High resolution SZ observations for cluster cosmology with NIKA2

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On behalf of the NIKA2 collaboration

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Outlines

1. Cosmological context and the NIKA2 experiment
2. From galaxy clusters maps to their thermodynamical properties
3. Morphological study
4. Conclusion

Sunyaev-Zel'dovich effect

Galaxy clusters

- The largest gravitationally bound objects in the universe with $M \in 10^{13} - 10^{15} M_{\odot}$
- Final step of hierarchical large scale structure formation : $z < 3$
- Multi-component systems : ~ 3% of galaxies, ~ 12% of hot ionised gas (ICM), ~85% of dark matter

Multi-wavelengths observables

The thermal Sunyaev-Zel'dovich effect (tSZ)

Spectral distortion of the cosmic microwave background (CMB) spectrum induced by the Compton scattering of the CMB photons by the electrons of the ICM

- Independent of the redshift
- Decrease in the intensity at frequencies ≤ 218 GHz
- Increase in the intensity at frequencies ≥ 218 GHz

Catalogues of several thousands clusters detected via tSZ

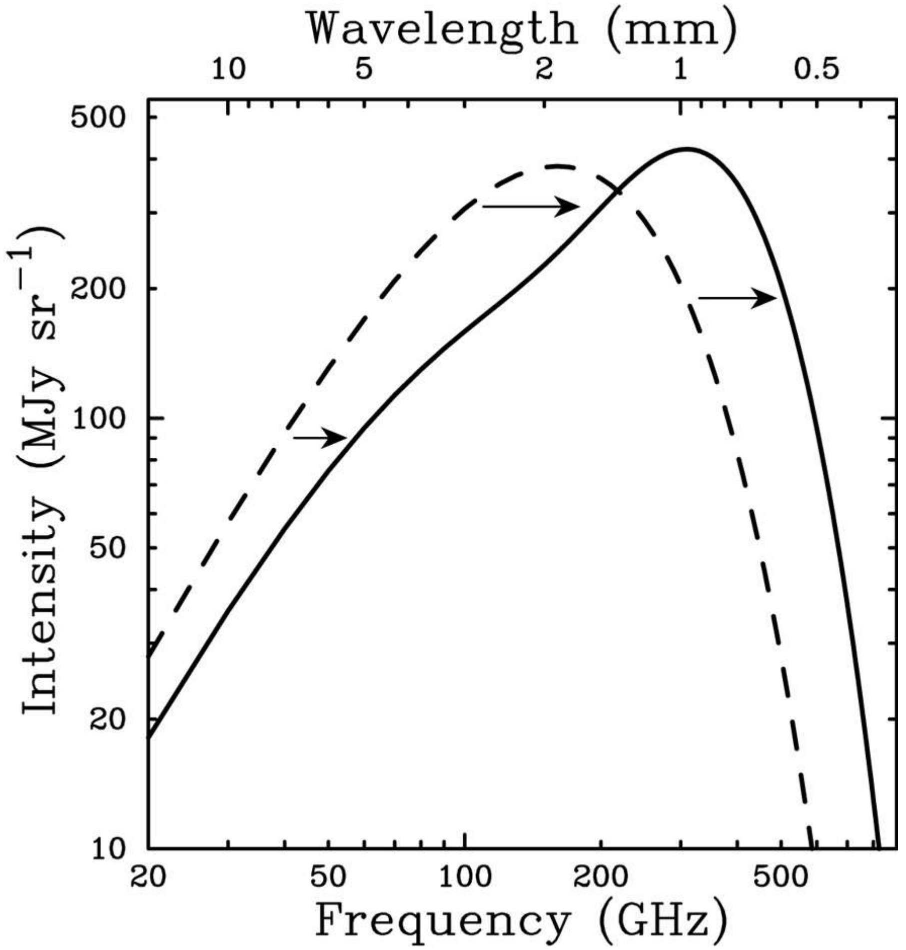


Illustration of the tSZ effect (exaggerated)

