Characterization of the gas density fluctuations in the X-COP cluster sample

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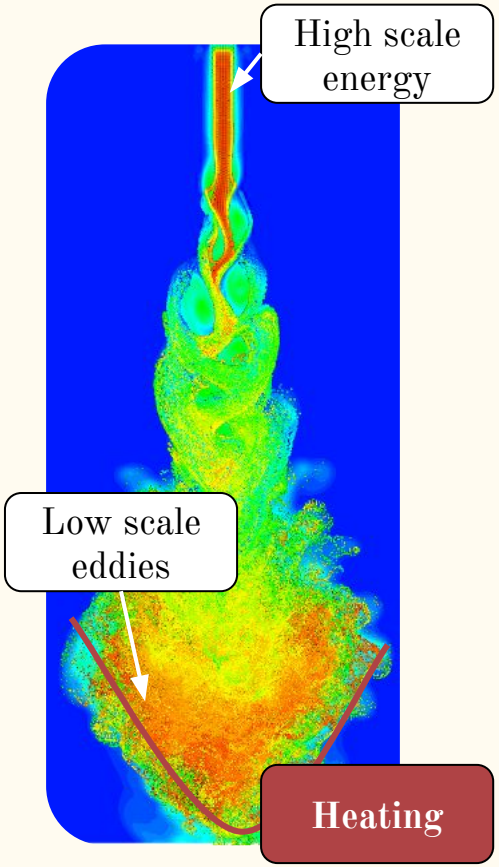
N. Clerc, D. Eckert, E. Pointecouteau

Athena scientific conference 2022

Turbulence in galaxy clusters



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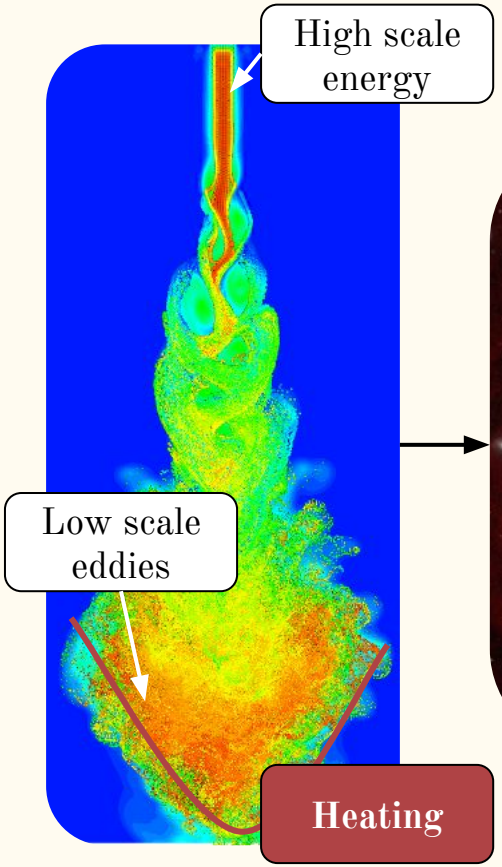
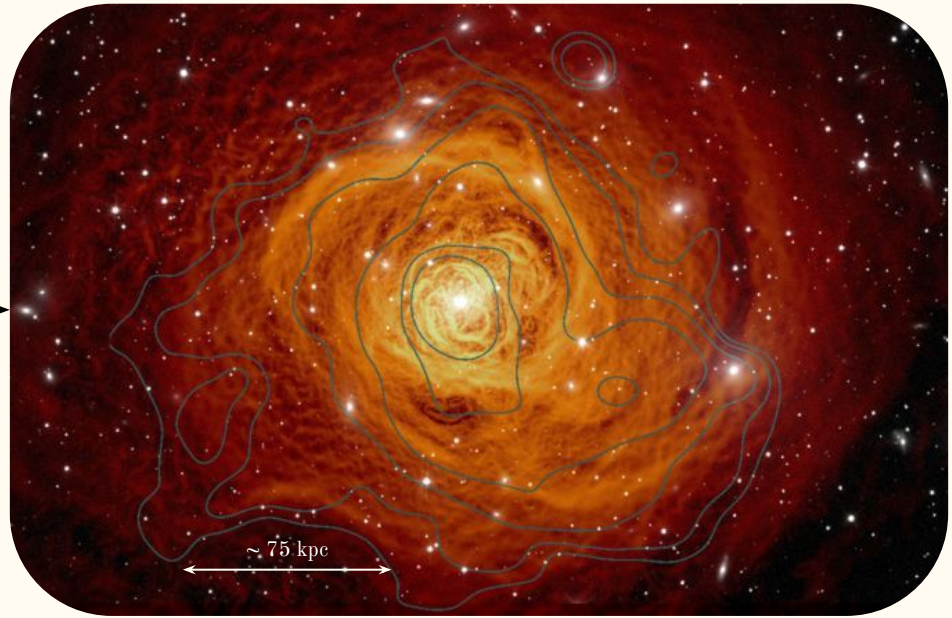


Multiple sources of turbulence in galaxy clusters



X-ray surface brightness for Perseus Cluster, gradient emphasized (orange)
Radio contour, JVLA 230-470MHz
(Credit : Sanders & al 2016 (X-ray), M.L. Gendron-Marsolais (Radio))

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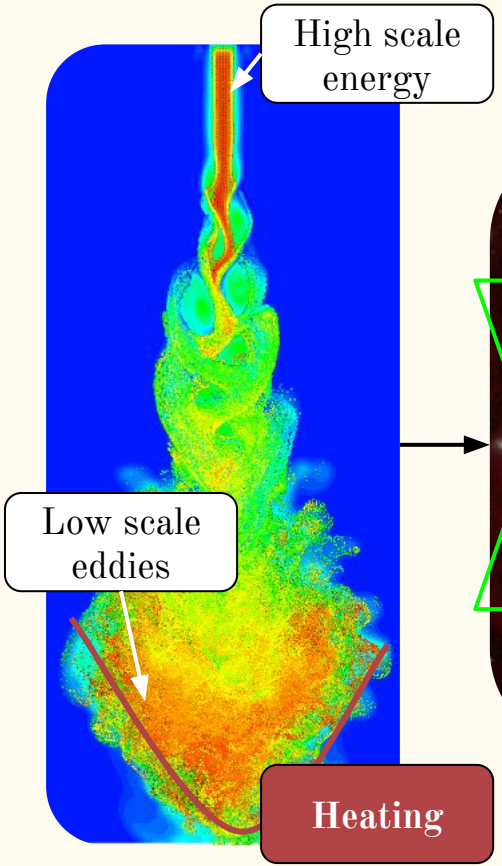

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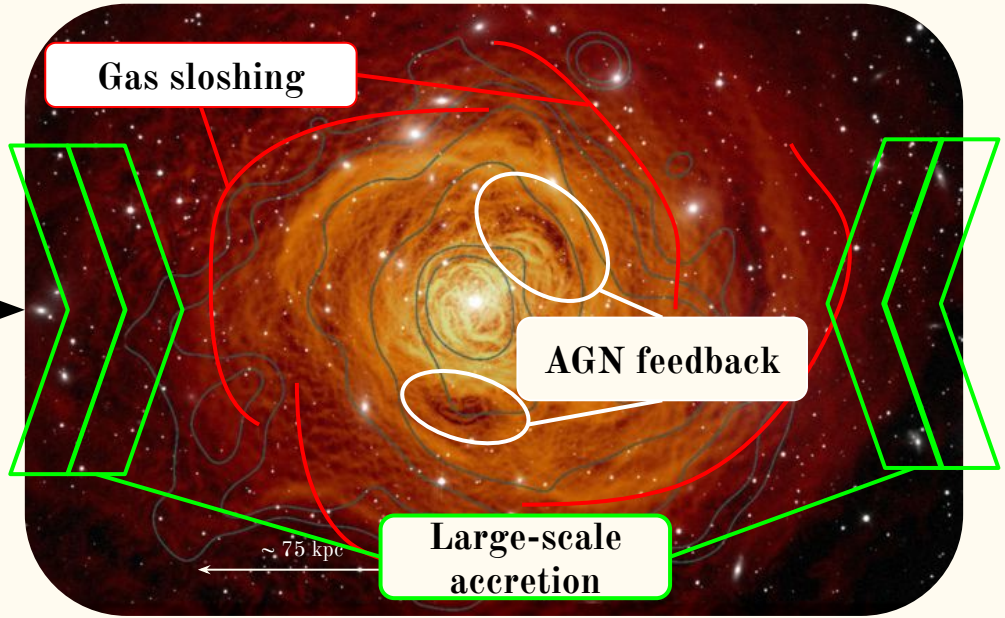

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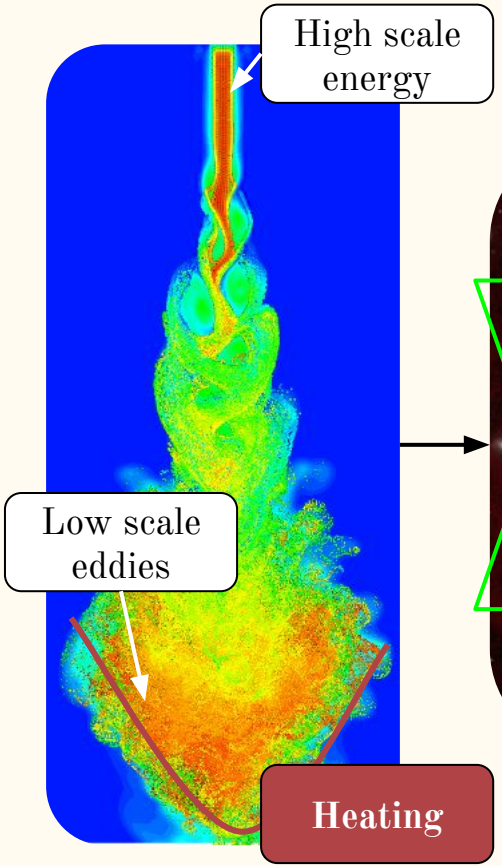

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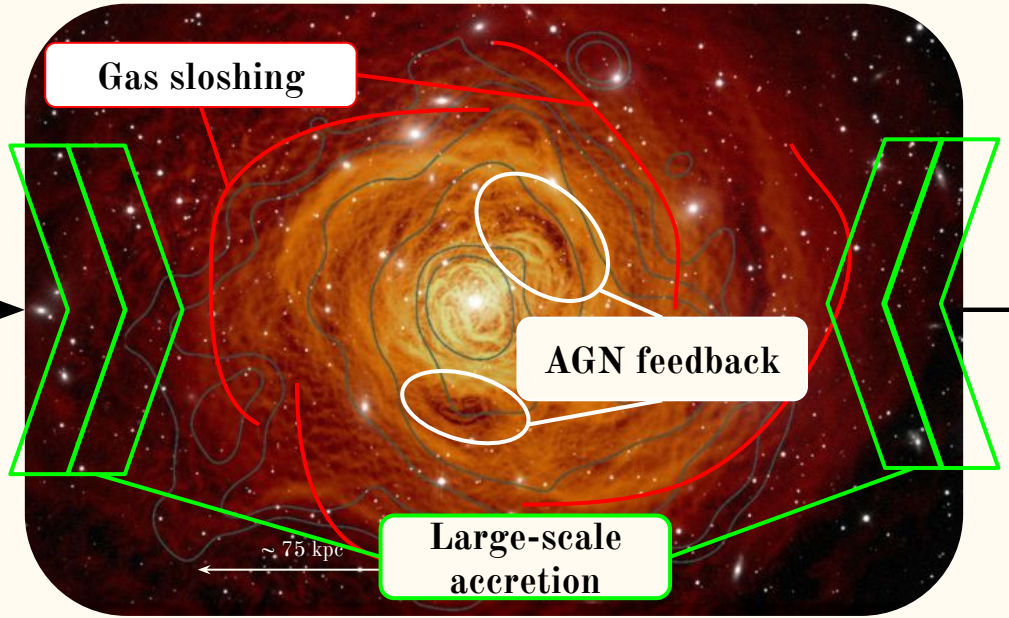

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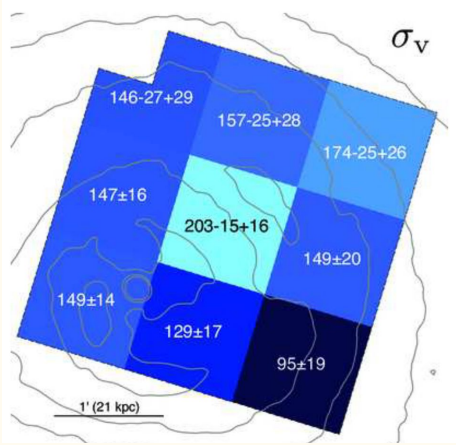
- Biased mass ⇏ Clusters as cosmological probes?
- Physics of the gas?
- Dynamic assembly of galaxy clusters?

