

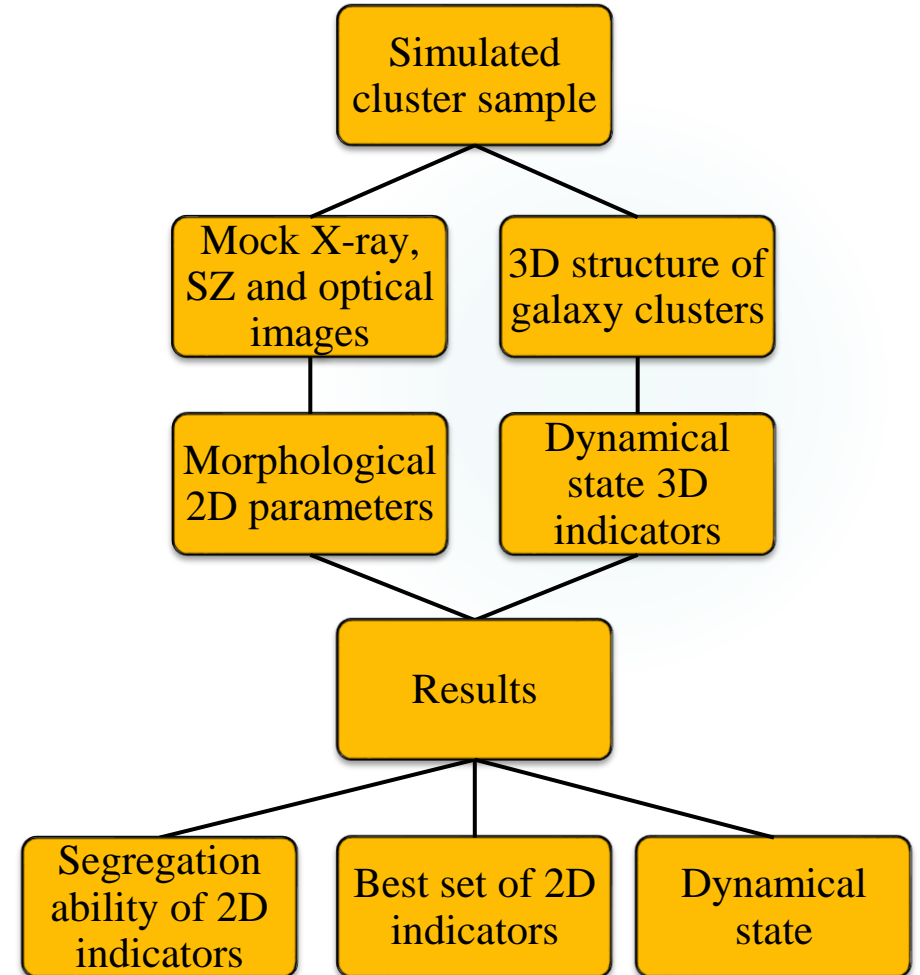
# The THREE HUNDRED Project: Dynamical state of galaxy clusters and morphology from multi-wavelength synthetic maps

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# Introduction

Galaxy cluster dynamical state has a direct impact on many cluster properties (cluster mass reconstruction, ICM thermodynamical profiles, halo formation time and concentration, etc.). Since clusters morphology is strictly related to dynamical state, one way to establish it is through morphological analysis on cluster maps from different observations. Thanks to numerical simulations, it is possible to select and tune the best morphological estimators to further apply in observations. For this purpose, we used **THE THREE HUNDRED** Project simulations of galaxy clusters.



# The THREE HUNDRED galaxy clusters sample

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Clusters from GADGET-X hydrodynamical run.

