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 and experimental context
2. From raw data to NIKA2 maps
3. From NIKA2 maps to galaxy cluster masses and pressure profiles
4. Beyond the standard hypotheses
5. Conclusion

Galaxy clusters

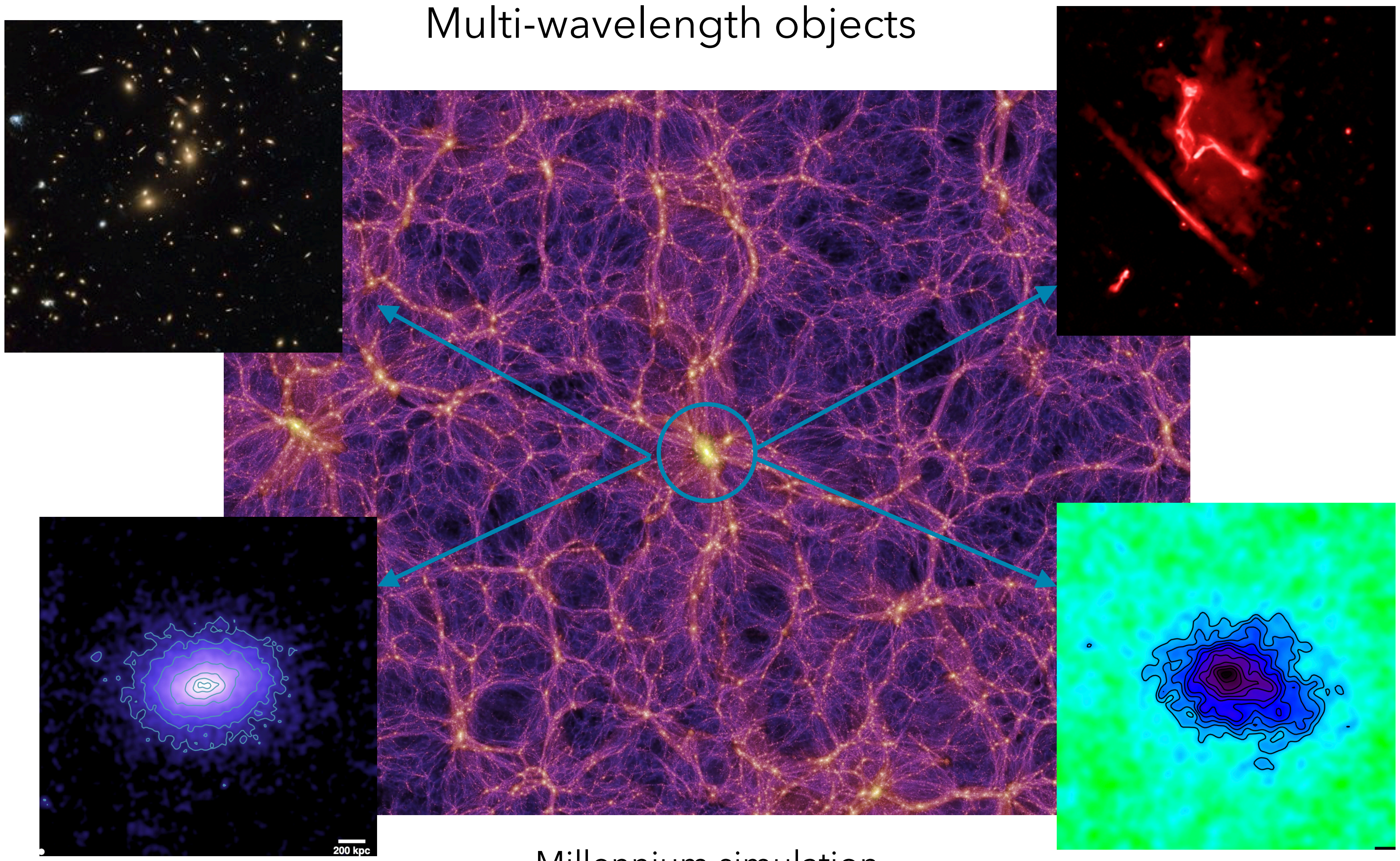
- The largest gravitationally bound objects in the universe with $M \in 10^{13} - 10^{15} M_{\odot}$
- Final step of hierarchical large scale structure formation : $z < 2$
- Multi-component systems : ~ 3% of galaxies, ~ 12% of hot ionised gas (ICM), ~85% of dark matter

Scale invariants because dominated by dark matter

Multi-wavelength objects

Optics

Radio



X-ray

SZ

Millennium simulation

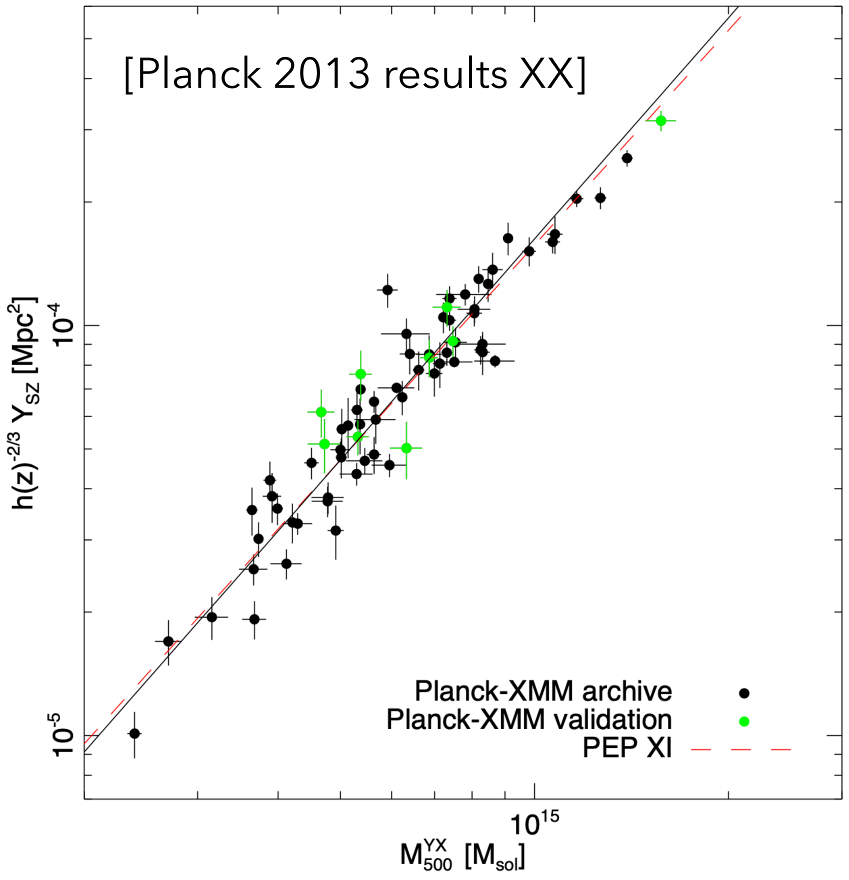
SZ cosmology

Cluster number count

The cluster abundance in intervals of mass and redshift

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

SZ-M scaling relation

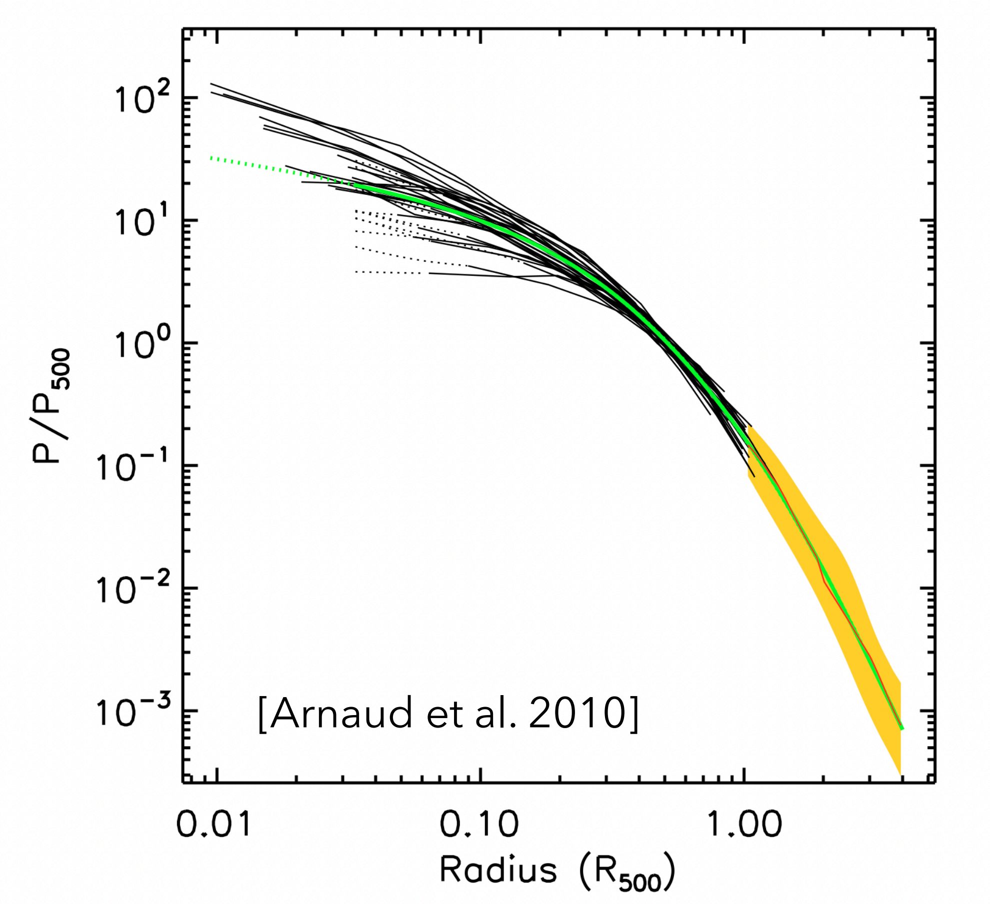


SZ power spectrum

Angular power spectrum of the SZ-map

$$C_l^{SZ}$$

Mean pressure profile



We need a precise characterization of both products for SZ cosmology

Cluster hydrostatic mass

Two hypotheses : - At the hydrostatic equilibrium
- Spherical

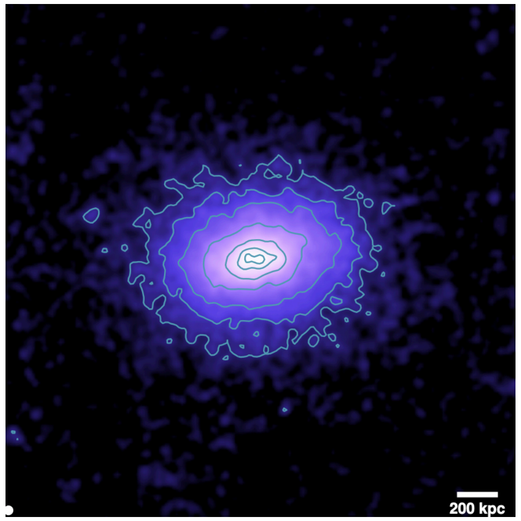
$$M_{HSE}(<r) \propto \frac{r^2}{n_e(r)} \frac{dP_e(r)}{dr}$$

Multi-wavelengths mass calibration

Electronic density from X-rays

X observable : Surface brightness

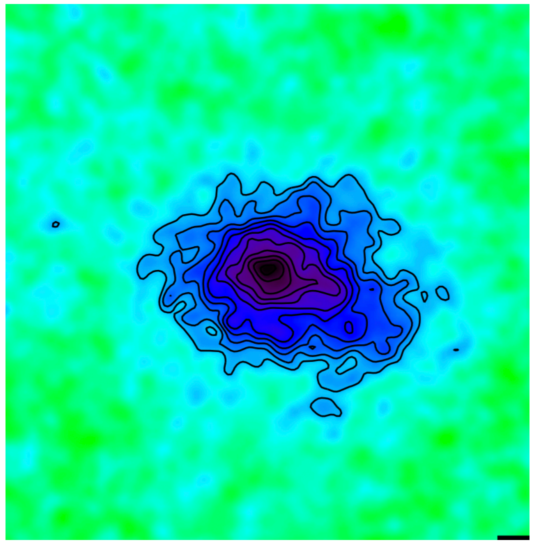
$$S_X \propto \int n_e^2 \longrightarrow \text{XMM-Newton}$$



Electronic pressure from SZ data

SZ observable : Compton parameter y

$$y \propto \int P_e \, dl \longrightarrow \text{NIKA2}$$



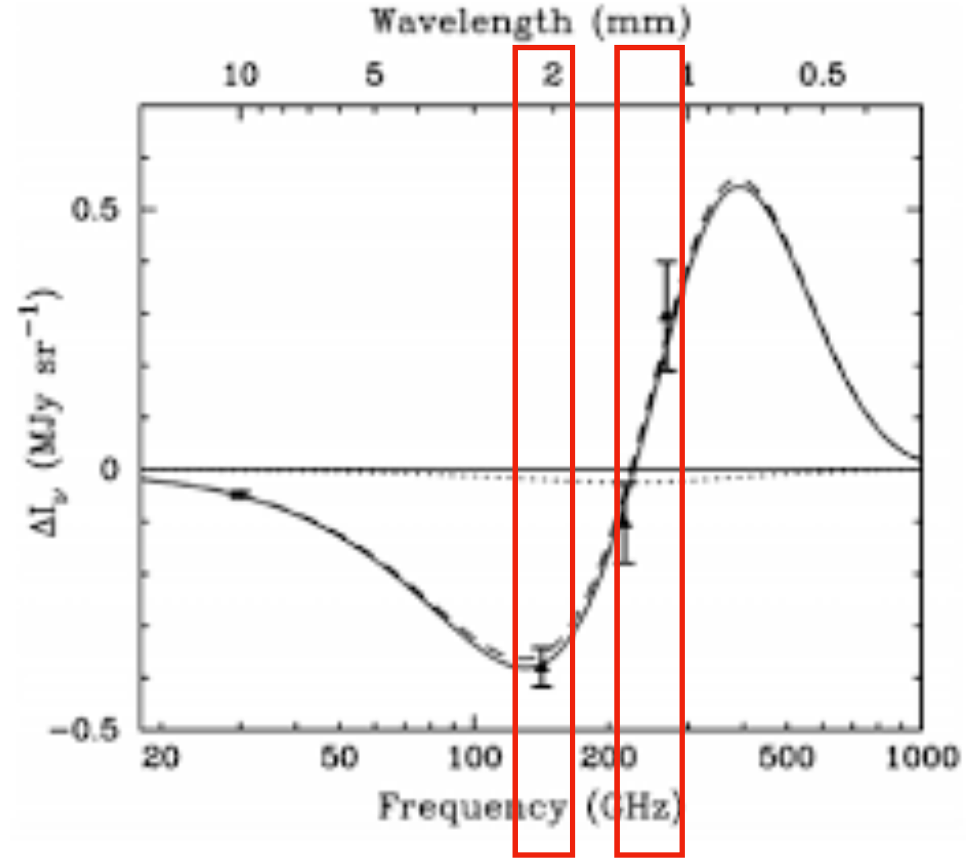
Powerful method when SZ and X-ray resolutions are similar

