KID instrumentation & NIKA2 experiment

The KID@IN2P3 Team

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The NIKA2@IN2P3 Team

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Activités KID

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1. Abstract

The goal of this document is to present the R&D activities on Kinetic Inductance Detectors (KID) and related instrumentation within the IN2P3 laboratories (APC and LPSC).

The Grenoble collaboration (Institut Néel, LPSC, IPAG and IRAM) has pioneered the utilization of Kinetic Inductance Detectors (KID) at millimeter frequencies and it has been consolidated through a GIS (groupement d'interet scientifique). Today, all these laboratories participate in preparing the next generation instrument based on KID technology in different scientific domains.

The NIKA2[Adam et al. (2018)]]. and CONCERTO [Concerto collab. (2020)]. instruments are installed at IRAM 30-m telescope at Pico Veleta, and in APEX 12m-telescope in Atacama desert respectively and they represent the state-of-the-art of millimeter science KID-based facilities worldwide. In a parallel development, APC and GEPI (Observatoire de Paris) have designed and tested KID for the SPIAKID project in the visible and NIR bands for spectro-photometric imaging.

2. Scientific Context

During the last two decades, Cosmic Microwave Background observations from space (most recently by the European Space Agency's Planck satellite [Planck Collaboration et al.(2019)] but also with several balloon-borne and ground-based instruments as for example BOOMERanG, MAXIMA, Archeops, Dasi, QUaD, ACT, POLARBEAR, BICEP to cite some of the most prominent experiments) have significantly increased our understanding of the standard model of cosmology, allowing percent constraints on the cosmological parameters. Nonetheless, the current model remains incomplete. The nature of dark energy and dark matter is still unknown. The current expansion rate (H0) of the Universe measured using the cosmic distance ladder and time delay of gravitationally lensed quasars is discrepant at the 5 σ level with the one inferred from observations of the early Universe. The amplitude of matter fluctuation (σ8) measured from clusters of galaxies and galaxy surveys is in tension with the one predicted from the CMB [Planck Collaboration et al.(2019)]. Cosmology seems to be at the edge of a crisis, and one way to reveal new physics beyond the standard model is through the advent of the new generation spaceborne experiments and of high resolution ground based CMB telescopes.

The next generation of experiments therefore must not only achieve higher precision and make an unambiguous detection of inflationary B-modes, but eventually also precisely measure the distortion of the CMB spectrum which is becoming an important and complementary tool. By distortions we mean those produced from the out-of-equilibrium energy exchange between matter and radiation before the last scattering surface and through the inverse Compton scattering by high-energy electrons in galaxy clusters. In this case, the low-energy CMB photons receive an overall energy boost during collisions with the high-energy cluster electrons (Sunyaev–Zel'dovich effect). Based on these scientific motivations, several ground-based experiments such as ACT [Salatino(2017)], BICEP3/Keck Array [Bischoff(2018)], SPT [Pan(2019)] and Polar Bear [Lee et al. 2008] have been deployed, and future ground-based CMB Stage-4 experiments [Keating(2019)], Simons Observatory [Ade et al. (2019)] and space mission LiteBIRD [Lee et al.(2019)] are under construction. Current experiments have a focal plane on the order of several 10,000 detectors which improves the mapping speed by at least one order of magnitude in comparison to that of the first generation precision cosmology experiments.
In this context, new generation cryogenics detectors Kinetic Inductance Detectors (KID) are now mature enough to answer to these challenges in particular thanks to their sensitivity, the assembly simplicity, and the possibility to arrange them in in large arrays. KIDs are a particular type of non-equilibrium superconducting photon detector, where incident radiation is absorbed in a superconducting material which is arranged in a resonant circuit. They were first developed by Peter Day and other scientists at the California Institute of Technology and the Jet Propulsion Laboratory in 2003 [Day et al.(2003)]. The primary attraction of KIDs is that, unlike most of the other low temperature detectors, they present several advantages:

- Easy to fabricate, in most cases, a single layer deposition is sufficient (a week is necessary to make them, two weeks to test them, compared with other technologies where the lifecycle is more like a year)
- Very sensitive, reaching the photon noise limit for most applications.
- They can be used in a very broad band.
- Fast, with a small time constant (from tens of microseconds to hundreds of microseconds) for a large range of optical loads.
- Highly multiplexed (which means that making large arrays is simple).
- Relatively insensitive to micro-phonics and Electromagnetic interference (EMI).
- Very low sensitive to the base temperature fluctuations

In order to absorb incident millimetre and submillimetre radiation, it is necessary to match the impedance of the detector absorber to free space. In the case of KIDs developed by our collaboration we use *Lumped-Element* KID (LEKID) where the inductive meander section is designed to act as a solid absorber for the target frequencies. By accounting for the resonator and substrate impedance and the cavity formed with the sample holder, it is possible to directly impedance match the LEKID to free space [Doyle et al.(2010)].

3. Project

Our development is driven by the scientific cosmological context as expressed in the previous section. In this direction we have both a fundamental R&D on the detectors-readouts, and an instrumental program in order to develop and optimize photometers, polarimeters and interferometers devoted to observe galactic polarization and CMB B-modes (NIKA2 and ongoing discussions on a participation to the Simons Observatory/Stage-4 network), distortion of the CMB spectrum via the S-Z effect (NIKA2, KISS and CONCERTO) and intensity line mapping (CONCERTO).

From an instrumental point of view, in order to be competitive for the future challenges, this involves four areas of development in the case of KID technology:

1. Development of a large-scale focal plane with tens of thousands of photon noise-limited detectors.
2. Developments of low energy consumption reading electronics with very high multiplexing factors.
3. Large optical elements (mirrors and lenses).
4. Very good control of systematic errors induced by the technology.

To better monitor each of these points, we have both a fundamental R&D on the detectors, readouts and annex instrumentation. Considering the sensitivity of existing CMB-dedicated ground-based experiments such as ACT, BICEP2/Keck, SPT and expectations for upcoming CMB Stage III and Stage IV experiments, characterized by of order 10,000 detectors as the Simons Observatory and the LAT experiments, it is obvious that access to an experiment with the same order of detectors will be needed to remain at the forefront of CMB science. While it is not the case in the US, in France, for the 120 to 350 GHz frequency range, Kinetic Inductance Detectors (KID) are currently the most advanced solution in terms of technology readiness. This has been shown thanks to the NIKA2, 3k-pixel camera and CONCERTO, 4k-pixel spectro-imager, that KIDs can have Background Limited Instrument Performance (BLIP) for ground-based applications. The final goal of all this development is directly related to the preparation of the next generation instruments for a timescale of 7-8 years. In particular we can identify:

- ***Short-term goal*** *(2023-2025)*: maintaining activity with existing instrument NIKA2, CONCERTO ensuring upgrades to increase the performances.

