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CHARACTERIZING THE BULK AND TURBULENT GAS MOTIONS IN GALAXY CLUSTERS

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Abstract. The most massive halos of matter in the Universe grow via accretion and merger events throughout cosmic times. These violent processes generate shocks at many scales and induce large-scale bulk and turbulent motions. These inject kinetic energy at large scales, which is transported to the viscous dissipation scales, contributing to the overall heating and virialisation of the halo, and acting as a source of non-thermal pressure in the intra-cluster medium. Characterizing the physical properties of these gas motions will help us to better understand the assembly of massive halos, hence the formation and the evolution of these large-scale structures. We base this characterization on the study of the X-ray and Sunyaev-Zel'dovich effect brightness fluctuations. Our work relies on three complementary samples covering a wide range of redshifts, masses and dynamical states of clusters. We present the results of our X-ray analysis for the low redshift sample, X-COP, and a subsample of higher redshift clusters. We investigate the derived properties according to the dynamical state of our clusters, and the possibility of a self-similar behaviour based on the reconstructed gas motions power-spectra.

Keywords: X-rays: galaxies: clusters, galaxies: clusters: intracluster medium, turbulence

1 Introduction

The baryonic content of galaxy clusters is largely dominated by the hot gas that constitutes the intracluster medium (ICM). The processes governing the growth, as well as the physics of the ICM, introduces perturbations at various scales within the gas. The resulting turbulent motions transport kinetic energy, which cascades to the dissipation scale and contributes to the virialisation of the halo through non-thermal heating of the ICM (e.g Vazza et al. 2018).

Direct measurements of these turbulent processes can be achieved using spatially resolved X-ray spectroscopy (Böhringer & Werner 2010; The Hitomi Collaboration 2016), and will be fully enabled in the future with the upcoming XRISM and Athena missions (XRISM Science Team 2020; Nandra et al. 2013). These turbulent processes are expected to induce fluctuations in the thermodynamic properties of the ICM, that should be detectable in the related observables (Simionescu et al. 2019). For instance, the X-ray surface brightness and Sunyaev-Zel'dovich distortion scale respectively with the squared density and pressure, integrated along the line of sight. Studies on the nearby Coma and Perseus clusters (Churazov et al. 2012; Zhuravleva et al. 2015; Khatri & Gaspari 2016) have demonstrated the feasibility of this approach in both X-ray and SZ, and was already extended to a small sample ($N = 10$) to derive statistical trends (Zhuravleva et al. 2018).

With this work, we aim at characterizing the X-ray surface brightness and SZ distortion fluctuations for a large cluster sample ($N > 150$) spanning a large range of redshifts, masses and dynamical states. This should allow us to better constrain the properties and impact of turbulence in the ICM, considering the assembly of massive halos.

2 Data

We rely on three cluster samples, built over the Planck (The Planck Collaboration 2014, 2016) and the Atacama Cosmology Telescope (ACT, Mallaby-Kay et al. 2021) cluster catalogues:

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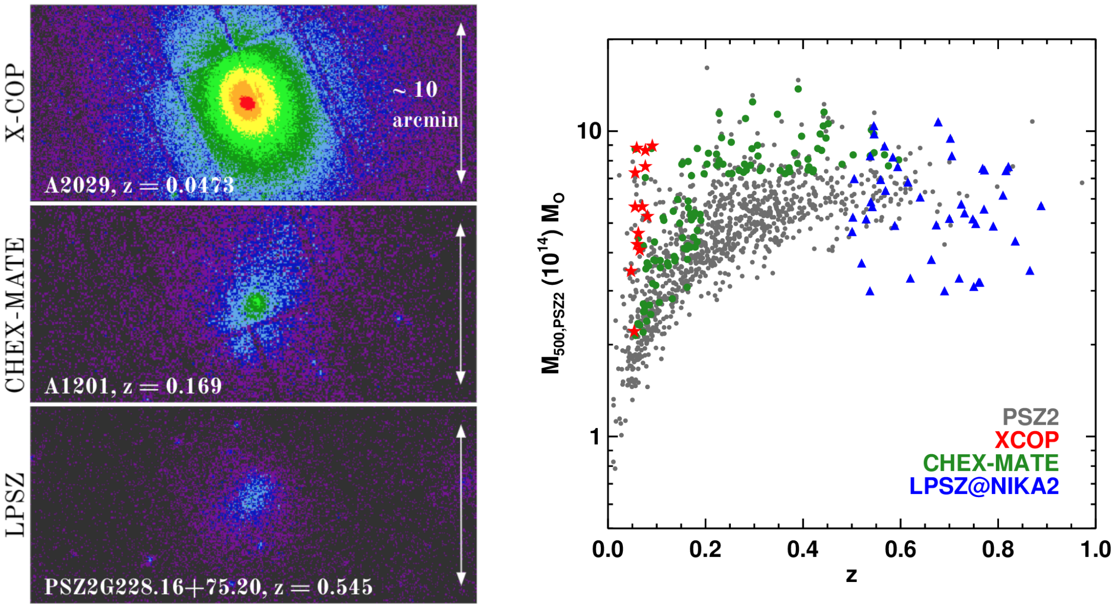

