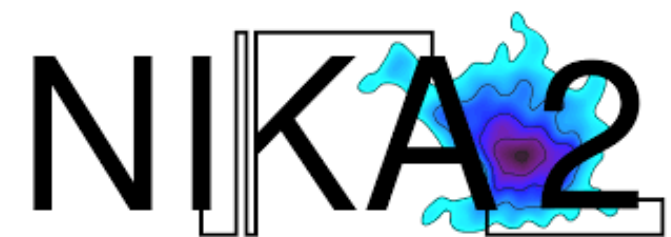


Galaxy cluster cosmology with NIKA2

Corentin HANSER

Under the supervision of Laurence PEROTTO
in COSMO-ML team

PhD seminars 27/03



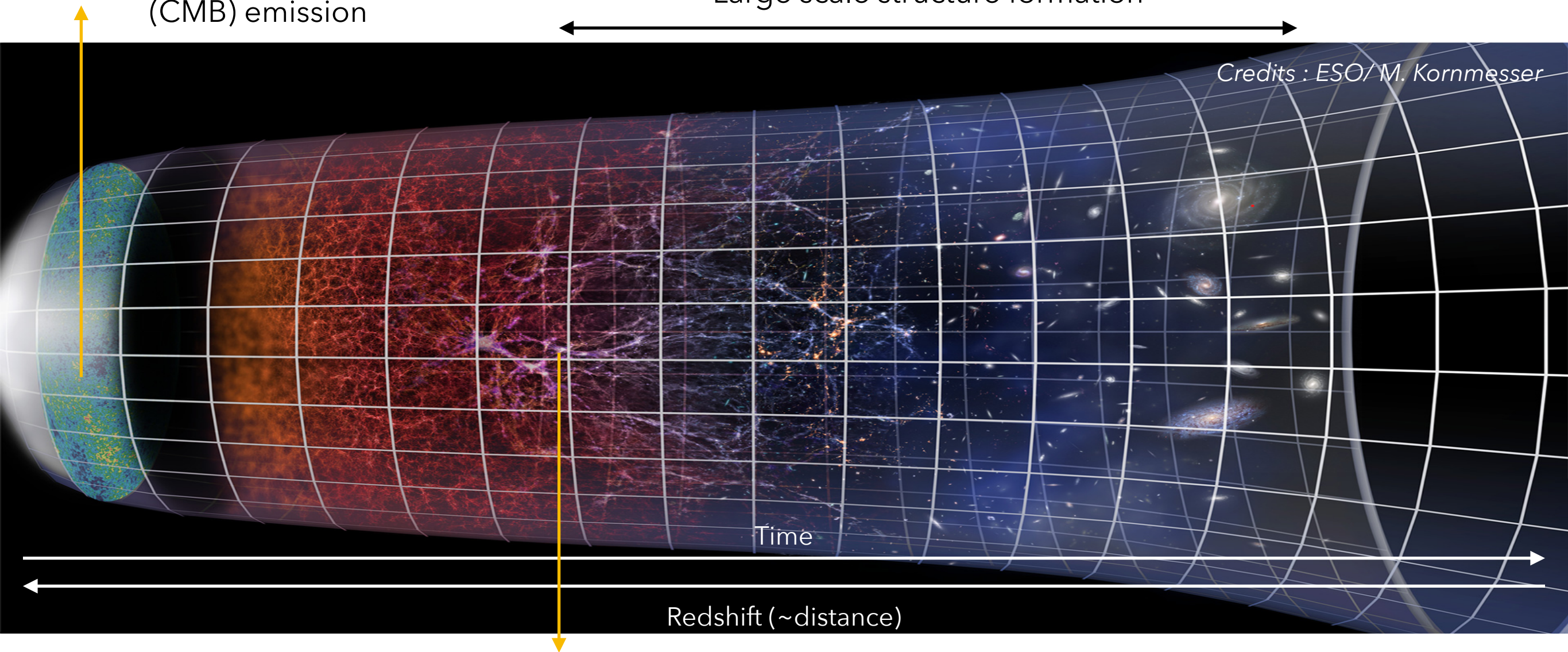
1. Cosmology with galaxy clusters and the NIKA2 experiment
2. From raw data to cluster thermodynamical properties
3. Mean pressure profile estimates
4. Conclusion and perspectives

Galaxy clusters in the history of the universe

Some steps in the Universe history :

Cosmic Microwave background
(CMB) emission

Large scale structure formation



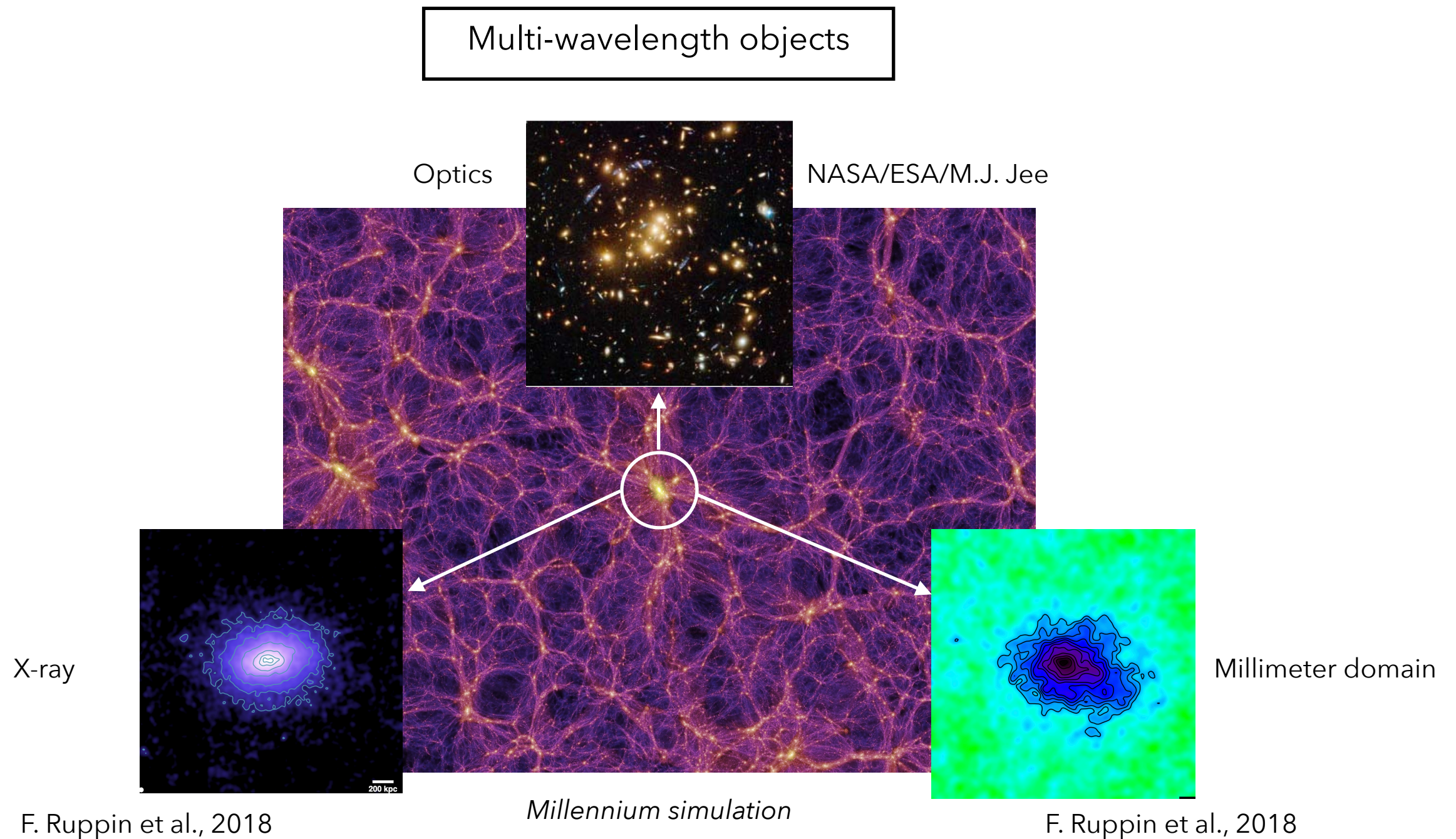
Galaxy clusters form at the intersection of the filaments

- Final step of hierarchical large scale structure formation : $z < 2 - 3$
- The largest gravitationally bound objects in the universe with $M \in 10^{13} - 10^{15} M_{\odot}$

