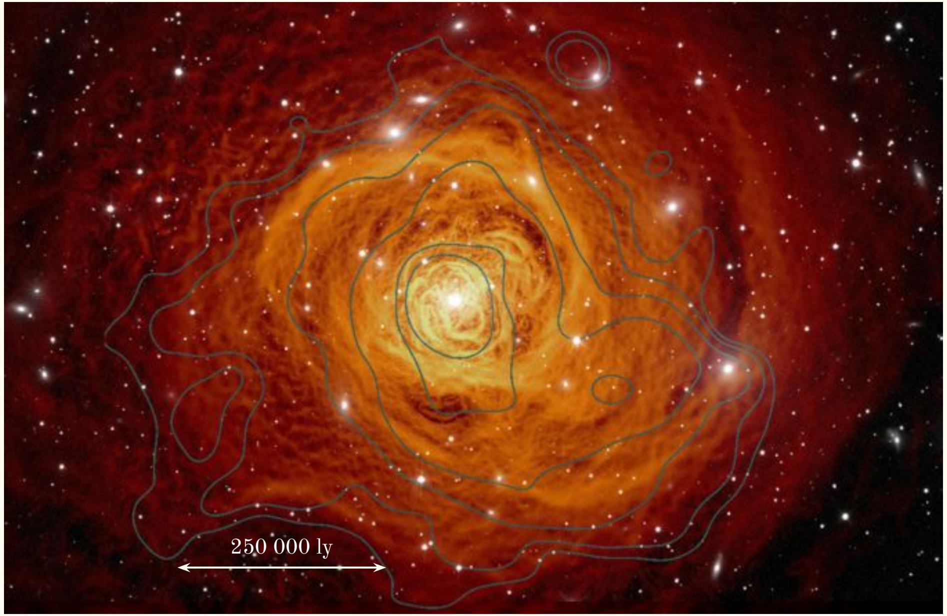
Characterizing the bulk and turbulent gas motions in galaxy clusters

S. Dupourqué (IRAP, Toulouse)
Collaborators : E. Pointecouteau, N. Clerc, D. Eckert, XCOP collab., CHEX-MATE collab., LPSZ@NIKA2 collab.

Observing the millimeter Universe @ NIKA2, 30/06/2021

Turbulence in galaxy clusters



X-ray surface brightness for Perseus Cluster, gradient emphasized
(Credit : Sanders & al 2016 (X-ray), M.L. Gendron-Marsolais (Radio))

- Turbulence : chaotic process in fluid flows that efficiently converts kinetic energy into heat
- Turbulence occurs in the intracluster medium
  - Central AGN feedback
  - Galaxy movements
  - Accretion & Merger
  - MHD instabilities

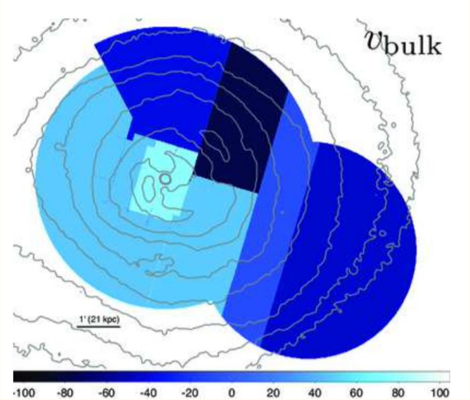
→ Non thermal heating

- Scientific issues :
  - Mass determination
  - Better constraints on cosmological models
  - Dynamical assembly of galaxy clusters
  - Underlying plasma physics

