# High-resolution SZ observations for cluster cosmology with NIKA2

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Séminaire doctorant, 01/07/2020

Thèse dirigée par F. Mayet, au sein de l'équipe *"Cosmologie Multi-$\lambda$"*

financé par
**IDEX Université Grenoble Alpes**

# OUTLINE

**Cosmology with galaxy clusters**

High-resolution SZ with NIKA2

NIKA2/XMM-*Newton* analysis of a faint cluster

Perspectives, conclusion

# COSMOLOGY WITH GALAXY CLUSTERS

- **Galaxy clusters = largest gravitationally bound structures in the Universe**

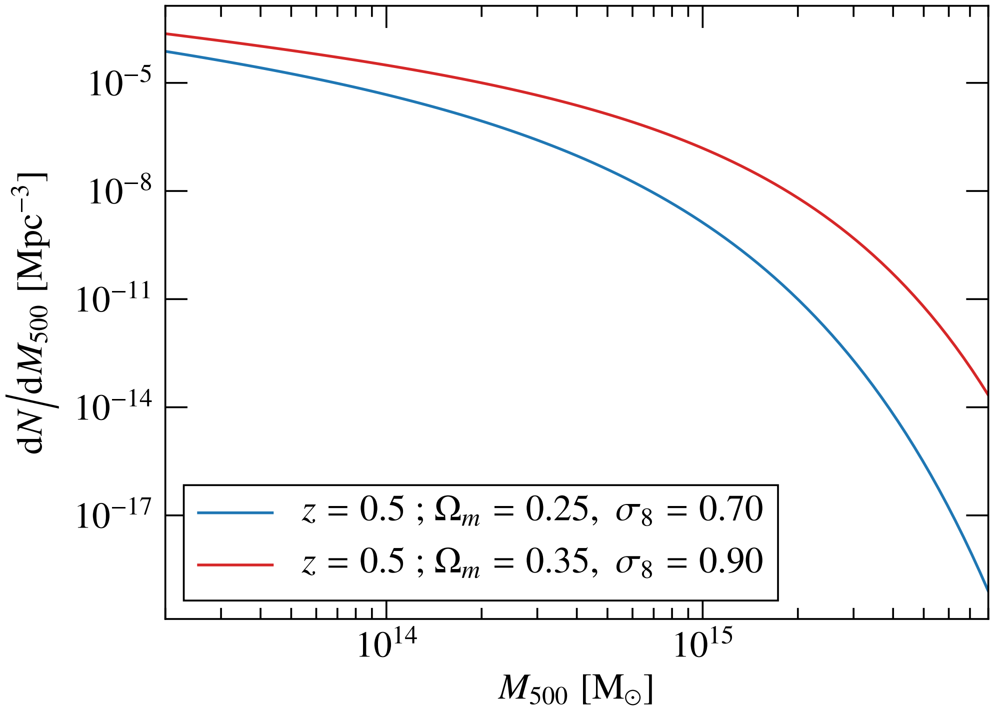
- Formed in the late universe ($z < 3$) through gravitational collapse of matter + accretion of surrounding material

  → **Probes of matter distribution in the Universe**

- Distribution of clusters in the Universe depends on the **mass function**
  - Expected # of clusters at a given mass and redshift
  - Depends on cosmological parameters

→ We can count clusters in bins of mass and redshift to measure cosmological parameters

→ **Need a large number of clusters**



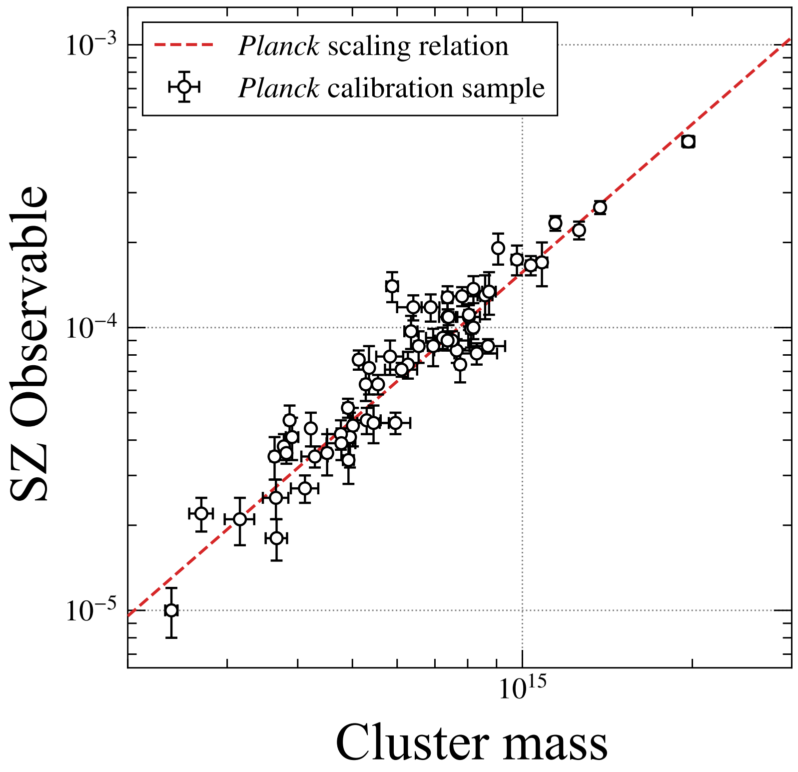
→ For cosmology, we need a **survey** of galaxy clusters and an estimation of their **redshifts** and **masses**

# OBSERVABLE — MASS SCALING RELATIONS

**Masses are not directly observable in surveys**

- We only have access to measured quantities
  *Example: # of galaxies, X-ray brightness, SZ, …*
- We need to link measured quantities to cluster masses

→ Scaling relations between observable and mass calibrated on samples with known masses



→ Need to have a well-calibrated relation for precision cosmology

# THE HYDROSTATIC MASS AND X-RAY MEASUREMENTS

**Definition**

**Hydrostatic equilibrium** (HSE): mass $M^{\mathrm{HSE}}(r) \propto \frac{r^2}{n_e} \frac{\mathrm{d}P_e}{\mathrm{d}r}$

| |
|---|
| 🟦 Pressure |
| 🟧 Density |

→ Cluster mass through thermodynamical properties of the intracluster medium (ICM)

Thermodynamical properties of the ICM can be measured in X-rays:

- **X-ray emission**
  - Due to thermal *bremsstrahlung* in the ICM
  - Signal linked to the ICM electron **density** integrated along the line of sight:

$$\boxed{S_X \propto (1+z)^{-4} \int_{\mathrm{LoS}} \Lambda(T_e)\, n_e^2 \, \mathrm{d}\ell}$$

→ Used to measure the **density** in the ICM

- **X-ray spectroscopy** can be performed with enough photons:
  - Gives access to the electron **temperature** of the ICM
  - Combination with density gives the **pressure** through $P_e = n_e \, kT_e$

→ **Hydrostatic mass**

**Limitation**

Redshift dependence

→ time-consuming at high z (especially spectroscopy)

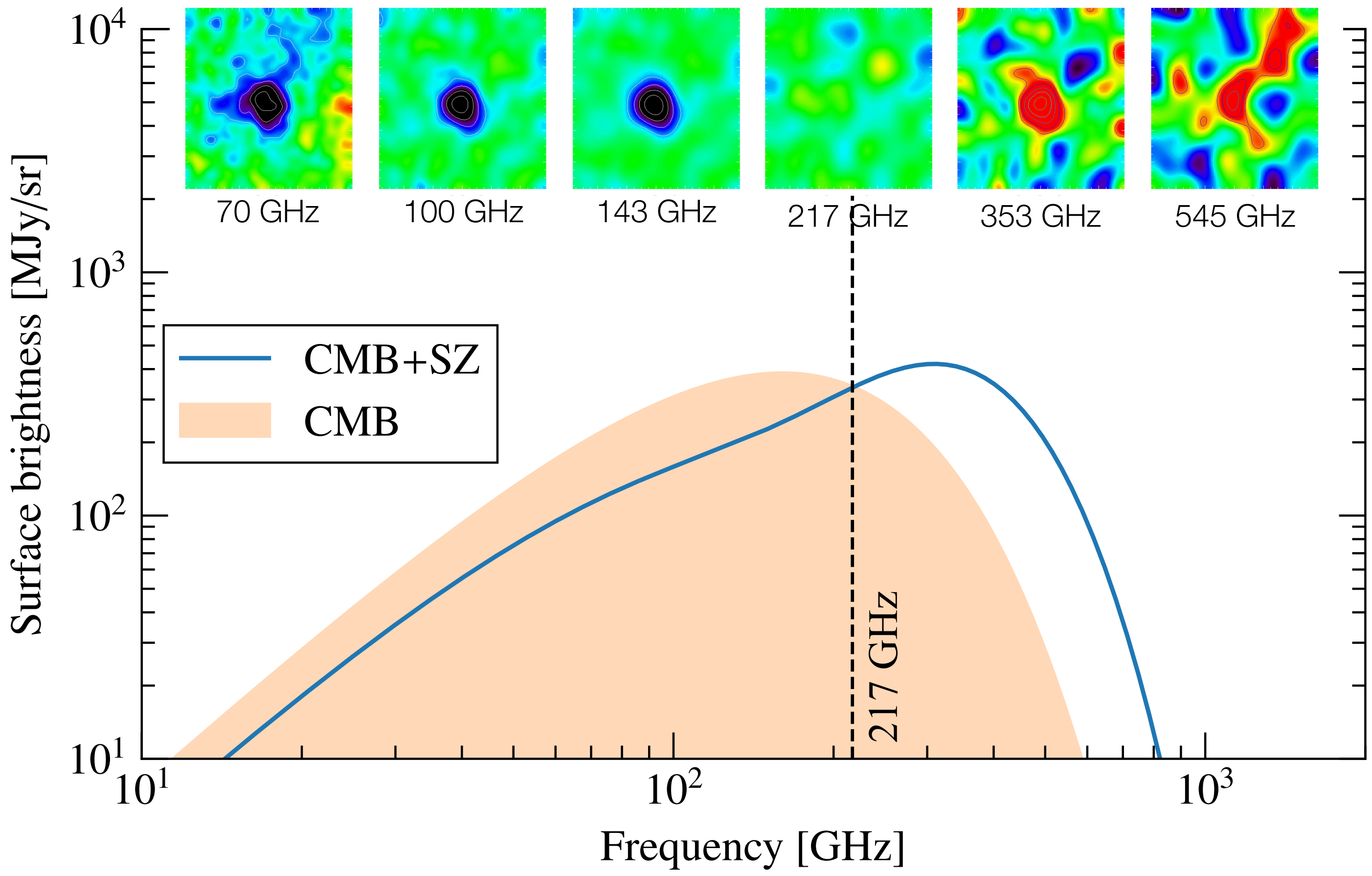
# THE SUNYAEV-ZEL’DOVICH (SZ) EFFECT

- Spectral distorsion of the cosmic microwave background *(Sunyaev & Zeldovich, 1972)*
- Inverse Compton scattering on hot ICM electrons → CMB photons gain energy
- Observed amplitude linked to the ICM electron **pressure** integrated along the line of sight (LoS):

$$\boxed{\textbf{Compton parameter } y \propto \int_{\text{LoS}} P_e \, \mathrm{d}\ell}$$

- Redshift independent

*Planck* view of A2319 *(Planck collaboration VIII, 2011)*



### X—SZ synergy

- Pressure $P$ → *measured in SZ*
- Density $n$ → *measured in X-rays*

→ HSE mass $M^{\text{HSE}} = f(P, n)$

→ Go deeper in redshift than X alone (no need for spectro)