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



- 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*

[Perotto et al. 2020]

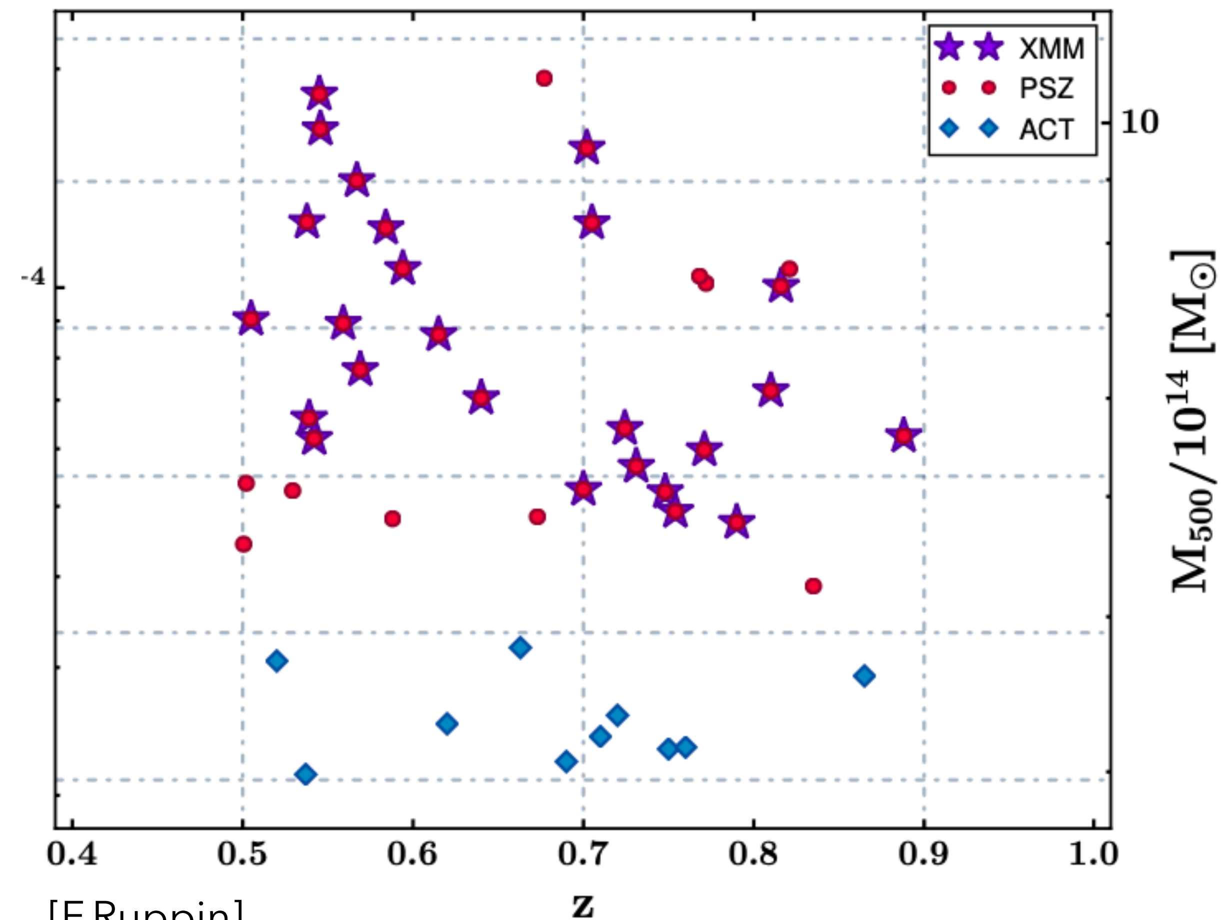
High angular resolution follow-up of 45 Planck and ACT galaxy clusters

[Mayet et al. 2020]

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

Outlines

From raw data to NIKA2 maps

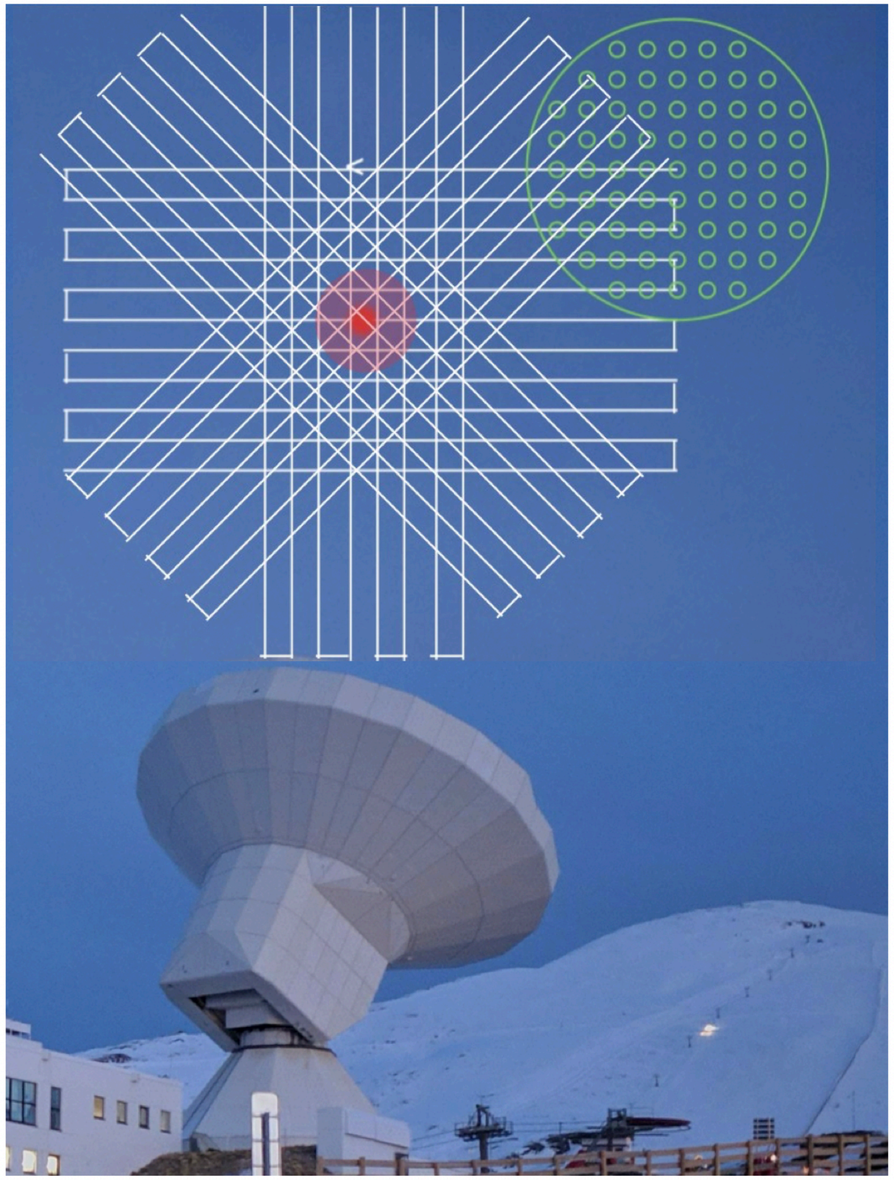
Time Ordered Information : raw data from the detectors (KIDs)

$$TOI_k(t) = S_k(t) + \underbrace{A(t) + E_{B_k}(t) + WN_k(t)}_{\text{Noise } N_k(t)}$$

At a fixed time t the detectors see :

- Same atmosphere $A(t)$
- Different astrophysic signal $S_k(t)$
- Correlated electronic noise $E_{B_k}(t)$
- Intrinsic noise $WN_k(t)$

We want to subtract the correlated noise $A(t) + E_{B_k}(t)$



Scan strategy

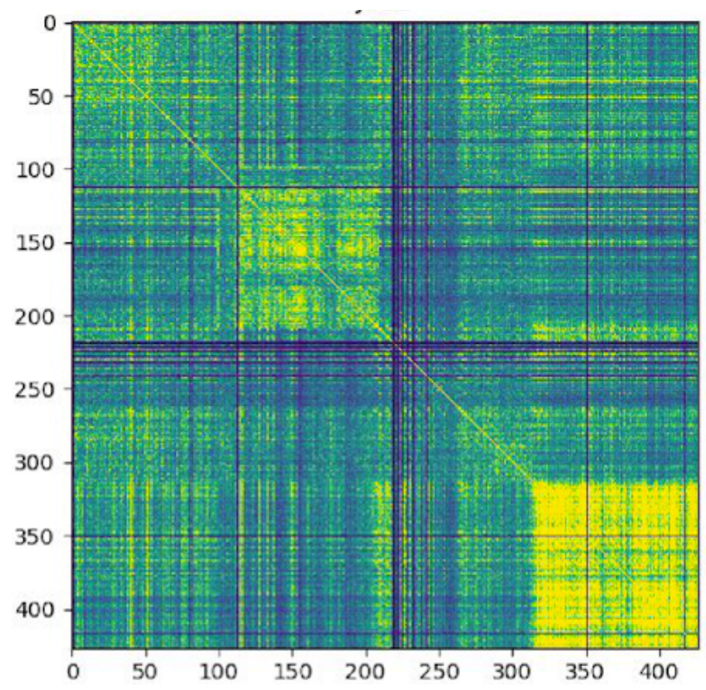
Decorrelation method used so far : Most Correlated Kids

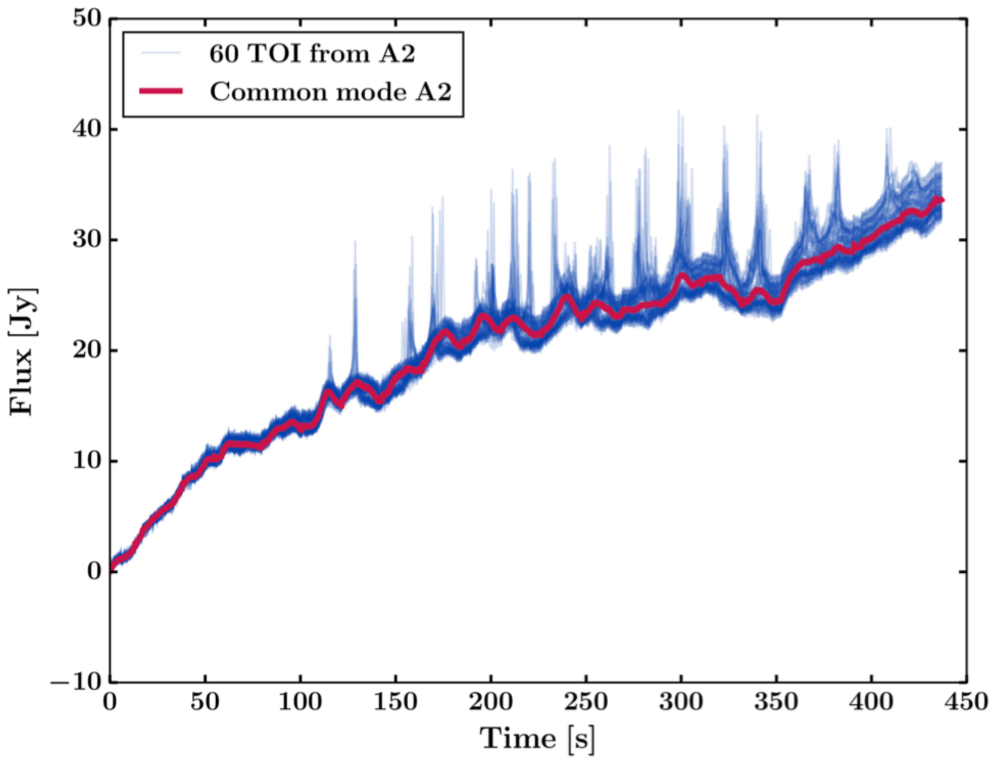
1. Compute the kid to kid correlation matrix and get blocks of most correlated kids

