

## Overview of final results from the NIKA2 Sunyaev-Zeldovich Large Program

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**Abstract.** The NIKA2 SZ Large Program (LPSZ) is devoted to the high-angular resolution SZ mapping of a representative sample of SZ-selected clusters, at intermediate to high redshift, drawn from the catalogues of the Planck satellite and of the Atacama Cosmology Telescope. Central to this program is the synergy between SZ observations and X-ray data, utilizing measurements from NIKA2 and XMM-Newton or Chandra. The main goal of this program is to provide the community with unprecedented measurements of cluster maps at 150 and 260 GHz, thermodynamic profiles and integrated quantities. This paper describes the LPSZ scientific objectives, the first public release and its science-ready products, the published results on individual clusters and the upcoming publications on the full sample.

## 1 Introduction

Galaxy clusters correspond to the most massive and rarest peaks in the matter density field, forming at the intersections of the filamentary structures of the cosmic web. They represent the final stage of hierarchical structure formation in the Universe [1]. Consequently, galaxy clusters serve not only as key astrophysical laboratories for studying baryonic and dark matter processes, but also as powerful cosmological probes and critical benchmarks for testing and calibrating hydrodynamical simulations. Clusters of galaxies are permeated by a hot, ionized gas known as the intracluster medium (ICM). This medium can be probed both through its X-ray emission and via the Sunyaev–Zeldovich (SZ) effect, which is a spectral distortion of the cosmic microwave background (CMB) caused by inverse Compton scattering of CMB photons by the energetic electrons in the ICM [2].

The thermal Sunyaev–Zeldovich (tSZ) effect is particularly powerful for cosmological studies, as it provides a redshift-independent observable for detecting and characterizing galaxy clusters, thereby enabling the construction of extensive cluster catalogues. Large-scale SZ surveys such as *Planck*, Atacama Cosmology Telescope (ACT), and the South Pole Telescope (SPT) have made it possible to build samples of thousands of galaxy clusters. However, their relatively low angular resolution — from  $5'$  for *Planck* [3] to  $\sim 1'$  for SPT [4] — limits the ability to resolve the internal structure of high-redshift systems. High-angular-resolution SZ observations,  $17.6''$  at 150 GHz for NIKA2, are therefore essential to map the pressure distribution within clusters, identify substructures, and refine mass estimates. Moreover, combining such SZ data with X-ray observations of comparable angular resolution (e.g. *XMM-Newton*) provides a powerful multi-wavelength approach for studying the thermodynamic properties of the intracluster medium.

The NIKA2 SZ Large Program (LPSZ) aims to deliver a homogeneous, high-resolution follow-up of 38 SZ-selected clusters at intermediate redshifts ( $0.5 \lesssim z \lesssim 0.9$ ), with the dual goal of advancing SZ-based cluster cosmology and investigating cluster astrophysics. NIKA2 SZ data are combined with X-ray data from *XMM-Newton* [5] or Chandra. Specifically, the

program focuses on calibrating the SZ–mass scaling relation, constraining the universal pressure profile, and probing the physical processes governing cluster formation and evolution.

This paper presents the LPSZ scientific objectives, the first public release, the science-ready products (maps, thermodynamic profiles, and integrated quantities), the published results on individual clusters and the upcoming series of publications [8–14] on the full sample.

## 2 The NIKA2 SZ Large Program

The NIKA2 Sunyaev–Zeldovich Large Program (LPSZ) is part of the NIKA2 guaranteed time, allocated by the IRAM Scientific Committee to the NIKA2 collaboration [15, 16].

### 2.1 Scientific objectives

The LPSZ was designed to exploit the unique capabilities of the NIKA2 camera [17, 18] to obtain high-resolution tSZ observations of a representative sample of SZ-selected galaxy clusters. As proposed in 2015, its scientific objective was, and remains, to investigate the thermodynamic and physical properties of galaxy clusters over more than 3 Gyr of cosmic evolution, spanning a wide range of redshifts and masses.