- ***Mid-term goal*** *(2023-2028):* upgrade the KID technology and the annex instrumentation to rise the technology readness level of the technology in millimetric, visible and NIR domain.

- ***Long-term goal*** *(2023-2032):* be ready to answer to the expectations of the S4 network. Be a valid candidate for covering the focal plane of the next generation space mission devoted to the CMB B-modes of polarization or/and CMB spectral distortions.

Together with the development directly related to the KID, we study also all the aspect related to the readout and more in general the instrumentation. In particular we can distinguish three axes of objectives that we want pursuit as follows:

1. KID **Detectors**
2. KID cold and warm **Readout**
3. **Instrumentation** (Silicon Lenses, Acquisition software, tech-bench for laboratory characterization, etc…)

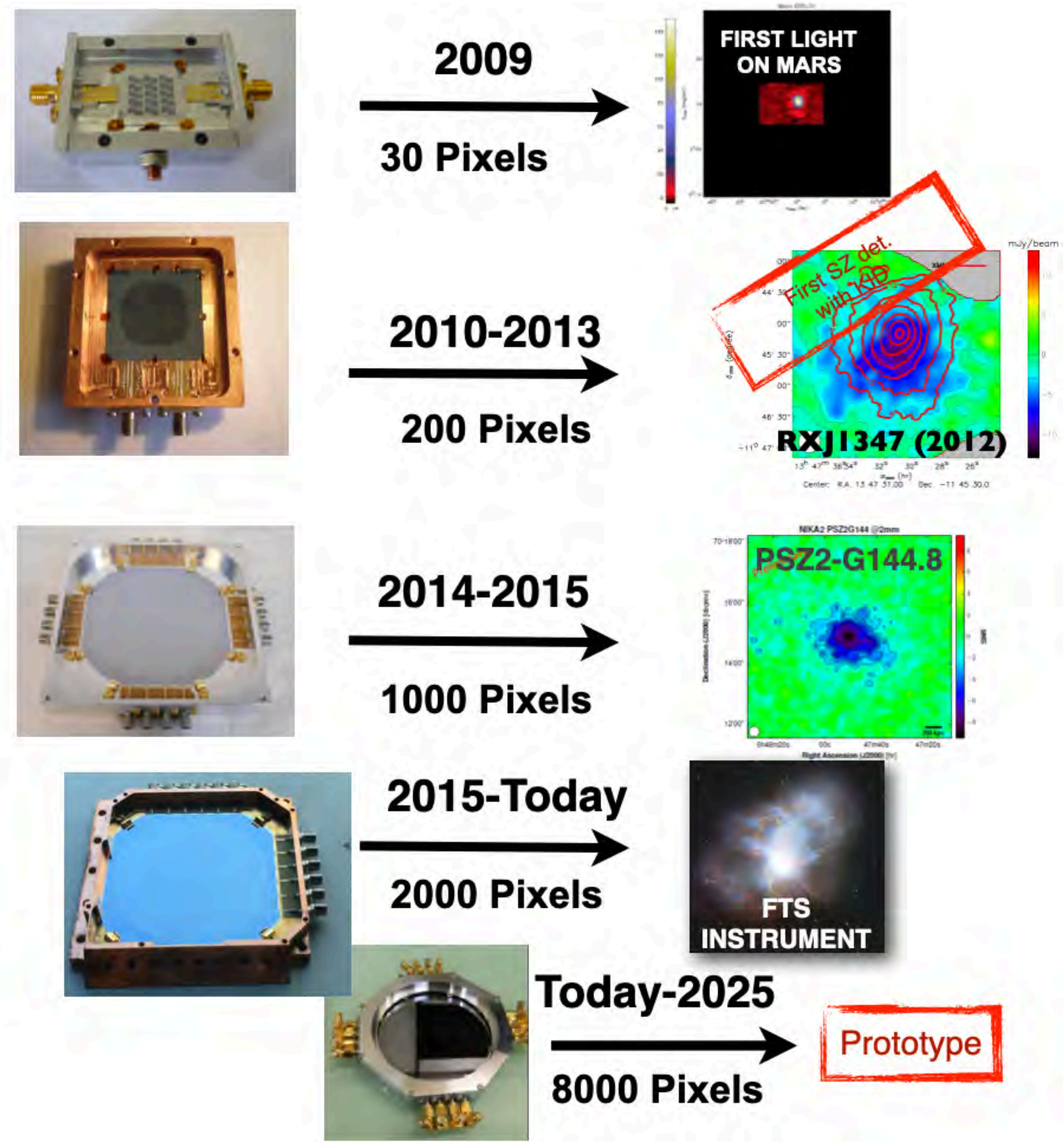

Fig.1: KID array development during the last 14 years. From the first 30-pixel prototype of 2009 which has observed a first light at IRAM 30m telescope through the 200 pixels NIKA1 array which has performed the first observation of the Sunayaev-Zel'dovich effect with KID, up to the last 10k-pixels prototype fabricated and tested in our lab.

4. Genesis and Calendar

For about 25 years, *IPAG*, *LPSC*, *Institut Néel* and *IRAM* have collaborated on leading projects in millimetric astronomy and cosmology. Our expertise in operating telescopes, cryogenics, nanotechnologies, electronics and data analysis have enabled us to carry out successful projects on ground (Diabolo, NIKA and NIKA2), on balloon (Archeops) and satellite (Planck).

For the next years our plans, already expressed in several forms (as for example CNES working group on mm and sub-mm LEKID and instrumentation, Labex FOCUS road map and IN2P3 *prospectives* 2030) are to extend our range of action both in the frequency coverage (60-1500 GHz, from the present 80-500 GHz) and in dynamic range (space and ground conditions). We also work on the different architectures of the planar antennas coupled with KID (antenna-coupled KID) in order to reduce the size of the focal plane and to be directly sensitive to polarization. We complement these studies by our "spectroscopic" work carried on in parallel and described in this document. In parallel to these studies which are essentially focused on single pixel optimization, we transfer our knowledge on bigger arrays of detectors (of the order of few 10k-pixels).

