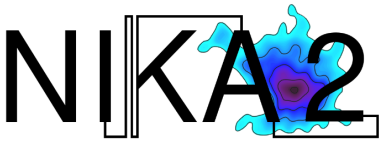
Overview of (*almost*) final results

from

the NIKA2 Sunyaev Zeldovich Large Program

F. Mayet
on behalf of the NIKA2 Collaboration



Outline

1. The need for high-resolution SZ observations of a SZ-selected sample
2. The NIKA2 SZ large program (2018-2023)
   A sample of 38 SZ-detected clusters observed in SZ and X-ray
3. LPSZ Results
   a) 160 and 250 GHz maps
   b) Thermodynamic profiles
   c) Integrated quantities
   d) Universal Pressure Profile
   e) Y-M Scaling Relation
4. Conclusions

On the Road to Public Release

Context

There is need for a SZ-selected sample of clusters of galaxies

- at medium to high redshift (0.5-0.9)
- observed with high angular resolution (10-20 ‘’)

It is useful for:

1. **cluster cosmology**
   - Universal pressure profile for SZ power spectrum
   - SZ-mass scaling relation for cluster count

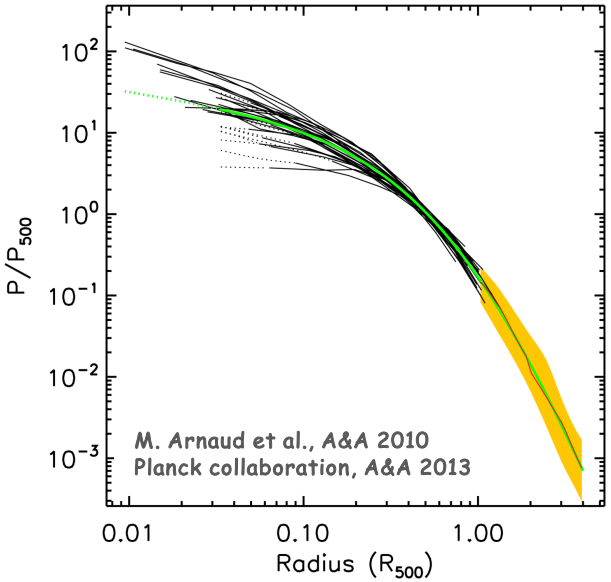
→ SZ signal is a low-scatter proxy of the thermal content (mass)

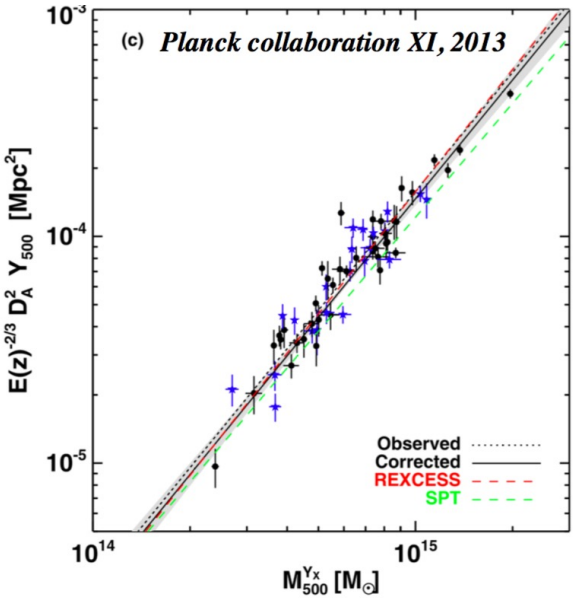
→ *Caveat: hydrostatic bias wrt the cluster mass*

→ No redshift deeming

→ SZ- X-ray synergy is major asset

$$M_{\rm HSE}(<r) \propto \frac{r^2}{n_e(r)} \frac{{\rm d}P_e}{{\rm d}r}$$



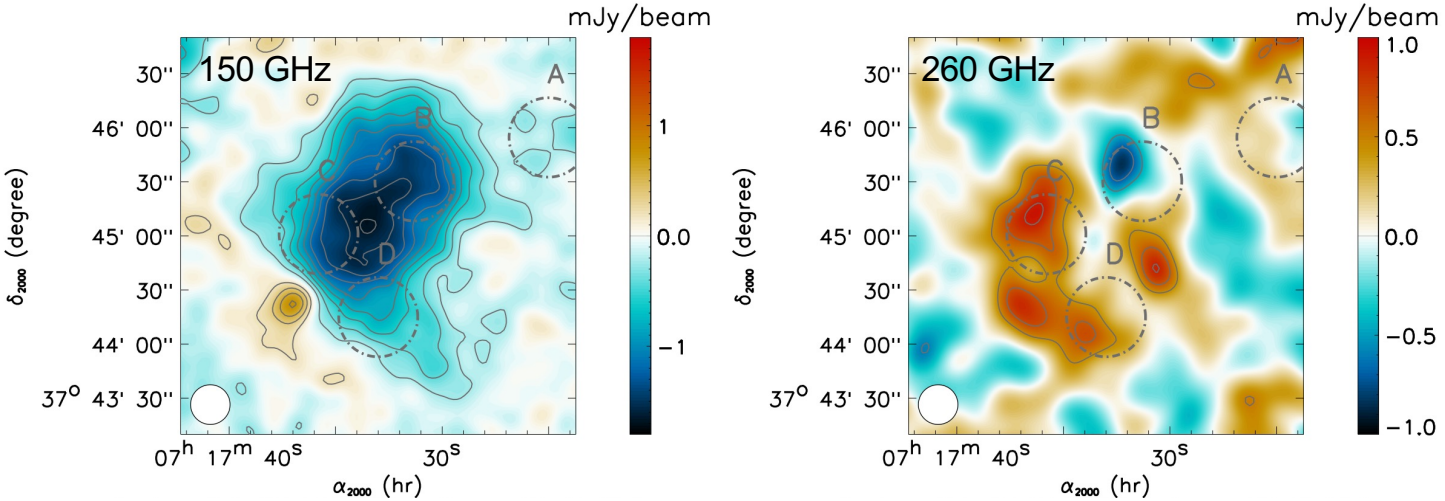


Context

It is also useful for:

2. cluster science

- Study of shocks, merging events, …
- Non-thermal pressure content
- kSZ, rSZ, …



MACJ0717.5+3745

as seen by NIKA

R. Adam *et al.*, A&A 2017

→ Needed for

- for multi-wavelength studies (SZ and X-ray, radio, visible, …)
- at similar resolution

back in 2016

(proposal)

Detector wish list for SZ science

- High angular resolution

  → to resolve inner structures

- High sensitivity

  → to reduce integration time

- Large Field of View

  → to map the whole cluster (up to R_{500})

- More than one frequency band

  → below and above 217 GHz

⇨ NIKA2

The NIKA2 camera

L. Perotto *et al.*, A&A 2020

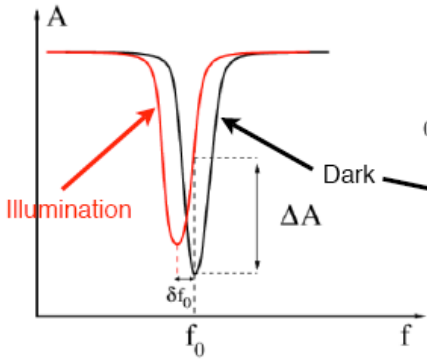
NIKA2

- KID-based camera

  Kinetic Inductance Detectors

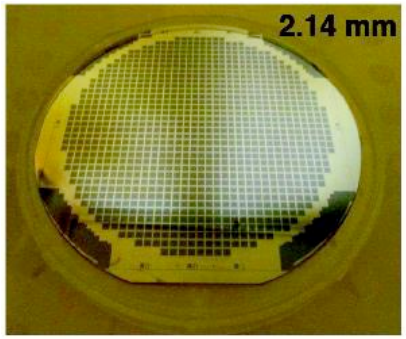
  High quality factor superconducting resonators

  Frequency shift proportional to the incoming optical power



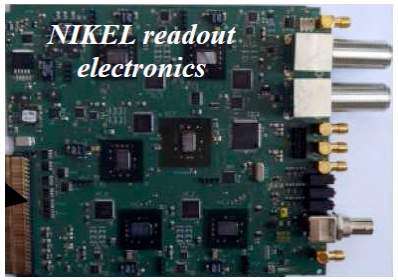
- installed at the IRAM 30m telescope
- Operated at 150 mK
- Dual-band: 150 and 260 GHz (3 arrays)
- Wide field of view: 6.5 arcmin – 2466 valid detectors
- High angular resolution: 17.6 and 11.1 arcsec
- State-of the art sensitivity: 9 and 30 mJy.s$^{1/2}$ (at null opacity)

  → high S/N observation of clusters in 2 to 15 hours



These values are measured performance: see L. Perotto et al., A&A 2020

The NIKA2 camera

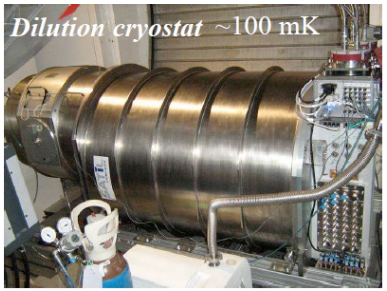


Readout electronics

KID detector

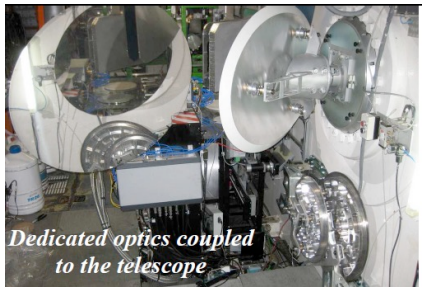
The NIKA2 camera has been built by the **NIKA2 Collaboration**

- 14 laboratories
- 110 members of the collaboration



Dilution cryostat

Dedicated optics



The NIKA2 camera

- has been installed in Sep. 2015 at the **IRAM-30m telescope** (Granada, Spain)
- **is operated since 2017**
- **is opened to the scientific community**

IRAM 30-m telescope
at Pico Veleta (Spain)

The NIKA2 Sunyaev Zel'dovich Large Program (LPSZ)

A sample of 38 SZ-detected clusters observed in SZ and X-ray

- One of the 5 Large Programs of the NIKA2 Guaranteed time
- 300 hours of observations to observe 38 clusters
- Proposal accepted in Nov. 2016 → observation completed in Jan. 2023