Existing works

Direct measurements

- Spectral lines centroïd shift and broadening

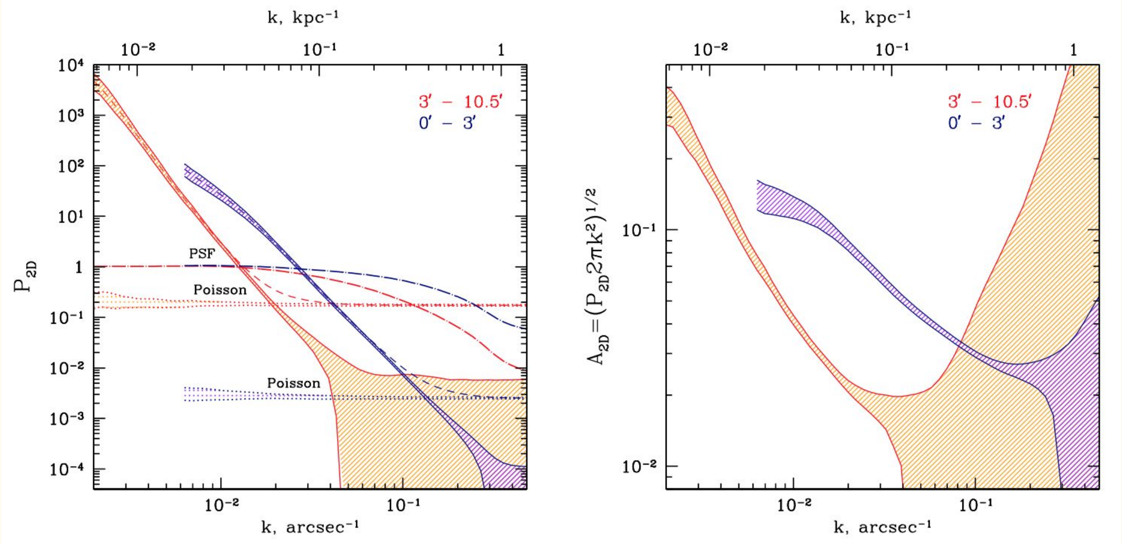


Bulk velocity, Perseus cluster center region (Hitomi Collaboration, 2018)

- Require X-ray IFUs for velocity fields (XRISM, Athena X-IFU…)

→ Indirect measurements

- X-Ray surface brightness (SB) and Sunyaev-Zel'dovich fluctuations
- Previous work on Perseus and Coma clusters (eg. Churazov & al 2013, Zhuravleva & al 2015, Khatri & Gaspari 2016)



Power spectrum and characteristic amplitude of X-ray surface brightness fluctuations, Perseus cluster (Zhuravleva & al, 2015)

Quantifying turbulence using X-Rays & SZ

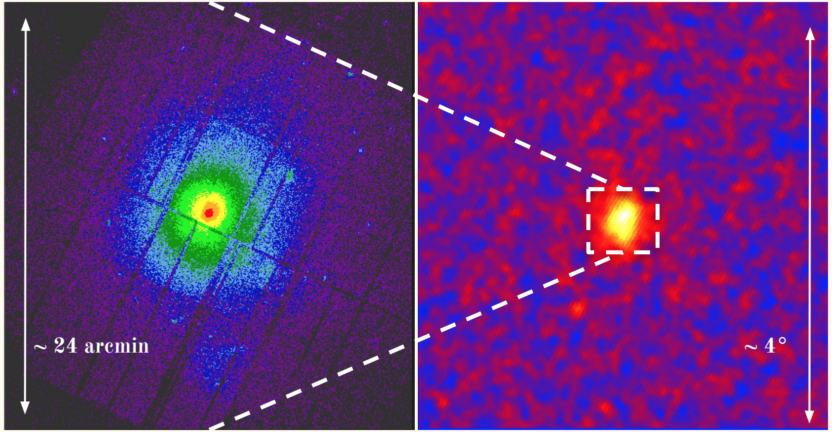
Turbulence introduces fluctuations → impact on related observables

X-ray surface brightness (SB)

Sunyaev-Zel'dovich distortion (y)

Thermal bremsstrahlung in the intracluster plasma

$$SB \propto \int \rho^2$$



A85 X-ray SB (XMM Mosaic, 0.7 - 1.2 KeV)

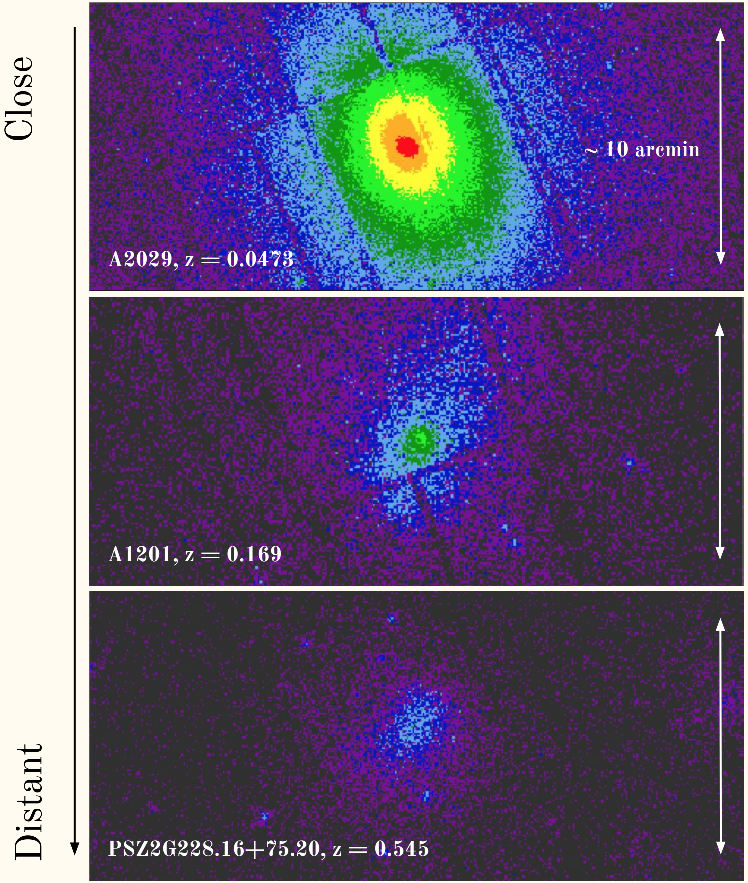
A85 SZ distorsion (MILCA Map, computed from Planck data)