Current measurements of turbulence in the ICM

Direct measurements

- Spectral lines centroid shift and broadening



Velocity dispersion, Perseus cluster center region (Hitomi Collaboration, 2018)

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

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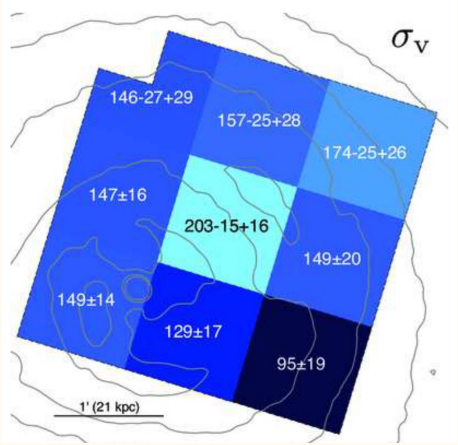

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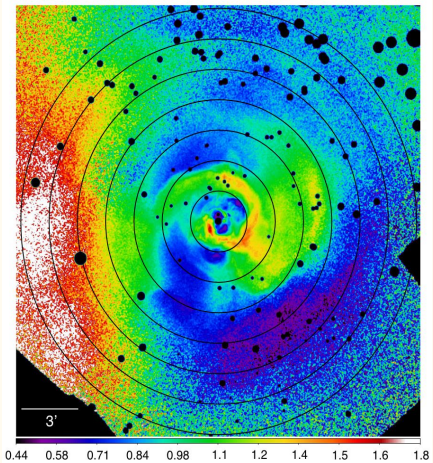
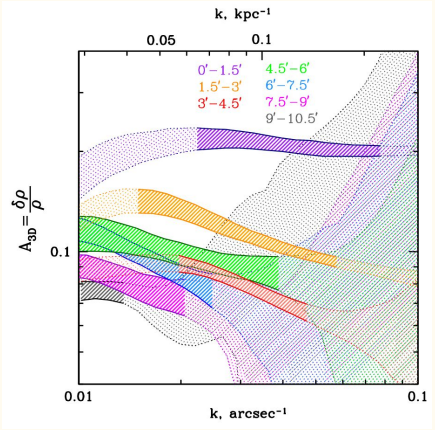
- Turbulence displaces gas and create fluctuations in ρ, P, T...
- Surface brightness fluctuations (SB) in X-rays (e.g. Churazov+2013, Zhuravleva+2015, Zhuravleva+2018) or Sunyaev-Zel'dovich (e.g. Khatri+2016)





X-ray surface brightness fluctuations and 3D density fluctuations power spectrum, Perseus cluster (Zhuravleva & al, 2015)

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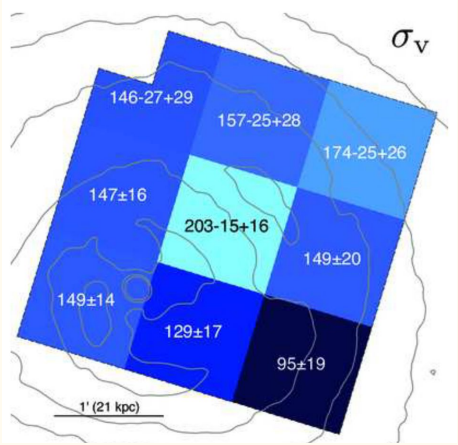

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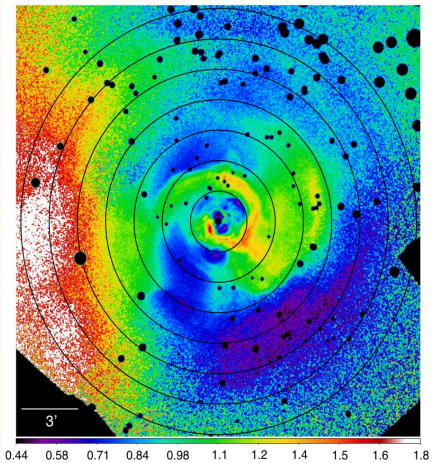
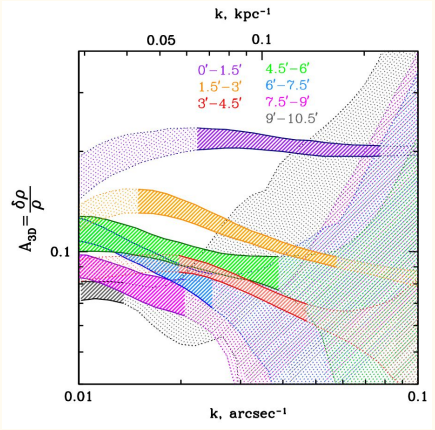
- Strong link between density fluctuations and turbulent velocities (e.g. Zhuravleva+2014, Mohapatra+2019, Simonte+2022) $\sigma_\delta \propto \sigma_v = \mathcal{M}_{3D}$





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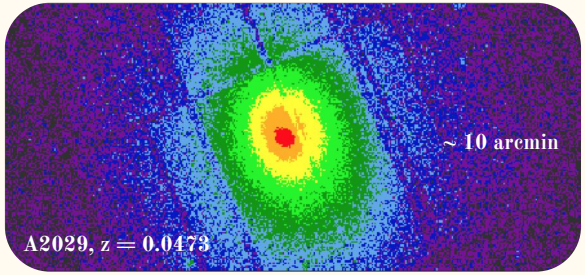
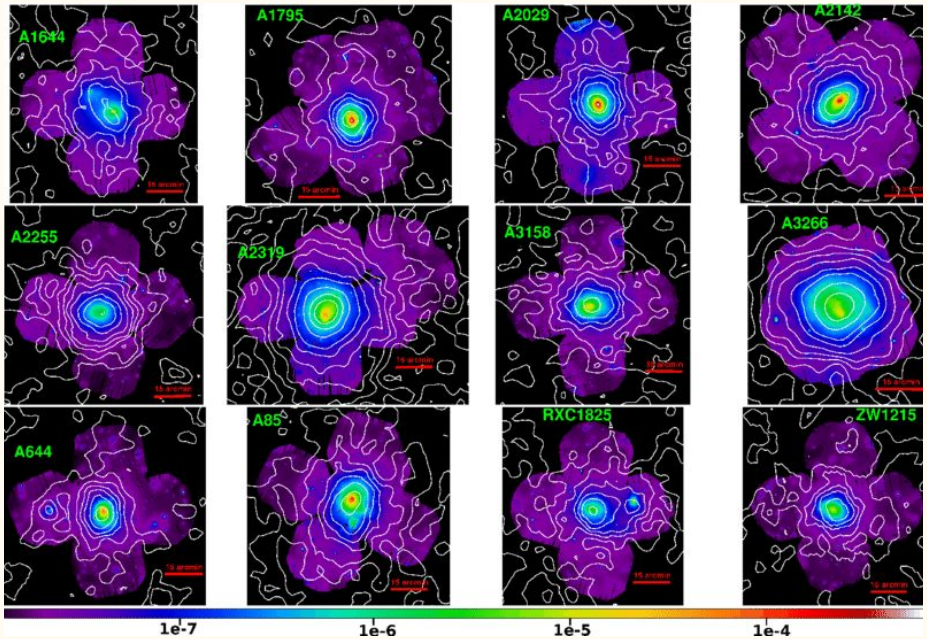
Application to the X-COP sample

X-COP (Eckert+, 2017)
Redshift ≲ 0.07
Planck selected (S/N>12)
Outskirt physics (N=12)





Adaptively smoothed X-ray surface brightness in [0.7-1.2] keV band (Ghirardini & al. 2018)

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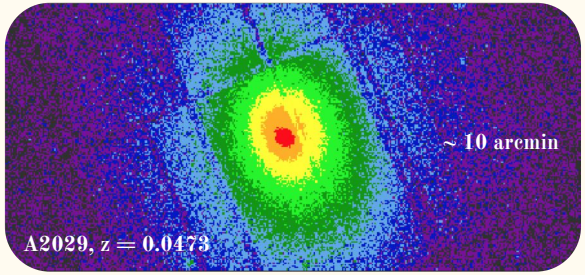
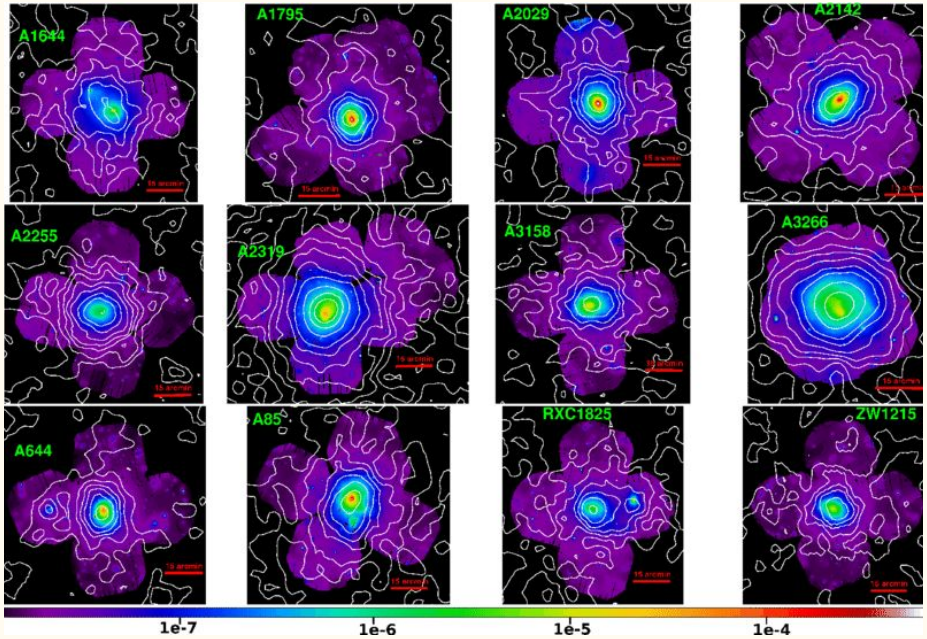




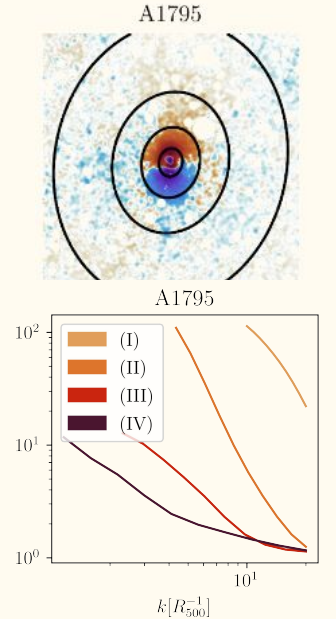
Adaptively smoothed X-ray surface brightness in [0.7-1.2] keV band (Ghirardini & al. 2018)

1 cluster
1 observation
High sample variance

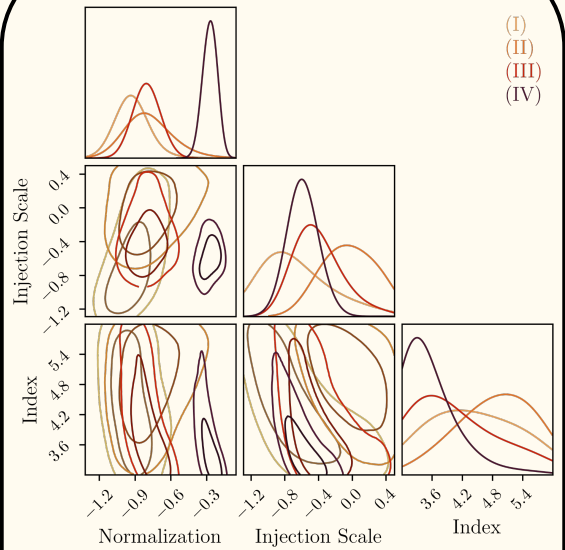
<u>Assumption:</u>
fluctuations in different clusters result from the same physical process