PI: L. Perotto & F. Mayet

The NIKA2 LPSZ sample strategy is built upon

1. **An homogeneous sample of SZ-selected clusters**
2. **SZ-X-ray synergy**

NIKA2 & XMM-Newton

NIKA2 LPSZ: cluster sample

The LPSZ sample

- 45 SZ-selected clusters
  - 10 from ACT catalog
  - 35 from Planck catalog
- 38 have been observed
- 34 with X-ray data

  (from XMM-Newton follow-ups)
- 29 with high-quality data

  → Used for SR and UPP

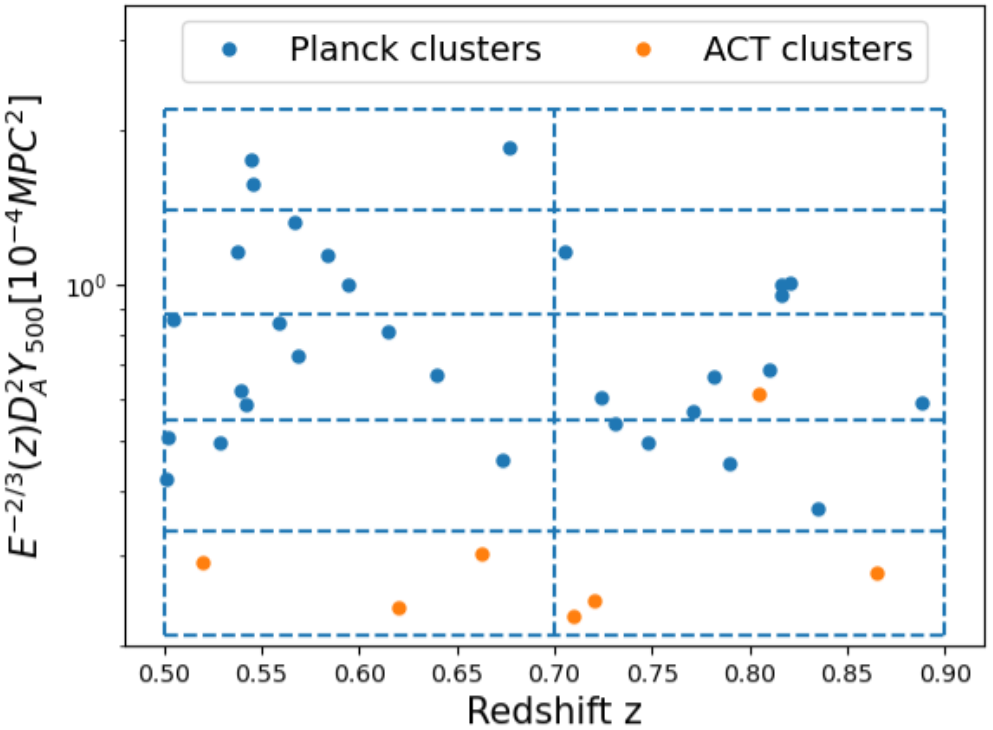
Constraints

- the sample must be representative

→Warning:

  - selection function
  - data analysis
  - data quality : S/N=3 on P(r) @ R_{500}

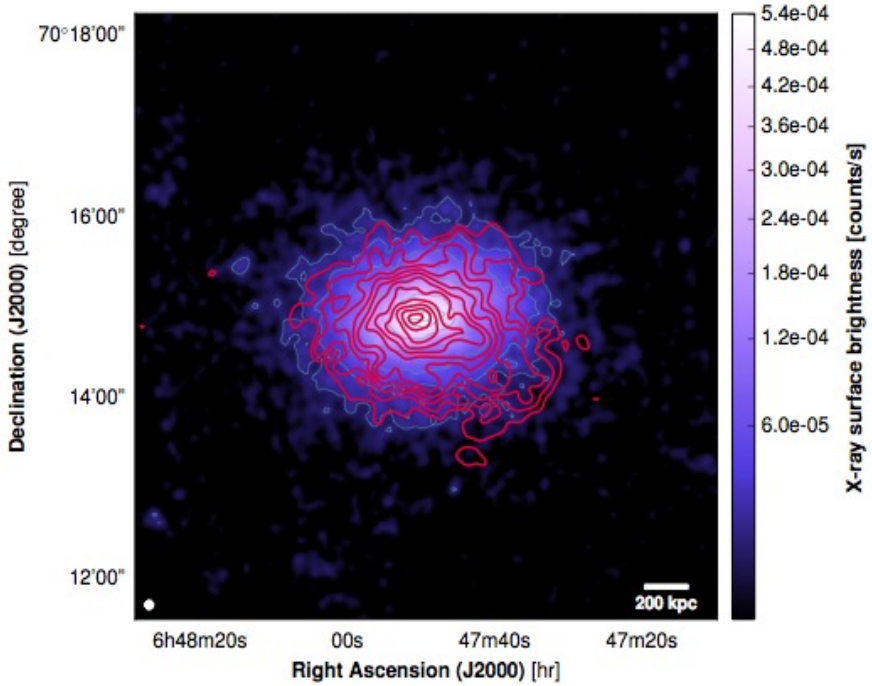
LPSZ Cluster sample



- $z = 0.5 - 0.9$
- $M_{500} = (3 - 10) \times 10^{14} M_{\odot}$

NIKA2 LPSZ: **SZ-X-ray synergy**

- 34 clusters have X-ray data (mainly XMM-Newton), from dedicated follow-up or archival
- We take advantage of high-quality SZ and X-ray data.



