Study of the dynamic assembly of the largest halos of matter in the Universe

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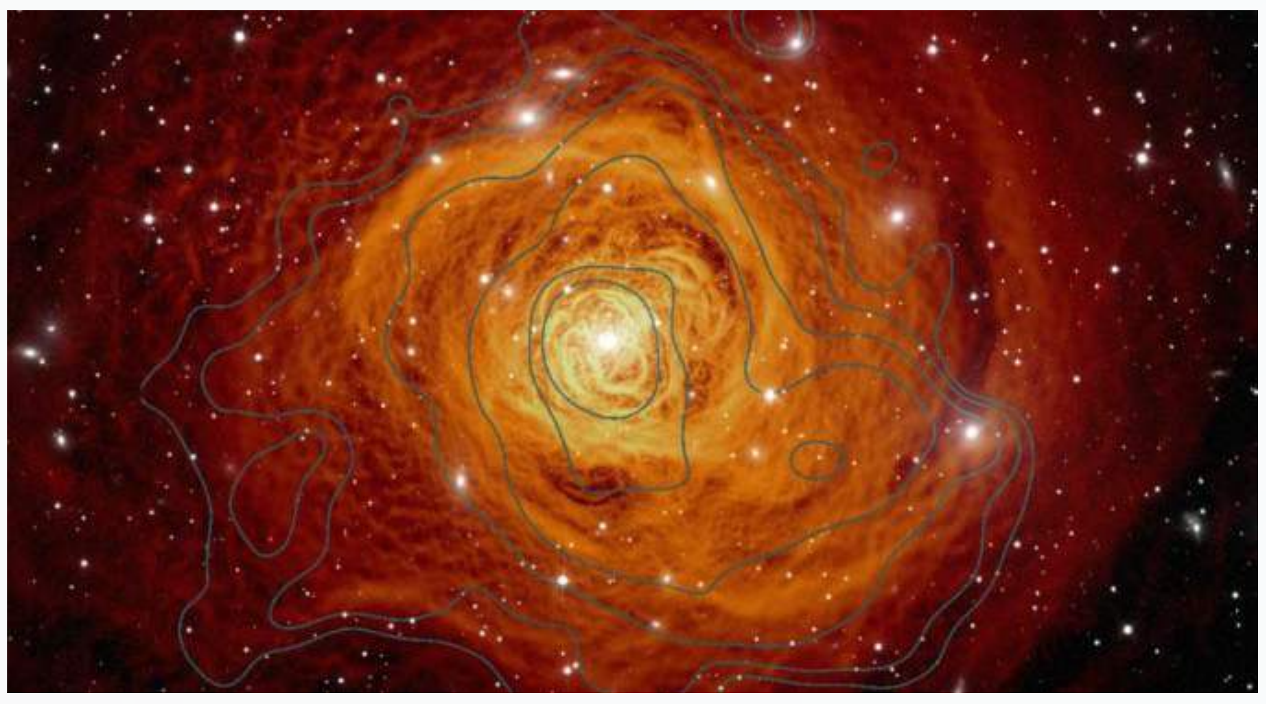
We aim at characterizing the turbulent gas motions in the intracluster medium via the study of the statistics of the X-ray surface brightness and Sunyaev-Zeldovich distortion fluctuations. Our work is based on three complementary samples observed in X by XMM-Newton and in SZ by Planck and/or ACT and NIKA2, covering a wide range of redshifts and dynamical states of clusters.

