The suburbs of galaxy clusters

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Probing **substructure** with hydrodynamical **simulations** and Sunyaev-Zel'dovich signals

Abstract

The Λ-Cold Dark Matter model predicts that large galaxy clusters should retain a complex and dynamic substructure, characterising both the dark matter distribution as well as their baryonic component. The hot ionised gas, shock-heated by the clusters' deep gravitational potential, is known to comptonise the photons from the Cosmic Microwave Background, giving rise to the thermal (tSZ) and kinetic (kSZ) Sunyaev-Zel'dovich effects. In this study, the MAssive ClusterS and Intercluster Structures (MACSIS) hydrodynamical simulation provided a sample of 390 clusters with total masses between 10^{15} - 10^{16} M_{SUN}, which constitute an exceptional probe for the dynamics of substructures using kSZ information. The hot gas bound to substructures was analysed using the outputs from the *subfind* code and the results from a pipeline dedicated to the reconstruction/analysis of galaxy cluster kSZ maps. The combination of these two independent methods allowed the computation of the fraction of *subfind* substructures that were detected by the pipeline algorithms.

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Introduction

- Why should galaxy clusters exhibit **substructures**?
  Galaxy clusters are some of the largest objects in the Universe and are known to arise from *hierarchical structure formation* processes. Self-gravitating objects that survive at late times in cosmic history must have formed at early times, before merging into larger cluster systems. This condition implies that large galaxy clusters are not expected to be virialised, hence showing a high degree of substructure.
  Alternative formulation: for a typical galaxy cluster, the *two-body relaxation time* is found to be much greater than the Hubble time.

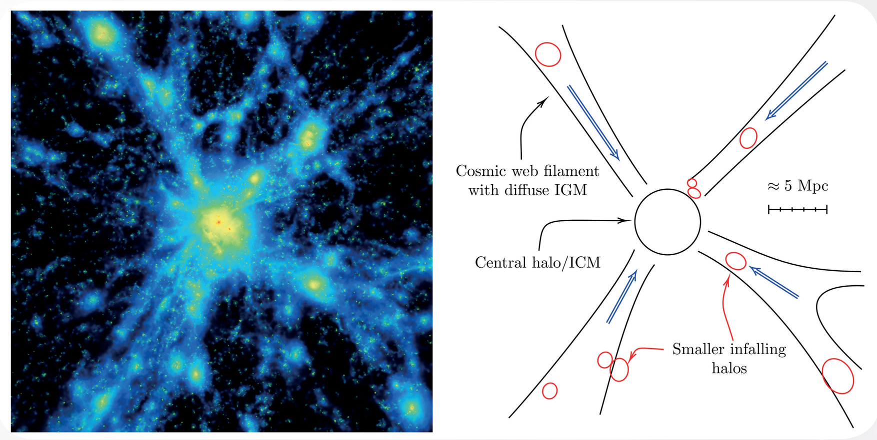
- Why are substructures **important**?
  Substructures, also known as **subhalos**, are self-bound objects, populated by 10 - 100 galaxies, dark matter and hot gas. Given their lower mass, the majority of them must have formed at early times, before merging into larger cluster systems. As a consequence, they are expected to retain **memory** of the **formation history** of the galaxy cluster they populate. Their kinematic and thermodynamic properties should then provide information about galaxy cluster physics, in the context of Λ-Cold Dark Matter cosmology.

- Are the **Sunyaev-Zel'dovich (SZ)** effects good probes for substructure physics?
  Predicted in 1969, the Sunyaev-Zel'dovich (SZ) effects are distortions of the CMB spectrum, caused by **inverse Compton scattering** between low-energy CMB photons and high-energy electrons in the Inter-Galactic Medium (IGM). Microscopically, the magnitude of the effects depends upon the electrons' velocity vectors. Macroscopically, it depends upon the **temperature** of the IGM (**thermal-SZ**) and a line-of-sight **bulk motion** of the IGM with respect to the CMB (**kinematic-SZ**). SZ physics is therefore sensitive to the thermodynamics and kinematics of the subhalos' IGM and can be (*in principle!*) probed observationally.