PSZ2-G144

- map: XMM-Newton
- contours: NIKA2

- Both angular resolution and spatial extension are comparable

→ Fruitfull combination of SZ and X-ray data

F. Ruppin *et al.*, A&A 2018

LPSZ Results

a) 150 and 260 GHz maps

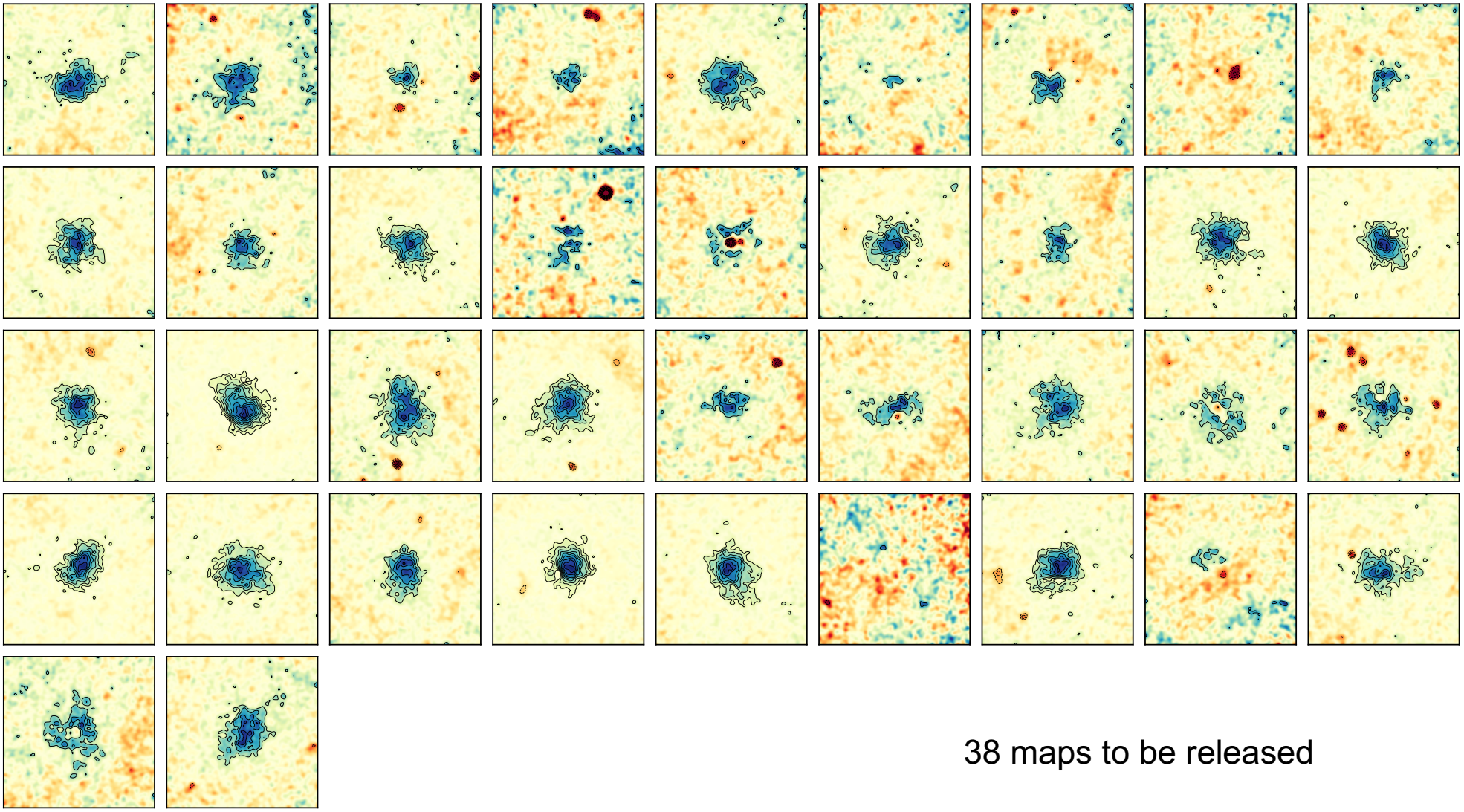
b) Thermodynamic profiles

c) Integrated quantities

d) Universal Pressure Profile

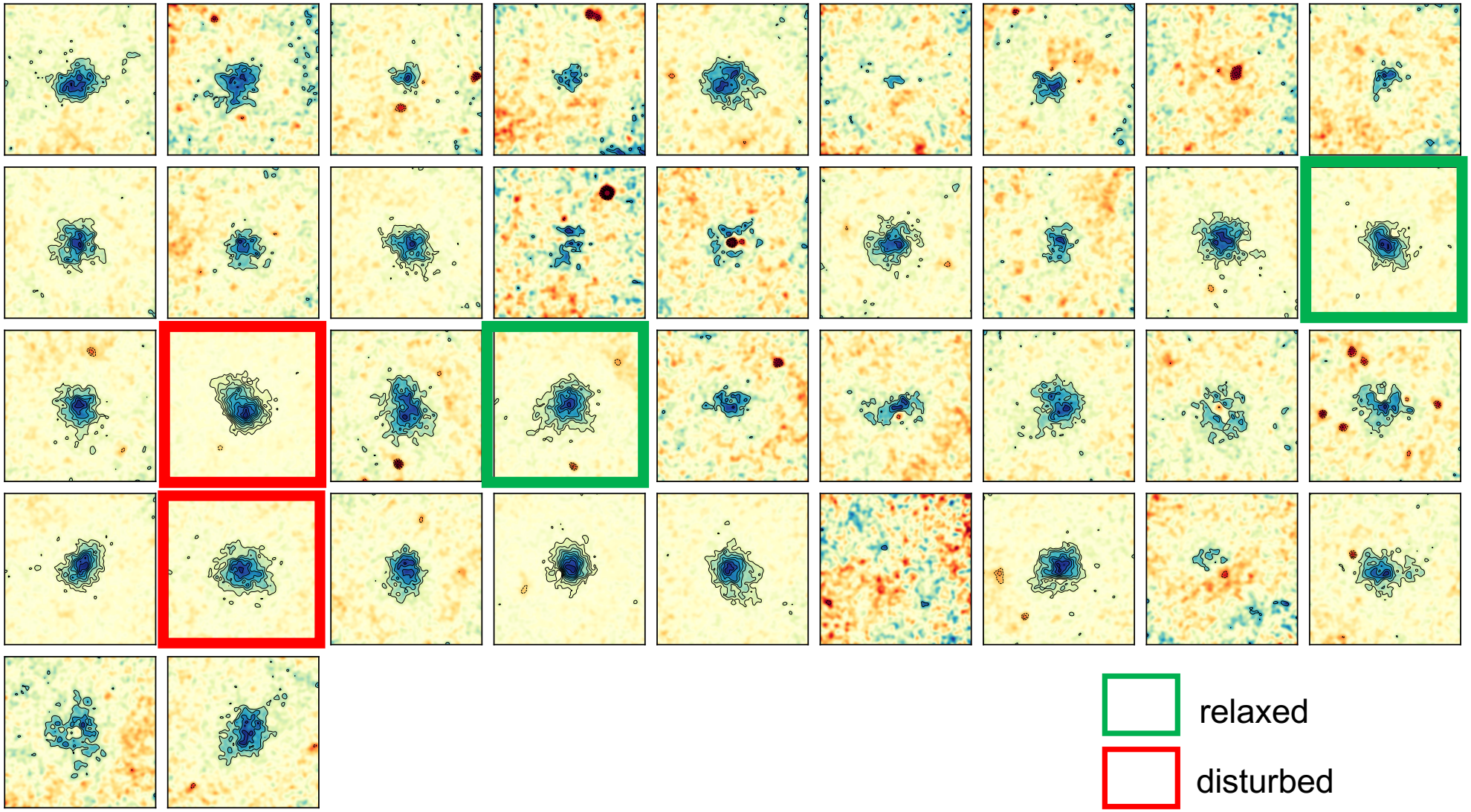
e) Y-M Scaling Relation

LPSZ results – SZ maps @ 150 GHz

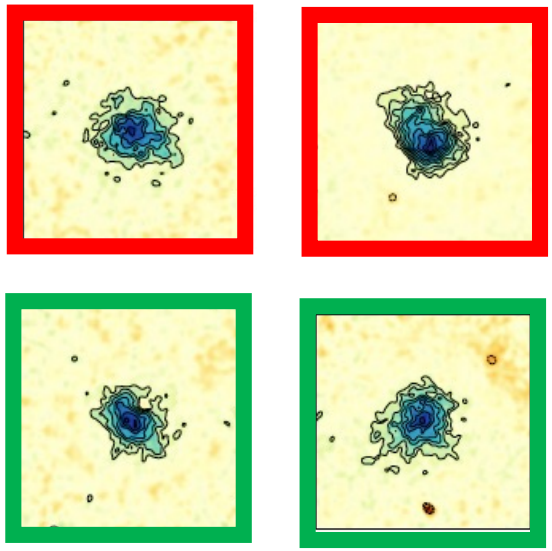


38 maps to be released

LPSZ results – SZ maps @ 150 GHz

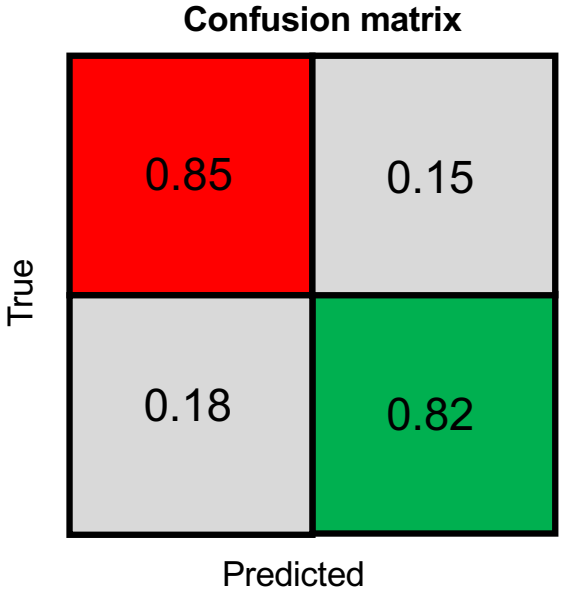


LPSZ results – cluster classification



Cluster

Classification



Twin sample from The300 Simulation

Cluster classification

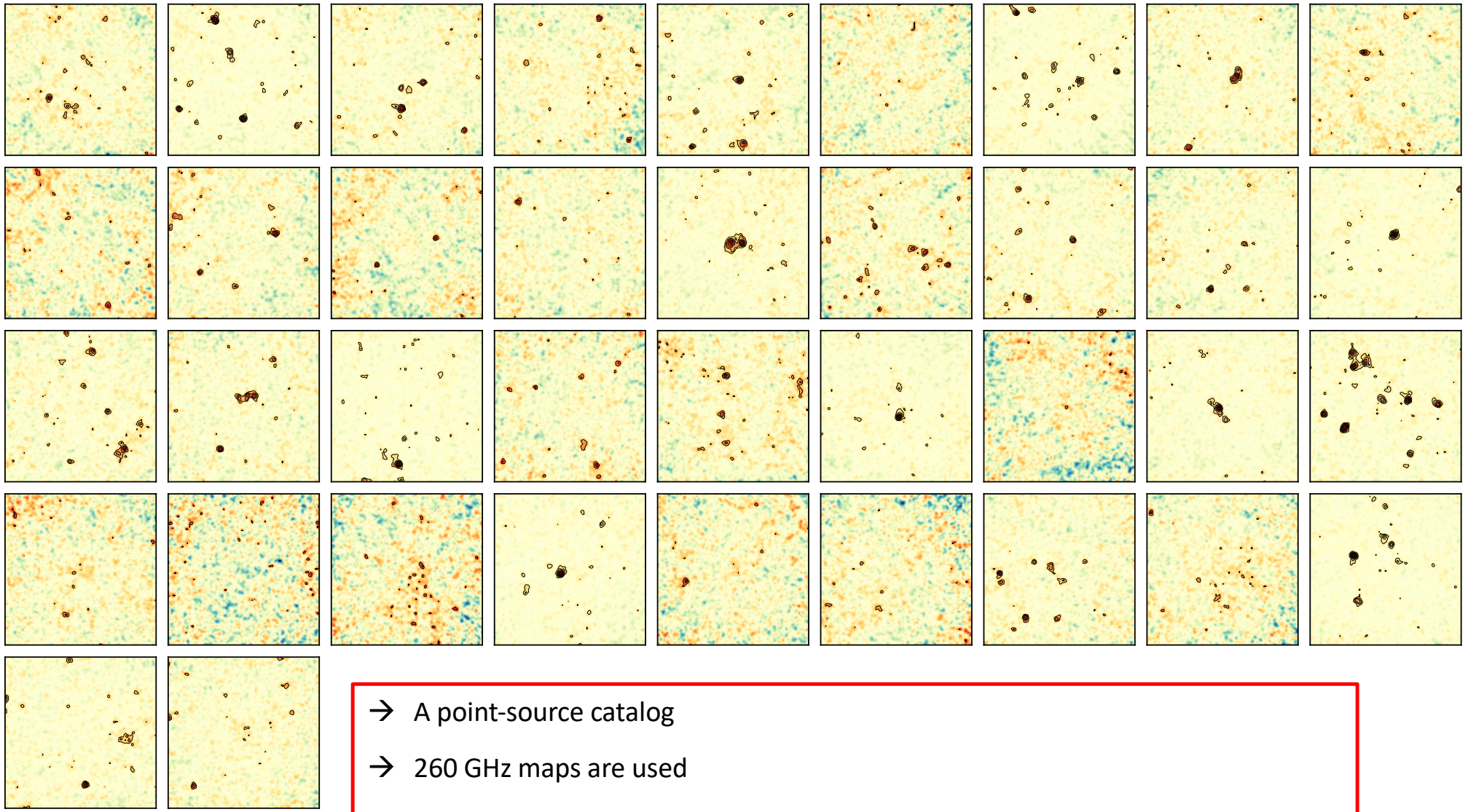
- exploits morphological information from SZ maps
- is trained on *The300* simulations (synthetic twin sample)
- uses 2 complementary methods
  - Zernike polynomials
  - Machine learning classification

