametric continuum model plus an array of emission lines. To perform this task, we further restricted the energy band over which we perform the fit to the 0.3–0.9 keV energy range, where the most prominent emission lines dominate over the continuum. We fitted the continuum with a power law (with photon index free to vary) plus a thermal component with no emission line (APEC component with no emission line). Additionally, we added four emission lines to reproduce the O\,VII, the O\,VIII, and the C\,VI.
emission, plus a weaker line at $E \sim 0.423$ keV to reproduce the N vii triplet.

The energies and normalizations of the emission lines are free to vary, while their widths are fixed to $\sigma = 1$ eV for the hydrogen-like lines, while to $\sigma = 4$ eV for helium-like lines, to account for the ensemble of the triplet lines. The top and bottom panels of Fig. 6 show the best fit energy of the O vii and O viii emission lines, respectively, as observed by the different cameras aboard eROSITA, during e12 and e0 in black and red, respectively. The horizontal dashed lines indicate the expected energies of the lines (the three lines show the energies of the O vii triplet). The error bars reported in Fig. 6 correspond to the 1$\sigma$ statistical uncertainty, as derived from the fit.

The energy of the O vii line in the e0 spectra (which has the highest signal-to-noise ratio) is determined with high precision (see Fig. 6). Such small statistical uncertainties reveal the systematic uncertainties associated with the reconstructed absolute emission lines for each camera, which does not exactly match the incident line energy (see Dennerl et al. 2020). In particular, we observe a systematic shift that can be as large as $\Delta E \sim 2$–3 eV at the energy of the O vii line$^{15}$, which is consistent with the current calibration of the energy scale (Dennerl et al. 2020).

From the results above, we conclude that the analysis of spectra containing emission lines is very demanding with respect to the energy calibration as errors in the absolute energy scale of a few eV can already cause significant residuals and may lead to wrong conclusions. In order to mitigate this problem, we allow for fine adjustments of the absolute energy scale in the spectral fits of the total spectrum by using a velocity shift (VASHIFT component in Xspec; see Table 2 and bottom panel of Fig. 5). Although this technique conceptually be understood only as an approximation, the resulting energy shifts seem to be sufficiently small to justify this simplified approach. A significant improvement of the fit ($\Delta \chi^2 = 27.7$ and $\Delta \chi^2 = 30.5$ for the addition of five free parameters in the case of negligible and high SWCX contribution, respectively; see Table 2) is observed by the addition of a shift in the energy scale. The standard deviation of the observed shifts is $\sigma \sim 1$ eV, at the O vii line energy, and it can be as large as $\sim 3$ eV.

7.3. Is the Galactic corona in thermal equilibrium?

To investigate the thermal equilibrium of the plasma in the Galactic corona we substitute the APEC model for the Galactic corona with a recombining plasma model (rnei model in XSPEC). This model reproduces the emission from plasma that was initially hot and then rapidly cooled on a timescale shorter than the one required to reach thermal equilibrium. As a consequence of the low densities characteristic of the Galactic corona, we might expect that this plasma might be out of thermal equilibrium. One possible scenario for this might be in the form of a hot outflow (or the rising part of a fountain) from the Galactic disk, which would maintain the Galactic corona constantly replenishing it with energy, plasma, metals, and energetic particles (Bregman 1980; Fraternali et al. 2015; Putman et al. 2012). In addition to solar abundances, we also assumed an initial plasma temperature of 1.2 keV to match the typical temperatures of the hot plasma in the Galactic disk, while we left the current plasma temperature ($kT_{\text{Coro}}$) as a free parameter in the fits.

A significant improvement of the fit ($\Delta \chi^2 = 15.8$ and $\Delta \chi^2 = 15.2$ for the addition of one free parameter in the case of negligible and high SWCX contribution, respectively; F-test probability of $3 \times 10^{-2}$; see Table 2) is observed once a recombining plasma model is used. Both panels of Fig. 7 show that the recombining plasma component is able to better reproduce the data leaving lower residuals in the $\sim 1$ keV band.

The best fit plasma temperatures are $kT_{\text{Coro}} = 0.49 \pm 0.09$ keV and $kT_{\text{Coro}} = 0.47 \pm 0.09$ keV in the case of negligible and high SWCX contribution, respectively, and therefore significantly higher than that of the circumgalactic medium. From the normalization of the coronal emission, we derive an emission measure of $0.9 \pm 0.3 \times 10^{-6}$ cm$^{-6}$ kpc, which corresponds to an electron density of $n_e \sim 0.9 \times 10^{3}$ cm$^{-3}$ for a depth of $\sim 1$ kpc. Assuming that the recombining plasma model is an accurate description of the coronal emission, the best fit provides us with an estimate of the ionization timescale which results in $\tau = (10.7 \pm 3)$ and $(9.9 \pm 3) \times 10^{10}$ s cm$^{-3}$ in the case of negligible and high SWCX contribution, respectively (see Table 2). For an electron density of $n_e \sim 0.9 \times 10^{3}$ cm$^{-3}$, this timescale would correspond to an ionization timescale of about $\sim 4$ Myr, which is longer than the timescale needed for an outflow originating from hot plasma ($kT \sim 1$ keV) in the Galactic disk and moving at the sound speed ($v_s \sim 500$ km s$^{-1}$) in an outflow replenishing the Galactic corona. Such hot plasma would be able to cover $\sim 1$ kpc in $\sim 2$ Myr, which seems in line with the observation that the coronal plasma is possibly out of thermal equilibrium.

Both panels of Fig. 7 show that, even at its peak, the emission from the Galactic corona is comparable to, but lower than, the instrumental background and a factor of $2.5$–$3$ times lower than the emission from the CXB. The relative weakness of the emission from the Galactic corona is in line with the fact that it has only recently been recognized (Das et al. 2019a,b, 2021) as a separate feature in addition to the Galactic halo component and different from the emission from dwarf M stars (Masui et al. 2009; Wulf et al. 2019).

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$^{15}$ The larger statistical uncertainties prevent us from investigating the systematic scatter in either the O viii line or the O vii line in the lower statistic e12 spectrum.
8. Constraining the properties of the hot CGM

The eROSITA data allow us to place robust constraints on the physical properties of the CGM.