Comptonization of the CMB photons

$$y \propto \int \rho T$$

Density and pressure fluctuations can be probed using X-ray SB and SZ distortion

Constraining turbulences with cluster samples



XMM Mosaics, 0.7 - 1.2 KeV

XCOP (Eckert & al , 2013)

Physics of the outskirt

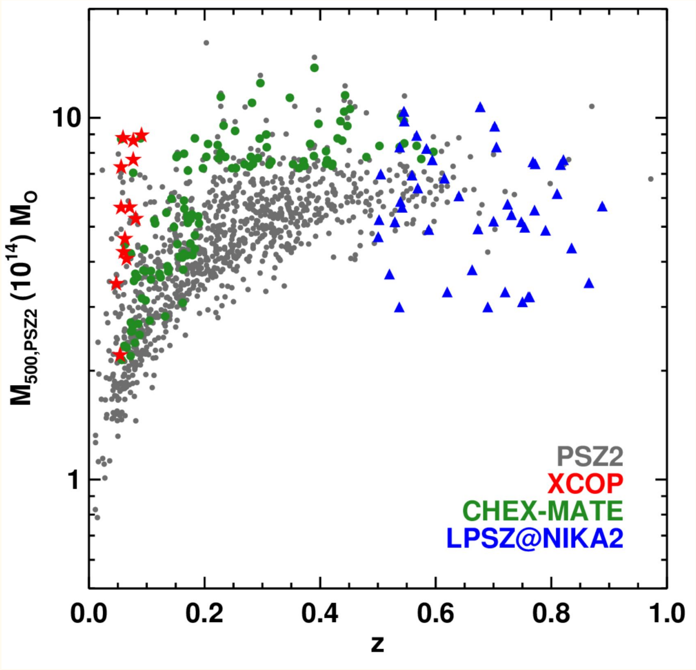
CHEX-MATE (CHEX-MATE Collaboration, 2020)

SZ selected, local to intermediate redshifts

LPSZ@NIKA2 (Mayet & Al, 2018)

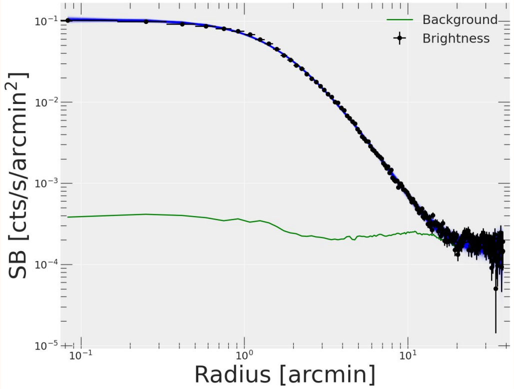
Cosmology, distant universe

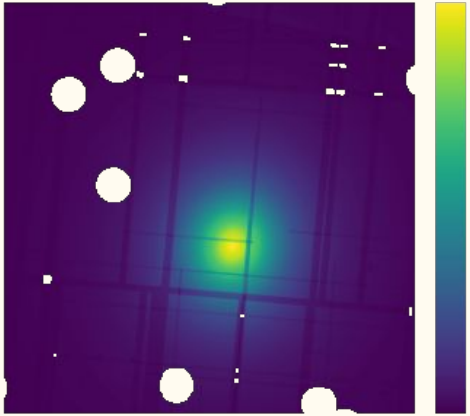
Aim : study SB and SZ fluctuations in galaxy clusters from the local to the distant universe



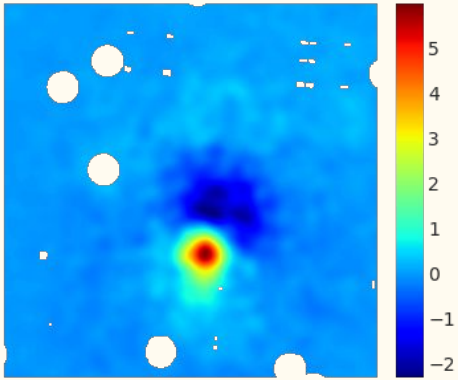
X-ray from XMM, SZ from Planck, ACT and NIKA2