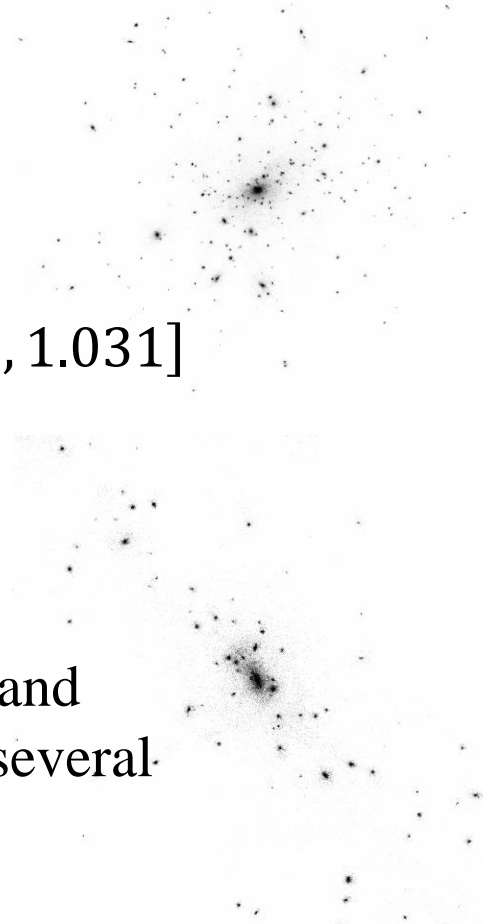
Total number of objects: 3240

Redshift range (10 snapshots):  $z \in [0, 1.031]$

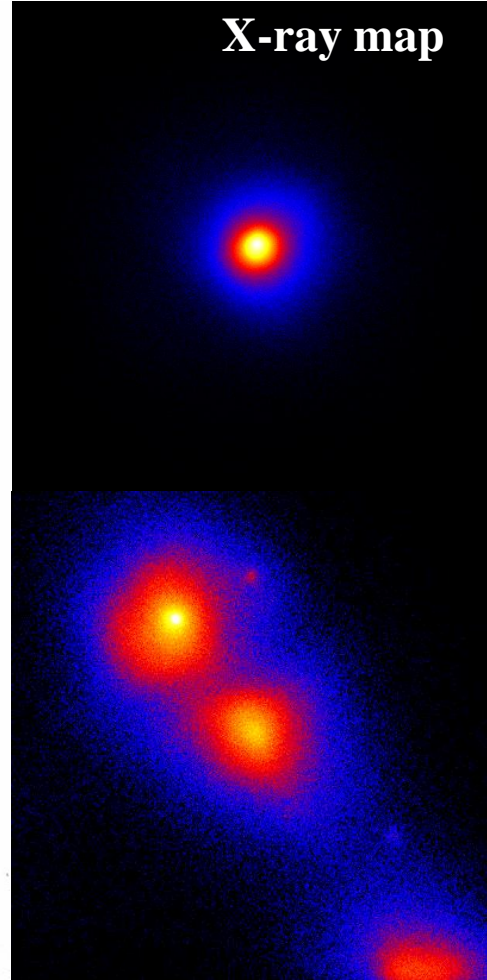
Mass range:  $M_{500} \in [0.15, 17.58] \times 10^{14} h^{-1} M_{\odot}$

Morphological analysis based on a multiwavelength analysis: X-ray, SZ and optical maps have been studied with several morphological parameters.

