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Dynamical state and morphology from multi-wavelength synthetic maps of Three Hundred Project Galaxy Clusters

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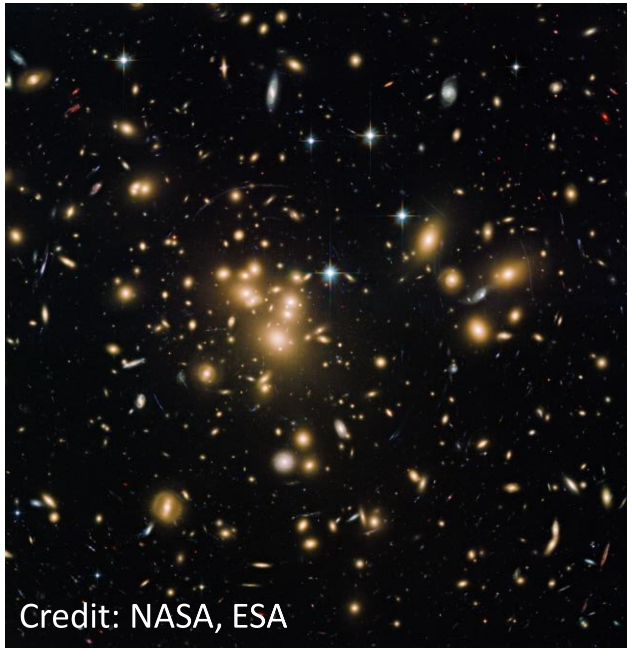
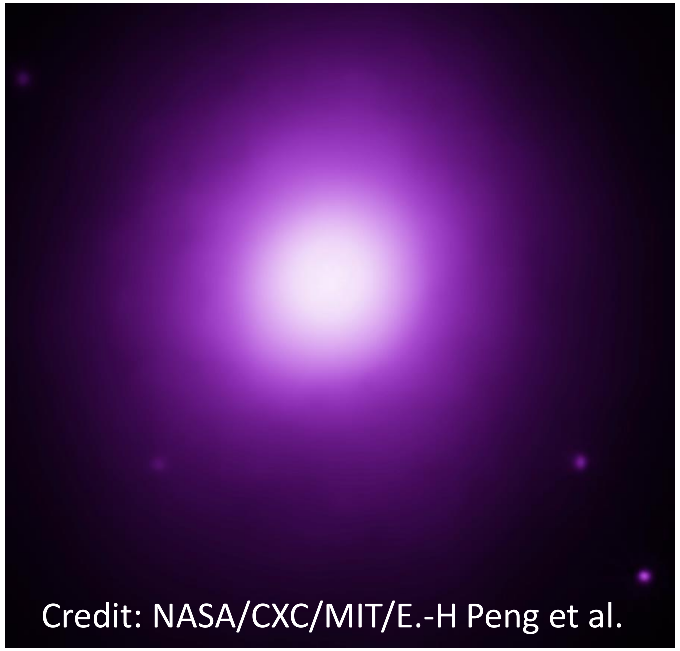
01 Galaxy clusters: a unique crossroads between physics, astrophysics and cosmology.

Galaxy clusters represent the most massive, gravitationally bound structures in the Universe. They are constituted mainly by Dark Matter (~85%), that held together the baryonic components: hundreds of galaxies and the hot X-ray emitting gas ($T \sim 10^8\ K$), known as the Intra-Cluster Medium (ICM). ICM is also responsible of the inverse Compton scattering of Cosmic Microwave Background (CMB), or Sunyaev-Zel'dovich effect.

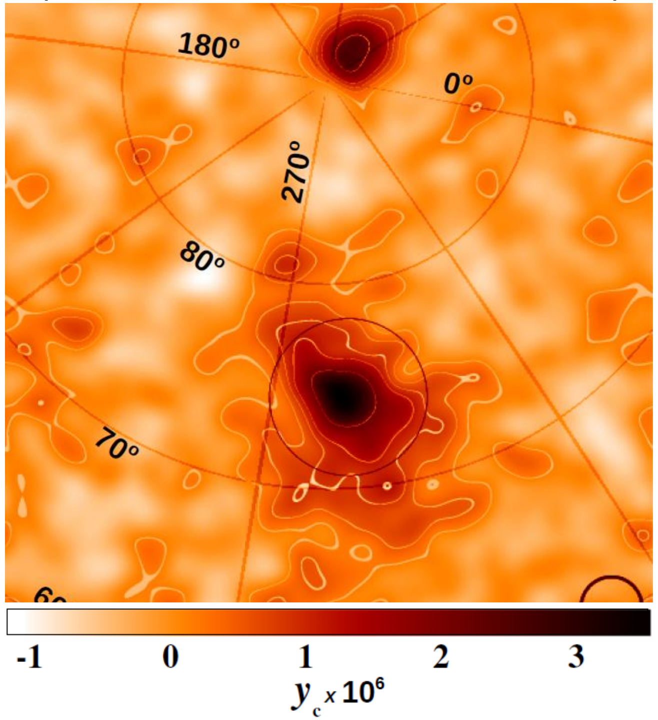
Hubble image of Abell 1689



X-ray Chandra image of Abell 1689



SZ effect Planck map of Virgo Cluster (DOI: 10.1051/0004-6361/201527743)