Introduction

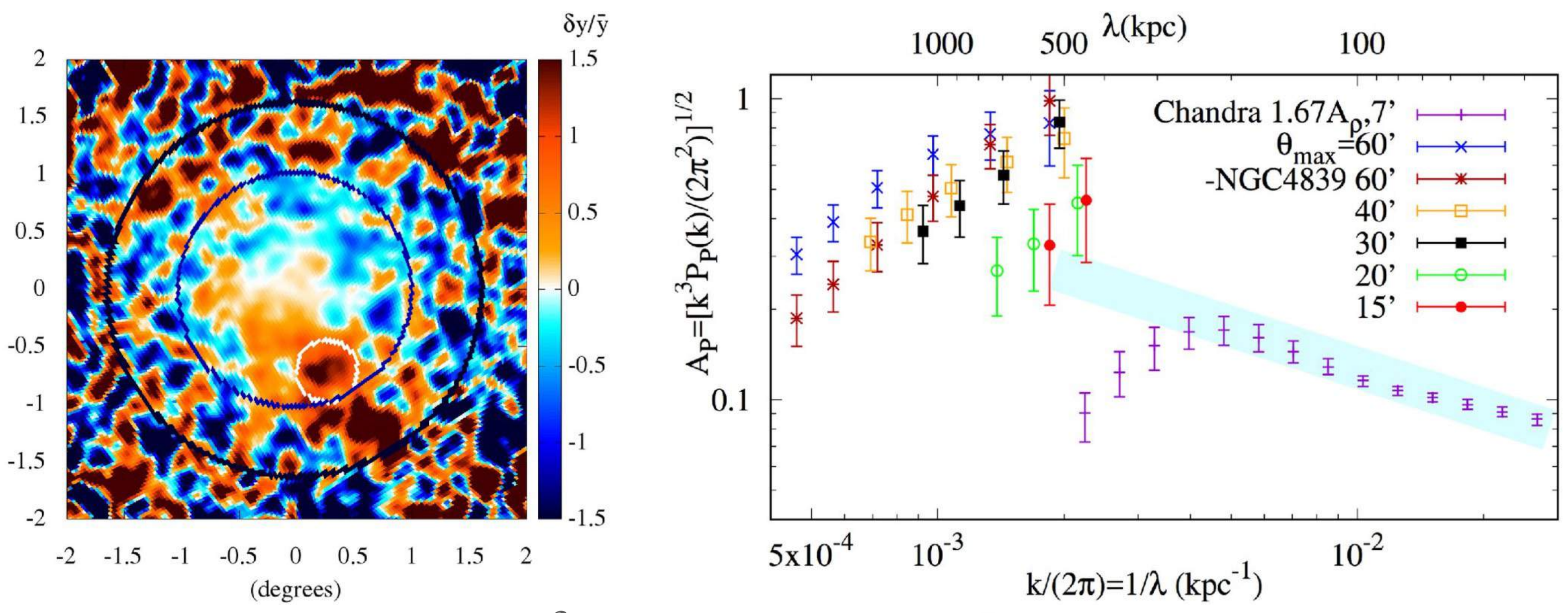
- Turbulence appears at all scales of astrophysical flows
- The intracluster medium (ICM) is subject to many phenomena (merger events, central AGN feedback...) introducing large scale kinetic energy that will be transported to the viscous dissipation scales
- These turbulent cascades may contribute significantly as a non thermal pressure component of the ICM, which helps with the virialization of the halo, and, when not accounted for, can also introduce biases in the measurement of their hydrostatic mass.



A: Inner 400 kpc of Perseus Cluster in X-ray, filtered to show fine structure, superposed with r-band image from the Sloan Digital Sky Survey and radio contours. The intracluster environment, here in orange, reveals its dynamics and its complex physics

Motivations

- Turbulent motions induce **fluctuations** with respect to the average properties of the cluster (gas density, pressure) which are reflected in the associated observables (X-ray surface brightness [1], Sunyaev-Zeldovich (SZ) distortion [2])
- The statistics of these fluctuations are directly related to the **turbulent power spectrum**, and provide information about the **physics** of the ICM
- Characterizing the physical properties of these gas motions helps us to better understand the **assembly** of massive halos, hence the **formation** and the **evolution** of these large scale structures



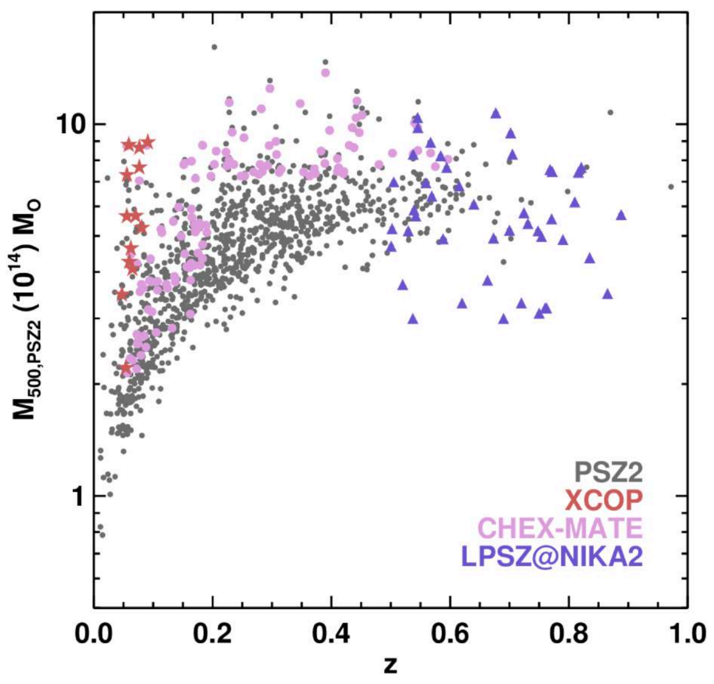
B: Left : SZ distorsion fluctuation δy divided by mean profile $\bar{y}$ in Coma cluster. Right : Amplitude spectrum of pressure fluctuations of Coma cluster for varying extraction radius θ_{max} (SZ fluctuation maps), for Planck and Chandra data (violet; Gaspari & Churazov 2013). The SZ and X-ray data here probe different scales of the power spectrum.