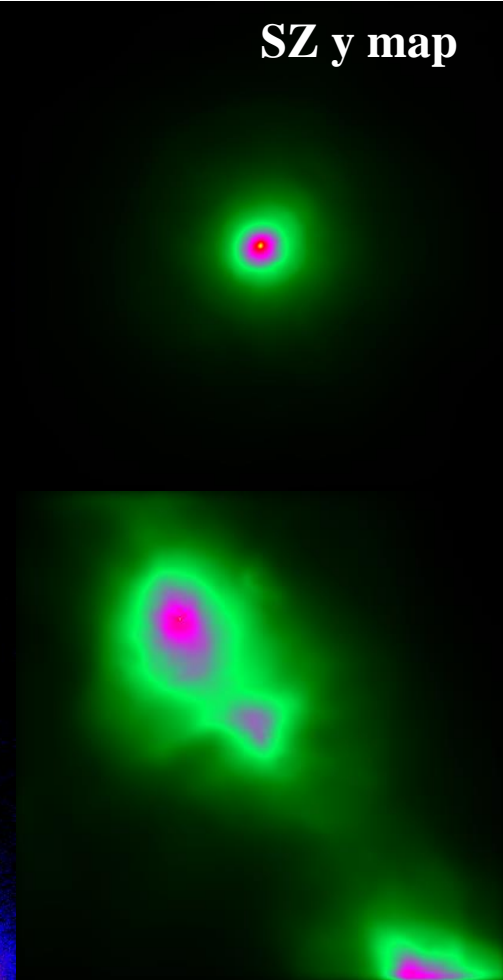
SDSS r-band



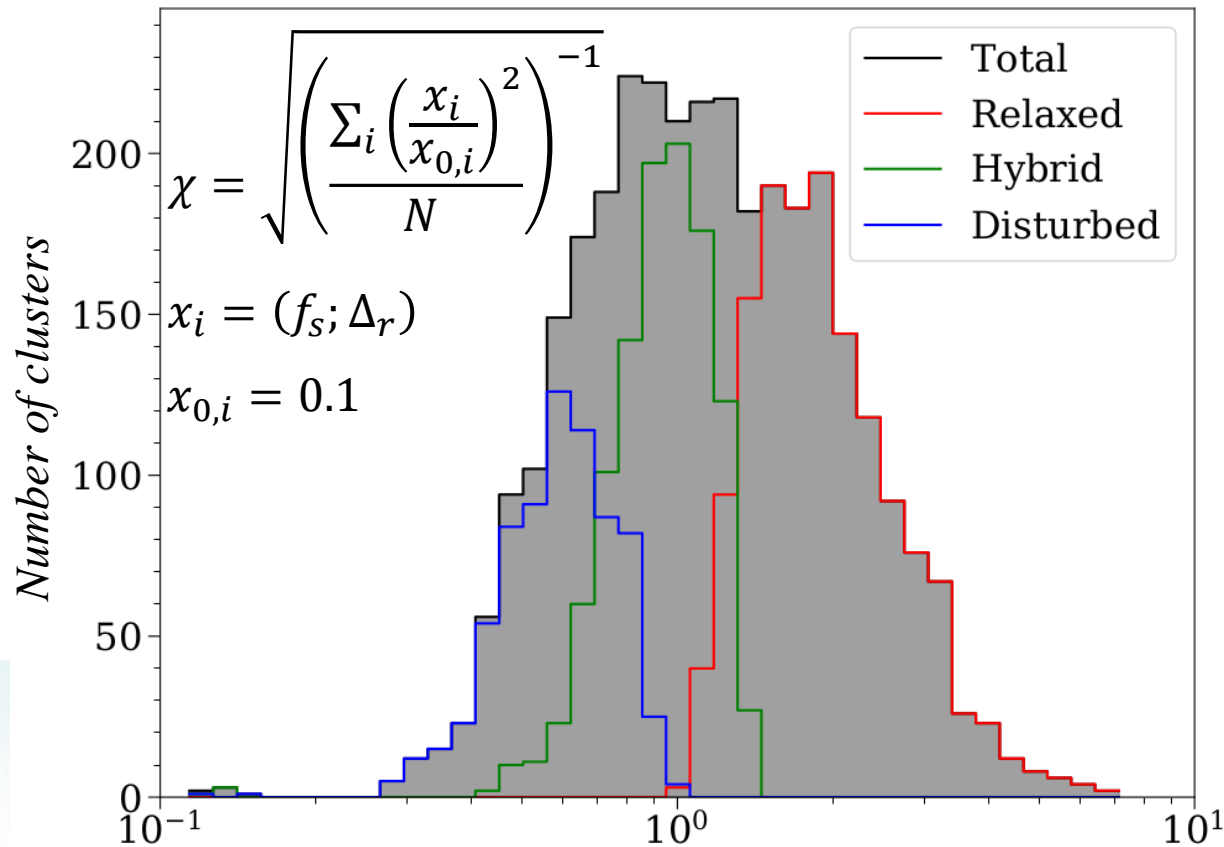
X-ray map



SZ y map



# Dynamical state



Clusters are dynamically characterised using the combined (and continuous)  $\chi$  indicator and considering 3 classes:

**Relaxed:**  $f_s < 0.1$  and  $\Delta_r < 0.1$

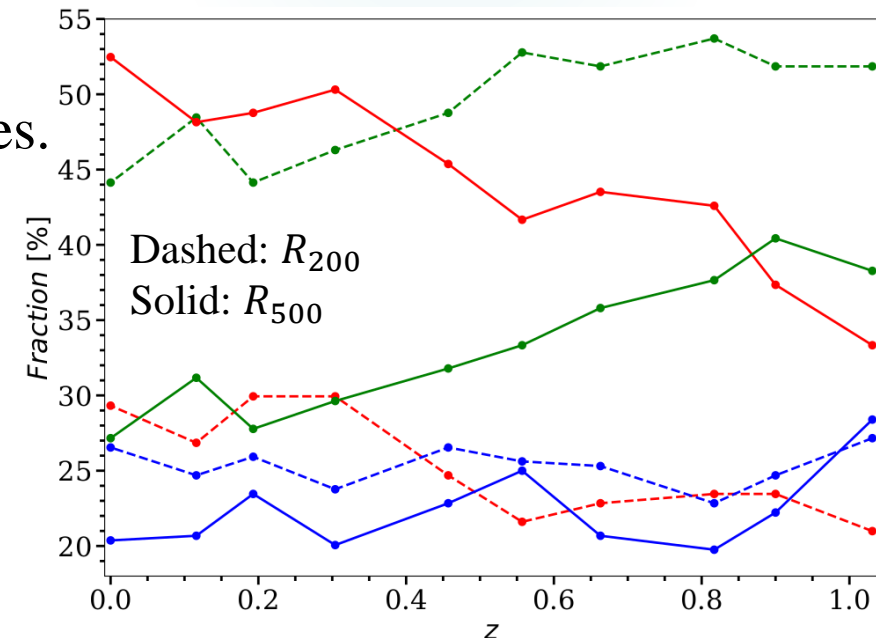
**Disturbed:**  $f_s > 0.1$  and  $\Delta_r > 0.1$

**Hybrid:**  
all the other cases.

$$f_s = \frac{\sum_i M_{s,i}}{M_{R_\Delta}}$$

$$\Delta_r = \frac{|R_{cm} - R_c|}{R_\Delta}$$

$$\rho(R_\Delta) = \Delta \cdot \rho_{cr}$$



$\chi$  definition from Hagggar et al (2020):  $\chi$   
[doi.org/10.1093/mnras/staa273](https://doi.org/10.1093/mnras/staa273)

# Morphological state

## Morphological indicator $V_i$ used:

- Asymmetry parameter A
- Light concentration parameter c
- Strip parameter S
- Third order power ratio P
- Gaussian fit G
- Centroid shift parameter w

Tuning procedure: from Cialone et al (2018):

<https://doi.org/10.1093/mnras/sty621>

## All combined in a weighted average:

$$M = \frac{1}{\sum_i W_i} \left( \sum_i W_i \frac{\log_{10}(V_i^{\alpha_i}) - \langle \log_{10}(V_i^{\alpha_i}) \rangle}{\sigma_{\log_{10}(V_i^{\alpha_i})}} \right)$$

