Dark matter distribution in X-ray luminous galaxy clusters with Emergent Gravity

S. Ettori\textsuperscript{1,2}, V. Ghirardini\textsuperscript{1,3}, D. Eckert\textsuperscript{4}, F. Dubath\textsuperscript{4}, E. Pointecouteau\textsuperscript{5,6}

\textsuperscript{1} INAF, Osservatorio Astronomico di Bologna, via Pietro Gobetti 93/3, 40129 Bologna, Italy
\textsuperscript{2} INFN, Sezione di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy
\textsuperscript{3} Dipartimento di Fisica e Astronomia Università di Bologna, via Pietro Gobetti 93/2, 40129 Bologna, Italy
\textsuperscript{4} Department of Astronomy, University of Geneva, ch. d’Ecogia 16, 1290 Versoix, Switzerland
\textsuperscript{5} CNRS; IRAP; 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France
\textsuperscript{6} Université de Toulouse; UPS-OMP; IRAP; Toulouse, France

ABSTRACT

We present the radial distribution of the dark matter in two massive, X-ray luminous galaxy clusters, Abell 2142 and Abell 2319, and compare it with the quantity predicted as apparent manifestation of the baryonic mass in the context of the “Emergent Gravity” scenario, recently suggested from Verlinde (2016). Thanks to the observational strategy of the \textit{XMM-Newton} Cluster Outskirts Programme (X-COP), using the X-ray emission mapped with \textit{XMM-Newton} and the SZ signal in the Planck survey, we recover the gas density, temperature and thermal pressure profiles up to $\sim R_{200}$, allowing to constrain at unprecedented level the total mass through the hydrostatic equilibrium equation. We show that, also including systematic uncertainties related to the X-ray based mass modelling, the apparent “dark” matter shows a radial profile that has a shape different from the traditional dark matter distribution, with larger discrepancies (by a factor 2–3) in the inner ($r < 200$ kpc) cluster’s regions and a remarkable agreement only across $R_{500}$.

Key words: galaxies: clusters: general – cosmology: miscellaneous – X-rays: galaxies: clusters.

1 INTRODUCTION

The distribution of the gravitating mass in galaxy clusters is one of the key ingredients to use them as astrophysical laboratories and cosmological probes (see e.g. Allen, Evrard & Mantz 2011, Kravtsov & Borgani 2012). In the present favourite $\Lambda CDM$ scenario, galaxy clusters are dominated by dark matter (80\% of the total mass), with a contribution in the form of hot plasma emitting in X-ray and detectable through the Sunyaev-Zeldovich (SZ, Sunyaev & Zeldovich 1972) effect (about 15\% of the total mass, i.e. $M_{DM}/M_{gas} \sim 4 - 7$) and the rest in stars (few per cent; see e.g. Gonzalez et al. 2013). Although an intriguing and plausible explanation to the observed gravitational effects induced from galaxy clusters, the still unknown nature of the dark matter invites to consider alternative scenarios.

In this paper, we present and discuss the application of one such alternative model, the “Emergent Gravity” theory proposed recently in Verlinde (2016), to the mass distribution in X-ray luminous galaxy clusters. The “Emergent Gravity” theory is a theoretical framework in which spacetime and gravity emerge together from the entanglement structure of an underlying microscopic theory. Although a description of the cosmology is not yet available for this theory, where, in the approximation used by Verlinde, the dark energy dominates our universe and ordinary matter only leads to small perturbations, the use of an effective $\Lambda CDM$ background cosmology to convert from angular to physical scales is still a reasonable approximation at the low redshift regime where we operate. For the $\Lambda CDM$ model, we adopt the cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 1 - \Omega_\Lambda = 0.3$. In a similar context, the “Emergent Gravity” theory has already shown a good capability to reproduce the observed signal of the galaxy-galaxy lensing profiles (Brouwer et al. 2016) and the velocity dispersion profiles of eight dwarf spheroidal satellites of the Milky Way (Diez-Tejedor et al. 2016).