Objectives

- **Quantify the turbulent motions** in the ICM analyzing the **surface brightness fluctuation** in X-ray and SZ
- Study a **large sample** of clusters (>100) to infer **statistically significant** properties for the turbulent **power spectra** over the cluster population
- Search for and characterize **trends** as w.r.t, e.g, time, dynamical state

→ **Three samples** at various redshift, covered in X with XMM and SZ with Planck and/or ACT, NIKA-2.

Sample name	N° of clusters	Redshift
XCOP [4]	12	z < 0.1
CHEX-MATE [5]	118	0.1 < z < 0.5
LPSZ@NIKA2 [6]	45	0.5 < z

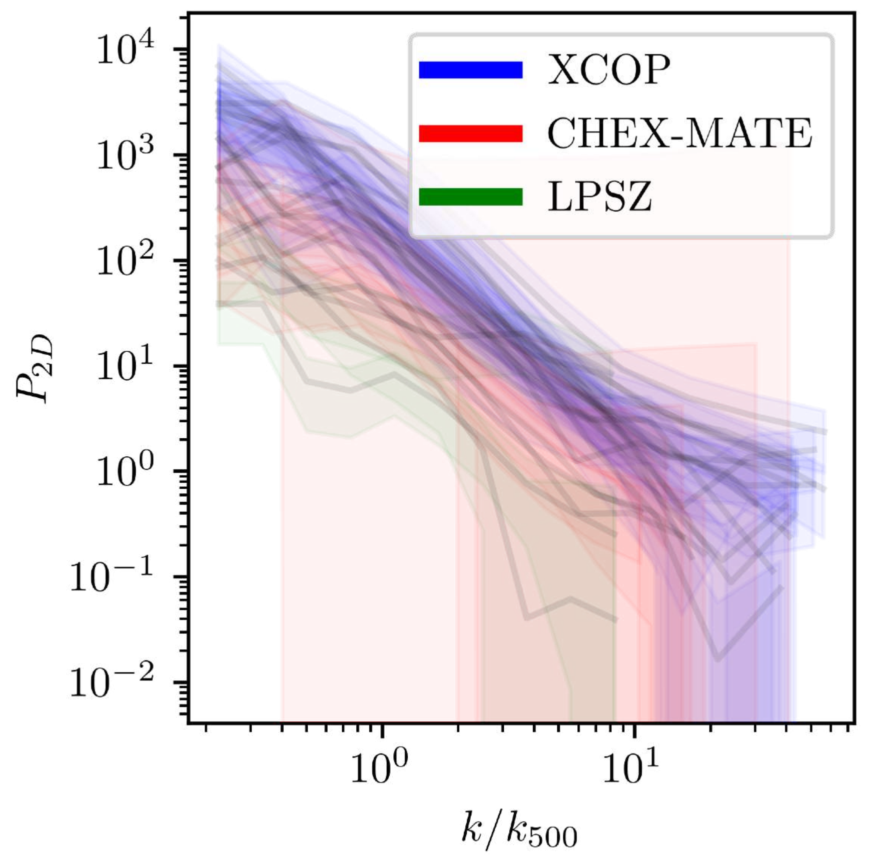


C: Clusters used for the analysis represented in the mass-redshift plane, superimposed on the clusters of the PSZ2 catalog

2D-power spectrum

- Extraction of a **radial profile** using principal component analysis
- Fit and ellipticization of a **mean profile** to generate a map of **fluctuations**
- **Filtering** this map to extract the power at **different scales**, using Mexican Hat method [3] to derive the power spectrum

→ This power spectrum can be related to the 2D projected power spectrum of the **turbulent velocities**