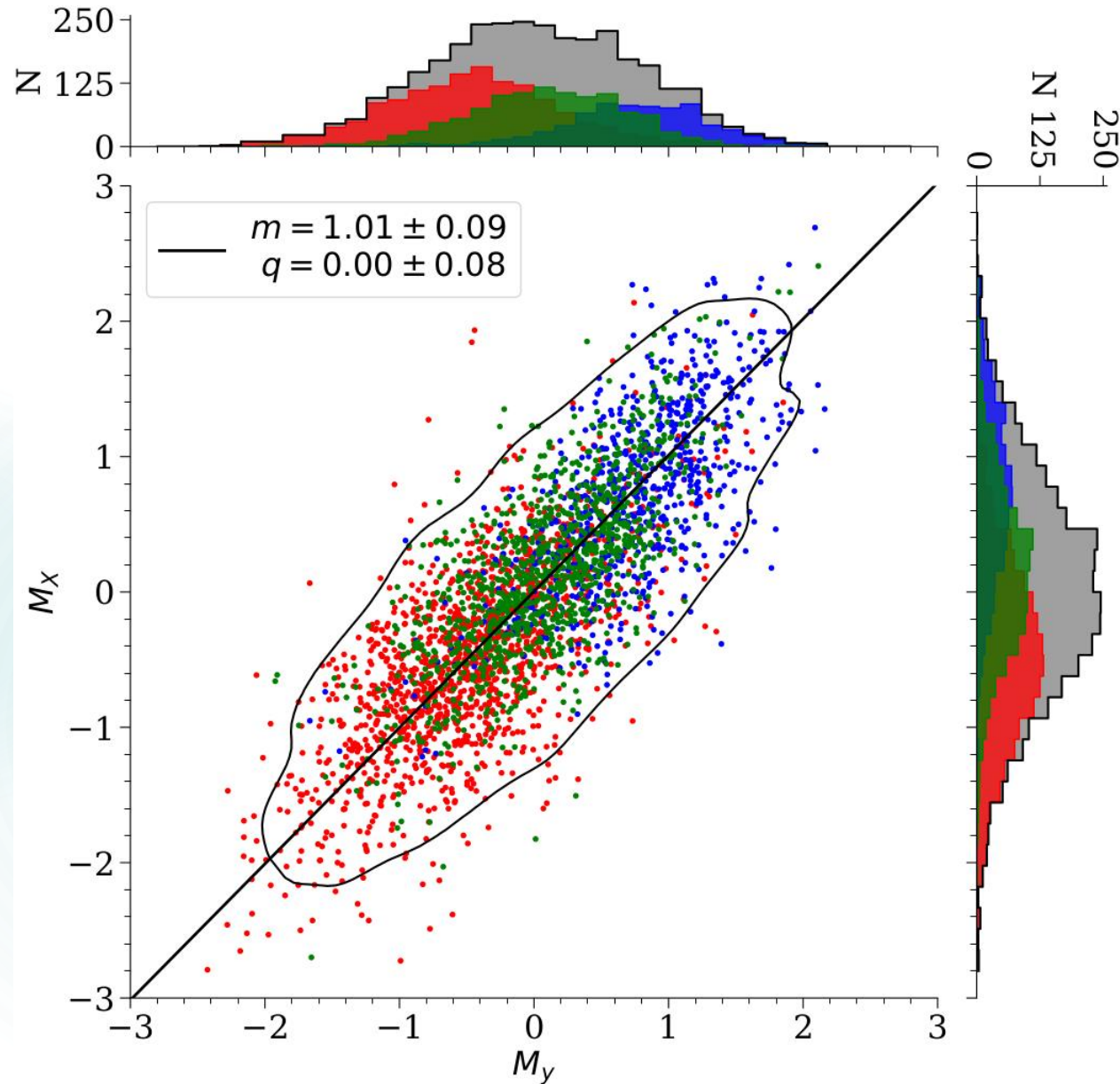


Where the weights reflect the 3D prior:  
we use the median p-value of the KS test  
over the different redshift.

$$W_i = \left| \log_{10} \min_{\{R_{ap}\}} K \widetilde{S}_p \right| \rightarrow$$