Galaxy clusters are tracers of the matter density field and evolution history of the Universe

Galaxy clusters

Multi-component systems : ~85% of dark matter, ~ 3% of galaxies, ~ 12% of hot ionised gas



We detect clusters in the millimeter domain via the thermal Sunyaev-Zel'dovich effect

Sunyaev-Zel'dovich effect

The thermal Sunyaev-Zel'dovich effect (tSZ)

Sunyaev & Zel'dovich 1972

Spectral distortion of the CMB spectrum induced by the scattering of CMB photons with energetic electrons from the Intra-cluster medium (ICM)

- Independent of the redshift
- Decrease in the intensity at frequencies ≤ 217 GHz
- Increase in the intensity at frequencies ≥ 217 GHz

$$\text{Relative variation in intensity of the CMB : } \left[\frac{\Delta I}{I_0} \right]_{SZ} = y f(\nu, T_e)$$

$$\text{Compton parameter : } y = \frac{\sigma_T}{m_e c^2} \int P_e dl$$

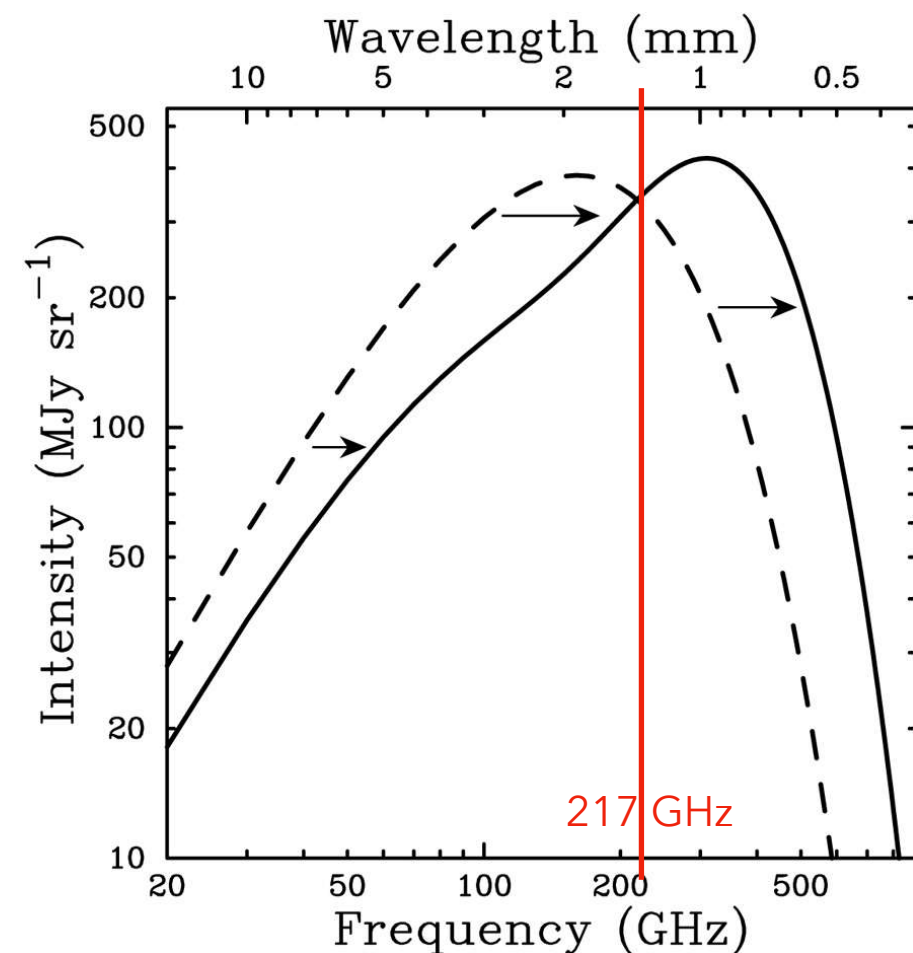
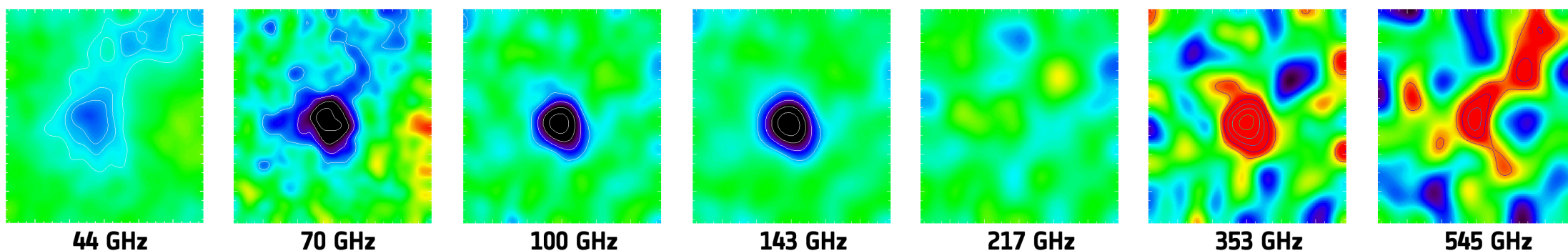


Illustration of the tSZ effect (*1000)

Abell 2319 [*Planck*]



Catalogues of several thousands clusters detected via tSZ

SZ cosmology : Methods

Cluster number count

The cluster abundance in intervals of mass and redshift

$$\frac{d^2N}{dMdz} \sim \int d\Omega \int d\mathcal{O} \left[\frac{d^2V}{dzd\Omega} \frac{dn}{dM} P(\mathcal{O} | M) \right]$$

Volume : background cosmology

Halo mass function

→ Highly sensitive to cosmology

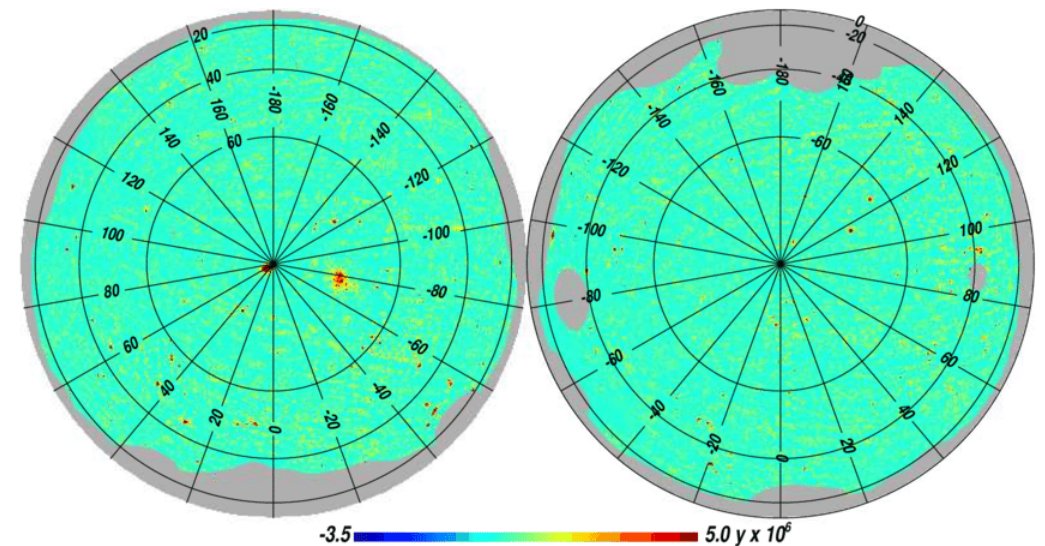
Holder et al., 2001

Mass is not an observable

→ SZ-M Scaling relation

SZ power spectrum

Angular power spectrum of the SZ-map



Planck Collaboration XXII 2015

$$C_l^{tSZ} \sim \int dz \int dM \left[\frac{d^2V}{dzd\Omega} \frac{dn}{dM} |y_l(M, z)|^2 \right]$$

We need to model cluster SZ signal

→ Mean pressure profile

We need a precise characterization of both these products

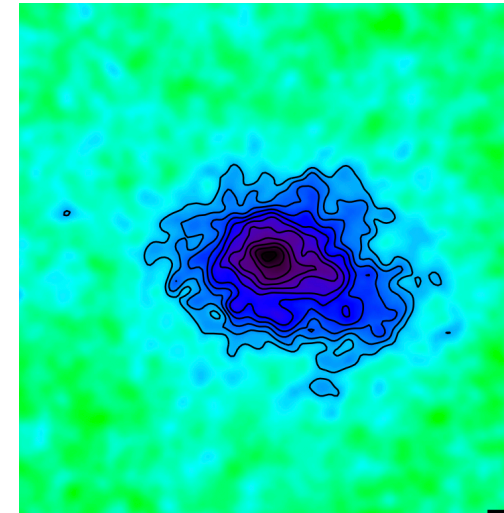
Synergy between X-ray and SZ observations