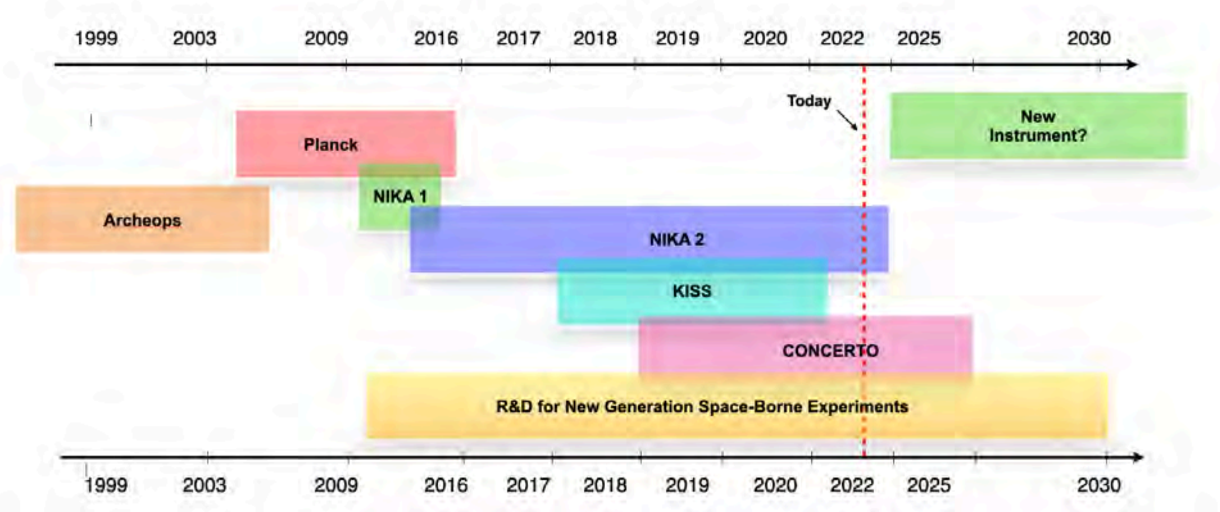

Fig.2: historical timeline of the instruments developed by the GIS-KID collaboration.

5. State of the Art

KID for astrophysics and cosmology is one of the most active areas of research, with several groups in Europe, United States and Japan actively developing detectors and KID-based instruments. Today, several instruments observe the millimetre sky using large-format focal plane arrays. A number of projects operating at millimetre (TolTEC [Toltec web page], SuperSpec [Shirokoff et al. (2014)], GroundBIRD [Nagasaki et al. 2018], OLIMPO [Paiella et al.2020]) and submillimetre (AMKID [Baselmans J. 2018], Deshima [Takekoshi et al. 2020], BLAST-TNG [Galitzki et al (2014)]) wavelength. The first instrument making science with KID was the first prototype, NIKA, detecting the cluster of Galaxy RX J1347.5-1145 via the Sunyaev Zel'dovich effect in February 2012 [Adam et al. 2014]. This instrument was designed, fabricated and exploited by our collaboration.

To date, experiments designed specifically to measure the CMB have been led by instruments based on arrays of transition edge sensors (TESs) [Benson et al. 2014, Thornton et al. 2016]). State-of-the-art CMB experiments are at *Stage 2-3*, with focal planes containing 5000–10,000 TES. KID are coming into play in particular thanks to the discussions in progress for a participation of our collaboration in the Stage-4 network. Further improvements in sensitivity can only be achieved by increasing total focal plane area and number of detectors which is a significant technological challenge. The advantages of KIDs could therefore play an important role in this sense.

6. Funding and People Involved

The R&D activities related to the KID have obtained several funding over the years. In particular we have received support for the CNES through the R&T budget and Labex (FOCUS and ENIGMASS). NIKA2 instrument has been funded by ANR and the IRAM. CONCERTO has been funded by an ERC program.

The IJCLAB is potentially interested to join this collaboration but they do not currently hire technical staff but participates to discussions for the definition of a proposal for a hardware contributions. It will re-evaluate its participation in the KID master project in the coming months with a view to it being part of such a future joint project effort.

Chercheurs IN2P3

Nom	Prénom	Laboratoire	Statut
Catalano	Andrea	LPSC	CR
Macías Pérez	Juan	LPSC	DR
Piat	Michel	APC	PR

Chercheurs hors IN2P3

Nom	Prénom	Laboratoire	Statut
Monfardini	Alessandro	Institut Néel (GIS-KID)	DR

Ponthieu	Nicolas	IPAG (GIS-KID)	CR
Driessen	Eduard	IRAM (GIS-KID)	Senior Researcher
Désert	Xavier	IPAG (GIS-KID)	Astronomer

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Nom	Prénom	Laboratoire	Statut
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Tourres	Damien	LPSC	IE
Marpaud	Julien	LPSC	IE
Marton	Marc	LPSC	IR
Hoarau	Christophe	LPSC	IR
Bounmy	Julien	LPSC	IR
Chapron	Claude	APC	IR
Prêle	Damien	APC	IR
Thermeau	Jean-Pierre	APC	IR
Voisin	Fabrice	APC	IR
Torchinsky	Steve	APC	IR

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Garde	Gregory	Institut Néel (GIS-KID)	IE
Boussaha	Faouzi	GEPI	IR

7. Technical realisations

IN2P3 has a strong implication on these activities. In particular in terms of direct costs (personnel, equipment, maintenance, etc...) several engineers and scientists are involved in this R&D in particular at LPSC and APC. The critical parts of the developments described in this document are designed and often fabricated in-house. The fabrication of the most challenging sub-systems will be done in our labs by our highly-skilled technical groups. Local subcontractors will be in charge of the standard (lower cost and risk) mechanics and electronics subsystems. This makes the cost of this development plausible. We think that it is very important that the French community maintains and develops its expertise on CMB science related instrumentation. Few key persons are still in a non-permanent position therefore there is a high risk coefficient that skills are lost in the years to come. In addition, the growing number of projects requires a growing man-power.