By overcoming current limitations in cluster astrophysics, the LPSZ aims to establish the foundation for high-resolution studies of cluster physics and to reduce systematic uncertainties in cluster-based cosmology and cluster physics. The LPSZ provides the first SZ-selected cluster sample in this redshift regime with sufficient angular resolution to resolve the intra-cluster medium (ICM) in detail. This enables a comprehensive study of the physical processes governing the evolution of massive halos, as well as a quantification of the thermal content and spatial distribution of the ICM as clusters grow through accretion and mergers. The scientific strategy of the LPSZ relies on a strong synergy between NIKA2 tSZ observations and X-ray data from the *XMM-Newton* satellite, both offering high angular resolution<sup>1</sup>. The joint analysis of tSZ and X-ray measurements constitutes a powerful approach to probe the thermodynamics of the ICM. The first objective of the LPSZ was to deliver to the community a homogeneous set of high-quality tSZ maps, thermodynamic profiles, and integrated quantities for the entire cluster sample. These data serve as a well-characterized reference for detailed studies of the cluster population at intermediate and high redshifts. Specifically, the program was designed to:

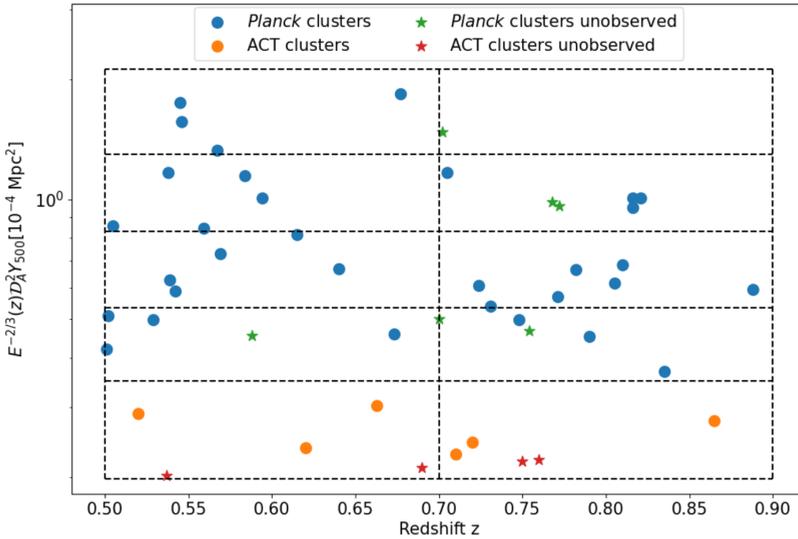
- (i) test the universality of the pressure profile and assess its potential redshift evolution,
- (ii) calibrate the mass–SZ scaling relation and constrain its redshift dependence,
- (iii) detect and quantify substructures and deviations from spherical symmetry,
- (iv) define and validate morphological indicators of the cluster dynamical state directly from tSZ observations.

### 2.2 The LPSZ cluster sample

In order to ensure a homogeneous coverage of the  $(z, Y_{500})$  parameter space<sup>2</sup>, the initial selection of the LPSZ sample was performed using a “box selection” strategy. Two redshift intervals were defined,  $z \in [0.5, 0.7]$  and  $z \in [0.7, 0.9]$ , together with five logarithmically

<sup>1</sup>  $\sim 15''$  in the case of *XMM-Newton*

<sup>2</sup>  $Y_{500}$  is the SZ integrated signal at a radius  $R_{500}$  at which the density is 500 times the critical density at this redshift.



**Figure 1.** The final LPSZ sample composed of 38 clusters in the  $Y_{500}$ - $z$  plane.

spaced bins in  $Y_{500}$ , approximately corresponding to cluster masses  $M_{500} \in [3, 10] \times 10^{14}, M_{\odot}$ . For each box, i.e. two-dimensional cells in the  $(z, Y_{500})$  plane, five clusters were randomly selected from the tSZ cluster catalogues available at the beginning of the program [3, 19–21]. This approach allowed us to mitigate biases associated with the underlying mass function of the parent catalogues. However, the box selection comes at the cost of introducing a complex selection function, which may affect the calibration of the scaling relations (see [12]).