# THE PLANCK SZ—MASS SCALING RELATION

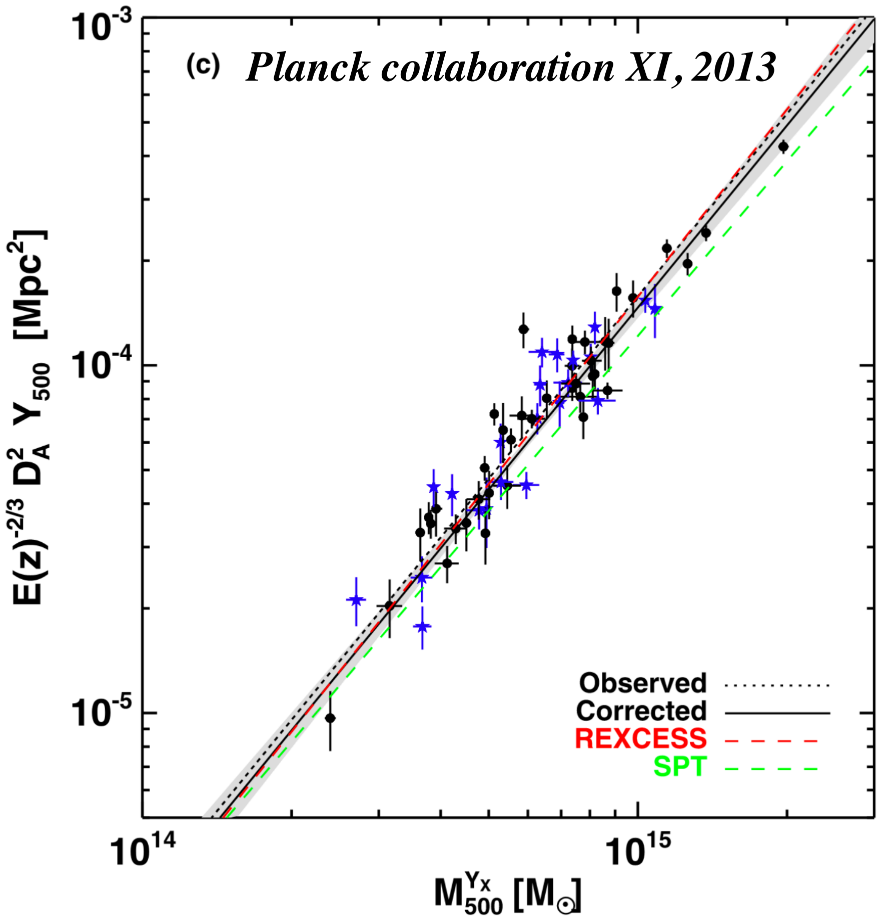
## Definition: Integrated quantities

- Characteristic radius to describe clusters: $R_{500}$ (radius with average density $= 500\,\rho_{\rm crit}$)

→ SZ signal within $R_{500}$ → $Y_{500} \propto \int_0^{R_{500}} P(r)\,{\rm d}^3 r$, Mass within $R_{500}$ → $M_{500}$

## SZ—Mass scaling relation: $Y_{500} = f(M_{500})$

- So far measured:
  - With X-ray only masses
  - At low redshift ($z < 0.5$)
- Planck SZ survey detected clusters up to $z = 1$
- The relation could evolve with redshift (different cluster properties at high z)



Possible evolution with redshift could impact cosmological results

→ Could be detected with X—SZ

# CONCLUSION

## Cosmological analyses require:

○ Large catalogs of galaxy clusters for cosmological analyses

→ **SZ surveys**

✓ Planck, SPT, ACT

○ Small representative samples of clusters with well known properties to calibrate the tools needed for cosmology

→ **X—SZ synergy**

→ NIKA2 SZ Large Program

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# THE NIKA2 COLLABORATION AND LPSZ

## The NIKA2 collaboration

- International collaboration
- ~150 members
- Grenoble leadership:
  Institut Néel (leaders), IPAG,
  IRAM, LPSC
- Built the NIKA2 camera

## The NIKA2 SZ Large Program

- PIs: F. Mayet, L. Perotto (LPSC)
- 25 members across 13 institutes
- Specialists in SZ/X-rays/visible, astrophysics/cosmology, numerical simulations, …

→ 300 h NIKA2 guaranteed time

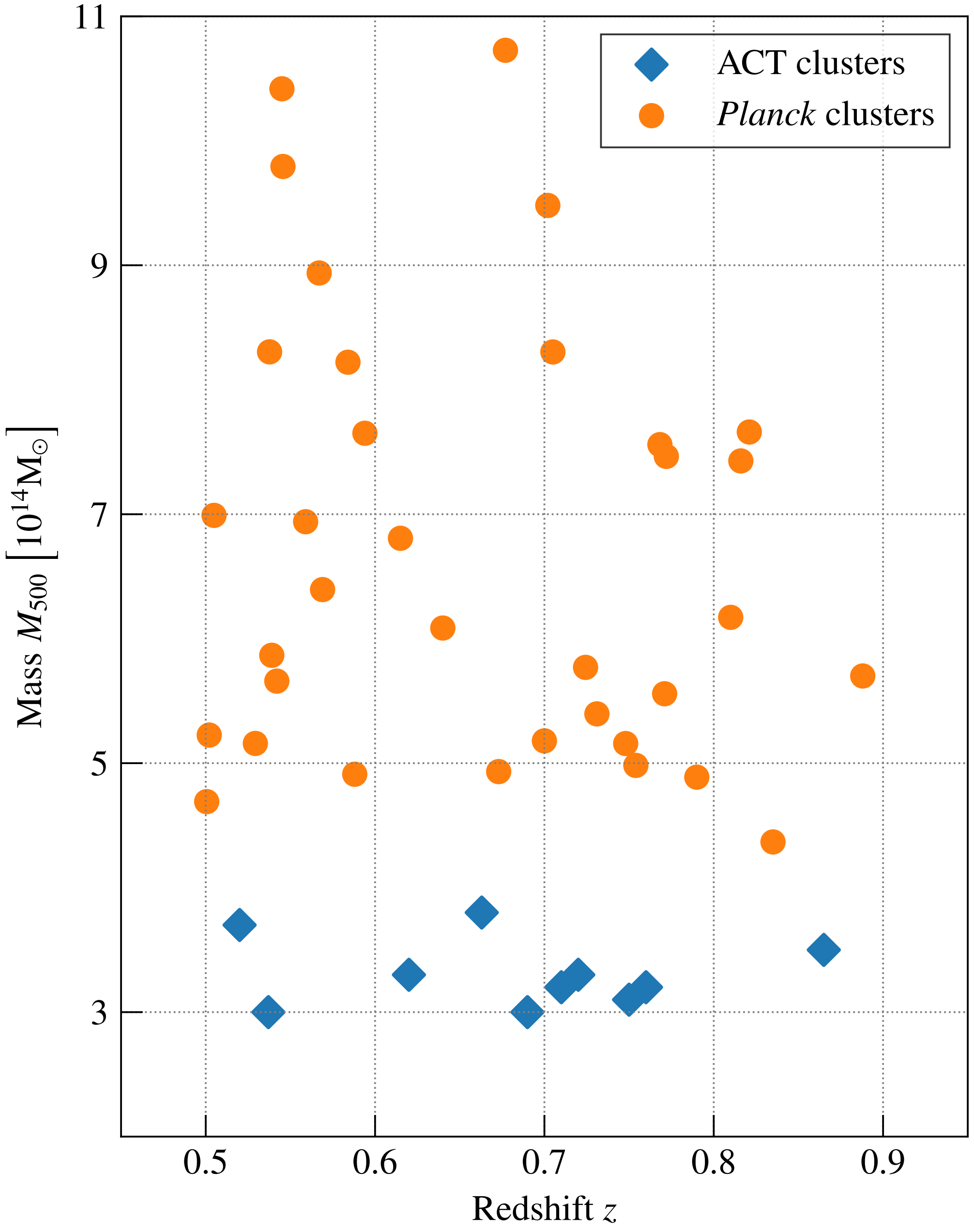
Nicolas PONTHIEU
François-Xavier DESERT
Laurence PEROTTO
Juan MACIAS-PEREZ
Florian KERUZORE
Frédéric MAYET
Rémi ADAM
Florian RUPPIN
Charles ROMERO
Etienne POINTECOUTEAU
Nicolas CLERC
Nabila AGHANIM
Marian DOUSPIS
Jean-Baptiste MELIN
Monique ARNAUD
Gabriel PRATT
Iacopo BARTALUCCI
Hervé AUSSEL
Alexandre BEELEN
Marco DE PETRIS
Gustavo YEPES
Rafael BARRENA DELGADO
Antonio FERRAGAMO
Jose Alberto RUBINO MARTIN
Chiara FERRARI

MADRID

# THE NIKA2 SZ LARGE PROGRAM (LPSZ)

- SZ follow-up of ~50 clusters
- Combination of high-resolution SZ & X-rays
- Measurement of the tools needed for cosmology:
  - the SZ — Mass scaling relation
  - the ICM mean pressure profile
- Improvement over previous measurements:
  - at high redshift $(0.5 < z < 0.9)$
    *more accurate for more distant objects*
  - high angular resolution SZ observations
    *identification of substructures, contamination…*

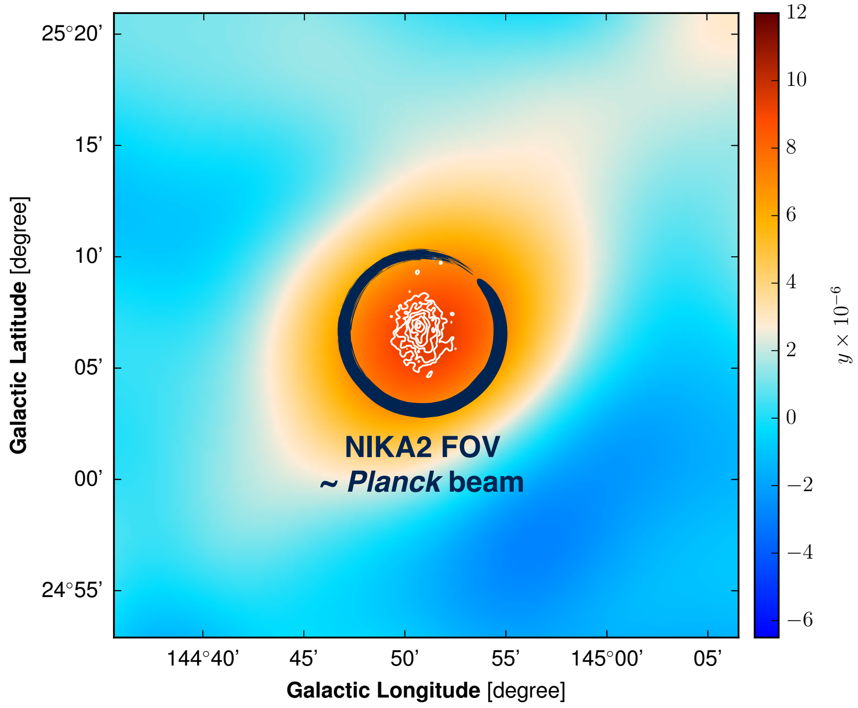
**→ Detailed information** on **distant clusters**