SZ cosmology

Cluster number count

The cluster abundance in intervals of mass and redshift

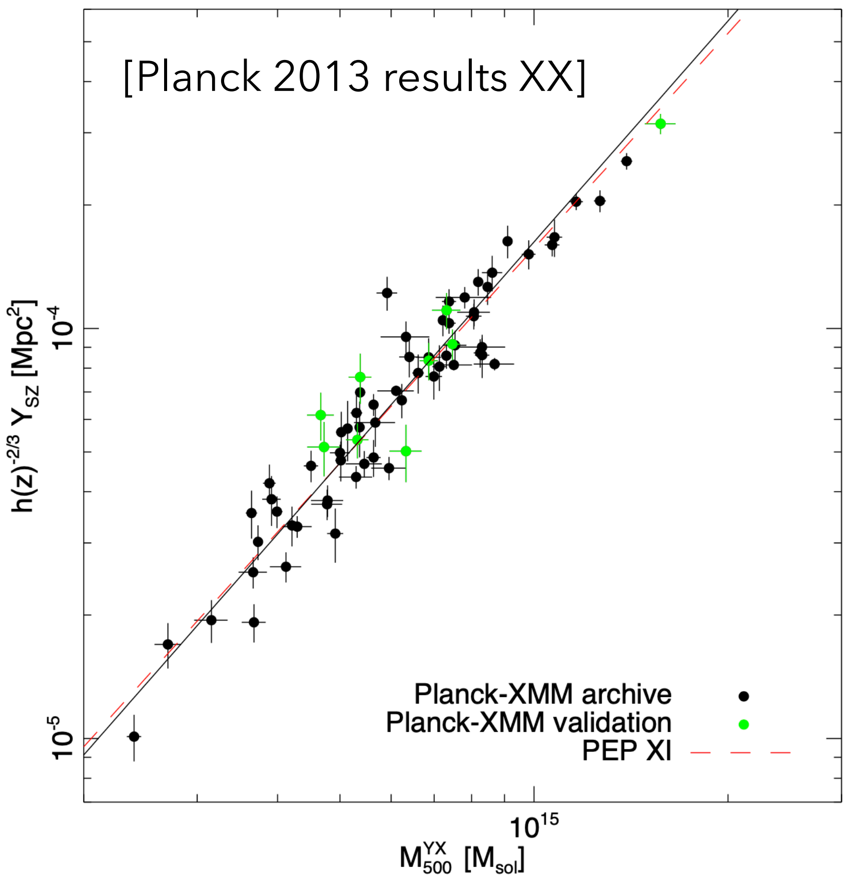
$$\frac{d^2N}{dMdz}$$

SZ power spectrum

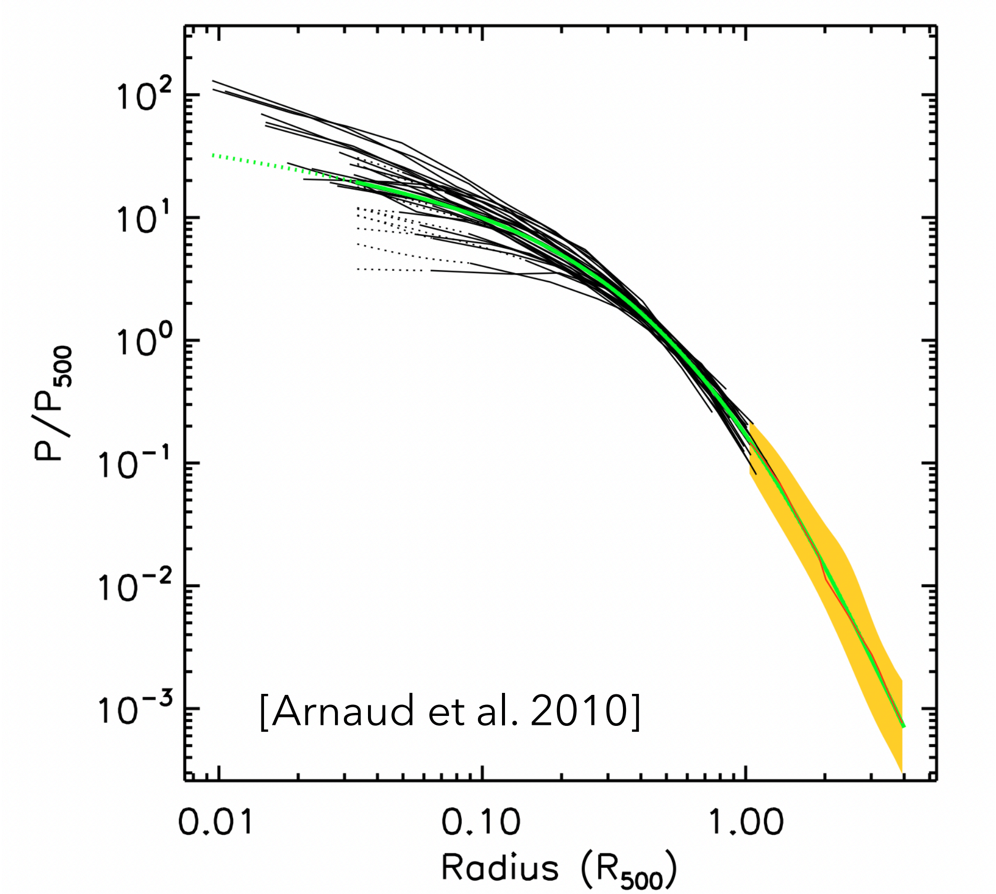
Angular power spectrum of the SZ-map

$$C_l^{SZ}$$

SZ-M scaling relation



Mean pressure profile



We need a precise characterization of both products for SZ cosmology

Cluster hydrostatic mass

Two hypotheses : - At the hydrostatic equilibrium
- Spherical

$$M_{HSE}(<r) \propto \frac{r^2}{n_e(r)} \frac{dP_e(r)}{dr}$$

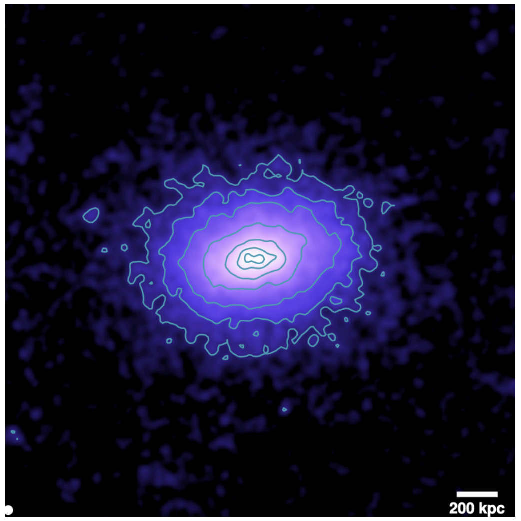
Multi-wavelengths mass calibration

Electronic density from X-rays

X-ray observable : Surface brightness

$$S_X \propto \int n_e^2$$

→ XMM-Newton



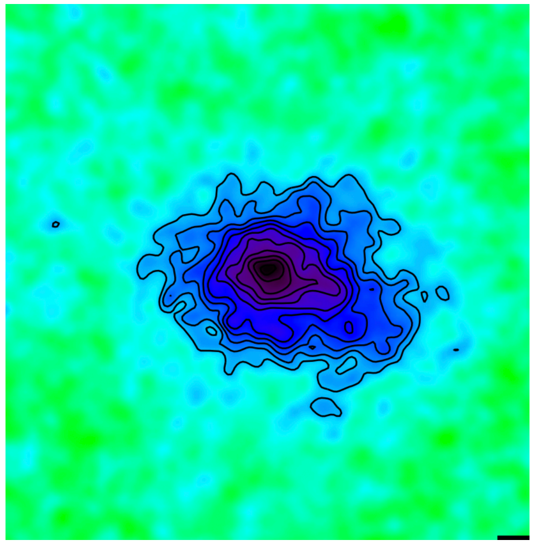
Electronic pressure from SZ data

SZ observable : Compton parameter

$$\Delta I_{tSZ}/I_0 = yf(x, T_e)$$

$$y \propto \int P_e \, dl$$

→ NIKA2



Powerful method when SZ and X-ray resolutions are similar

NIKA2

The NIKA2 instrument : Millimeter camera of 2900 Kinetic Inductance Detectors (KIDs) installed at the IRAM 30m telescope and operating since 2017

Performances

Observing band	150 GHz	260 GHz
FWHM [arcsec]	17.6 ± 0.1	11.1 ± 0.2
Field of view [arcmin]	6.5	6.5
Mapping speed $[\text{arcmin}^2 \cdot \text{mJy}^{-2} \cdot \text{h}^{-1}]$	1388 ± 174	111 ± 11

[Perotto et al. 2020]

- Dual band
  → *Enables the exploitation of the spectral dependence of SZ*
- High angular resolution
  → *Provides detailed information about the structure of the ICM*
- Large field of view
  → *Allows us to map extended regions*
- High sensitivity
  → *Efficient at mapping faint signal*

Powerful instrument to study the tSZ effect

The NIKA2 Sunyaev Zel'dovich Large Program (LPSZ)

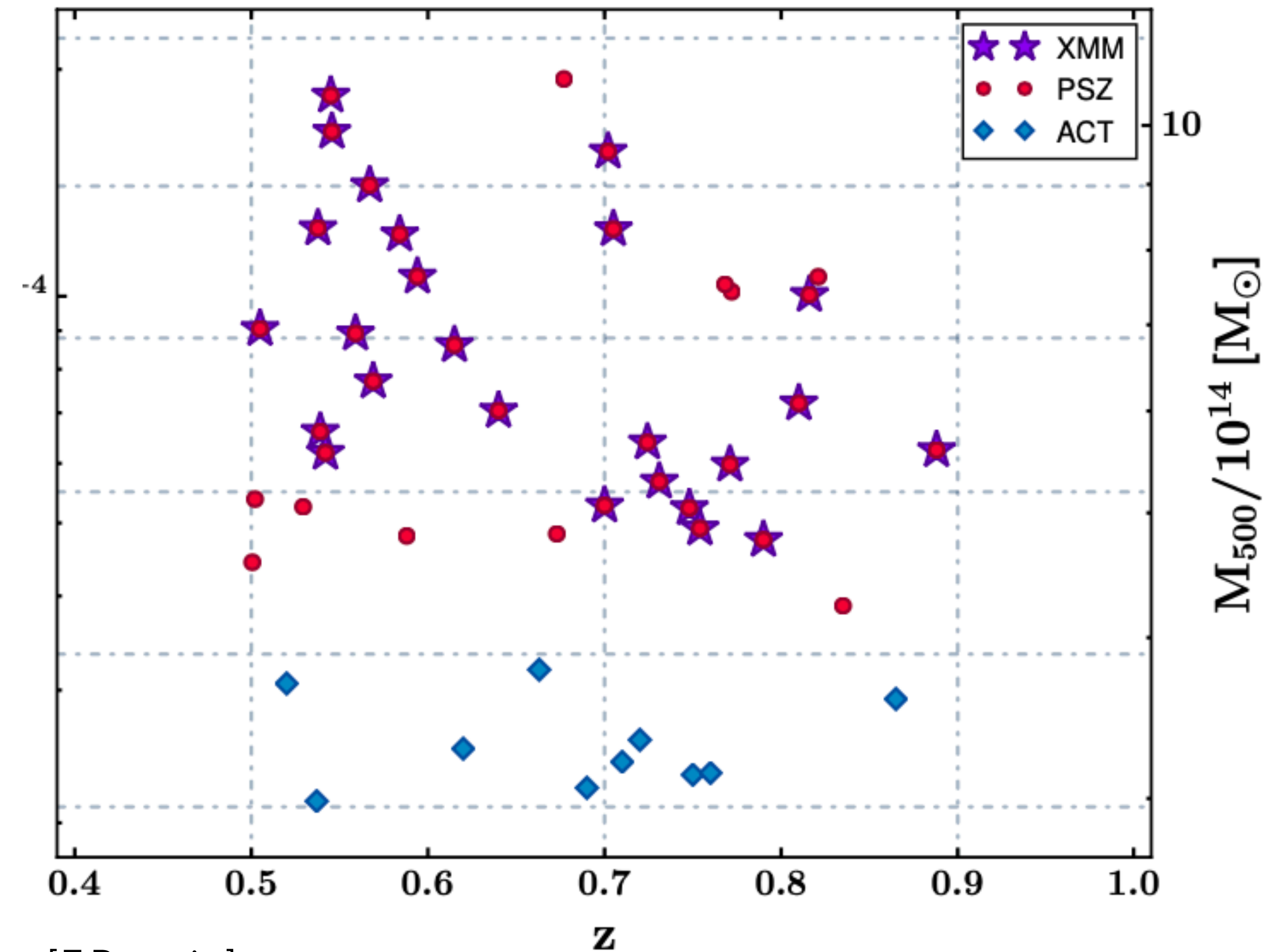
High angular resolution follow-up of 45 Planck and ACT galaxy clusters

[Mayet et al. 2020] [Perotto et al. 2021]

Synergy between NIKA2 and XMM-Newton

Precise estimation of hydrostatic masses

Precise characterization of the mean pressure profile and SZ-M scaling relation



[F.Ruppin]

Status of the LP-SZ

For now : 40/45 clusters already observed

–> On-going study on a sub-sample of 20 clusters (at least 3 per mass bin)