Electronic pressure from SZ data

SZ observable : Compton parameter

$$y \propto \int P_e dl$$

→ NIKA2



Mass computation : 2 hypotheses

- At the hydrostatic equilibrium
- Spherical

→

Multi-wavelengths calibration :

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

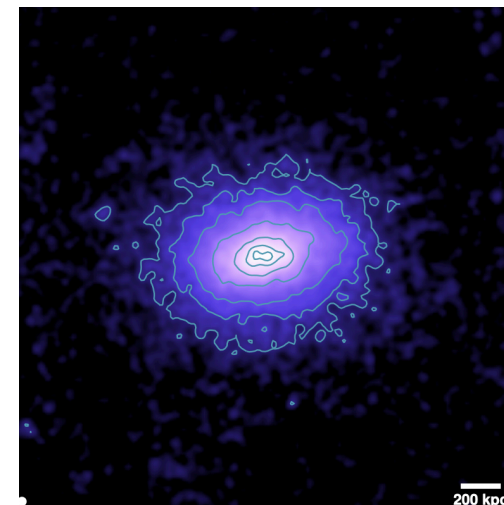
Electronic density from X-rays

X-ray observable : Surface brightness

$$S_X \propto \int n_e^2 \Lambda(Z, T_e) dl$$

→

XMM-Newton



Powerful method when SZ and X-ray resolutions are similar

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)

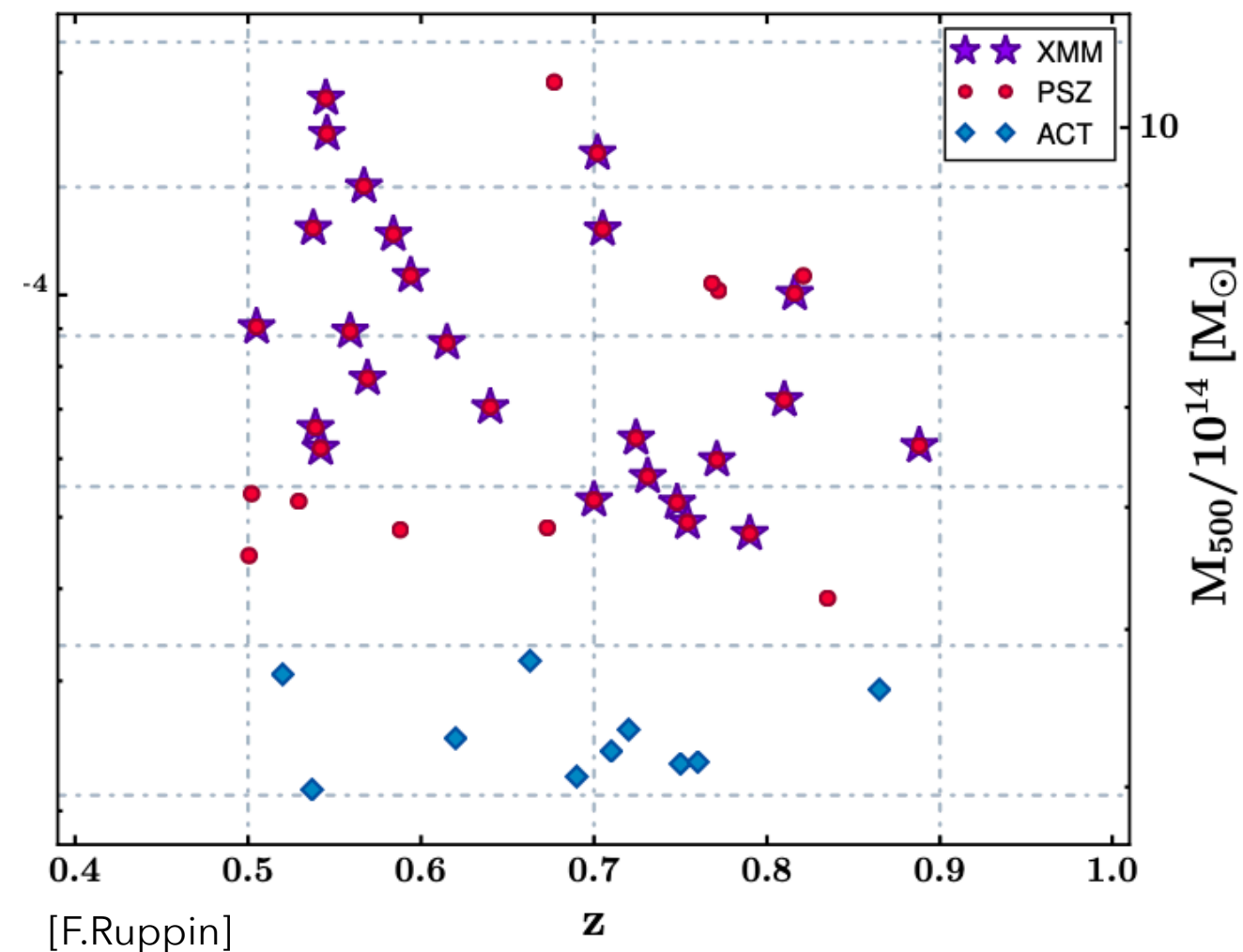
High angular resolution follow-up of
45 Planck and ACT galaxy clusters

[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



Main PhD objectives

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

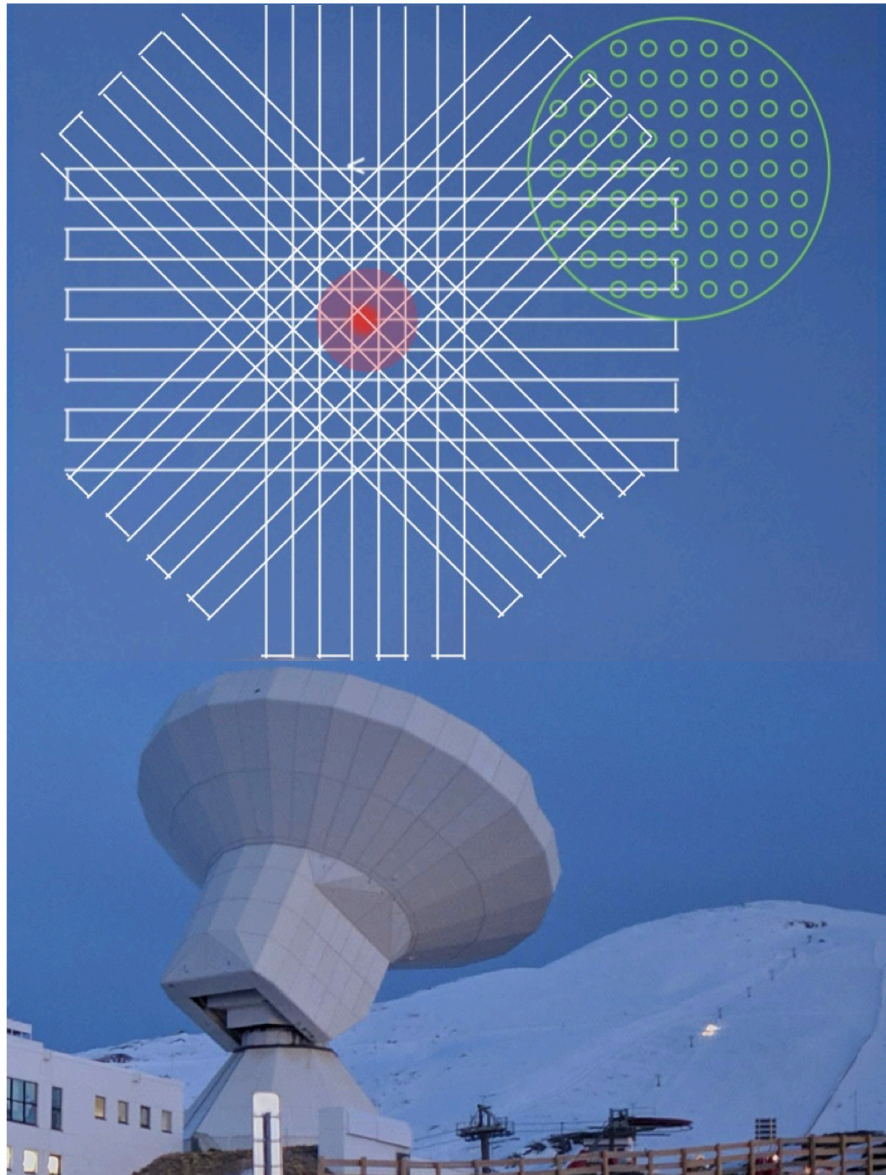
- SZ map
- Pressure profile
- Mass profile
- Integrated quantities : R_{500} , M_{500} , Y_{500}