D: Some 2D power spectra from a subsample of 24 clusters, rescaled to the size of the clusters. A strong power law behavior is exhibited

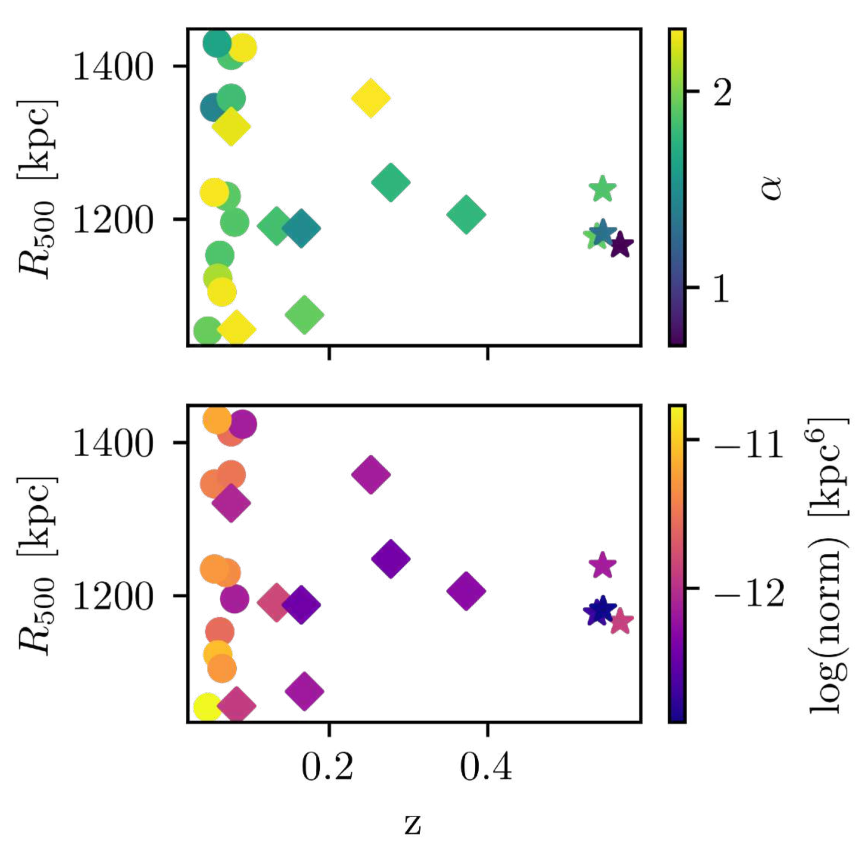
Early results

- The 2D power spectra correspond to the **projection of a 3D velocity field**.
- To estimate a 3D spectrum, we use a functional corresponding to a power law spectrum with an injection scale :

$$P_{3D} \propto k^{-\alpha} \exp - \left(\frac{k_{\text{inj}}}{k} \right)^2$$

- This spectrum is **projected and fitted** against the 2D power spectra.

→ **No specific trends** in normalization or slope of the turbulent power spectrum **with the redshift**



E: 3D power spectrum best-fit parameters in the radius-redshift plan

Perspectives

- Study the derived properties according to the dynamical state of our clusters
- Investigate the possibility of a self-similar behavior on the basis of the reconstructed gas motions power-spectra
- Extension of the current work to a larger sample.

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References:

[1] Churazov, E. et al. X-ray surface brightness and gas density fluctuations in the Coma cluster. MNRAS **421**, 1123–1135 (2012).
[2] Khatri, R. & Gaspari, M. Thermal SZ fluctuations in the ICM: probing turbulence and thermodynamics in Coma cluster with *Planck*. MNRAS **463**, 655–669 (2016).
[3] Arévalo, P., Churazov, E., Zhuravleva, I., Hernández-Monteagudo, C. & Revnivtsev, M. A Mexican hat with holes: calculating low-resolution power spectra from data with gaps. MNRAS **426**, 1793–1807 (2012).
[4] Eckert, D. et al. The XMM Cluster Outskirts Project (X-COP). Astron.Nachr./AN **338**, 293–298 (2017).
[5] The CHEX-MATE Collaboration, The Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation. I. Programme overview. arXiv:2010.11972 (2021).
[6] Mayet, F. et al. Cluster cosmology with the NIKA2 SZ Large Program. EPJ Web Conf. **228**, 00017 (2020).

Credits:

A. S. Walker (X-ray), M.L. Gendron-Marsolais (Radio contour)
B. R. Khatri, M. Gaspari