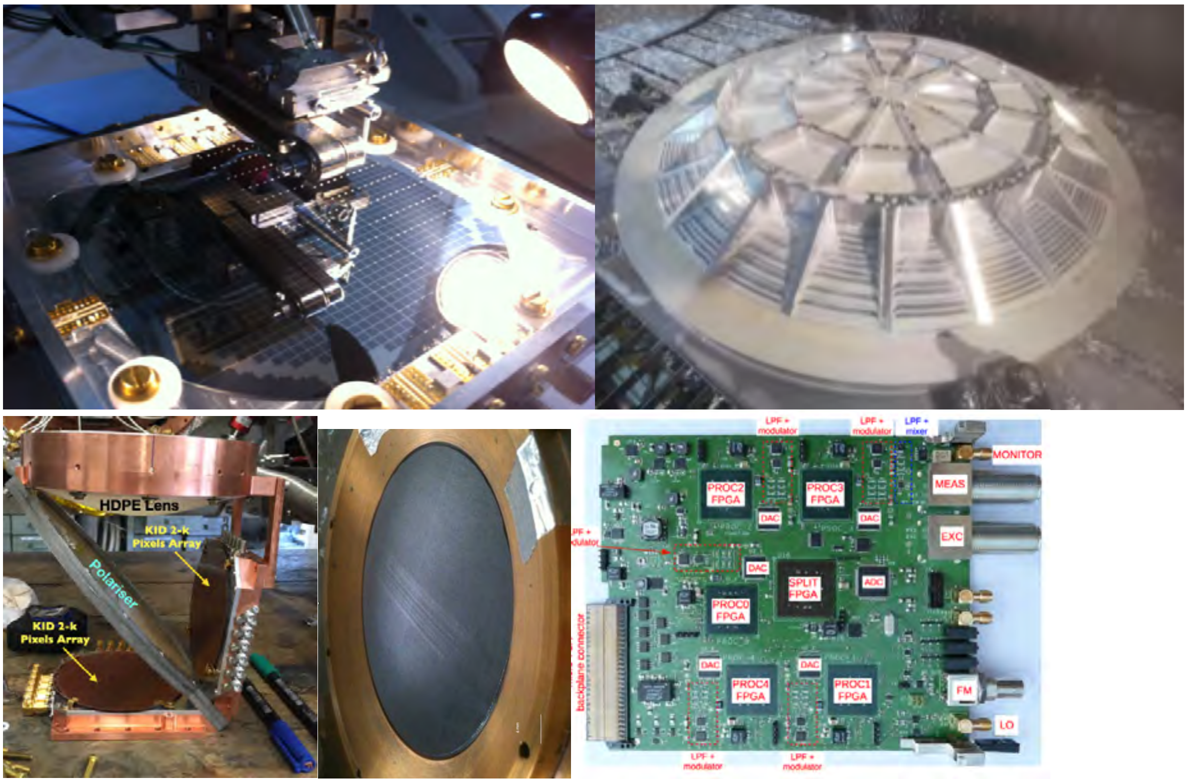

Fig.3: Examples of different realization realized within our collaboration:

-Top left : NIKA2 k-pixels array. It has been fabricated at the "Plateforme Technologie Avancée" (PTA) at the CEA-Grenoble.
-Top right : Concerto Mirror M8 designed by GIS- Collaboration and fabricated at the LPSC workshop.
-Bottom left : 100mK block containing copper mechanics, two K-pixels KID arrays, a polarizer at 45 degrees and a high density polyethylene lens. All these sub-systems have been designed and fabricated between LPSC and Néel Institut.

-Bottom centre : a prototype of a silicon lens developed as R&D at the LPSC.
-Bottom right: Warm electronics of the KID developed by the electronics service of the LPSC.

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NIKA2 experiment

NIKA2 is a millimeter camera installed on the 30-meter telescope of the IRAM (Institut de Radio-Astronomie Millimétrique) to shed new light on a wide range of astrophysics and cosmology fields. The covered areas of study range from planetary and stellar formation and their evolution with respect to redshift or environment, to the emission properties of galactic dust and magnetic fields, the cosmic evolution of the Dusty Star-Forming Galaxies population up to the epoch of reionization, and the physics of galaxy clusters as cosmological probes of the formation of large structures and the evolution of the universe.

1 The NIKA2 project

NIKA2 is equipped with 2900 kinetic inductance detectors (KID) distributed in 3 arrays to observe simultaneously in two frequency bands centered at 150 and 260 GHz, with an angular resolution of 17.6 and 11.1 arcseconds, respectively (Adam et al. 2018; Perotto et al. 2020). The focal plane and internal optical elements are cooled to 100 mK to ensure a sensitivity reaching 9 and 30 mJy $\cdot$ $s^{1/2}$ at 150 and 260 GHz. As an indication, a point-like source with a flux of one mJy at the center of the map can be detected at a 3σ level within less than 3 hours in both frequency bands in average atmospheric conditions. Additionally, NIKA2 is equipped with a rotating half-wave plate and a polarizer, providing polarization capability at 260 GHz.

In the landscape of high-angular-resolution millimeter experiments (better than one arcminute), NIKA2 presents several unique characteristics. Firstly, it surpasses the mapping speed of its pathfinder instrument, NIKA, a KID-based millimeter camera installed on the IRAM 30-meter telescope between 2012 and 2015 (Monfardini et al. 2010; Catalano et al. 2014), by an order of magnitude. Furthermore, it represents a breakthrough compared to previous experiments, including GISMO (Staguhn et al. 2011), its predecessor at the IRAM 30-meter telescope, which observed at 150 GHz with lower sensitivity, as well as the Large APEX BOlometer CAmera, LABOCA (Siringo et al. 2009) or SCUBA-2 (Holland et al. 2013) on the James Clerk Maxwell Telescope (JCMT). Among current experiments, MUSTANG-2 installed at the Green Bank 50-m Telescope and capable of observing at 90 GHz with a 9 arcsecond resolution complements NIKA2 interestingly, as well as CONCERTO (Lagache 2018), the millimeter spectrometer installed on the 12-meter APEX telescope, which also benefits from the involvement of IN2P3 and offers spectral resolution opening up interesting synergies with NIKA2. Other sub-arcminutes angular resolution millimeter instruments include TolTEC on the Large Millimeter Telescope Alfonso Serrano (LMT Wilson et al. 2020, ;) and CCAT-Prime (Duell et al. 2020) currently in construction. At even higher angular resolutions, other synergies exist with the Atacama Large Millimeter/submillimeter Array (ALMA, Hills & Beasley 2008) and NOEMA. Thus, NIKA2 has no direct competitors until 2030.