The final sample slightly differs from the original selection owing to observational constraints. Several clusters were excluded after being identified as false detections in the *Planck* catalogues. In addition, four low-mass clusters were removed to preserve the signal-to-noise ratio (S/N) of the remaining targets, as their integration times had been underestimated due to overestimated input  $Y_{500}$  values. Ultimately, 38 clusters were observed. Among them, four lack X-ray counterparts, two exhibit insufficient S/N for a reliable  $Y_{500}$  determination, one was only partially observed, and one shows an SZ signal significantly offset from its X-ray peak. Further differences arise from updated NIKA2-based measurements of cluster properties, notably  $Y_{500}$  and  $M_{500}$ , which in some cases are substantially lower than the original *Planck* estimates. Consequently, several clusters shifted to different  $(z, Y_{500})$  boxes or even below the initial selection range. To account for these variations, we slightly redefined the LPSZ box boundaries, i.e., the effective selection function. The final distribution of the LPSZ sample in the  $Y_{500}$ -redshift plane is shown in Fig. 1.

We used the NIKA2 dual-band millimetre camera<sup>3</sup>, operating at 150 and 260 GHz on the IRAM 30-m telescope, to obtain high-sensitivity SZ maps for the full LPSZ sample. The data were processed with a dedicated reduction pipeline that performs detailed noise characterization, filtering transfer functions, and ensures rigorous control of systematic uncertainties.

<sup>3</sup>under the IRAM project numbers 199-16 and 171-22.

Pressure profiles were derived using the `panco2` pipeline<sup>4</sup> [6], while SZ fluctuation analyses were conducted with the `pitszi` pipeline<sup>5</sup> [7].

### 3 LPSZ results and Public release

LPSZ data were first used in the context of individual cluster analyses. In [22] we have evaluated the implication of cluster substructures for the pressure profile and mass estimate, applied in the case of PSZ2 G144.83 that is the first SZ mapping of a LPSZ cluster. In [23], we published the data of ACT-CL J0215.4, the most challenging cluster to analyze (low mass, high redshift, and contaminated by point sources). We presented an analysis method that accounts for point sources directly within the likelihood function used in the MCMC. In [24], we studied the impact of systematic effects on mass reconstruction in the case of the CL J1227 cluster. Comparison with lensing data allowed us to estimate the hydrostatic bias. In [25], we showed that the cluster ACT-CL J0240 is a disturbed system for which we provided a robust and accurate estimation of the hydrostatic mass. In [26], we have presented a comparison between the hydrostatic and lensing mass profiles of the cluster MACS J0647.7+7015 and found significant variation in the cluster mass estimate depending on the observable, the modeling of the data, and the knowledge of the cluster's dynamical state.

The public release and the scientific results are presented in a series of publications.

- In [8], we describe the methods and the product associated with SZ map-making. We present the flux density maps at 150 and 260 GHz, transfer functions, null maps and covariances matrices.
- In [9], we present the catalog of the 261 point sources detected at either of the two wavelengths. We compare number counts in the vicinity of clusters with blank fields and present evidence for a gravitational lensing effect.
- In [10], we present the thermodynamic profiles and the integrated quantities ( $Y_{500}$  and  $M_{500}$ ) for the full LPSZ cluster sample, obtained from a combination of NIKA2 and *XMM-Newton* or Chandra data.
- In [11], we introduce a new method to estimate the universal pressure profile, accounting for individual errors and intrinsic dispersion. We show the impact of this universal profile on cluster cosmology.
- In [12], we developed a dedicated calibration method to infer the SZ–mass scaling relation, accounting for selection function and the intrinsic scatter. We show the impact of this new scaling relation on cluster cosmology.
- In [13], we present the measurement of SZ fluctuations in galaxy clusters, providing the first estimate of the mean pressure fluctuation power spectrum from a cluster sample.
- In [14], we use Zernike Polynomials to model cluster morphology and to infer their dynamical state.

All science-ready products will be available on the IRAM webpage<sup>6</sup> and on the LPSZ one<sup>7</sup>. This includes: SZ NIKA2 maps, thermodynamic profiles, and integrated quantities, point sources, SZ NIKA2 map noise properties as well as universal pressure profile, mass-SZ scaling relation, cluster classification and mean pressure fluctuation power spectrum.

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<sup>4</sup><https://github.com/fkeruzore/panco2>

<sup>5</sup><https://github.com/remi-adam/pitszi>

<sup>6</sup><https://oms.iram.fr/>

<sup>7</sup><https://lpsc.in2p3.fr/NIKA2LPSZ/>

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