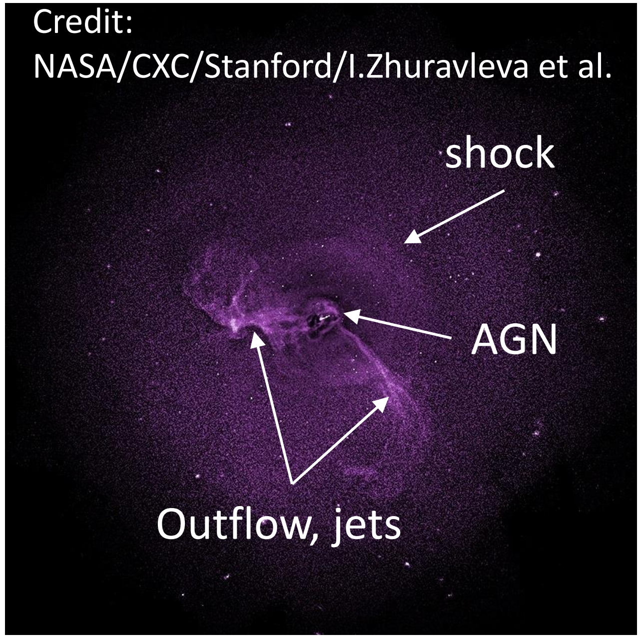


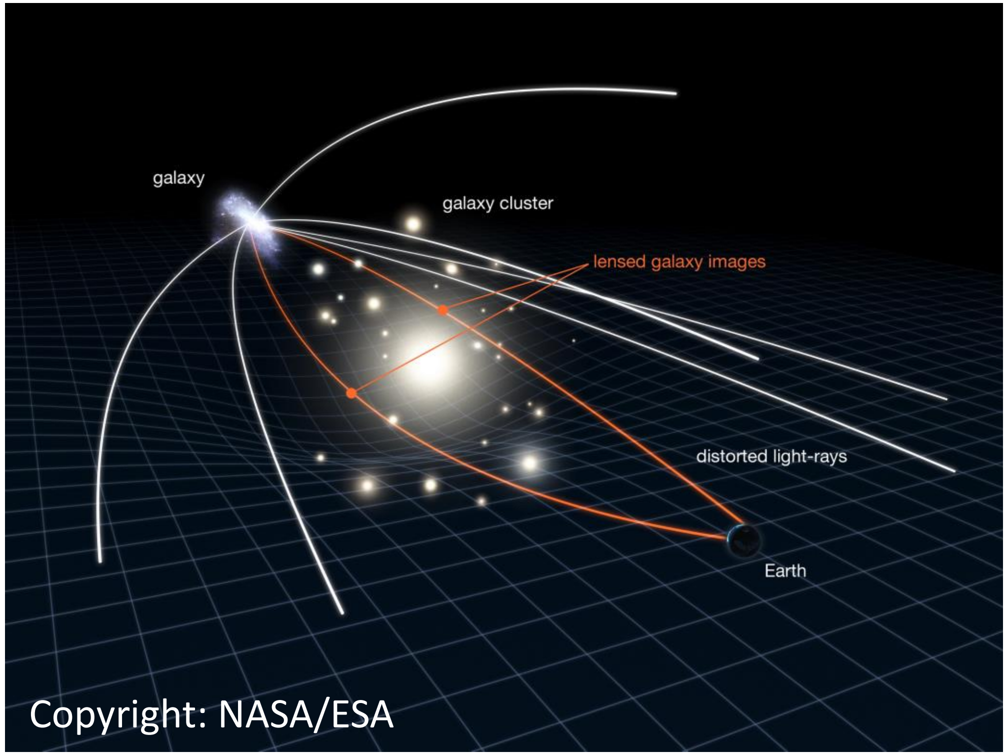
01

Galaxy clusters: a unique crossroads between physics, astrophysics and cosmology.

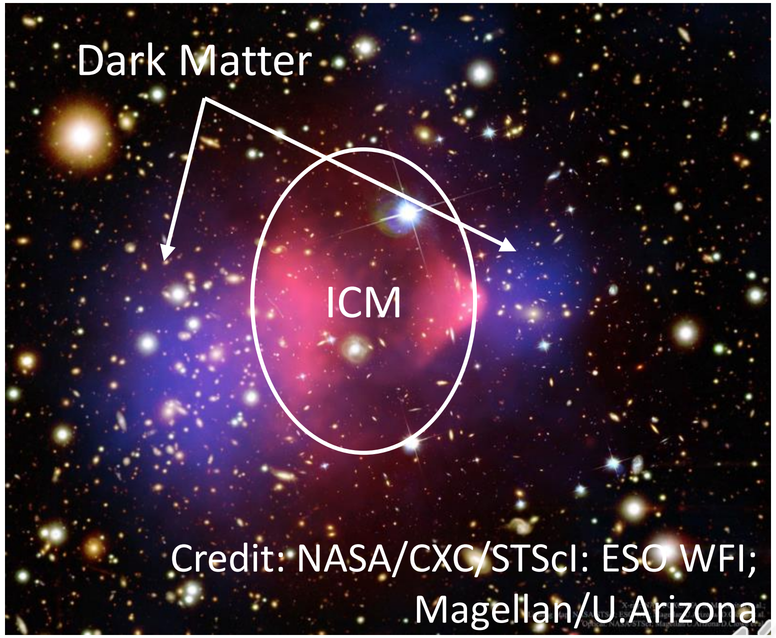
Galaxy clusters provide a unique sight on many astrophysical and physical processes, as gravity, the physics of plasma, star formation, galaxy evolution and their interaction with the environment, as gravitational lensing of background sources and turbulence in the X-ray emitting ICM due to supermassive black hole accretion and active galactic nucleus (AGN) feedback.