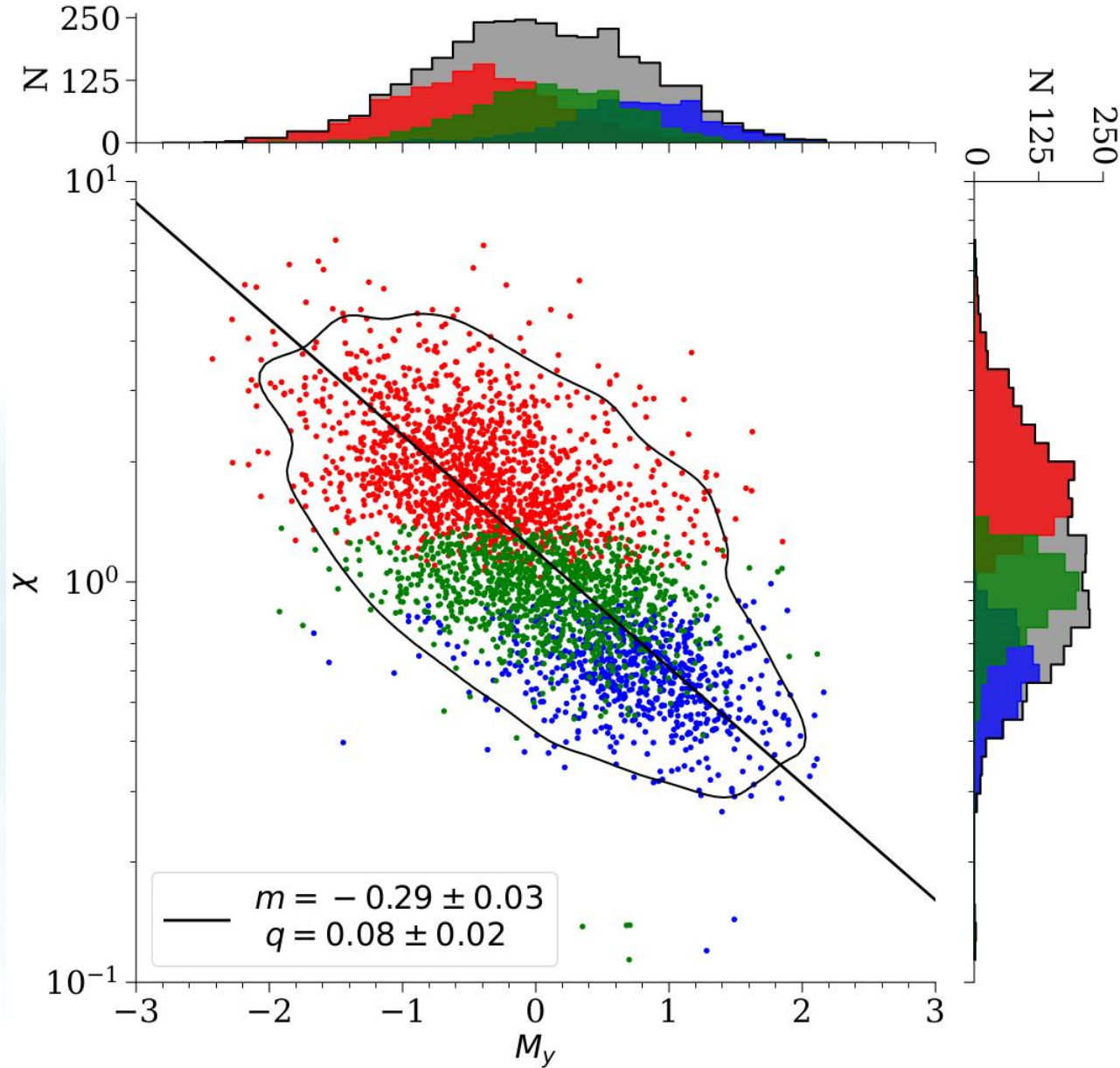


# Morphological state: ICM morphology



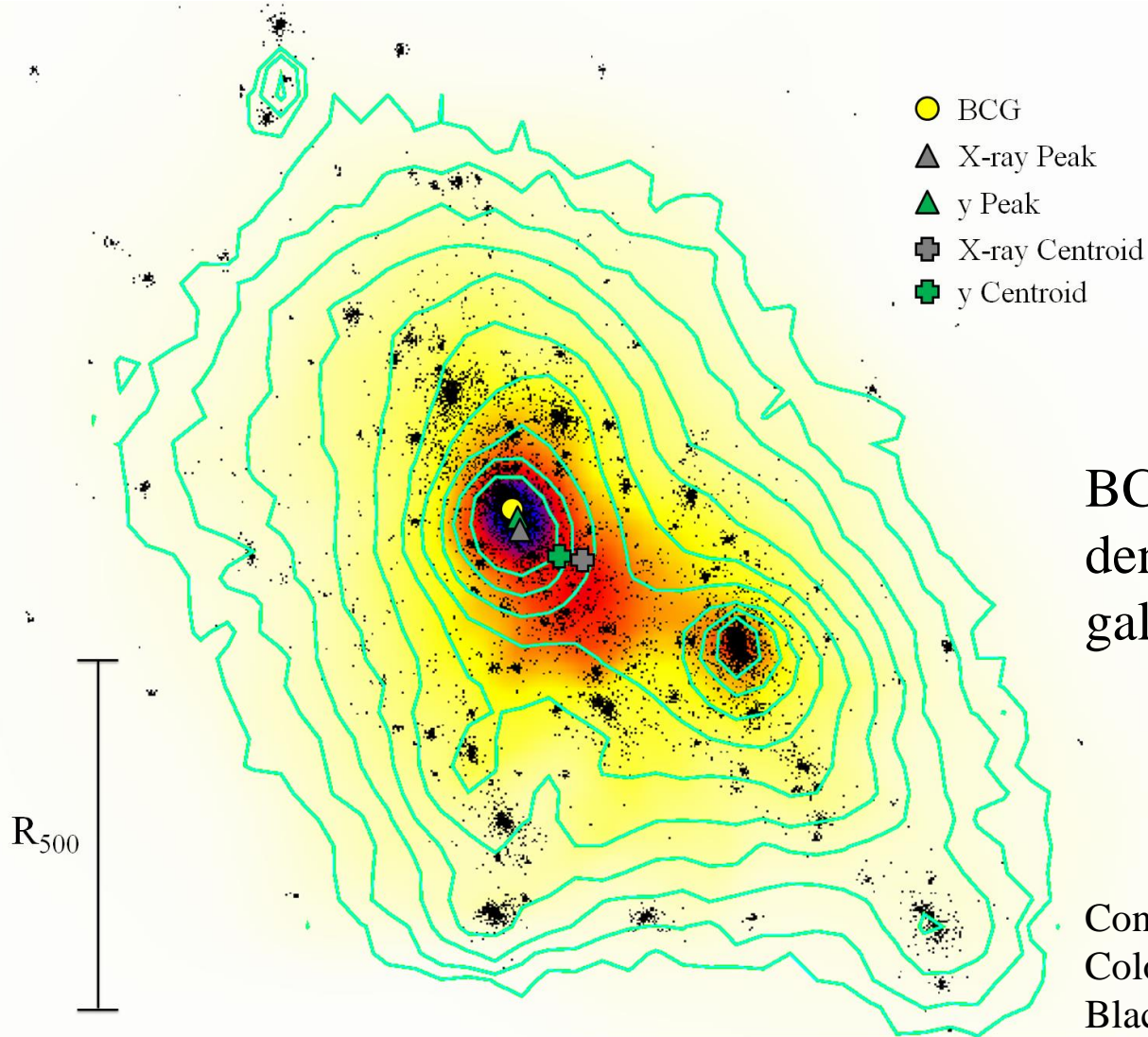
The morphology is consistent between X-ray and SZ maps. Spearman correlation coefficient:  $\rho = 0.80$