8.1. Temperature of the CGM constrained by the O VII and O VIII emission lines

For optically thin hot plasma in thermal equilibrium, the energy and intensity of the emission lines can be used as a powerful tool to estimate the temperature of the plasma, independently from the shape of the underlying continuum.

During e12, the best fit energy of the O VII line is $E_{\text{O VII}} \sim 0.571$ keV (black dotted line in Fig. 6), and therefore consistent with being dominated by the recombination line, as expected in the case of collisionally ionized plasma. On the other hand, the best fit energy of the O VII line is observed to shift to $E_{\text{O VII}} \sim 0.568$ keV during e0 (black dotted line in Fig. 6). We attribute this shift of the best fit energy to a larger contribution of the forbidden line, which is dominant in the SWCX component. Therefore, this corroborates the idea that the higher flux of the O VII emission line during e0 is produced by enhanced SWCX.

For the O VII line in the e0 spectrum, the statistical uncertainties are significantly smaller than the differences in energies ($\Delta E \sim 2–3$ eV) measured by the different instruments. This confirms that the observed scatter is due to systematic uncertainties in the calibration of the energy scale of the different cameras aboard eROSITA.

To measure the O VII $G$-ratio and the O VII-to-O VIII line ratio, we fitted the spectra of each TM with the same parametric model used in Sect. 7.2 (composed of a power law plus an apec component with no emission line); however, we substituted the four emission lines with six narrow emission lines with Gaussian profiles (three for the O VII triplet, plus C VI, O VIII, and the weaker line at $\sim 0.423$ keV, which reproduces the N V II triplet), with energies fixed at the expected values of each transition and shifted by a common value for each camera (produced by the vashift component in XSPEC). To avoid degeneracy due to the fact that the lines of the O VII triplet cannot be separated at the

The $G$-ratio is defined as $G = (f + i)/r$, where $f$, $i$, and $r$ are the intensities of the forbidden, intercombination, and recombination lines, respectively (Porquet & Dubau 2000).

CCD resolution of the eROSITA cameras (Predehl et al. 2021), we fixed the ratio of the forbidden to intercombination lines at 3.5, as expected for plasma at densities as low as those considered here. We expect that the combination of the C VI and O VIII lines will constrain the cross-calibration across the different cameras by determining the inter-camera shift of the energy scale. This will then allow us to estimate the $G$-ratio of the O VII triplet (Porquet & Dubau 2000; Porquet et al. 2001).

The black and red points in the top panel of Fig. 8 show the $G$-ratio of the O VII triplet in the e12 and e0 spectra, respectively.17 Because of the large error bars and scatter associated with the determination of the $G$-ratio, the top panel of Fig. 8 shows the $y$-axis in logarithmic scale. $G$-ratios as high as 20 are observed; however, these high values are characterized by very large uncertainties (Fig. 8). We compute the best fit $G$-ratio by performing a fit with a constant, which is equivalent to a weighted mean. In particular, we observe that during e12 a fit of the $G$-ratio observed by each camera provides the best fit value of $G = 0.9^{+0.6}_{-0.5}$. It is well known that the $G$-ratio is a good temperature diagnostic (Porquet & Dubau 2000; Porquet et al. 2001). By comparing the measured $G$-value and its uncertainties (dashed lines in Fig. 9) with the expectations from the models of collisionally ionized plasma (black circles in Fig. 9), we obtain that the temperature of the plasma producing the O VII triplet must be higher than $kT > 0.06$ keV.

The bottom panel of Fig. 8 shows the ratio of the best fit intensities of the O VII to the O VIII lines, obtained by fitting the total spectrum. The fit of the ratio with a constant provides a best fit value of about $7.7 \pm 0.9$. This line ratio is also a very sensitive temperature diagnostic tool. The red circles in Fig. 9 show the expected ratio as a function of the temperature of the plasma,18 under the assumption that a single optically thin and collisionally ionized component is producing all of the flux from the O VII and O VIII lines. By comparing our measurement with the expected relation (see the dashed red lines in Fig. 9), we place

16 The $G$-ratio is defined as $G = (f + i)/r$, where $f$, $i$, and $r$ are the intensities of the forbidden, intercombination, and recombination lines, respectively (Porquet & Dubau 2000).

17 The ability to determine the $G$-ratio through this technique is somewhat hindered by leaving the energy scale anchored to the C VI and O VIII lines, which are significantly weaker than the O VII line. This is then reflected into the rather large error bars associated with the determination of the $G$-ratio.

18 Such lines show the $G$-ratio and line ratios as expected for optically thin collisionally ionized plasma in thermal equilibrium (the APEC model in Xspec).
a tighter constraint on the temperature of the plasma producing the O VII and O VIII lines of $0.152 < kT < 0.160 \text{ keV}\)\(^{19}\).

The best fit temperature of the CGM component results to be $kT = 0.157 \pm 0.004 \text{ keV}$, while it increases to $kT = 0.173 \pm 0.005 \text{ keV}$ for a high SWCX contribution. If the SWCX component provides a significant fraction of the O VII line, then the temperature estimate derived from the line ratio will be biased low.

Even though the statistical uncertainty on the measurement of the CGM temperature is as low as $\sim 3\%$, we conclude that the systematic uncertainty induced by the uncertainty on the amplitude of the SWCX emission during e12 is as large as $\sim 10\%$. In particular, assuming a larger contribution due to SWCX does result in a hotter CGM plasma (i.e., $kT = 0.173 \pm 0.005 \text{ keV}$).

Finally, we estimate an upper limit to the soft X-ray line widths. After assuming that all six lines, which have been fitted, are broadened by the same amount, we measured an upper limit to the line widths of $\Delta v \leq 500 \text{ km s}^{-1}$.