2. For each block compute a common mode (median of the TOIs)

3. Subtract the common mode (CM) from the TOIs and project them on a map

$$TOI_k - CM_k \approx S_k + \delta N_k$$





An example with Uranus observation

Residual noise

The low frequency residual noise is one of the most important systematic effect

–> Corresponds to the cluster scale in the map

We want to characterize the data quality

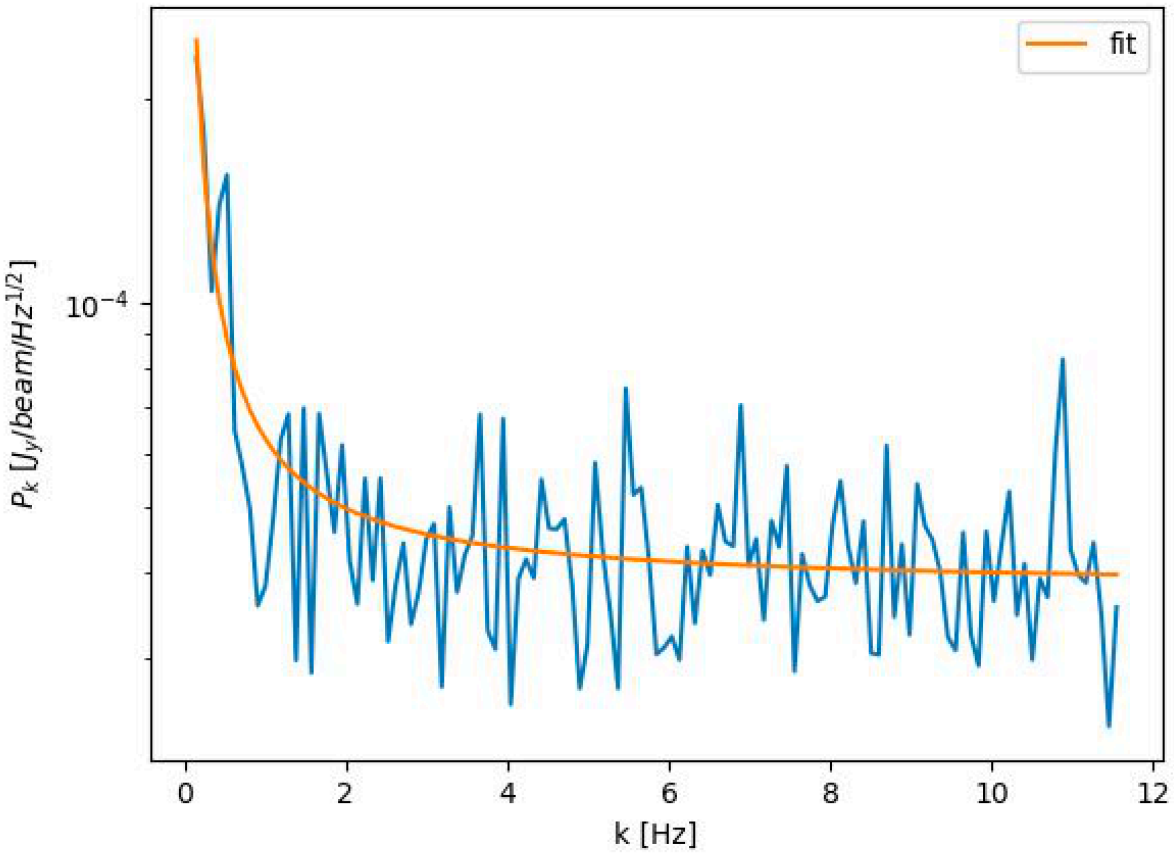
Method : compute the noise power spectrum of each TOI after decorrelation

Model : Low frequency + White noise

$$F(f) = B^2 \left(1 + \frac{f_{knee}}{f}\right)^{\alpha}$$

3 parameters : B, f_{knee}, α

–> Result : $B * f_{knee}^{\alpha}$



Power spectrum of one TOI from one KID (blue) and associated fit (yellow)

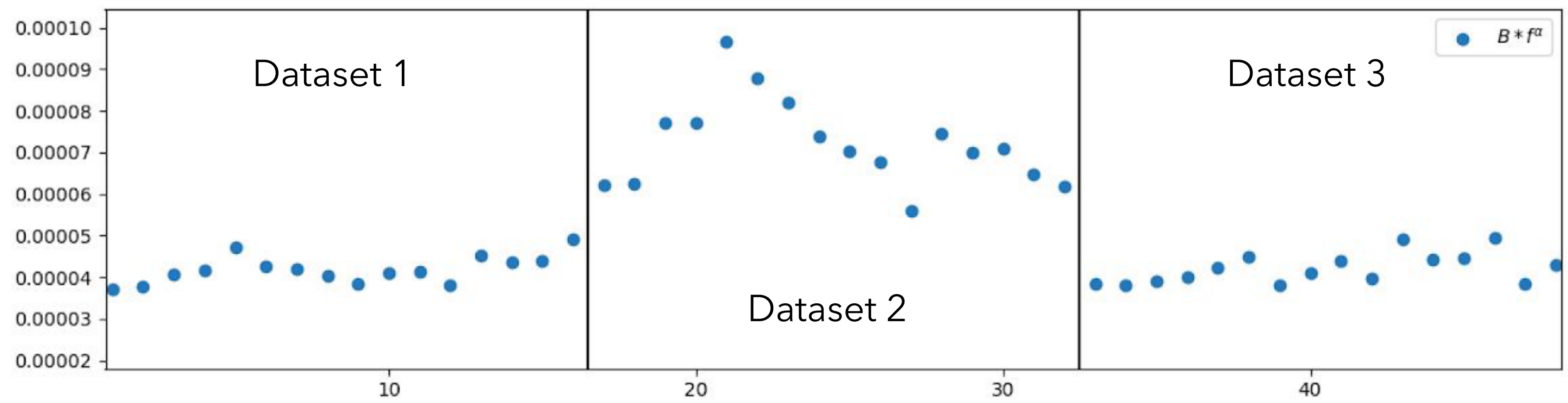
We can compute the average results for each scan

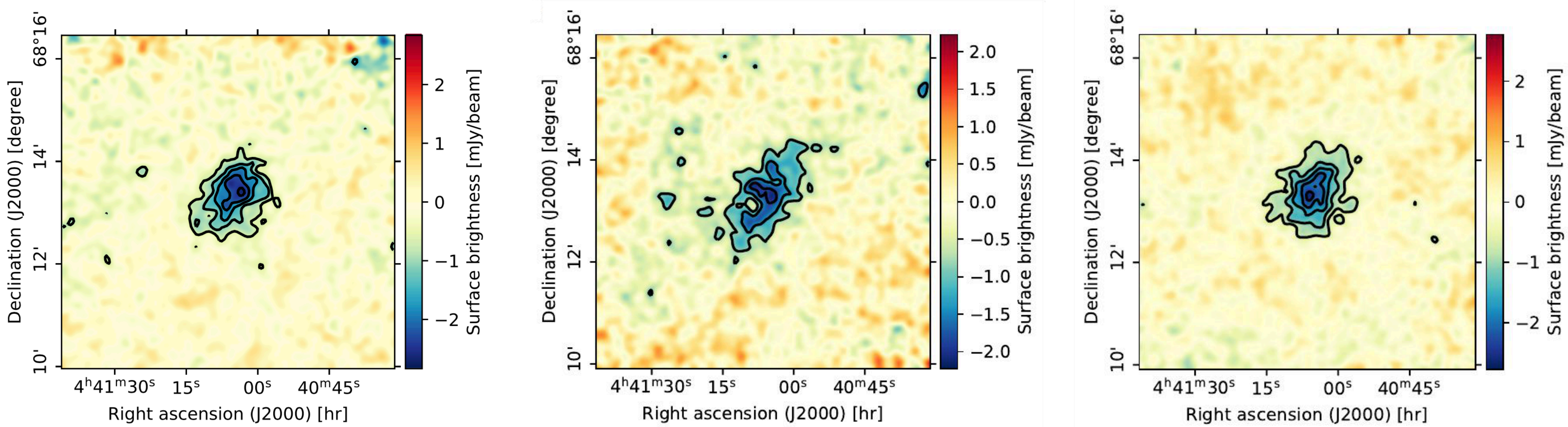
–> We can use this as a data quality criterion

Results on one cluster

PSZ2G141 : Most massive cluster in the second redshift bin (3 datasets from 3 observations)

Results obtained for each scan





150GHz maps of PSZ2G141

Levels : signal on noise ratio beginning at $\pm 3\sigma$ with 1σ spacing

Low frequency residual noise has an important impact

–> We can control it by performing a scan selection

150 GHz maps for the selected sub-sample

Status of the LP-SZ

For now : 40/45 clusters already observed

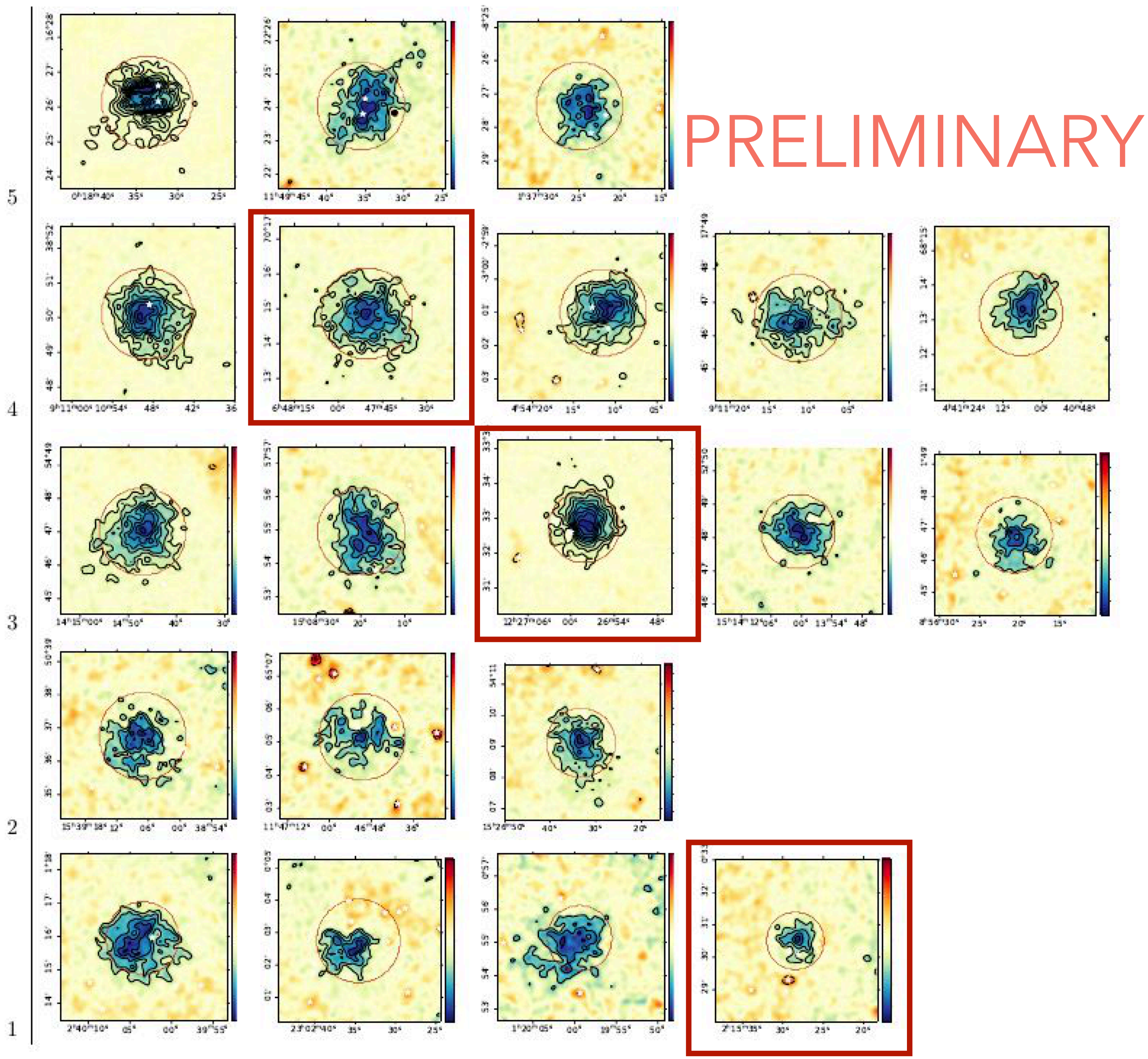
–> On-going study on a sub-sample of 20 clusters (at least 3 per mass bin)