2D Power spectrum (e.g A2255) (I)

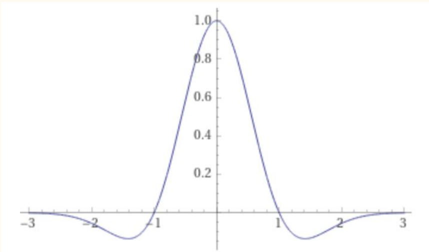




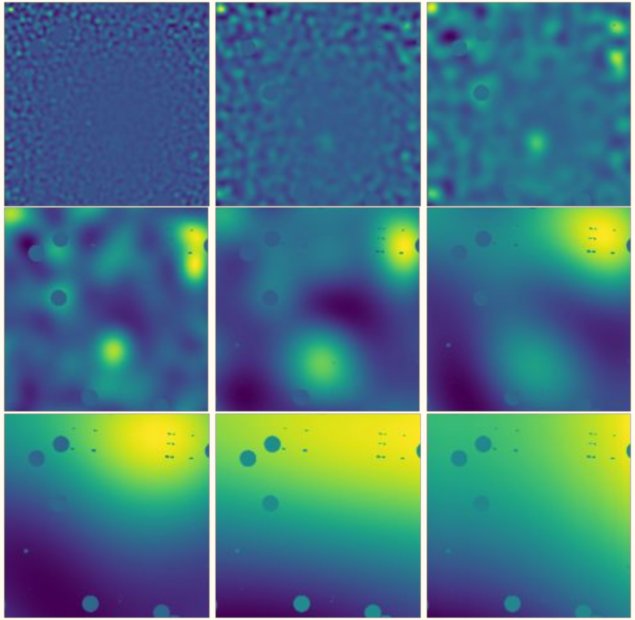
(i) Mean profile determination



+ *convolution with Mexican Hats for gaps handling* (Arévalo & al, 2012)

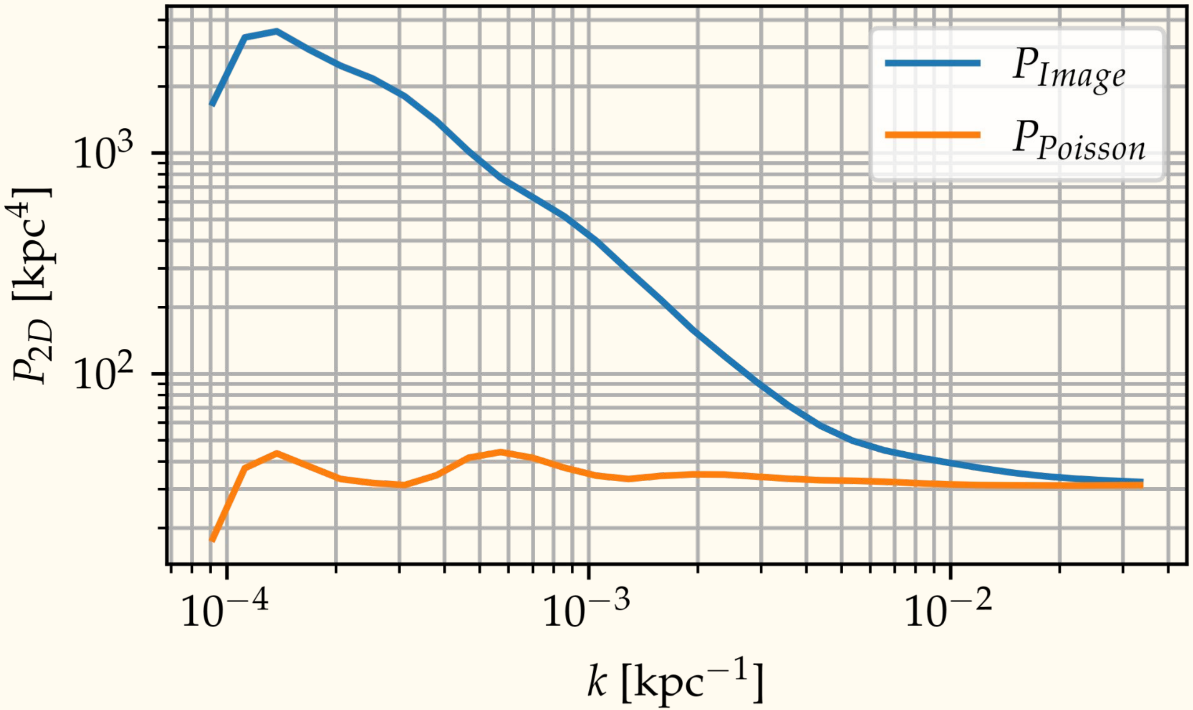


(ii) Residual fluctuations



(iii) Power at different scales

2D Power spectrum (e.g A2255) (II)