8.2. Determining the metal abundances of the hot CGM

We note that the best fit metal abundances of the CGM component is $Z_{\text{CGM}} = 0.068 \pm 0.004 Z_\odot$ and $Z_{\text{CGM}} = 0.058 \pm 0.006 Z_\odot$ for negligible and high SWCX contribution, respectively, which correspond to a statistical uncertainty on the order of $\sim 5\%$. Such remarkable statistical accuracy is due to the fact that the CGM component produces both the soft X-ray emission lines as well as most of their underlying continuum. The systematic uncertainty on the metallicity induced by the poorly constrained SWCX contribution is only $\sim 15\%$. In particular, the best fit with high SWCX contribution corresponds to lower abundances, in agreement with the fact that SWCX provides a larger contribution to the lines than to the continuum.

The best fit metal abundance appears to be remarkably low, with best fit values on the order of $Z_{\text{CGM}} \sim 0.06-0.07 Z_\odot$ for the Lodders (2003) abundances, regardless of the model employed (see Table 2). This is dictated by the low equivalent widths of the soft X-ray emission lines, such as O VII and O VIII. Figures 5 and 7 both show that the thermal component associated with the emission of the CGM reproduces not only the bulk of the emission lines, but also the bulk of the soft X-ray continuum

\(^{19}\)As for the $G$-ratio, the higher O VII to O VIII ratio observed during e12 is a consequence of the additional contribution due to SWCX.

8.2.1. Impact of the CXB on the measured CGM abundances

As detailed in Sect. 6.2, the shape of the CXB is well known above $\sim 1 \text{ keV}$, while significant uncertainties are related with its contribution below $\sim 1 \text{ keV}$. To take into account the impact of these uncertainties on the determination of the metal abundances of the CGM component, we refitted the eFEDS spectrum substituting the CXB component first with its harder possible spectrum (CXBh; see Sect. 6.2).

The left columns of Table 3 show the best fit results once the CXB component is substituted with CXBh, for the case of negligible and high SWCX flux in the first and second column, respectively (Table 3). We observe, as a result of the introduction of the CXBh component, that the best fit CGM abundance drops significantly to values of $Z_{\text{CGM}} = 0.057 \pm 0.003$ and $Z_{\text{CGM}} = 0.046 \pm 0.003 Z_\odot$, and the quality of the fit worsens ($\chi^2 = -2.1$ and $-4.2$ for the same degrees of freedom) in the case of negligible and high SWCX scenarios, respectively. This confirms the expectation that, if a smaller fraction of the soft X-ray continuum is produced by the CXB, then the CGM will be required to have lower metal abundances to produce the same lines and vice versa.

We then refitted the eFEDS spectrum substituting the CXB component with its softer possible spectrum (CXBs; see Sect. 6.2). Once the spectrum if fitted with this model, we observe that the normalization of the LHB component rises to high values ($N_{\text{LHB}} = 0.0041 \pm 0.0004 \text{ pc cm}^{-6}$), which
are inconsistent with those observed by ROSAT ($N_{\text{LHB}} \sim 0.0027$ pc cm$^{-6}$). If the LHB emission were so high, then it would predict a flux in the R1 and R2 ROSAT bands significantly larger than was observed. Therefore, we fix the normalization of the LHB to the value observed by ROSAT.

The central columns of Table 3 show the best fit results, once the CXB component is substituted with CXBs, for the case of negligible and high SWCX flux, respectively (Table 3). Again, the quality of the fit worsens ($\Delta\chi^2 = -12.7$ and $-19.8$ for one less degree of freedom); however, we observe that the best fit CGM abundance rises significantly to values of $Z_{\text{CGM}} = 0.093 \pm 0.008$ and $Z_{\text{CGM}} = 0.089 \pm 0.009 Z_\odot$ in the case of negligible and high SWCX, respectively (Table 3). This suggests that CGM abundances as high as $Z_{\text{CGM}} = 0.1 Z_\odot$ are not excluded by the data if a soft CXB component is assumed. In particular, this exercise shows that, although the statistical uncertainty on the measurement of the CGM abundance is as small as $\sim 5\%$, the uncertainty on the true contribution to the soft X-ray continuum of the CGM component induces a larger systematic uncertainty of $\sim 70\%$. In fact, changing the assumptions on the shape of the CXB below $\sim 1$ keV, we measure an abundance within the range from $Z = 0.046 \pm 0.003$ to $Z = 0.093 \pm 0.008 Z_\odot$.

8.2.2. An additional non-thermal component to the soft X-ray diffuse emission?

An alternative option to recover larger metal abundances for the CGM would be to assume that a new hypothetical component would produce the bulk of the continuum in the $\sim 0.3$–1 keV band. Such component shall not produce emission lines, therefore it must be non-thermal$^{20}$. Additionally, such

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20 We think it unlikely that a thermal and optically thick component, such as blackbody emission, could be associated with the rarefied plasma producing the diffuse emission over large portions of the sky in extragalactic fields.
law must be associated with a thermal component from the distant Universe\textsuperscript{21}.

Filaments in the Universe as well as hot baryons in the outskirts of virialized regions are expected to have temperatures lower than 1 keV and to have low abundances $Z \sim 0.05$--0.1 $Z_\odot$ (Roncarelli et al. 2012; Vazza et al. 2019). In theory, if filaments at different redshifts contributed to the soft X-ray emission, then the emission lines associated with the thermal spectra of the filaments would appear smeared out by the redshift distribution. Therefore, the resulting spectrum is expected to appear as a rather steep power law with slope of $\Gamma \sim 1.5$ and $\Gamma \sim 3.8$ at 0.3--0.8 and 0.8--2.0 keV, respectively (Roncarelli et al. 2012). Although the slope of the additional power law appears somewhat steeper than these values, we note the resemblance between the expected spectrum from the hot baryons in filaments at different redshifts and the power law observed here.

Roncarelli et al. (2012), after assuming different recipes for galactic winds and black hole feedback, estimated the surface brightness of the whole intergalactic medium (i.e., all the gas) and of only its warm-hot component. They find the surface brightness for the former and the latter to be $\sim 3.1$--24.5 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ and $\sim 0.9$--3.2 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, respectively, in the 0.5--2.0 keV band. Instead, in the 0.3--0.8 keV band they find a surface brightness of $\sim 2.2$--12.0 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ and $\sim 1.0$--3.3 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, respectively.