→ Relaxed/disturbed classification

→ To be used for cosmology (SR, UPP) and cluster science

LPSZ results – SZ maps – 260 GHz

@ 260 GHz → No SZ signal given the noise level



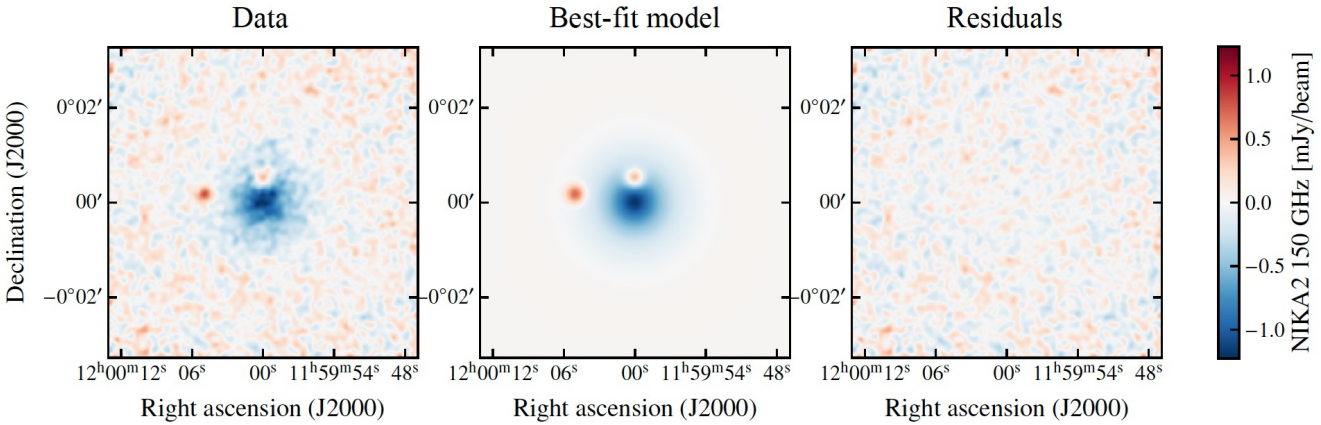
→ A point-source catalog

→ 260 GHz maps are used

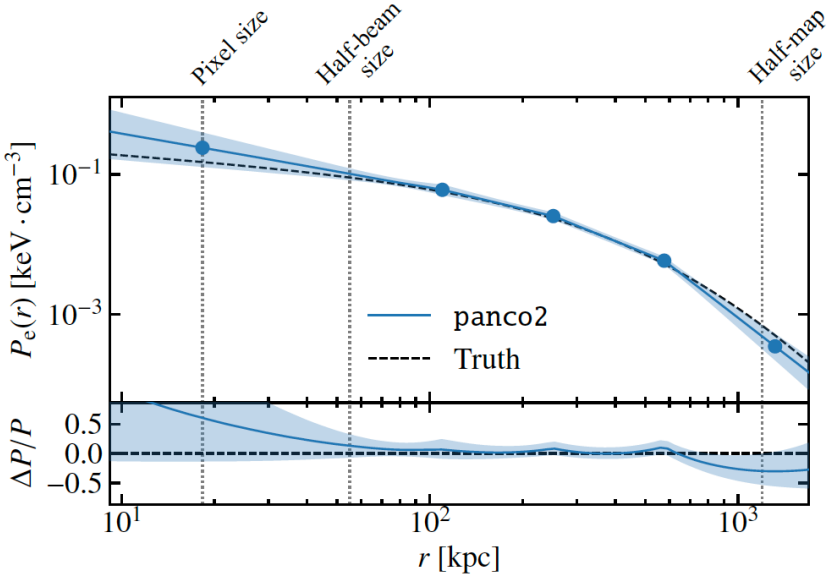
- to identify **point sources** that may compensate SZ signal at 150 GHz
- in the Likelihood model

LPSZ results – Pressure profiles

- Pressure profiles are extracted from maps using the panco2 code
  - forward modeling of the total observed signal (SZ+point sources), large radii constraints (Planck Y_{500})
  - takes into account: beam smearing, data processing filtering, covariance matrix, …



LPSZ-like simulation



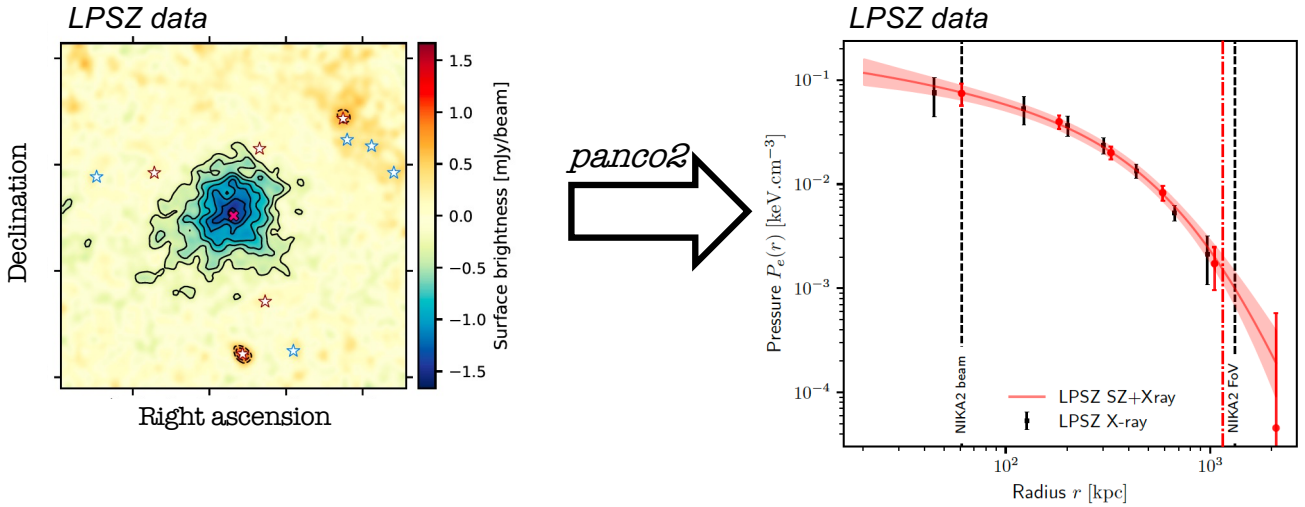
→ radially-binned pressure profile

→ gnfW pressure profile

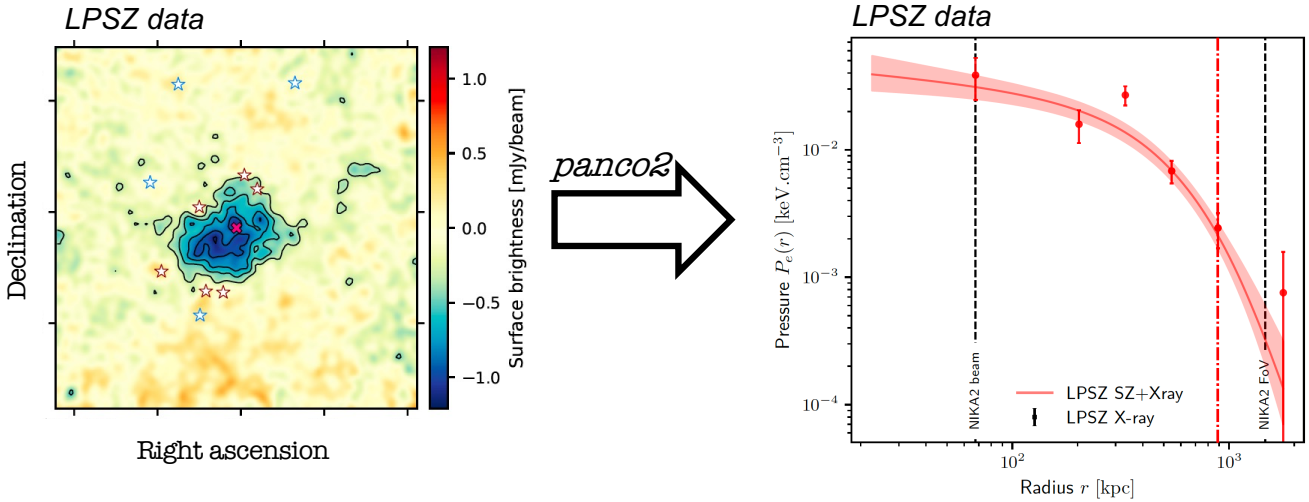
F. Kéruzoré *et al.*, OJA 2025

https://github.com/fkeruzore/panco2

LPSZ results – Pressure profiles



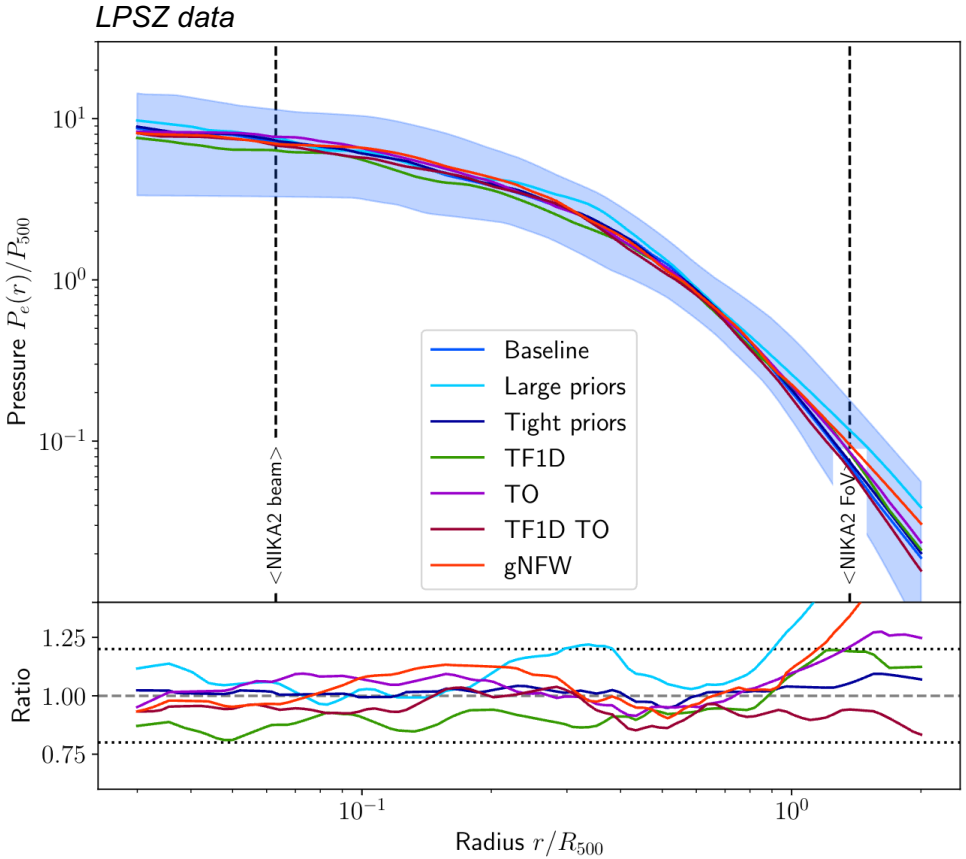
- Regular cluster
- P(r) between beam and FoV
- Good agreement between SZ and X-ray Pressure profiles