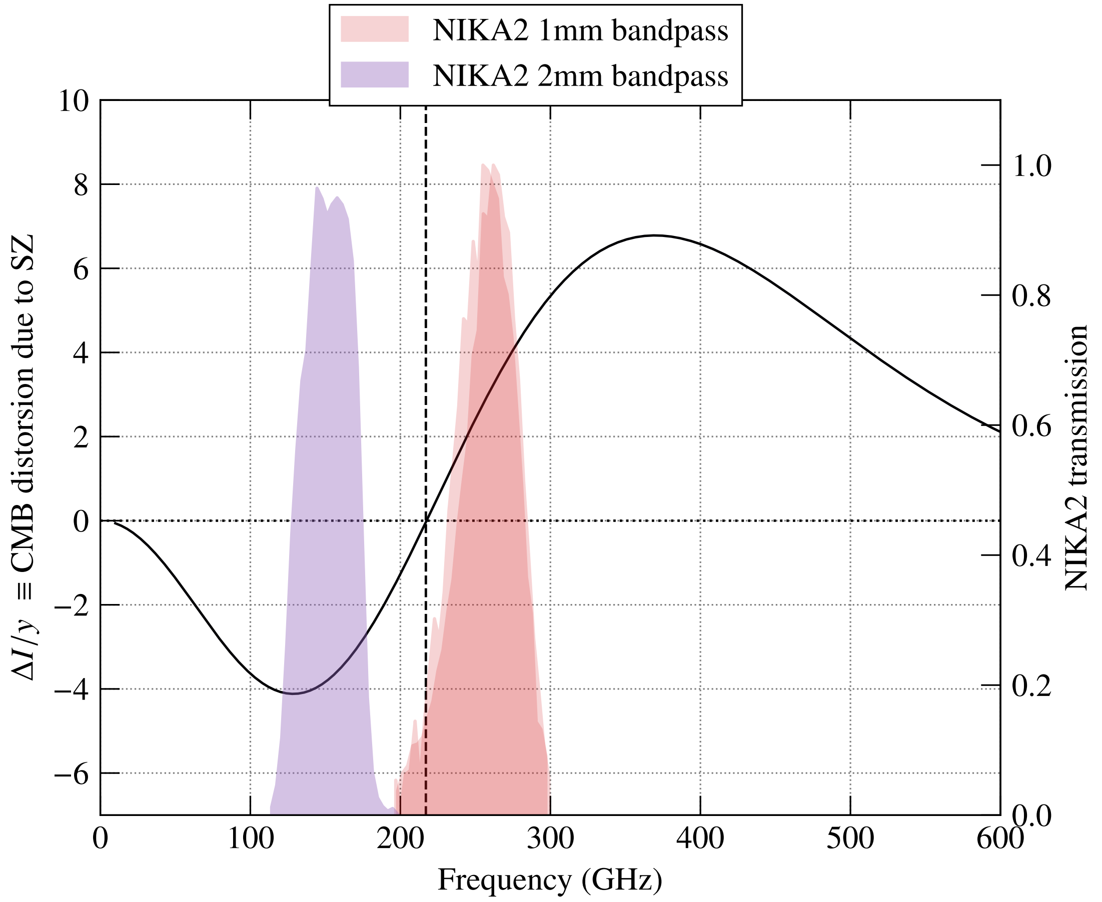


# NIKA2: AN IDEAL INSTRUMENT FOR SZ

- Kinetic Inductance Detectors (KIDs) camera
- 30 meter telescope, Sierra Nevada, Spain
- Well-suited to SZ observations:
  - Dual band
    → *Allows to exploit the spectral dependence of SZ*
  - High angular resolution
    → *Provides detailed information about the structure of the ICM*
  - Large field of view
    → *Allows to map extended regions*
  - High sensitivity
    → *Efficient at mapping faint signal*

| ✓ | | 1.2 mm | 2 mm |
|---|---|---|---|
| ✓ | FWHM [arcsec] | 11.1 ± 0.2 | 17.6 ± 0.1 |
| ✓ | Field of view [arcmin] | 6.5 | |
| ✓ | Sensitivity $[\mathrm{mJy} \cdot \mathrm{s}^{1/2}]$ | 30 ± 3 | 9 ± 1 |
| ✓ | Mapping speed $[\mathrm{arcmin}^2 \cdot \mathrm{mJy}^{-2} \cdot \mathrm{h}^{-1}{}^{1/2}]$ | 111 ± 11 | 1388 ± 174 |





# THE NIKA2 PIPELINE: FROM RAW DATA TO MAPS

The telescope scans the sky following a “zigzag” pattern

→ Each detector sees the evolution of incident luminosity with time: **Time-Ordered Information (TOI)**

Astrophysical Signal

Electronic noise

Glitches

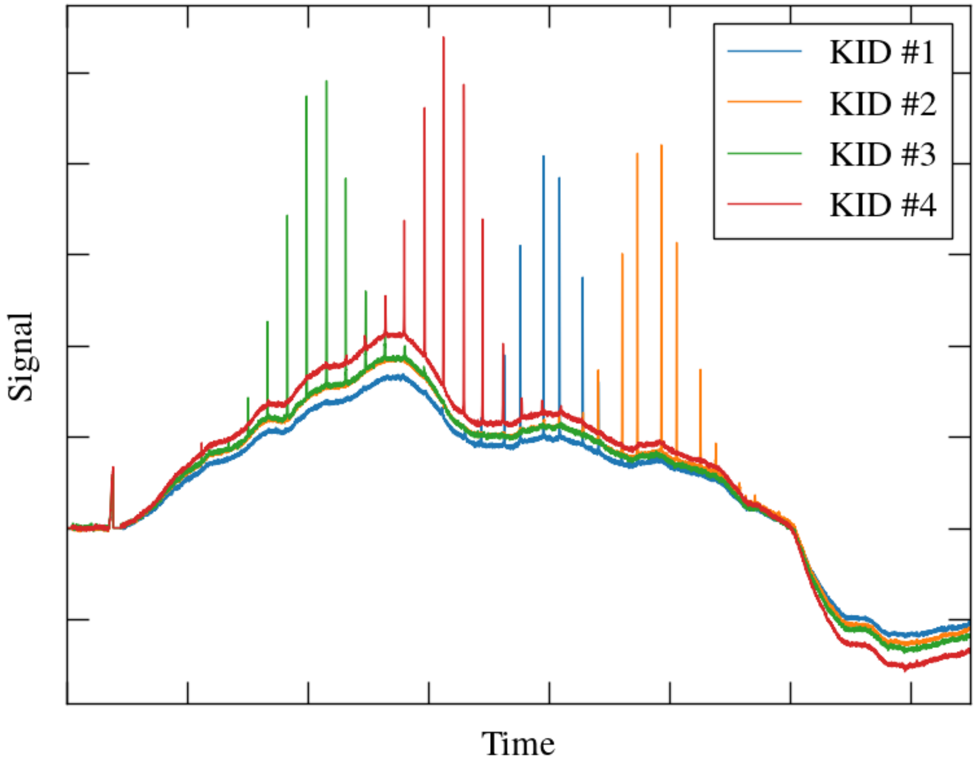
$$\mathrm{TOI}_k(t) = S(t) + A(\nu, t) + E_k(t) + N_k(t) + G_k(t) + C_k(t)$$

Atmospheric emission

Detector noise

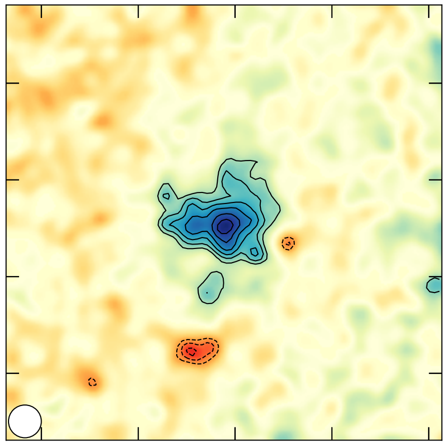
Cryostat vibrations

Atmosphere emission is highly dominant and needs to be removed



- At any given time, detectors see the same atmosphere, but different astro signal
- Noise = common mode of the TOIs
- Subtracted from the data → signal-dominated TOIs
- Clean data projected on a map

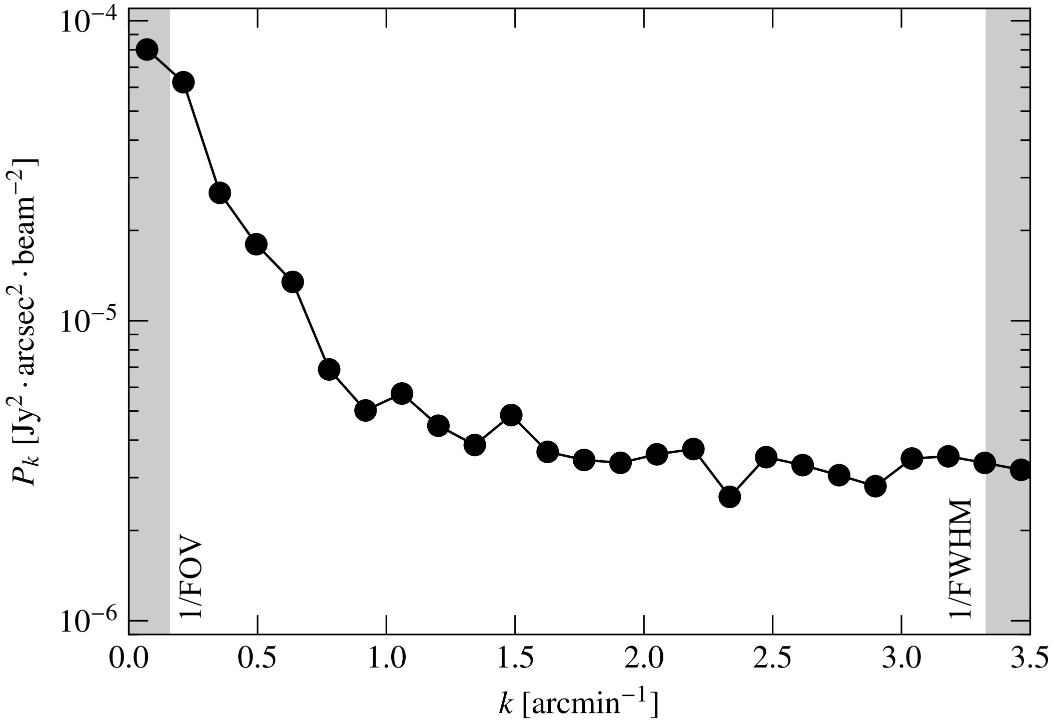
# NOISE AND TRANSFER FUNCTION



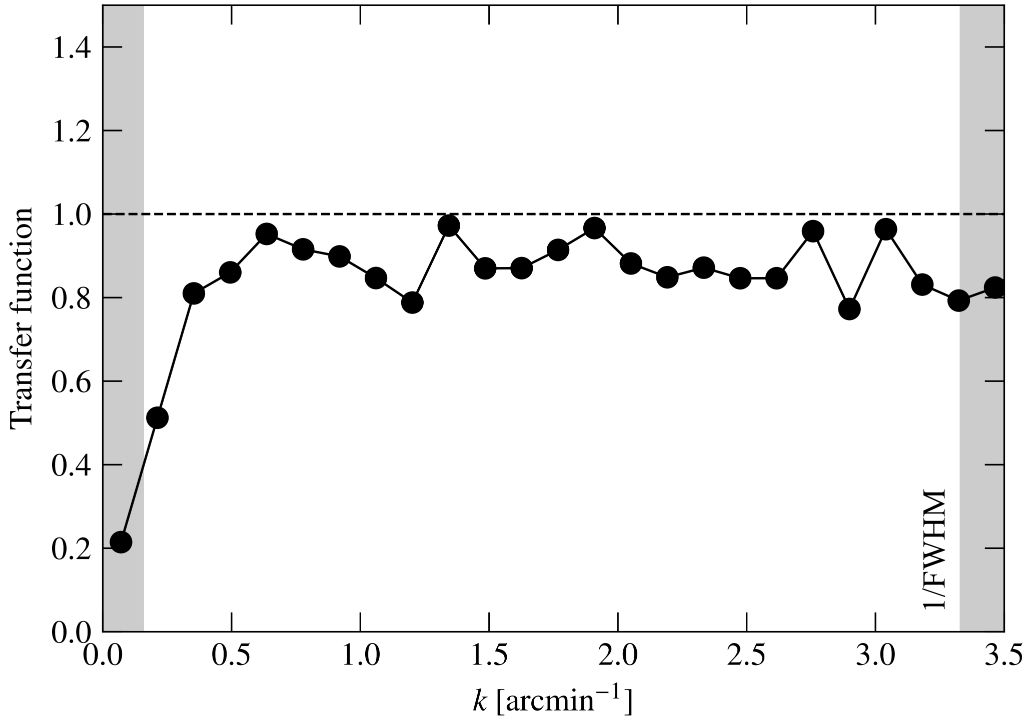
**Products of the data reduction:**

- ○ NIKA2 Maps
- ○ Noise power spectrum
  - Evaluated on null maps
  - Quantifies the noise remaining in our maps
  - → Can be used to measure the noise covariance
- ○ Transfer function
  - Evaluated by processing simulations the same way we processed data
  - $\mathrm{TF} = P_k^{\mathrm{in}} / P_k^{\mathrm{out}}$
  - Quantifies the filtering of signal due to our data processing
  - → Needs to be taken into account when fitting models