☐ Analysis already performed and published

High signal to noise measurements

Diversity of morphologies
Some of them are contaminated by point sources

Targeted clusters



Outlines

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

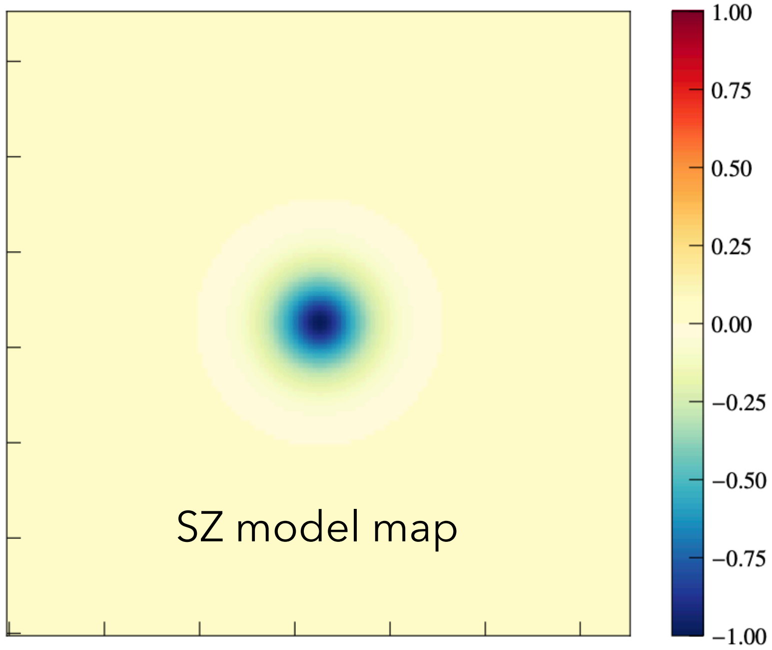
r_p, a transition radius/ steepness

b, c internal/ external slopes

Forward modelling

Integrated along the line of sight

Convolved by the NIKA2 instrumental response



Fit a model on the data using a MCMC

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

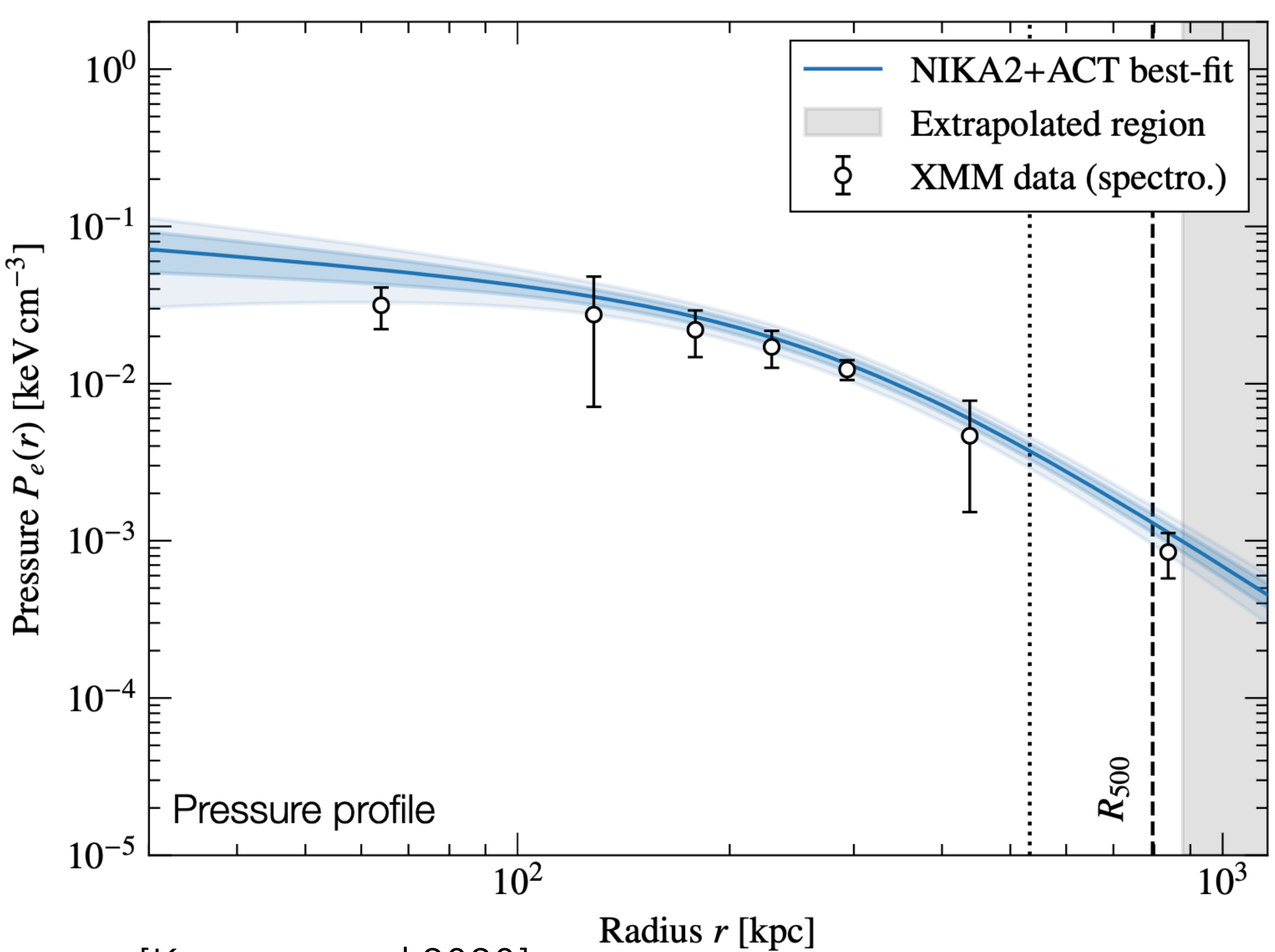
Constraints from NIKA2 150GHz map

Constraints from Planck/ACT integrated signal

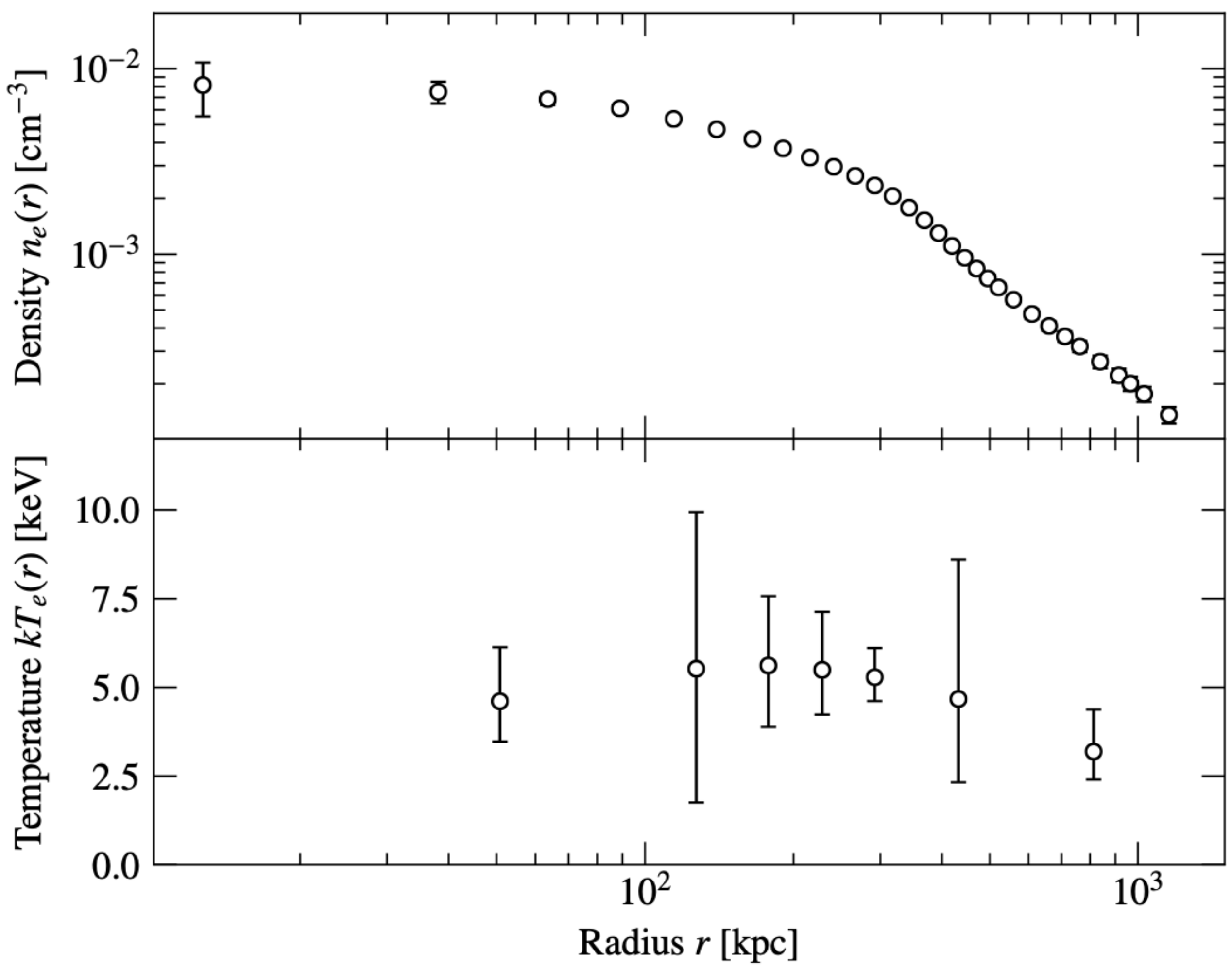
Pressure and density profiles

XMM-Newton + NIKA2 data

Thermodynamical profiles



[Keruzore et al 2020]



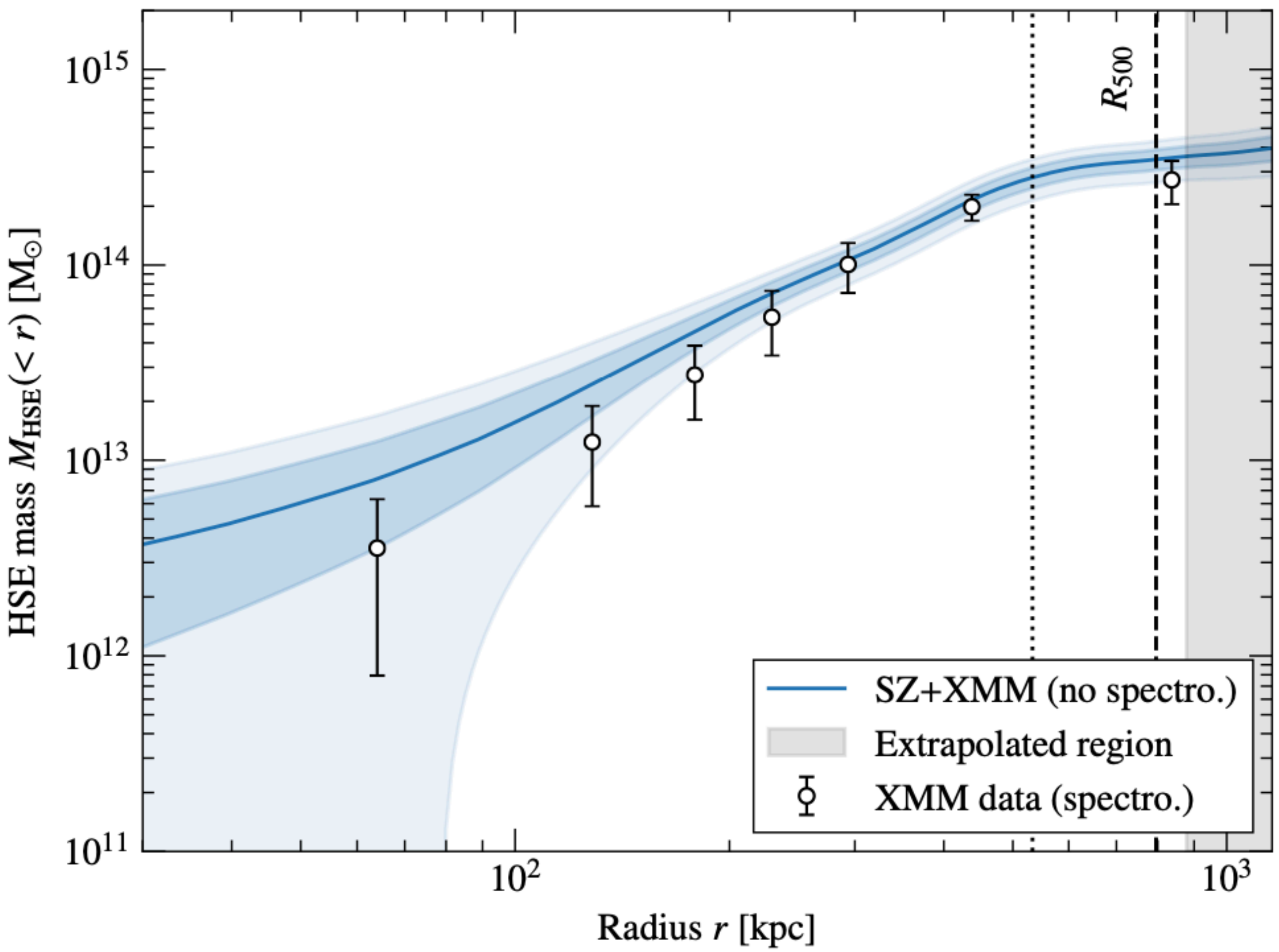
Get a pressure profile from X-data : $P_e = n_e k_b T_e$

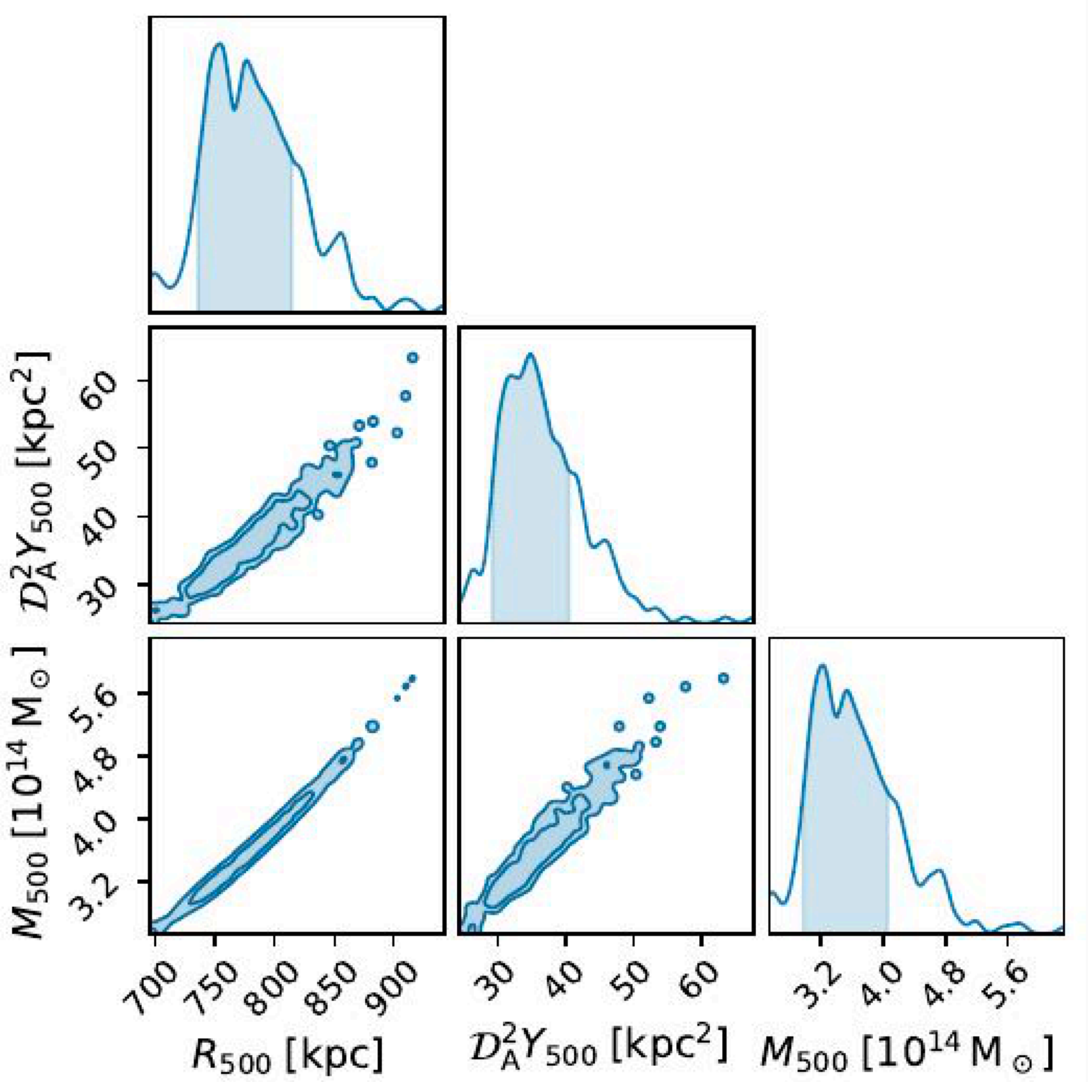
Mass profile and integrated quantities

XMM-Newton + NIKA2 data

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

$$M_{500} = 500 * \frac{4}{3} \pi \rho_{crit} R_{500}^3$$





Panco2 public release (Keruzore et al. 2022 in prep.)