Cluster sample
Multiple observations
Reduced sample variance

General methodology

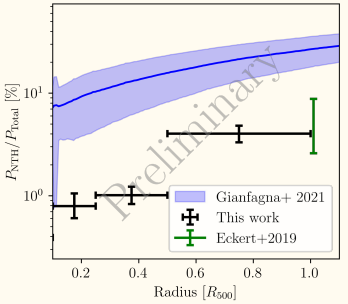


Fluctuation map & SB power spectrum



Constraints on the density fluctuation properties

$$\sigma_\delta \propto \sigma_v = \mathcal{M}_{3D}$$

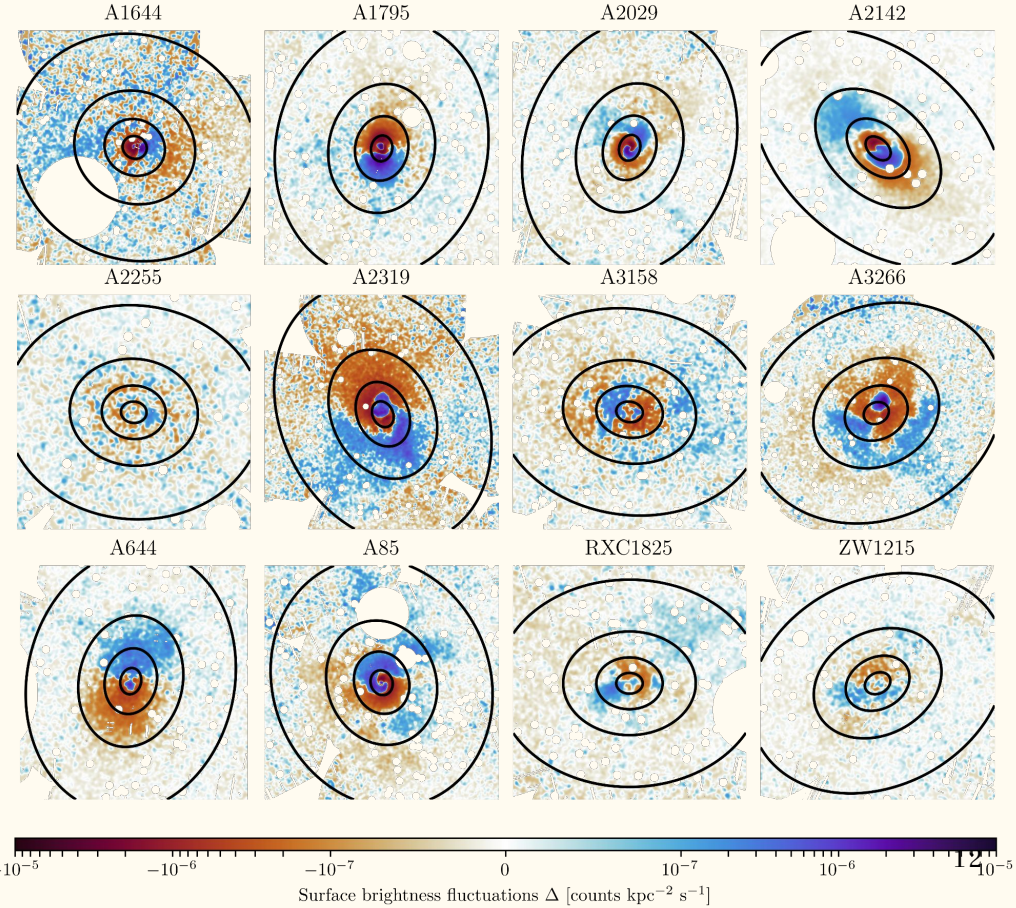


Relation to turbulent motion

Mean surface brightness (SB) profile

Meticulous modelling of surface brightness
⇔
Less arbitrary induced fluctuation

Best-fit fluctuations maps in the X-COP sample



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<u>Example:</u> using **elliptical model** on simulations can **reduce fluctuations by a factor 2** (Zhuravleva+ 2022)

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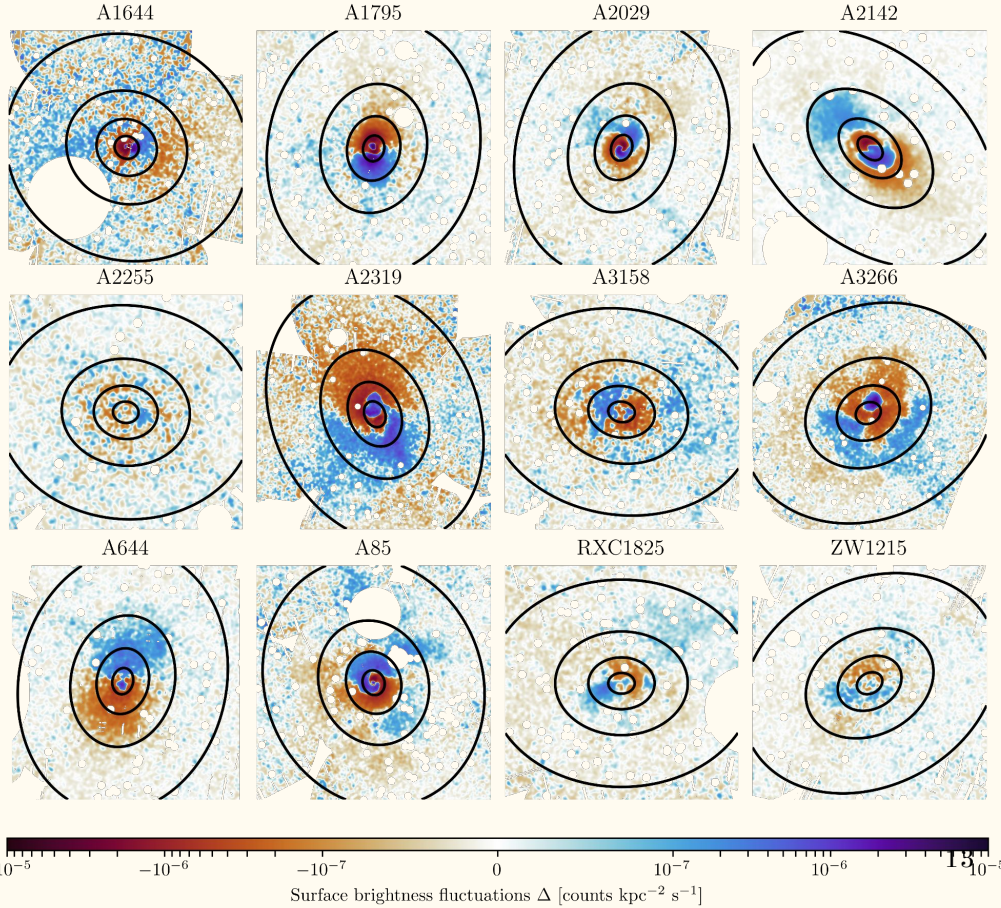

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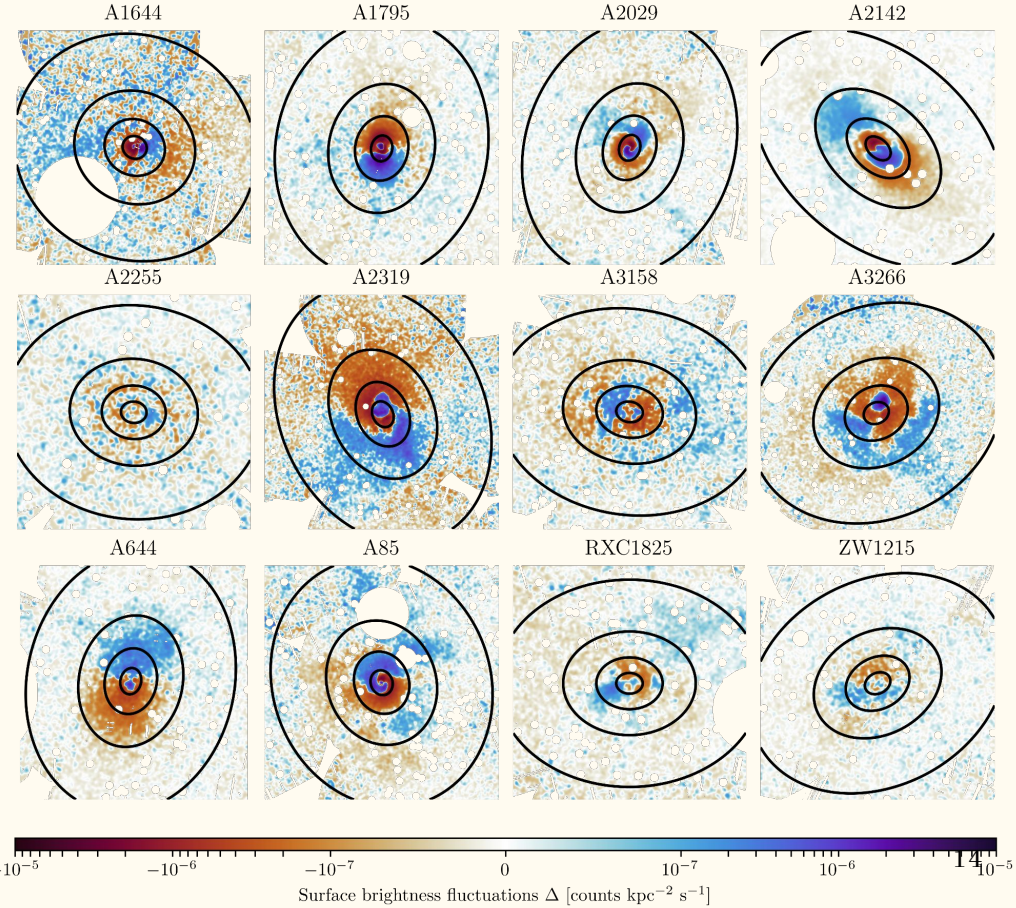
Example: using **elliptical model** on simulations can **reduce fluctuations by a factor 2** (Zhuravleva+ 2022)

Non-Gaussian features : sloshing, cool-cores, sub-mergers...

Region	Radius
(I)	$0 < r < R_{500}/10$
(II)	$R_{500}/10 < r < R_{500}/4$
(III)	$R_{500}/4 < r < R_{500}/2$
(IV)	$R_{500}/2 < r < R_{500}$

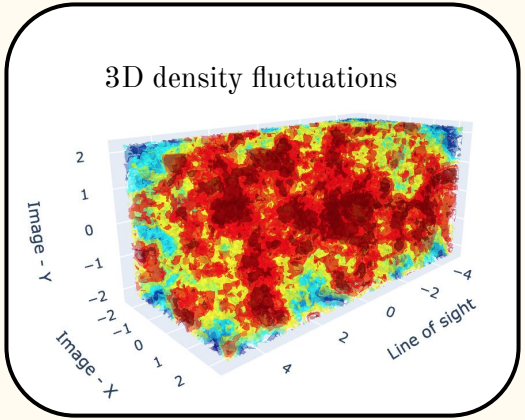
Best-fit fluctuations maps in the X-COP sample



From SB fluctuations to density fluctuations

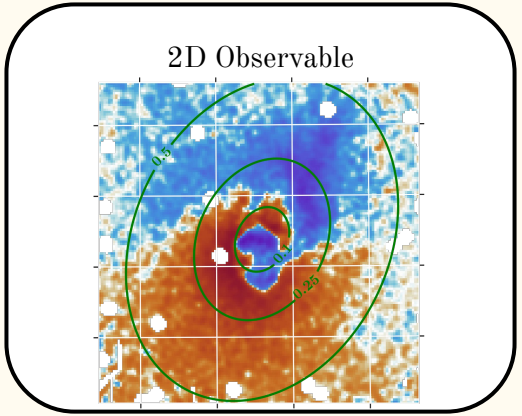
Hypothesis:

- SB fluctuations exclusively come from density fluctuations
- Gaussian Kolmogorov density fluctuations



Projection

?