–> Study the systematics affecting the pressure and mass profiles reconstruction

NIKA2 150 GHz maps for the selected sub-sample

Status of the LP-SZ

On-going study on a sub-sample of 20 clusters

☐ Analysis already performed and published

Ruppin et al. 2018

Keruzore et al. 2020

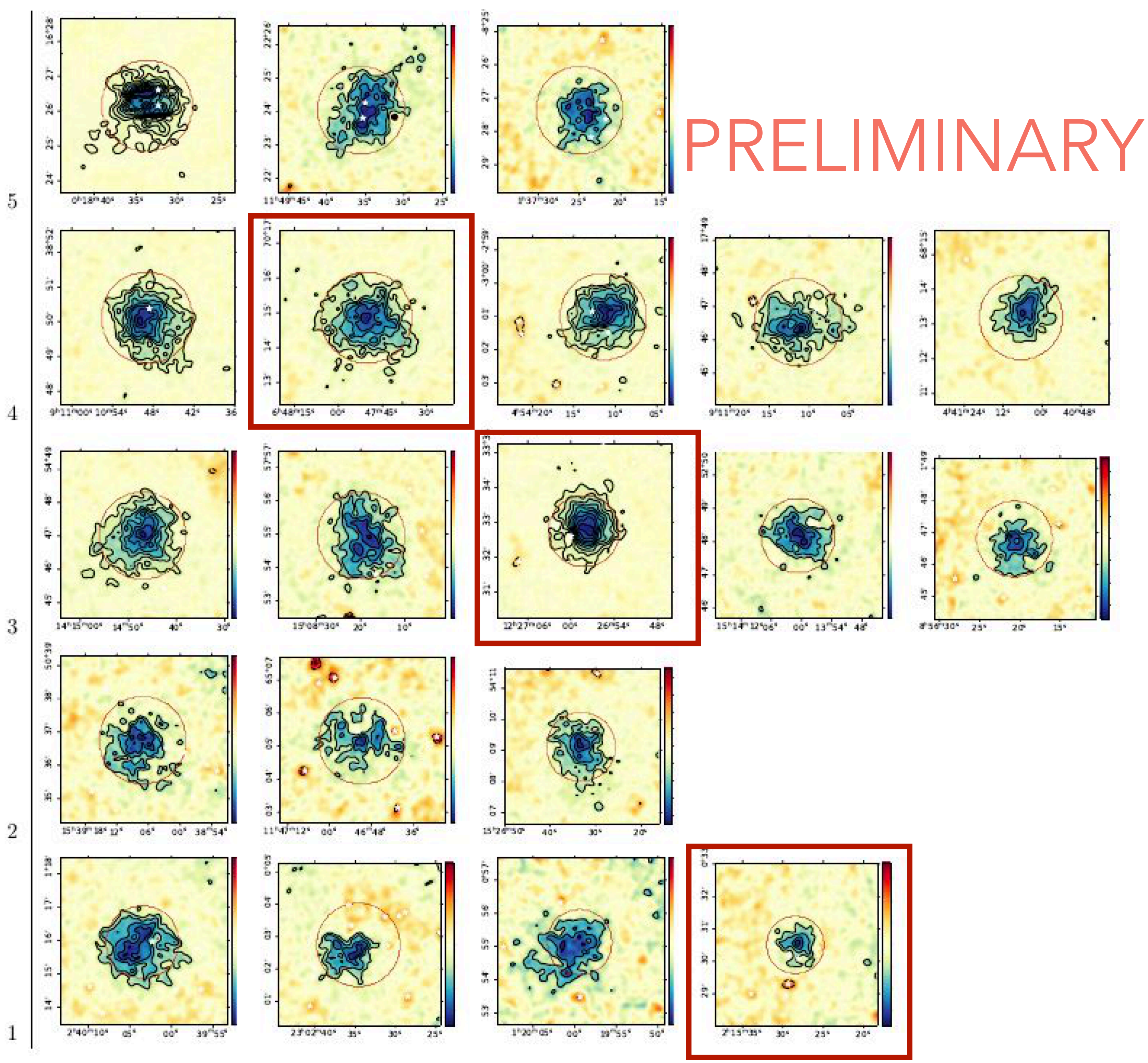
Muñoz-Echeverría et al. 2022

High signal to noise measurements

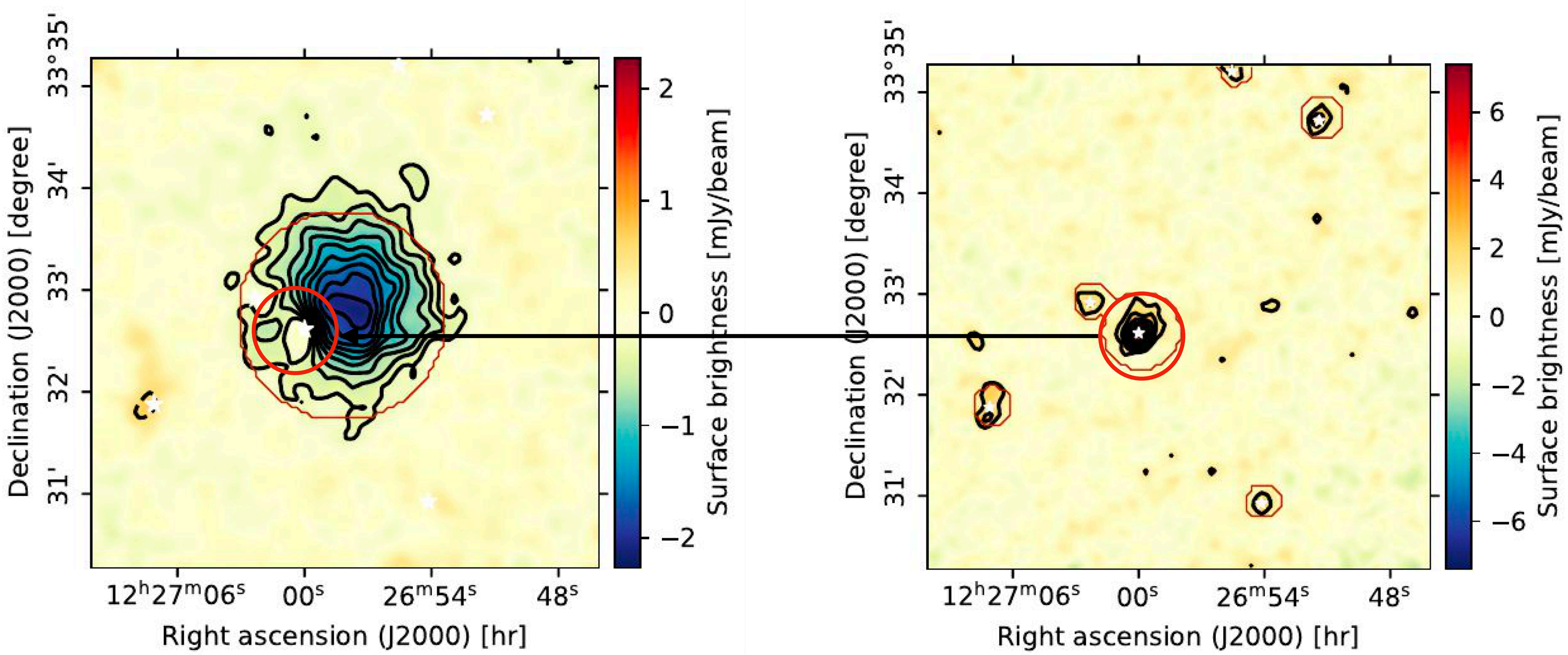
Diversity of morphologies

Some of them are contaminated by point sources

Targeted clusters



Point sources



150 GHz (left) and 260 GHz (right) maps of PSZ2G160
Levels : signal on noise ratio beginning at $\pm 3\sigma$ with 2σ spacing

At 150 GHz :

Hint of point sources contamination
Sources with positive SZ flux compensate the SZ decrement

At 260 GHz :

No cluster signal detected (as expected)

Point sources contamination confirmed
Sources close to the cluster

Need to take this contamination into account

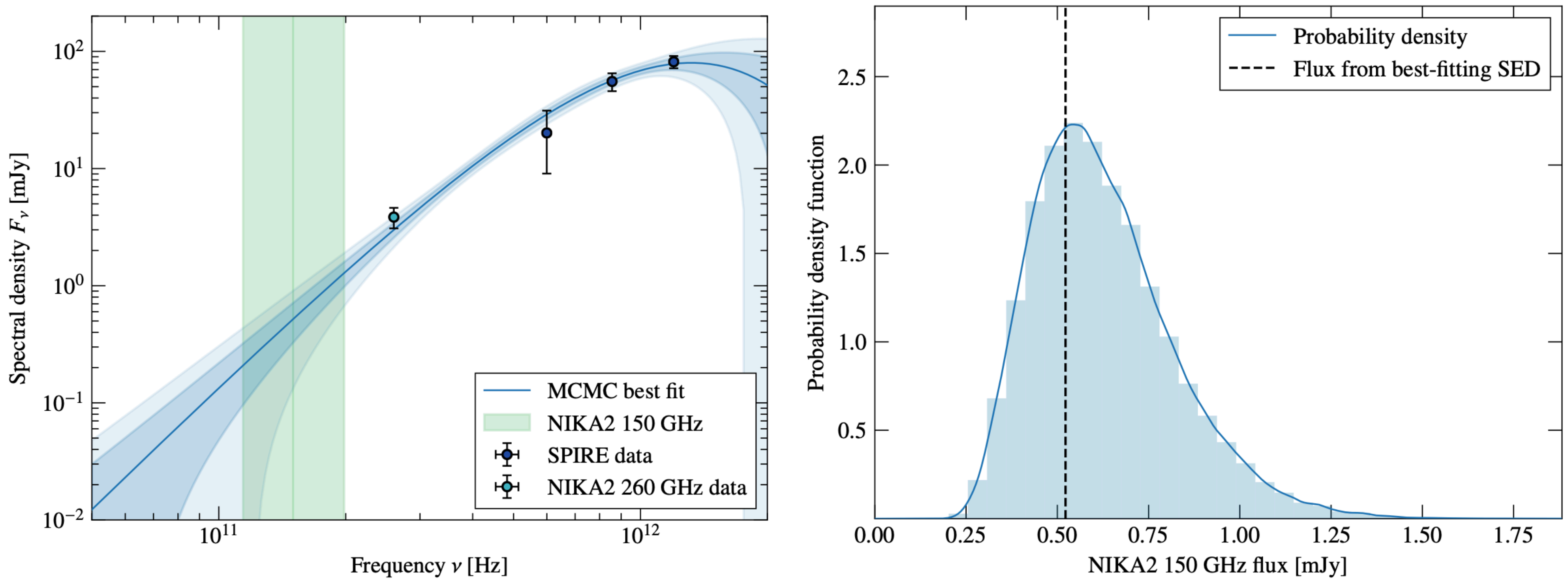
Point sources flux estimate

Methods

Using the 260 GHz NIKA2 map : fit of the flux in the map as a 2D Gaussian

Method 1 : We can extrapolate the flux at 150 GHz ($\propto$ 260 GHz estimated flux)