In this study, we refer often to radii, $R_\Delta$, and masses, $M_\Delta$, that are the corresponding values estimated at the given overdensity $\Delta$ as $M_\Delta = 4/3 \pi \Delta \rho_c R^3_\Delta$, where $\rho_c = 3H^2/(8\pi G)$ is the critical density of the universe at the observed redshift $z$ of the cluster, and $H_z = H_0 [\Omega_\Lambda + \Omega_m(1 + z)^3]^{0.5}$ is the value of the Hubble constant at the same redshift.

The paper is organized as follows. In Section 2, we describe the “Emergent Gravity” scenario and how an apparent dark matter distribution can be associated to the observed baryonic mass. In Section 3, we present the dark matter profiles reconstructed through techniques based on X-ray and SZ data only in two massive galaxy clusters that are part of the X-COP sample, an \textit{XMM-Newton} Large Program which targets the outer regions of a sample of 13 mas-
sive clusters in the redshift range $0.04 - 0.1$ at uniform depth. In Section 4, we compare these dark matter profiles with the ones recovered though “Emergent Gravity”, assessing the systematic uncertainties affecting the X-ray mass measurements, and summarize our main findings in Section 5. Unless mentioned otherwise, the quoted errors are statistical uncertainties at 1σ confidence level.

2 APPARENT DARK MATTER IN THE EMERGENT GRAVITY

In the ‘Emergent Gravity’, dark matter can appear as manifestation of an additional gravitational force describing the “elastic” response due to the entropy displacement, and with a strength that can be described in terms of the Hubble constant and of the baryonic mass distribution for a spherically symmetric, static and isolated system as (equation 7.40 in Verlinde 2016):

$$\nabla^2_{\text{EG}} = -\kappa \frac{\delta_{\text{B}}(r)}{\rho_{\text{B}}(r)}$$

where $\delta_{\text{B}}$ is equal to $\rho_{\text{B}}(r)/\bar{\rho}_{\text{B}}$, with $\bar{\rho}_{\text{B}} = M_{\text{B}}(r)/V(< r)$ representing the mean baryon density within the spherical volume $V(< r)$. In our case, the gas mass has been obtained from the integral over the cluster’s volume of the gas density that is obtained from the geometrical deprojection of the observed surface brightness (Fig. 1) including a careful treatment of the background subtraction. This allows to resolve the signal out to about $R_{500}$. The stellar mass has been estimated using a Navarro-Frenk-White (NFW, Navarro et al. 1997) profile with a concentration of 2.9 (see e.g. Lin et al. 2004) and by requiring the $M_{\text{stellar}}(< R_{500})/M_{\text{gas}}(< R_{500}) = 0.39 \, (M_{500}/10^{14} M_{\odot})^{-0.84}$ (Gonzalez et al. 2013).

It is worth noticing that Eq. 2 can be expressed as an acceleration $g_{\text{EG}}$ depending on the acceleration $g_{\text{B}}$ induced from the baryonic mass

$$g_{\text{EG}} = G \frac{M_{\text{DM,EG}} + M_{\text{B}}}{r^2}$$

where $y = 6/(cH_0) \times g_{\text{B}}/(1 + 3\delta_{\text{B}})$. Equation 3 takes a form very similar to the one implemented in MOND (e.g. Milgron & Sanders 2016) with a characteristic acceleration $a_0 = cH_0(1 + 3\delta_{\text{B}})/6$.