Fig. 1. Left: XMM-Newton image (0.7-1.2 keV band) of A2029, A1201 and PSZ2G228.16+75.20 which belong to X-COP, CHEX-MATE and LPSZ@NIKA2. **Right:** Distribution of the X-COP, CHEX-MATE and LPSZ@NIKA2 samples alongside the PSZ2 catalogue, in the mass-redshift plan.

- The XMM Cluster Outskirts Project (X-COP, Eckert et al. 2017), a SZ selected sample based on the Planck catalogue, designed to study the outer regions of 12 nearby ($z < 0.1$) galaxy clusters.
- The Cluster HEritage project with XMM-Newton (CHEX-MATE, The CHEX-MATE Collaboration 2021) : a SZ selected sample, based on the Planck catalogue, of 118 clusters designed to obtain an accurate vision of the statistical properties of the cluster population at low to intermediate redshifts ($0.1 < z < 0.5$).
- The NIKA2 SZ Large Program (LPSZ@NIKA2, Mayet et al. 2020), a SZ-selected sample from both Planck and ACT catalogues, including 50 intermediate to high redshift clusters ($0.5 < z < 0.9$) designed to perform evolution studies and cosmological analysis.

In this paper, we present our preliminary results on the full X-COP sample, and pilot sub-samples of 8 and 4 clusters for CHEX-MATE and LPSZ@NIKA2, respectively.

3 Method

3.1 *Mean profile determination*

To determine the mean X-ray surface brightness map, an analytical elliptical model is fitted on the photon count image. We first estimate the centroid of emission and the ellipticity using a principal component analysis in a region of $0.5R_{500}$, centred on the emission peak. Then we extract the total photon count in concentric elliptical annuli to obtain a radial surface brightness profile with a 10” binning. The parameter distributions of a β-Model (Cavaliere & Fusco-Femiano 1976) fitting this profile is determined using Bayesian inference, assuming that the number of counts in each annulus follows a Poisson distribution.

3.2 *Fluctuation map and 2D power spectrum*

The surface brightness image I is directly dependent on the 3D density profile n_e, which can be decomposed into a mean component n_0 and relative fluctuations δ:

$$I(x, y) = \int_{-\infty}^{+\infty} \Lambda(T) n_e^2(\vec{r})\, dz = \int_{-\infty}^{+\infty} \Lambda(T) n_0^2(\vec{r})(1 + \delta(\vec{r}))^2\, dz \tag{3.1}$$