## 2mm null map power spectrum



## 2mm transfer function



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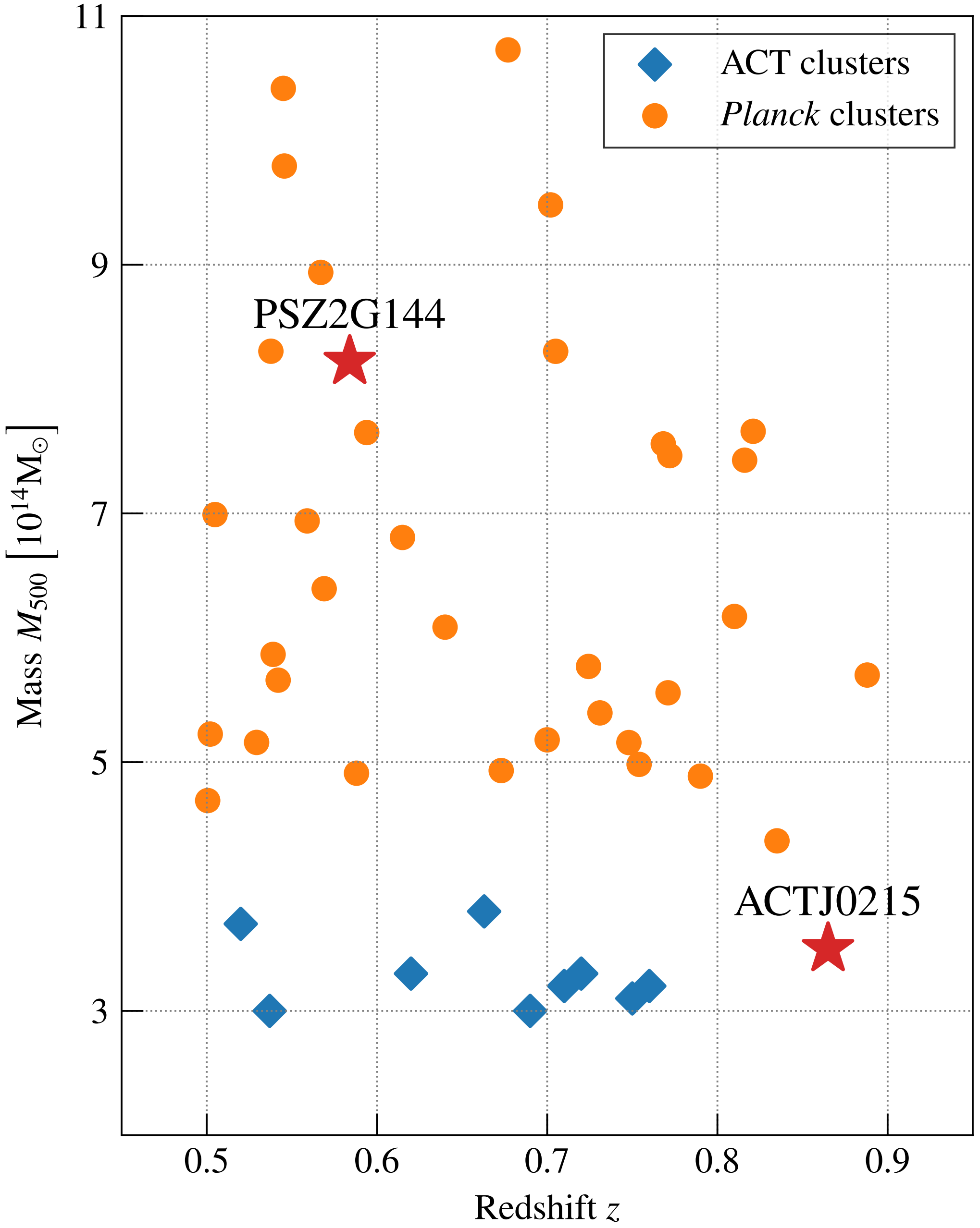
# CHOICE OF TARGET

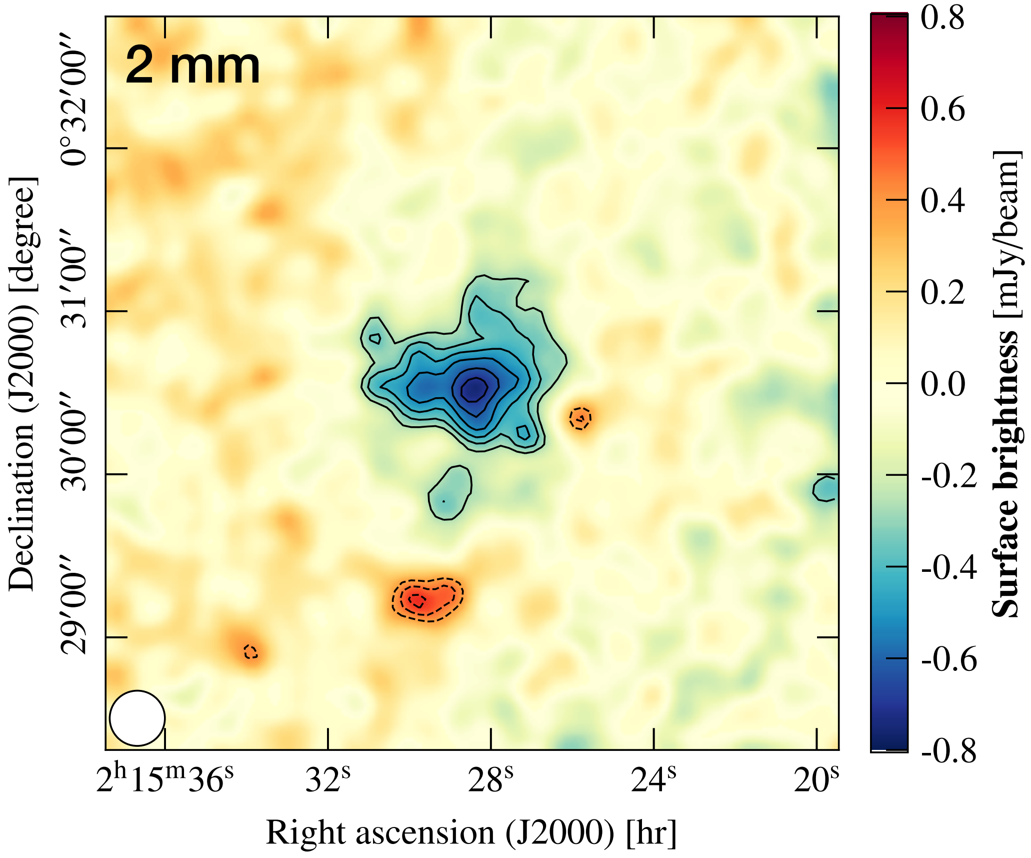


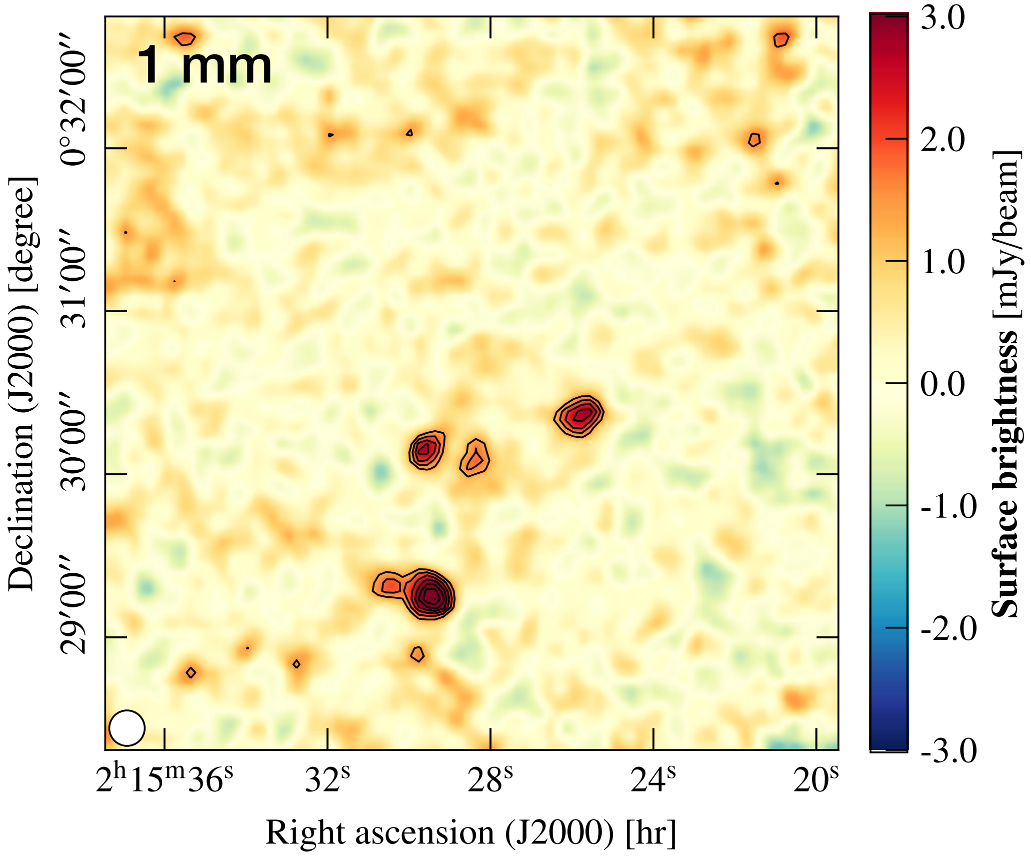
- **First cluster seen by NIKA2:** Science verification
  - Target: PSZ2-G144.83+25.11 ***Ruppin et al. (2018)***
  - *Planck*-detected cluster
  - High mass, low redshift
  - High observation time → high SNR
- **Next target:** tackle different possible challenges
  - Not detected by *Planck*
  - Low mass, high redshift
  - Standard observation time → normal SNR

→ **Next target:** ACT-CL J0215.4+0030
(aka ACTJ0215)

***Kéruzoré et al. (2020, submitted)***

# NIKA2 MAPS OF ACTJ0215





## At 150 GHz (2 mm):

- **SZ decrement** detected at $\sim 9\sigma$
  *Low: first NIKA2 cluster was* $\sim 14\sigma$
- **Faint** (<1 mJy peak), **small** (NIKA2 beam in bottom left corner)
- Large residual noise bands
- **Hints of point source contamination:**
  *Sources with positive fluxes compensate the SZ decrement*

## At 260 GHz (1.2 mm):

- No SZ detected (none expected given the noise level)
- Confirmation of point source contamination