Mean pressure profile with high redshift objects and implication for SZ cosmology

1. Cosmological context and the NIKA2 experiment
2. From raw data to cluster thermodynamical properties
3. Mean pressure profile estimate
4. Conclusion and perspectives

From raw data to NIKA2 maps

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



NIKA2 scan strategy

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

Noise terms

At a fixed time t the detectors see :

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

We subtract $A(t) + E_{B_k}(t)$ using a decorrelation method

But the residual correlated noise is one of the main systematic effects affecting NIKA2 maps

Data quality

- The **low frequency noise residuals** corresponds to the cluster scale in the map
- We want to assess the quality of the noise decorrelation

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

Model : Low frequency + White noise

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

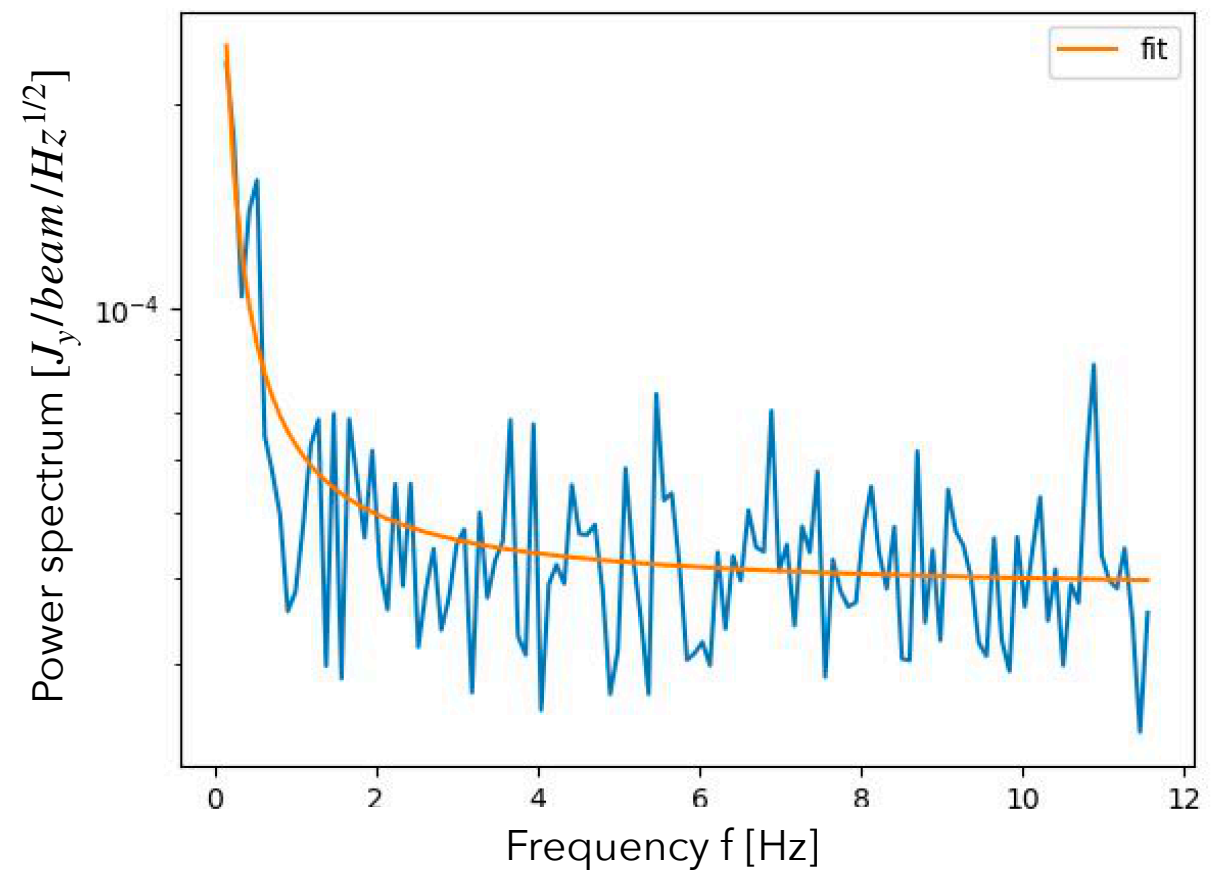
3 parameters : B, f_{knee}, α

Criterion $\sim fct(B, f_{knee}, \alpha)$

How 'harmful' is the residual noise

We can compute the average results for each scan