Systematics

Filtering estimate : Quantifies at which angular scales we lost signal in the analysis (what we filter)

–> has to be taken into account in the SZ model map

Uncertainty of the noise modeling : Way to compute C^{-1} in the likelihood

→ See Muñoz-Echeverría et al. 2022 : sub-dominant effects

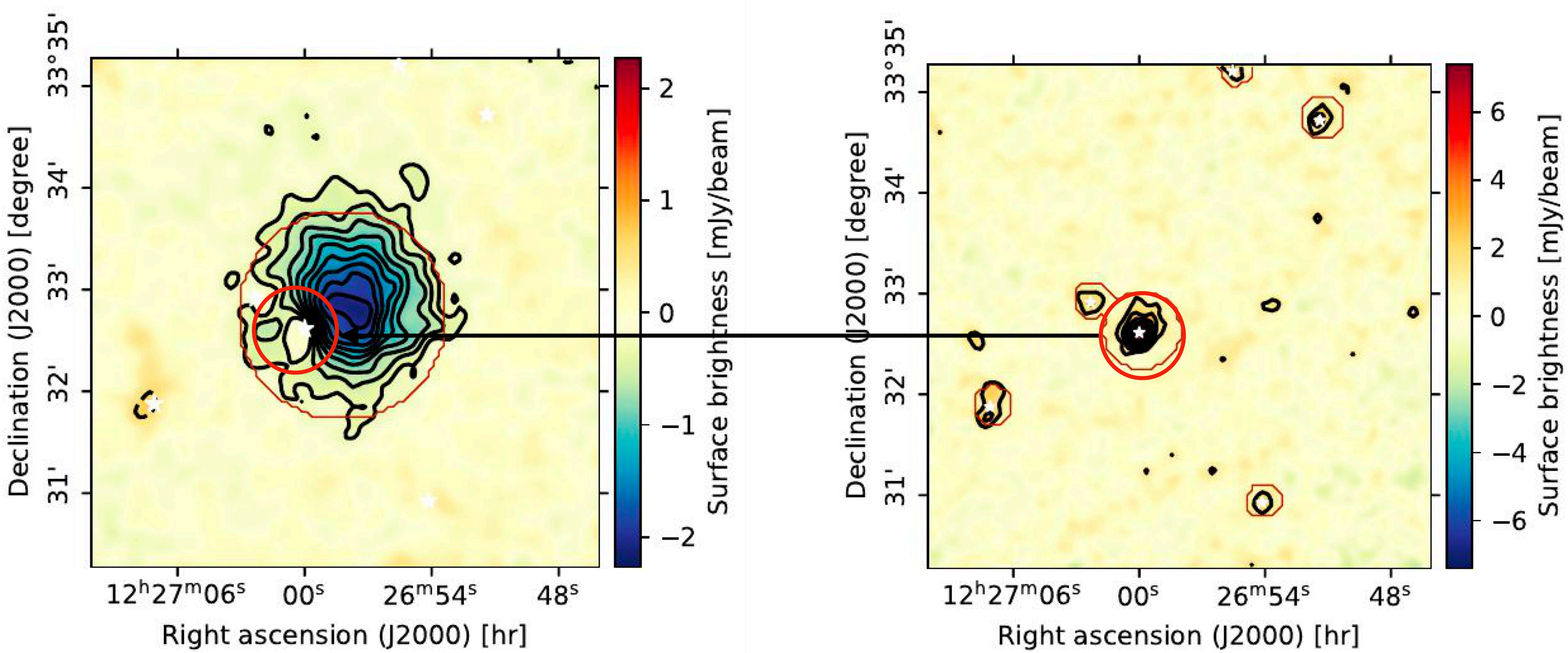
Point sources residuals : Contaminate the 150 GHz SZ map

- Sub-millimeter galaxies
- Radio sources

Chosen model for the pressure profile : compare several models

Impact of the morphology : beyond the hypotheses of sphericity/ hydrostatic equilibrium

Point sources



150 GHz (left) and 260 GHz (right) maps of PSZ2G160
Levels : signal on noise ratio beginning at $\pm 3\sigma$ with 1σ 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

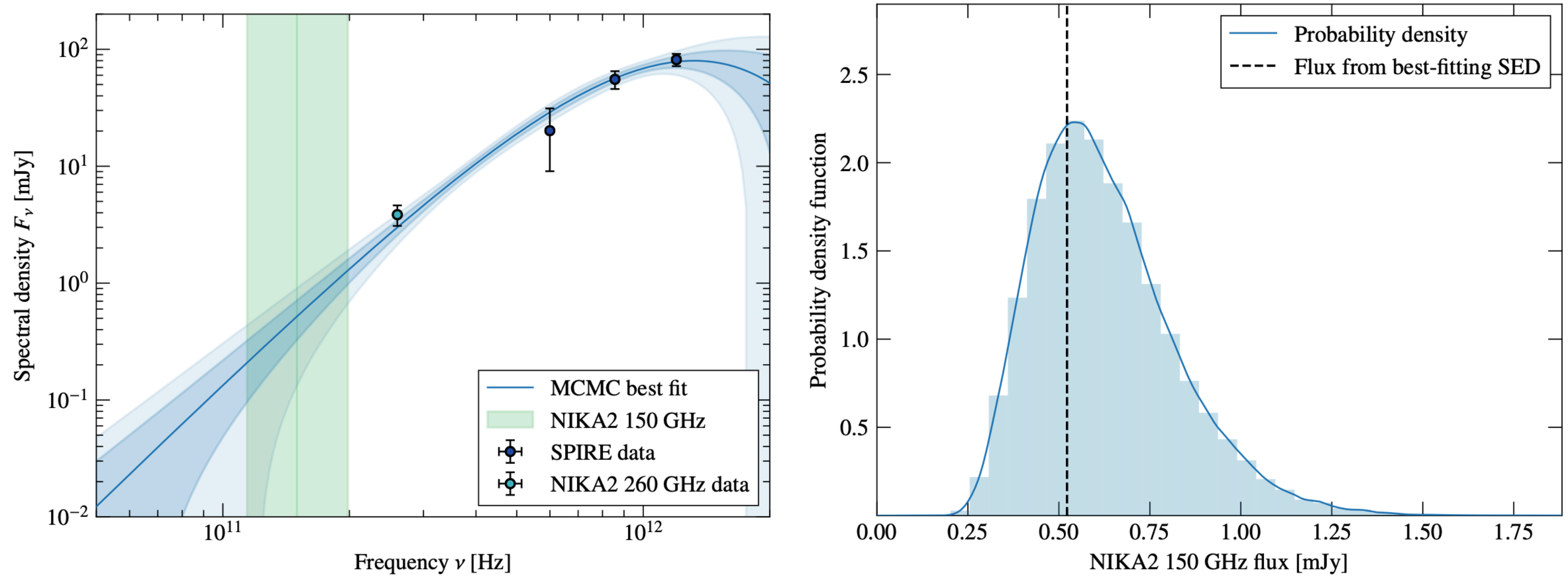
Point sources flux estimate

Methods

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

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

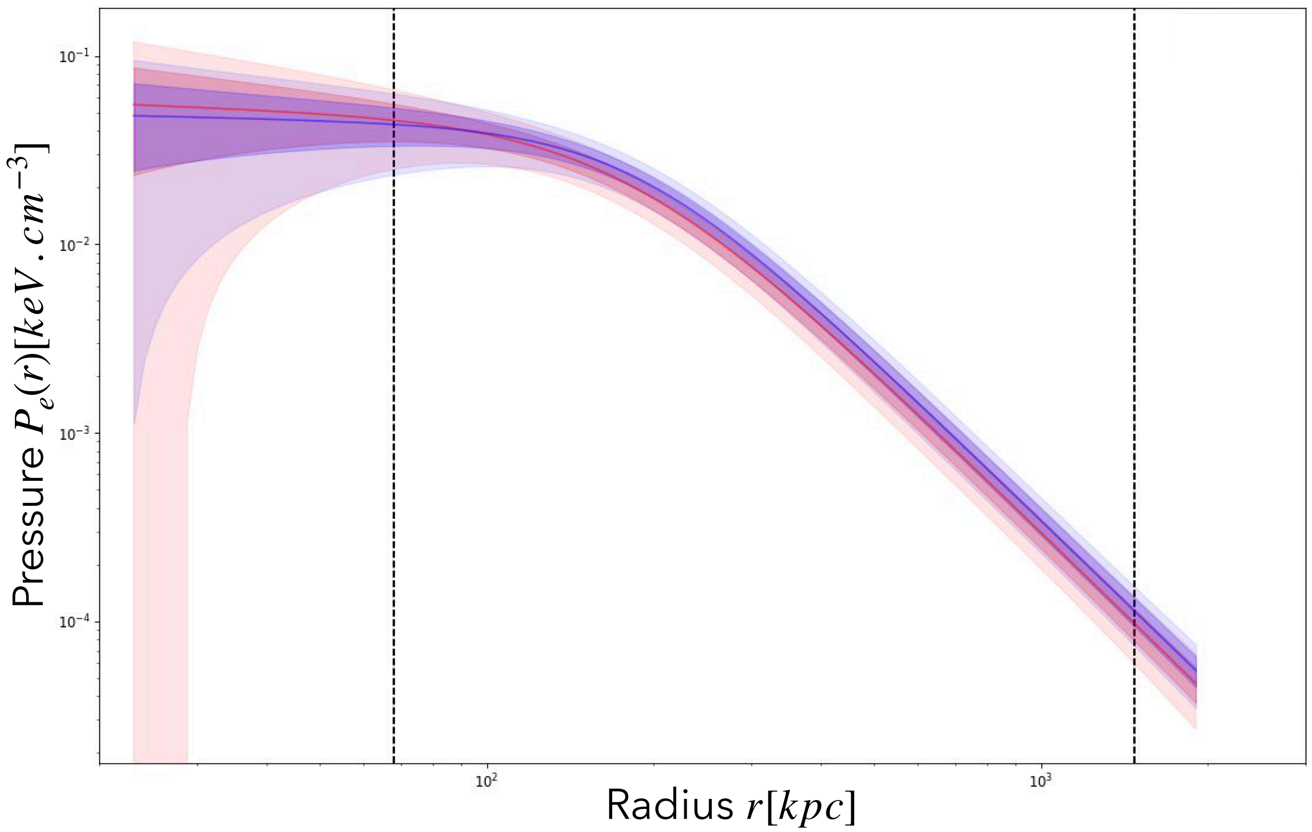
–> free parameter in the pressure profile fit with this PDF as a prior

BUT we don't have external data for all clusters

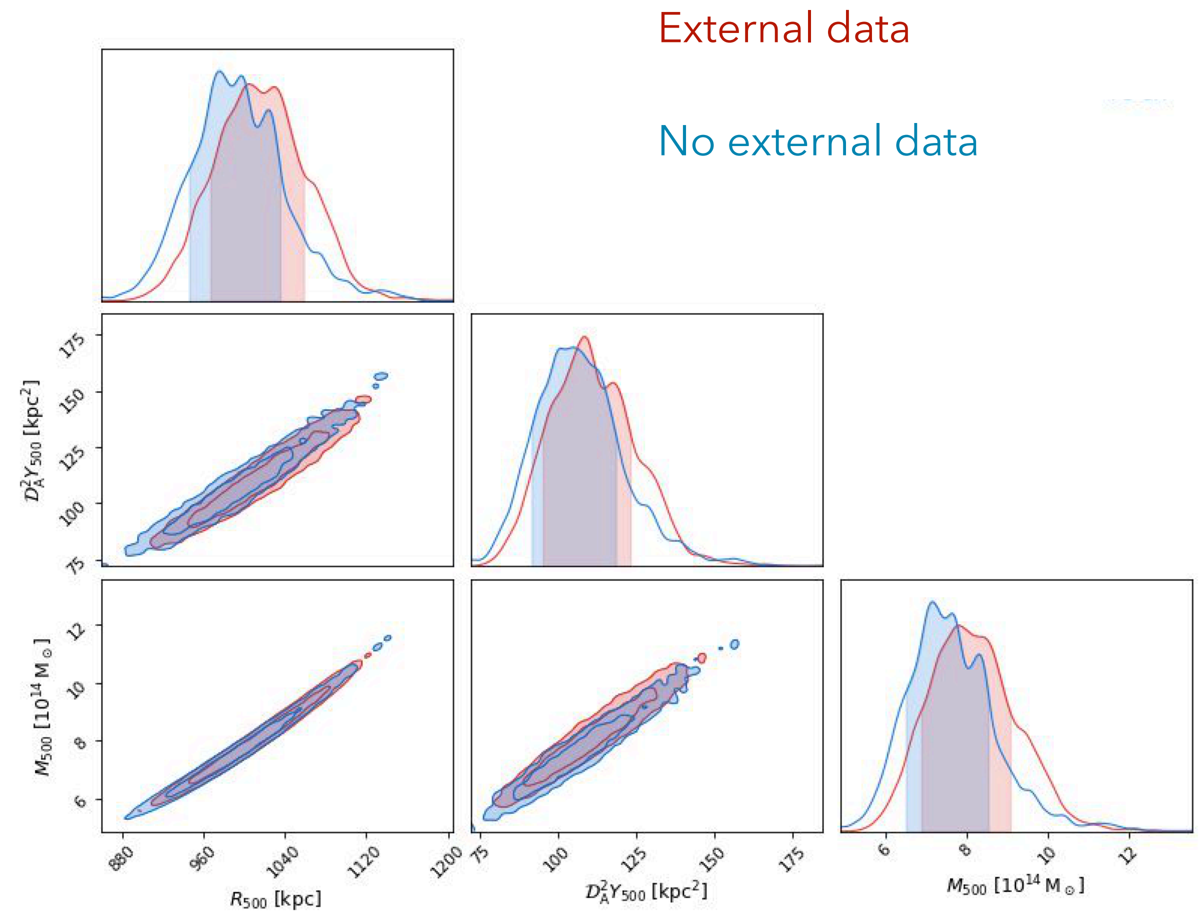
–> free parameter in the pressure profile fit with a flat prior ∝ 260 GHz estimated flux

Can we get accurate results without external data ?