3 DARK MATTER WITH THE HYDROSTATIC EQUILIBRIUM EQUATION

We evaluate how the apparent dark matter profile described in eq. 2 reproduces the mass distribution recovered by using the hydrostatic equilibrium equation applied to two massive, X-ray luminous galaxy clusters that are part of the X-COP sample. The XMM-Newton Cluster outskirts Project (X-COP; Eckert et al. 2016) has been built to target the outer regions of a sample of 13 massive clusters ($M_{500} > 3 \times 10^{14} M_{\odot}$) in the redshift range $0.04 - 0.1$ at uniform depth. The sample was selected based on the signal-
to-noise ratio in the Planck SZ survey (Planck Collaboration et al. 2011) with the aim of combining high-quality X-ray and SZ constraints throughout the entire cluster volume. Our observing strategy allows us to reach a sensitivity of $3 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ in the [0.5-2.0] keV range thanks to a good control of systematic uncertainties. The two objects in exam, Abell 2142 and Abell 2319, are the first targets of the X-COP sample for which the complete XMM-Newton analysis of their gas properties out to $R_{200}$ has been completed (see Fig. 1). Abell 2142 ($z = 0.091$) shows a relatively relaxed morphology extended along the SE/NW axis, and is undergoing some minor mergers in its outskirts (Owers et al. 2011; Eckert et al. 2014). This cluster was mapped in the framework of X-COP pilot project (Tchernin et al. 2016). Abell 2319 ($z = 0.056$, Struble & Rood 1999) is also a massive system in which the galaxy distribution indicates that it is a merger of two main components with a 3:1 mass ratio, the smaller system being located $\sim 10'$ north of the main structure (Oegerle et al. 1995). The cluster exhibits a prominent cold front SE of the main core (Ghizzi et al. 2010) and a giant radio halo (Farnsworth et al. 2013; Storm et al. 2015). This is one of the most significant SZ detections in the Planck catalogue (Planck Collaboration et al. 2014) and its complete X-ray analysis, combined with the SZ pressure profile and resolved in 8 azimuthal sectors, will be presented in a forthcoming paper (Ghirardini et al. in prep.). Considering the merging state of this galaxy cluster, we present here the analysis performed in the most relaxed sector, the one enclosed between Position Angles 180° and 225°. Under a reasonable approximation, these clusters are following Verlinde’s prescriptions for the validity of the EG equilibrium equation (see e.g. Ettori et al. 2013).

The physical quantities directly observable are the density $n_{\text{gas}}$ and temperature $T_{\text{gas}}$ of the X-ray emitting gas, and the SZ pressure profile $P_{\text{gas}}$. The gas density is obtained from the geometrical deprojection of the X-ray surface brightness in Fig. 1. Thanks to the observational strategy implemented in X-COP, we are able to correct the X-ray emission for the presence of clumps both by masking substructures spatially resolved with XMM-Newton and by measuring the azimuthal median, instead of the azimuthal mean, out to $\sim 1.2R_{200}$, with a median relative uncertainty of 6% and 1% in A2142 and A2319, respectively. The estimates of the gas temperature are based on the modelling with an absorbed thermal component of the XMM-Newton spectra extracted from concentric annuli around the X-ray peak in the [0.5–12] keV energy band and corrected from the local sky background components (see Tchernin et al. 2016 for details). A typical statistical error lower than 5% is associated to these spectral measurements, with a profile resolved in 12 bins out to 1.4 Mpc in A2142 and in 14 bins out to 1.9 Mpc in A2319. The SZ electron pressure profile is obtained from the deprojection of the azimuthally-averaged integrated Comptonization parameter $y$ extracted from a re-analysis of the SZ signal mapped with Planck (e.g. Tchernin et al. 2016, Planck Collaboration et al. 2013) and that extends up to $\sim 3$ and 4 Mpc in A2142 and A2319, respectively. The electron density, temperature and SZ pressure profiles are presented in Fig. 2.

Under the assumption that the intracluster medium has a spherically-symmetric distribution and follows the perfect gas law ($P_{\text{gas}} = kT_{\text{gas}}n_{\text{gas}}$, where $k$ is the Boltzmann’s constant, and $n_{\text{gas}}$ is the sum of the electron and proton densities $n_e + n_p \approx 1.83n_e$), the gas density, combined with the X-ray spectral measurements of the gas temperature and/or the SZ derived gas pressure, allows to evaluate the total mass within a radius $r$ through the hydrostatic equilibrium equation (see e.g. Ettori et al. 2013)

$$M_{\text{tot}}(<r) = -\frac{rP_{\text{gas}}}{\mu m_u G n_{\text{gas}}} \frac{d\log P_{\text{gas}}}{d\log r},$$