After the instrumental success and the demonstration of scientific potential by the NIKA pathfinder (e.g. Adam et al. 2014), NIKA2 was selected by IRAM in 2014 to become the permanent imaging instrument on the 30-meter telescope. Like NIKA, NIKA2 was constructed by Institut Néel, IRAM, Cardiff University, and LPSC (Roesch et al. 2012; Doyle et al. 2008; Calvo et al. 2013; Shu et al. 2018). In particular, LPSC developed the readout and excitation electronics for the KID arrays, allowing optimal utilization of the multiplexing capabilities offered by this technology (Bourrion et al. 2012, 2016). Starting from late 2015, NIKA2 was installed on the 30-meter telescope and underwent an extensive commissioning and testing period to optimize the instrumental setup and characterize the instrument under real conditions (Adam et al. 2018). After a phase of commissioning, scientific verification, and performance characterization led by LPSC, NIKA2 was delivered to IRAM in September 2017, opening it to the community in October 2017 (Perotto et al. 2020). Since then, scientific observations of interest have been continuously carried out for 6 years, with approximately ten observation campaigns per year. In parallel, the commissioning and performance characterization in polarization took place between 2017 and 2022, the polarized observation of science interests started in January 2022 within the collaboration, and the opening of NIKA2 in polarized mode (NIKA2Pol) to the community is expected next year. NIKA2 is expected to continue observations on the 30-meter telescope at least until 2027, with potential instrument improvements currently under evaluation within the collaboration.

1.1 NIKA2 polarization

The LPSC team has been key in the development of polarisation within the NIKA and NIKA2 collaborations. Both for NIKA and NIKA2 we have taken in charge, under the coordination of A. Catalano, the design and construction of the polarisation modulator based on a rotating half-wave plate (see Pisano et al. (2022) for more details in the HWP). This was possible thanks to the excellent contributions of the SERM, SDI and electronic workshops. Furthermore, during A. Ritacco PhD thesis the polarisation data processing pipeline for NIKA and NIKA2 was developed in collaboration with the IPAG team. This allowed us to obtain first ever scientific results in polarisation with KID filled arrays (Ritacco et al. 2017, 2018). Recently, the team has been also deeply involved in the commissioning of the NIKA2 polarisation facilities (Ritacco et al. 2020), which has also allowed us to obtain first scientific results (Ritacco et al. 2022). These excellent results have motivated IRAM to start observations of the B-FUN project, and we expect a call for polarisation open times to be opened next year.

2 The NIKA2 collaboration

The NIKA2 collaboration is responsible for the construction, commissioning in intensity and polarization, performance characterization, maintenance, and instrument upgrades. This collaboration brings together world-renowned specialists in instrumentation, data analysis, and scientific interpretation in astrophysics and cosmology, with a total of 163 researchers and engineers from 33 Institutes across 9 countries (France, Spain, Italy, Ireland, Belgium, Greece, UK, Iran & USA). In France, NIKA2 mobilizes 112 specialists from 13 laboratories affiliated with IN2P3, INSU, CEA, INP and IRAM. France holds the majority of leading responsibilities, with a strong contribution from IN2P3. The NIKA2

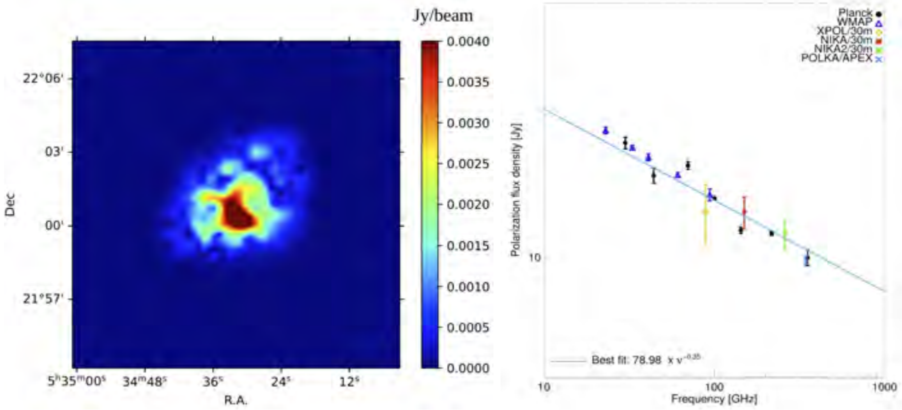

FIGURE 1 – Left : NIKA2 polarized intensity map of the Crab nebula obtained from NIKA2 observation at 260 GHz during the commissioning campaign of November 2020. Right : spectral energy distribution obtained by previous measurements accounting for the new value obtained from NIKA2 (green). Figure from Ritacco et al. (2022)

collaboration is led by the Principal Investigator, Alessandro Monfardini at Institut Néel (INP), and the Project Scientist, Juan-Francisco Macías-Pérez at LPSC (IN2P3). The data usage, delivery, and publication of results are organized by an Editorial Board, chaired by Laurence Perotto at LPSC (IN2P3), and including a representative from each of the contributing institutes. The majority of construction, commissioning, data analysis, and result interpretation activities take place within the Core Team, which comprises about forty specialists from all partner institutes.

As compensation for the construction and commissioning of NIKA2, IRAM guarantees the collaboration 1,300 hours of observation time on the 30-meter telescope. The collaboration has decided to allocate this guaranteed time to ensure a balance between flagship scientific objectives in millimeter astrophysics and cosmology. Accordingly, 600 hours have been allocated to two major cosmology programs : the Large Program for resolved observation of galaxy clusters via the Sunyaev-Zel'dovich effect (LPSZ, 300 hours, led by F. Mayet (LPSC) & L. Perotto (LPSC)), which will be the focus of Sect. 4 and the NIKA2 Cosmological Legacy Survey (N2CLS, 300 hours, led by G. Lagache (LAM), A. Beelen (LAM) & N. Ponthieu (IPAG)), which aims to observe Dusty Star-Forming Galaxies at very high redshifts in two reference deep fields (Bing et al. 2023). The remaining 700 hours are distributed among three major programs of interest in galactic astrophysics : the Galactic Star Formation with NIKA2 program (GASTON, 300 hours, led by N. Peretto (Cardiff)) for the observation of the galactic plane and two galactic regions with high star formation rates (Peretto et al. 2020, 2022), the Interpreting the Millimeter Emission of Galaxies with IRAM and NIKA2 program (IMEGIN, 200 hours, led by S. Madden (CEA)) for the observation of 22 nearby galaxies (Katsioli et al. 2022), and the Probing the B-Field in Star-Forming Filaments Using NIKA2-Pol program (B-FUN, 200 hours, led by P. André (CEA)) dedicated to polarization observations of magnetized galactic filaments (Ajeddig et al. 2022).