The observed surface brightness of the best fit additional power law is $\sim 1.9$--3.5 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, in the 0.6--2.0 keV band, in the case of high and negligible SWCX contribution, respectively. This is within the expected range of fluxes expected from the warm-hot intergalactic medium and, as expected, it is much fainter than the total intergalactic medium emission. The emission from galaxy clusters is already included in our fiducial CXB model (Gilli et al. 2007).

On the contrary, in the 0.3--0.8 keV band the observed surface brightness of the best fit power-law emission is $\sim 7.6$--9.9 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, and therefore compatible with the highest estimates for the whole intergalactic medium and a factor of $\sim 3$--10 times higher than the surface brightness of only its warm-hot component. This indicates that either the contribution of clusters is underestimated in our fiducial CXB model or that the additional power law is physically not well justified and the CGM abundance is low. We note again that if all of the flux associated with the additional power-law component is associated with the warm-hot intergalactic medium, then it would be a lucky coincidence that the power law contributes to the total spectrum in such a way to reproduce the continuum of the CGM emission.

To conclude, it is most likely that the warm-hot intergalactic medium contributes to the soft X-ray background; however, to assess whether its contribution is strong enough to significantly affect the estimated CGM abundance, a self-consistent modelling of the contributions of the different components of the extragalactic CXB emission (i.e., AGN; galaxies; clusters; groups; warm-hot intergalactic medium) must be performed in a self-consistent way both in the data and in the simulations. Unfortunately, this is beyond the scope of the current work; however, this calls for a deeper understanding of the contribution of warm-hot intergalactic medium to the soft X-ray background.

8.2.3. Other biases on the observed CGM metal abundance

Early observations of non-virialized hot plasma have found somewhat lower abundances, compared with expectations, when fitted with a single temperature component (as done here). It is now recognized that plasma with a significant spread in temperature can obtain best fit values of the metal abundance that are biased toward lower values when fitted with single temperature models. In theory, this might also be a concern for the CGM of the Milky Way. On the other hand, the indication that the CGM temperature derived from the continuum, the oxygen line ratio, and the $G$-ratio of the O viiii triplet agree with each other suggests that the spread in temperature of the CGM plasma might be small enough to induce only a small bias in the best fit metal abundances measured here. However, we leave the detailed investigation of this issue for future works.

We conclude that the best fit metal abundance of the CGM along the direction of the eFEDS field is $Z_{\text{CGM}} = 0.068 \pm 0.004$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10.png}
\caption{Same spectrum and color scheme as in Fig. 7. Left panel: Best fit model (shift-LHB-CGM-Coro2-CXB-PL in Table 3) after the inclusion of an additional non-thermal component (power law; shown with the orange solid line) to the same spectrum and model components shown in Fig. 7. Right panel: Same as left panel, but with the addition of the SWCX component (shift-LHB-CGM-Coro2-CXB-PL-SWCX model).}
\end{figure}

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\textsuperscript{21} We also exclude that the additional power law is induced by a constant flux of soft protons interacting with the structure and detectors of eROSITA. Although a stable and faint flux of soft protons might still be present, even after applying the FLAREGTI tool, thus potentially inducing soft X-ray emission, the same soft X-ray emission must then also be observed during the filter wheel closed observations. On the contrary, the additional power-law component is not detected during the filter wheel closed data.

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The development of a comprehensive galaxy-CGM-corona model requires the position of the soft X-ray background to be the first step toward understanding the role of the Galactic corona. This decomposition from the LHB; the CXB; the CGM; and the Galactic corona. Within the corona the intermediate and high velocity clouds (IVC and HVC, respectively) are observed, composed primarily of atomic hydrogen (red ellipses). It is likely that the intermediate velocity HI clouds represent the other phase of a cycle where hot material is expelled from the disk to then come back as cold gas.

9. Discussion

After removing the periods affected by emission from SWCX (during e0 and e3) and performing simplifying assumptions on the level of SWCX contamination during e12, we fitted the integrated X-ray emission observed by eROSITA in the eFEDS field with a combination of four components: the unabsorbed emission from the LHB; the CXB; the CGM; and the Galactic corona.

We note that the presence of the Galactic corona, in addition to the CGM component, is already strictly required by the eROSITA data. Additionally, we tested the impact on our best fit results induced by a non-negligible SWCX flux during e12. This decomposition of the soft X-ray background is the first step toward understanding the development of a comprehensive galaxy-CGM-corona model (Fig. 11). In particular, a schematic picture of this interaction is discussed in Sect. 9.6.

The mean surface brightness observed by eROSITA in the eFEDS field in the total (0.3–2 keV), the soft (0.3–0.6 keV), and the medium (0.6–2 keV) bands is $12.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, $5.1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, and $7.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, respectively (Table 4).

9.1. Is a contribution due to SWCX emission during e12 required?

When comparing the best fit models with the assumption of negligible and high SWCX fluxes, we note that the former provide significantly better fits ($\Delta \chi^2 = 33.6$ for the same degrees of freedom; see Table 2). However, the detailed comparison of the residuals shows that the highest deviations occur in the softer band, below ~0.35 keV, where a non-negligible contribution due to the electronic noise of the eROSITA cameras is possible. Therefore, we do not think that this evidence can be considered a demonstration that the SWCX emission must be negligible during e12. Instead, we leave this measurement for future works (which will better address the contribution of electronic noise and of the time variations of SWCX; Dennerl et al., in prep., Yeung et al. 2023).

9.2. Composition of the observed background and CXB resolved fractions

The emission in the 0.6–2 keV band is dominated by the CXB component, which alone composes more than $>83\%$ of the flux, both in the case of negligible and high SWCX contribution. The remaining emission is due to the Galactic corona, which produces about $\sim$8–9% of the flux, and the CGM, which contributes $\sim$6–7% of the total. This is consistent with the fact that about $\sim$81% of the flux in the 0.5–2 keV band has been resolved into discrete sources thanks to ultra-deep surveys with Chandra and XMM-Newton (Luo et al. 2017). Additionally, this suggests that the majority of the remaining X-ray flux (~15%) is truly diffuse and is likely due to the emission from the CGM and the Galactic corona. However, we expect that the fractional contribution due to the Galactic emission varies greatly with Galactic latitude. In particular, we expect that the emission from the Galactic corona drops significantly at higher Galactic latitudes (see Locatelli et al., in prep.). We note that most of the ultra-deep surveys were carried out at high Galactic latitudes ($b > 50\degree$). Therefore, we expect that the contribution from the Galactic corona might be smaller than the amount observed in the eFEDS field (~9%) along the lines of sight investigated in such ultra-deep fields (Brandt & Yang 2022).