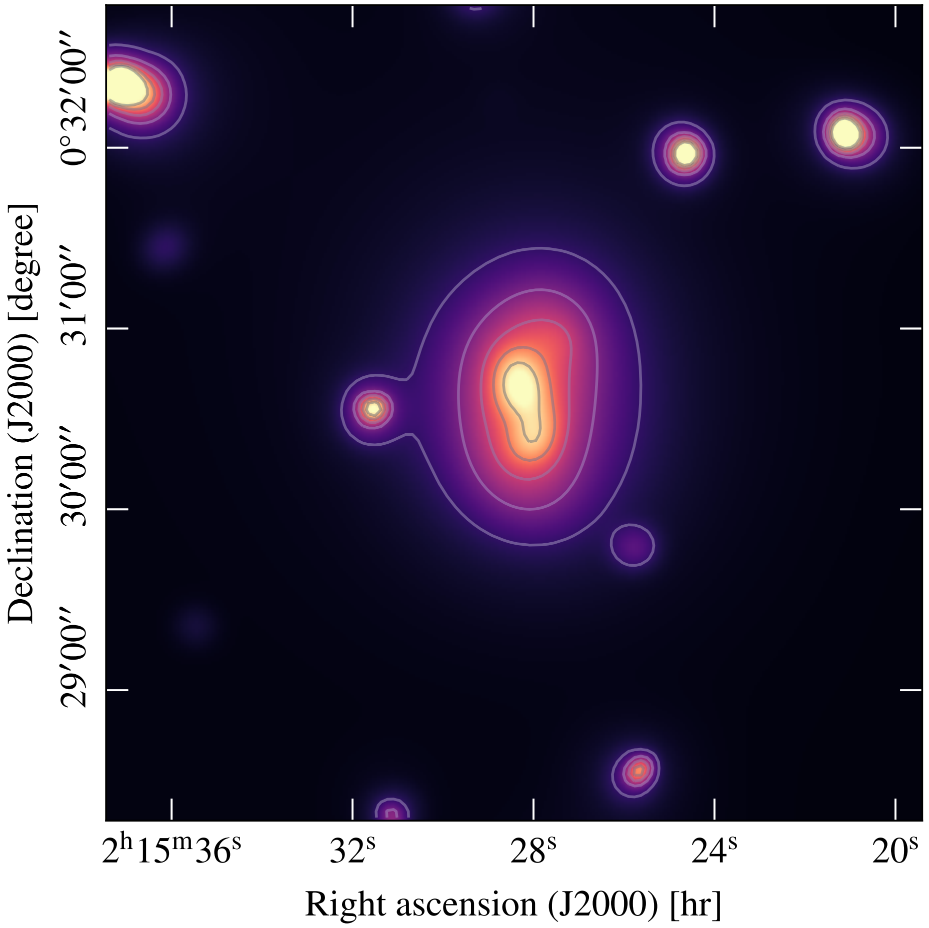
# X-RAY DATA

## XMM-*Newton* observations of the cluster:

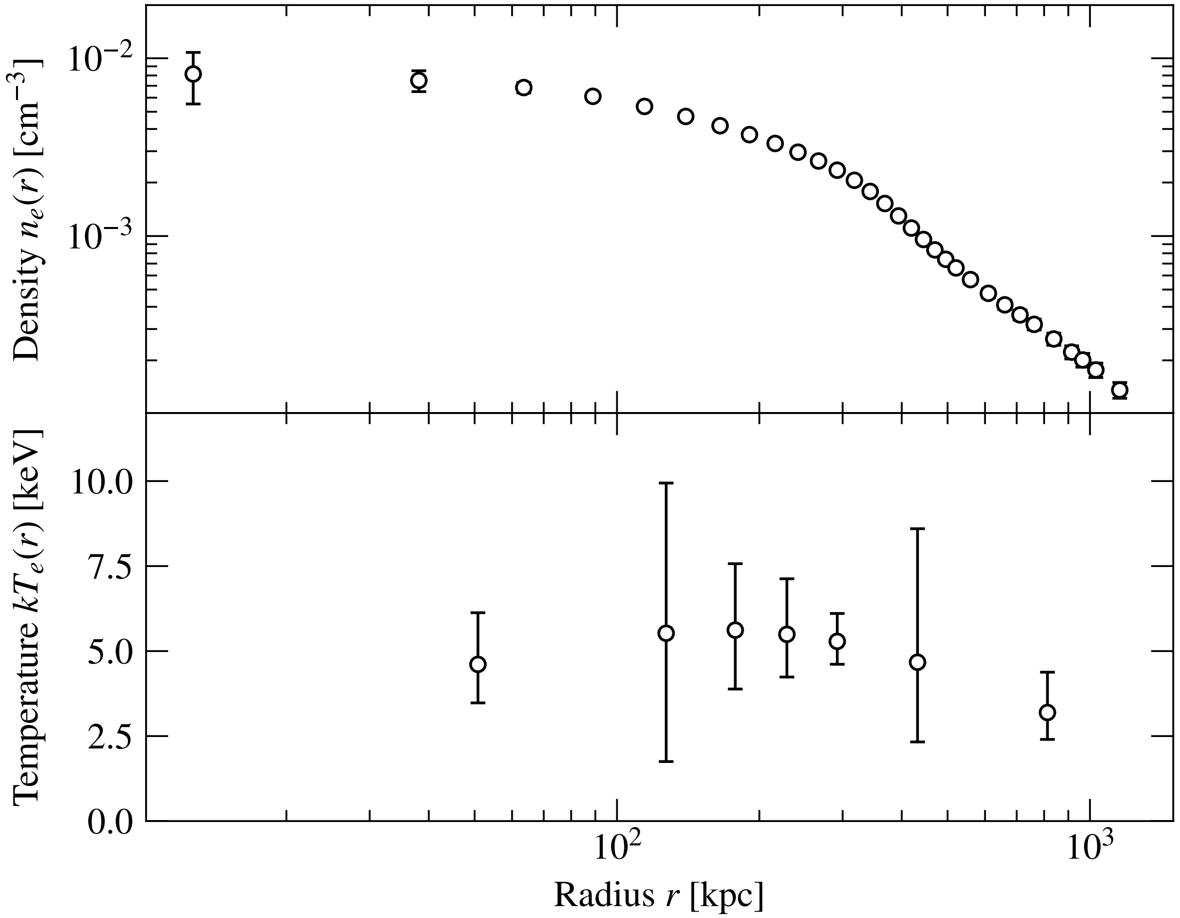
Deep: $t_{\text{obs}} = 37\ \text{ks}$ → deep enough to measure the **temperature** of the ICM through **X-ray spectroscopy**

→ **Very rare** at this mass and redshift: X-rays usually only give access to the density

### XMM-*Newton* map



### Thermodynamic profiles

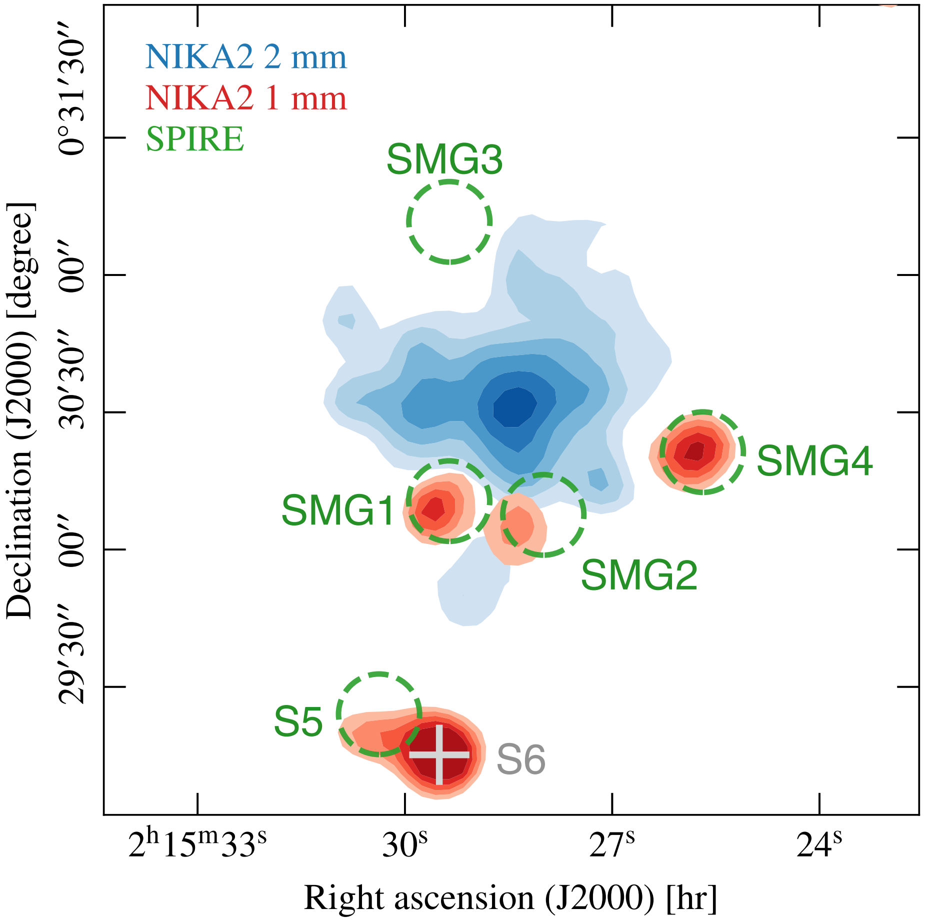


# IDENTIFICATION OF POINT SOURCES

## Are the point sources already known?

- **5 sub-millimeter galaxies (SMGs)** in our field according to *Herschel*
- SMG1, SMG2, SMG4 easily cross-matched with NIKA2 1 mm detections
- SMG3 has SNR<3 in NIKA2 at 1 mm
- Unclear situation for S5&6 (two sources?)
  - Far enough from the cluster that they are not an inconvenience
  - We remove them from the NIKA2 2mm map
- Other sources:
  - Fit a modified blackbody spectrum with *Herschel* data + NIKA2 1mm
  - Extrapolate at 2mm

  → Probability density for the 2mm flux

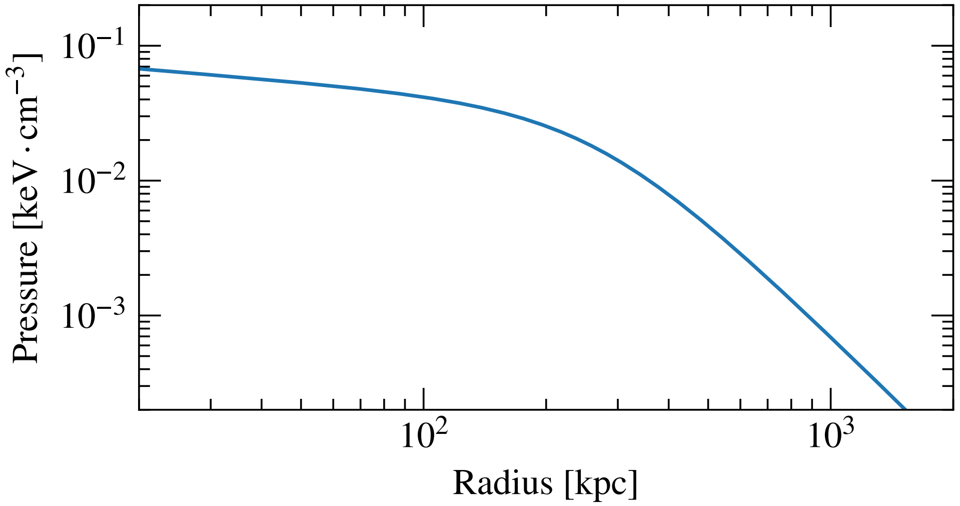


# JOINT SZ-POINT SOURCES MODEL

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

→ *Extension of the NIKA2 SZ pipeline to perform joint fits of SZ + point sources*

## 1) ICM SZ signal



○ Spherical symmetry → ICM pressure profile

gNFW model: $P_e(r) = P_0 \left(\frac{r}{r_p}\right)^{-c} \left[1 + \left(\frac{r}{r_p}\right)^{a}\right]^{(c-b)/a}$