# Morphological state: ICM morphology



ICM morphology in X-ray and SZ maps shows a moderately strong correlation with the dynamical state:  $\rho = -0.66$

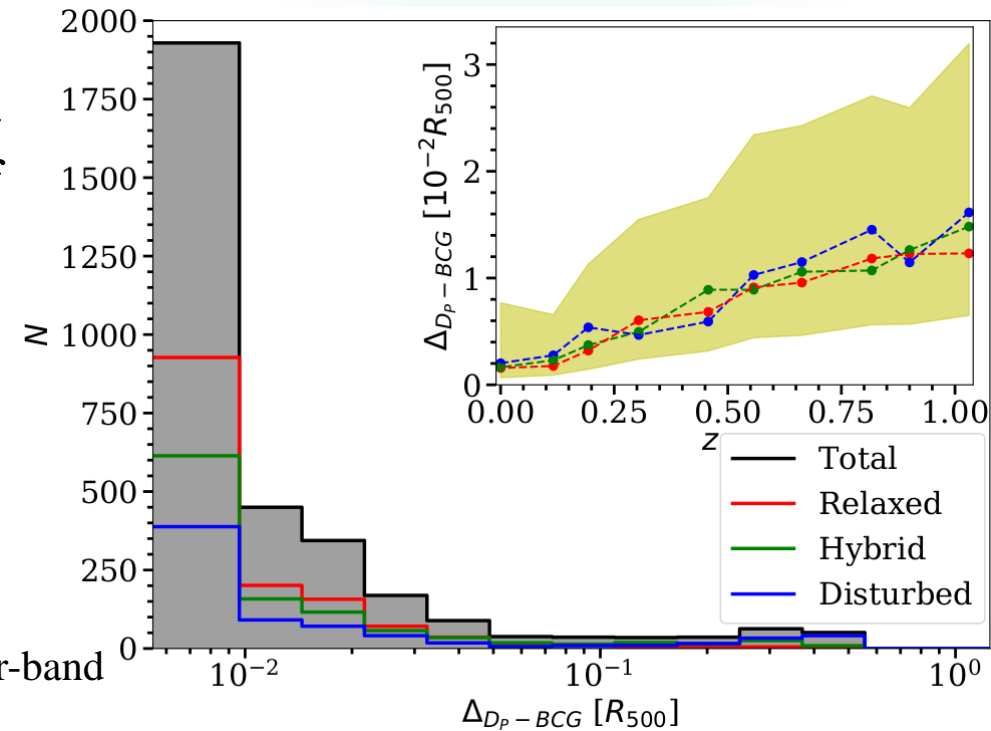
# Morphological state: Offset indicators



Offsets between Brightest cluster galaxy (BCG) and X-ray/SZ centroid or peaks are commonly used in observation as morphological indicators.

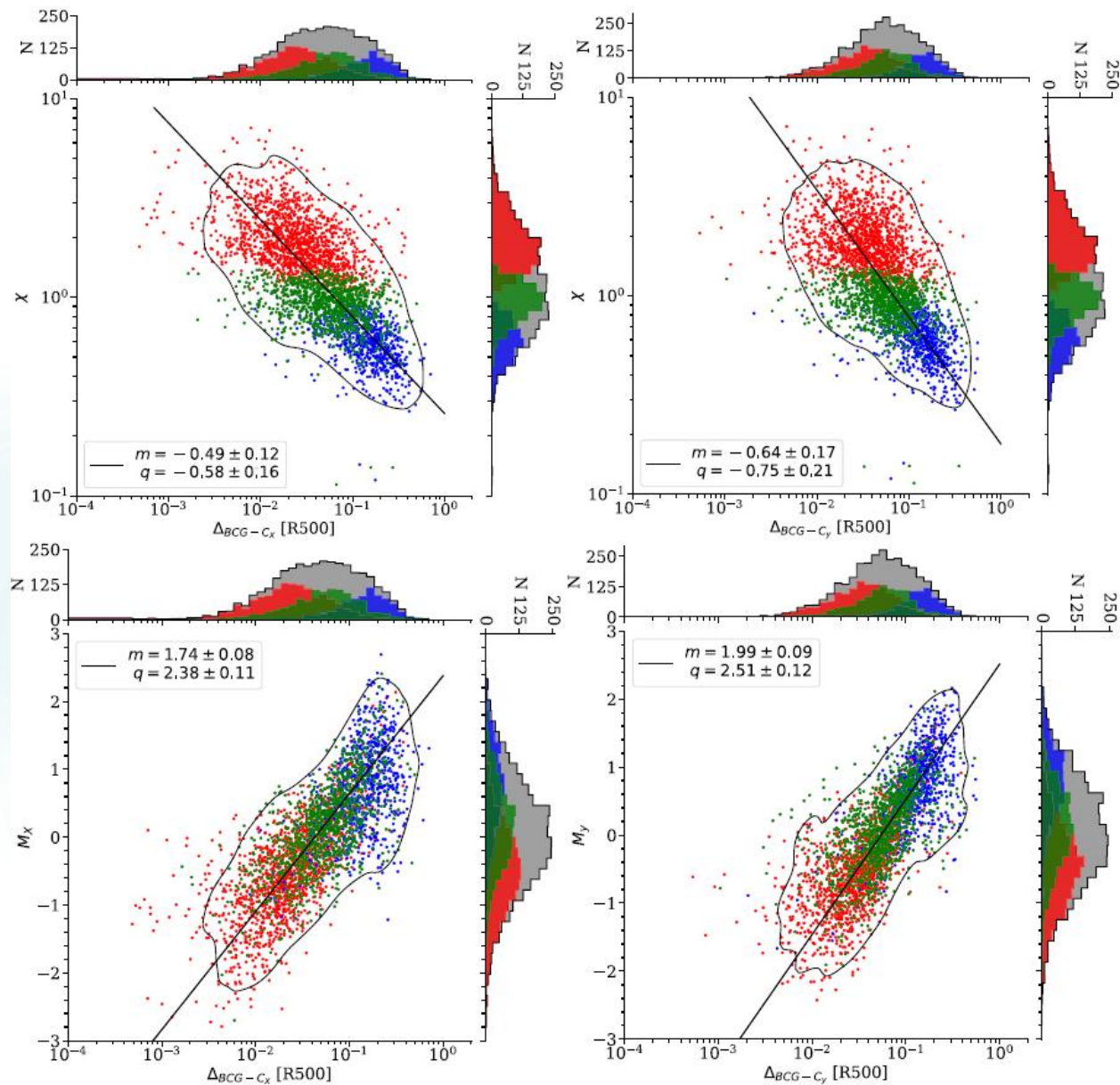
BCGs trace the density peak of galaxy clusters