(4)

where $G$ is the gravitational constant, $m_u = 1.66 \times 10^{-24}$ g is the atomic mass unit, and $\mu = 0.61$ is the mean molecular weight in atomic mass unit. In this analysis, we have applied both the backward and the forward method. In the backward method, a parametric mass model is assumed and combined with the gas den-
Figure 3. Dark matter profiles obtained using (i) the {	extit{backward}} method with a NFW mass model; (ii) the {	extit{forward}} method by fitting with functional forms the gas density profile and either the deprojected temperature profile (A2142) or the SZ pressure profile (A2319). In the latter case, the mass profiles are shown only within the radial range where the data are fitted. The dark matter profiles (blue curve) predicted from the “Emergent Gravity” framework as obtained from equation (4) are also shown. The thickness of the lines shows the statistical uncertainty associated to the best-fit mass model. Dotted/dashed/solid lines indicate only within the radial range where the data are fitted. The dark matter profiles obtained using (i) the {	extit{backward}} method with a NFW mass model; (ii) the {	extit{forward}} method by fitting with functional forms the gas density profile and the deprojected temperature profile (A2142) or the SZ pressure profile (A2319). In the latter case, the mass profiles are shown only within the radial range where the data are fitted. The dark matter profiles (blue curve) predicted from the “Emergent Gravity” framework as obtained from equation (4) are also shown. The thickness of the lines shows the statistical uncertainty associated to the best-fit mass model. Dotted/dashed/solid lines indicate only within the radial range where the data are fitted.

### 4 RESULTS ON THE DARK MATTER MASS PROFILES

From equation (4) using a {	extit{backward}} method with a NFW model, we measure in A2142 a total mass of $M_{200} = 8.7 \times 10^{14} M_\odot$, with a relative statistical error of 3 per cent, and $R_{200} = 2211 \pm 47$ kpc, with the gas density that extends up to $r = 2890$ kpc. As discussed in Tcherem et al. (2016), the hydrostatic mass profile agrees well with the one obtained by weak lensing and caustics measurements out to $R_{200}$. In A2319, we measure $M_{200} = 7.5 \times 10^{14} M_\odot$, with a relative statistical error of 2 per cent, and $R_{200} = 2084 \pm 13$ kpc, with the outermost radius for the gas density at 3 Mpc. A systematic uncertainty of about 10 per cent on these mass measurements is estimated by applying the {	extit{forward}} method (with both the temperature and pressure profiles). The dark matter distribution is then $M_{DM} = M_{tot} - M_{B}$, where $M_{B}$ is the baryonic mass estimated as described in Section 2.

In Figure 3, we show the mass profiles obtained both in a context of a $\Lambda CDM$ model and following the prescriptions for an emergent dark matter contribution. An encouraging match between the two mass profiles is obtained at $r \approx R_{200}$, where we measure $M_{DM}/M_{DM,EG} = 1.01 \pm 0.04$ in A2142 and $0.81 \pm 0.02$ in A2319, where the errors include only the propagation of the statistical uncertainties. On the contrary, $M_{DM,EG}$ underpredicts significantly, by up to a factor of $2-3$, the requested amount of matter to maintain the hydrostatic equilibrium in the central regions, $r < 200$ kpc. We conclude that, although the total masses within $R_{200}$ are in good agreement, the overall shape of the DM profiles looks quite different, with EG lacking some NFW-type curvature.
By inverting the hydrostatic equilibrium equation, and assuming as boundary condition $P_{\text{out}} = P(R_{500})$, we can also estimate the gas temperature profiles that the computed $M_{\text{DM,EG}}$ would imply for the measured gas density profiles. The tension below 1000 kpc can then be translated in a difference in the gas temperature of 2–4 keV, that can be hardly accommodated with the present observational constraints, also accounting for potential systematics due to the calibration of the X-ray instruments (e.g. Schellenberger et al. 2015). Otherwise, this discrepancy might suggest that some temperature (or gas entropy) contribution, with an effect comparable with a modulation by some scale radius and larger in the inner cluster’s regions, is still missing in the Verlinde’s formula. Massive (probably sterile) neutrinos can also accomodate this tension (e.g. Nieuwenhuijen 2016).

A larger sample of high-quality data, as the ones that will be available in the X-COP project in the next future, will improve the statistical constraints on the reliability of any alternative scenario, as the “Emergent Gravity” here discussed, to the dark matter.

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