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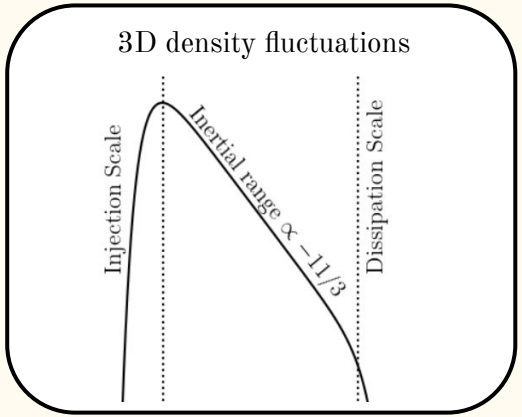

Density fluctuation power spectrum

Projection

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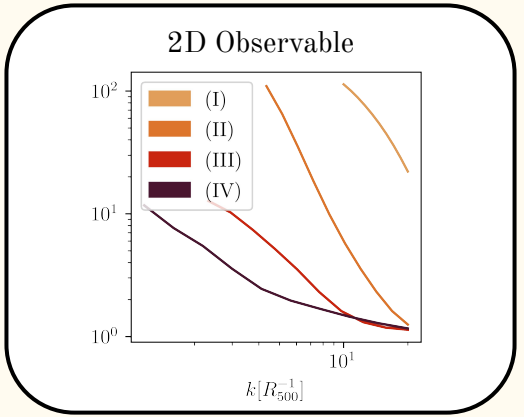

SB fluctuation power spectrum
(exceeding the Poisson noise)

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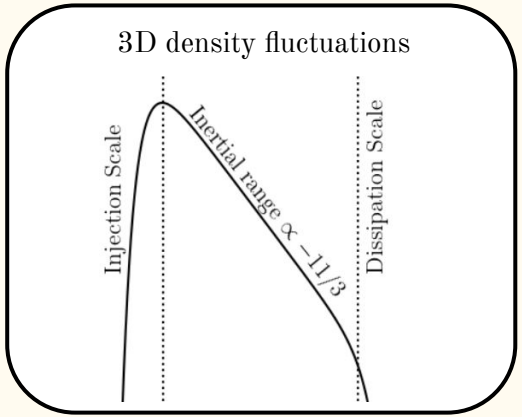


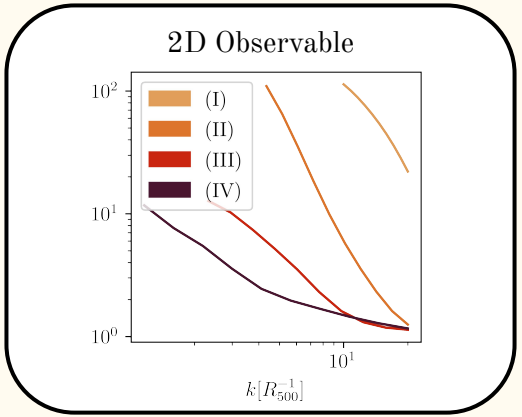
Density fluctuation power spectrum

Projection

Simulation-based inference

Approximate likelihood using a **neural network** & **modelled observables** (and with complete error budget, including **sample variance**)

~100000 mock observable for each cluster



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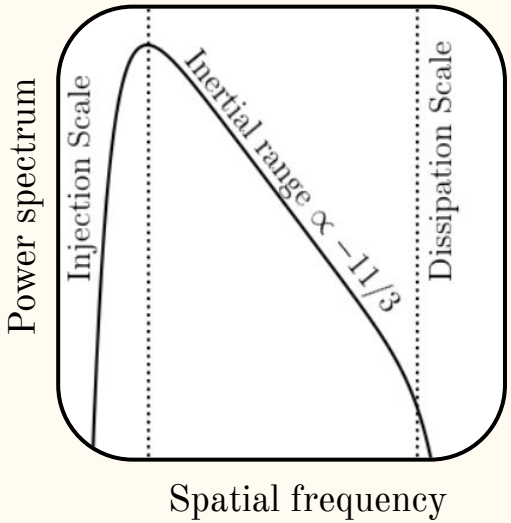
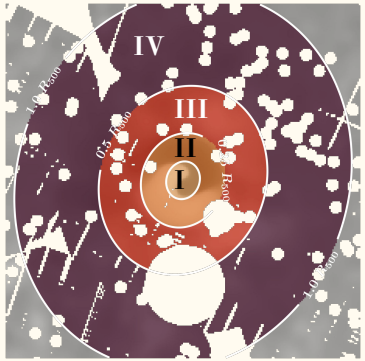
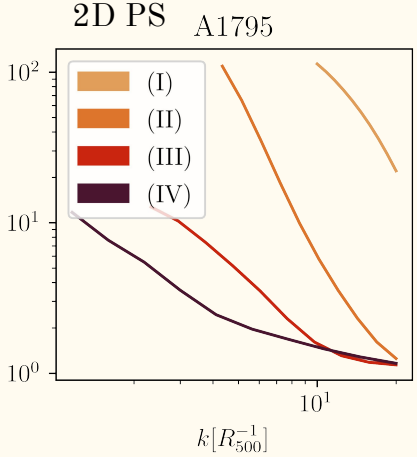
Constraining the 3D power spectrum







Free parameters :

- normalization,
- injection
- spectral index
- ~~dissipation~~

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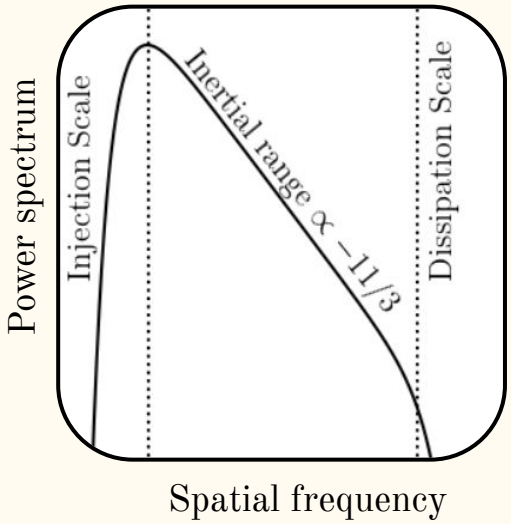

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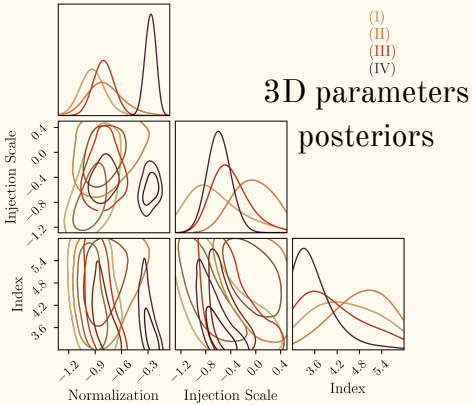

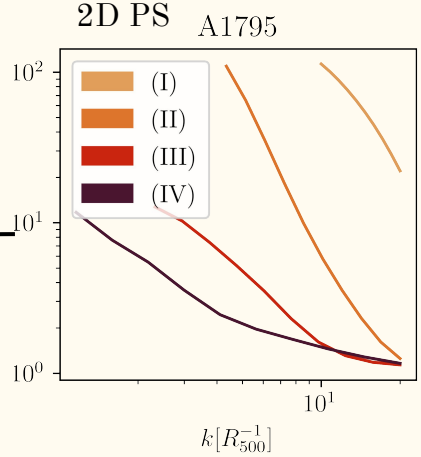

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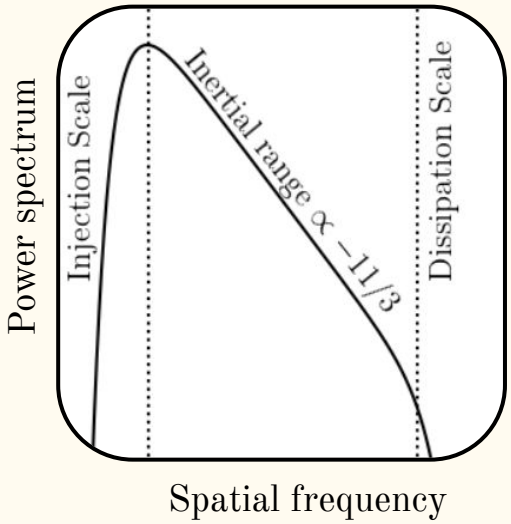

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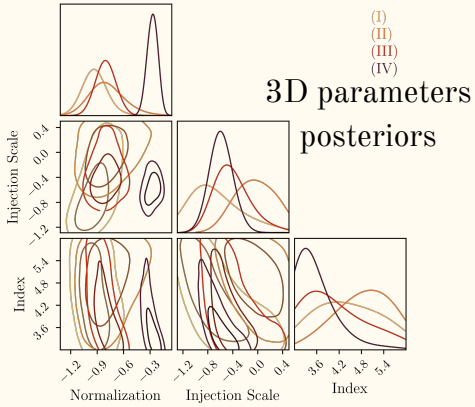
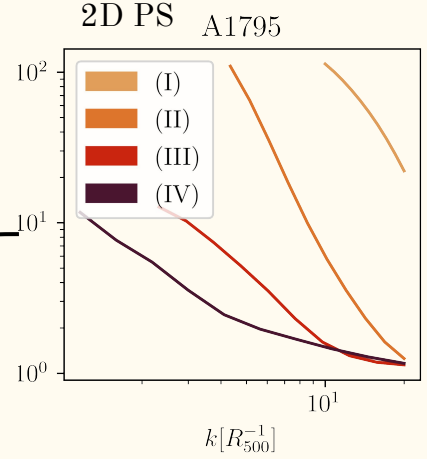
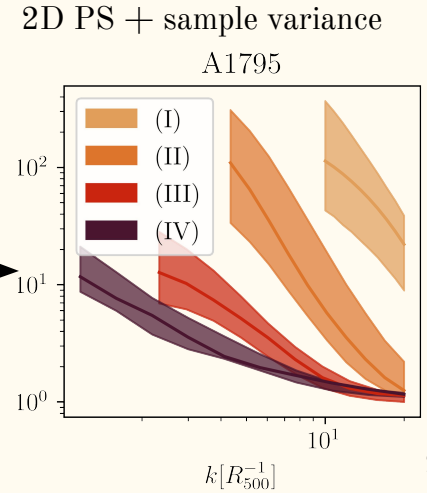