Results for PSZ2G160



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



Integrated quantities

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

Method tested and validated on different clusters

Pressure profile modeling

Pressure profile modelling can have an impact on final results

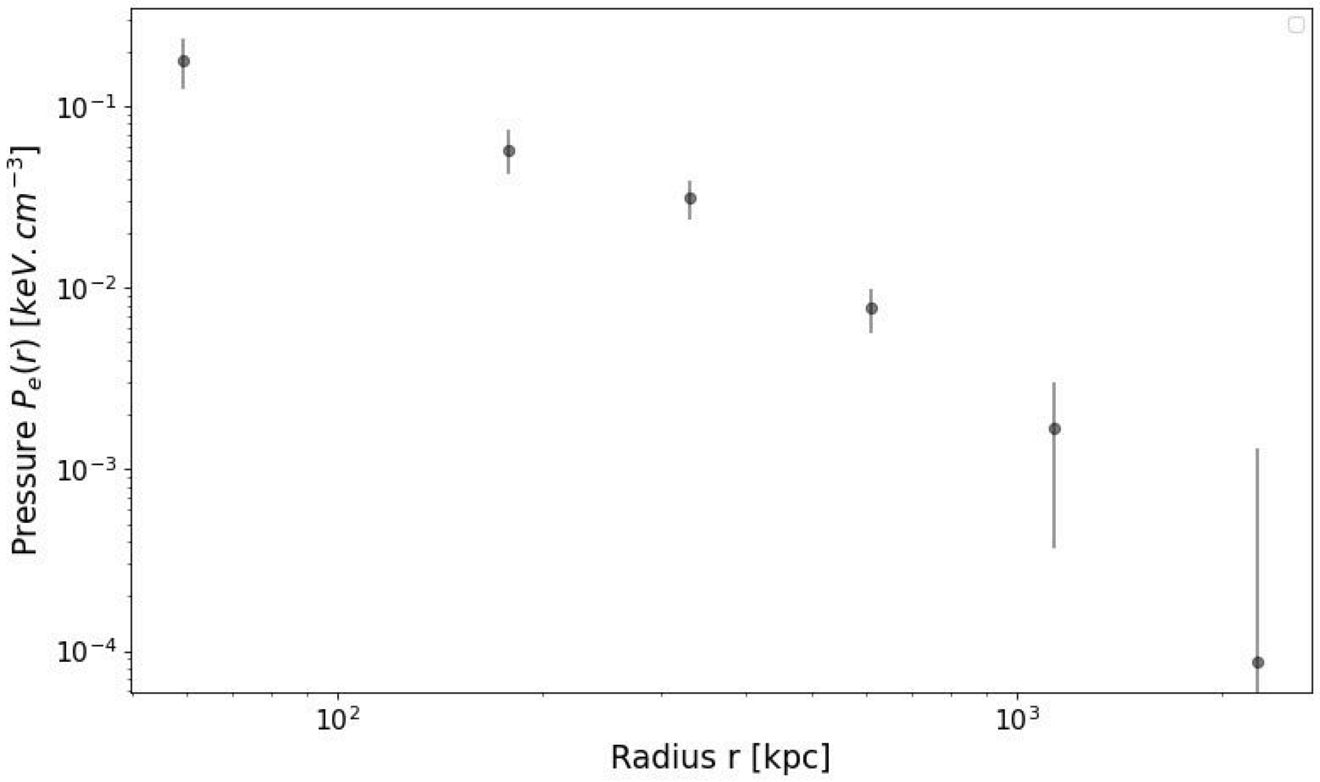
We develop different models in order to check the robustness of the results

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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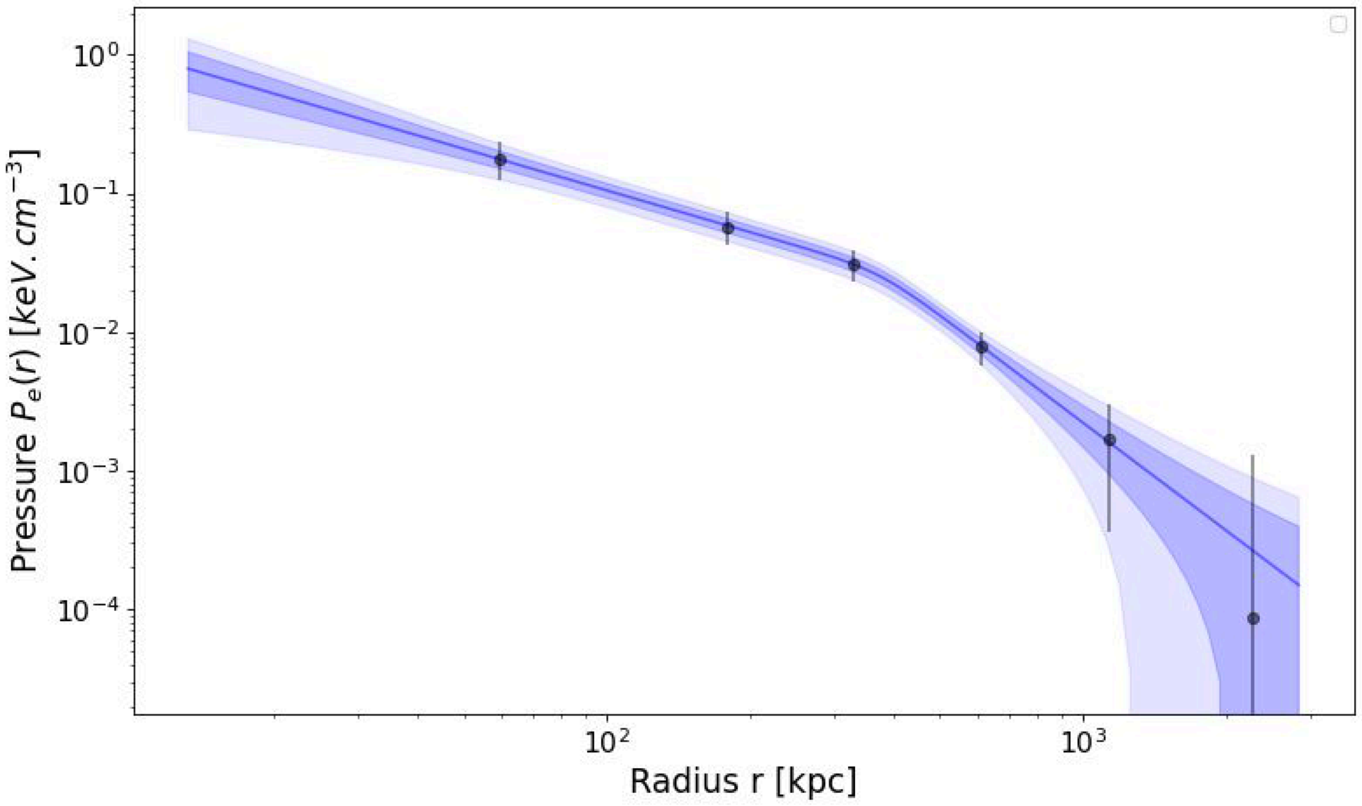
Radially binned model :

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, …



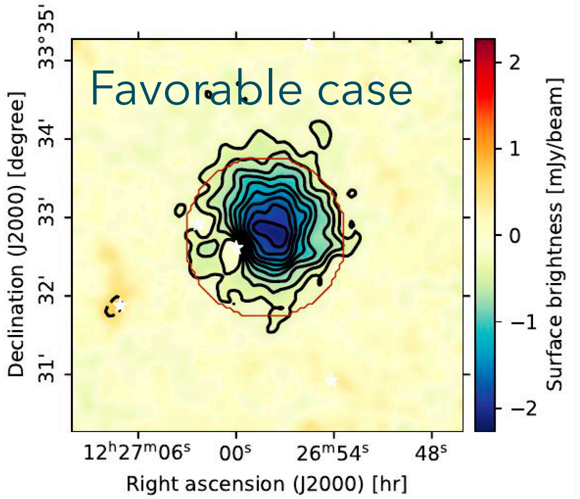
–> Check the robustness of the radially binned model on noisy data

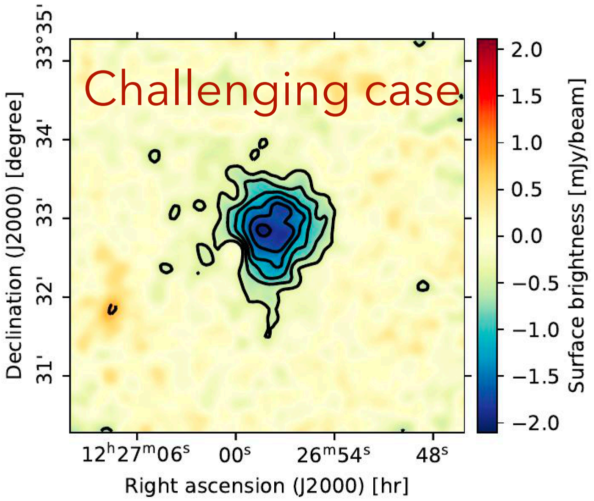
Results for PSZ2G160

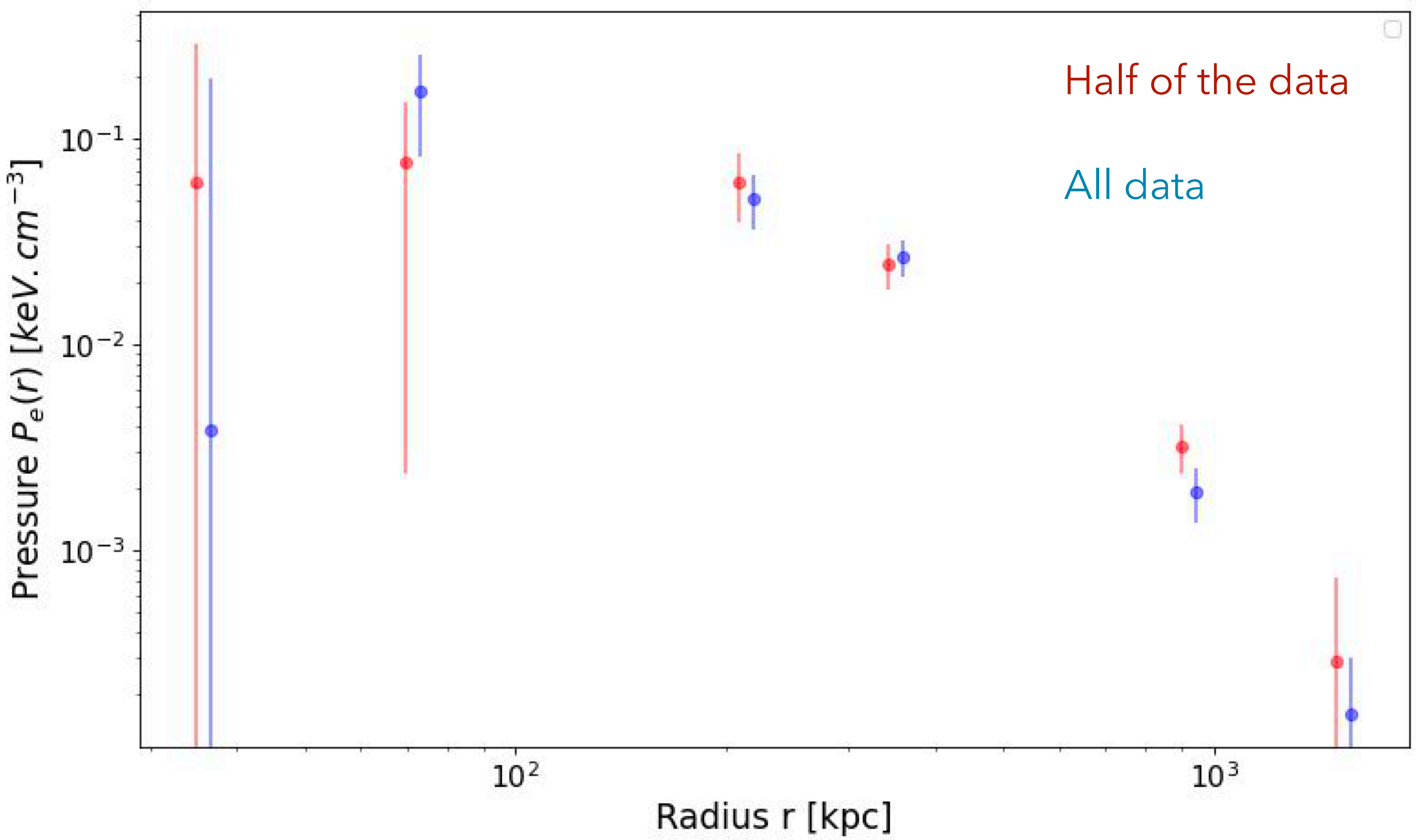
Cluster observed twice the planned time : half of the data should be enough to do the analysis