22 As mentioned in Sect. 7.1, a fraction of the emission that we attribute to the Galactic corona might be due to M dwarf stars.
In the soft band (0.3–0.6 keV), one-third of the flux is produced by the CXB component. We note once more that the extrapolation of this component at energies lower than 0.5–1 keV carries significant uncertainties. The observed flux from the CGM, which carries most of the flux in the soft band, is highly affected by the assumed flux of the SWCX component. The CGM is observed to encompass ∼47% of the flux under the assumption of negligible SWCX, while this percentage drops to ∼30% in the case of high SWCX flux. Considering that the SWCX component, under the assumption of a high SWCX flux, contributes to the level of ∼15%, this is consistent with the idea that all of the flux attributed to the SWCX component is taken from the CGM component, while the flux of the LHB and of the Galactic corona appear to be nearly unaffected by the assumption on the SWCX flux. The former is observed to contribute to ∼18–19% to the soft X-ray emission, while the latter has a negligible contribution of ∼2% to the soft X-ray emission.

We have shown that if the CGM abundances is \( Z_{\text{CGM}} = 0.3 Z_\odot \), then a steep (\( \Gamma = 4.3 - 4.8 \)) power-law component (likely associated with the warm-hot intergalactic medium) is required to fit the diffuse emission from the eFEDS region. This component must have a flux of \( F_{PL} \sim (7 - 10) \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{deg}^{-2} \) in the 0.3–0.6 keV band, therefore contributing to ∼15–19% to the soft X-ray background.

### 9.3. A posteriori validation of the best fit

We observe that the parameters of our best fit models show a weak dependence on the extrapolation of the CBX component below ∼1 keV. When comparing the final best fit models, we observe that all the best fit parameters are consistent with each other, apart from the temperature, normalization, and metal abundance of the CGM\(^{22} \) (see Tables 2 and 3).

When comparing in detail each single best fit model with its version including SWCX, we observe that the addition of the SWCX component induces a significantly hotter CGM and a correspondingly lower CGM normalization. In particular, consistent temperatures are measured for models considering either a negligible or a high SWCX contribution. Additionally, as detailed in Sect. 9.2, for each model the addition of the SWCX component decreases the flux attributed to the CGM component, causing its normalization to drop (see Tables 2, 3, and 4). We observe that, although it is a free parameter of the model, the normalization of the CXB and CBXs components are consistent with the expectations. The normalization of the LHB component is also consistent, within 1.5\( \sigma \) (\( N_{\text{LHB}} = 0.0032 \pm 0.0005 \) and \( 0.0034 \pm 0.0006 \) \text{pc cm}^{-6} \) for the shift-LHB-CGM-Coro2-CXB and shift-LHB-CGM-Coro2-CXB-SWXC models, respectively) with its expected value (\( N_{\text{LHB}} = 2.7 \times 10^{-3} \) \text{pc cm}^{-6} \)). This, therefore, verifies a posteriori that the soft X-ray flux attributed to the LHB component is consistent with the flux observed by ROSAT along the same line of sight (Liu et al. 2017). As specified in Sects. 8.2.1 and 8.2.2, for the shift-LHB-CGM-Coro2-CXB and shift-LHB-CGM-Coro2-CXB-PL models (and their versions including the SWCX component), we observed that the initial best fit was able to find a normalization of the LHB component which produced a flux in the R1 and R2 bands that was significantly larger than that observed by ROSAT. For these reasons, we fixed the LHB normalization in those models.

### 9.4. Temperature of the CGM

By fitting the spectrum of the eFEDS field, we constrained the temperature of the CGM to a very small statistical uncertainty on the order of ∼3% (Table 2). We measured that the poorly constrained SWCX contribution during e12 would induce a variation in temperature from \( kT_{\text{CGM}} = 0.157 \pm 0.004 \) keV to \( kT_{\text{CGM}} = 0.173 \pm 0.005 \) keV for negligible and high flux, respectively, therefore a systematic uncertainty as large as ∼10%.

Assuming the validity of the virial theorem and that the gravitational potential is dominated by a Navarro et al. (1997) profile of the dark matter halo, then theoretical arguments suggest that the CGM should be isothermal (although we know that this is not true for galaxy clusters). In particular, assuming the validity of the equation \( kT_{\text{vir}} = \frac{GM_\bullet m_p}{2 \sigma^2} \) (where \( G \) is the gravitational constant, \( \mu \) is the mean atomic number per atom, and \( m_p \) is the proton mass), we can estimate an order of magnitude for the virial temperature\(^{25} \).

We compute the mean atomic number per atom, which corresponds to the solar abundances assumed here (Lodders 2003). For all the elements X heavier than He, the solar abundance \( z(X) \) value is rescaled for a constant factor \( \zeta \) to fit the data. The mean atomic number per atom \( \mu \) can then be derived as

\[ \mu = \frac{GM_\bullet m_p}{2 \sigma^2} \]

As a consequence of the assumption on the CBX shape, the normalization of the CBX emission is different in the two models; however, it is consistent with the expected values of 0.260 photons s\(^{-1}\) cm\(^{-2}\) at 1 keV and 0.34 photons s\(^{-1}\) cm\(^{-2}\) at 1 keV for the CBX and CBXh models, respectively. This is not surprising. The CBX component is anchored by the data at high energy, and therefore a different assumption on its extrapolation in the soft X-ray band, which then induces a different normalization of the CBX component at 1 keV.

Different assumptions (e.g., the presence of pressure at the virial radius) can lead to expected virial temperatures that differ by ∼30% or more.