Error sources :

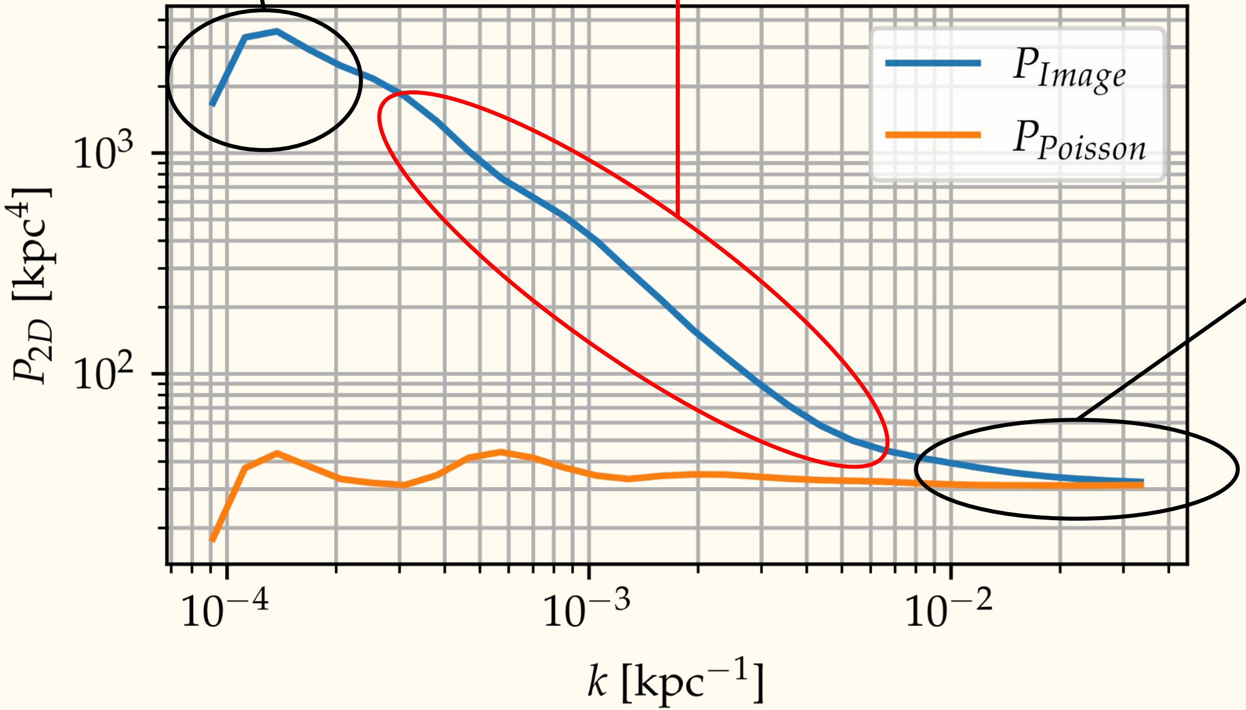
- Best fit parameters
- Poisson noise (X-ray)
- Sample variance

Error propagation using MCMC sampling

2D Power spectrum (e.g A2255) (III)

Power drop : **injection scale**, convolution with emissivity profile and/or the finite field of view

Inertial range (power law): exploitable information about the fluctuations

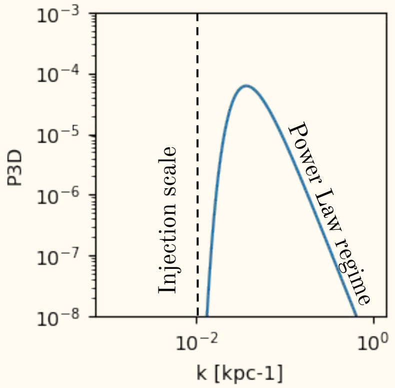


Flattening : Poisson noise is equivalent to a white noise at low scales

3D Power spectrum projection

WORK IN PROGRESS

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



$**$

$P_\eta \hat{=}$ 3D Power spectrum of the emissivity limited to the field of view