2 maps : One with all the available data

One with the worst half scans sample chosen with criteria described previously







–> Results in agreement in a challenging case (half data + low frequency noise residuals)

–> Further studies on simulations

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)

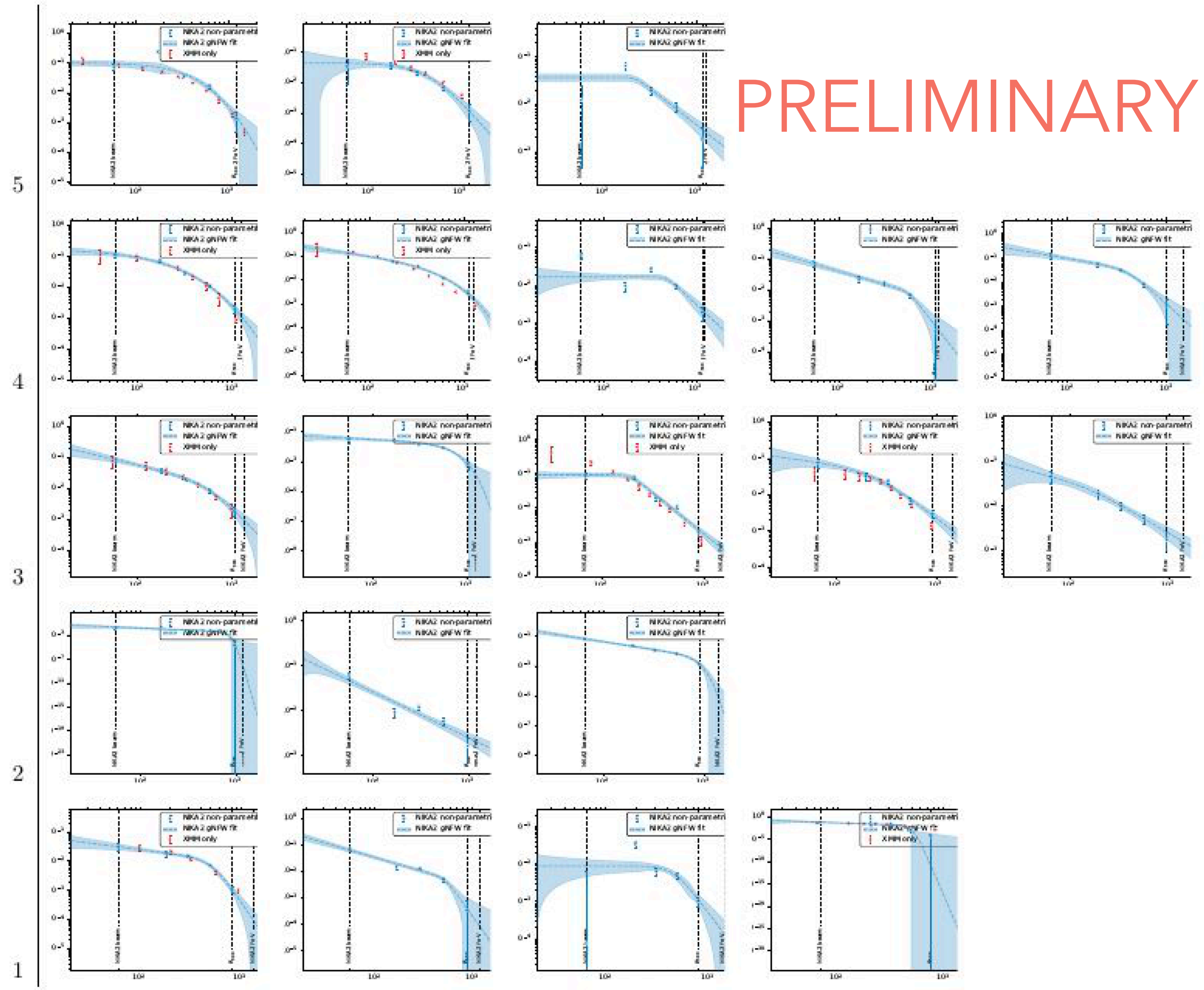
- Results obtained with the Radially binned approach
- gNFW give promising results as well
- Using both methods for consistency check

On-going work :

Study the systematics on complex simulations
First estimate of the mean pressure profile at high redshifts

Targeted clusters

PRELIMINARY



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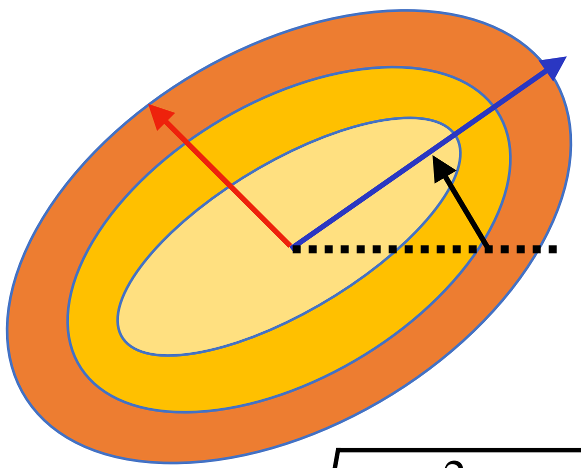
Morphological studies

NIKA2 high angular resolution : allows the study of complex morphologies

- Shocks (Artis et al. 2022 in prep)
- Disturbed clusters : under/over-pressured regions (Ruppin et al. 2018)
- Non-spherical clusters



a_x, a_y, ϕ_0

Idea : add elliptical parameters in the MCMC

Method : Simulate an elliptical cluster

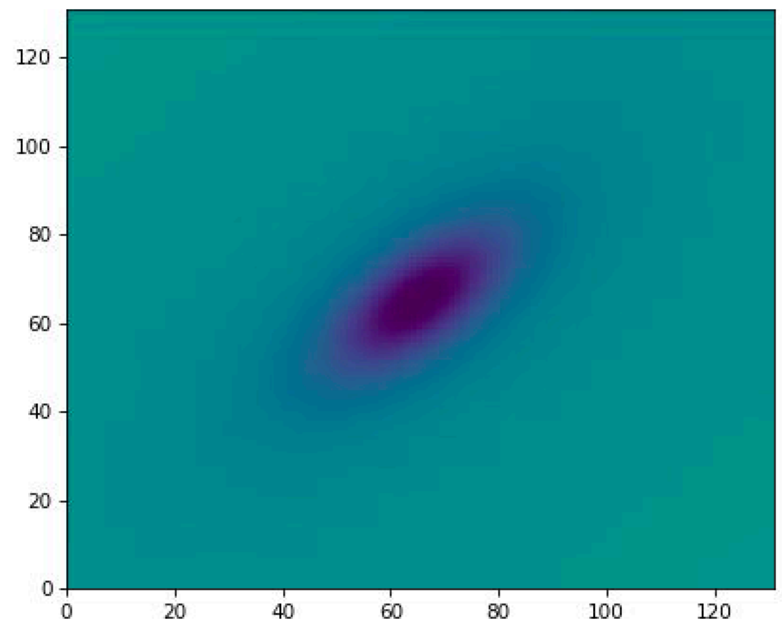
–> Same method presented previously and change of coordinates

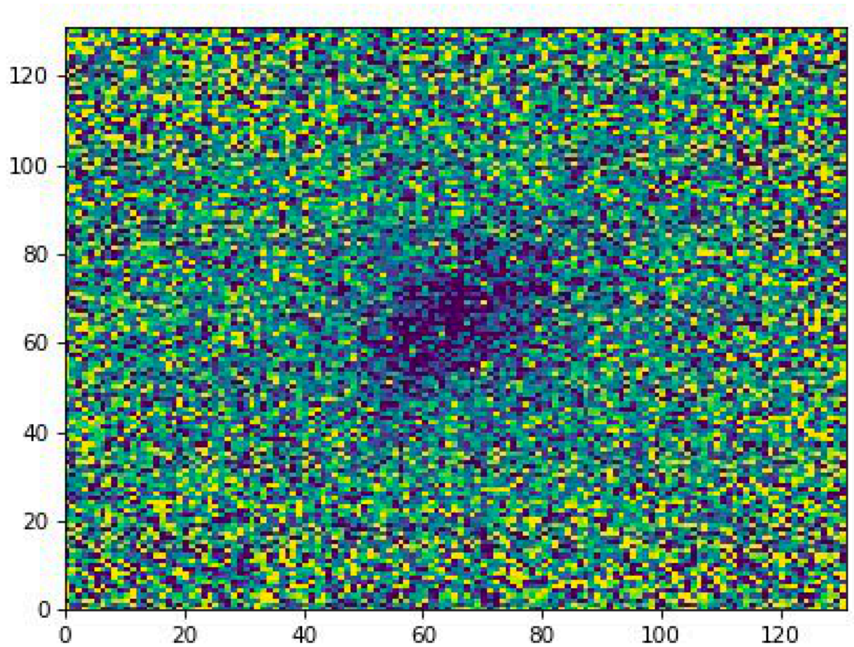
$$R_{ell} = R_c/e(\phi),\ \ e(\phi) = \sqrt{\frac{cos^2(\phi - \phi_0)}{a_x^2} + \frac{sin^2(\phi - \phi_0)}{a_y^2}}$$

Two analyses :

- Without noise (left)

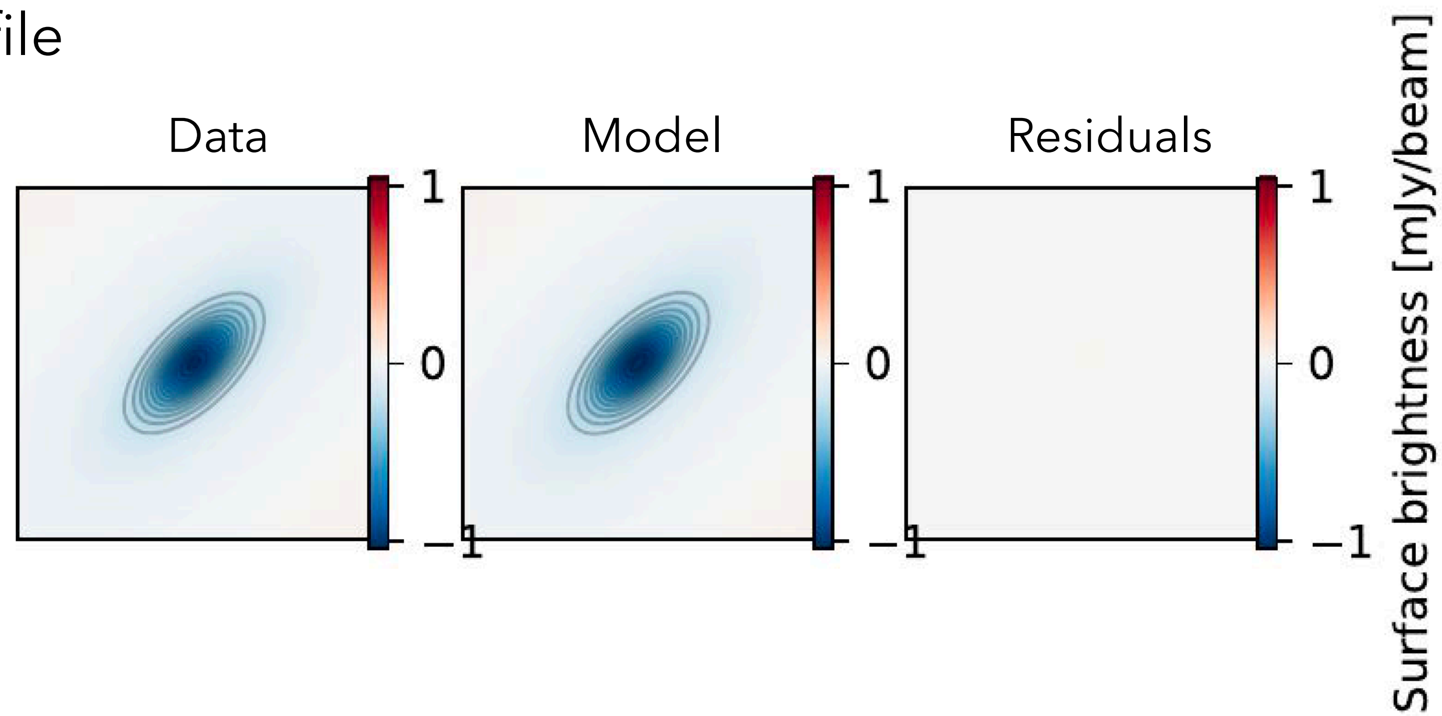
- Add a white noise (right)