- Overpressure
- Non-parametric P(r)

→ Enables to identify departures from gNFW

LPSZ results – Pressure profiles



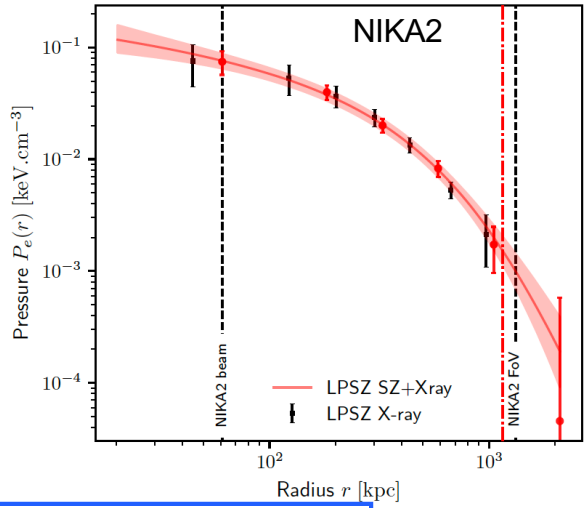
- Pressure profiles have been shown to be robust against details of the analysis
- …

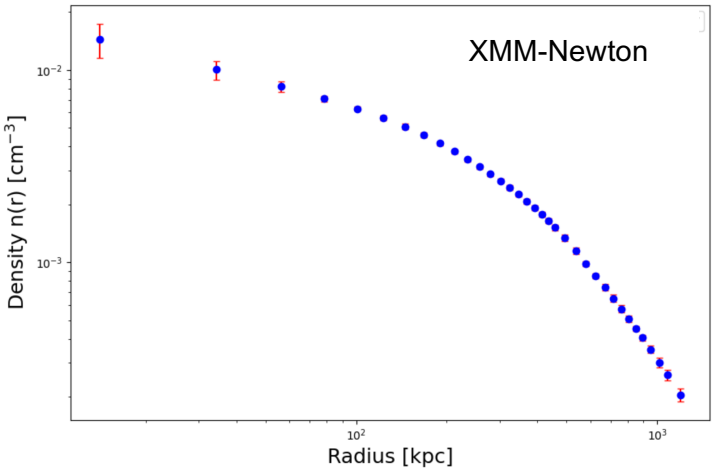
34 pressure profiles will be

→ included in the public release

→ used to evaluate the universal pressure profile

LPSZ profiles – Thermodynamic profiles





$$M_{\rm HSE}(<r) \propto \frac{r^2}{n_e(r)} \frac{{\rm d}P_e}{{\rm d}r}$$

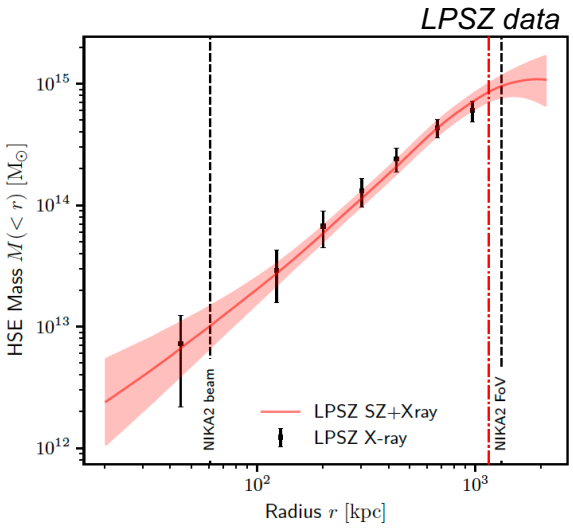
Mass profile

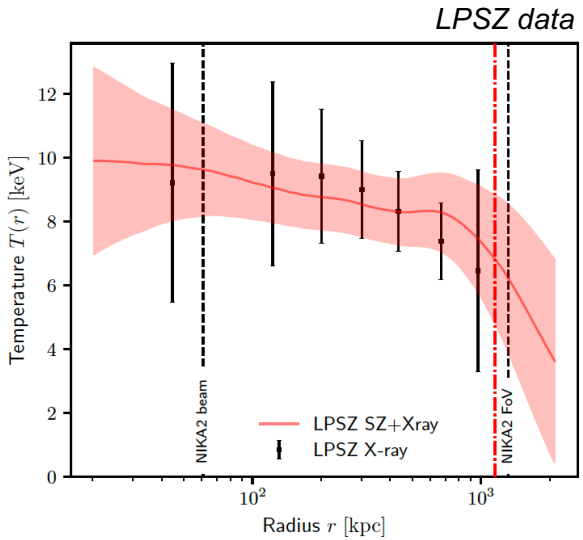
$$k_{\rm B}T(r) = \frac{P(r)}{n(r)}$$

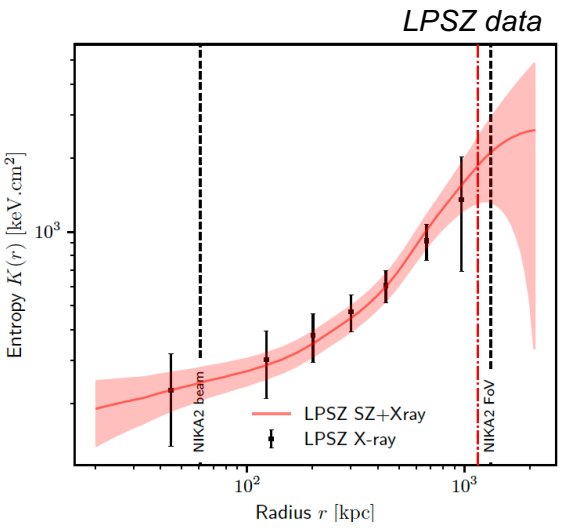
Temperature profile

$$K(r) = \frac{P(r)}{n(r)^{5/3}}$$

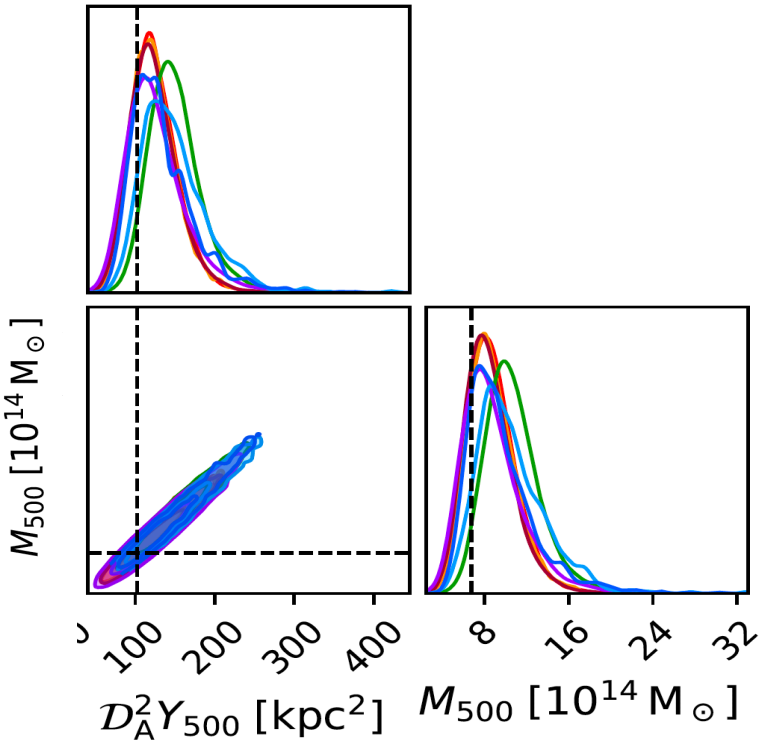
Entropy profile







LPSZ results – Integrated quantities



Integrated quantities

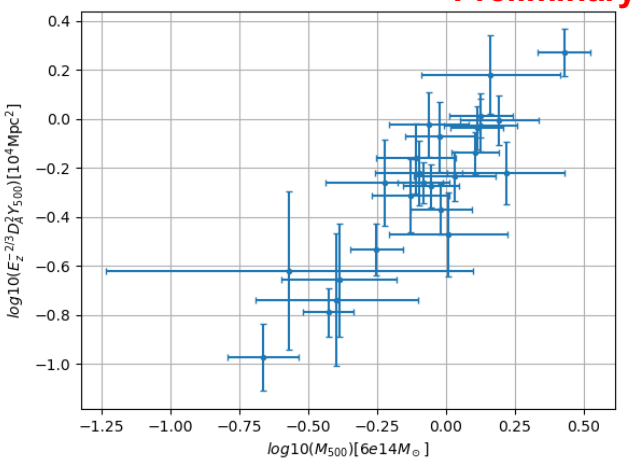
- are evaluated on profiles (M_{HSE})

$$R_{500}, M_{500}, Y_{500}$$

- are shown to be robust against analysis details
- Pdf includes all systematics effects

Preliminary

Y_{500}



M_{500}

29 clusters with integrated quantities will be

→ included in the public release

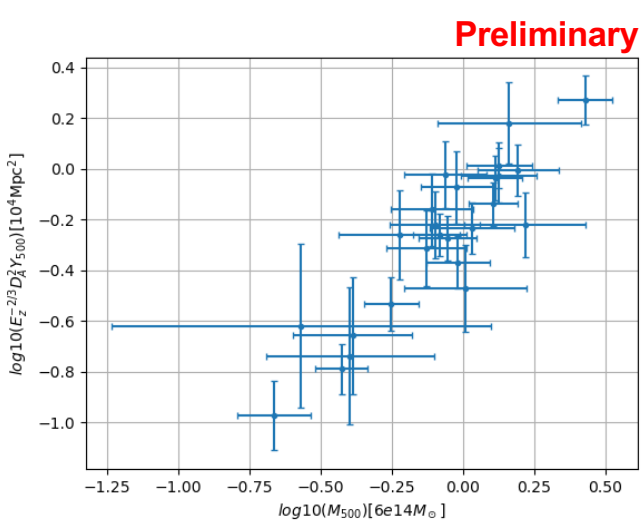
→ used to evaluate the scaling relation

LPSZ results – Scaling relation

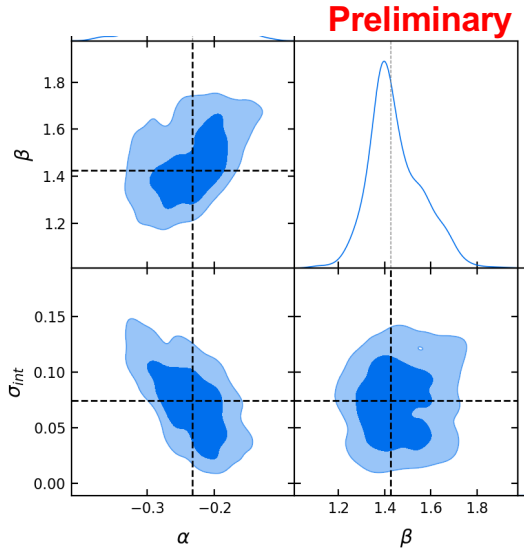
- Méthode : LIRA + SBI

  →LPSZ selection function accounted for.