Each of these large programs is led by 1 to 3 principal investigators who organize the observations, data analysis, and publication of results after an internal review within

Name		Laboratory	Current	Role &
Last	First		Position	responsabilities
Current NIKA2@IN2P3 Cosmology Team				
Catalano	Andrea	LPSC	researcher (CR)	Core Team
Chérouvrier	Damien	LPSC	PhD student	Collaborator
Hanser	Corentin	LPSC	PhD student	Core Team
Macías Pérez	Juan	LPSC	senior researcher (DR)	Project Scientist
Mayet	Frédéric	LPSC	full professor (PR)	P.I. of the LPSZ
Moyer	Alice	LPSC	PhD student	Collaborator
Muñoz-Echeverría	Miren	LPSC	PhD student	Core Team
Perotto	Laurence	LPSC	researcher (CR)	Editorial Board Chair
Savorgnano	Sofia	LPSC	PhD student	Collaborator
Ruppin	Florian	IP2I	associate professor (MdC)	Core Team
Past NIKA2@IN2P3 Cosmology Team				
Adam	Rémi	OCA (INSU)	researcher (CR)	Core Team
Artis	Emmanuel	MPE Garshing (Deutchland)	post-doc	Core Team
Comis	Barbara	non-academic		
Kéruzoré	Florian	Argonne (USA)	post-doc	Core Team
Ritacco	Alessia	INAF (Italy), ENS	post-doc	Core Team
Electronics team				
Bounmy	Julien	LPSC	research engineer (IR)	Collaborator
Bourrion	Olivier	LPSC	research engineer (IR)	Core Team
Hoarau	Christophe	LPSC	engineer (IE)	Collaborator
Vescovi	Christophe	LPSC	research engineer (IR)	Collaborator
Mechanics team : Servive Étude et Réalisation Mécanique (SERM)				
Angot	Julien	LPSC	research engineer (IR)	Collaborator
Menu	Johan	LPSC	engineer (IE)	Collaborator
Roni	Samuel	LPSC	engineer (IE)	Collaborator
Roudier	Sébastien	LPSC	engineer (IE)	Collaborator
Detector team : Service Détecteurs et Instrumentation (SDI)				
Marpaud	Julien	LPSC	engineer (IE)	Collaborator
Software team				
Dargaud	Guillaume	LPSC	research engineer (IR)	Collaborator
Fulachier	Jérôme	LPSC	research engineer (IR)	Collaborator
Lambert	Fabian	LPSC	research engineer (IR)	Collaborator
Odier	Jérôme	LPSC	research engineer (IR)	Collaborator

TABLE 1 – NIKA2 team at IN2P3

the NIKA2 collaboration, and is supported by a team of co-investigators. Each LP has set priority scientific objectives and follows a programmatic schedule for publishing key papers. The observations of the four LPs using intensity-only capabilities were completed in January 2023, and they have all entered a phase of producing prioritized results. The polarization LP observations started in January 2022 and are expected to continue until 2025. The delivery of the first astrophysical and cosmological products of interest is scheduled for 2024 under the responsibility of the NIKA2 collaboration.

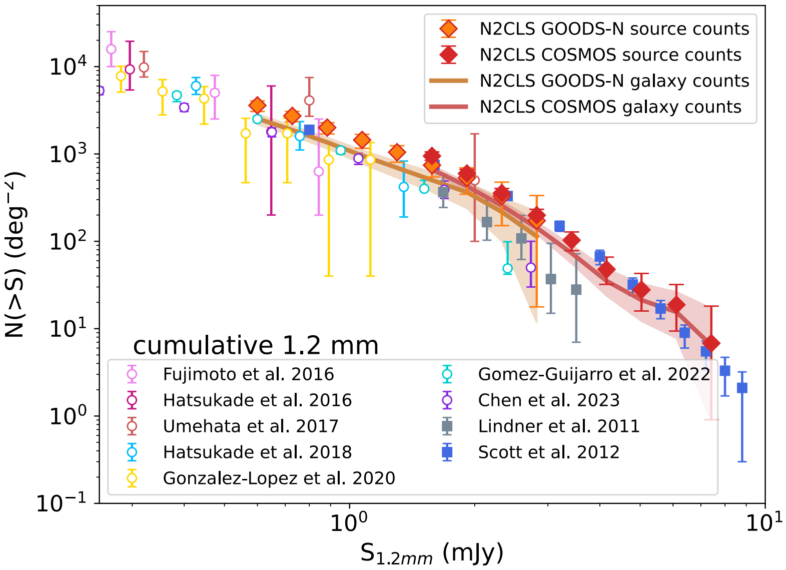

FIGURE 2 – N2CLS GOODS-N (orange diamonds) and COSMOS (red diamonds) source number counts at 260 GHz and comparison with previous results from interferometric (open circles) and single dish (filled squares) observations in the same frequency band. Results from both fields agrees within 1σ and cover the full range explored by the previous surveys in a homogeneous way. Figure from Bing et al. (2023)

In France, the strategy of multi-institute synergy between INP, INSU, IN2P3, and CEA, which forms the foundation of the successes of NIKA and NIKA2, is widely recognized. This approach has allowed us to secure two ANRs (French National Research Agency grants) : "NIKA" (ANR-15-CE31-0017), dedicated to the construction of the NIKA2 instrument, and "NIKA2Sky" (ANR-15-IDEX-02), awarded to support the scientific utilization of data from the 4 LPs (Large Programs) led by France. At the European level, NIKA2 has received support from the European Research Council Advanced Grant ORISTARS, under the European Union's Seventh Framework Programme (Grant Agreement no. 291294).

