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The NIKA2 Sunyaev-Zeldovich Large Program

Sample and upcoming product public release

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Abstract. The NIKA2 camera operating at the IRAM 30-m telescope excels in high-angular resolution mapping of the thermal Sunyaev-Zel'dovich effect towards galaxy clusters at intermediate and high-redshift. As part of the NIKA2 guaranteed-time, the SZ Large Program (LPSZ) aims at tSZ-mapping a representative sample of SZ-selected galaxy clusters in the catalogues of the Planck satellite and of the Atacama Cosmology Telescope, and also observed in X-ray with *XMM-Newton* or *Chandra*. Having completed observations in January 2023, we present tSZ maps of 38 clusters spanning the targeted mass ($3 < M_{500}/10^{14} M_{\odot} < 10$) and redshift ($0.5 < z < 0.9$) range. The first in-depth studies of individual clusters highlight the potential of combining tSZ and X-ray observations at similar angular resolution for precised mass measurements under the hydrostatic assumption $M_{\rm HSE}$. These were milestones for the development of a standard data analysis pipeline to go from NIKA2 raw data to the thermodynamic properties of galaxy clusters for the upcoming LPSZ data release. Final products will include measurements of the mean pressure profile of unprecedented quality and $M_{\rm HSE}$-observable scaling relation using a distinctive SZ-selected sample, which will be key for ultimately improving the accuracy of cluster-based cosmology.

1 Introduction

Obtaining accurate measurements of the mass of galaxy clusters and understanding deviations from the self-similar model due to baryonic physics are key challenges when using these valuable tracers of large-scale structures as cosmological probes [1]. High-angular resolution observation of galaxy clusters through the thermal Sunyaev-Zel'dovich (tSZ) effect [2] presents a promising way forward. The tSZ effect is independent of redshift and yields the Compton parameter reflecting electronic pressure within the intra-cluster medium. High-angular resolution mapping the tSZ effect towards clusters provides a radial pressure profile estimate via straightforward deprojection. When combined with X-ray observations allowing density profile deprojection [3], cluster masses can be inferred assuming sphericity and hydrostatic equilibrium [1].

Such measurements require advanced millimetre-domain experiments that offer a sufficiently large field of view to cover the typical sizes of clusters and high angular resolution to resolve their detailed structure. NIKA2, at the IRAM 30-meter telescope, uniquely combines a wide 6.5' field-of-view diameter with 17.6 and 11.1 arcsecond FWHM Gaussian beam at 150 and 260 GHz, respectively [4].

The SZ Large Program of NIKA2 (LPSZ; 300 hours of guaranteed time; P.I. F. Mayet & L. Perotto) maps the tSZ effect at high angular resolution for a representative sample of 38 galaxy clusters selected from the Planck and ACT catalogues and covering a wide range of mass and redshift. This extends existing calibration samples (e.g. [5], [6]) to higher redshifts or lower masses. Using this unique sample, our main goal is to improve the measurement of the mean pressure profile of clusters and the scaling relation between SZ observable and hydrostatic mass. These key tools for many SZ cosmological analyses will ultimately contribute to improving the accuracy of cluster-based cosmology.

2 The LPSZ cluster sample

The selection of the LPSZ sample occurred in 2015, utilizing the available Planck [7] and ACT [8] catalogues at that time. Two primary objectives guided this selection: to ensure representativity with respect to morphology and to achieve homogeneous coverage across the mass-redshift plane, including redshifts greater than 0.5 and a mass range as broad as permitted by the total 300 hours of NIKA2 Guaranteed Time of observation. To this end, clusters were selected based on their detected SZ signal amplitude, effectively minimizing biases linked to cluster morphology or dynamical state. For a homogeneous distribution across the mass-redshift plane, 10 mass-redshift bins were defined by partitioning the mass range from 3×10^{14} to $10^{15} M_{\odot}$ into 5 logarithmic spaced intervals, and the redshift range from 0.5 to 0.9 in two linear bins. In each mass-redshift bin, 5 clusters were randomly selected using their integrated Compton parameter measurements and the mass-observable relation from [9]. Consequently, the original 2015 selection comprised 45 clusters, 35 from the Planck catalogue, and 10 ACT clusters covering lower mass ranges. The choice of the number of bins and clusters per bins were optimized from observation time consideration. For each cluster, the goal was to obtain a 3σ measurement of the Compton parameter radial profile at a radius θ_{500}, the angular diameter subtended by the typical cluster size. This size is given by R_{500}, the radius of a sphere centered on the cluster in which the average density is 500 times the critical density of the Universe. This requirement is referred to as the *target SNR* hereafter.