### Table 4. Surface brightness of the various components of the diffuse emission.

| Energy (keV) | SWCX | SWCX | SWCX |
|-------------|------|------|------|
| 0.3–2.0 keV | 9.5  | 10.1 | 9.2  |
| 0.3–0.6 keV | 9.2  | 9.8  | 0.3  |
| 0.6–2.0 keV | 8.2  | 7.6  | 0.7  |

**Notes.** Nomenclature as in Table 2. Listed in each pair of columns is the surface brightness derived from the best fit obtained with the models shift-LHB-CGM-Coro2-CXB (left) and shift-LHB-CGM-Coro2-CXB-SWXC (right), (see Table 2). For the shift-LHB-PL model, we report the flux of SWCX (right), (see Table 2). For the CXB-PL we report the flux of SWCX (right), (see Table 3). Fluxes are in units of \( 10^{−13} \) erg cm\(^{-2}\) s\(^{-1}\) deg\(^{-2}\).
\[ \mu = 1 + 2 \times z(He) + \sum_X 2 \times z(X) \times \zeta \times \xi(X) \], where \( z(X) \) is the atomic number of the element \( X \). For \( \zeta \approx 0.1 \) and the assumed solar abundance values, we obtain \( \mu = 1.32 \). Then, by assuming a virial mass and radius of \( M_{\text{vir}} = 1.3 \pm 0.3 \times 10^{12} M_\odot \) and \( R_{\text{vir}} = 282 \pm 30 \) kpc, respectively (Bland-Hawthorn & Gerhard 2016), we obtain \( kT_{\text{vir}} \approx 0.14 \pm 0.04 \) keV, which is consistent with the observed value.

It is reassuring that looking outward, toward directions where the influence of the dark matter is expected to be greater, the CGM temperature corresponds to the virial prediction. However, this assumption breaks down close to the Galactic disk, where the CGM plasma is heated to form the Galactic corona (as this work demonstrates) as well as close to the Galactic center, where the eROSITA bubbles and Galactic center chimneys testify the presence of significantly hotter plasma (Ponti et al. 2019, 2021; Predel et al. 2020).

We also note that other studies, looking toward other lines of sight, measured different temperatures of the CGM (Henley et al. 2010; Henley & Shelton 2015; Miller & Bregman 2013, 2015; Yoshino et al. 2009; Nakashima et al. 2018; Kataoka et al. 2018). Therefore, it is most likely that the real scatter on the CGM temperature is significantly larger than our statistical uncertainty.

9.5. CGM abundances

We measured the abundance of the hot CGM with a statistical uncertainty of \( \sim 5\% \). We note that the systematic uncertainty on the abundances, induced by the SWCX contribution during e12, is on the order of \( \sim 15\% \); therefore, the abundance is estimated to be within the range from \( Z_{\text{CGM}} = 0.058 \pm 0.006 Z_\odot \) to \( Z_{\text{CGM}} = 0.068 \pm 0.004 Z_\odot \) (Table 2). Additionally, we showed that the uncertainty on the proper extrapolation below 1.4 keV of the CXB component results in a larger systematic uncertainty on the order of \( \sim 70\% \), with an abundance within the range \( Z_{\text{CGM}} = 0.04 \pm 0.10 Z_\odot \). These values are several times lower than the value \( (Z_{\text{CGM}} = 0.3 Z_\odot) \) typically assumed to model the observed emission and absorption lines induced by the CGM (see Bregman et al. 2018 and references therein). Therefore, we expect that this difference will have a significant impact on some of the derived parameters of the hot CGM, such as its density and total mass.

The observed abundances, although lower than typically assumed, are in good agreement with predictions from cosmological simulations, which forecast an abundance of \( \sim 0.1 \) solar or lower for the outer hot CGM in Milky Way galaxies in the present-day Universe (Crain et al. 2010). Cosmological simulations suggest that the CGM gets enriched with metals within a central funnel, where outflows can produce features such as the eROSITA bubbles (Predel et al. 2020; Pillepich et al. 2021). Additionally, the energetic activity within the Galactic disk is expected to drive super-bubbles, fountains, and chimneys, which are collectively sustaining a metal-enriched corona present just above the Galactic disk such as the one observed in this work. On the other hand, the outer CGM, away from the central funnel, appears to be less affected by outflows and feedback, and therefore its metal abundance is closer to that in the filaments of the large-scale structure and the pristine composition.

The question arises of whether the metal abundance measured here is in agreement with independent constraints. The line of sight toward the Large Magellanic Cloud allows us to estimate the metal abundance in that direction by combining the electron column density derived from the pulsar dispersion measure and the equivalent width of the O VII line (Wang et al. 2005; Yao et al. 2009; Fang et al. 2013; Miller & Bregman 2013, 2015; Miller et al. 2016). Assuming the current best fit model for the density distribution within the CGM, several authors have estimated the CGM abundances being larger than 0.3 solar (see Bregman et al. 2018 and reference therein). We point out that the current state-of-the-art models of the density of the CGM might be affected by the hot plasma associated with the eROSITA bubbles (Locatelli et al., in prep.). These models were developed before the discovery of the eROSITA bubbles and are biased. Although those works avoided lines of sight passing through the Fermi bubbles, they contain lines of sight through the eROSITA bubbles, which might bias the density distribution of the CGM in the center. Additionally, a fraction of the electrons contributing to the dispersion measure might be associated with the Galactic corona, which still misses a solid model for its density distribution (but see Kaaret et al. 2020). Therefore, until a detailed understanding of these effects is properly taken into account, we cannot conclude that the CGM abundances must be higher than 0.3 solar between us and the LMC or whether it can be consistent with the value observed in this work of \( Z_{\text{CGM}} \approx 0.04 \pm 0.1 Z_\odot \), as has been observed toward the eFEDS field.

A metal-rich CGM implies the detection of the warm-hot intergalactic medium

We have shown that, by postulating the presence of an additional non-thermal component (a power law), it is possible to recover CGM abundances as high as \( Z_{\text{CGM}} \approx 0.3 Z_\odot \) (Sect. 8.2.2). Additionally, the properties of this component are somewhat reminiscent of the expected emission from the warm-hot intergalactic medium. We conclude that, if it can be demonstrated that the CGM has to be metal rich \((Z_{\text{CGM}} \gg 0.3 Z_\odot)\), then a significant fraction \((\sim 15\% - 19\%\) of the soft X-ray background is required to be produced by the warm-hot intergalactic medium.