Chandra X-ray image of Virgo cluster



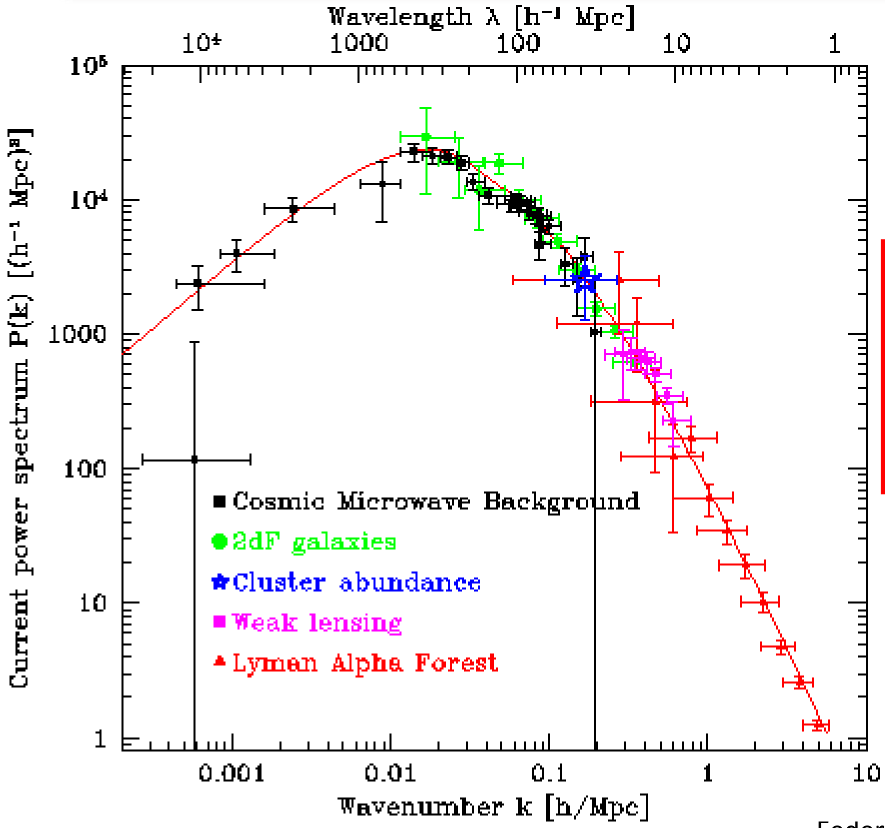


Multiwavelength image of Bullet cluster

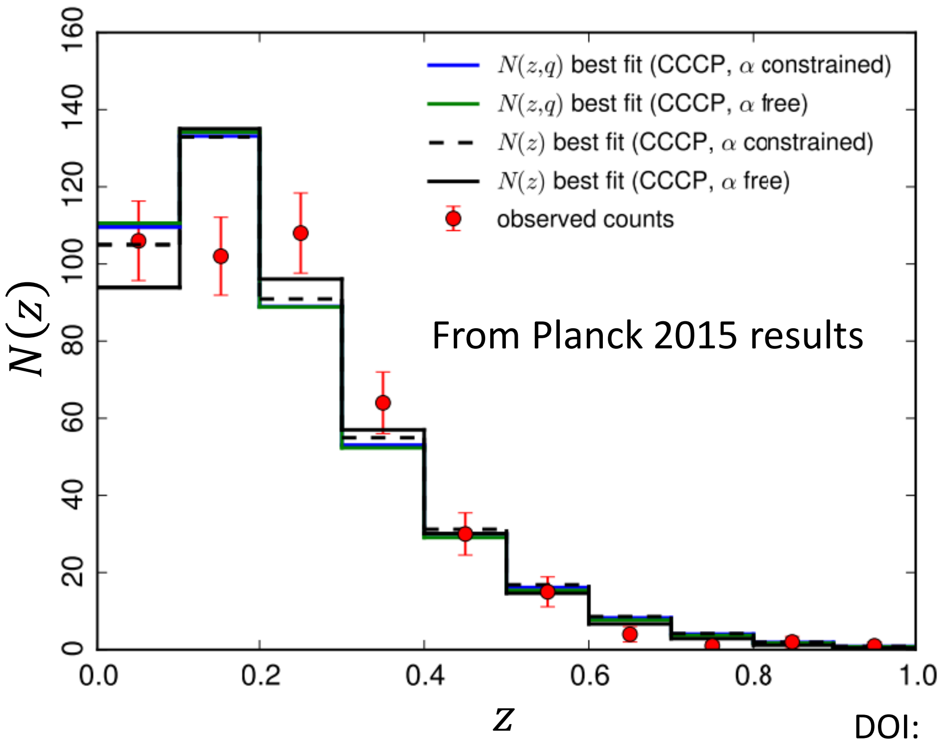


01 Galaxy clusters: a unique crossroads between physics, astrophysics and cosmology.

Laying at the top of structures of matter on the largest scales, galaxy clusters formation and evolution can be studied to characterize the fundamental properties of the Universe itself, as the fraction of matter Ω_m, the expansion rate of the Universe H_0 and its acceleration due to the effect of the cosmological constant Ω_Λ, and the characterization of structure formation history.



Most of the cosmological constraints are based on the knowledge of the clusters dynamical state.

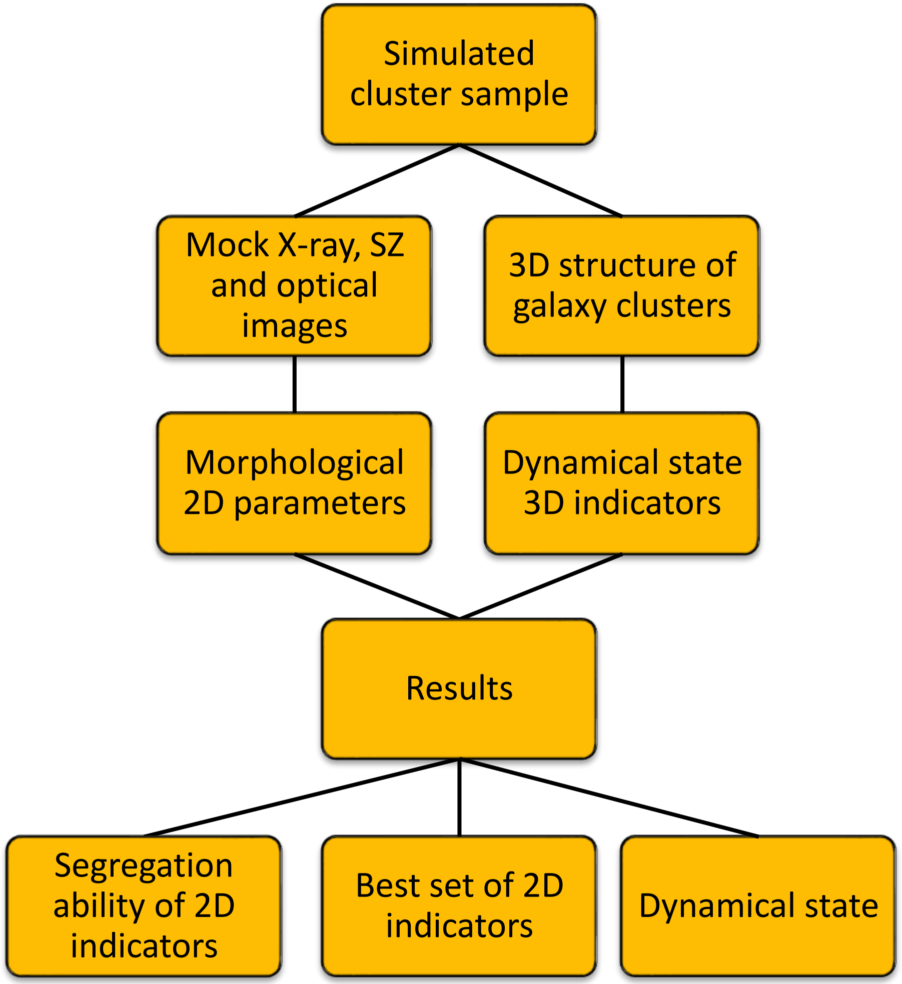


From Planck 2015 results

DOI: 10.1051/0004-6361/201525833

02 The method

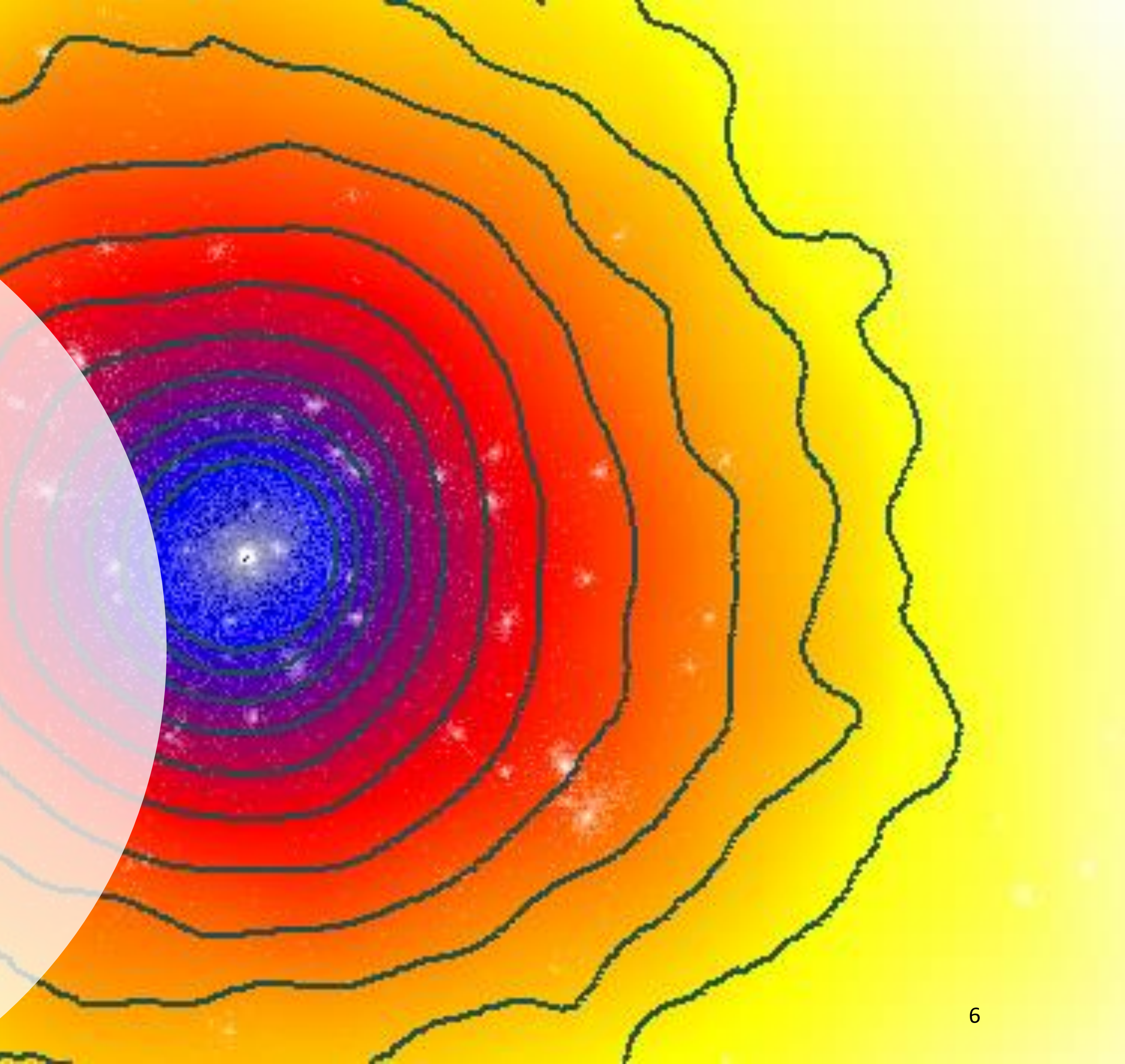
Since clusters morphology is strictly related to their dynamical state, one way to establish it is through morphological analysis on cluster maps from different observations. Thanks to numerical simulations, it is possible to select and tune the best morphological estimators to further apply in observations. For this purpose, we used ***The Three Hundred Project*** simulations of galaxy clusters.