Method 2 : External data from the Herschel SPIRE instrument : gives fluxes at other frequencies
  –> We can fit the 150 GHz flux using a MCMC



[Keruzore et al. 2020]

We get a PDF of each point source flux at 150 GHz

We can model point source fluxes jointly with the cluster's pressure profile using this PDF as prior

From maps to thermodynamical properties

NIKA2 150 GHz map = ICM SZ signal + point sources + noise

ICM SZ signal

Spherical symmetry : 3D ICM pressure profile

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

–> 5 parameters : P_0 amplitude

r_p, a transition radius/ steepness

c, b internal/ external slopes

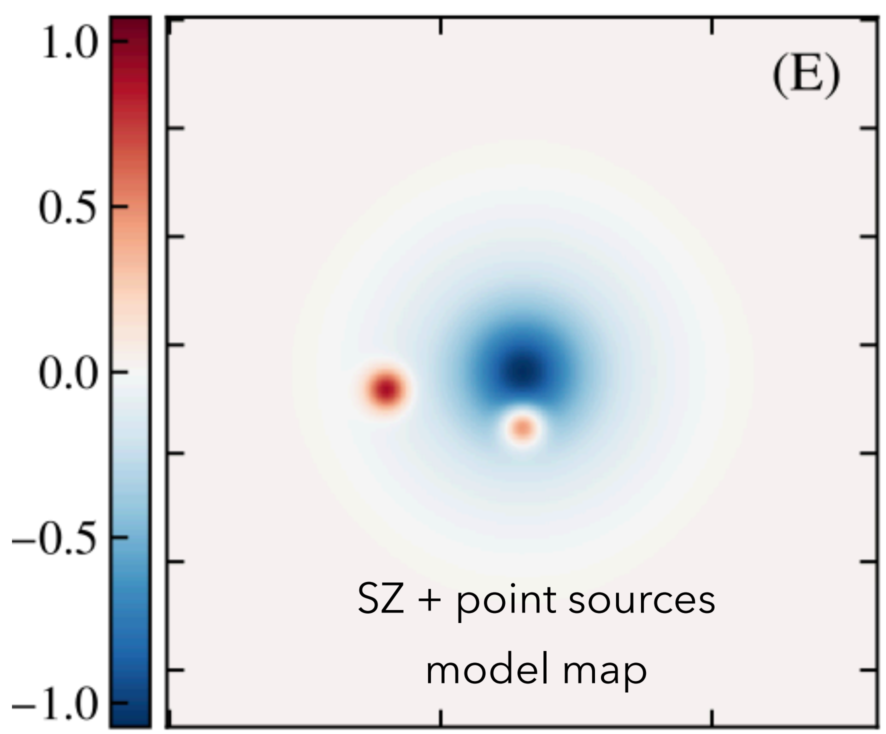
Points sources

Flux : free parameter in the MCMC

Forward modelling

Integrated along the line of sight

Convolved by the NIKA2 instrumental response



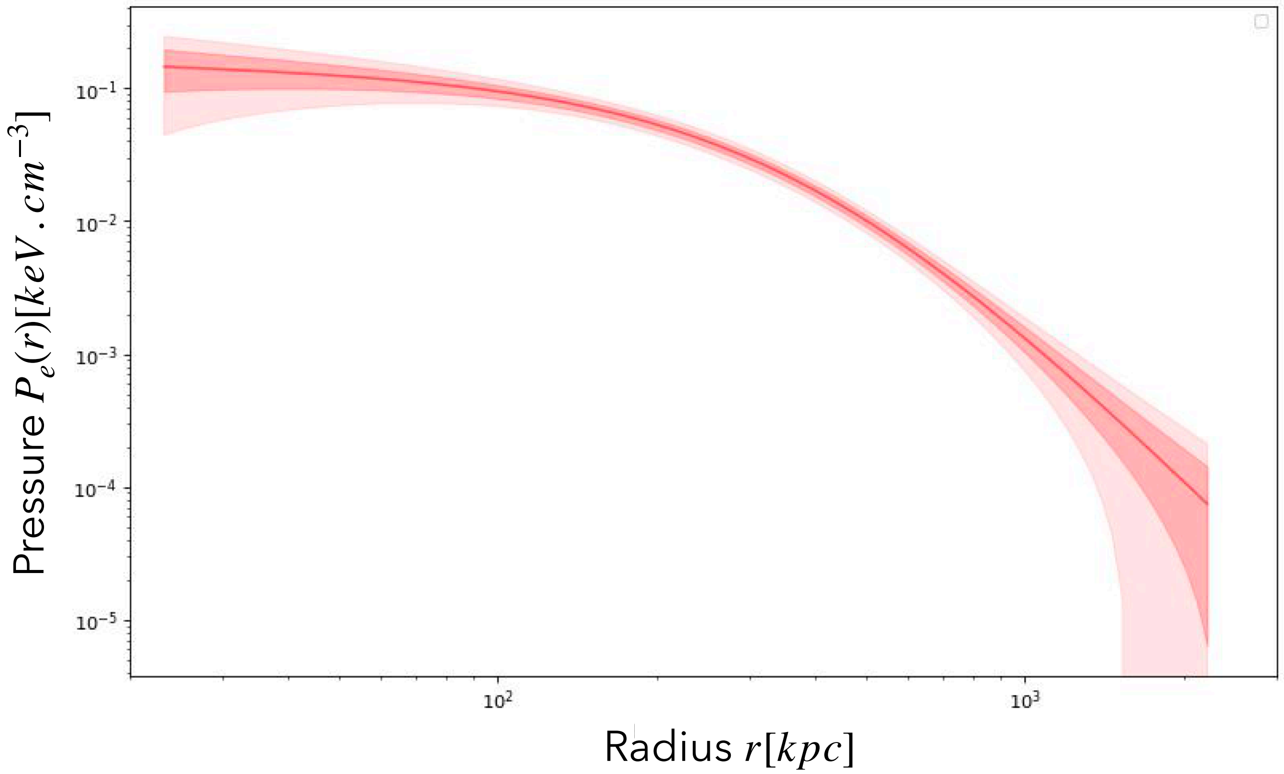
Likelihood : $-2log\mathscr{L}(\theta) = \sum_{pixels} (D - M(\theta))^T C^{-1} (D - M(\theta)) + \left(\frac{Y_{500}^{meas.} - Y_{500}^{Model}}{\Delta Y_{500}^{meas.}}\right)^2$