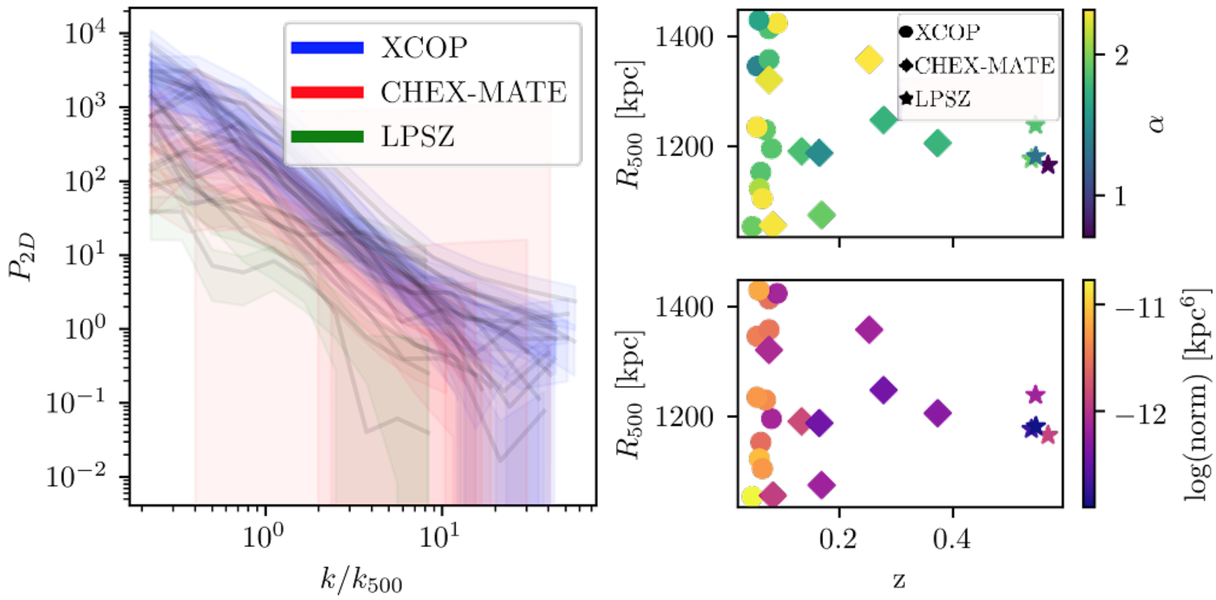

Fig. 2. Left: 2D power spectra, P_{2D} [kpc^4], for the set of clusters we are using (See. Sec. 2) plotted as a function of the normalized scale, k/k_{500}. The shaded envelopes correspond to the 1σ dispersion about each individual P_{2D}. **Right:** 3D power spectrum best-fit slope α (11/3 corresponds to a Kolmogorov cascade) and normalization in the R_{500}-z plane.

By linearizing for δ and dividing by the previously determined mean count image I_0, we obtain the map of surface brightness fluctuations, J (see Churazov et al. 2012):

$$J(x,y) = \frac{I(x,y)}{I_0(x,y)} = 1 + 2\int_{-\infty}^{+\infty} \eta(\vec{r})\delta(\vec{r})\,dz; \quad \eta = \frac{n_0^2(\vec{r})}{\int_{-\infty}^{+\infty} n_0^2(\vec{r})dz} \tag{3.2}$$

The associated power spectrum, latter referred to as P_{2D}, is defined as the squared complex modulus of $\mathcal{F}_{2D}\{J\}$, the 2D Fourier transform of the fluctuation map :

$$P_{2D}(k) = |\mathcal{F}_{2D}\{J\}(k)|^2 = \left| \int J(\vec{\rho})e^{-2i\pi \vec{k_\rho}\cdot\vec{\rho}}d^2\vec{\rho} \right|^2 \tag{3.3}$$

For each cluster, the power spectrum, P_{2D}, is computed following the method by Arévalo et al. (2012). It uses Mexican hat filtering at various scales and handles properly masked data (e.g., source exclusions, gaps, and borders effects). The uncertainties due to the shot noise was estimated by computing P_{2D} for 100 Poisson realizations of the image I_0. The power spectrum is also affected by the uncertainty related to the sample variance, which we consider in the following way : assuming that the velocity field is Gaussian, and as in this context, density fluctuations field are proportional to velocity fluctuations (Zhuravleva et al. 2014; Gaspari et al. 2014), the standard deviation of the 3D power spectrum, P_{3D}, is proportional to the power spectrum itself. As the projection operations from P_{3D} to P_{2D} are linear, we assume that the variance of P_{2D} follows the same law. We therefore added to the P_{2D} variance a term of $(P_{2D}/3)^2$.

3.3 *Projection and fitting of the 3D power spectrum*

To recover the properties of the inherent 3D density fluctuations power spectrum, we first express the previously obtained 2D power spectrum as a function of the P_{3D}. After introducing the power spectrum of the profile P_η, of the PSF $P_{\rm PSF}$, the power spectrum of the Poisson noise $P_{\rm Poisson}$ and by designating the 2D convolution with the $**$ operator, we can show that the observed P_{2D} is linked to the P_{3D} with the following dependence :

$$P_{2D}(k_x, k_y) = P_{\rm Poisson} + 4P_{\rm PSF}\int (P_\eta ** P_{3D})(x,y,z)\,dz \tag{3.4}$$

We use a simple power law representation, $P_{3D} = 10^A \left(k/k_{\rm ref}\right)^{-\alpha}$, where the normalization, 10^A [kpc^6], and slope, α, are free parameters. The pivot is set to $k_{\rm ref} = 10^{-3}{\rm kpc}^{-1}$. This model is projected using Eq. (3.4) and fitted against the measured P_{2D} for each individual cluster.