Contours: X-ray  
Colour map: y map  
Black points: SDSS r-band





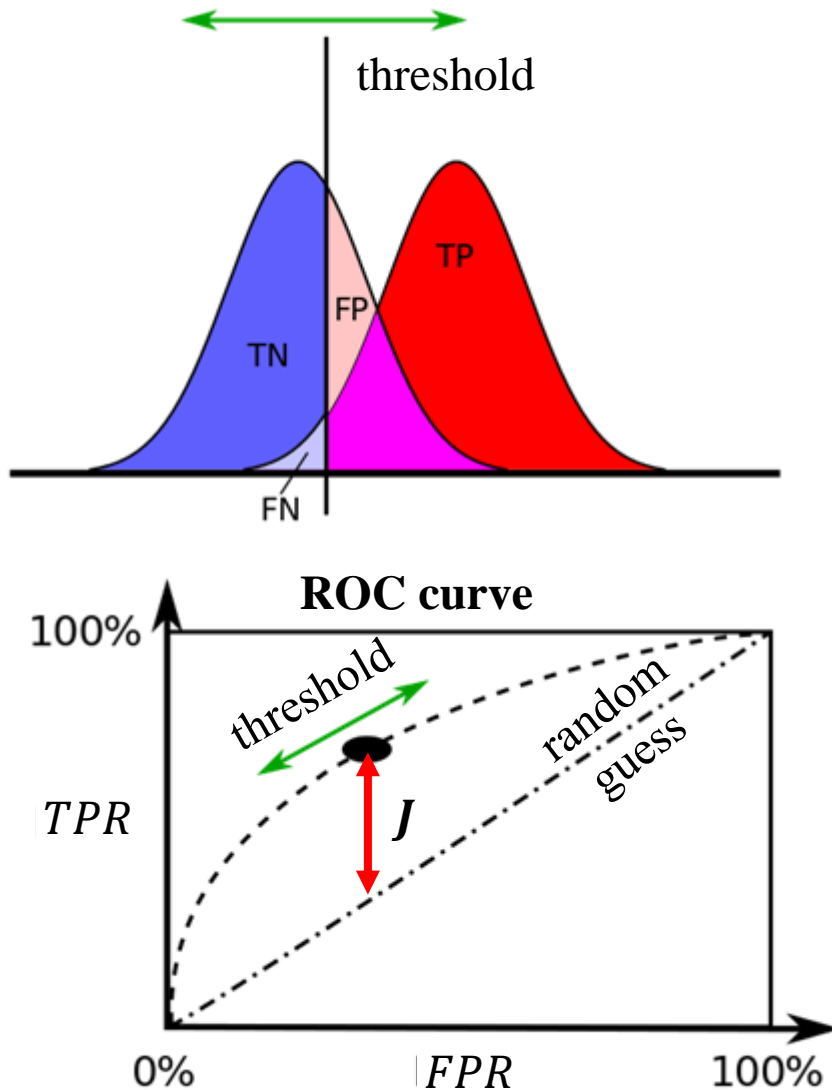
# Morphological state: Offset indicators



Offsets between BCGs and X-ray or y centroids are well correlated with ICM morphology in the two bands ( $\rho \sim 0.80$ ) and, as the combined  $M$ , show a moderate high correlation with  $\chi$ :

- $\rho = -0.63$  for y centroid;
- $\rho = -0.69$  for X-ray centroid.