02 The sample

The Three Hundred Project[1] consists in hydrodynamic simulations of 324 clusters with a cosmology consistent with Planck Collaboration et al. (2016). In this work we analyzed 3240 clusters coming from 10 selected redshifts in $z \in [0,1.031]$.

[1]https://the300-project.org/



03 Dynamical state of simulated clusters: relaxation criterion and classification.

We describe the dynamical state of clusters using a set of well known dynamical indicators, combining them in a continuous indicator of relaxation **χ** defined by Haggar et al. (2020) and using a multi-class system.

Dynamical indicators x_i:

Fraction in mass indicator $f_s = \frac{\sum_i M_{s,i}}{M_{R_\delta}}$

Centre of mass offset indicator $\Delta_r = \frac{|\boldsymbol{R}_{cm} - \boldsymbol{R}_c|}{R_\delta}$

$$\chi = \sqrt{\left(\frac{\sum_i \left(\frac{x_i}{x_{0,i}}\right)^2}{N}\right)^{-1}}$$

M_{R_δ}: total mass inside a spherical aperture of radius R_δ, where density drops δ times the critical density: $\rho(R_\delta) = \delta \cdot \rho_{cr}$

Relaxed clusters

$$\begin{cases} f_s < 0.1 \\ \Delta_r < 0.1 \end{cases}$$

Disturbed clusters

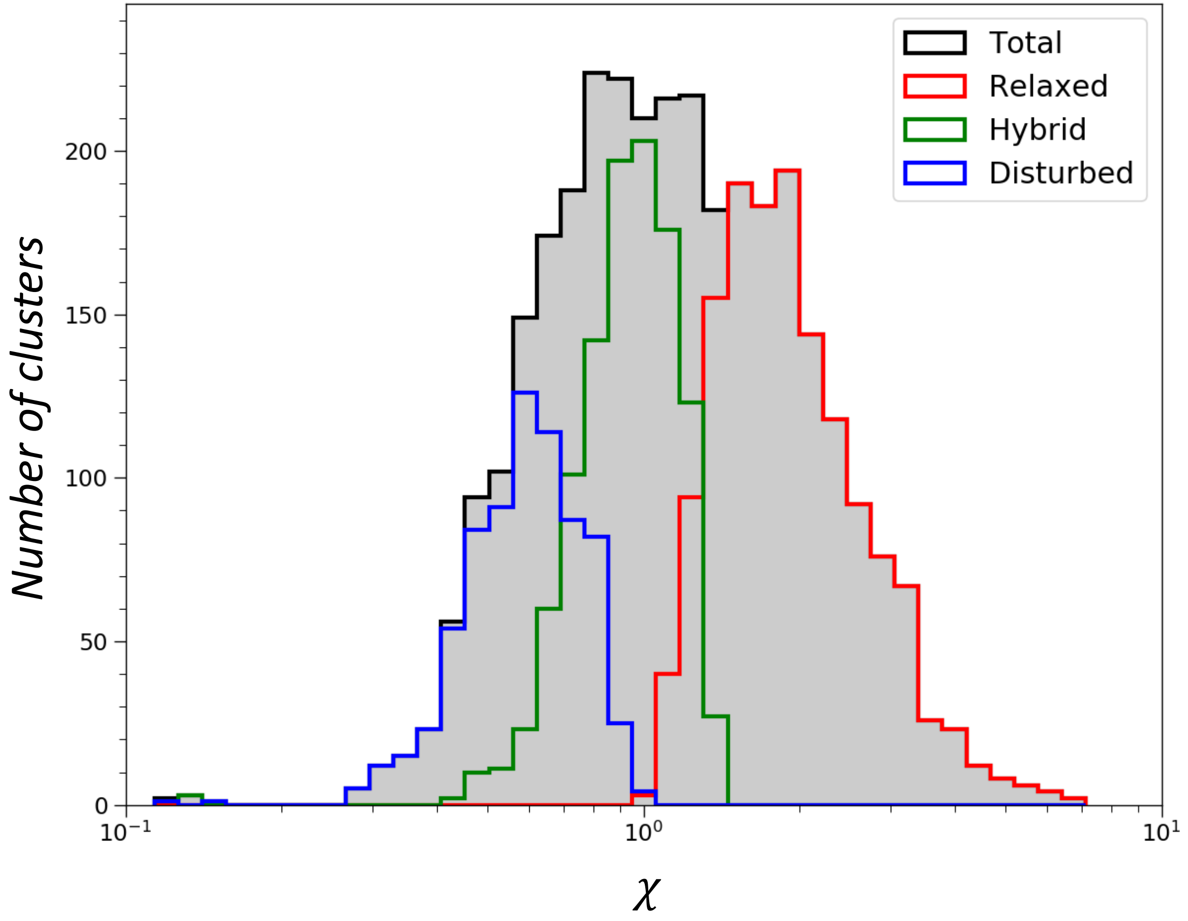
$$\begin{cases} f_s \geq 0.1 \\ \Delta_r \geq 0.1 \end{cases}$$