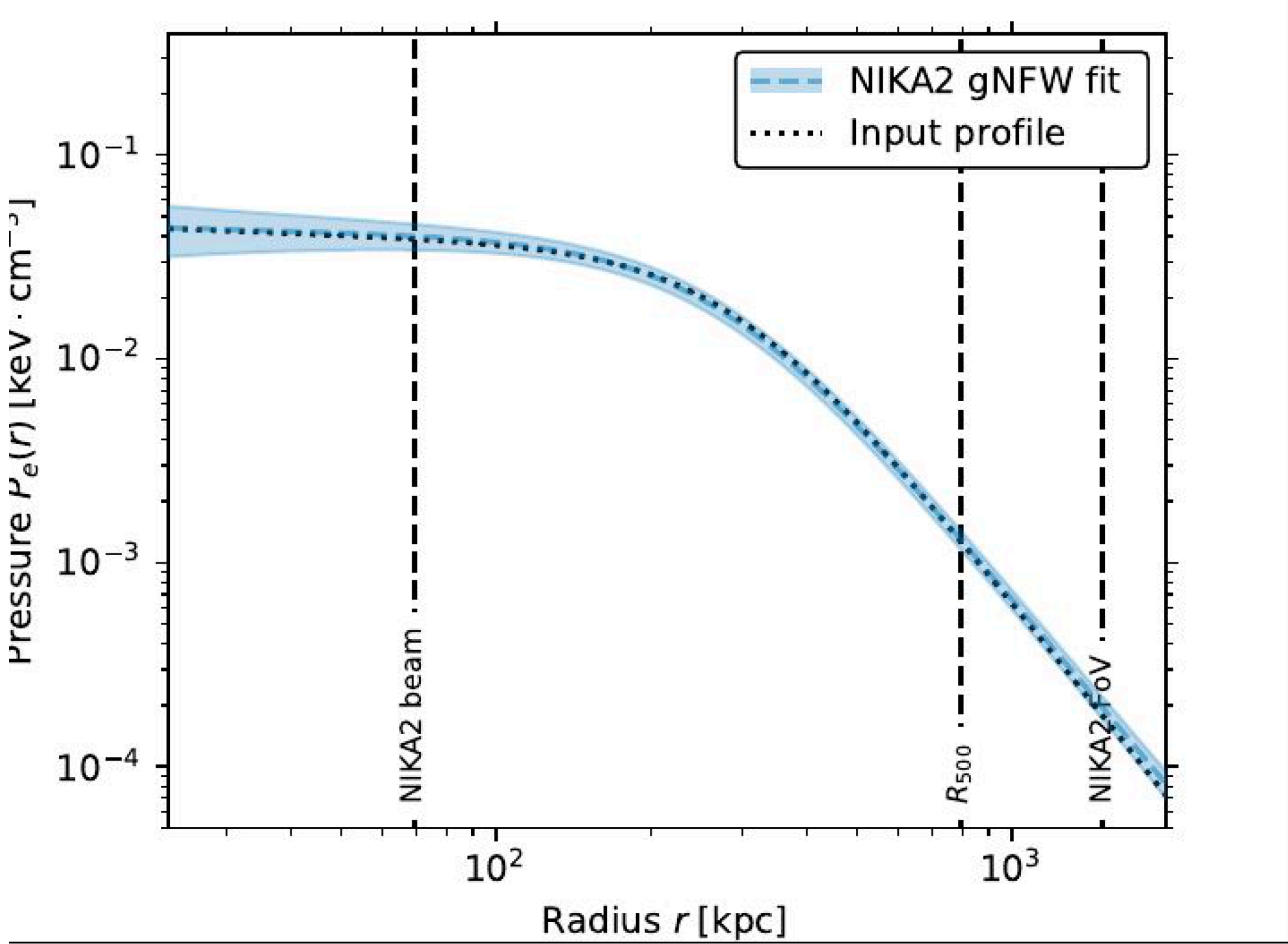


Simulation : we know the spherical input profile

Data (left) - Model (center) - Residuals (right)



Input and output pressure profile

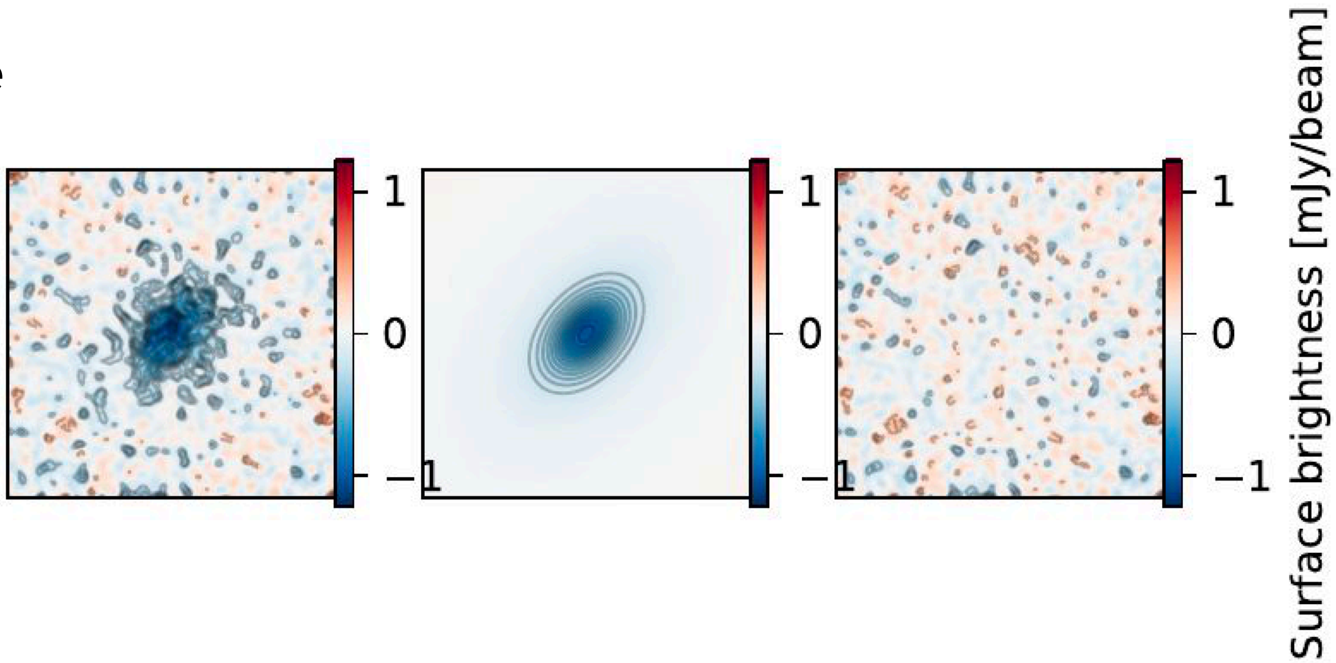


We recover the input profile

Results with a white noise

Simulation : we know the spherical input profile

Data (left) - Model (center) - Residuals (right)



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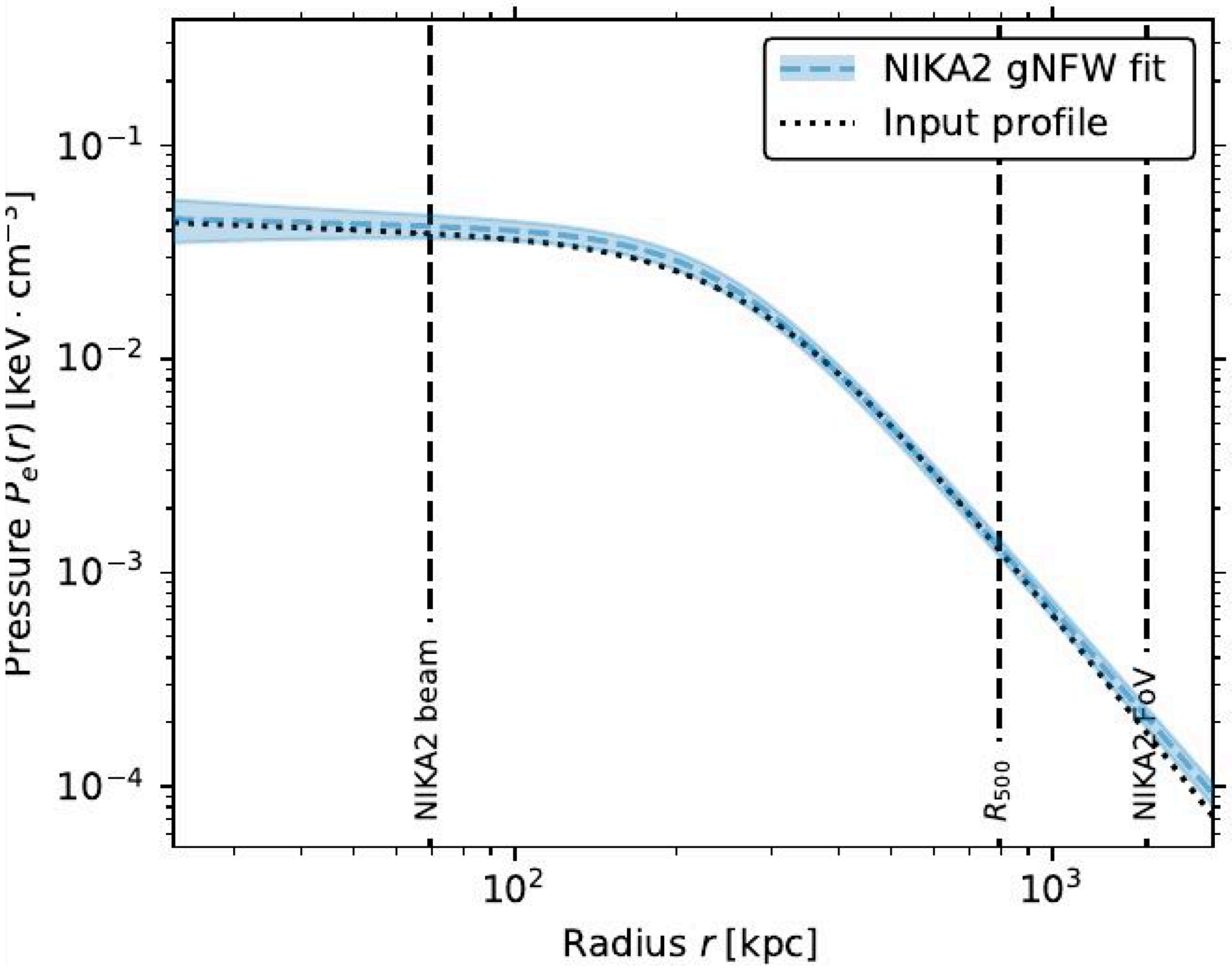


We recover the input profile

Perspectives :

- Test with a correlated noise
- Test on more complex simulations
- Test on LP-SZ data

We want a mass estimate more robust to projection effects

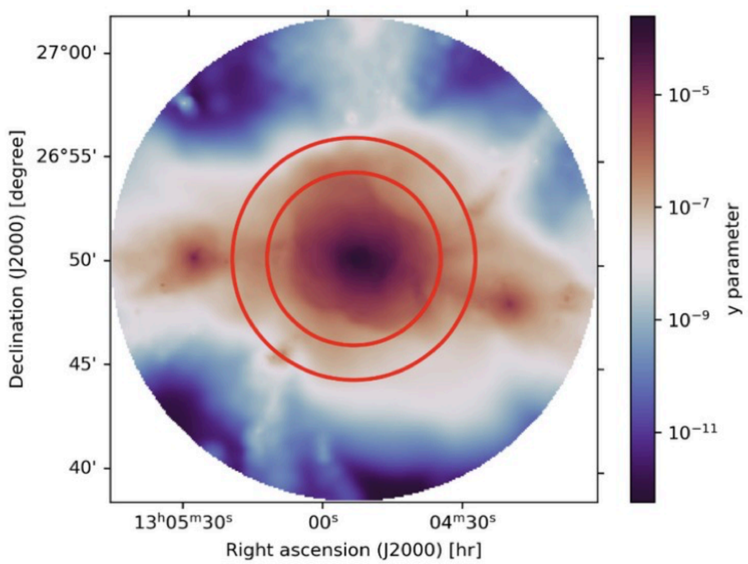
Forthcoming studies on simulations

The300 sample

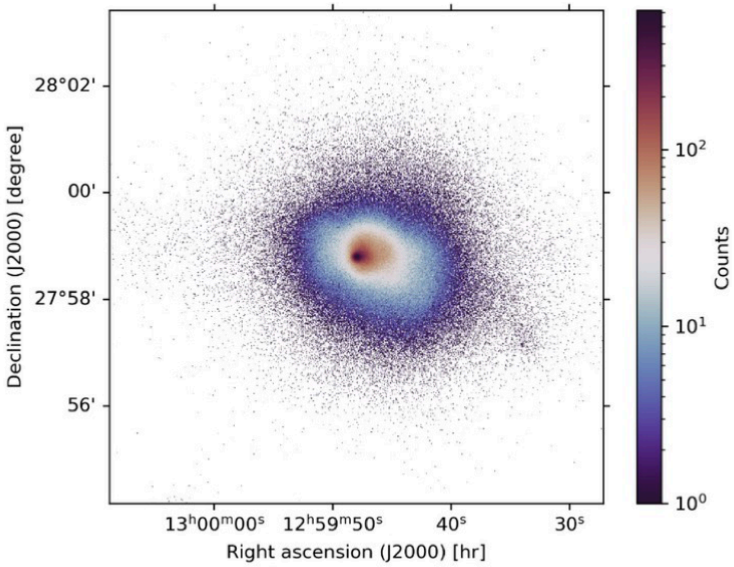
Hydrodynamic re-simulation of a previous dark matter simulation
~300 regions with a massive cluster [W.Cui et al., 2018]

Twin sample of the LP-SZ

A.Paliwal et al. 2021 Proceeding mmUniverse Conference



SZ map



X map

- Knowledge of the 'true' mass
- Many orientations available

Essential to study the systematics affecting the mass reconstruction

Conclusion

Status of the analysis

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

LP-SZ data allow to resolve intermediate to high redshift galaxy clusters in SZ

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

Characterization of the data quality : control the low frequency residual noise by performing a scan selection

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