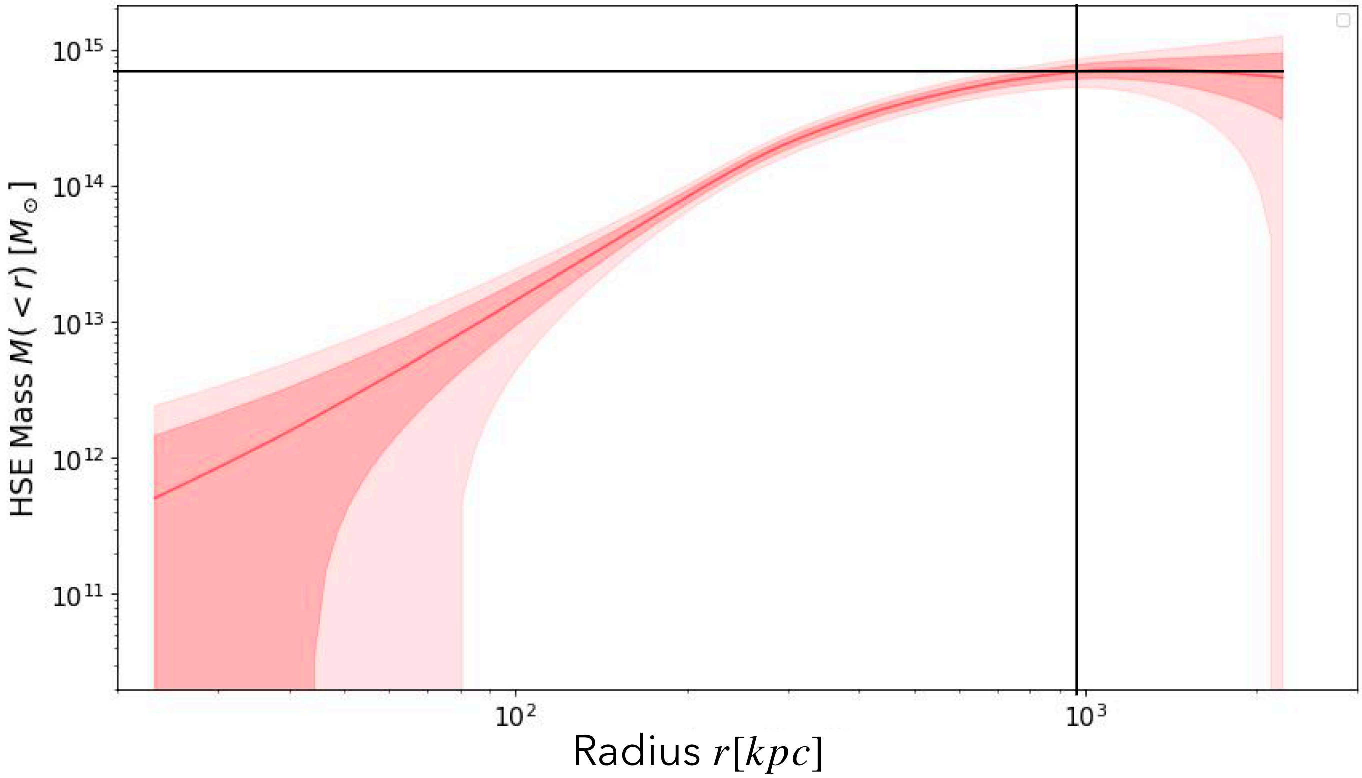
Constraints from NIKA2 150GHz map

Constraints from Planck/ACT integrated signal

Thermodynamical properties

$$M_{HSE}(<r) \propto \frac{r^2}{n_e(r)}\frac{dP_e(r)}{dr}$$





Pressure (left) and mass (right) profiles

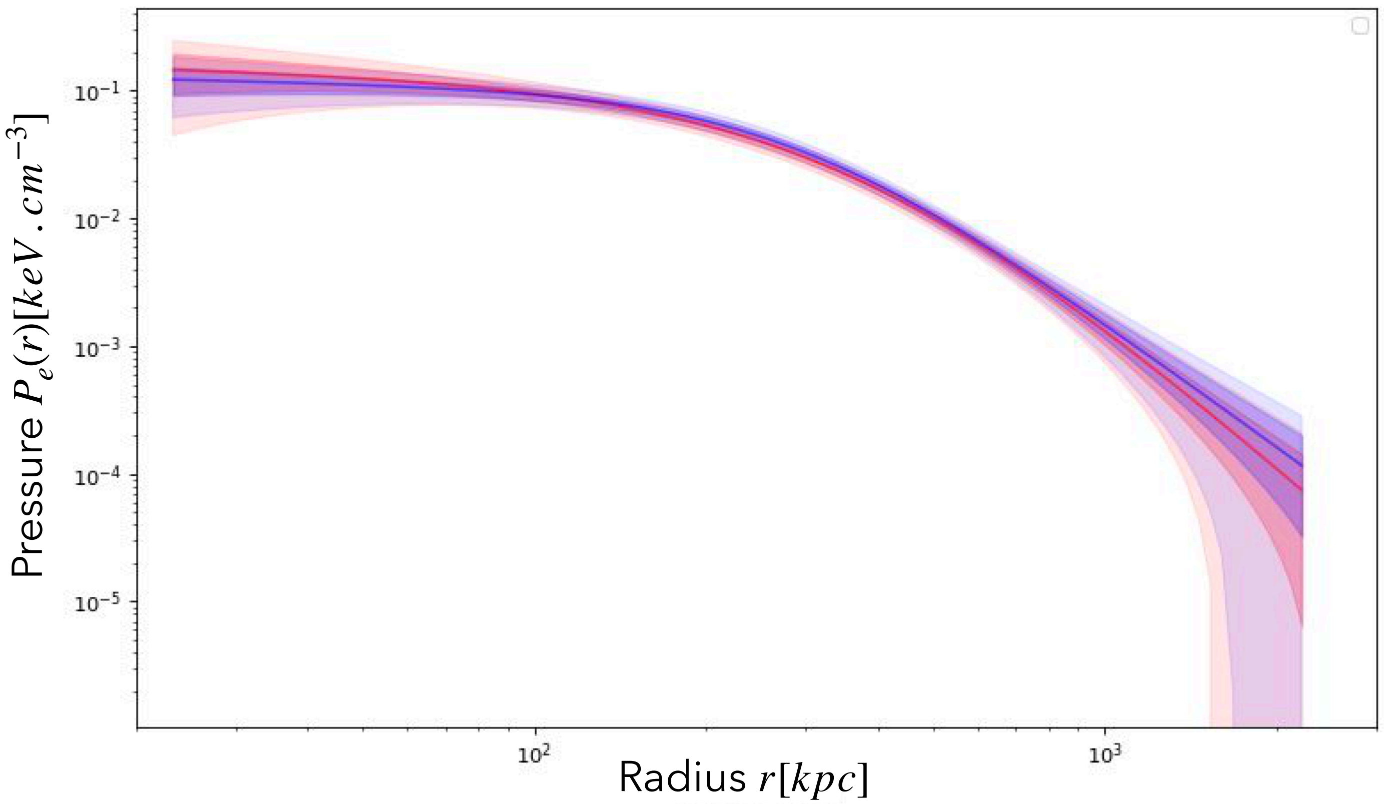
Get the integrated quantities ⟶ $$M_{500} = 500 * \frac{4}{3}\pi\rho_{crit}R_{500}^3$$

Results obtained using method 2 (external data for point sources)

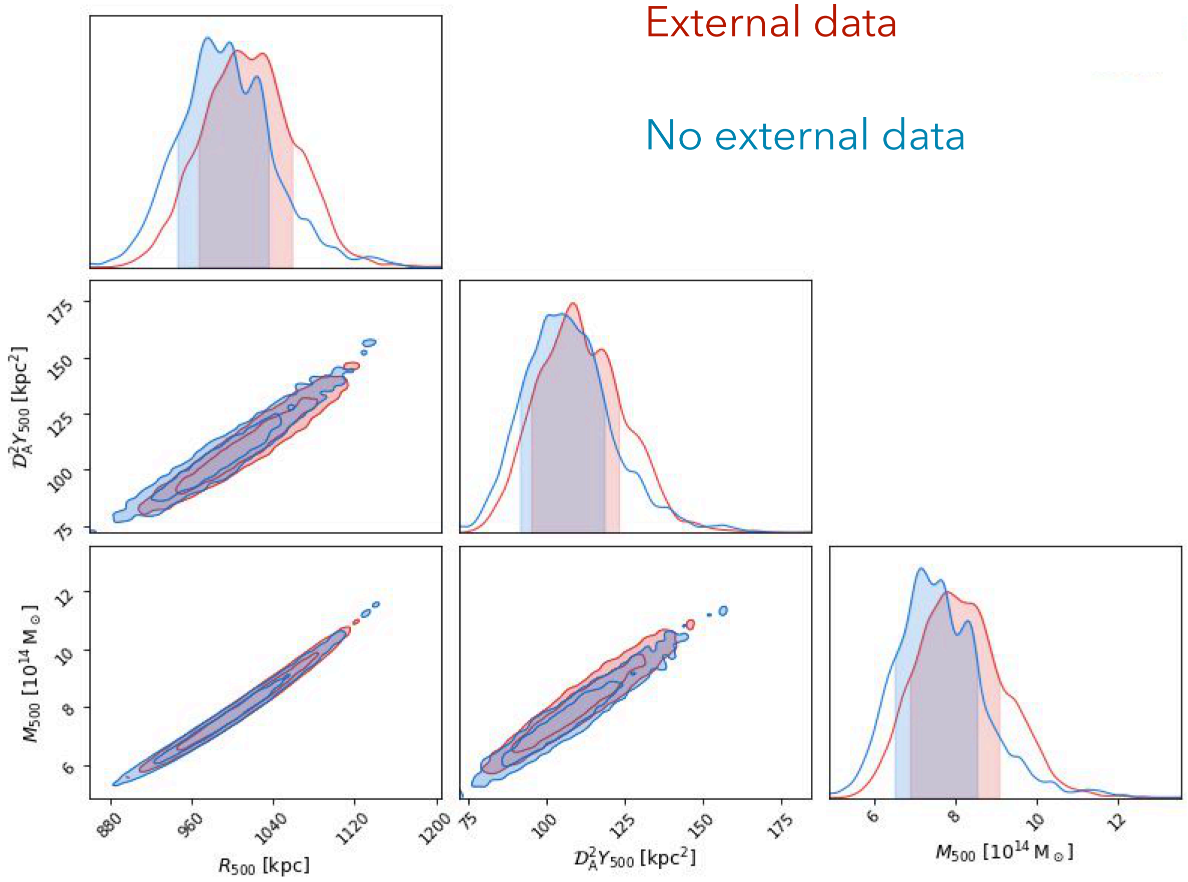
BUT no external data for all point sources