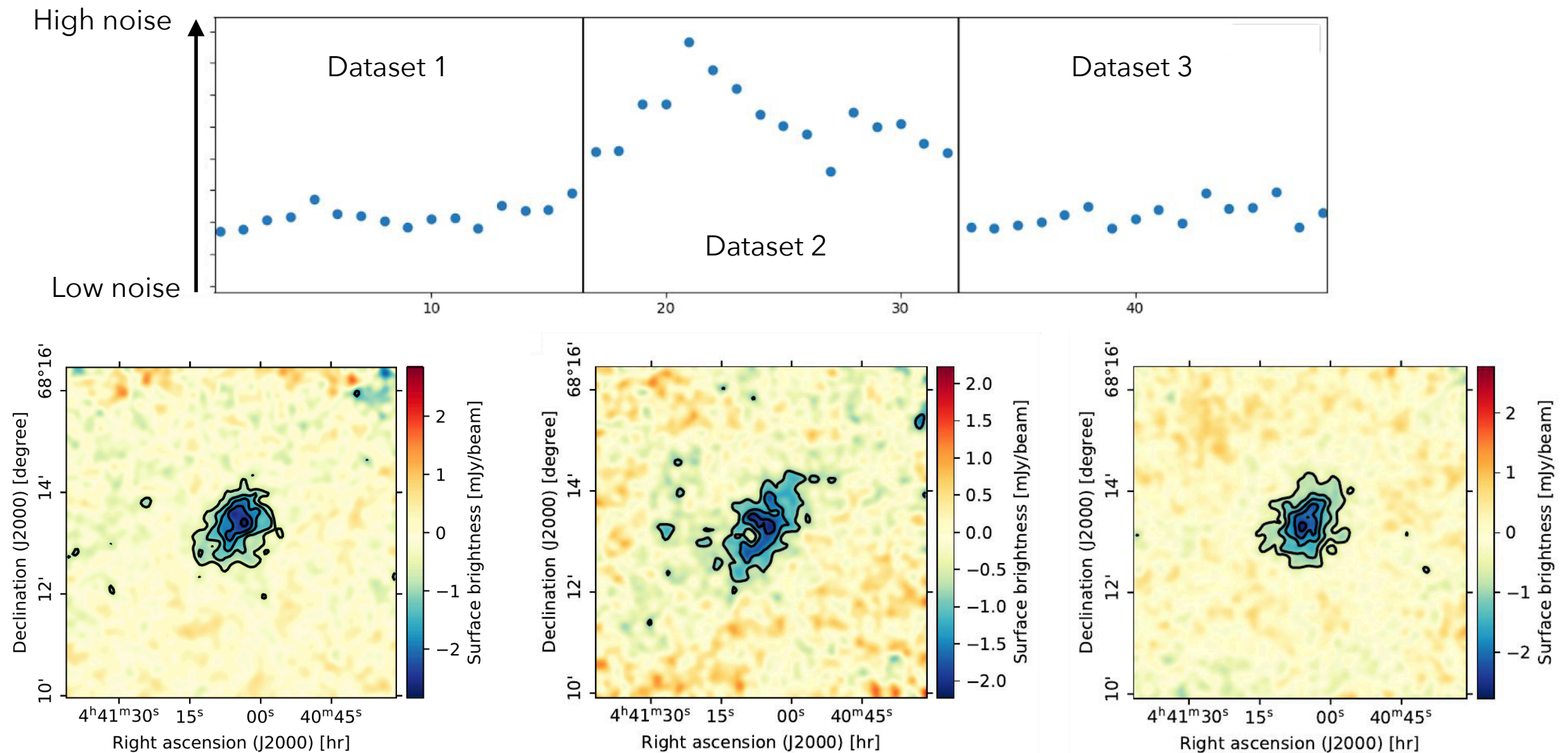
→ Data quality criterion



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

Results on one cluster

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



150GHz maps of PSZ2G141

Levels : signal on noise ratio beginning at $\pm 3\sigma$ with 2σ spacing

Low frequency residual noise has an important impact

→ We can control it by performing a scan selection


NIKA2 150 GHz maps for the selected sub-sample

Status of the LP-SZ

~35/45 clusters 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

 Analysis already performed
and published

Ruppin et al. 2018

Keruzore et al. 2020

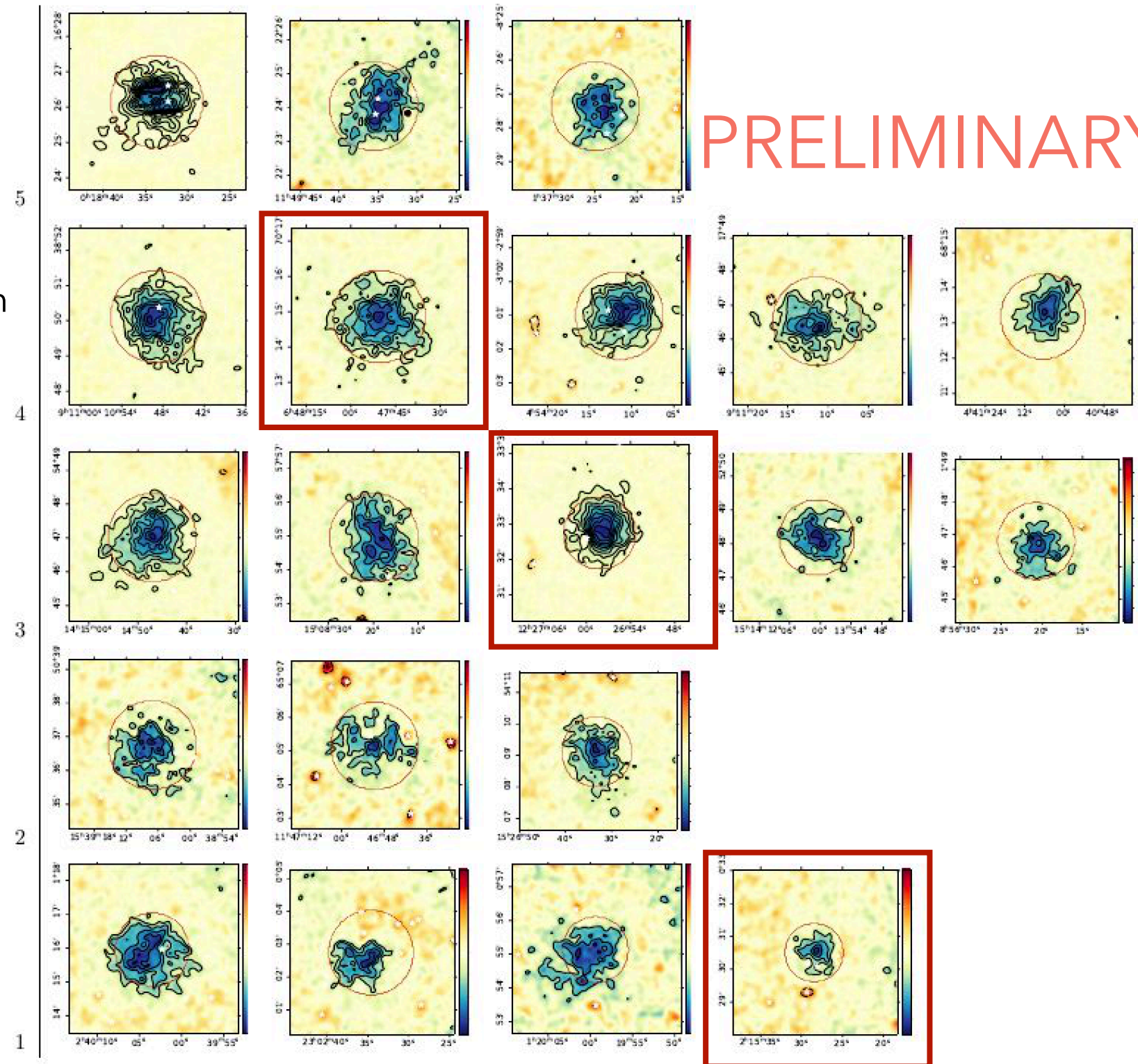
Muñoz-Echeverría et al. 2022

High signal to noise measurements

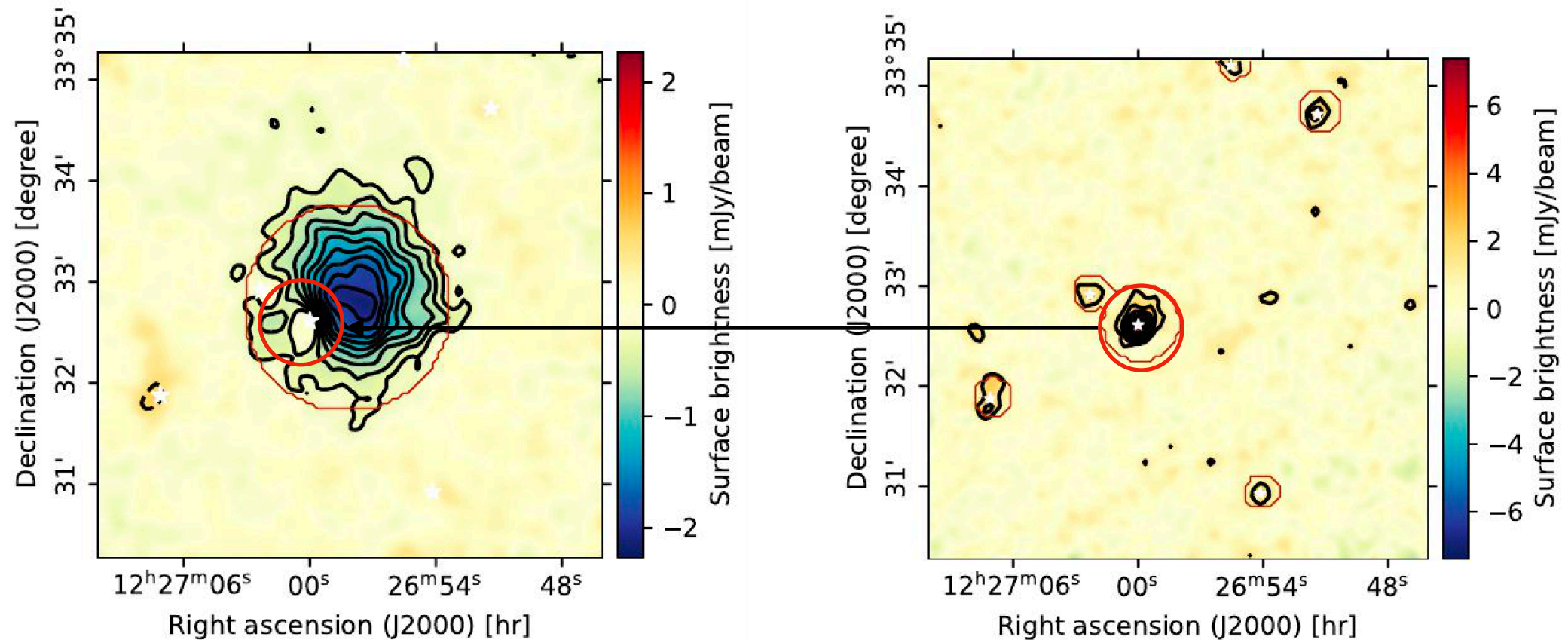
- Diversity of morphologies
- Clusters contaminated by point sources

Targeted clusters

Mass bin



Point sources



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

At 150 GHz :

Hint of point sources contamination

Sources with positive flux compensate the SZ decrement

Need to take this contamination into account

At 260 GHz :

No cluster signal detected (as expected)