$\int dz$

$\times$

$P_{\mathrm{PSF}} \hat{=}$ 2D Power spectrum of the instrument PSF

$+$

$P_{\mathrm{Noise}} \hat{=}$ 2D Power spectrum of the image noise

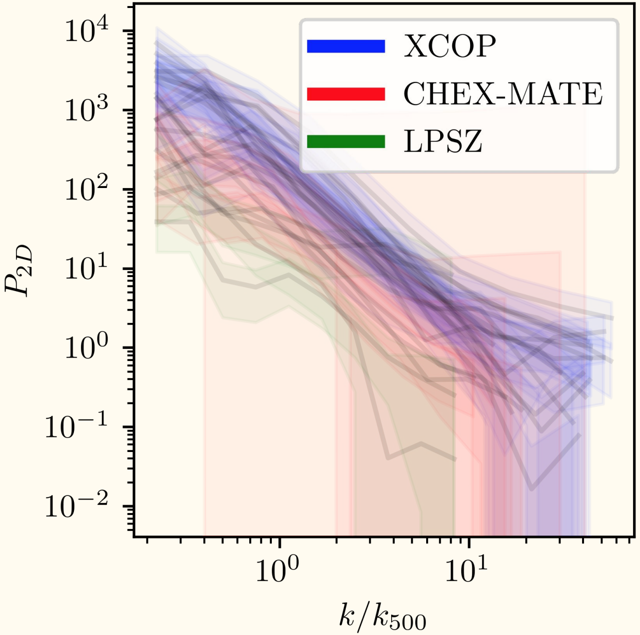
Observed 2D power spectrum

Application to XCOP, CHEX-MATE and LPSZ

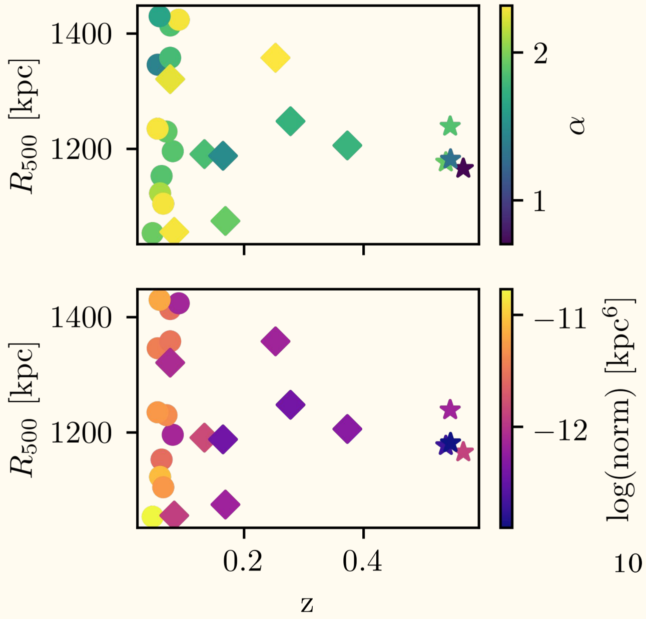
WORK IN PROGRESS

- 2D Power spectrum for a reduced number of clusters (Beta model)
- All our subsamples yield similar results
- No particular trend identified at this time

● XCOP
◆ CHEXMATE
★ LPSZ@NIKA2



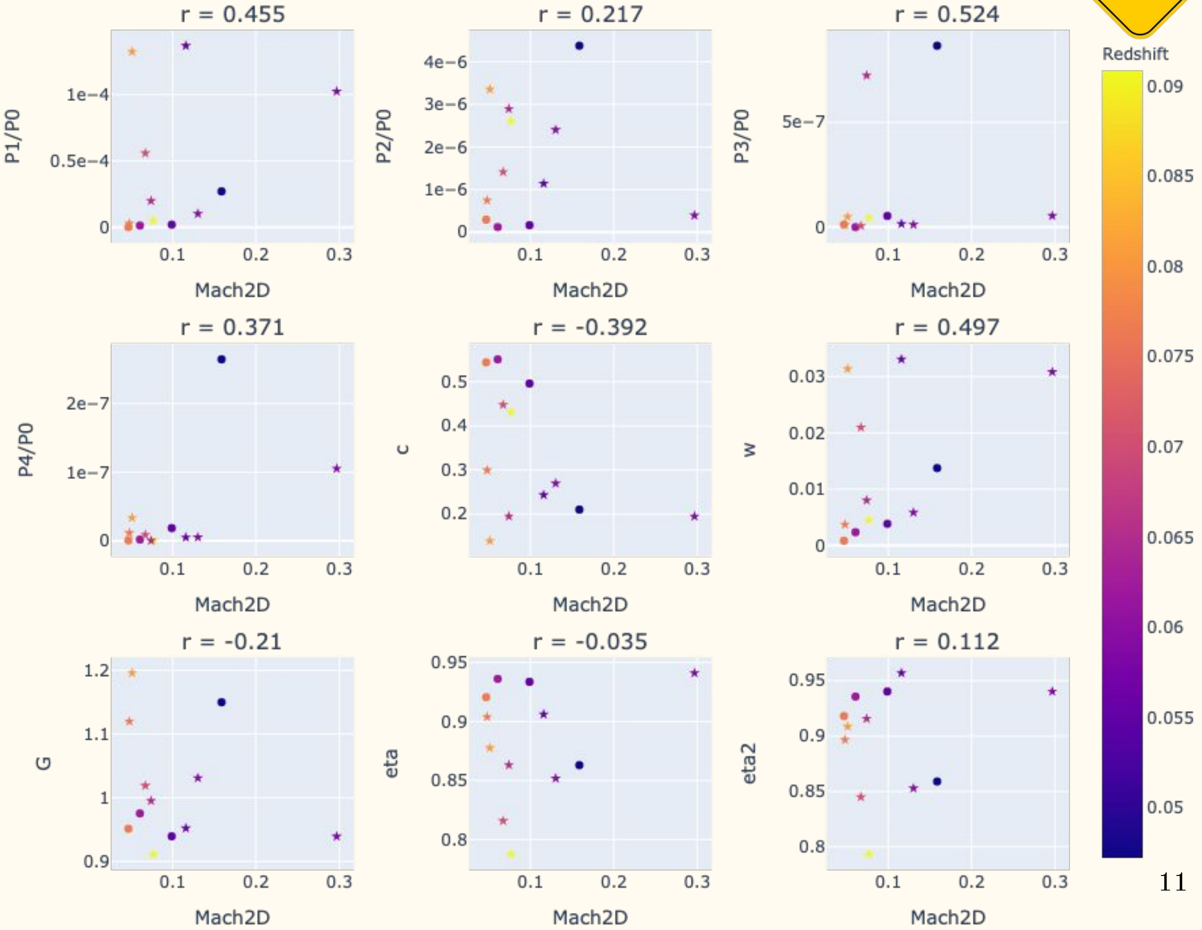
$$P_{3D} = 10^{\mathrm{norm}} \left(\frac{k}{k_{\mathrm{ref}}}\right)^{-\alpha}$$