Modelling with posterior distributions



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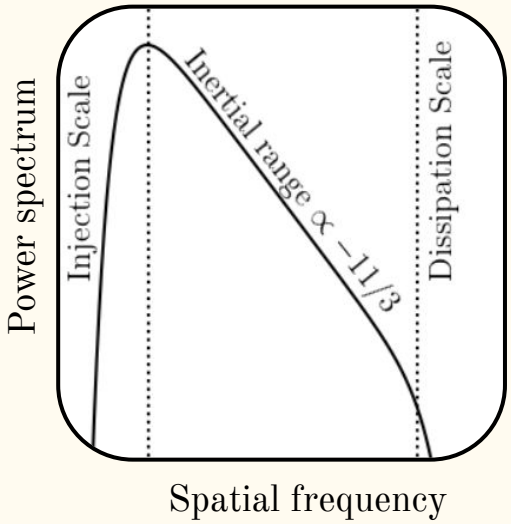
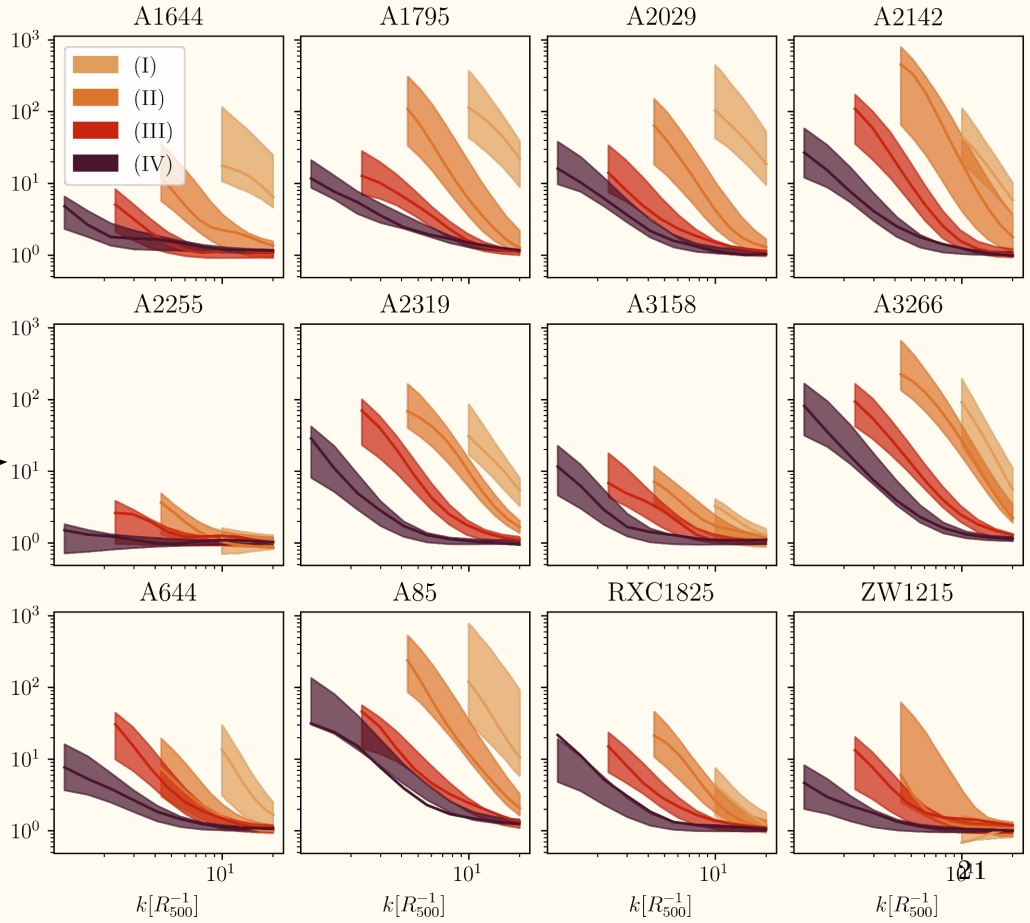


2D PS for each cluster in X-COP sample



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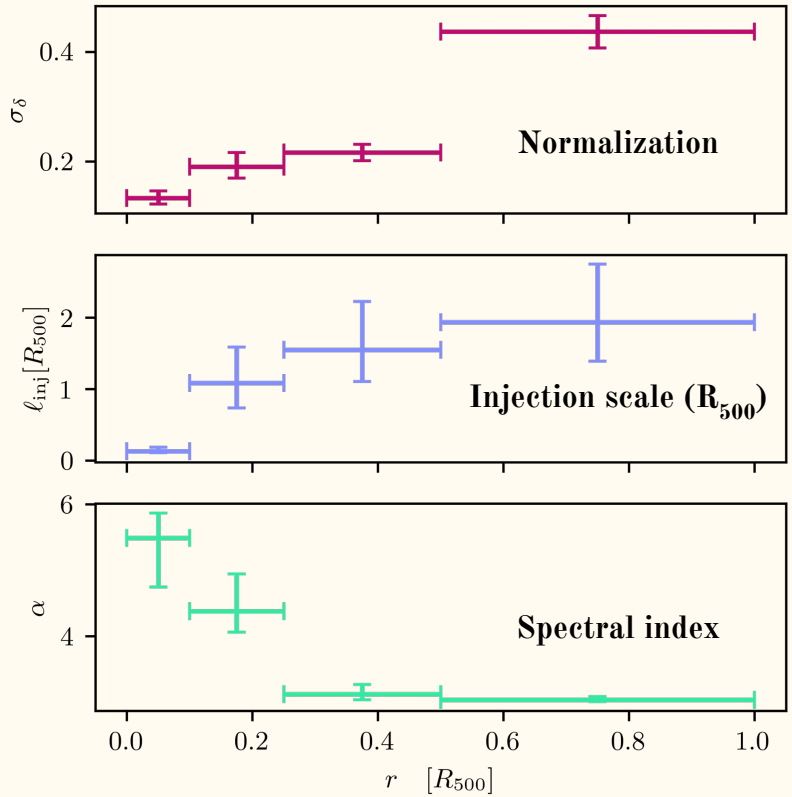
Results : constraints for density-fluctuation PS

Joint parameters for a Kolmogorov power spectrum for the whole X-COP sample



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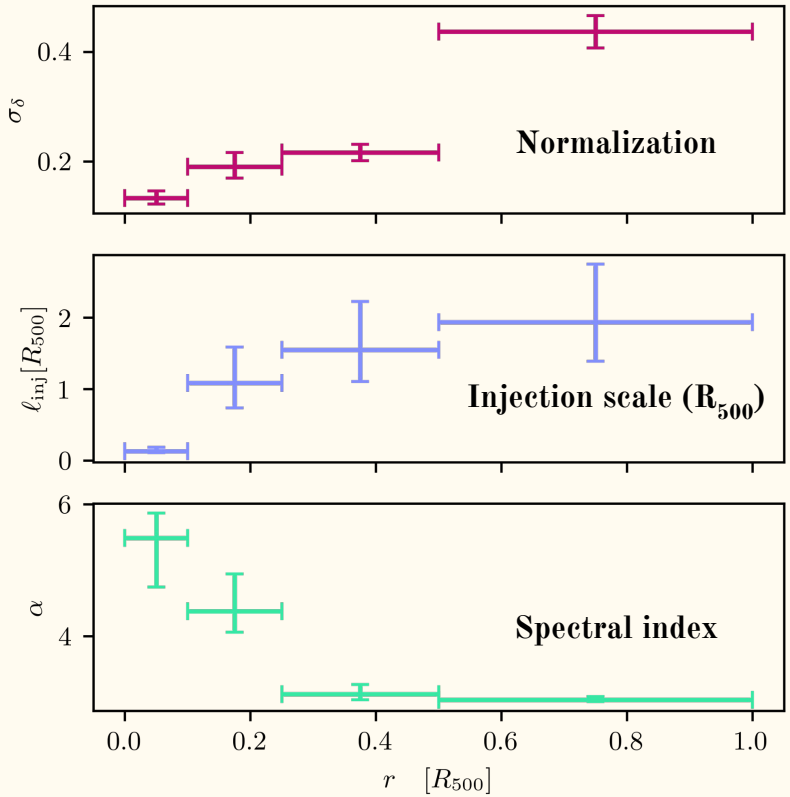

Increasing with radius
⇔
Gas disturbance increases away from the centre
Core is more relaxed than outskirts

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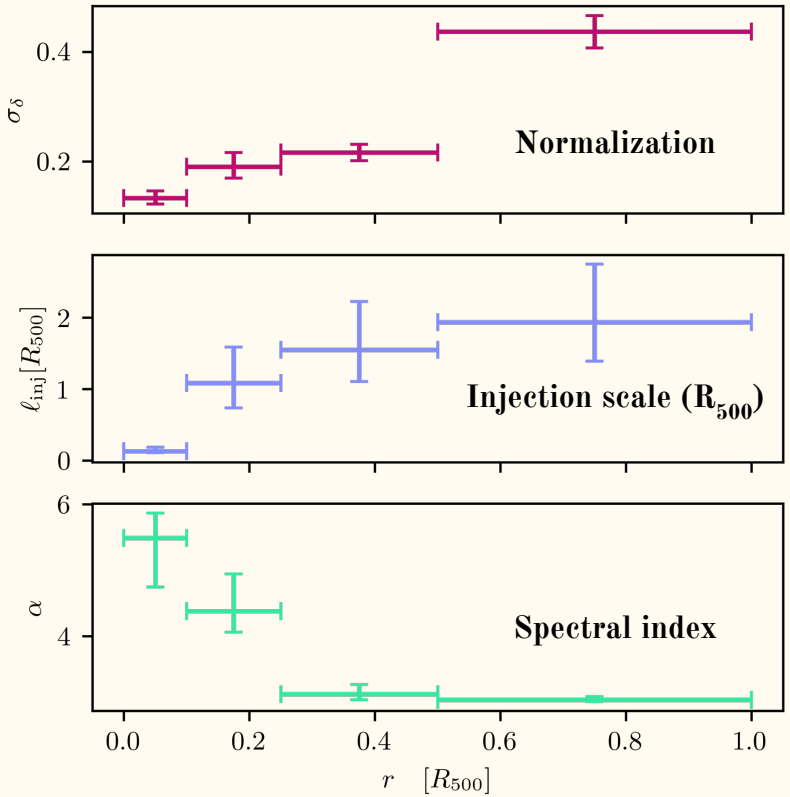

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AGN Feedback < Sloshing < Merger events / accretion

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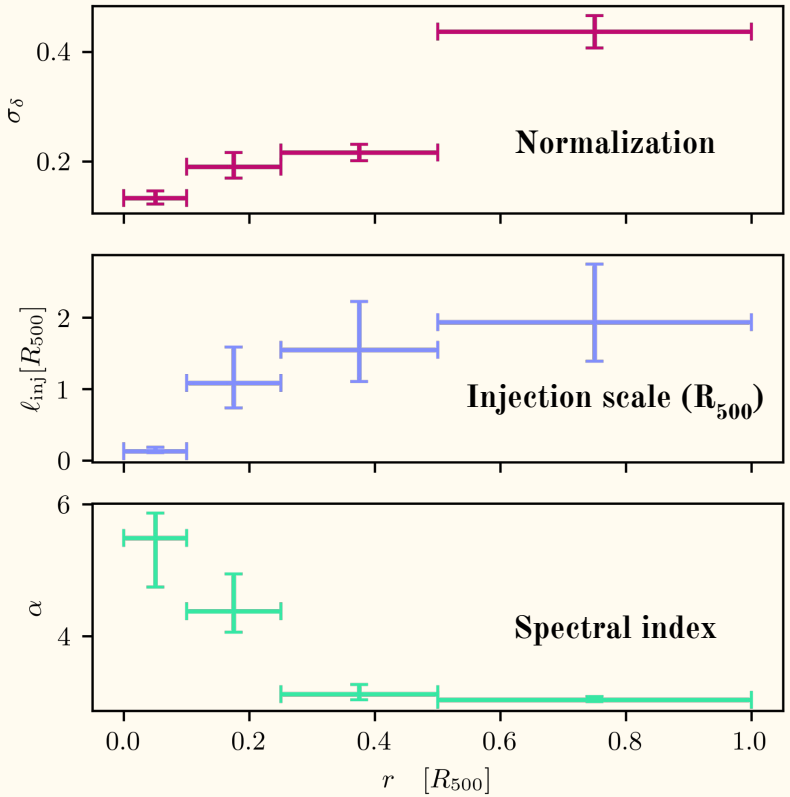

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Poorly constrained in outer parts (Poisson Noise)

Results : correlation with the dynamical state

- Morphological indicators relate to the dynamical state of a cluster
- Correlation with various indicators (c, w, Pi/P0, Cz...)