Point sources contamination confirmed

Sources close to the cluster

Point source flux estimates

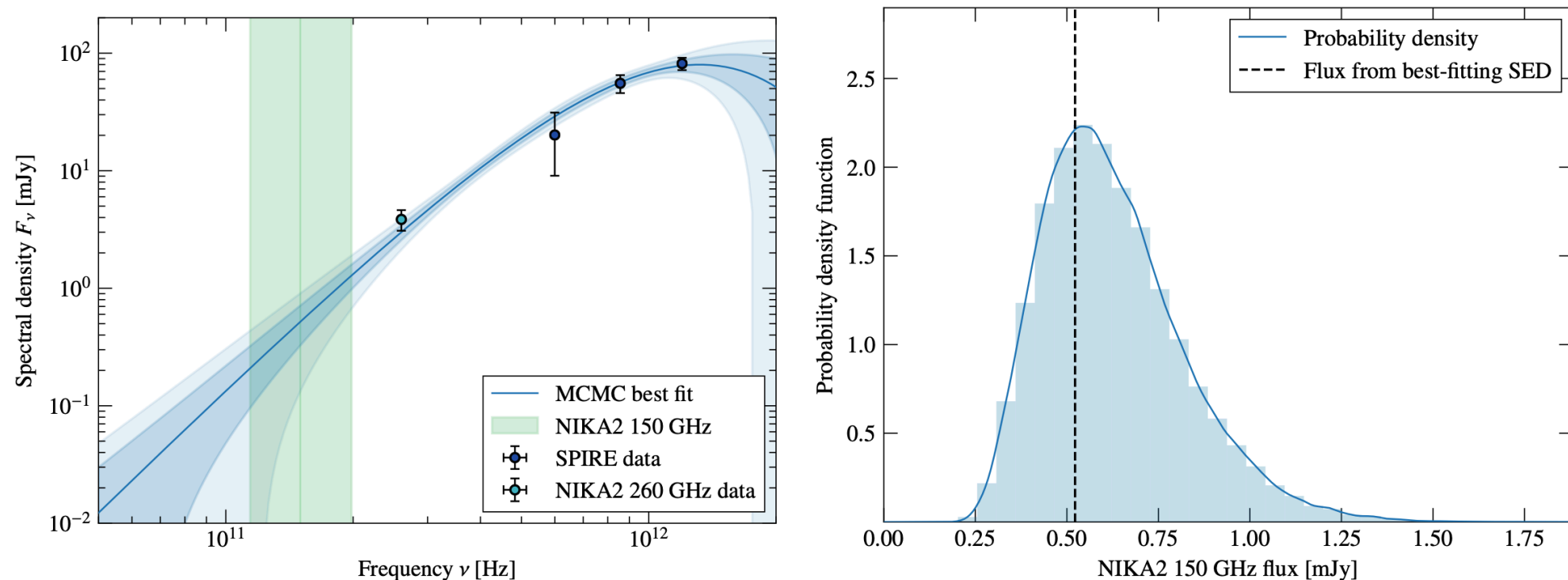
Detection : Using the 260 GHz NIKA2 map : fit of the flux in the map as a 2D Gaussian

150 GHz flux estimate :

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 modified black body model



Kéruzoré 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 SZ signal

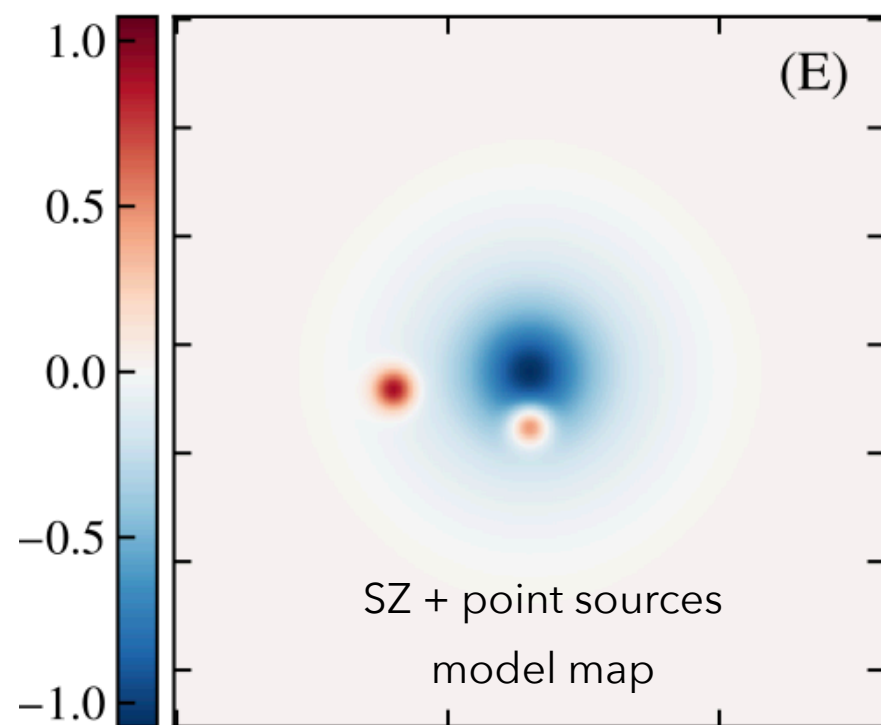
Pressure profile deprojection

$$\text{NIKA2 150 GHz map} = \text{SZ signal} + \text{point sources} + \text{noise}$$

Forward modelling

Integrated along the line of sight

Convolved by the NIKA2 instrumental response



SZ signal

Spherical symmetry : 3D pressure profile

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

→ 5 parameters : P_0 amplitude

r_p, a transition radius/ steepness

c, b internal/ external slopes

Points sources (PS)

Flux : free parameter in the MCMC

Likelihood : $-2\log\mathcal{L}(\theta) =$

$$\sum_{\text{pixels}} (D - M(\theta))^T C^{-1} (D - M(\theta))$$

Constraints from
NIKA2 150GHz map

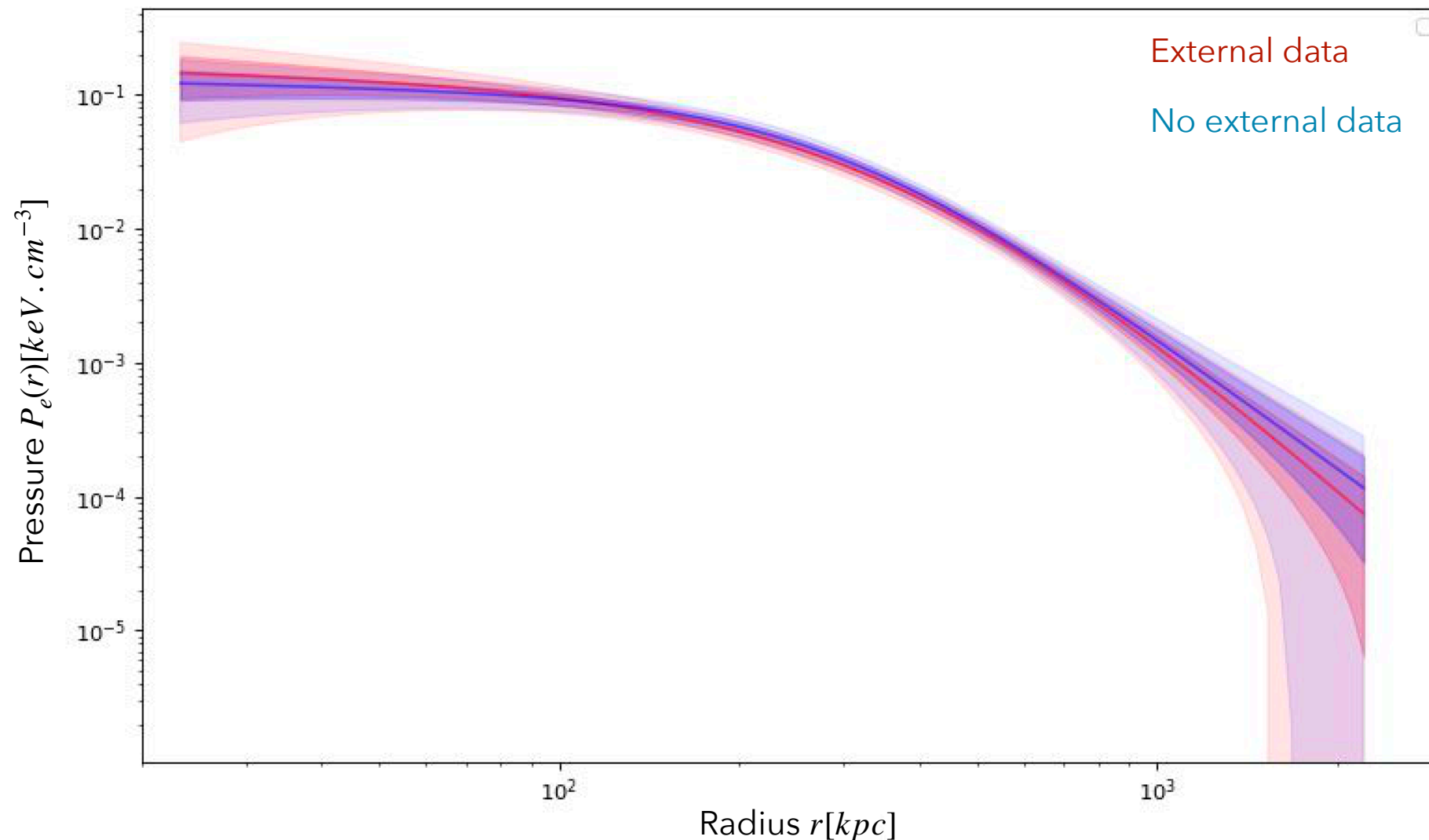
$$\left(\frac{Y_{500}^{\text{meas.}} - Y_{500}^{\text{Model}}}{\Delta Y_{500}^{\text{meas.}}} \right)^2$$