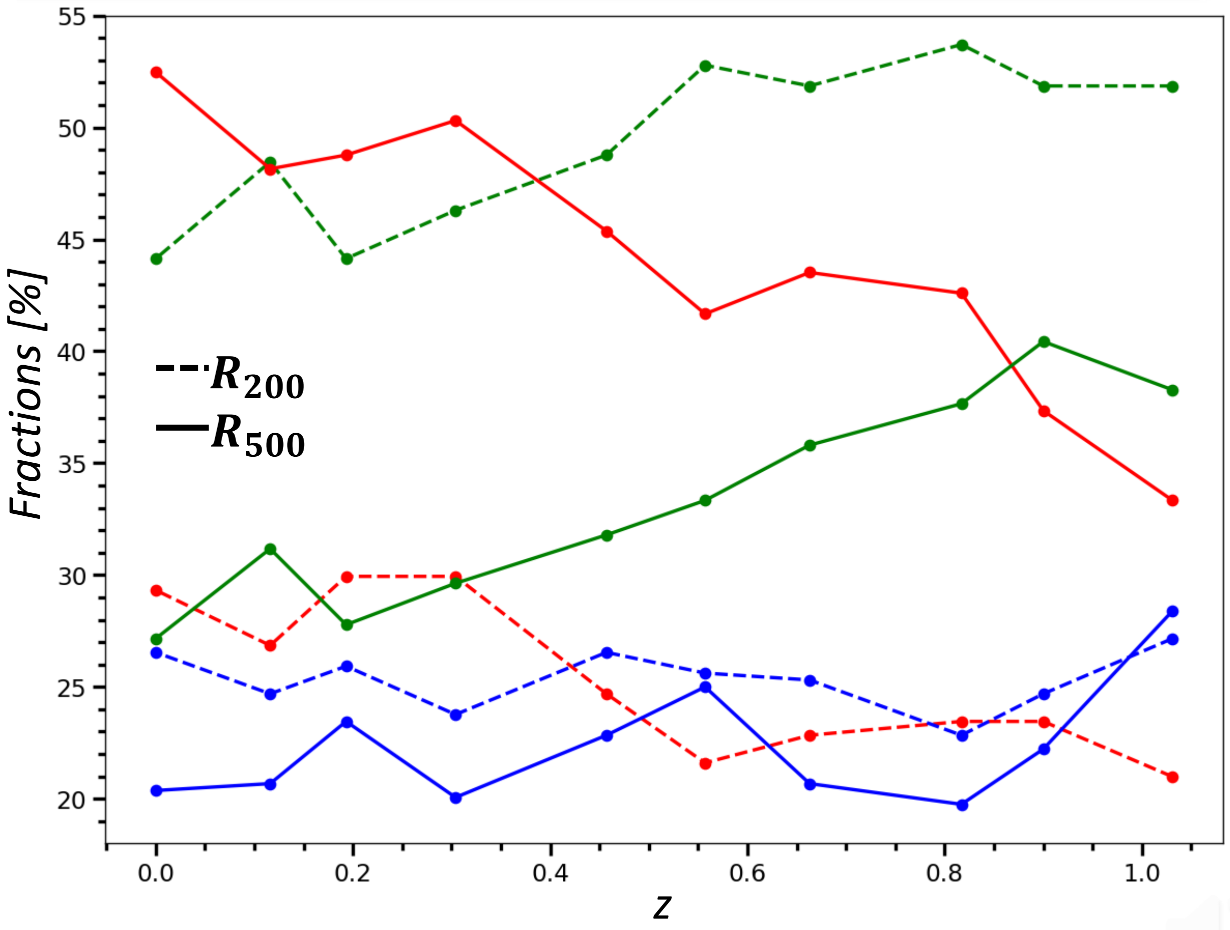
Hybrid clusters

$$\begin{cases} f_s \geq 0.1 \\ \Delta_r < 0.1 \end{cases} \vee \begin{cases} f_s < 0.1 \\ \Delta_r \geq 0.1 \end{cases}$$

03 Dynamical state of simulated clusters: relaxation criterion and classification.

The dynamical state depends on the explore volume and the redshift of the clusters. Spherical radii used: R_{200} and R_{500}.





03 Morphological state of galaxy clusters.

The morphology of X-ray and SZ maps of clusters is studied with a weighted average M of a set of well known X-ray morphological indicators, as done by Cialone et al. (2018)…

Morphological indicators $\boldsymbol{V_i}$ used:

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

All combined in a weighted average:

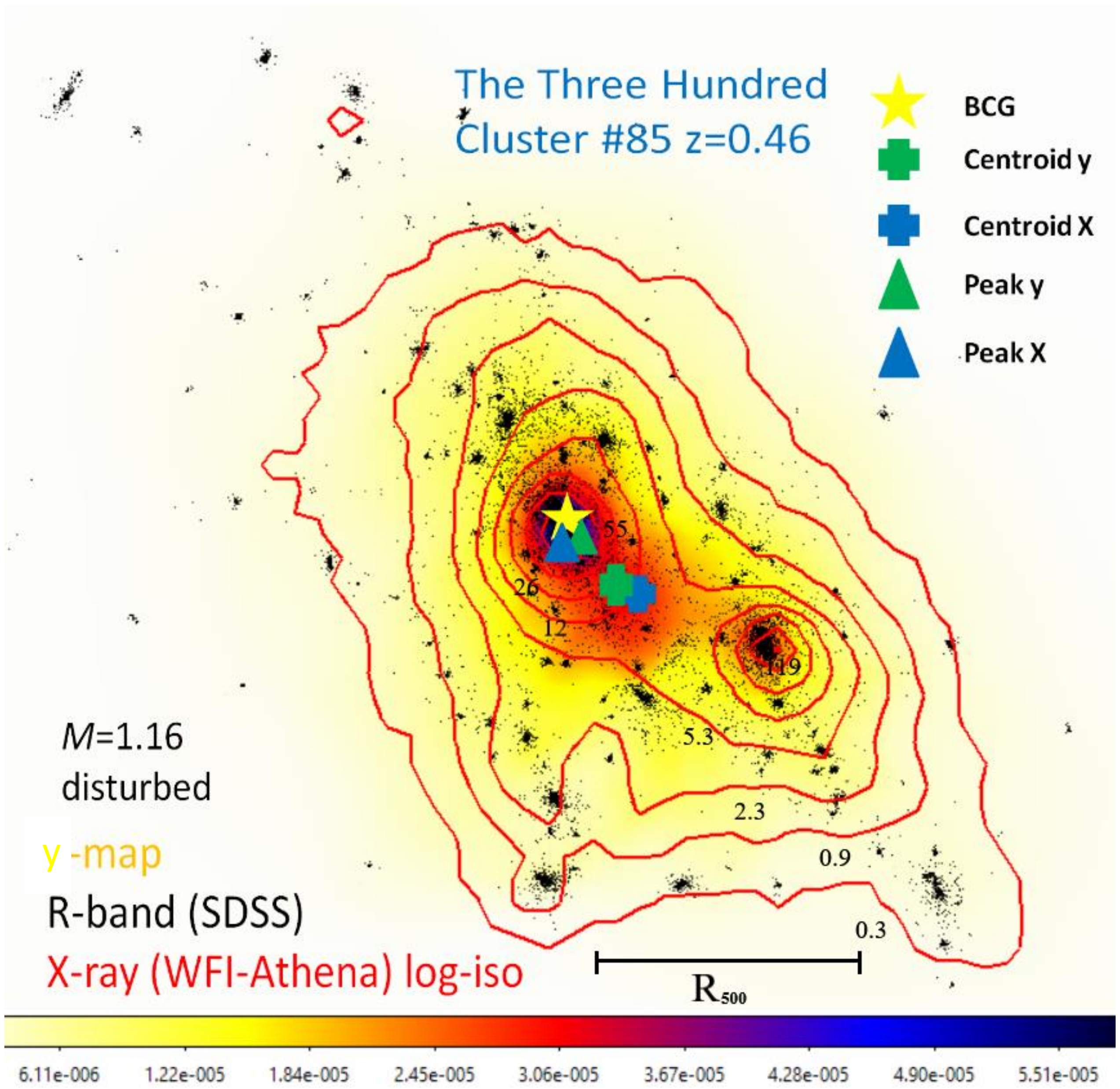
$$M = \frac{1}{\sum_i W_i}\left(\sum_i W_i \frac{\log_{10}\left(V_i^{\alpha_i}\right) - \left\langle \log_{10}\left(V_i^{\alpha_i}\right)\right\rangle}{\sigma_{\log_{10}\left(V_i^{\alpha_i}\right)}}\right)$$

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

Where the weights reflect the 3D dynamical state prior: we use the median (symbol $\sim$) p-value of the Kolmogorov-Smirnov (KS) test over the different redshift.