MACSIS

MAssive ClusterS and Intercluster Structures

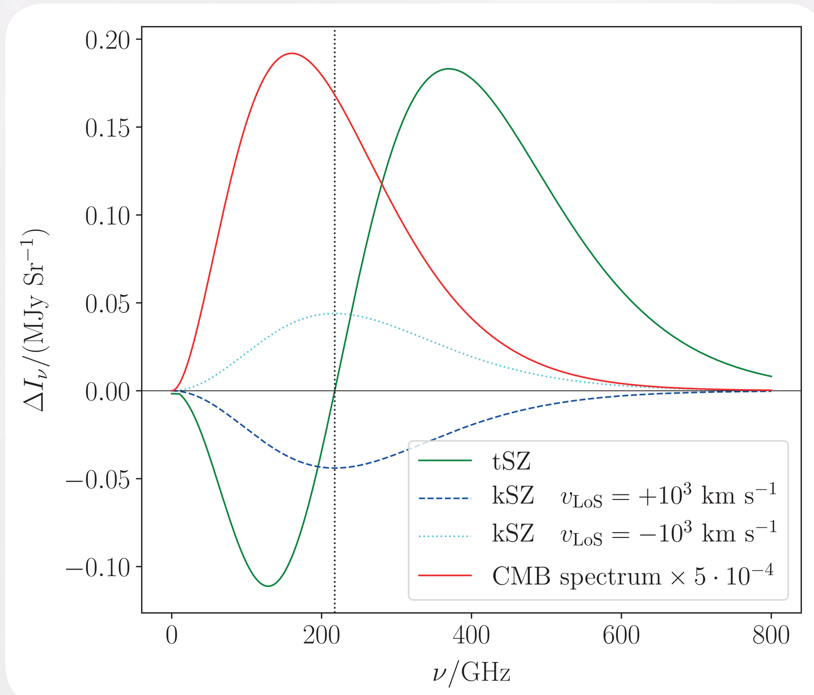
- Developed by Barnes *et al.* (2015, 2017) using the TreePM-SPH *Gadget-3* code.
- Includes high-resolution *zoom* simulations of **390 clusters**, with dark-matter-only and hydrodynamic runs.
- Cluster masses: $10^{15} < M_{200}/M_{SUN} < 10^{16}$.
- Mass resolution: 10^9 M_{SUN} = particle mass.
- The *subfind* code (Springel *et al.*, 2001) identified self-bound subhalos larger than 20 particles → **subfind catalogue**.



MACSIS HYDRO cluster 0: gas density (left) and relative schematic (right).