Comparison with and without external data

Impact on thermodynamical properties



Pressure profiles with (red) and without (blue) external data



Integrated quantities

Compatible results but point sources have a significative contribution to the error

Robust method to account for point sources even without external data

Pressure profile modeling

Pressure profile modelling can have an impact on final results

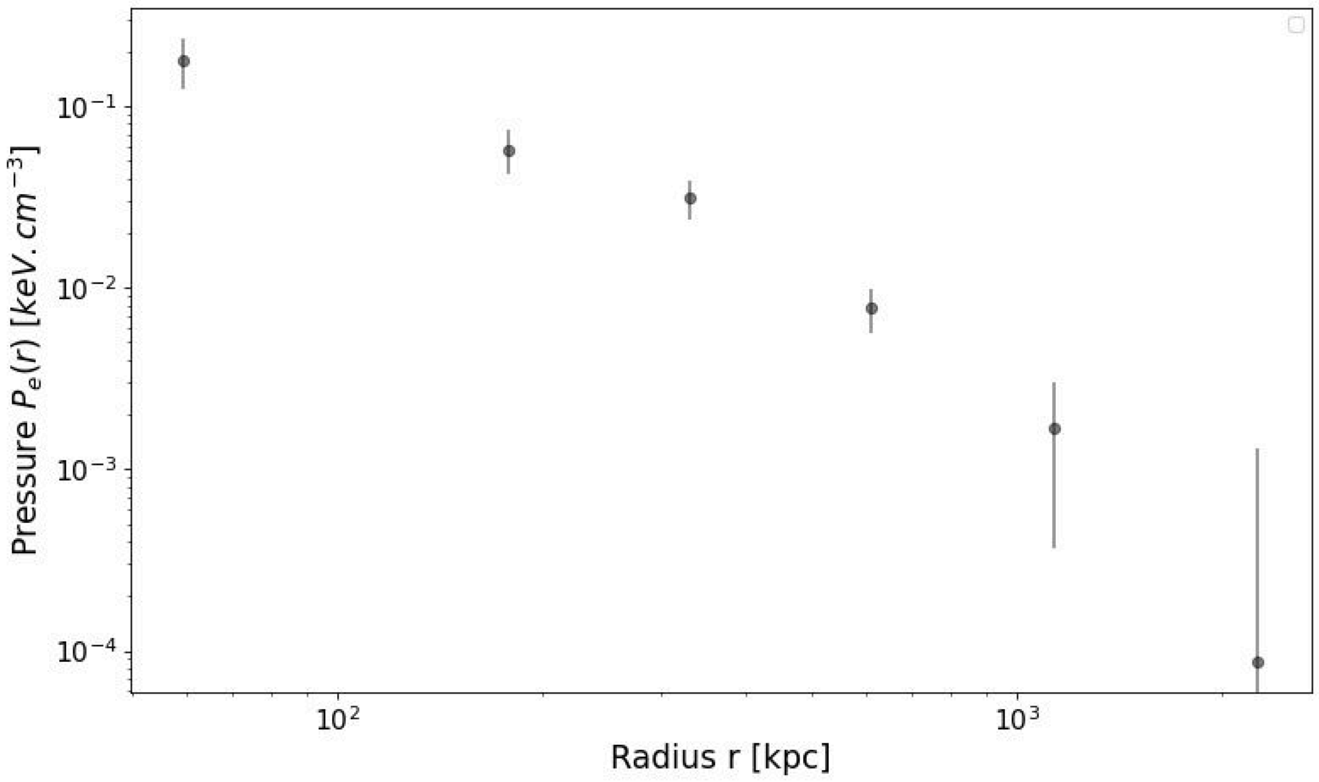
We develop different models in order to check the robustness of the results

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

Radially binned model :

Choose a binning : N points logarithmically spaced from NIKA2 beam ($< 100kpc$) to NIKA2 FoV (up to $2Mpc$)

–> N parameters : P_i amplitude of the pressure at R_i



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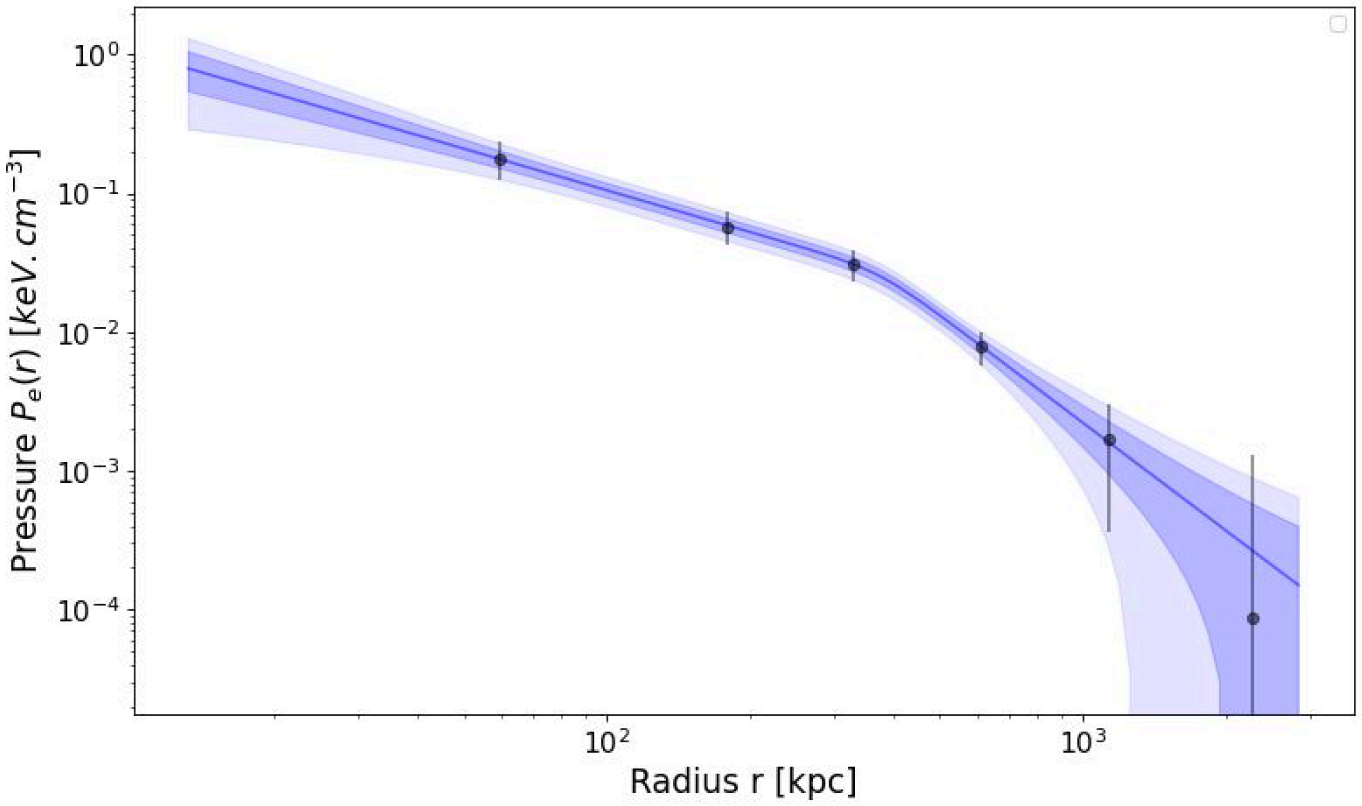
Radially binned model :

Choose a binning : N points logarithmically spaced from NIKA2 beam ($< 100 kpc$) to NIKA2 FoV (up to $2 Mpc$)

–> N parameters : P_i amplitude of the pressure at R_i

Fit a pressure profile on $\{P_i\}_{i\in[1,N]}$ to compute $\frac{dP}{dr}$

–> gNFW, …



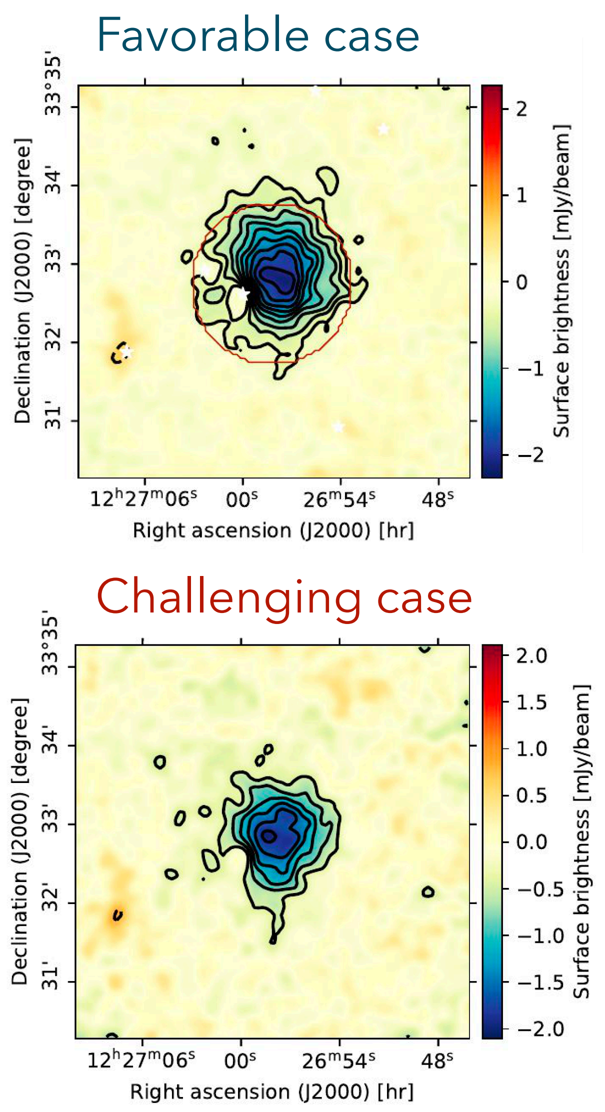
Check the robustness of the radially binned model