Correlation with dynamical state for XCOP

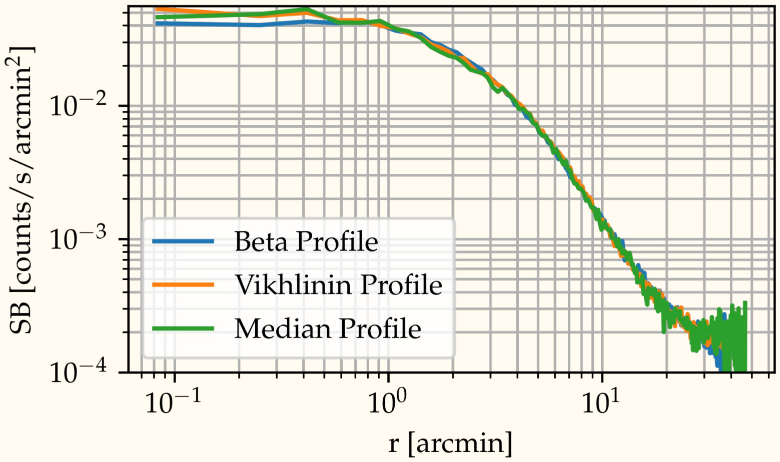
- Correlation with the 2D Mach number from the P2D (convolved with the emissivity profile)
- Weak correlation for some parameters (Spearman test)

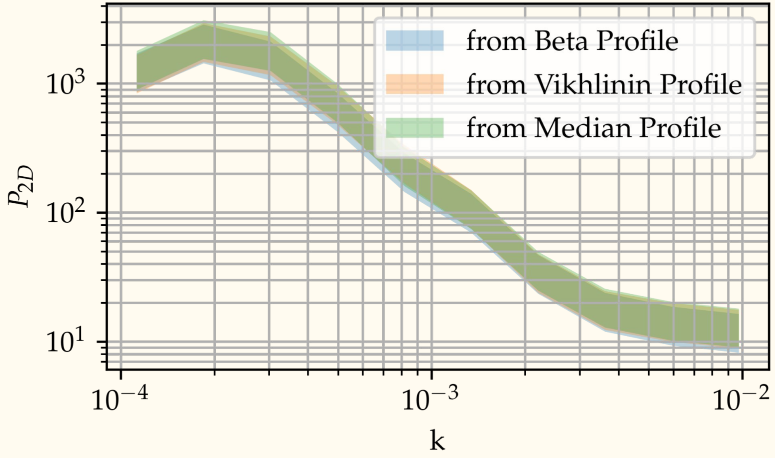
η = 1- e	Eccentricity
Pm/P0	Power ratios
w	Centroïd shift
c	Concentration
G	Gini coefficient



Mean surface brightness model (e.g A3158)