SZ effects

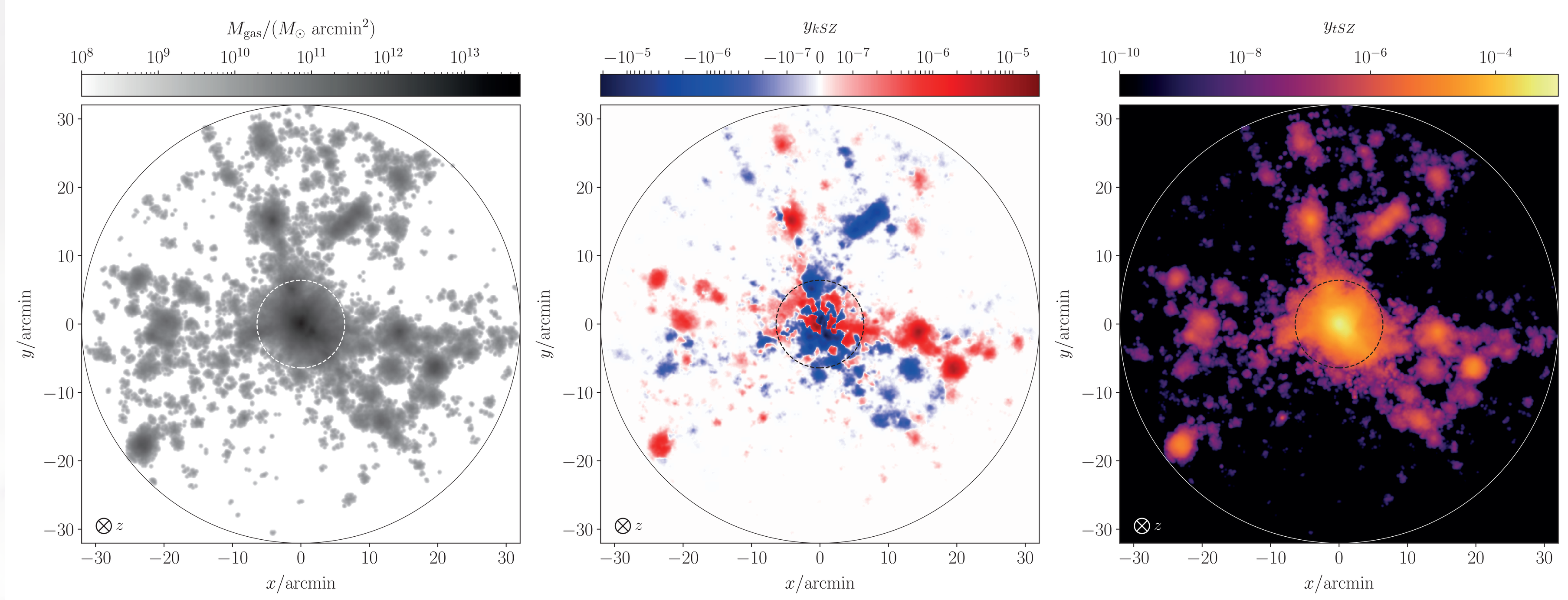
- **Spectral distortion**: flux decrement below 217 GHz and flux increment above this threshold.
- Quantified by the Compton y-parameter: $\frac{\Delta T_{CMB}}{T_{CMB}} \approx y_{SZ}$.