Constraints from
Planck/ACT integrated signal

Pressure profile : Impact of point source subtraction

Method 1 : Extrapolate the flux at 150 GHz \rightarrow flat prior in the MCMC

Method 2 : Fit the 150 GHz flux with external data \rightarrow PDF prior in the MCMC



Compatible results at 1σ

- \rightarrow Poor a-priori knowledge on PS fluxes seems to have a low impact
- \rightarrow We want to see the impact on final products (= integrated quantities)

Mass profile and integrated quantities

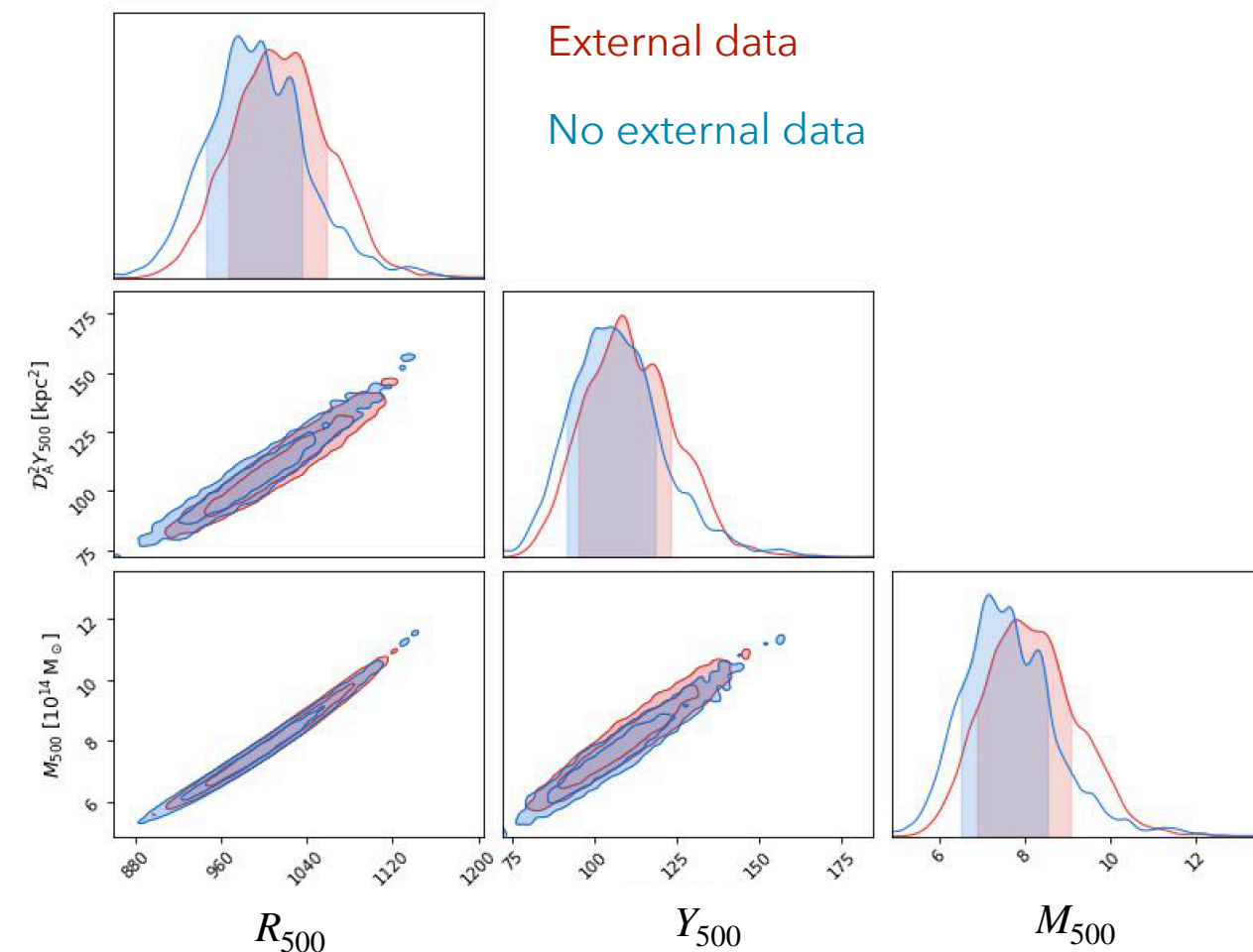
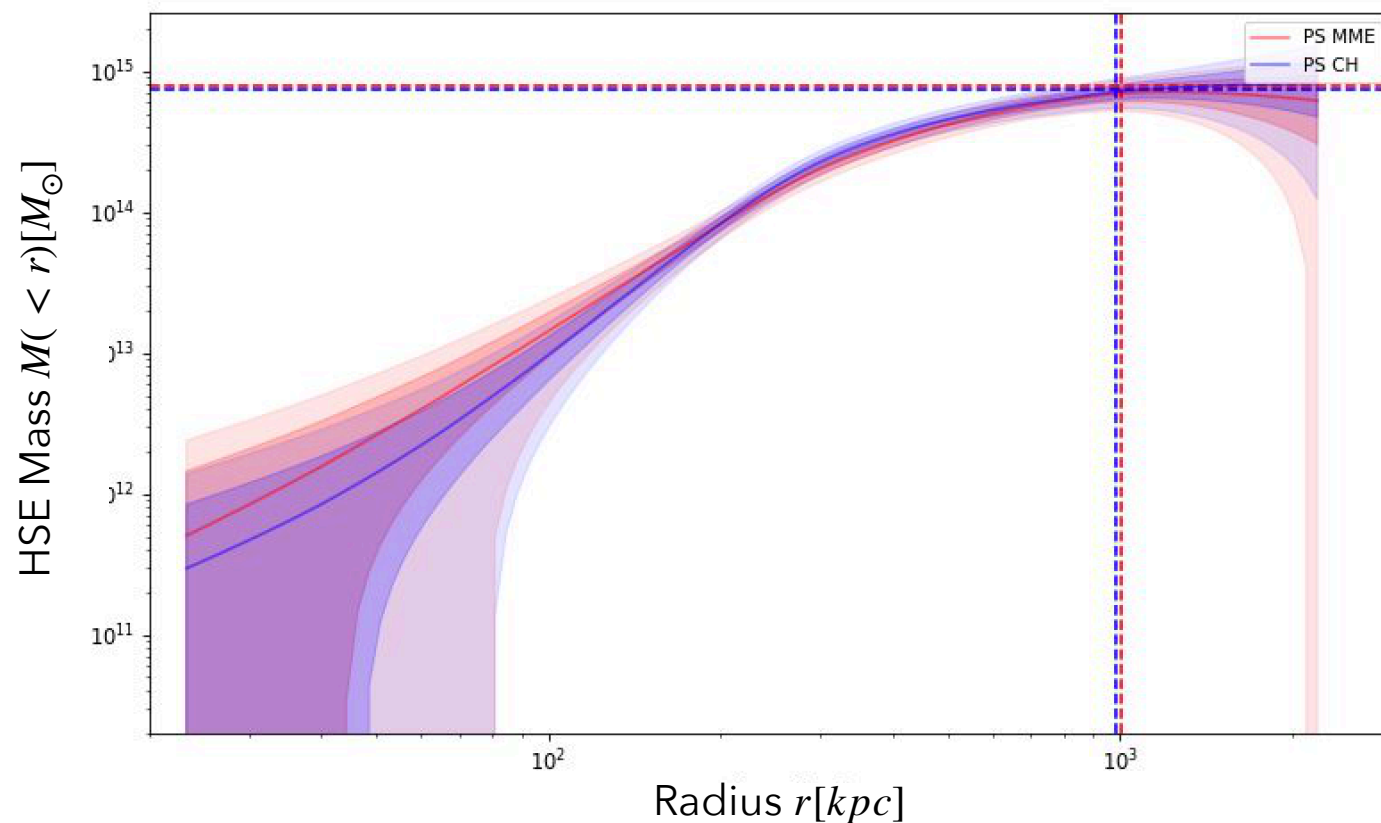
Compute the mass profile using SZ+X-ray data

