MASSIVE MERGING CLUSTER PSZ2G091 AS SEEN BY THE NIKA2 CAMERA

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PSZ2 G091.83+26.11 is a galaxy cluster with \(M_{500} = 7.43 \times 10^{14} M_\odot\) at \(z = 0.822\). This object exhibits a complex morphology with a clear bimodality observed in X-rays. However, it was detected and analysed in the \(\textit{Planck}\) sample as a single, spherical cluster following a universal profile. This model can lead to miscalculations of thermodynamical quantities, like the pressure profile. As future multiwavelength cluster experiments will detect more and more objects at high redshifts, it is crucial to quantify this systematic effect. In this work, we use high-resolution observations of the NIKA2 camera to integrate the morphological characteristics of the cluster in our modelling. This is achieved by fitting a two-halo model to the SZ image and then by reconstruction of the resulting projected pressure profile. We then compare these results with the spherical assumption.

1 Cosmological inference from cluster counts

The number of clusters per unit of mass and volume, modelled as the halo mass function, constitutes a robust cosmological probe. However, the total mass of dark matter halos is not an observable quantity, and must be inferred from different physical phenomena, like the
Table 1: Characteristics of PSZ2 G091.83+26.11. $t_{\text{LPSZ}}$ is the scheduled duration of the observations, while $t_{\text{obs}}$ is the actual time during which the object has been observed.

| $z$   | $M_{500}$  | $\theta_{500}$ | $t_{\text{obs}}/t_{\text{LPSZ}}$ | tSZ decrement peak |
|-------|------------|----------------|----------------------------------|--------------------|
| 0.822 | $7.43 \times 10^{14} M_\odot$ | 2.2 arcmin      | 2.5h/2.5h=1                      | 14.9$\sigma$       |

thermal Sunyaev-Zel’dovich effect (tSZ). As a consequence, astrophysical systematic effects are biasing our measurements, and must be integrated in any cosmological analysis. Moreover, given the fact that the size of the catalogs will be increased by several orders of magnitude in the future, effects that are now neglected will play a crucial role.

The Large program SZ of the NIKA2 experiment (LPSZ) aims at investigating these issues, taking advantage of the spatial resolution and FoV of the NIKA2 camera. Here, we focus on the impact of cluster morphology on the reconstruction of thermodynamical quantities.

2 The case of PSZ2G091

As part of the LPSZ, PSZ2G091 was observed in October, 2017, with an average elevation of 58.5° and an average atmospheric opacity at 225 GHz of 0.243. These conditions are standard for observations at the IRAM 30 m telescope, at this season.

In figure 1, we show the results of the data reduction at 1 and 2 mm. The cluster is clearly elongated in the NE-SW direction. There is a clear departure from sphericity, and a hint of bimodality later confirmed in the X-ray surface brightness map. The peaks in the X-ray map are in good agreement with the ones observed in the NIKA2 2 mm map. This would imply the presence of two well-defined sub-halos in the first stages of a major merger.

3 Imaging analysis

We first consider a single spherical halo centred on the X-ray centroid coordinates. A forward modelling approach is incorporated in an MCMC sampling framework to fit the parameters of the pressure profile, as well as the point sources, with the collaboration software PANCO2. We use a power law model, where each of the 6 bins follows the identity

$$P(r) = P_i (r/r_i)^{-\alpha_i}.$$ (1)
Figure 2: Single spherical model fit of the NIKA2 2 mm map for PSZ2G091 centered on the X-ray centroid coordinates (top), and 2-halo model (bottom). From left to right, we display the data, the model, with the point sources treated, and the residuals. The maps are given in a $5' \times 5'$ area, and for display purposes, each map is smoothed with a gaussian kernel. The contours are showing the SNR level sets, starting at $3\sigma$ and increasing with a step of $1\sigma$.

The top row of figure 2 shows the results of the fitting procedure. The spherical symmetry clearly does not encapsulate the bimodal nature of the cluster. It is then required to improve our modelling.

Then, instead of considering a single pressure profile, we jointly fit two halos at the positions of the X-ray peaks. The results of the fits are shown on the bottom row of figure 2. It is clear that the two-halo model yields a more realistic representation of the dynamical state of the cluster. Additionally, the residuals are slightly improved in the region of the northern subhalo. Of course, due to the non-spherical nature of this cluster, it is not possible to consider a radial pressure profile. However, in section 4, we describe how we recover an average radial profile for the two-halo model.

4 Pressure profile reconstruction

Thermodynamical profiles are usually considered with the goal of reconstructing a mass profile, using the hydrostatic equilibrium assumption. This requires the presence of a 1D pressure profile, when we previously fitted a 2D map. Thus, we use the following procedure to recover an average 1D profile. With the assumption of the two sub-halos lying in the same plane perpendicular to the line of sight, we recover a mean radial pressure profile by integrating both the profiles in annuli centered around the X-ray centroid coordinates. The pressure in the $i$-th bin reads:

$$P_i = \left( \int_{r_i}^{r_{i+1}} (P_N(r) + P_S(r)) 2\pi r dr \right) / \left( \pi (r_{i+1}^2 - r_i^2) \right),$$

where $P_i$ is the value of the pressure, $P_N$ and $P_S$ are respectively the profiles of the northern and southern subhalos, $r_i$ and $r_{i+1}$ being the inner and outer radii of the annulus. This allows us to reconstruct the profile shown in figure 3, where we compare our reconstructed quantities with the universal profile$^{16}$.

5 Conclusions

This analysis shows the challenges related to the complexity of cluster morphologies. In this work, we showed that for the case of the highly disturbed cluster PSZ2G091, taking into account
the merging state of the cluster yields results that are slightly different from the spherical profile. This is a promising result, as the pressure profile impacts the $Y_{500} - M$ relation. To complete this analysis, we plan to perform a full thermodynamical analysis of this cluster, recovering the 2D maps of physical quantities like the temperature and the entropy. This a precondition to assess the impact of the morphology of this cluster on its full mass reconstruction, and generally on cosmological inference using clusters.

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References

1. Planck Collaboration et al., A&A 594, A27 (2016), 1502.01598
2. M. Arnaud et al., A&A 517, A92 (2010), 0910.1234
3. L. Perotto et al., A&A 637, A71 (2020), 1910.02038
4. R. Adam et al., A&A 609, A115 (2018), 1707.09908
5. M. Calvo et al., Journal of Low Temperature Physics 184, 816 (2016), 1601.02774
6. O. Bourrion et al., Journal of Instrumentation 11, P11001 (2016), 1602.01288
7. W.H. Press, P. Schechter, ApJ 187, 425 (1974)
8. S.W. Allen et al., ARA&A 49, 409 (2011), 1103.4829
9. G.W. Pratt et al., Space Sci. Rev. 215, 25 (2019), 1902.10837
10. R.A. Sunyaev, Y.B. Zeldovich, Ap&SS 7, 3 (1970)
11. S. Bocquet et al. (2015), 1502.07357
12. E. Artis et al., A&A 649, A47 (2021), 2101.02501
13. A. Fumagalli et al., A&A 652, A21 (2021), 2102.08914
14. F. Mayet et al., EPJ Web of Conferences 228, 00017 (2020), 1911.03145
15. F. Kéruzoré et al., EPJ Web of Conferences 257, 00024 (2022), 2111.06493
16. Planck Collaboration et al., A&A 550, A131 (2013), 1207.4061