→ 5 parameters: $P_0$, global amplitude,

$r_p, a$, transition radius/steepness

$b, c$, external/internal slopes

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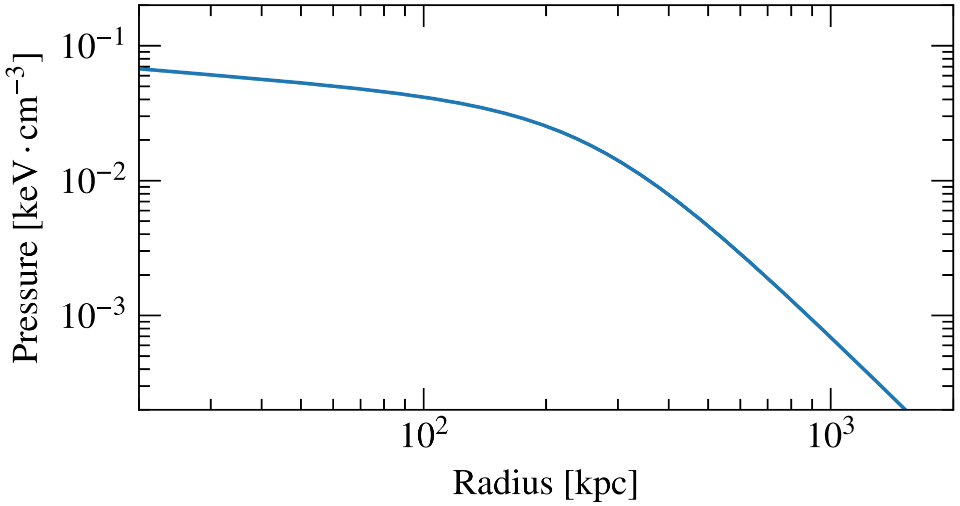
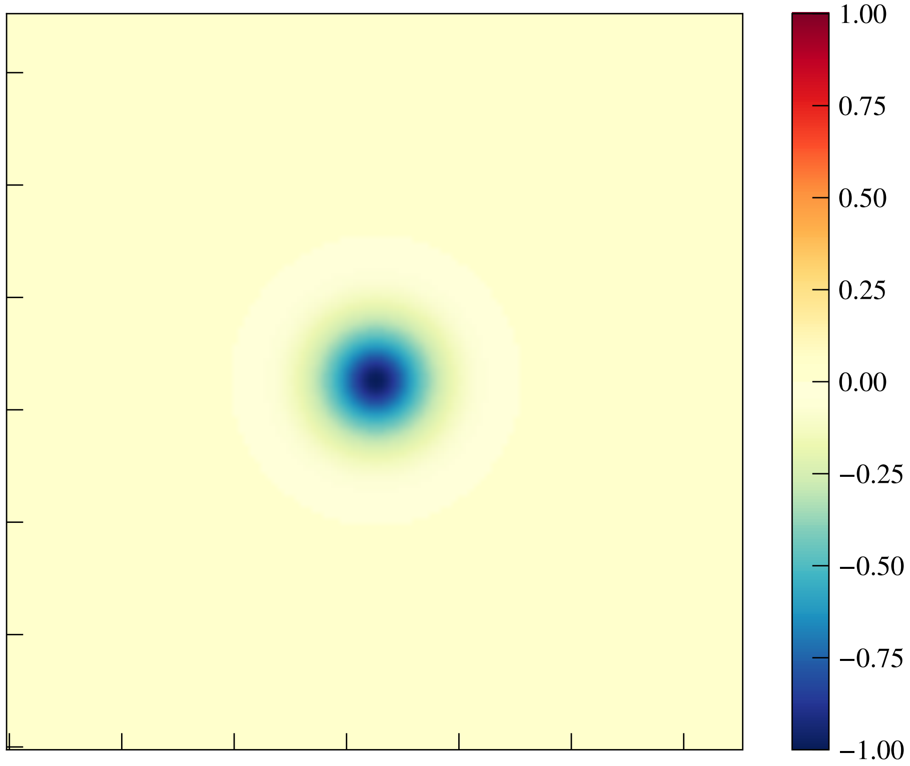


- Integrated along the line of sight & calibrated
  Convolved by the NIKA2 instrumental response

→ **SZ model map**



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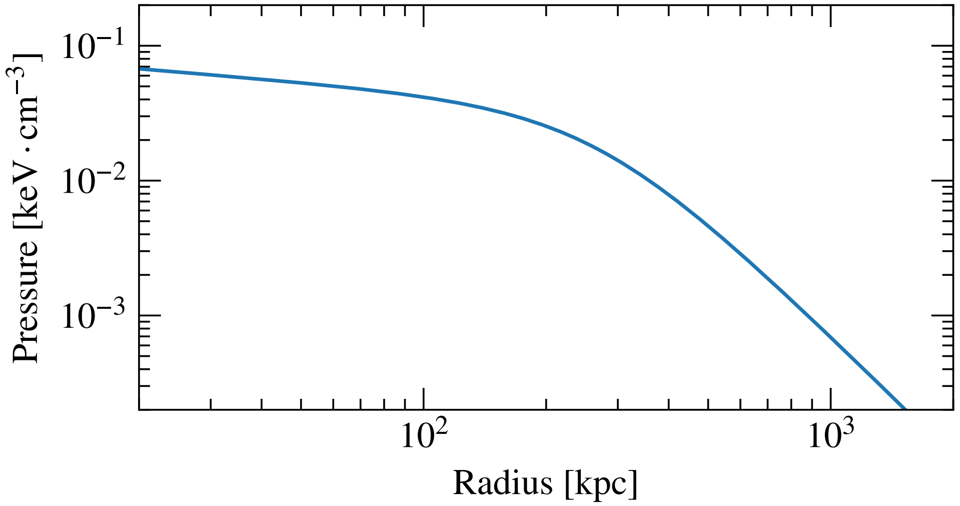
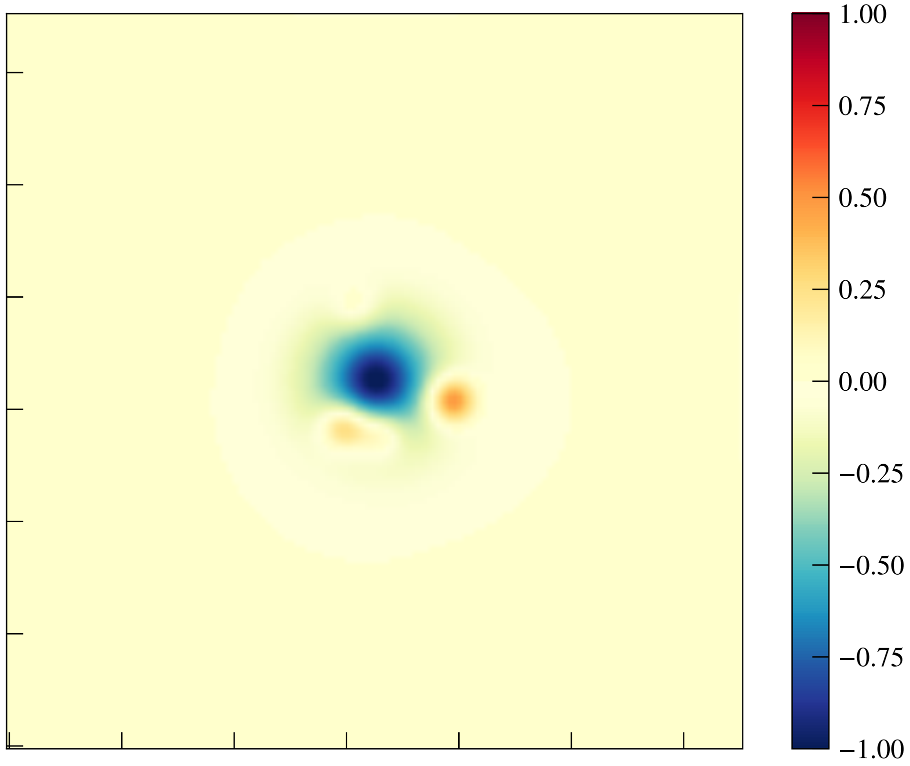


- Integrated along the line of sight & calibrated
  Convolved by the NIKA2 instrumental response

  → **SZ model map**

## 2) Point source contamination

- Model: NIKA2 PSF with variable amplitude
- Positions known from the NIKA2 260 GHz map
- Fluxes as free parameters with priors from SED extrapolation (NIKA2 + *Herschel*)



Parameters $\theta$ → model map $M(\theta)$

# JOINT MODEL FITTING

Fit the joint model (SZ + point sources) on the NIKA2 250 GHz map using MCMC

Likelihood: $$-2\log\mathcal{L}(\theta) = \underbrace{\sum_{\text{pixels}} \left(D - M(\theta)\right)^{\mathrm{T}} C^{-1} \left(D - M(\theta)\right)}_{} + \left(\frac{Y_{500}^{\mathrm{ACT}} - Y_{500}(\theta)}{\Delta Y_{500}^{\mathrm{ACT}}}\right)^2$$

*Constraints from NIKA2 150 GHz map*

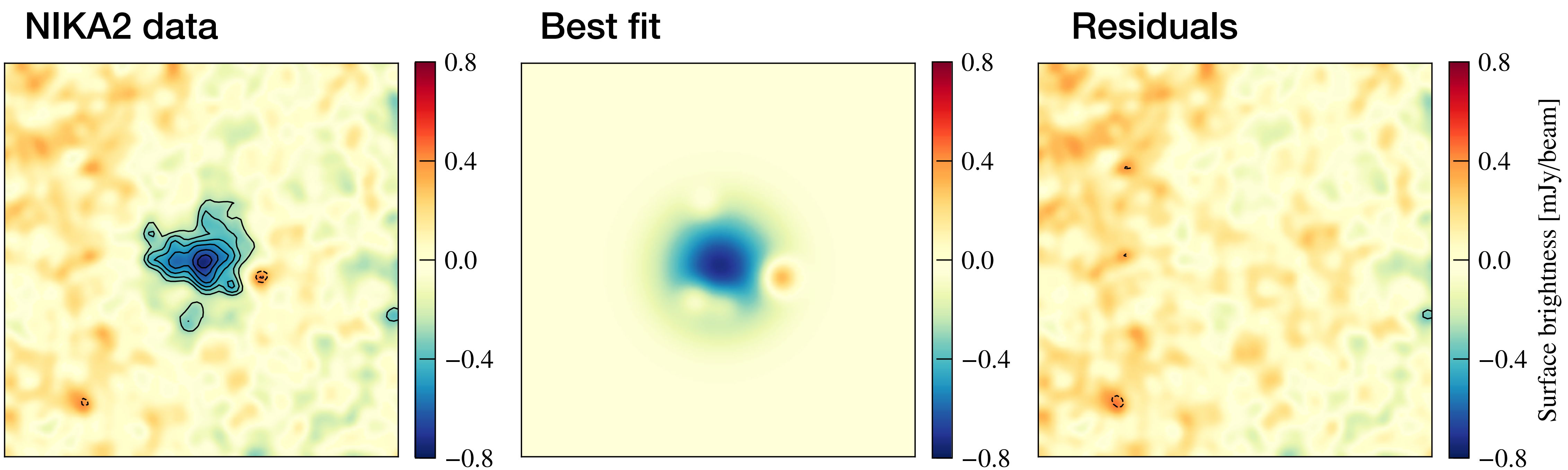
*Constraints from ACT integrated signal*