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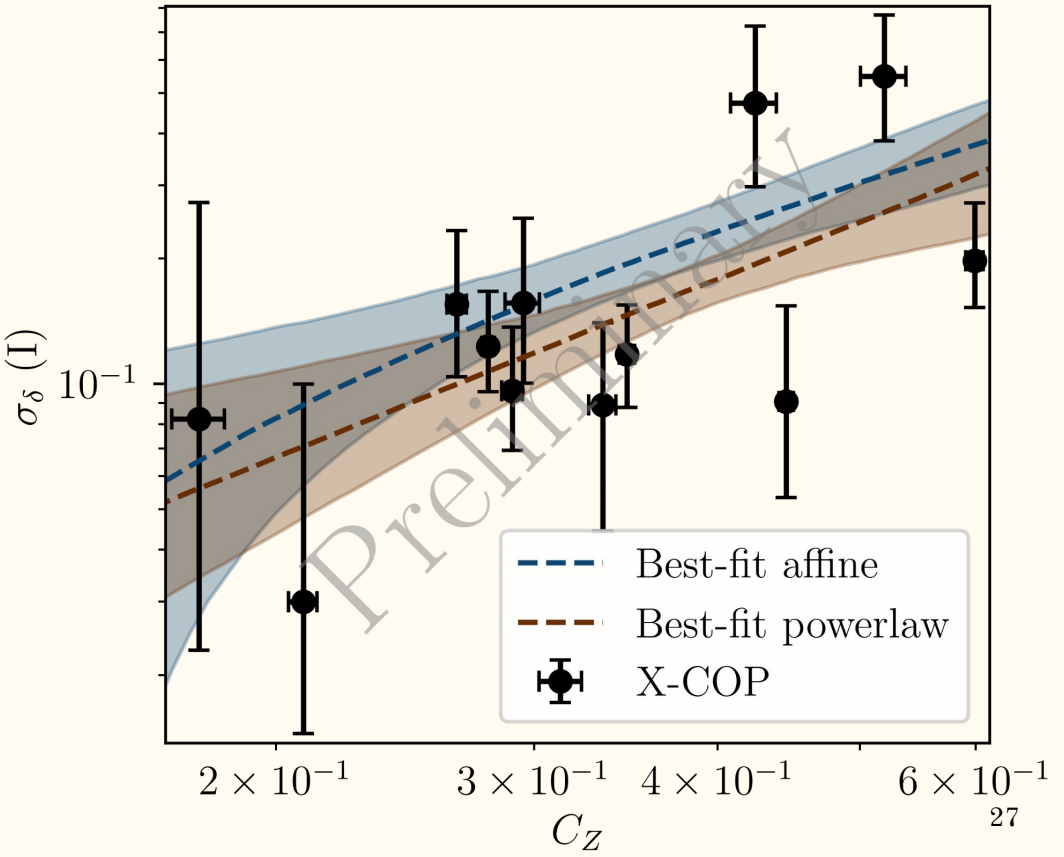
- Correlation with various indicators (c, w, Pi/P0, Cz...)

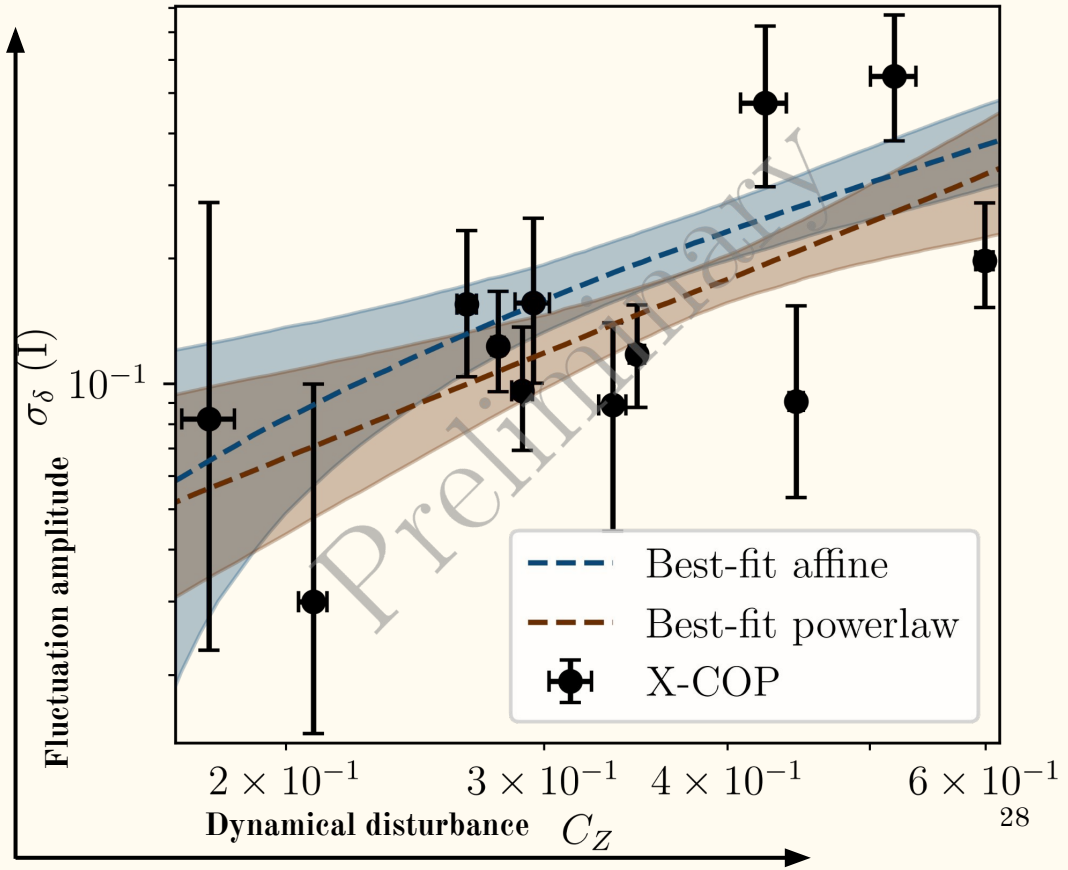
→ Correlation between Zernike moment (~asymmetry of the cluster) and the normalization of density fluctuations in central region



Results : correlation with the dynamical state

- Morphological indicators relate to the dynamical state of a cluster
- Correlation with various indicators (c, w, Pi/P0, Cz...)

→ Correlation between Zernike moment (~asymmetry of the cluster) and the normalization of density fluctuations in central region



Results : interpretation as turbulent motion

$$\sigma_\delta \propto \sigma_v = \mathcal{M}_{3D}$$

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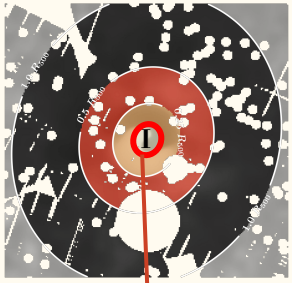
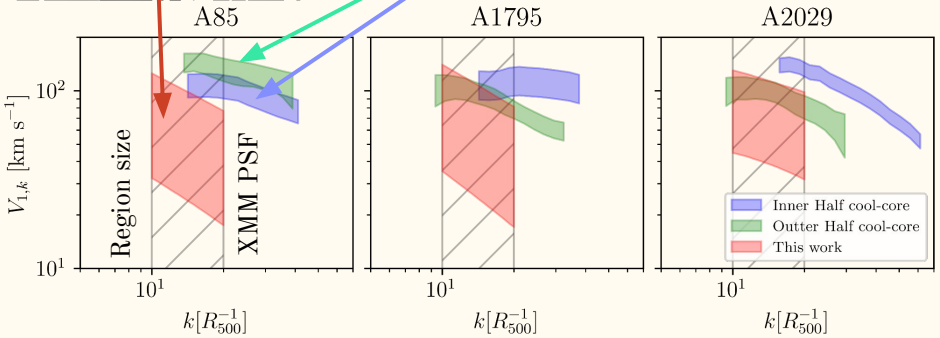


Comparison with previous work in the cool-cores of clusters (Zhuravleva+ 2018)

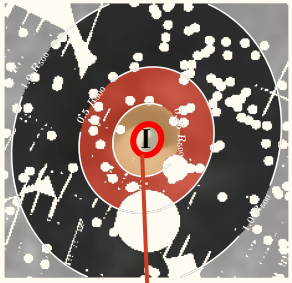


1σ compatible when the studied scales are comparable

Results : interpretation as turbulent motion

$$\sigma_\delta \propto \sigma_v = \mathcal{M}_{3D}$$

Non-thermal pressure support



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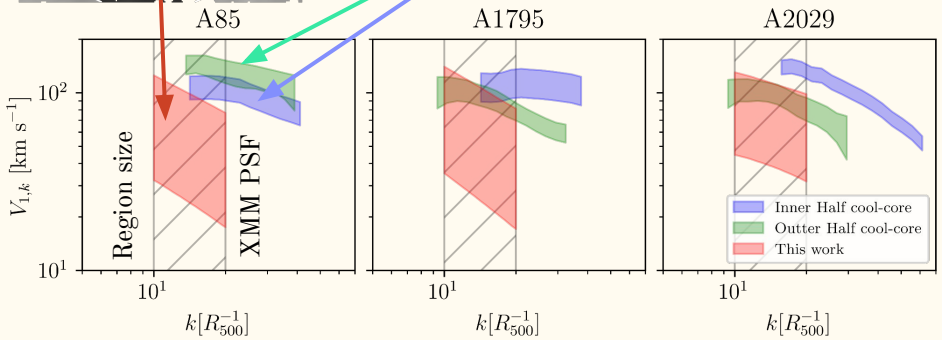

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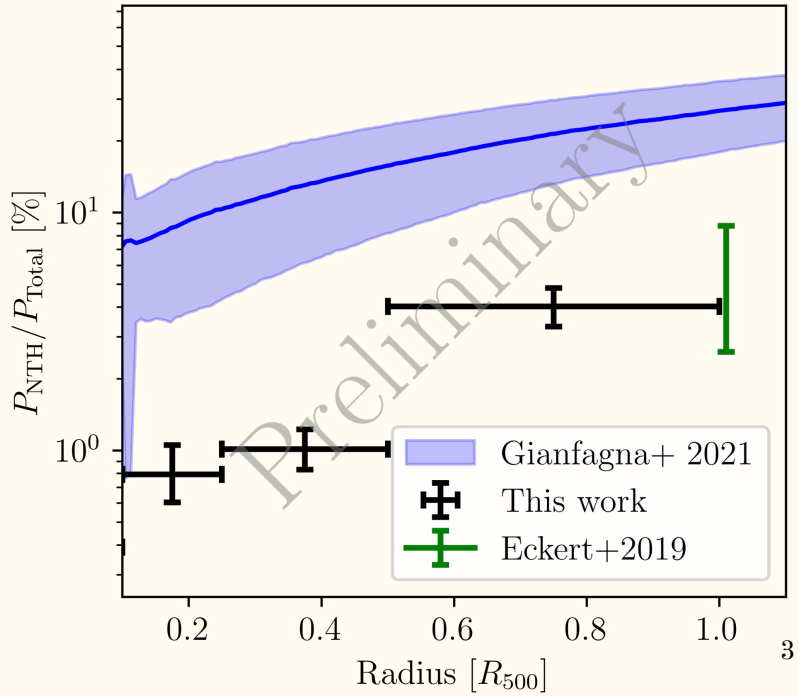
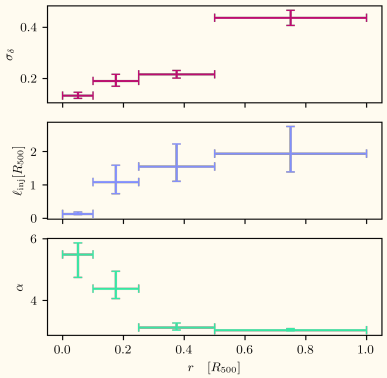


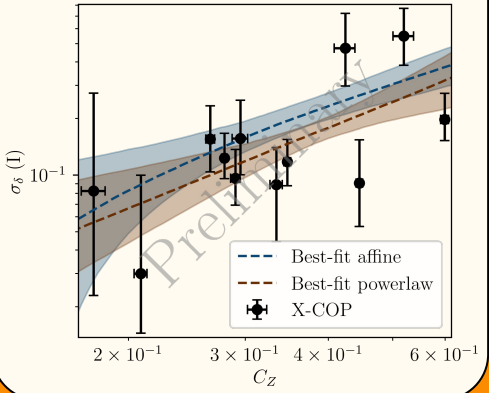
Topic : Statistics of SB (density) fluctuations, applied to the 12 massive and nearby clusters of the X-COP sample, novel approach considering the stochastic nature of fluctuations → complete error budget

Results : Dupourqué & al. to be submitted

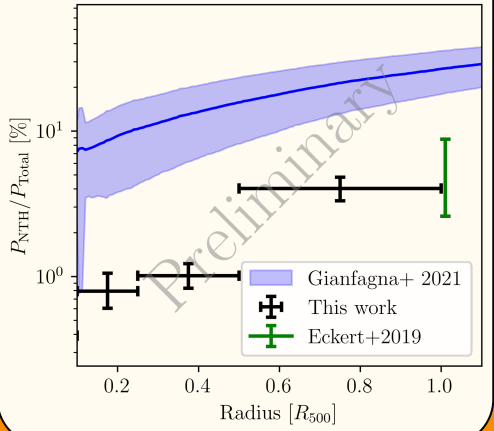
Original constraints for the density fluctuations power spectrum in the X-COP sample