9.6. A schematic view of the hot phase of the Milky Way

Figure 11 shows a schematic view of the different components to the diffuse soft X-ray emission observed in the eFEDS field. The yellow stripe along the Galactic plane represents the Galactic disk where the multi-phase ISM lies. Therefore, we represent this component with a thick stripe along the Galactic disk with a scale height of \( h = 1 \pm 0.1 \) pc, which corresponds to the scale height of the cold and molecular phase (Ferrière 2001).

The Sun is located within this stripe about \( \sim 24 \) pc above the mid-plane of the Milky Way (Bland-Hawthorn & Gerhard 2016). The emission associated with the SWCX is expected to be produced within several astronomical units, and therefore it appears too small to be drawn in Fig. 11. For this reason, we omit it.

The red circle in Fig. 11 represents the emission from the local hot bubble, which is characterized by a radius of \( \sim 200 \) pc with the Sun close to its center (Liu et al. 2017). It is expected (and observed) that the shape of the local hot bubble deviates significantly from the perfect sphere displayed in Fig. 11 as a consequence, for example, of greater resistance to its expansion encountered on the Galactic plane (Liu et al. 2017; Zucker et al. 2022).

We note that, for lines of sight spanning Galactic latitudes within \( 20^\circ < b < 40^\circ \) (e.g., for the eFEDS field), we do not expect to observe a large contribution from the hot phase of the ISM in addition to the emission from the LHB (for an ISM scale height of \( h = 1 \pm 0.1 \) pc; see Fig. 11). On the other hand, the geometry represented in Fig. 11 indicates that the emission observed in the
We define as IVC HI those clouds with line of sight velocities within $v_{LSR} \leq 40 \, \text{km} \, \text{s}^{-1}$, and very high velocity HI clouds those with $90 \leq v_{LSR} \leq 170 \, \text{km} \, \text{s}^{-1}$.

Given the low temperature of the CGM of the Milky Way, it is expected that rapid cooling will characterize the coolest regions if temperature fluctuations are present. The CGM plasma within these cool pockets will then rapidly radiate their energy and condense to form low temperature and high density gas, which might appear as UV-optical line emitter-absorbers or as HI clouds at several tens of kiloparsec from the Milky Way. If so, then a tight correlation between the physical properties of the hot Galactic phase (i.e., CGM and Galactic corona) and the colder phases must be present. The Milky Way contains a significant amount of extra-planar cold material moving at high speed through the CGM. Such cold (HI) clouds have been arbitrarily divided into very high, high, and intermediate velocity clouds (VHVCs, HVCs, and IVCs, respectively) on the basis of their observed speed. The physical origin of these clouds is still debated, and some argue that all clouds share the same origin, and that the VHVC and HVC are extreme examples of the IVC. Others point to a possible different origin where the VHVC and HVC are associated with stripping and/or accretion of satellites, condensation from the hot CGM, or accretion from the intergalactic medium, while the IVC is associated with gas launched from the activity in the disk, which then recondenses and forms a Galactic fountain (Fraternali et al. 2015; Marasco & Fraternali 2017; Putman et al. 2012; Gronke & Oh 2020).

The scenario depicted in Fig. 11 predicts that the colder phases are affected by the hot-volume-filling plasma which composes the hot CGM and corona. If so, then we would expect the VHVC and HVC to be distributed on a significantly larger scale and to have lower metal abundances, and the IVC to be closer to the disk and have nearly solar abundances. The current best estimates of the intermediate velocity clouds suggest that they have abundances close to solar (Wakker et al. 2001; Wakker et al. 2008), are distributed $< 1.5 \, \text{kpc}$ above the plane of the Milky Way, and have high covering factors $f_c \sim 0.9$ (Putman et al. 2012; Lehner et al. 2022; Marasco et al. 2022). This evidence is indeed in line with the idea that the hot Galactic corona is the volume-filling plasma in which such clouds are immersed (left panel of Fig. 11). On the other hand, the abundances of the VHVC and HVC are within the range of $0.1–0.3$ solar (Wakker et al. 1999; Fox et al. 2010; Shull et al. 2011; Richter et al. 2013, 2017; Collins et al. 2007); therefore, a large fraction of these clouds have significantly higher metallicities than those of the hot CGM ($Z_{CGM} \sim 0.06 \, Z_\odot$). This difference might appear rather surprising if it is assumed that all high velocity clouds are the product of re-condensation from the hot CGM. On the other hand, this difference might be reconciled with the picture proposed in Fig. 11 if we consider that part of these clouds might originate from plasma having even higher metallicities, such as the IVC, which then undergoes significant mixing with the metal-poor hot CGM phase observed in X-rays (Heitsch et al. 2022; Marasco et al. 2022). The gas stripped from satellites, large-scale Galactic outflows, among other processes, might be enriched in metals, and therefore have initial metallicities higher than the hot CGM phase.

The interplay between the hot (CGM and corona) and cold (VHVC, HVC, and IVC) phases of the Galaxy are important in order to understand galaxy evolution. The dense and cold HI plasma is observed to be primarily accreted onto the Galactic disk and to be used as material to form stars and to grow the galaxies. We note that, as a consequence of the higher temperature of the plasma within the Galactic corona ($kT \sim 0.4–0.7 \, \text{keV}$), the process of rapid cooling is less likely to spontaneously occur directly from the hot phase. However, the plasma in the Galactic corona is likely to be multi-phase and the interfaces between the colder and the hot phases might work as the seeds where rapid cooling occurs. Additionally, the hot CGM plasma might be propelled into the system by rapid cooling of the hot outflow; whenever this outflow cannot escape the system, it then goes back to the disk in the form of IVC, for example.

All these models assume that the hot and colder phases are in near pressure equilibrium. Unfortunately, we cannot test this essential point in this work. In future works, by developing a model of the density distribution within the CGM and corona, we expect to be able to verify whether this is in agreement with the full extent of the eROSITA all-sky survey data.