WORK IN PROGRESS





More fidelity / less high-scale fluctuations

- **Beta Model (Cavaliere & Fusco-Femiano 1976)**

$$\propto \left(1 + \frac{r}{r_c}\right)^{\frac{1}{2} - 3\beta}$$

- **"Vikhlinin" Model (Vikhlinin, 2006, Ghirardini 2018)**

$$\propto \frac{(r/r_c)^{-\alpha}}{(1 + r^2/r_c^2)^{3\beta - \alpha/2}} \frac{1}{(1 + r^\gamma/r_s^\gamma)^{\epsilon/\gamma}}$$

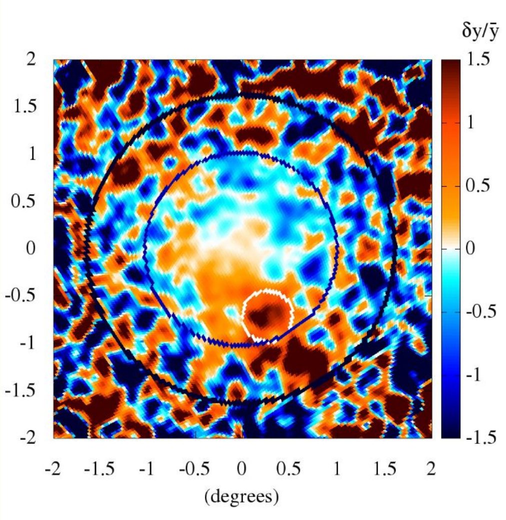
- **Median Model (D. Eckert, 2015)**

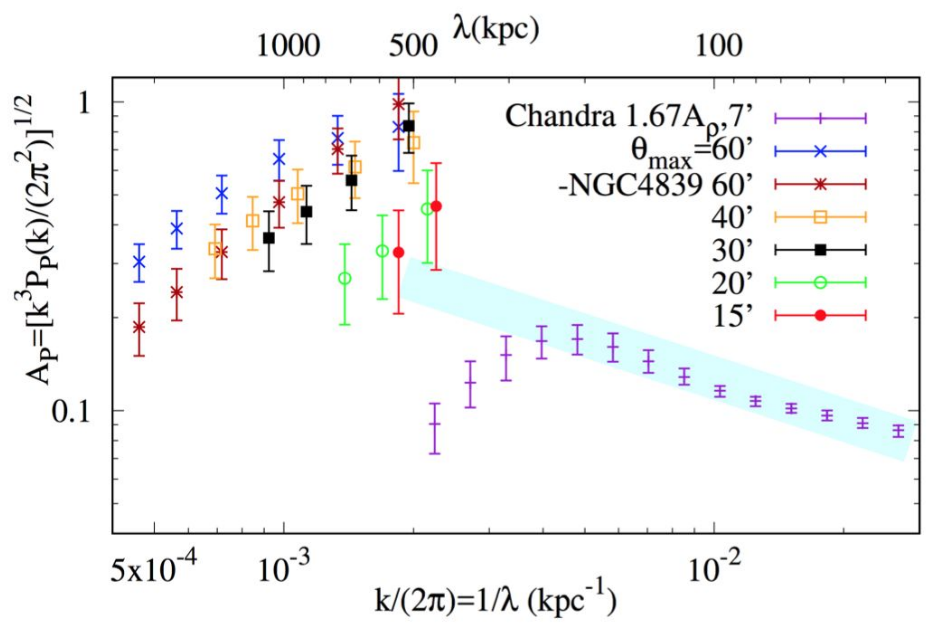
Consistent analysis between the different profiles
To be investigated further

Perspective on SZ fluctuations

WORK IN PROGRESS

Residual fluctuation map from MILCA map of the Coma cluster (Khatri & Gaspari 2016)





Characteristic amplitude of the pressure fluctuations, from SZ and X-SB (Kathri & Gaspari 2016)

Change from the X-ray SB fluctuations :

- $\Delta\rho^2 \rightarrow \Delta P$
- Poisson noise → Correlated noise
- PSF and transfer function (NIKA2)

Conclusion

Summary

- Turbulence occurs in the ICM
- It can be quantified using X-ray & SZ fluctuations as complementary observables
- Study turbulence in a large cluster sample at various redshifts to better understand the assembly of massive halos
- We have extracted the 2D power spectrum of X-ray SB fluctuations for ~20 clusters, focusing on XCOP as our test sample

Discussion & Perspectives

- Correlation of the 2D Mach number with morphological indicators
- Choice of the mean profile model, related arbitrary high scale fluctuations
- Extension of this work to the whole CHEX-MATE and LPSZ@NIKA2 samples
- Inclusion of SZ data from Planck, ACT and NIKA2

Thank you for your attention !