Clear correlation between density fluctuations and the dynamical state of the cluster



Radial characterization of Mach and non-thermal pressure support

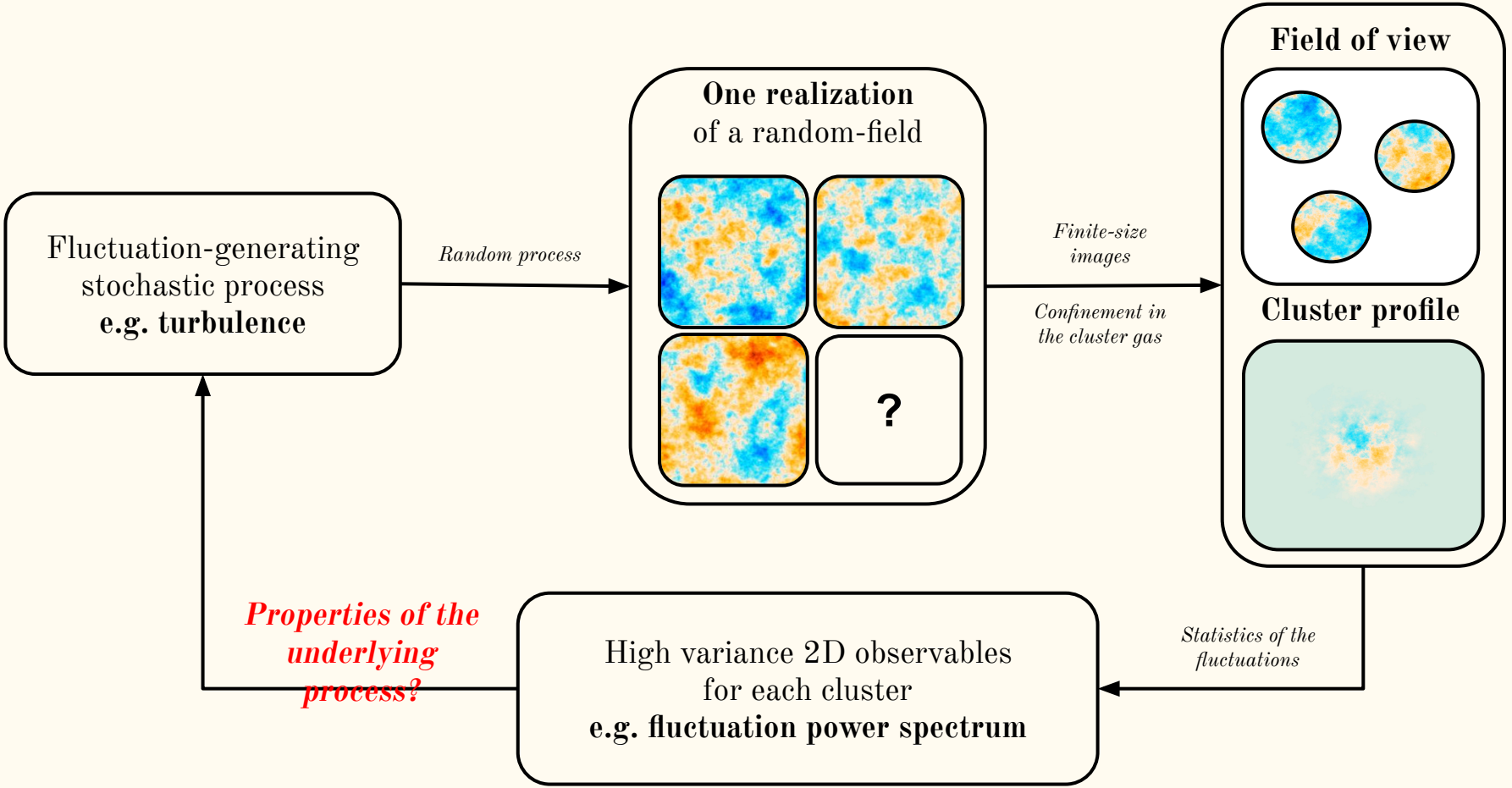


Perspective : Similar work on the CHEX-MATE sample with x10 more clusters

Thank you for your attention!

Backup slides

Backup : sample variance of fluctuations



Backup : Define the fluctuations

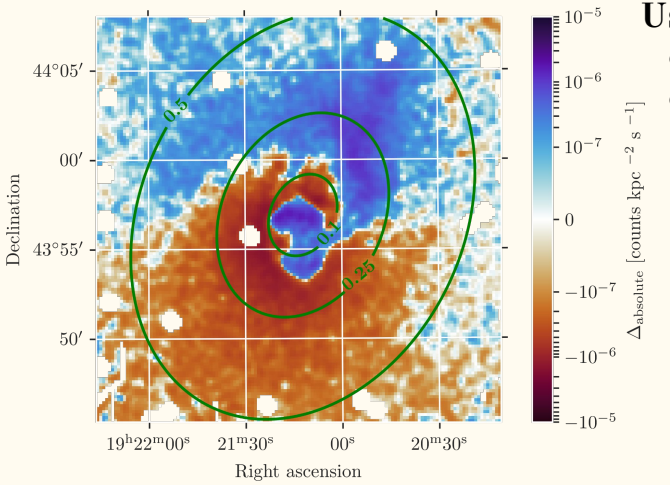
- Background noise is handled
- Fluctuations are not scaled

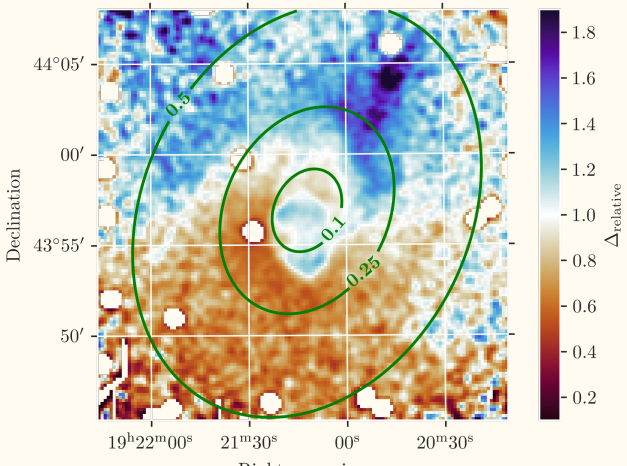
Absolute

Best-fit image

Relative

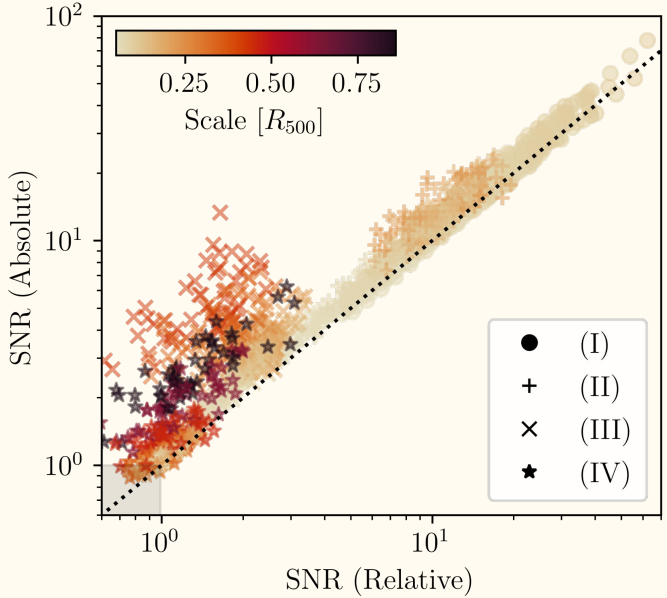
- Background noise explodes
- Fluctuations are scaled





Using simulations :

- Comparison of the SNR for both approaches
- SNR in each annulus + various scales



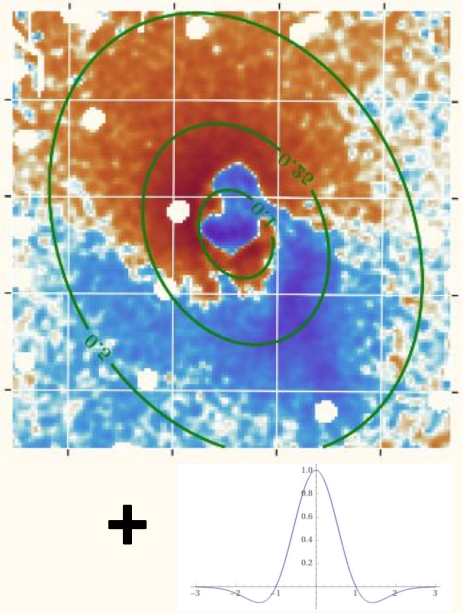
➔ Both methods are equivalent in the inner regions

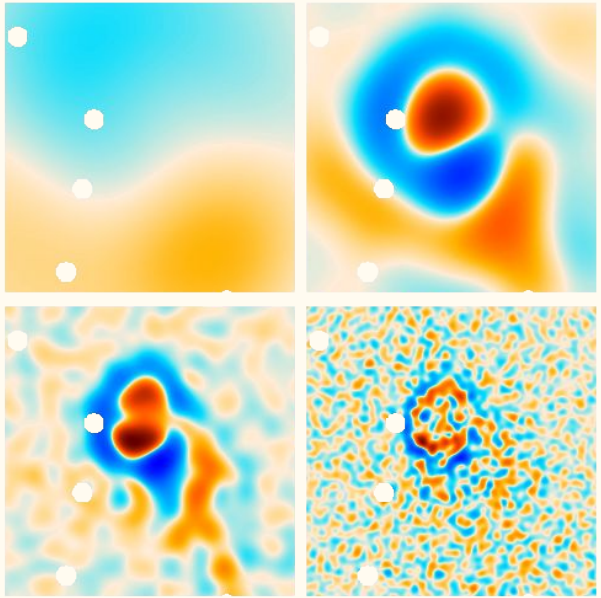
➔ Absolute method over performs in the outer regions

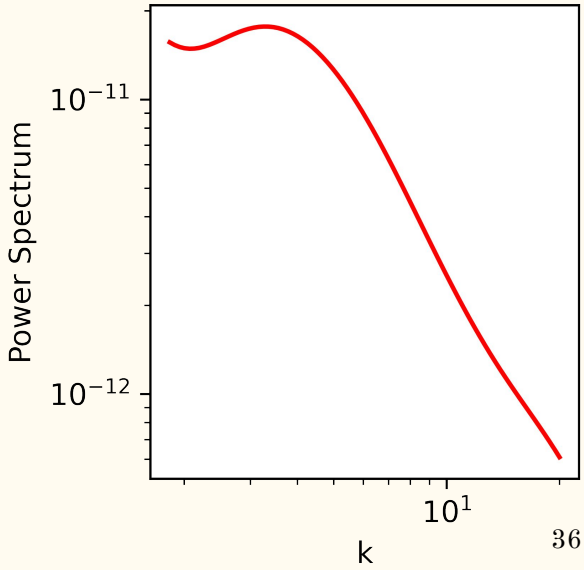
Backup : Extract the 2D observable

- 2D spatial power spectrum → Convolution with Mexican Hats
- Handle gaps and exposure maps (Arévalo & al, 2012)