Observations were conducted from October 2017 to January 2023 during 29 observation campaigns, each lasting one to two weeks, spread between October and March annually. Each campaign was guided by a detailed observation plan, with targets selected based on 1/ visibility, 2/ mass and redshift to gradually fill the LPSZ mass-redshift bins, and 3/ any additional decisive information from Planck cluster catalogue follow-up programmes. Notably, 4 clusters from the initial Planck selection were later either identified as false detections or appeared very faint in X-ray follow-ups. Additionally, 2 clusters lacked sufficient X-ray emissions for the necessary density profile deprojection to estimate hydrostatic mass. The former 4 objects were discarded, and the latter 2 received lower observation priority and ultimately remained unobserved. Following target selection, allocated observation times were re-evaluated iteratively, leveraging data from prior campaigns to meet the LPSZ SNR criterion. While this in-flight re-evaluation ensured each observed cluster supported LPSZ main goals, it also extended total observation time. Consequently, 4 ACT clusters, already at the visibility limit of the IRAM 30-meter telescope during observation months, were excluded in favour of redistributing observation time to Planck clusters. Additionally, 3 clusters, replacing the false detection within the corresponding mass-redshift boxes, were selected from the latest Planck and ACT catalogues [10, 11].

In conclusion, 38 galaxy clusters were observed. Figure 1 presents the 150 GHz map for each cluster, obtained during preliminary data quality assessment. These maps are not the final versions for publication. The iterative observation process facilitated a uniform coverage of the mass-redshift plane defined by LPSZ, ensuring a minimum of 3 clusters per mass-redshift box. Among these, the 150 GHz map for 30 clusters already meets the target SNR. In 5 other cases, the current SNR of the map should be effectively improved in resorting to a refined version of the analysis. Only 3 clusters exhibit a preliminary map that casts doubt on the feasability of deprojecting a resolved pressure profile. Detailed study of four LPSZ cluster has been published, as will be discussed in the subsequent section.

3 Recent results

Parallel to the observation and data quality analysis, the first in-depth studies of individual clusters have been published. Following the publication of the first galaxy cluster mapped through the tSZ effect with NIKA2 [12], we investigated a challenging low-mass, high-redshift cluster, demonstrating the feasibility of mass estimation across the entire sample [13]. These initial studies have marked important milestones for estimating systematic effects and

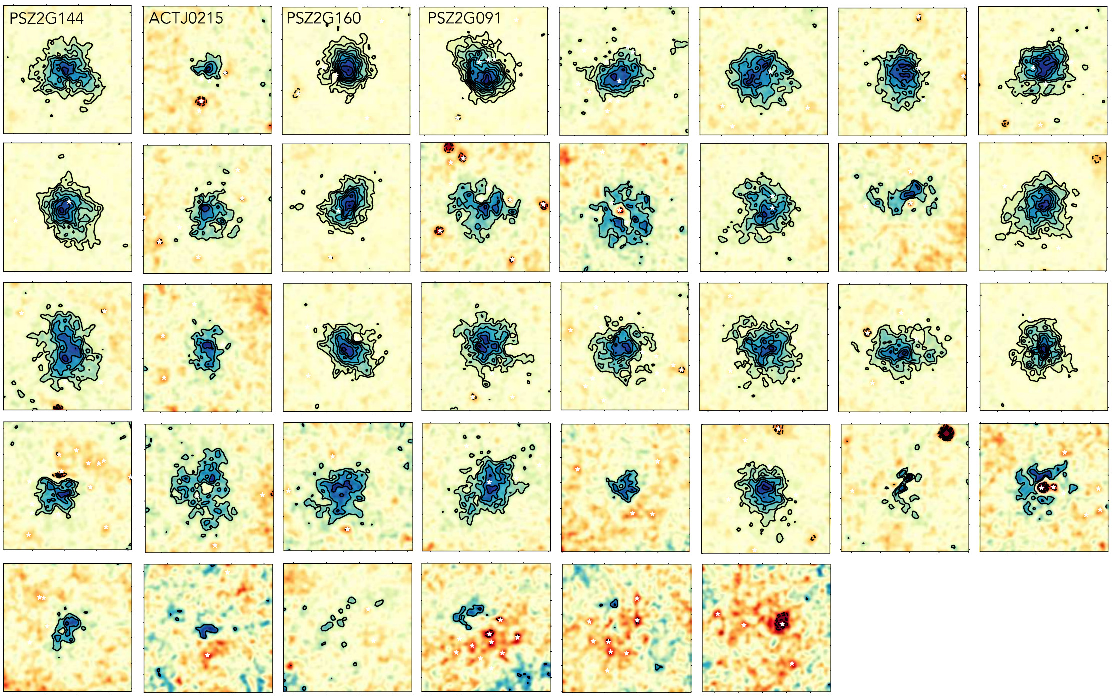

Figure 1. Preliminary analysis of the LPSZ sample after the end of observation: 150 GHz surface brightness maps of the 38 observed clusters, colour-coded in mJy/beam with an arbitrary scale. The top four maps correspond to the first in-depth analysis of the following LPSZ clusters: PSZ2 G144.83 + 25.11 [12], ACT-CL J0215.4 + 0030 [13], PSZ2 G160.83 + 81.66 (a.k.a. CLJ1226.9 + 3332) [14] and PSZ2 G091.83 + 26.11 [15], respectively. Using the evaluation of the SNR levels (showed as black contours) and prior information from the Planck and ACT catalogues, we find that 30 clusters are conservatively mapped at the requested SNR level for LPSZ core science goals. This sample is showed by the maps of the 4 aforementioned clusters and the randomized 26 remaining clusters. The five next maps show detected clusters for which refined analyses are needed to enhance the map quality.The three last maps show highly-contaminated or noise-dominated cases.

preparing cosmological results. Furthermore, the method described in [13] led to panco2, a public code for pressure profile estimation from SZ maps obtained from any millimeter-wave instrument, as detailed in [16].