- **Results**

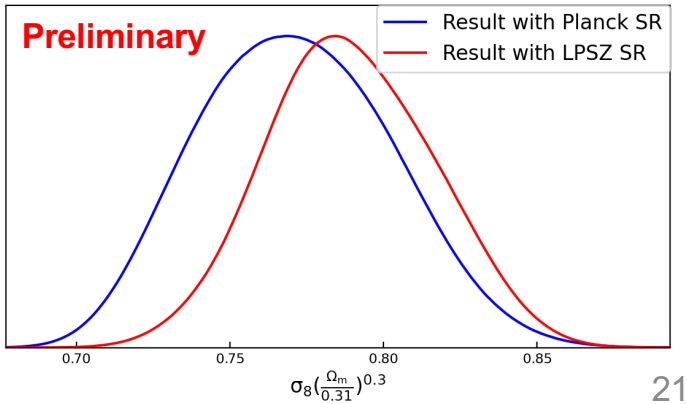


SR pipeline



Cosmology

- Cosmology survey: Planck Planck 2015 results. XXIV
- Cosmology code: Class-SZ B. Bolliet *et al.*, EPJ WOC 2024
- LPSZ Scaling relation

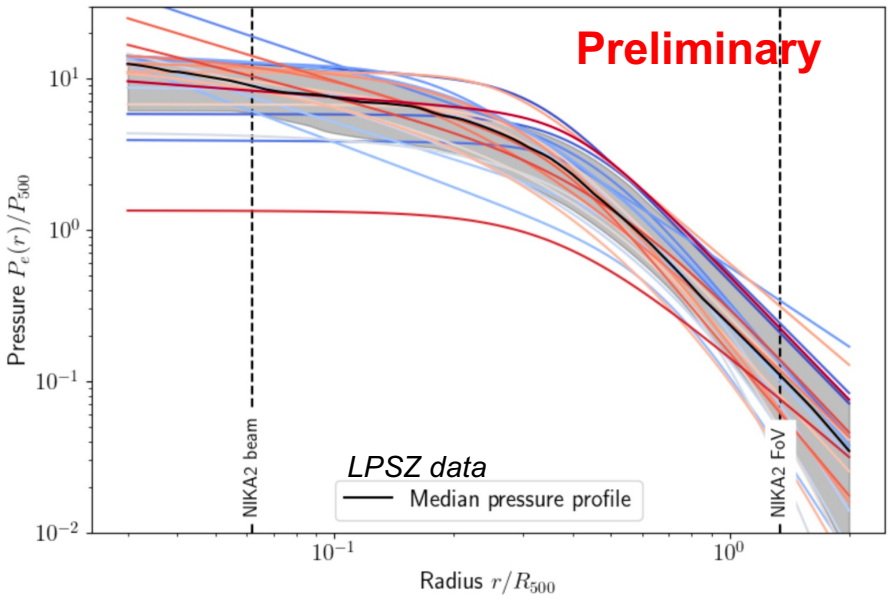


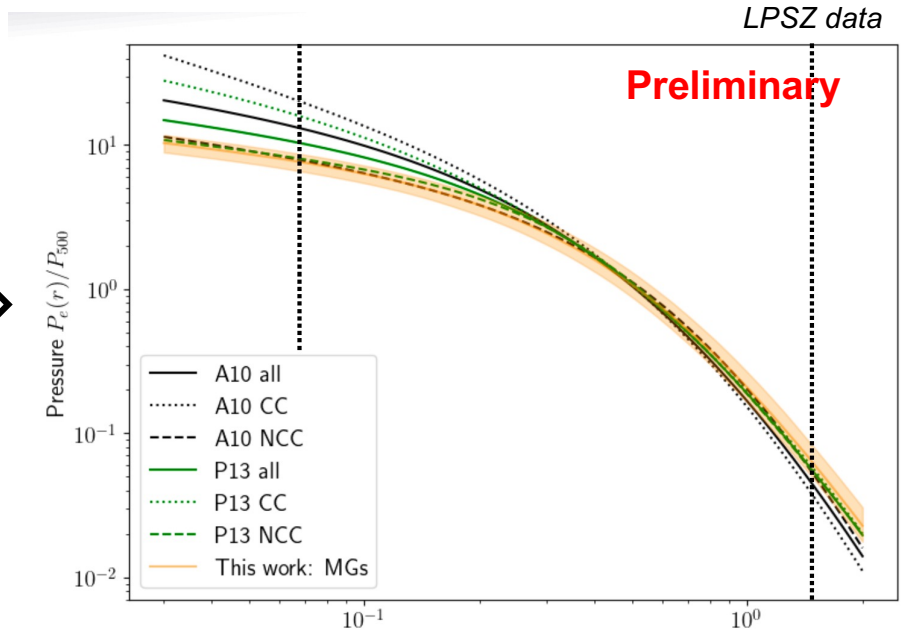
→ *See talk by Alice Moyer-Anin*

LPSZ results – Universal Pressure Profile

- **Méthod**
  - Combine the likelihood distributions of individual clusters
  - Approximate them with multivariate gaussians (or masked autoregressive flows)
  - Account for the intrinsic scatter using a hierarchical Bayesian model
  - *Validated on simulations*

Individual best-fit scaled pressure profiles compared to the median





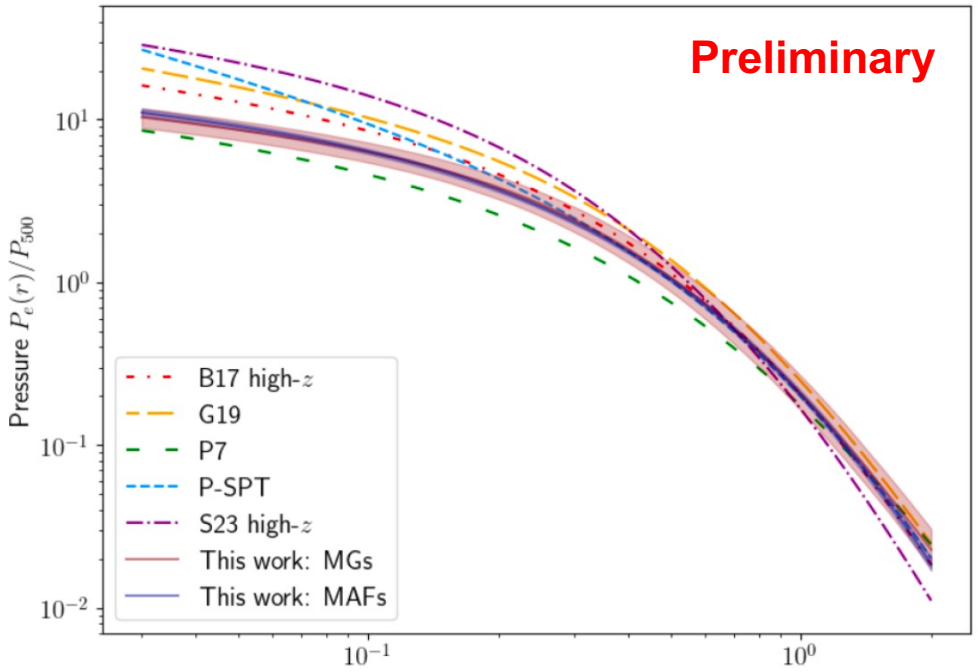
A10 : Arnaud et 2010

P13 ; Planck 2013

C. Hanser, PhD 2024

LPSZ results – Universal Pressure Profile

- **Results**



Good agreement
- with non cool-core clusters UPPs from A10 and P13
- at medium to high radii with
  - ✓ Bourdin et al. (2017) high-z
  - ✓ Melin and Pratt (2023)

- **Cosmology implication**
  - Data: Planck y-map Planck 2015 results. XXI.
  - Code: Class_SZ B. Bolliet *et al.*, EPJ WOC 2024
  - UPP: NIKA2-LPSZ

$$F = \sigma_8(\Omega_m/B)^{0.4}h^{-0.21}$$

Preliminary

UPP	F parameter
A10	$0.481^{+0.005}_{-0.004}$
P13	0.479 ± 0.004
NIKA2-LPSZ	0.475 ± 0.004

C. Hanser, PhD 2024

Conclusion

LPSZ: public release

Cluster catalog

- Maps: 1.2 and 2 mm calibrated maps, Transfer function, null maps, hit maps
- Catalog of point sources
- Thermodynamic profiles: pressure, density, mass, temperature, entropy, …
- Integrated quantities

Tools for cosmology

- Universal pressure profile
- Y-M scaling relation

⇨ Public release by the end of the year

LPSZ: conclusions

The NIKA2 LPSZ Program

📅 7 years of Observations

🔭 300 hours at the Telescope

✅ **Key Points**

- SZ–X-ray Synergy

  → *Successful combination of NIKA2 + XMM-Newton data*

- A SZ-selected cluster sample at high redshift

📦 **Outcomes for the Community**

🗃️ Public Cluster Catalog

→ Includes maps, profiles, integrated quantities, …

🔁 Cluster Cosmology Reanalysis

→ New insights with updated tools

🌟 **More to Come...**

NIKA2 LPSZ: team

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Emmanuel ARTIS
Hervé AUSSEL
Rafael BARRENA DELGADO
Iacopo BARTALUCCI
Alexandre BEELEN
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Charles ROMERO
Jose Alberto RUBINO MARTIN
Florian RUPPIN
Raphael WICKER
Gustavo YEPES

Thank you to the whole team for:

commissioning, SZ observations, NIKA2 pipeline, SZ pipeline, X-ray data, optical data, simulation, cosmological studies, …