Fluctuation map → *Filtering at various scales* → *2D Power spectrum*





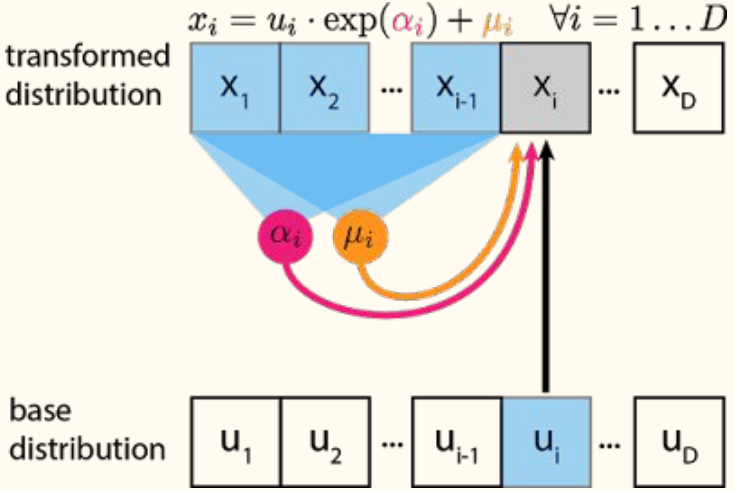


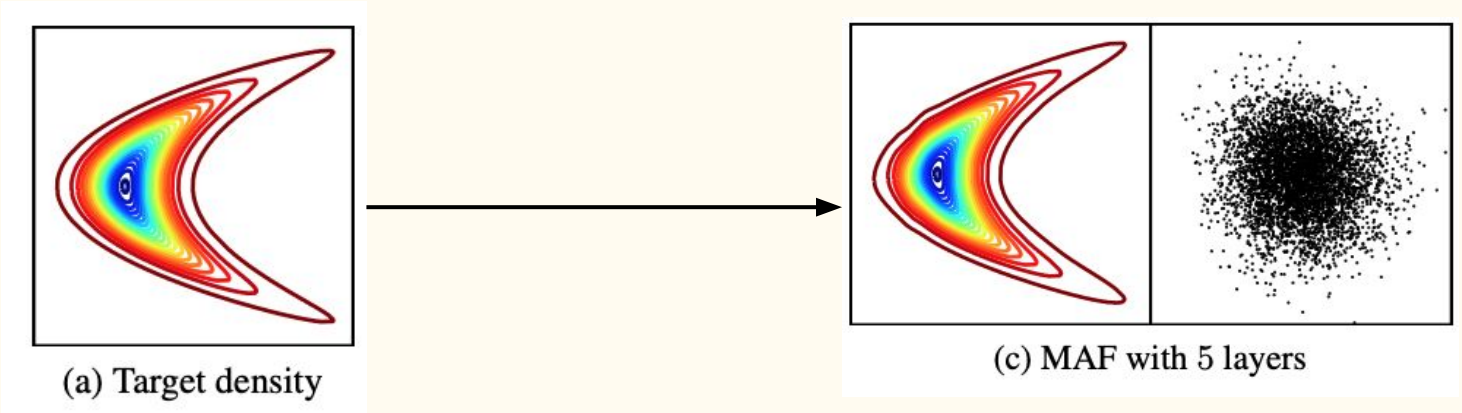
Backup : Neural Network

$$p(x) = \prod_i p(x_i \mid x_{1:i-1})$$

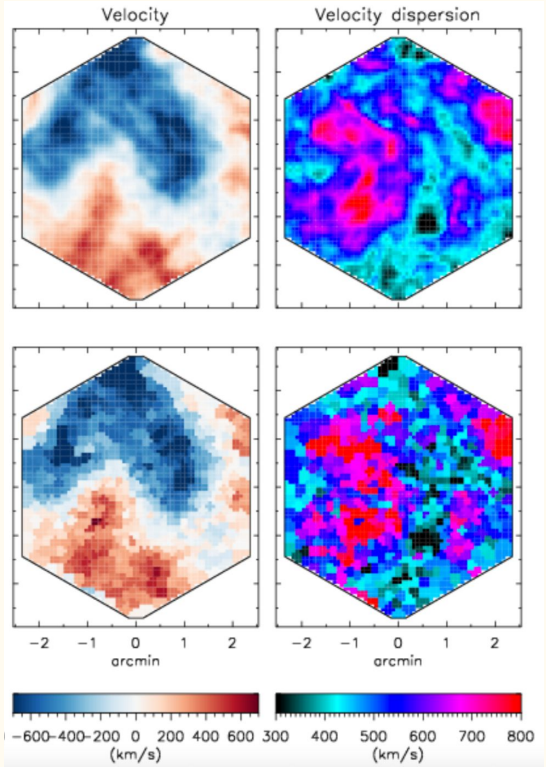
- sbi package (Python+Torch)
- Papamakarios+ 2018, 2019

(Masked) Autoregressive flow used as density estimators for the likelihood distribution

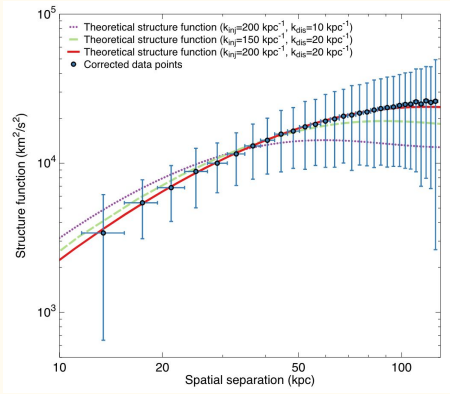




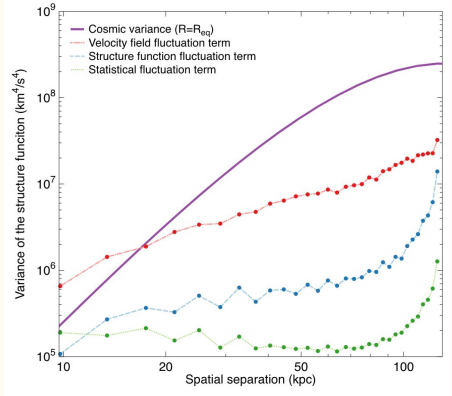
Backup : What about Athena ?



X-IFU (Adapted from Roncarelli+ 2018)

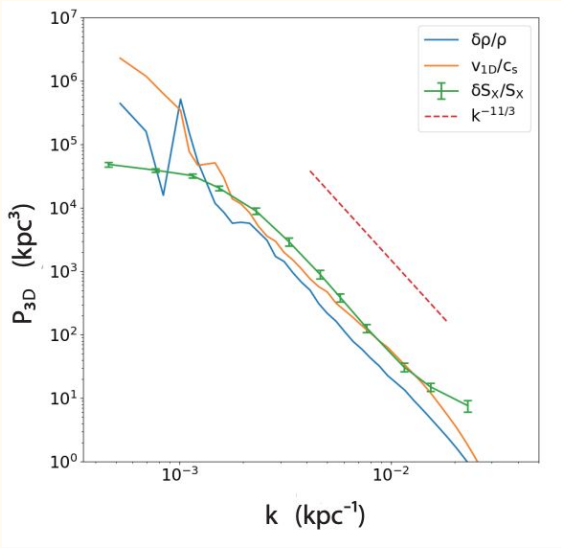


Comes with its bias



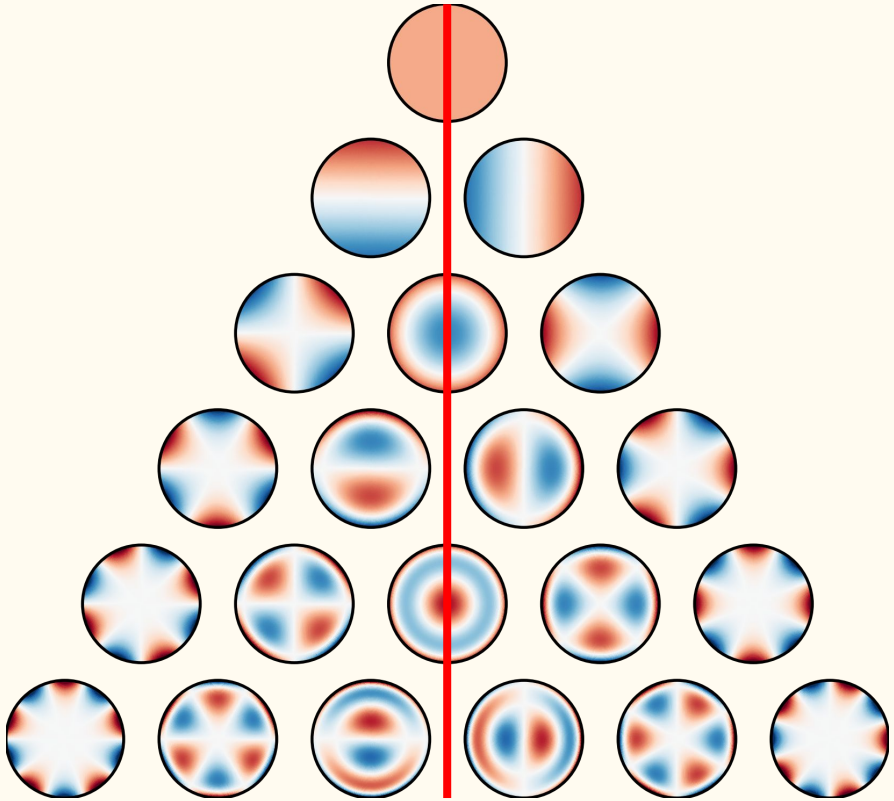
Don't forget sample variance!

See :
Toncarelli +2018
Clerc+ 2019,
Cucchetti + 2019
Talk by S. Beaumont



WFI (Adapted from Bulbul+ 2019)

Backup : Zernike Moment

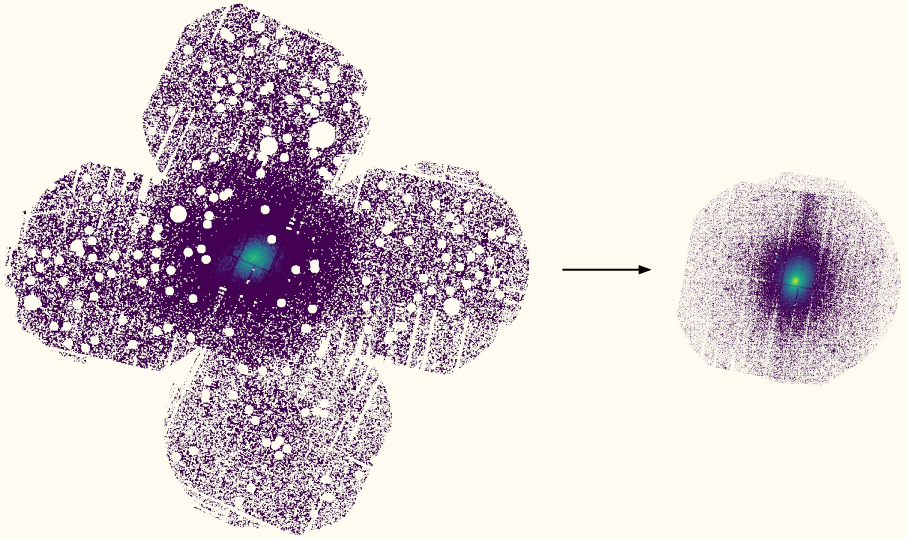


$$C_z = \sum_{n,m \neq 0} \sqrt{|c_{nm}|}$$

→ Sum of the development of the cluster image on a basis of polynomials, without any symmetric term

Backup : Perspectives

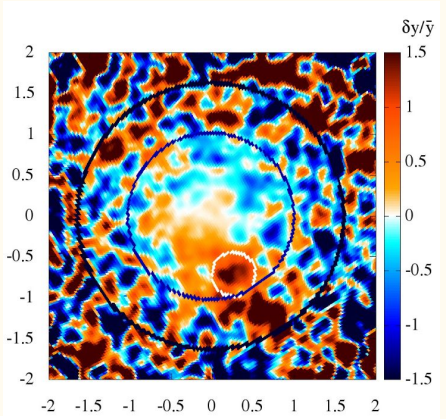
Extension to the CHEX-MATE sample



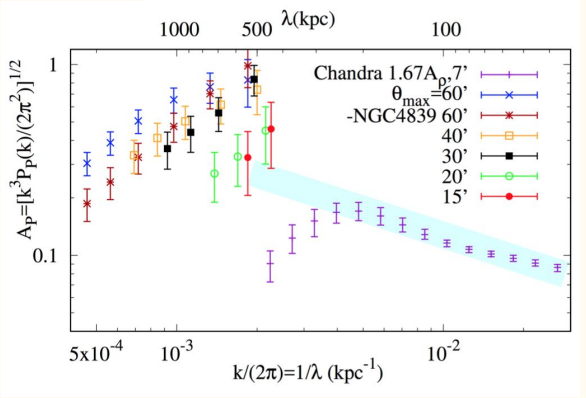
- Intermediate redshift clusters ($0.1 < z < 0.5$)
- Smaller mosaics
- Detected up to R500
- Cluster angular size closer to PSF
- x 10 in terms of cluster number

SZ fluctuations

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)



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