$\theta$ : parameters

$M$ : model map

$D$ : NIKA2 150 GHz map

$C$ : Noise covariance

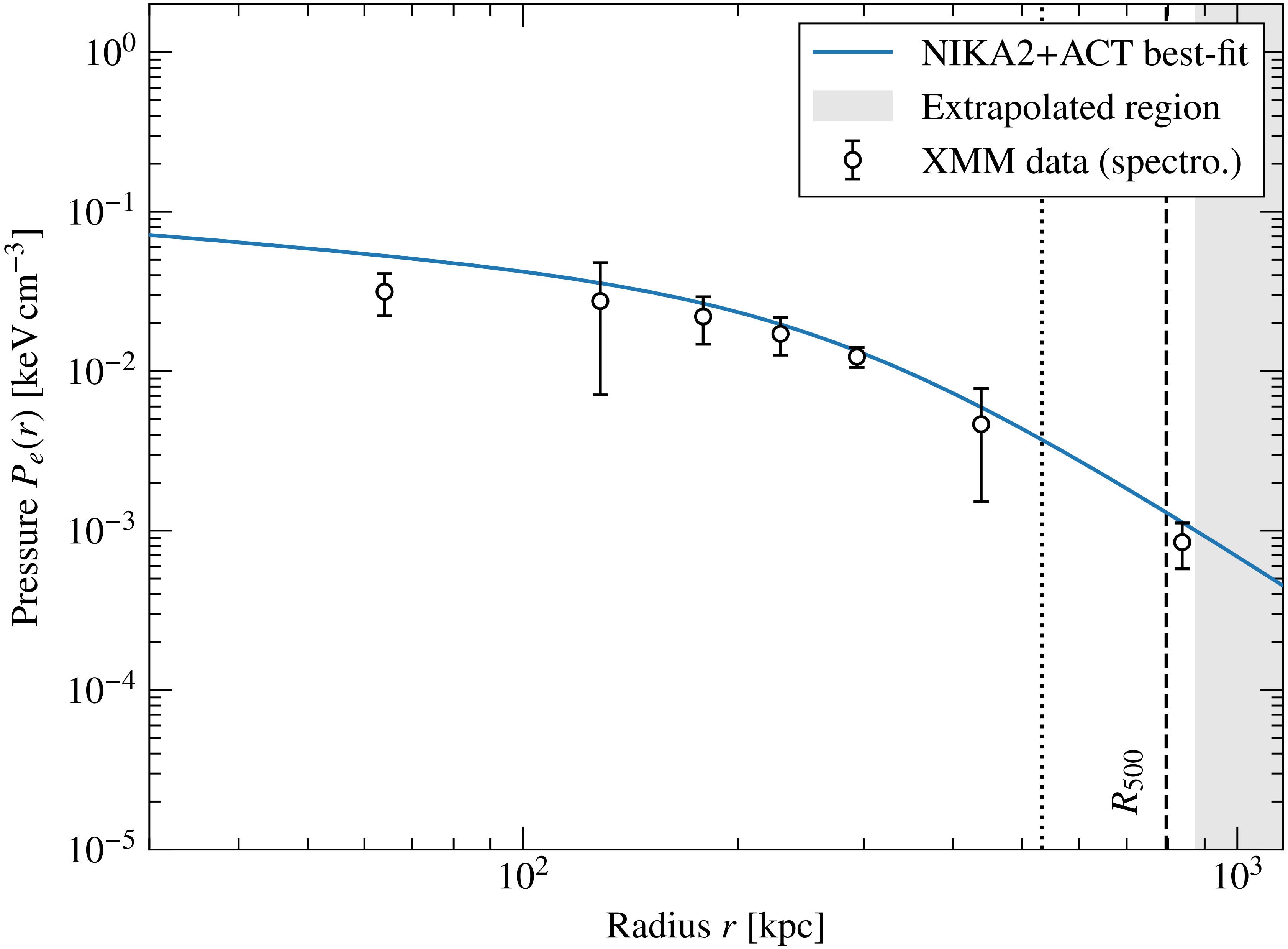


NB: SMG5&6 were subtracted

Residuals compatible with noise

→ The NIKA2 data are well-described by a gNFW pressure profile + point sources

# FIT RESULTS: PRESSURE PROFILE OF ACTJ0215



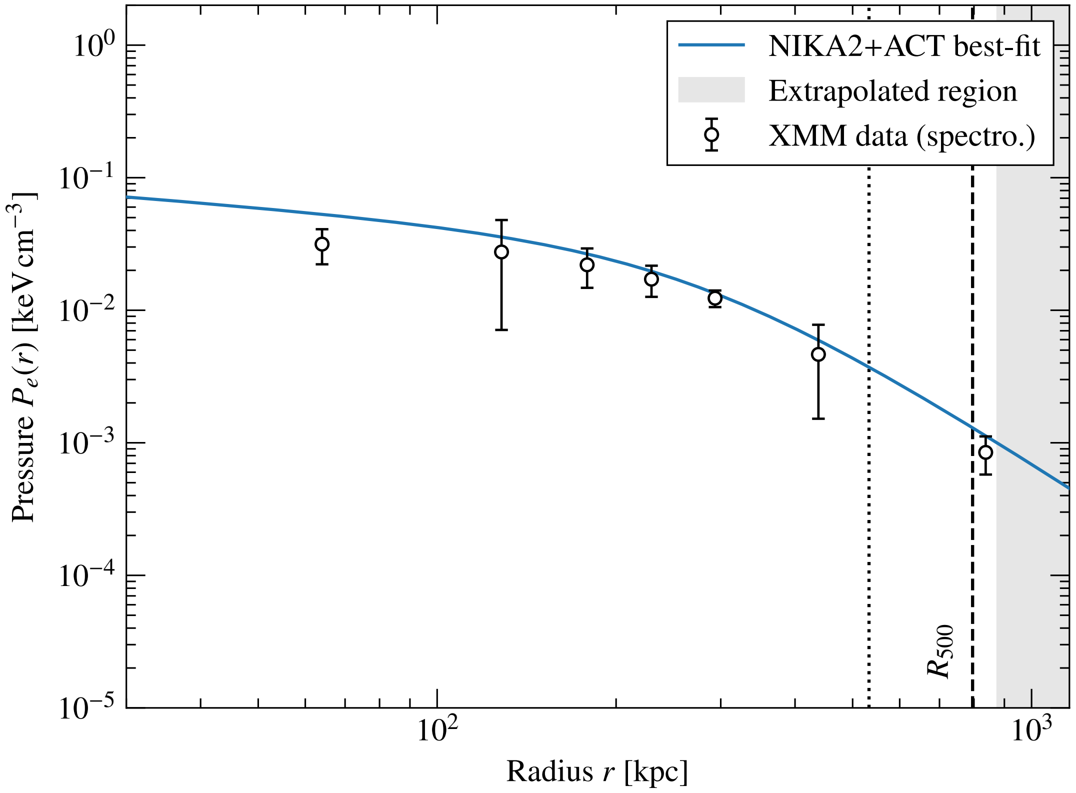
– – – : NIKA2+ACT+XMM $R_{500}$

·········· : NIKA2 SNR = 3 limit

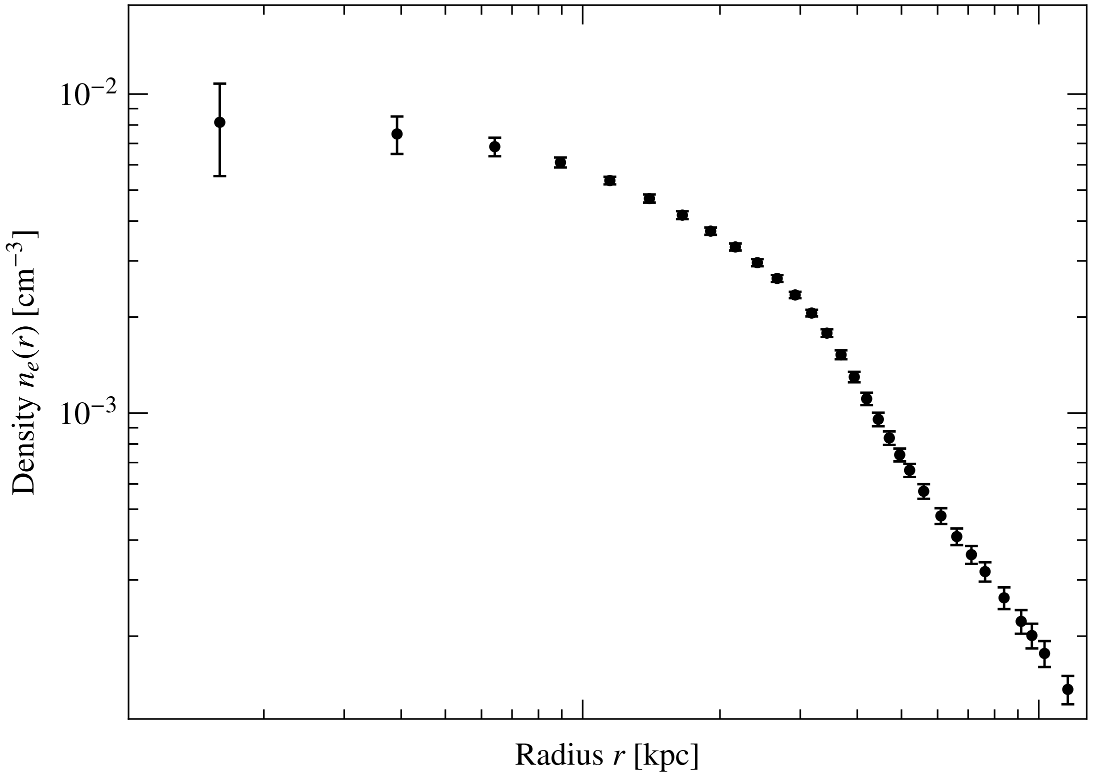
→ Pressure profile compatible with XMM-only data

# NIKA2+XMM THERMODYNAMICS

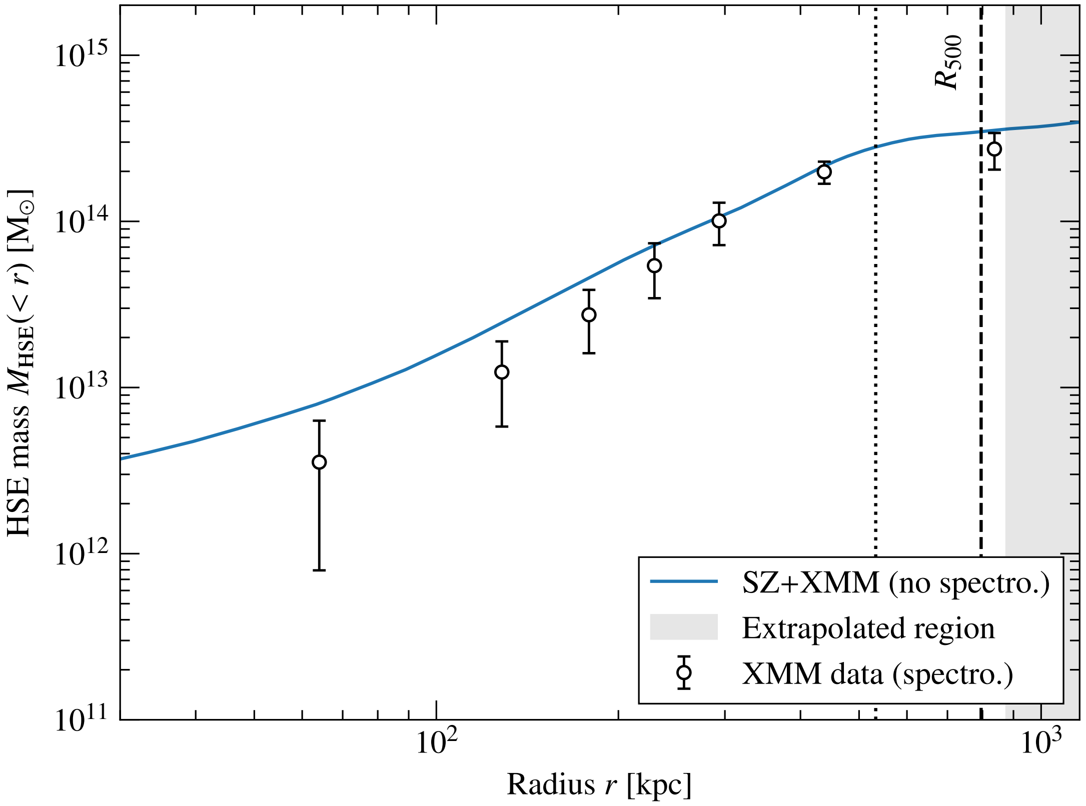
### NIKA2 pressure



### XMM density



**HSE Mass** $M^{\mathrm{HSE}}(r) \propto \frac{r^2}{n_e}\frac{\mathrm{d}P_e}{\mathrm{d}r}$



→ Good agreement between NIKA2+XMM and XMM-spectro

# INTEGRATED QUANTITIES

| | ACT | XMM-*Newton* | NIKA2+XMM |
|---|---|---|---|
| $R_{500}$ [kpc] | $877.8 \pm 46.2$ | $780.9 \pm 19.8$ | $810.1 \pm 41.9$ |
| $\mathcal{D}_A^2\ Y_{500}$ $[10^{-5}\ \mathrm{Mpc}^2]$ | $4.07 \pm 1.13$ | – | $3.76 \pm 0.39$ |
| $M_{500}$ $[10^{14}\ \mathrm{M}_\odot]$ | $3.5 \pm 0.8$ | $2.48 \pm 0.70$ | $3.79 \pm 0.58$ |
| | **From ACT & $Y_{500} - M_{500}$ scal. rel.** | *Hydrostatic mass* | *Hydrostatic mass* |