Back up

LPSZ: publication

Paper I: Maps and properties

Paper II: Catalog of point sources

Paper III: High-resolution SZ-X-ray Synergy (profiles and integrated quantities

Paper IV: Universal pressure profile

Paper V: Y-M scaling relation

Paper VI: Cluster dynamical state from Zernike polynomials

Paper VII: Cluster dynamical state from ML classifications

Paper VIII: SZ+X-ray Temperature maps

Paper IX: The non-thermal ICM content as seen from resolved SZ observations

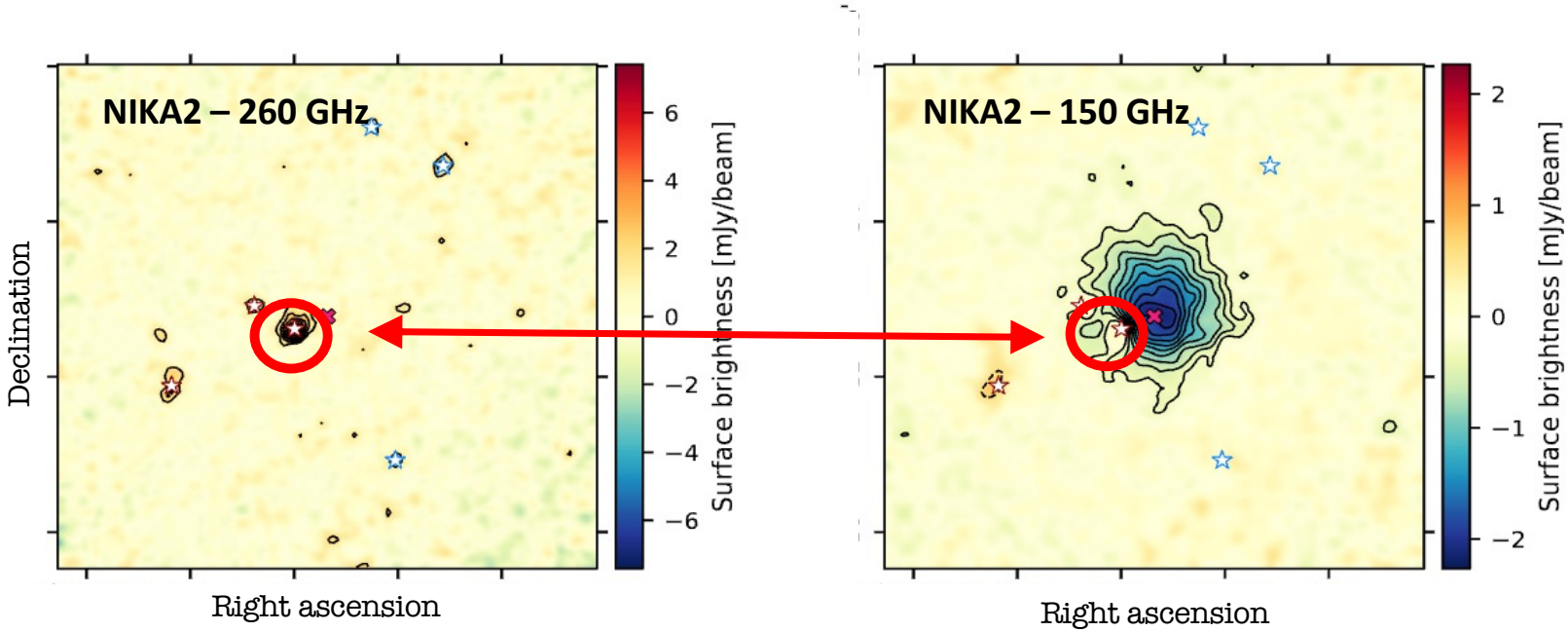
… and more to come

⇨ publication by the end of the year

LPSZ results – SZ maps

Dual-band observation

- no SZ signal is expected at 260 GHz (for this noise level)
- 260 GHz map is used to identify **point sources** that may compensate SZ signal at 150 GHz



point-sources taken into account when extracting SZ information

LPSZ profiles – Robustness tests

Baseline method

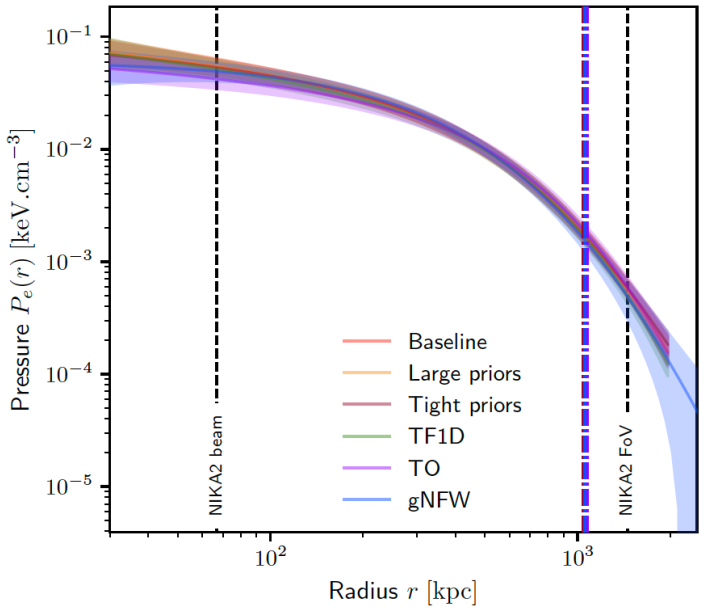
- deprojection of a binned model of the pressure profile
- Null map: "Iteration-order" (IO), half-diff of 4 consecutive scans
- Anisotropic filtering model using 2D TF
- gNFW fit from the binned model data points
- Flat priors [0, 5xA10] for p0, a, b, c, and rsprior [0,2.5Å~Rmeas500/c500xA10]
- Increasing mass constraint up to 1.2 R500_Planck/ACT

Alternative methods

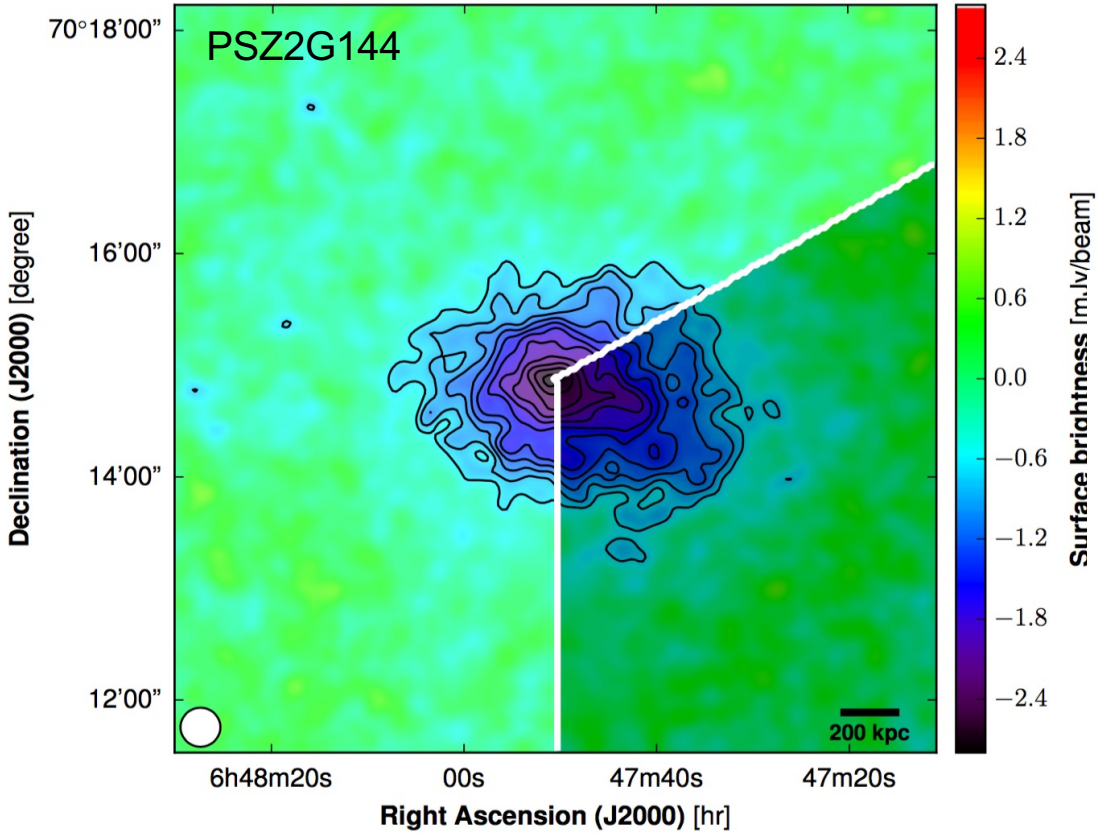
- TF1D isotropic filter
- Direct gNFW model
- Larger or tighter priors
- No mass constraint