We achieved this thanks to the good energy resolution, the stable and low level of instrumental background in the soft ($0.3–1.4 \, \text{keV}$) X-ray band, as well as the outstanding statistics provided by the eROSITA spectrum of the eFEDS field. The last point is the result of the combination of the unprecedented grasp of the eROSITA telescope, as well as the large sky area, the relatively deep exposure, and the intermediate Galactic latitudes of the eFEDS field. The good energy resolution of eROSITA has been essential to spectrally discriminate the emission from the Galactic corona from the other components. The coronal plasma has a temperature ($kT \sim 0.4–0.7 \, \text{keV}$), which is incompatible with that associated with either the local hot bubble ($kT \sim 0.1 \, \text{keV}$) or the CGM ($kT \sim 0.15–0.17 \, \text{keV}$).

Acknowledgments. We thank Mattia Sormani for helpful discussion and the referee for the comments, which significantly improved the paper. This work is based on data from eROSITA, the soft X-ray instrument aboard SRG, a joint Russian-German science mission supported by the Russian Space Agency (Roskosmos), in the interests of the Russian Academy of Sciences represented by its Space Research Institute (IKI), and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The SRG spacecraft was built by Lavochkin Association (NPOL) and its subcontractors, and is operated by NPOL with support from the Max Planck Institute for Extraterrestrial Physics (MPE). The development and construction of the eROSITA X-ray instrument was led by MPE, with contributions from the Dr. Karl Remeis Observatory Bamberg & ECAP (FAU Erlangen-Nuernberg), the University of Hamburg Observatory, the Leibniz Institute for Astrophysics Potsdam (AIP), and the Institute for Astronomy and Astrophysics of the University of Tübingen, with the support of DLR and the Max Planck Society. The Argelander Institute for Astronomy of the University of Bonn and the Ludwigs Maximilians Universitat Munich also participated in the science preparation for eROSITA. The eROSITA data shown here were processed using the eSASS software system developed by the German eROSITA consortium. This project acknowledges funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 865637). S.B. acknowledges financial support from the Italian Space Agency under grant ASI-INAF I/007/12/0 and from the PRIN MIUR project: “Black Hole winds and the Baryon Life Cycle of Galaxies: the stone-guest at the galaxy evolution supper”, contract number 2017PH3WAT.
Appendix A: The effects of assumed abundances

Table A.1. Best fit parameters obtained by fitting the e12 spectrum with different models, using the same nomenclature as in Table 2. The first, second, and third columns show the best fit results assuming the metal abundances from Anders & Grevesse (1989); Lodders (2003), and Wilms et al. (2000), respectively.

| SPECTRUM e12 | AnGr | Lod3 | Wilm |
|---------------|------|------|------|
| LHB-CGM-CXB   | 5.2 ± 0.2 | 4.4 ± 0.2 | 6.6 ± 0.2 |
| N_{LHB}       | 0.404 ± 0.002 | 0.412 ± 0.002 | 0.41 ± 0.02 |
| k_{CGM}       | 0.210 ± 0.003 | 0.184 ± 0.002 | 0.196 ± 0.002 |
| Z_{CGM}       | 0.044 ± 0.003 | 0.072 ± 0.004 | 0.078 ± 0.005 |
| N_{CGM}       | 29.2 ± 1.7 | 46 ± 2 | 36 ± 2 |
| \chi^2        | 1414.9 | 1519.3 | 1434.1 |
| dof           | 815 | 815 | 815 |

The different panels of Fig. A.1 illustrate the effects of changing the assumed metal abundances. Going from top to bottom the Anders & Grevesse (1989); Wilms et al. (2000), and Lodders (2003) metal abundances are assumed. Assuming the Anders & Grevesse 1989 to the more recently measured values is only of a factor of ~ 1.48, which is significantly lower than the values for the other metal lines dominating the emission in the soft X-ray band (e.g., O, N, Ne). In the current fits the normalization of the LHB component adjusts itself in order to reproduce the C vi emission line. Therefore, as a consequence of the lower metal-to-carbon fraction observed in Lodder et al. (2003), the contribution of the LHB component to the O vii line emission drops accordingly, with a larger fraction of flux instead being produced by the CGM component (where the C vi emission line is suppressed by the Galactic absorption) compared with the Anders & Grevesse (1989) values (see Fig. A.1).

Another consequence of the drop in the solar metal abundances is the drastic change in the best fit abundances of the CGM component, which changes from ~ 0.04 to ~ 0.07 – 0.08 solar (see Table A.1).

Fig. A.1. Spectrum fitted with three-component models (LHB+CGM+CXB) assuming different metal abundances. The red, blue, magenta, and black solid lines show the contribution from the local hot bubble, the circumgalactic medium, the cosmic X-ray background, and instrumental background, respectively. The dotted lines show the various contributions to the instrumental background. From top to bottom: Anders & Grevesse (1989); Wilms et al. (2000), and Lodders (2003) abundances are assumed. Assuming the Anders & Grevesse (1989) abundances, about half of the O vii line flux is due to the local hot bubble, while for later abundances the contribution to the O vii line drops significantly. Large residuals are present at the energy of the O viii line and between ~ 0.7 and 1 keV.
Appendix B: Background flares

As discussed in Sect. 2, we investigated the temporal evolution of the particle background during the eROSITA observations of the eFEDS field. No notable flare was detected during e1 and e2. The black spectrum in Fig. B.1 shows the e12 spectrum investigated in this work and the best fit shift-LHB-CGM-Coro2-CXB model. The red spectrum shows the same spectrum, but after filtering the events for background flares with the FLAREGTI tool. The consistency between these spectra corroborate the fact that important background flares do not affect the e12 spectrum, and therefore they do not have an effect on the results obtained here.

Fig. B.1. The black data show the e12 spectrum fitted with the best fit model shift-LHB-CGM-Coro2-CXB (same spectrum and color scheme as in Fig. 5). The red data show the e12 spectrum obtained after filtering the events with the FLAREGTI tool. The two spectra are consistent with each other. Notable background flares are not detected during the observation of the eFEDS region during e1 and e2.