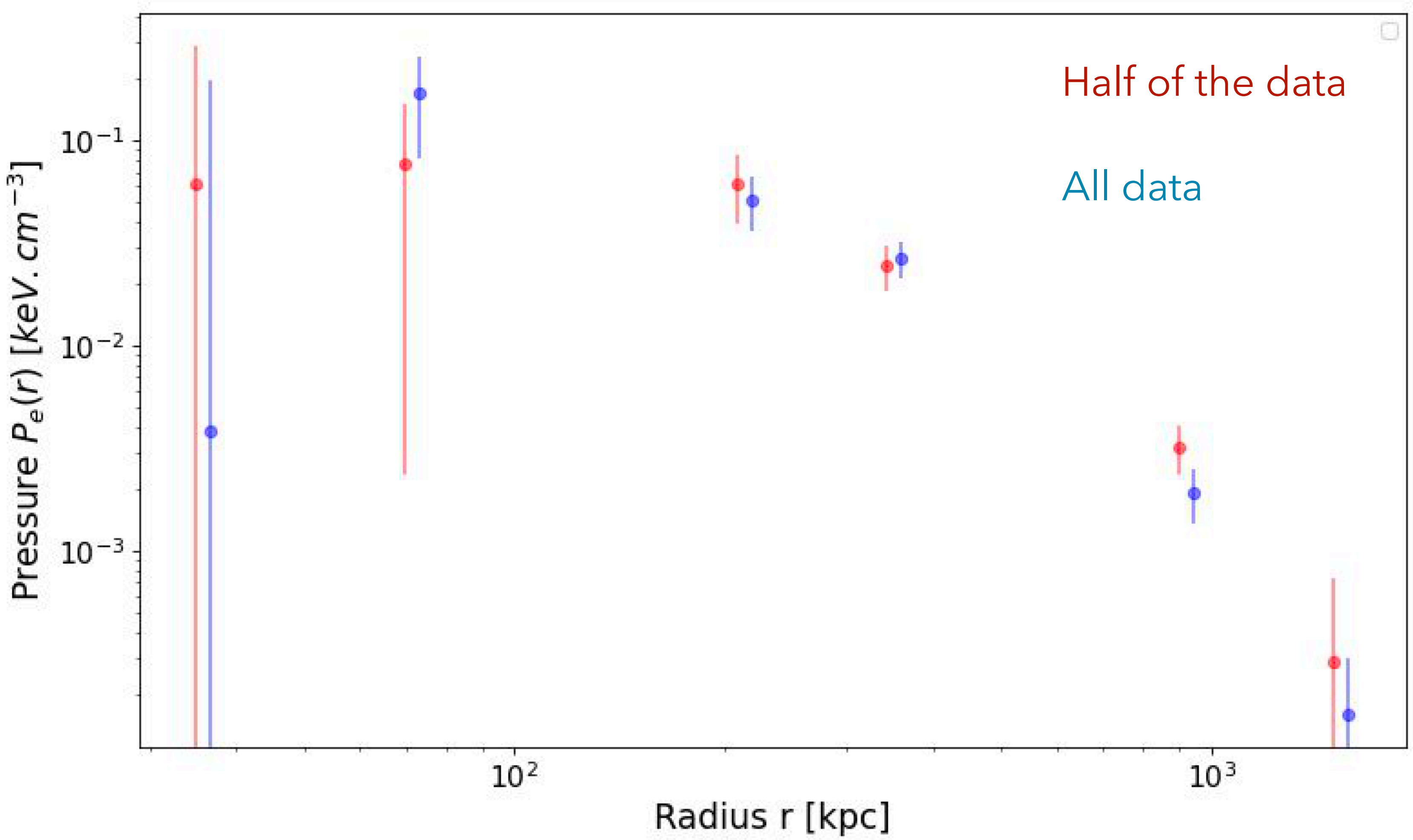
Results for PSZ2G160

Cluster observed twice the planned time : half of the data should be enough to do the analysis

2 maps : One with all the available data

One with the most noisy half data sample





–> Results in agreement

Robust method against noise residuals

Pressure profiles for the chosen subsample

Status of the LP-SZ

For now : 40/45 clusters already observed

–> On-going study on a sub-sample of 20 clusters (at least 3 per mass bin)

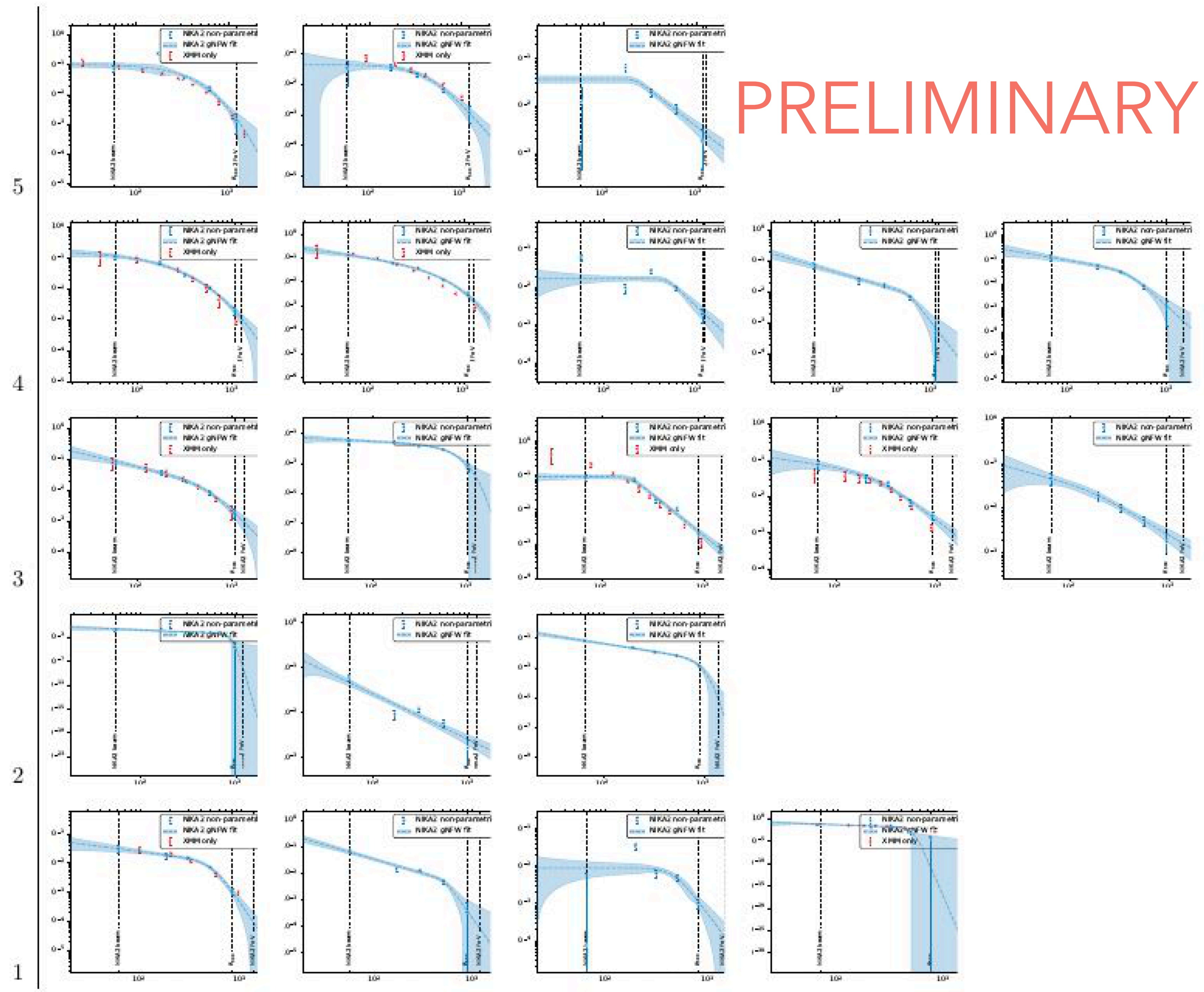
- Results obtained with the Radially binned approach
- gNFW give promising results as well
- Using both methods for consistency check

On-going work :