03 Morphological state of galaxy clusters.

…or combining optical information with X-ray and SZ maps: we use the offset between the positions of the Brightest Central Galaxy (BCG) and the X-ray or y centroids.



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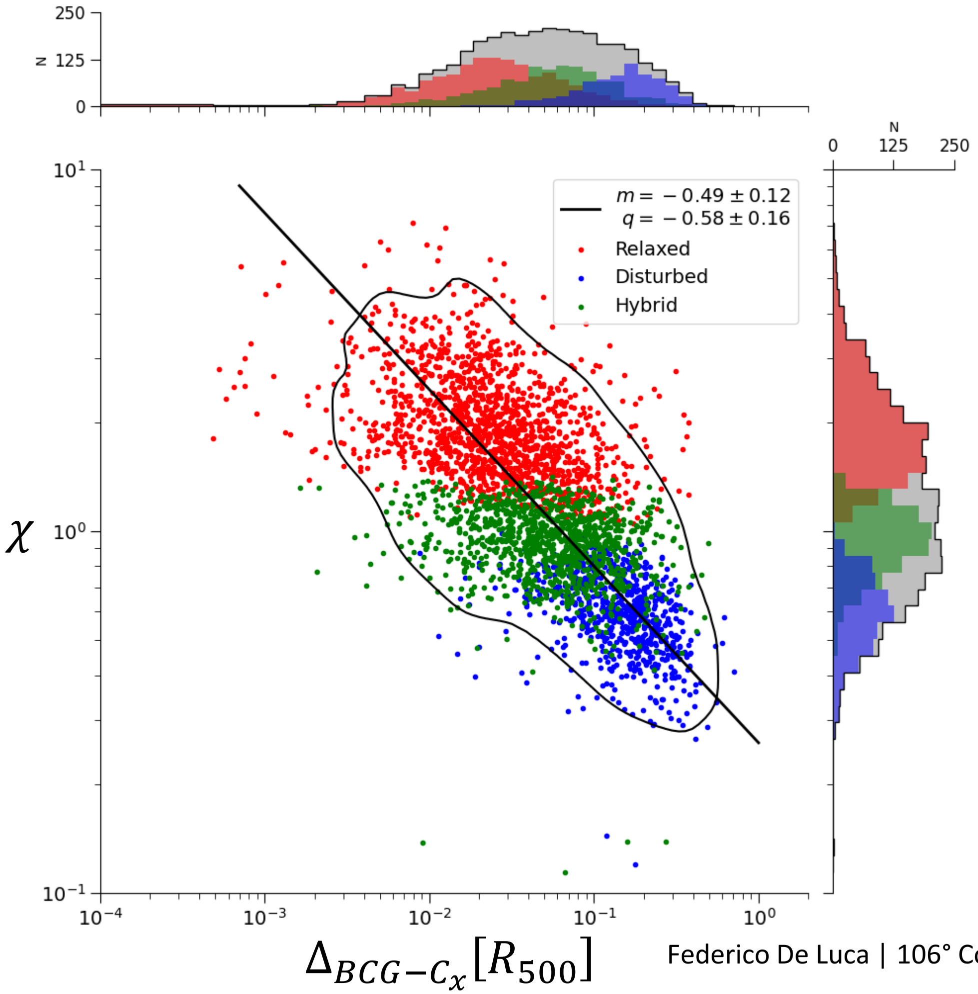
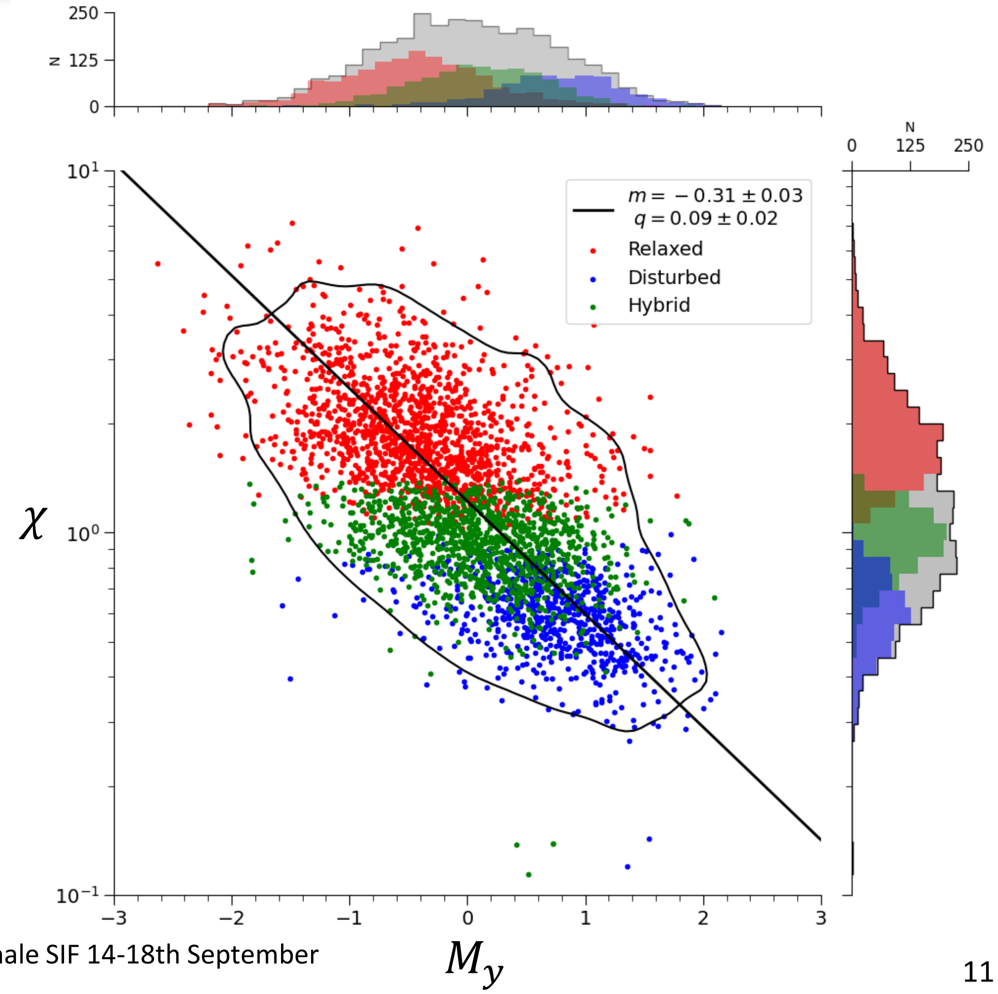
Morphological state of galaxy clusters.