4 Preliminary results

The 2D power spectra, computed for our pilot sample, are shown in the left of Fig. 2, re-scaled to $k_{500} = 1/R_{500}$, and exhibit a strong power-law behaviour in this test sample. The spectra do not seem to vary significantly from one sample to another. Thus, we do not see any trend that could correlate with the redshift (though the statistics of our intermediate and higher redshift sub-samples are very limited). The best values of our fit of P_{3D} are displayed in the $R_{500} - z$ plane in Fig. 2, right panel. From this preliminary analysis, we do not see any particular trend of the normalization nor slope of P_{3D} with the characteristic size or redshift of our clusters. Nevertheless, as the error propagation has not yet been done on these quantities, we cannot draw any solid conclusion about these results.

5 Perspectives

We presented here a preliminary analysis of the power spectrum of brightness fluctuations for a sample of galaxy clusters. We will test models with higher levels of complexity for P_{3D} by including, for instance, the injection scale starting the underlying turbulent cascade. We plan to investigate the correlation to morphological indicators, reflecting the dynamical state of each of our clusters. We will pursue our study and extend it to the whole CHEX-MATE and LPSZ@NIKA2 samples. We plan to extend this work to the fluctuations of the SZ signal (directly related to the fluctuations of the ICM pressure), making use of the Planck, ACT and NIKA-2 data.

References

Arévalo, P., Churazov, E., Zhuravleva, I., Hernández-Monteagudo, C., & Revnivtsev, M. 2012, Monthly Notices of the Royal Astronomical Society, 426, 1793, publisher: Oxford Academic

Böhringer, H. & Werner, N. 2010, The Astronomy and Astrophysics Review, 18, 127

Cavaliere, A. & Fusco-Femiano, R. 1976, Astronomy and Astrophysics, 500, 95

Churazov, E., Vikhlinin, A., Zhuravleva, I., et al. 2012, Monthly Notices of the Royal Astronomical Society, 421, 1123

Eckert, D., Ettori, S., Pointecouteau, E., et al. 2017, Astronomische Nachrichten, 338, 293, arXiv: 1611.05051

Gaspari, M., Churazov, E., Nagai, D., Lau, E. T., & Zhuravleva, I. 2014, Astronomy and Astrophysics, 569, A67

Khatri, R. & Gaspari, M. 2016, Monthly Notices of the Royal Astronomical Society, 463, 655, arXiv: 1604.03106

Mallaby-Kay, M., Atkins, Z., Aiola, S., et al. 2021, arXiv:2103.03154 [astro-ph], arXiv: 2103.03154

Mayet, F., Adam, R., Ade, P., et al. 2020, EPJ Web of Conferences, 228, 00017, arXiv: 1911.03145

Nandra, K., Barret, D., Barcons, X., et al. 2013, arXiv:1306.2307 [astro-ph], arXiv: 1306.2307

Simionescu, A., ZuHone, J., Zhuravleva, I., et al. 2019, Space Science Reviews, 215, 24

The CHEX-MATE Collaboration. 2021, arXiv:2010.11972 [astro-ph], arXiv: 2010.11972

The Hitomi Collaboration. 2016, Nature, 535, 117

The Planck Collaboration. 2014, Astronomy & Astrophysics, 571, A29, publisher: EDP Sciences

The Planck Collaboration. 2016, Astronomy & Astrophysics, 594, A13, publisher: EDP Sciences

Vazza, F., Angelinelli, M., Jones, T. W., et al. 2018, Monthly Notices of the Royal Astronomical Society: Letters, 481, L120

XRISM Science Team. 2020, arXiv:2003.04962 [astro-ph], arXiv: 2003.04962

Zhuravleva, I., Allen, S. W., Mantz, A., & Werner, N. 2018, The Astrophysical Journal, 865, 53, publisher: IOP Publishing

Zhuravleva, I., Churazov, E., Arevalo, P., et al. 2015, Monthly Notices of the Royal Astronomical Society, 450, 4184, arXiv: 1501.07271

Zhuravleva, I., Churazov, E. M., Schekochihin, A. A., et al. 2014, The Astrophysical Journal, 788, L13, publisher: IOP Publishing