3 First scientific outcomes

The NIKA2 collaboration has already achieved and published significant initial results. Following the publication of the analysis of the first galaxy cluster mapped through the SZ effect by NIKA2 (Ruppin et al. 2018), the LPSZ conducted an analysis of the most challenging cluster in the sample, which combines low mass and high redshift (See the NIKA2 SZ map of both clusters in Fig. 3). This analysis demonstrated the feasibility of mass estimation across the entire sample (Kéruzoré et al. 2020). More recently, Muñoz-Echeverría et al. (2023b) explored the relationship between mass estimated from the thermodynamic properties of cluster gas content and the mass reconstructed from the gravitational lensing effect clusters impose on background galaxies. In the field of deep survey studies, the N2CLS program published the first number count of DSFGs (Dusty Star-Forming Galaxies) in the GOODS-North and COSMOS fields in Bing et al. (2023) (see Fig. 2). Furthermore, the initial observations of the galactic plane from the GASTON program led to the identification of 321 previously-undetected clumps, with their accretion being a crucial factor in understanding the formation of the most massive stars (Rigby et al. 2021). The IMEGIN program has already conducted the analysis of two nearby galaxies : (Katsioli et al. 2023) utilized observations of the edge-on galaxy NGC 891 to prioritize the contribution of emission processes from the interstellar medium, while the grand design face-on spiral galaxy NGC6946 was chosen for mapping the distribution of dust emission (Ejlali et al. 2022). Additionally, the initial data from the NIKA2 collaboration have spurred several follow-up studies with other instruments, resulting in publications. For instance, Bing et al. (2022) leveraged the synergy between the IRAM NOEMA and the 30-m observatories to search for high-redshift DSFR (Distant Star-Forming Regions), and the GASTON program proposes to study the star formation process by following a sample of approximately 1000 sources presented in Rigby et al. (2021) with ALMA.

The results of the NIKA2 collaboration are annually presented at major international conferences. To give only one representative example, in 2022, the recent findings from LPSZ were shared at the Moriond Cosmology 2022 conference, the 31st Texas Symposium on Relativistic Astrophysics, and the Dark Side of the Universe 2022 conference. Additionally, the LPSC has established a new series of international conferences called Millimeter Universe. Its inaugural edition [1] took place in 2019 at LPSC, with the support of the ANR NIKA2sky. Initially catering to NIKA2 data users, this conference has seen its audience expand over subsequent editions [2]. The third edition [3], scheduled for June 26-30, 2023, is returning to LPSC and is welcoming about 115 researchers from the entire millimeter domain, spanning from CMB cosmology to the physics of astrophysical objects.

4 Focus on the SZ Large Program

In this section, we provide a brief overview of the LPSZ, the Large Program led by the LPSC within the NIKA2 collaboration.

4.1 Context and Scientific Objectives

The accuracy of estimating the mass of galaxy clusters currently poses the main limitation in utilizing these tracers of the large-scale structures of the Universe in Cosmology (for a review, see Pratt et al. 2019). The tension between cosmological models inferred from the CMB power spectrum and those based on the abundance of clusters and their spatial distribution in *Planck* satellite data (Planck Collaboration et al. 2014a,b; Ade et al. 2016; Aghanim et al. 2016) could potentially be explained by systematic effects affecting the mass-observable relation (Planck Collaboration et al. 2014a) or the universal pressure

1. https ://lpsc-indico.in2p3.fr/event/1765/page/145-overview
2. https ://agenda.infn.it/event/25056/
3. https ://lpsc-indico.in2p3.fr/event/2859/page/289-conference-series

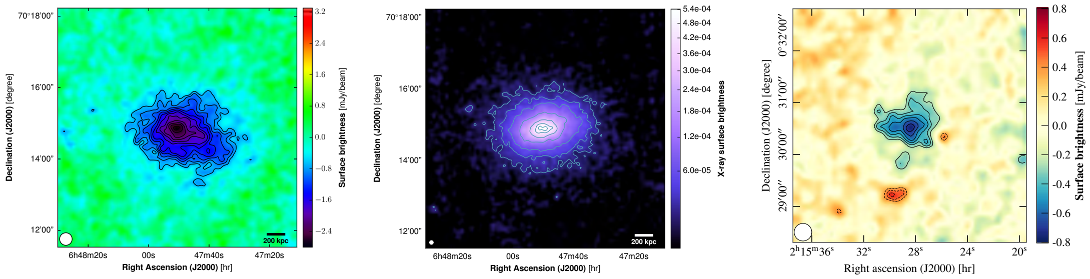

FIGURE 3 – Left : The first galaxy cluster (a.k.a PSZ2 G144.83+25.11, z=0.58) observed with NIKA2 as part of the Science Verification Phase ; NIKA2 maps the SZ effet in galaxy clusters with the same angular resolution and the same SNR as XMM-Newton space observatory does in X-Ray (center). Both figures are from Ruppin et al. (2018). Right : NIKA2 map in the 150 GHz band of the most challenging galaxy cluster (a.k.a ACT-CL J0215.4+0030, z=0.86) of the LPSZ sample. Contours show S/N levels starting from 3σ with a 1σ spacing. Resolved SZ effect is mapped with a high S/N level (shade of blue) while point-like sources partly compensate the signal (shade of red). Figure from (Kéruzoré et al. 2020).

profile of clusters (Ruppin et al. 2019). While the most recent analyses of the *Planck* data show an agreement between these two cosmological results (Salvati et al. 2018), a persistent trend for disagreement exists when considering the overall body of cluster-based studies (for a recent review, see Abdalla et al. 2022).

In this context, the LPSZ aims to measure the scaling relation between mass and the SZ observable, as well as the mean pressure profile within the intra-cluster medium (ICM), using a representative sample of approximately 35 clusters selected from the *Planck* and Atacama Cosmology Telescope (ACT) catalogs. This sample covers a broad range of masses and redshifts from 0.5 to 0.9 (Mayet et al. 2020; Perotto et al. 2022). The LPSZ leverages the unique capabilities of NIKA2, which combines a wide field of view, high angular resolution, and high sensitivity in two frequency bands, to map the SZ effect of clusters from their cores to their typical radii. This program allows for the full utilization of the synergy between X-ray and SZ observations, enabling the estimation of cluster masses under the assumption of hydrostatic equilibrium (balancing gas pressure and gravity). Additionaly, the LPSZ observations will be used for the measurement of the mean pressure profile of clusters, which is a key ingredient for accurate cosmological analyses based on the power spectrum of the SZ map. This profile will be measured by utilizing an observable directly dependent on pressure, covering the range from the typical radii of clusters to their central regions, which are not accessible to CMB experiments.