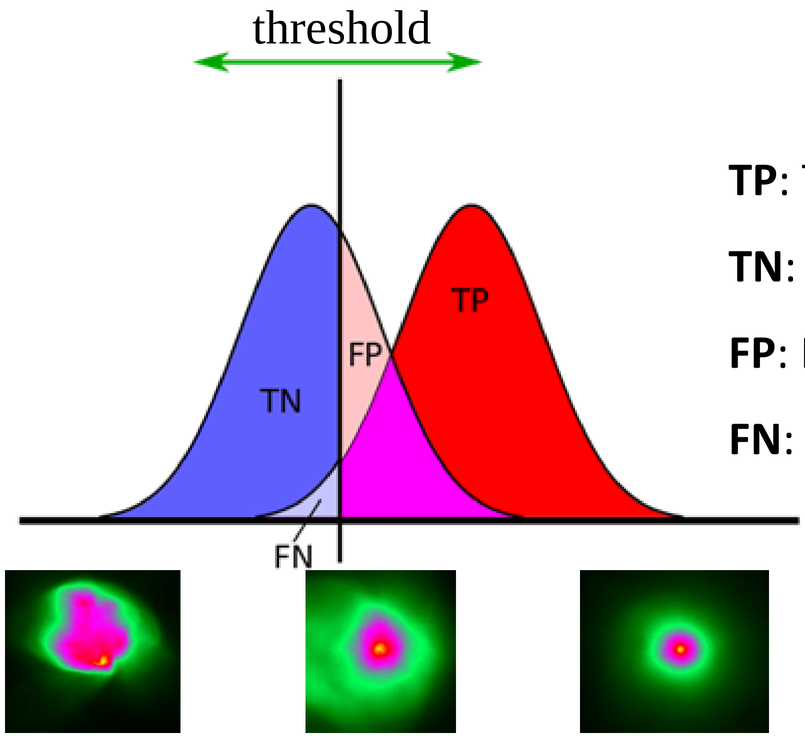
The combined M and the offsets parameters have a relatively strong correlation with the dynamical state. From Spearman correlation coefficient: $\rho \sim -(0.63 \div 0.69)$





04 Segregation efficiency and relaxed fraction from mock clusters images.

The diagnostic power of morphological parameter is studied with the **Receiver Operating Characteristic** (**ROC**) curves. Varying the classification threshold, the fraction of false detection and true detection will change, depending on the segregation efficiency of the classifiers.