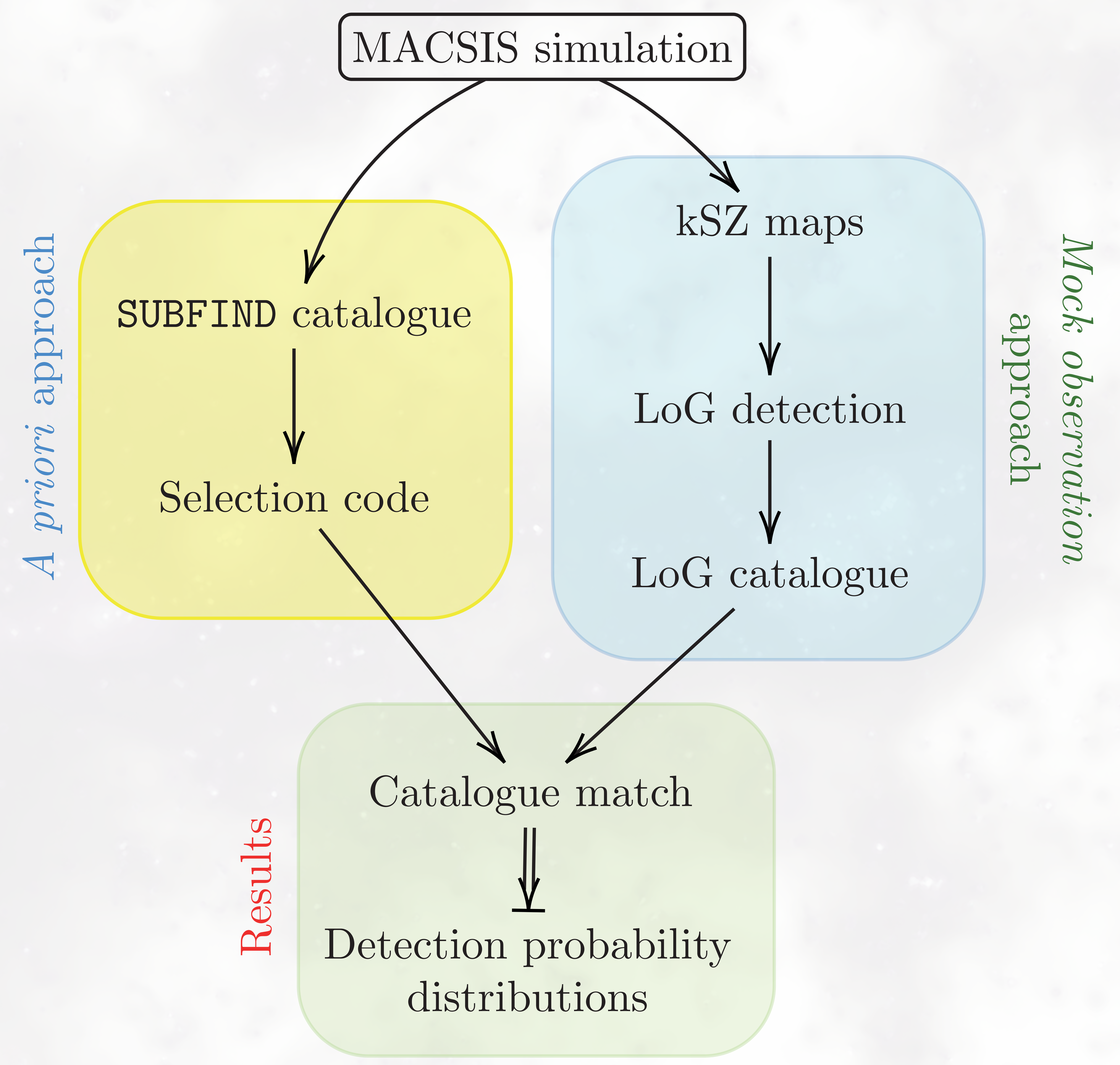
MACSIS goes SZ!

- The non-relativistic tSZ and kSZ effects were simulated on MACSIS data at redshift $z = 0.56$ (see Altamura, 2019 and Murin, 2019 for further details).
- The kSZ maps were scanned using the Laplacian of Gaussian (LoG) filter for detecting fluctuations in the y_{SZ} distributions → **LoG catalogue**.