# Morphological indicators efficiency



**TPR:** # of clusters correctly classified as relaxed / total number of relaxed objects.

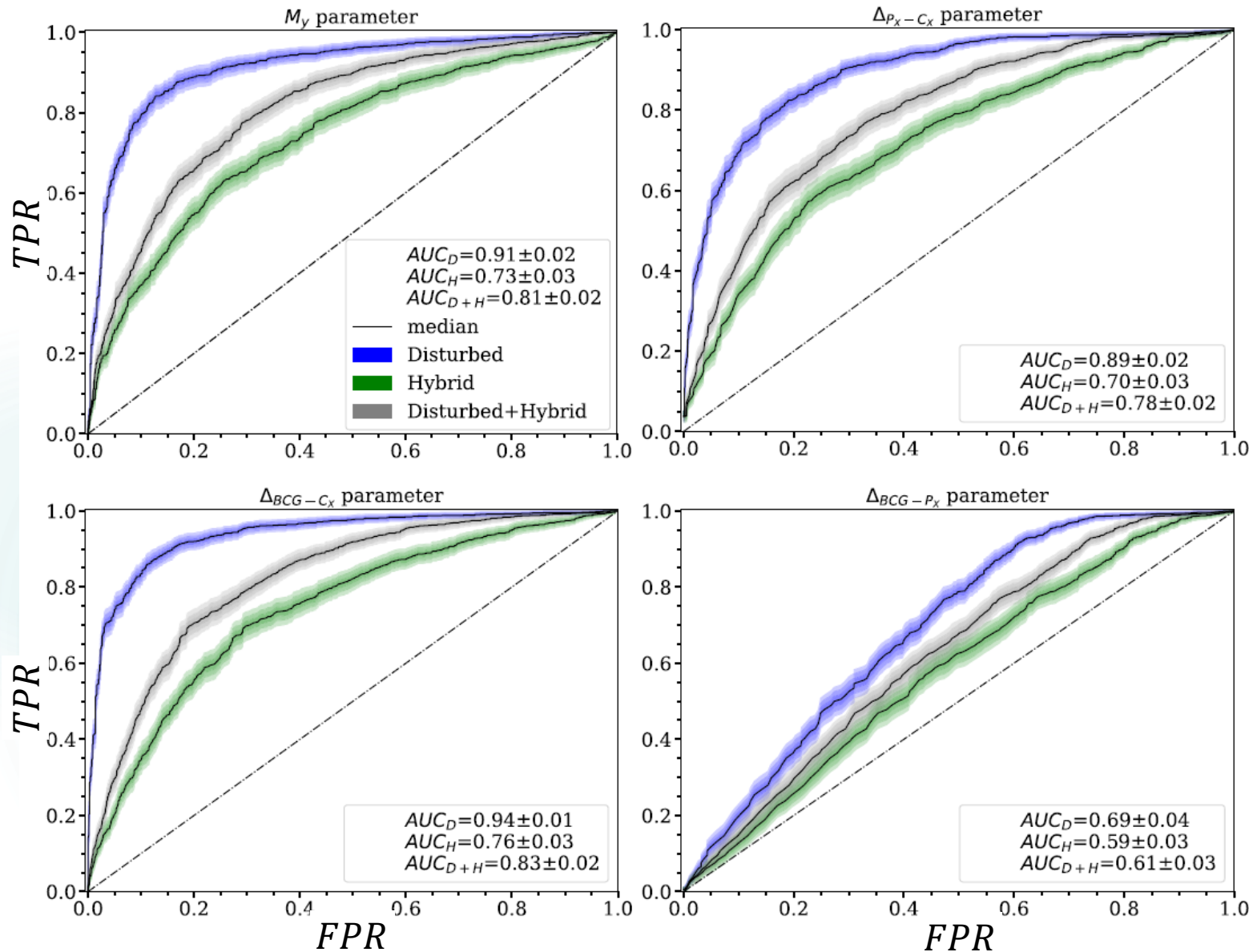
**FPR:** # of clusters incorrectly recognised as relaxed / total number of unrelaxed objects.

**ROC curves:** TPR vs FPR.

**AUC:** Area Under the curve.

**J:** Youden's J statistics. ROC height above random guess line.

# Morphological indicators efficiency



Morphological indicators divide more efficiently relaxed from disturbed objects.

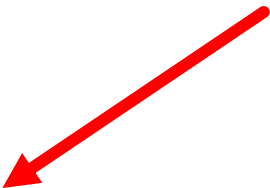
Offsets between BCGs and X-ray or y peaks are less affected by the dynamical state than centroids.

# Relaxed subsample

If we consider a class-based scheme for the entire sample:

- Relaxed subsample from dynamical indicators:  $\sim 44\%$ ;
- Relaxed clusters from morphological parameters:  $(44 - 49)\%$ .


Thresholds for morphological indicators: the one that maximizes the evaluation metrics on the ROC curves.



Comparable with observed samples:

- **Rossetti et al. (2017)**:  $\sim 52\%$ ;
- **Bartalucci et al. (2019)**:  $\sim 46\%$ ;
- **Lopes et al. (2018)**:  $(48 \pm 8)\%$ .

However, a direct comparison is not straightforward for the results obtained with different morphological parameters and based on different samples (e.g. see Cui et al 2017 [10.1093/mnras/stw2567](https://doi.org/10.1093/mnras/stw2567) and Cao et al 2021 [10.1093/mnras/stab605](https://doi.org/10.1093/mnras/stab605)).





# Summary

- Galaxy clusters dynamical and morphological states are better described by combined continuous indicators than single parameters and class-based scheme;
- The relaxed subsample is comparable with observational estimate of the relaxed fraction of galaxy clusters, even if a direct comparison is not straightforward due to selection effect, different indicators definition, etc.;
- BCGs and X-ray or  $\gamma$  peaks are good tracer of the matter density peak;
- All the studied morphological parameters are highly correlated and show a moderately strong correlation with dynamical indicators.

Thanks for the  
attention!