Study the systematics on complex simulations

First estimate of the mean pressure profile at high redshifts

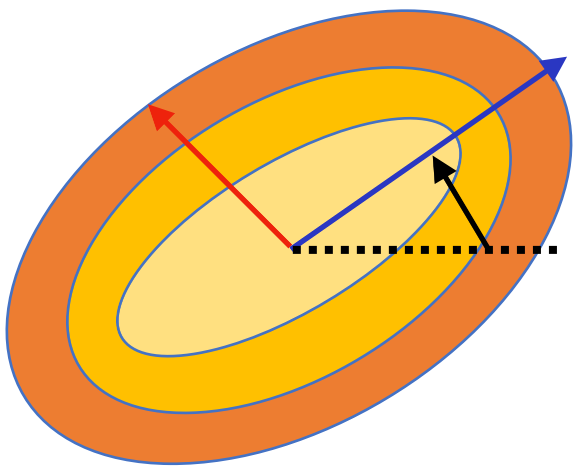
Targeted clusters



Morphological studies

NIKA2 high angular resolution : allows the study of complex morphologies

Idea : add elliptical parameters in the MCMC



a_x, a_y, ϕ_0

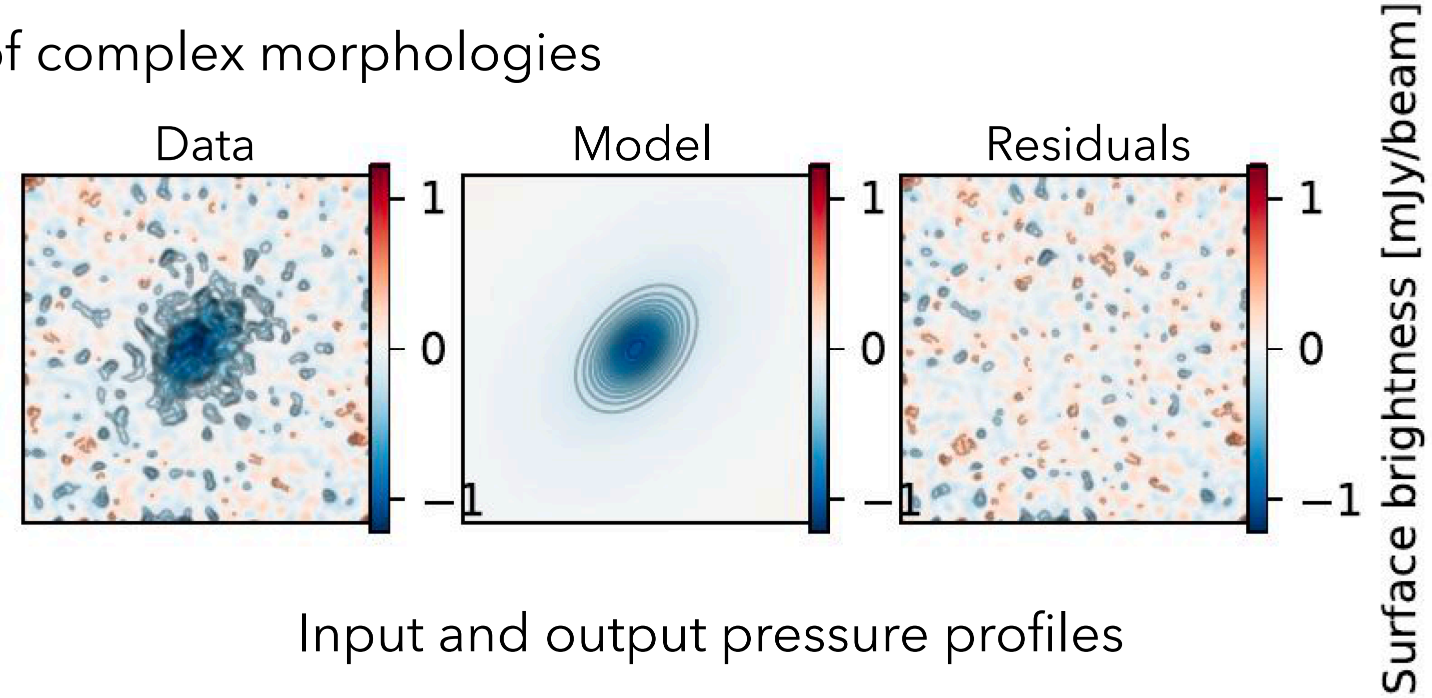
$$R_{ell} = R_c / e(\phi),\ e(\phi) = \sqrt{\frac{cos^2(\phi - \phi_0)}{a_x^2} + \frac{sin^2(\phi - \phi_0)}{a_y^2}}$$

Method : Simulate an elliptical cluster with a white noise

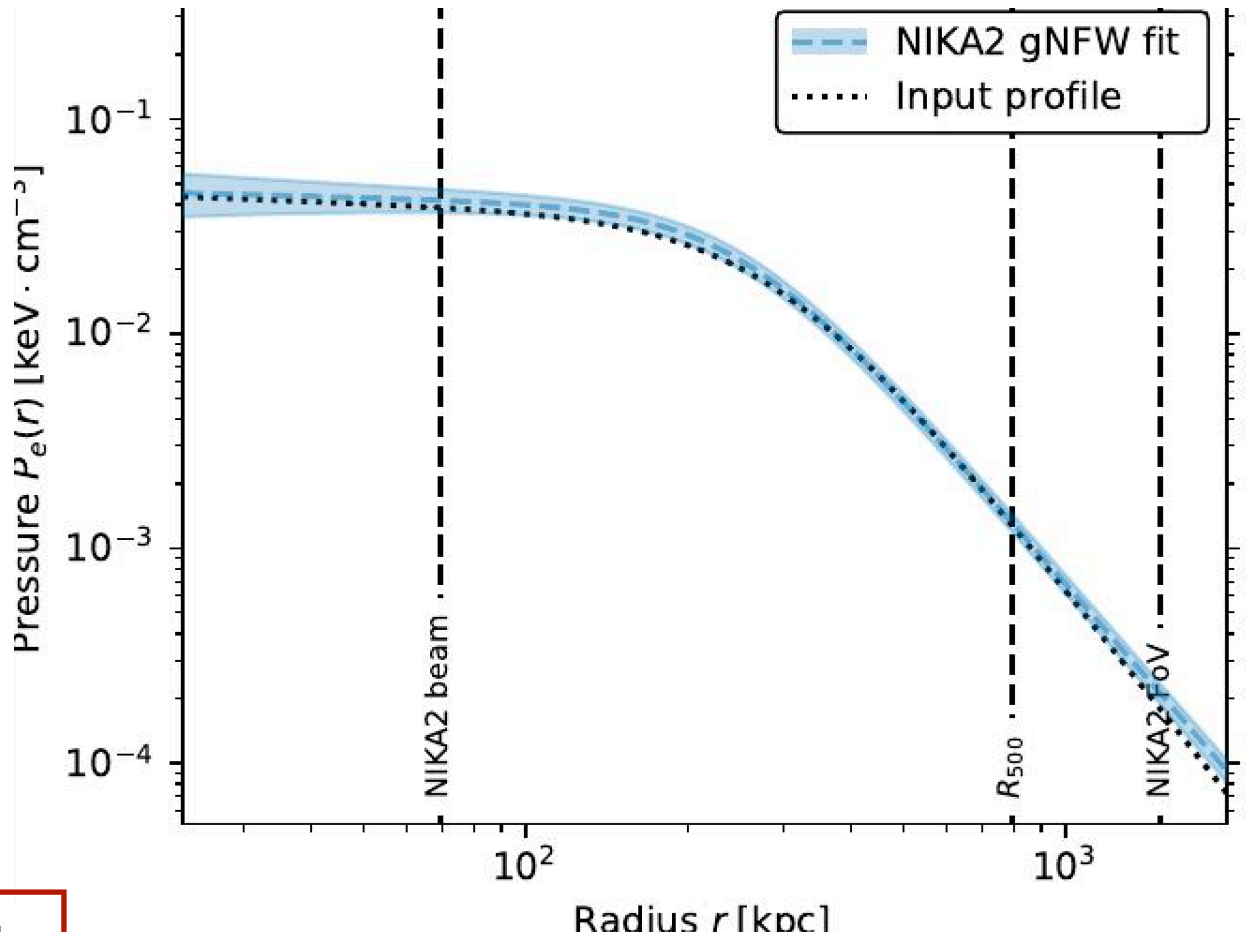
8 parameters to fit : - 5 gNFW parameters
- 3 elliptical parameters

We recover the input profile

Get a mass estimate more robust to projection effects



Input and output pressure profiles



Conclusion

Status of the analysis

NIKA2 data allow to resolve intermediate to high redshift galaxy clusters in SZ

NIKA2 - LP-SZ : observed 40/45 galaxy clusters at expected sensitivity

First standard analysis on a LP-SZ sub-sample toward mean pressure profile and mass scaling relation

Impact of point sources contamination : robust method without external data

Study on different models to reconstruct the pressure profile in order to perform consistency checks

Impact of the morphology : good perspectives with an elliptical model

Perspectives

Delivery of the first products of interest : complete characterization of the clusters

- SZ map
- Pressure profile
- Mass profile
- Integrated quantities : $R_{500}, M_{500}, Y_{500}$

Universal mean pressure profile with high redshift objects

NIKA2 will improve the accuracy of SZ cluster cosmology