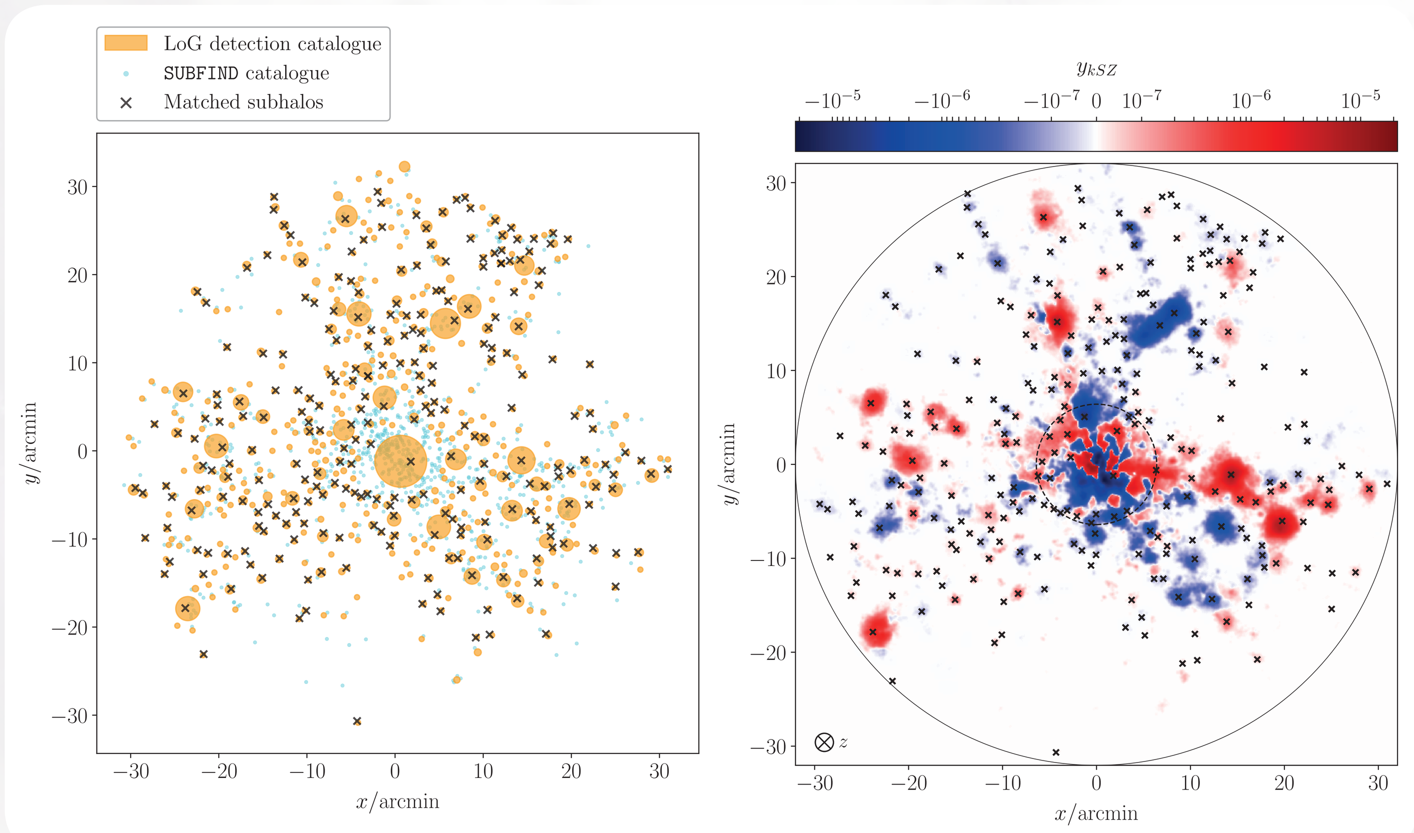
$$y_{kSZ} \equiv \int_{LoS} \sigma_T \, n_e \, \boldsymbol{n} \cdot \boldsymbol{\beta}_p \, dl \qquad y_{tSZ} \equiv \frac{\sigma_T}{m_e c^2} \int_{LoS} P_e \, dl$$