→ Results robusts against analysis choices

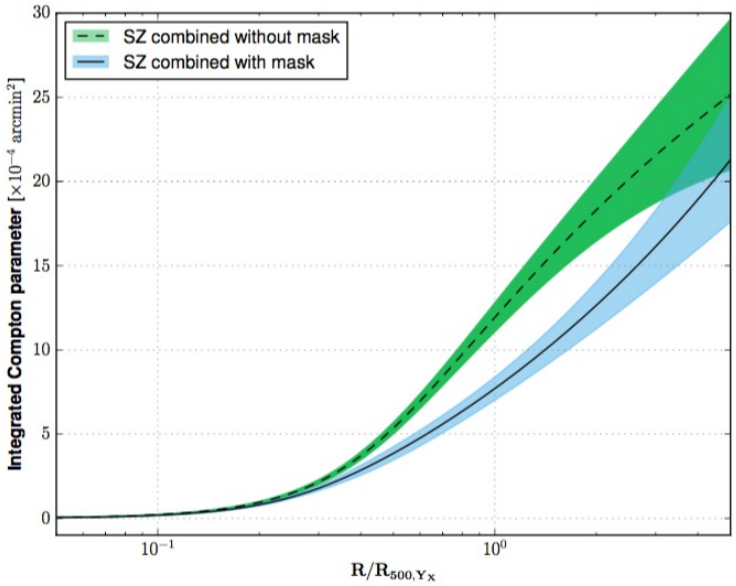
PSZ2-G085



First cluster observation – overpressure region



F. Ruppin *et al.*, A&A 2018



Discovery of an overpressure region

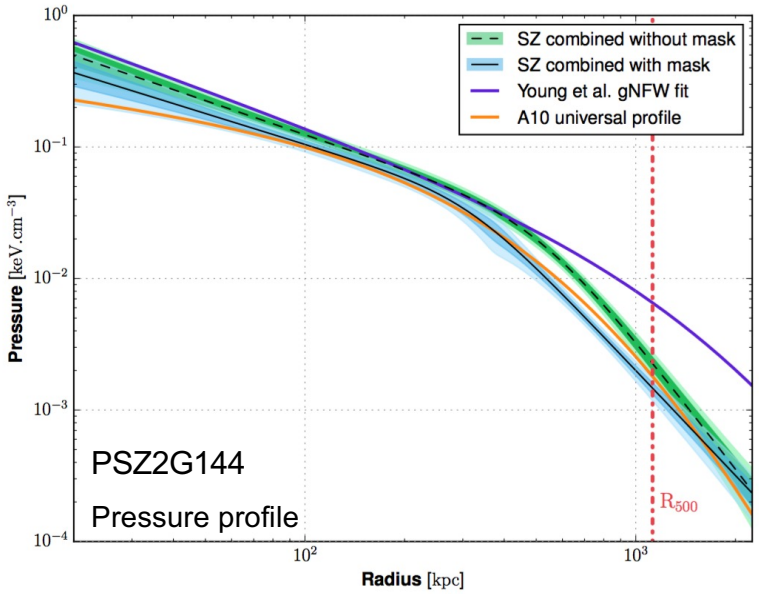
→ does impact integrated SZ signal and mass

→ highlight the need for high-resolution observations

this cluster is not resolved by Planck

First cluster observations – pressure profiles

F. Ruppin *et al.*, A&A 2018



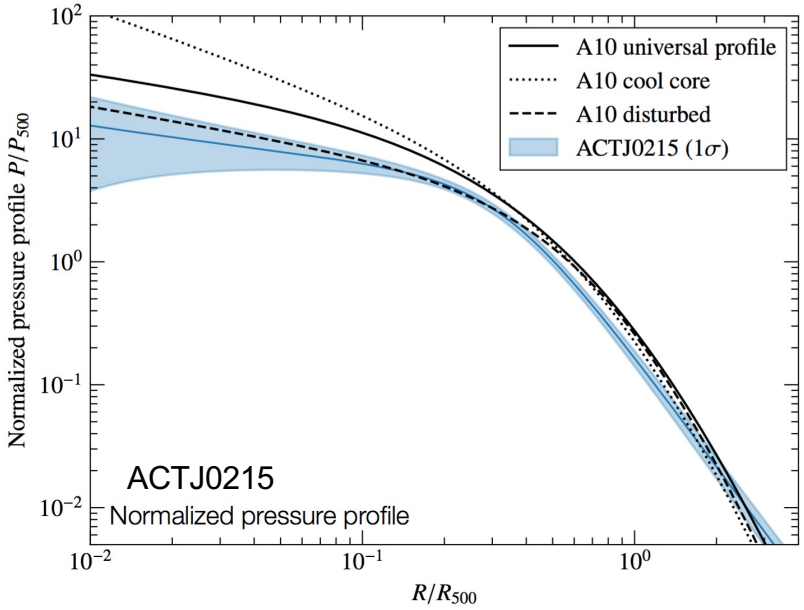
- significant differences w/wo overpressure (outer part)

  3σ between 500 and 900 kpc

→ impact of the overpressure region

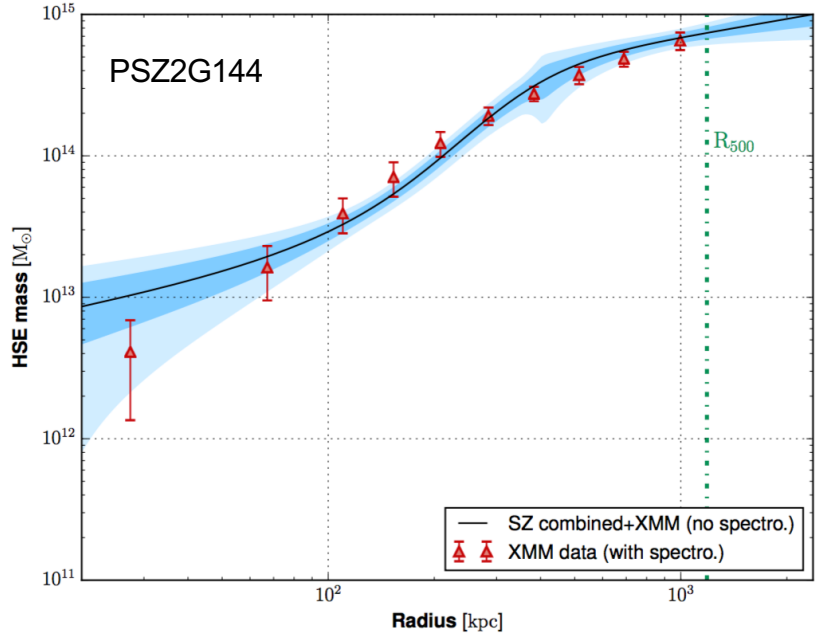
- comparison with A10 profile

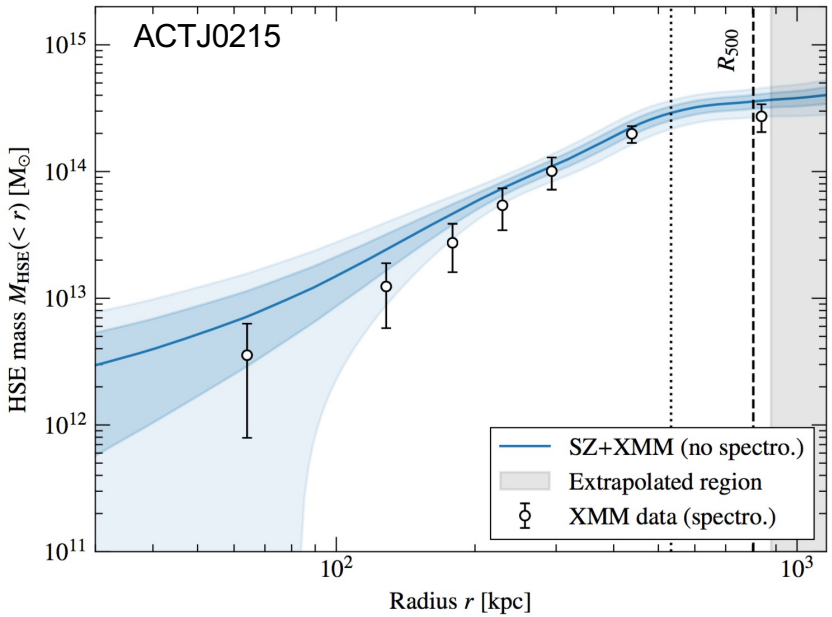
M. Arnaud et al., A&A 2010



- departure form universal profile
- compatible with disturbed A10 profile

First cluster observations – mass profiles





F. Ruppin *et al.*, A&A 2018

Mass profiles

- LPSZ : density (XMM) & Pressure (NIKA2)
- XMM-only : density & Temperature (XMM)

X-ray spectrocopy also provides the Temperature

→ Pressure directly from X-ray observations

→ Great … but very time consuming at high redshift (prohibitive)

in both cases

⇨

- mass profiles are in good agreement
- estimation of M_{500}

However, no conclusions can be drawn with 2 clusters…

First cluster observations - method

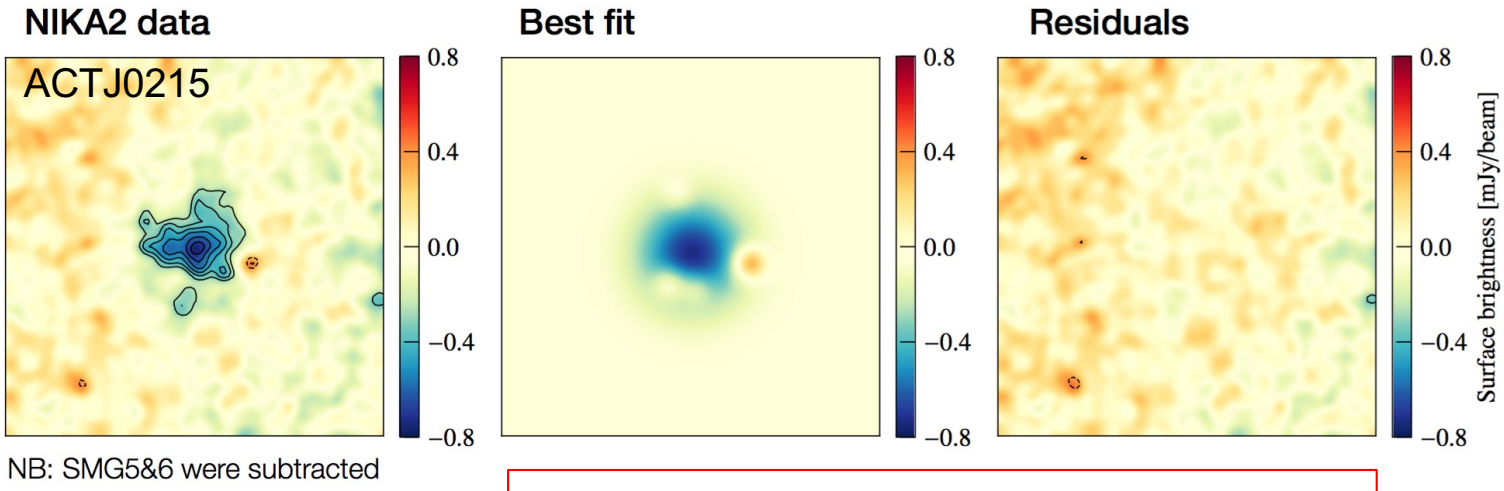
NIKA2 150 GHz map = ICM SZ signal + point source contamination (+ noise)

ICM SZ signal

- spherical symmetry
- gNFW model
- Integration along the line of sight + calibration + convolution by NIKA2 beam

Point source contamination

- position know from NIKA2 260 GHz map
- fluxes are free parameter with priors from SED extrapolation (NIKA2+Herschel)



NB: SMG5&6 were subtracted

NIKA2 data are well-described by

a gNFW pressure profile + point sources