- Our measurements agree with previous results
- Improved precision on $Y_{500}$ thanks to high angular resolution
- Improved precision on $M_{500}$
  - → Important: masses computed from scaling relations usually have smaller error bars than hydrostatic mass measurements *(and may be biased)*

# CONCLUSIONS OF THE ANALYSIS

- Study designed as a **“worst case scenario”** for the NIKA2 LPSZ:
  - A **faint** cluster (low mass, high z)
  - Detected with **modest SNR**
  - Strongly contaminated by point sources
- Nonetheless, we are able to precisely measure thermodynamical properties of the ICM by combining SZ and X-rays

Very promising for the future of the NIKA2 LPSZ
and its impact on cluster cosmology

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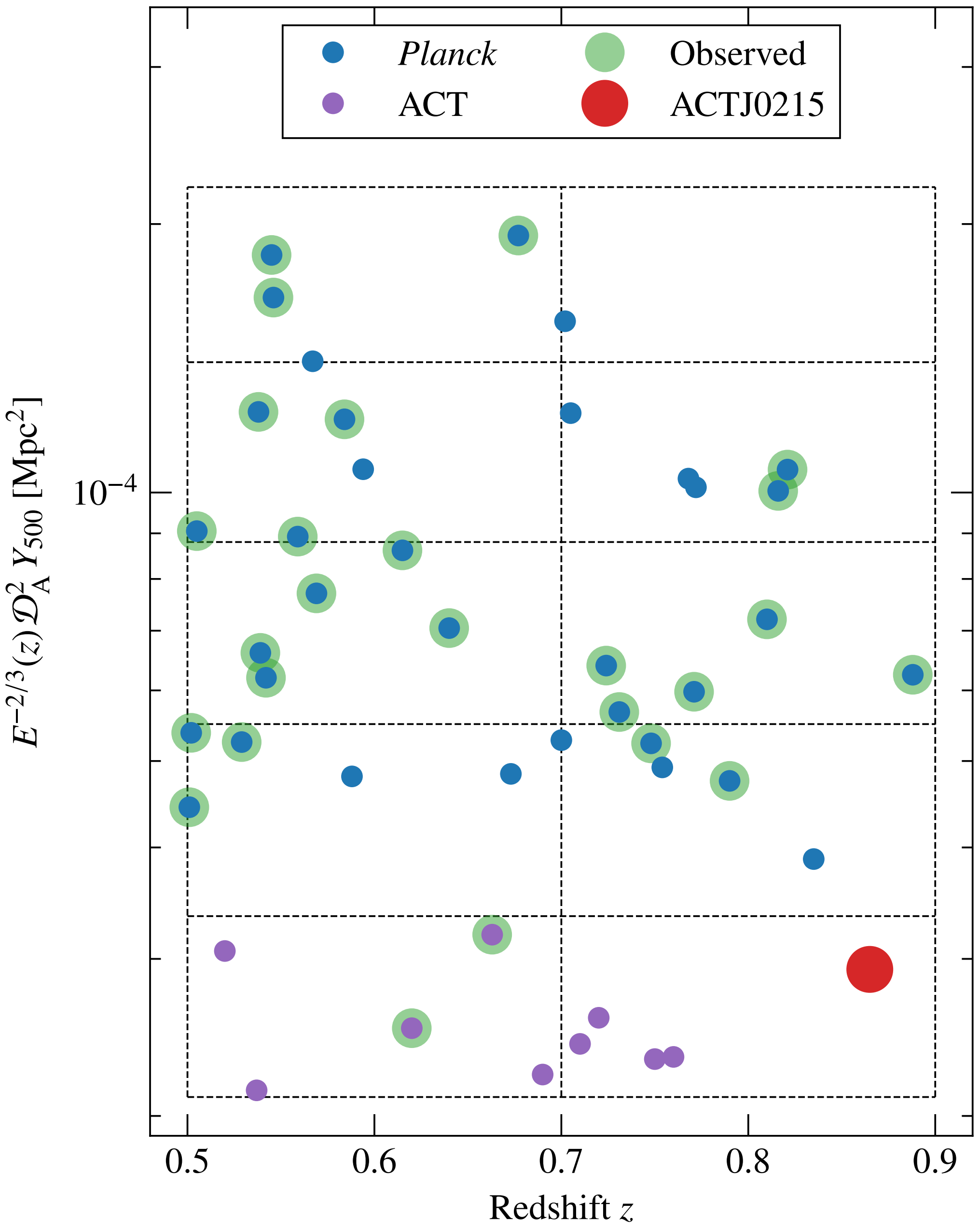
# LPSZ PARTIAL SAMPLE RESULTS



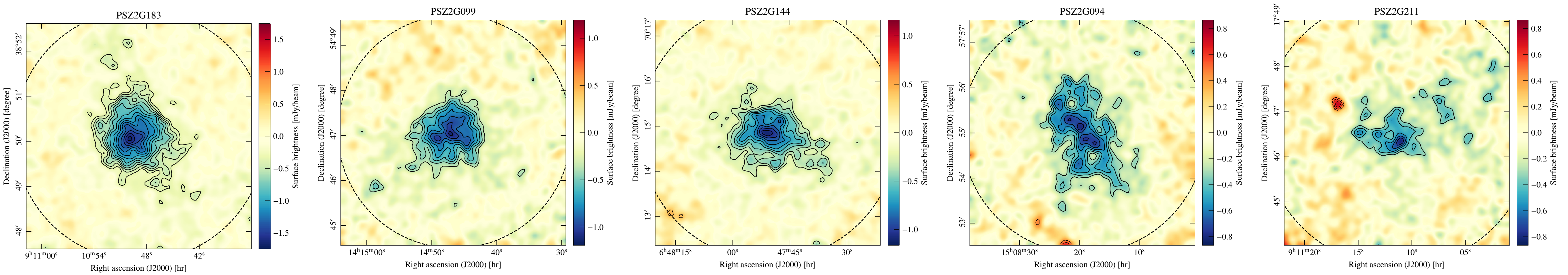
First redshift bin of the LPSZ almost entirely observed

→ Possibility to run a “full analysis” of the half sample:

- Mean pressure profile
- Scaling relation

To run this analysis, we need:

1. A standard method to remove noise in maps
2. An efficient pipeline to extract pressure profiles
3. Tools to fit a scaling relation



# 3RD YEAR PHD PLAN

1. Improvement of the noise removal process

   → Tradeoff between removing noise and keeping signal that works for all clusters

2. Acceleration of the pressure profile extraction

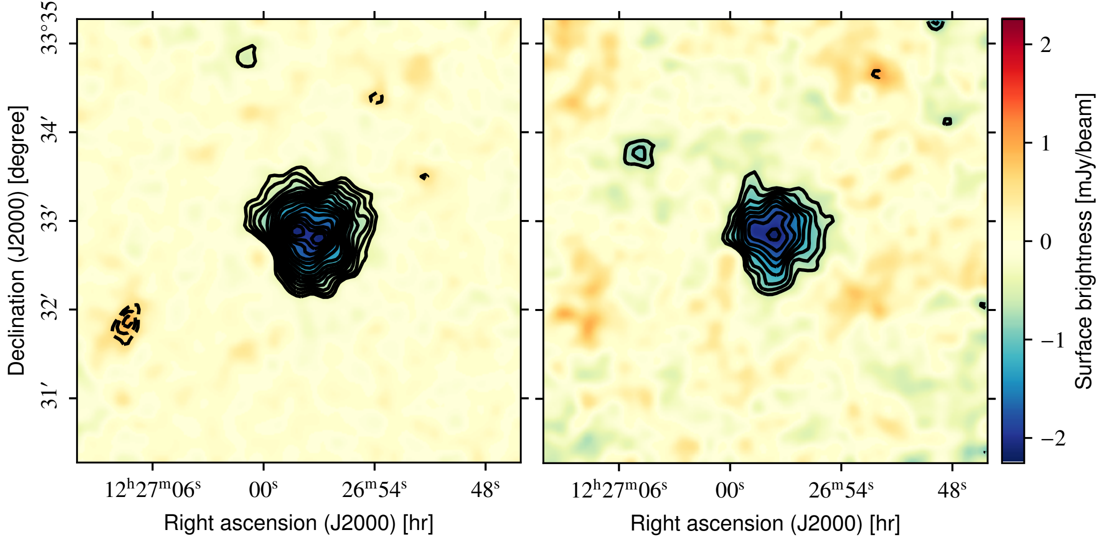
   → Factor 15~20 achieved, needs to be more thoroughly tested

3. Prepare scaling relations computations

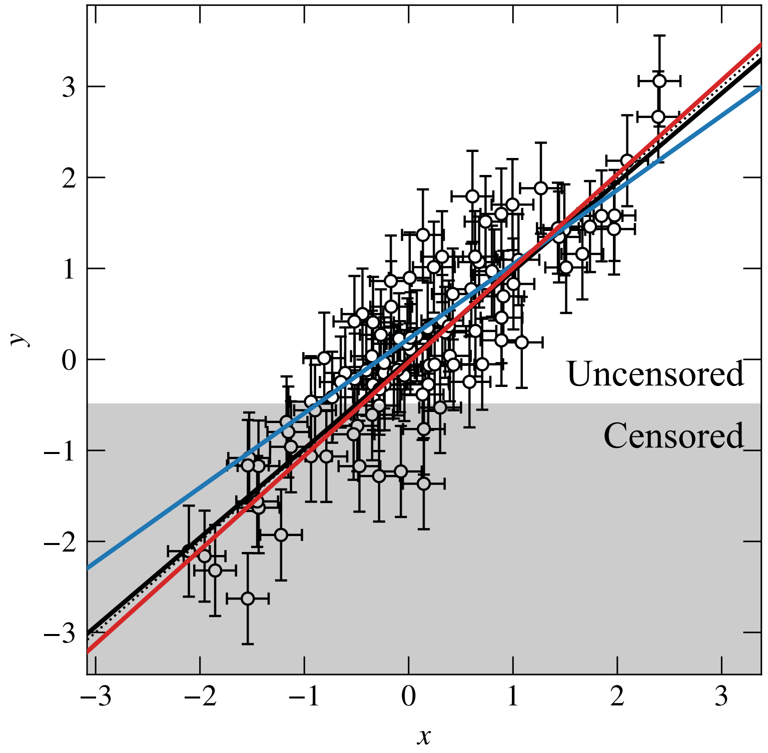
   → Not a trivial fit (selection effects, …)
   → Development in progress

   → Test on hydrodynamical simulations of galaxy clusters

*Maps by M. Muñoz*



| | PANCO | PANCO2 |
|---|---|---|
| Model computation time [ms] | 503 ± 60 | 27 ± 3 |



# CONCLUSIONS

- Context of my PhD: NIKA2 SZ Large Program
- First results on an individual target promising:
    - High-precision thermodynamical properties for a faint, small, contaminated target
    - Promising for the rest of the LPSZ, and for its impact on cosmology
- Ongoing developments towards the first LPSZ cosmological results (half sample)