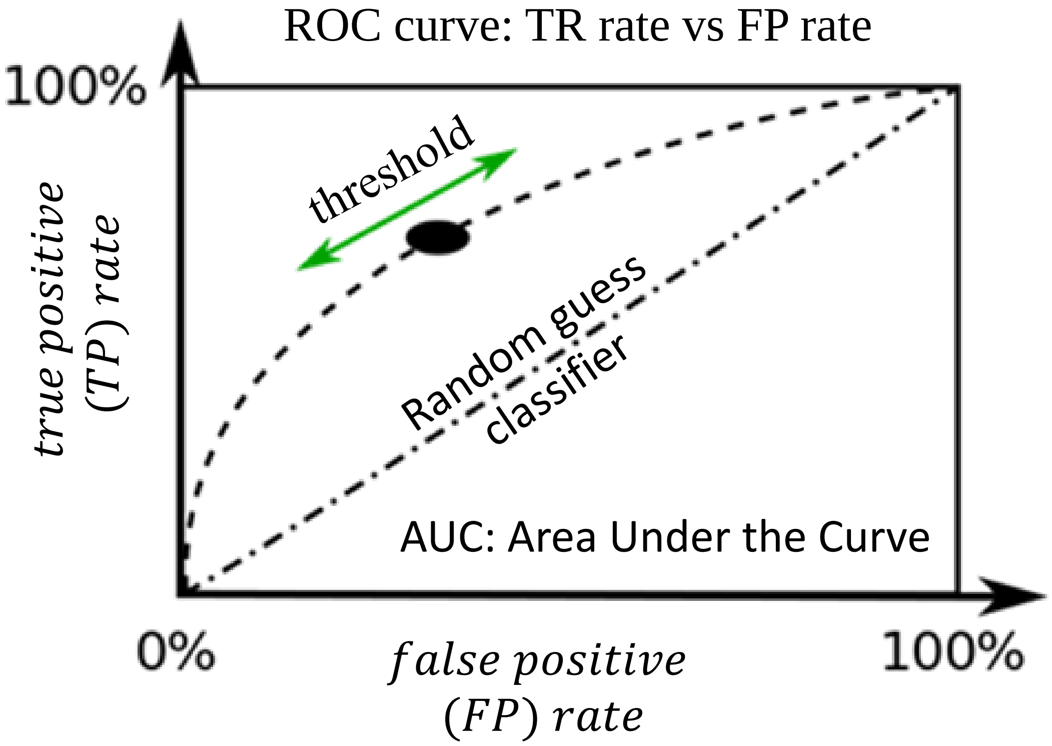


TP: True positive

TN: True negative

FP: False positive

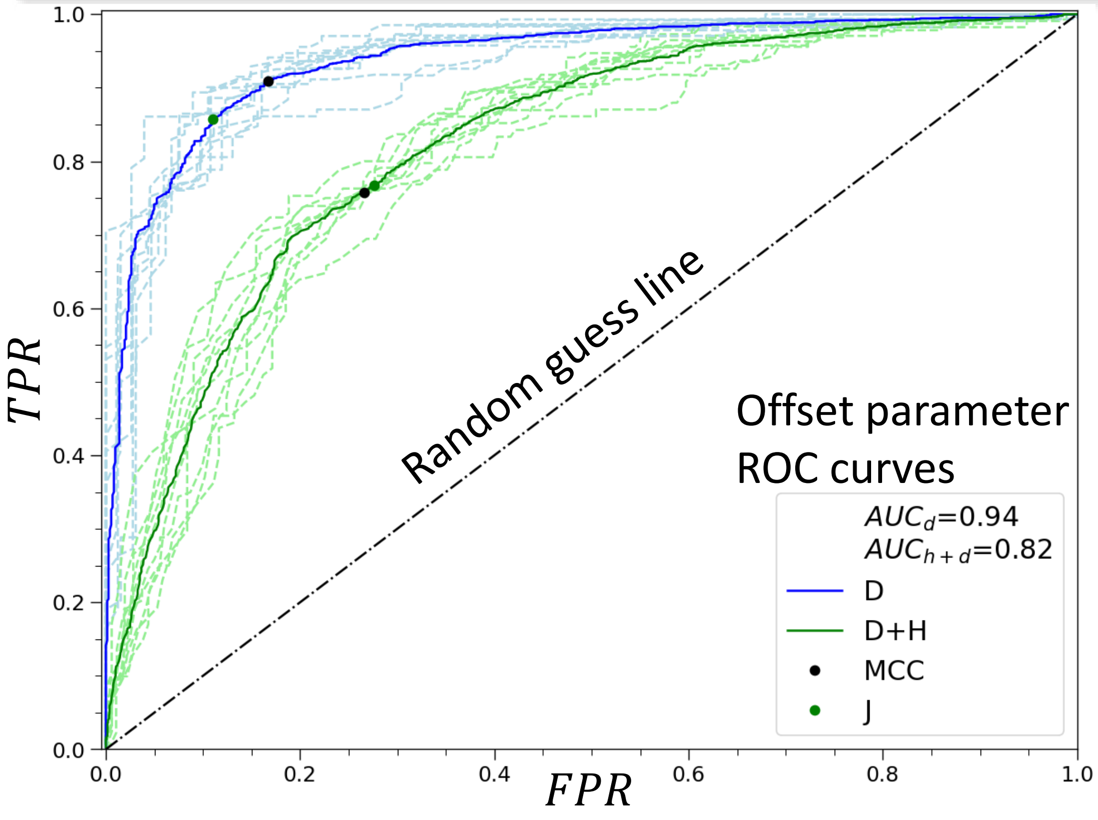
FN: False negative

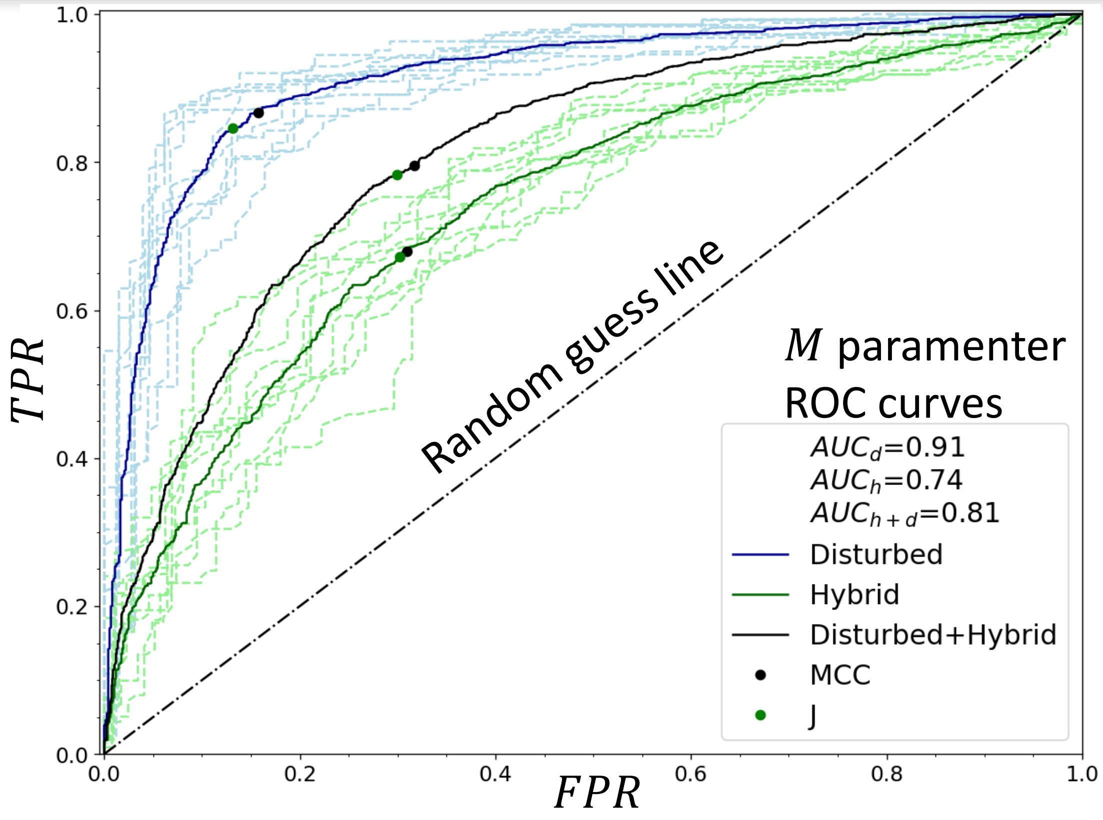


04

Segregation efficiency and relaxed fraction from mock clusters images.

The combined parameters are more efficient in segregate more relaxed clusters from disturbed ones, since they collect different properties of galaxy clusters. However, the intermediate hybrid clusters are the major sources of contamination when a threshold is applied to extract a relaxed subsample.

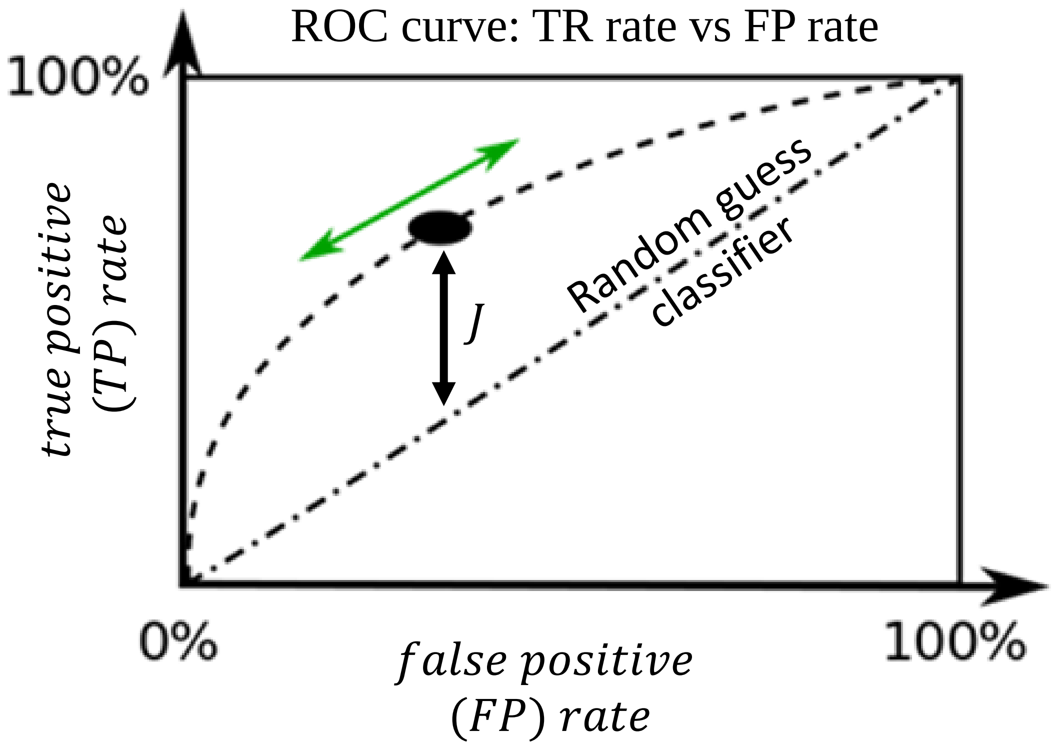




04

Segregation efficiency and relaxed fraction from mock clusters images.

Considering some summary statistic estimator in ROC curve we can select a non arbitrary threshold among segregate the most relaxed cluster from the disturbed ones. For this work, we use the Youden's J statistic, that it is graphically the height above the random guess line.



Paper in literature	Number of objects	Relaxed fraction [%]	Redshfit range
The Three Hundred	3240	47-49	<1.031
Mann & Ebeling (2012)	108	44	0.15-0.7
Rossetti et al. (2016)	132	52±4	0.02-0.87
Lopes et al. (2018)	40	48-53	0.01-0.1
Bartalucci et al. (2019)	74	46	0.08-1.13
Yuan & Han (2020)	964	51.2	<1.75

05 Conclusion

- For a virialized, regular, dynamically "relaxed“ cluster the hydrostatic assumption could be used by applying a simple description of the gas state. However, most of the clusters are not completely relaxed;
    - In The Three Hundred Project, the relaxed fraction from morphological parameters is $\sim$ 47-49%, comparable with other results in literature;
- The contamination in relaxed subsample is mainly due to hybrid clusters than disturbed ones;
- Dynamical state is better described by continuous indicators rather than classification schemes;
- The most efficient indicators are the combined parameters: they collect multiple properties of morphology or dynamical state in one single, continuous parameter.

Thanks for the attention!