In [14], we found the dominant systematic uncertainty on mass estimation to be related to the choice of the cluster pressure profile model, rather than residual noise or large-scale angular filtering induced by data reduction. Studies combining LPSZ observations with gravitational lensing reconstructions in the CLASH programme [14, 17] have demonstrated the potential of this approach to study the hydrostatic bias, linking the mass estimated under the assumption of hydrostatic equilibrium with the total mass of clusters as probed via gravitational lensing.

Additionally, leveraging high-resolution X-ray and tSZ observations, we studied a highly disturbed, massive, high-redshift cluster [15]. This provided an extreme case for investigating morphology and dynamical state impacts on mass estimates. This system being consistent with a scenario of a major merger event involving two main halos, we identified map regions most compatible with the hydrostatic equilibrium, facilitating the hydrostatic mass estimation of both halos.

Lastly, to assess LPSZ sample sensitivity to cluster physics and deviations from underlying assumptions in cluster-based cosmology, we constructed a series of LPSZ twin samples selected from the state-of-the-art simulation of *The Three Hundred* project [18–20].

4 Standard analysis and upcoming data release

We developed an analysis pipeline to go from Time-Ordered Information (TOI) to the products of interest for cosmology. This pipeline is divided in three blocks.

The first stage involves projecting raw TOI data into surface brightness maps, employing the NIKA2 collaboration IDL data reduction pipeline [4] with adjustments to preserve large angular scale signals while minimizing correlated noise. The scale filtering effect is modeled using a transfer function estimated from processing simulated inputs through the pipeline. Map noise properties are characterized through the angular power spectrum of sign-flipped co-added maps, and sample count maps. The 260-GHz map is utilized to detect point sources in the cluster neighbourhood, allowing for an upper limit estimation of contamination from sub-mm sources in the 150GHz map. Additionally, point sources around LPSZ clusters are systematically identified in ancillary radio, submillimetric, and NIR catalogues.

The second stage is the full characterization of the thermodynamic properties of each cluster. We use panco2 for the deprojection of 3D spherical pressure profiles from NIKA2 maps. This method consists of forward-modelling the NIKA2 map at 150 GHz, featuring the tSZ signal, realistic correlated noise and filtering, and the contribution of detected point sources, to estimate a spherical pressure profile. As in previous LPSZ work, we combine the pressure profile obtained from NIKA2 data with the density profile reconstructed from *XMM-Newton* observation using the method described in [3], for the full characterization of the thermodynamic properties of the clusters. In particular, we infer the radial hydrostatic mass profile, from which we estimate $M_{\mathrm{HSE},500}$, the hydrostatic mass enclosed in a sphere of radius R_{500}.

The last stage is the sample level analysis to build the products of interest for cluster-based cosmology. Using a simulation suite featuring realistic NIKA2 noise, we validate our methodology for estimating the M_{HSE}-observable scaling relation [21], as well as for deriving the mean pressure profile [22].

We expect to publicly release the main LPSZ products no later than mid-2025. This release will encompass several components : i) data products, such as frequency maps, noise characterization, and filtering, ensuring reproducibility of our results and facilitating subsequent combined studies; ii) a comprehensive characterization of clusters in the LPSZ sample, including their thermodynamic properties, and their hydrostatic masses; iii) derived products of interest, such as a catalogue of point sources detected in LPSZ maps, some of which may correspond to high-redshift galaxies magnified by the lensing of clusters; and iv) final products of interest for cosmology, particularly the mean pressure profile and the M_{HSE}-observable scaling relation.

5 Conclusion

Within the framework of NIKA2 LPSZ, a 300-hour guaranteed-time programme, we have achieved resolved SZ mapping of a SZ-selected sample of 38 clusters. The sample spans a redshift range from 0.5 to 0.9 and covers an order of magnitude in mass.

First in-depth analyses of four clusters showcase the potential of resolved SZ observations to open up novel insights on cluster physics and to obtain precise hydrostatic mass estimates. In particular, new perspectives were explored on the physics of disturbed clusters or on hydrostatic-to-lensing mass bias.

Having concluded the observations in January 2023, our preliminary assessments indicate that 35 clusters have been successfully mapped with a high SNR. We have a robust foundation for fulfilling the primary objectives of the LPSZ. In preparation for the forthcoming public data release, we are refining a standard analysis pipeline to go from raw TOI to the products of interest for Cosmology. These final products will include measurements of the mean pressure profile of clusters and the scaling relation between hydrostatic mass and SZ observable with unprecedented robustness against systematic effects. These promise to enhance the accuracy of SZ and cluster-based cosmological studies.

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