Concept workflow



Matching catalogues

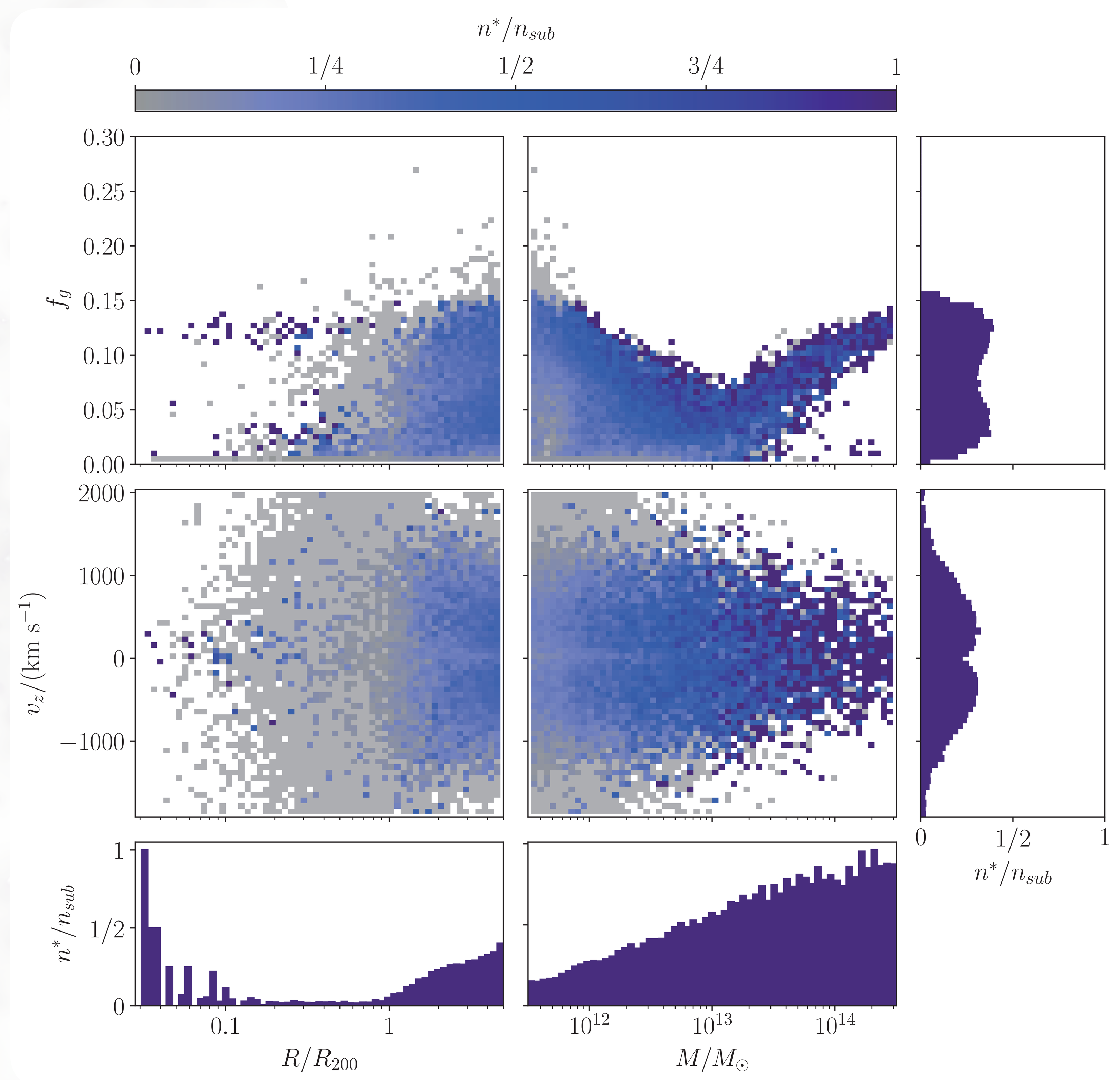


- For each LoG fluctuations, the pipeline flagged the largest *subfind* object within the LoG boundary.
- The subhalos that matched **both** the *subfind* and LoG catalogues increment the number n^* of **detected substructures**.

Results

(390 clusters)

Detection **probability** distributions of subhalo IGM through the **kSZ effect**



- f_g = subhalo gas fraction; n_{sub} = number of *subfind* subhalos; v_z = subhalo IGM bulk motion along the z line-of-sight; R = subhalo orbital distance from the centre of the main cluster
- White regions indicate absence of *subfind* candidates, while grey bins represent **undetected** *subfind* objects.

Implications

- **Ram pressure and stripping**
  Substructures within the ICM can be detected with < 5% probability on average, while outside the virial sphere the detection rate increases up to 41%.
- **Close mergers**
  The large values at $R < 0.1$ R_{200} are characterised by a considerable scatter, largely attributed to the contribution of the close mergers and the Poisson noise.
- **kSZ with $v_z = 0$?**
  The substructures with low values of the line of sight velocity are not expected to contribute to the kSZ signal. However, they may be geometrically aligned with independent (smaller) substructures which are moving faster. In such scenario, the LoG algorithm would detect one single fluctuation in the kSZ map and match it with the corresponding *subfind* candidate.
- **The microwave sky with NIKA2**
  NIKA2 is a microwave detector array, optimised for kSZ detections. The synergy between observational findings and the predictions from the present work may lead to much more accurate analyses for galaxy cluster dynamics.

References

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