4.2 The LPSZ Team

The LPSZ, led by F. Mayet & L. Perotto, brings together 29 researchers from France (LPSC, IP2I, CEA, IRAP, IAS, LAM, OCA), Italy (La Sapienza, University of Milano), Spain (University of Madrid, IAC), and the USA (Argonne, University of Pennsylvania). Our strength lies in including specialists from all key domains for SZ cosmology : SZ, X-ray, and radio data analysis, optical follow-ups, and hydrodynamic simulations.

Another strong point is the team's ability to train or contribute to the training of PhD students who become recognized experts in cosmology and astrophysics. Since R. Adam's thesis (currently a CNRS researcher at OCA) on the SZ analysis of NIKA pathfinder data in 2013-2015, F. Ruppin (currently a MdC at IP2I) defended the first PhD thesis 100% dedicated to LPSZ in 2018, followed by F. Kéruzoré (currently a postdoc at Argonne) in 2018-2021. Four other PhD students are currently focusing a significant part of their work on LPSZ data analysis : M. Muñoz-Echeverría (LPSC), A. Paliwal (La Sapienza), C. Hanser (LPSC), and A. Moyer (LPSC).

4.3 Status and First Results

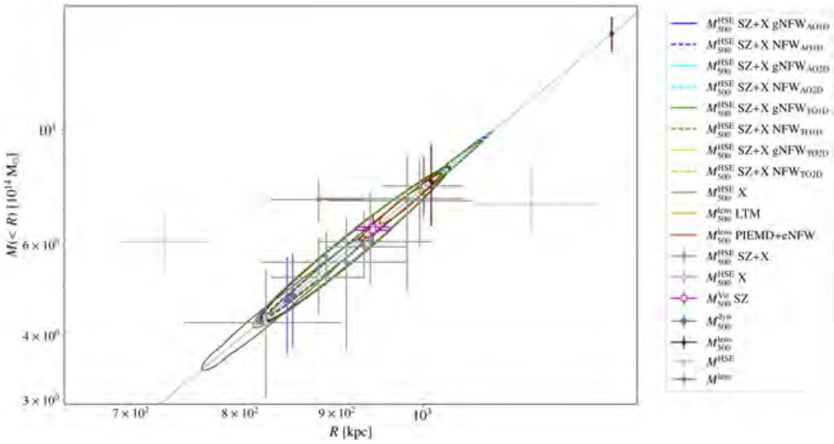

FIGURE 4 – Mass measurements of CL J1226.9+3332 cluster shown in the M (integrated masse in a sphere of radius R) vs R (integration radius) plane. Mass estimates from combining NIKA2 SZ and XMM-Newton X-ray data are shown with blue-green contours and are compared to XMM-Newton X-ray only mass estimate (grey contour) and CLASH lensing masses (orange contours). Other data points show a compilation of mass measurements for this cluster in the literature (see references in Muñoz-Echeverría et al. (2023b))

As mentioned in Sect. 3, the 300 hours of observation allocated to the LPSZ as part of the guaranteed time of the NIKA2 collaboration have been carried out between October 2017 and January 2023 and is now complete. A sample of 35 clusters has been mapped with high signal-to-noise ratio. This sample being well-distributed within the mass and redshift range covered by LPSZ, should allow us to achieve our primary scientific objectives.

Parallel to this data acquisition period, we have published the first in-depth studies of individual clusters as summarized in Sect.3. These initial studies have represented important milestones for estimating systematic effects and preparing cosmological results. Ruppin et al. (2018) investigated the impact of substructures on mass estimation, (Kéruzoré et al. 2020) developed tools to propagate uncertainties related to point source contamination to pressure profiles, and Muñoz-Echeverría et al. (2023b) demonstrated that the choice of the cluster pressure profile model is the dominant systematic effect in mass estimation compared to residual noise or large-scale angular filtering induced by data reduction. Furthermore, the method described in (Kéruzoré et al. 2020) led to the release of the public code PANCO2 (Kéruzoré et al. 2022) for pressure profile estimation from SZ maps described in Kéruzoré et al. (2023). Studies combining LPSZ observations with gravitational lensing reconstructions in the CLASH program (Ferragamo et al. 2022; Muñoz-Echeverría et al. 2023b, 2022) have demonstrated the potential of this approach for studying the hydrostatic bias, linking the mass estimated under the assumption of hydrostatic equilibrium with the true mass of clusters (See e.g. Fig. 4). Finally, to test the sensitivity of the LPSZ sample to cluster physics and deviations from the assumptions underlying cluster-based cosmology, we have constructed a series of LPSZ twin samples selected from the state-of-the-art simulation of *The Three Hundred* project (Paliwal et al. 2022). For example, Muñoz-Echeverría et al. (2023a) studied the impact of projection effects on mass estimation of LPSZ clusters. Other studies exploiting these samples are ongoing.

4.4 Deliverables and Implications for Cosmology

The production of results with implications for cosmology is well underway in the LPSZ project team. The first mean pressure profile and the first mass-observable relation obtained for a half-sample of LPSZ clusters are being validated within the LPSZ team. We expect to publicly release the main LPSZ products in 2024. This release will encompass several components : i) initial data processing products, such as frequency maps, noise characterization, and filtering, ensuring reproducibility of results and facilitating subsequent combined studies, ii) intermediate products resulting from LPSZ analysis, including a comprehensive characterization of clusters in the LPSZ sample, their thermodynamic properties, and their hydrostatic masses, iii) derived products of interest, such as a catalog of point sources detected in LPSZ maps, some of which, amplified by the lensing effect of clusters, may correspond to high-redshift galaxies, and finally iv) final products of interest for cosmology, particularly the mean pressure profile and the mass-observable relation.

Alongside the production of results, the team is preparing to investigate the implications of LPSZ results for cosmology. Specificall, we are preparing an updated cosmological analysis with the cluster number count and SZ power spectrum from Planck, incorporating the results from LPSZ. Beyond Planck and current SZ experiments (ACT, SPT), the LPSZ sample and its products of interest for Cosmology will become references for future SZ cosmological analyses based on CMB observations (SO, CMB-S4).

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