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



Get the integrated quantities

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



Integrated quantities

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

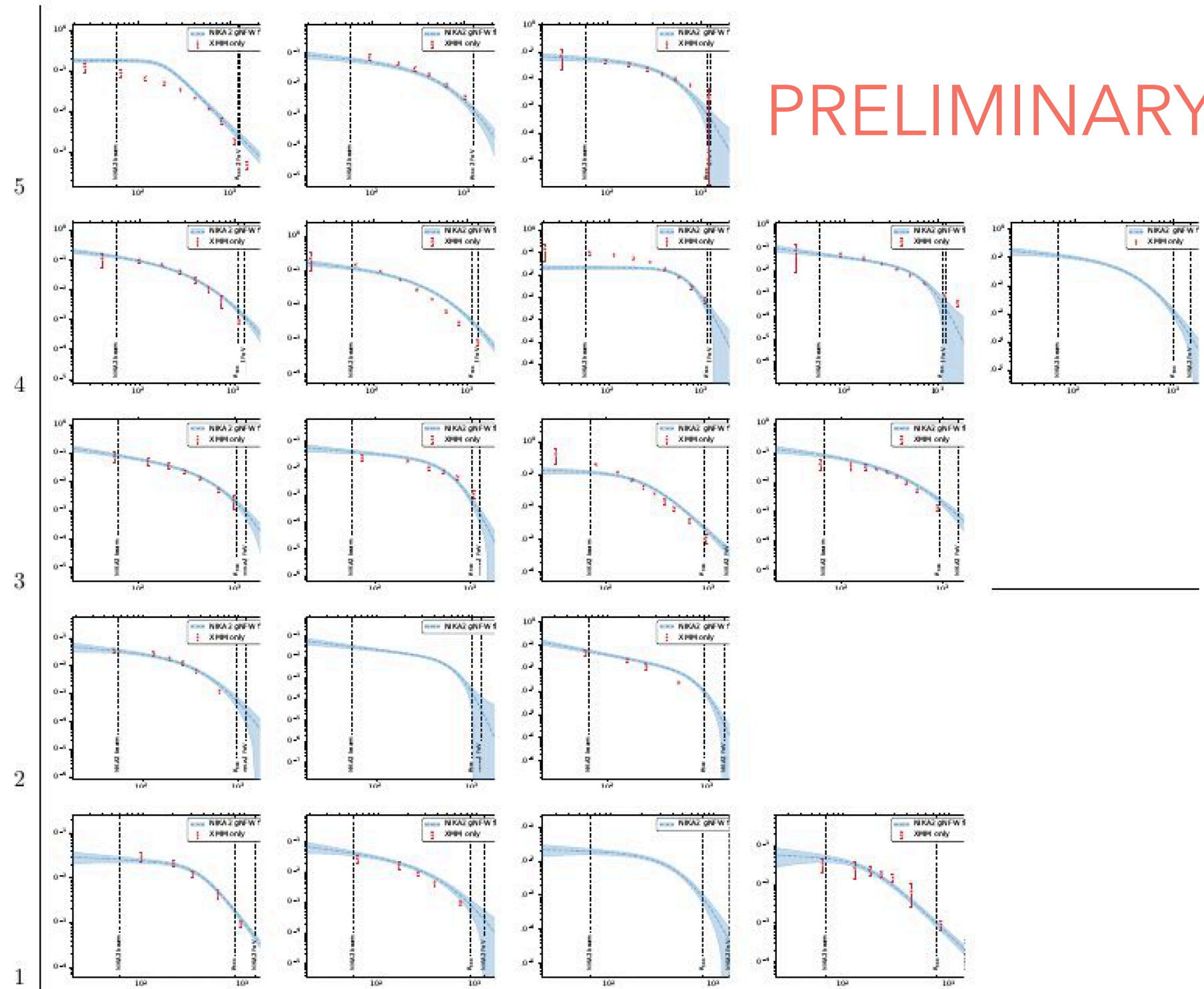
Robust method to account for point sources even without external data

Pressure profiles of the sub-sample

We have designed a first standard analysis pipeline

→ first measurement of the pressure profile on a sub-sample of the LPSZ

- gNFW fit
- XMM-Newton points



1. Cosmological context and the NIKA2 experiment
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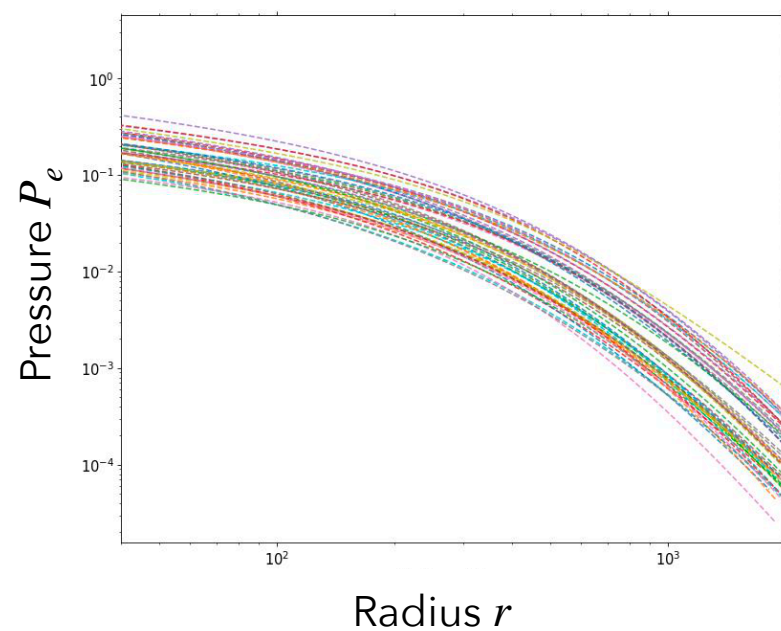
Self similar model

Idea

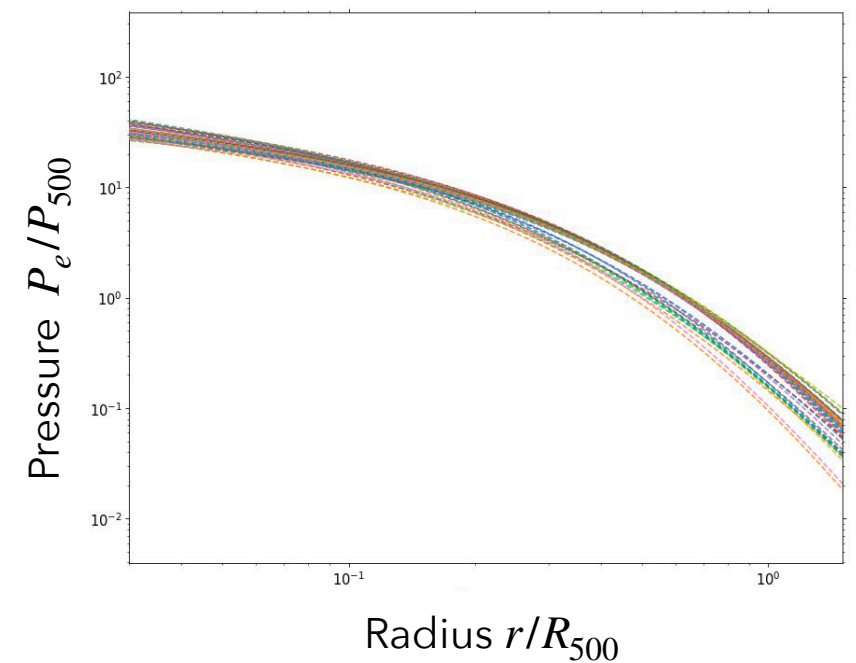
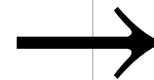
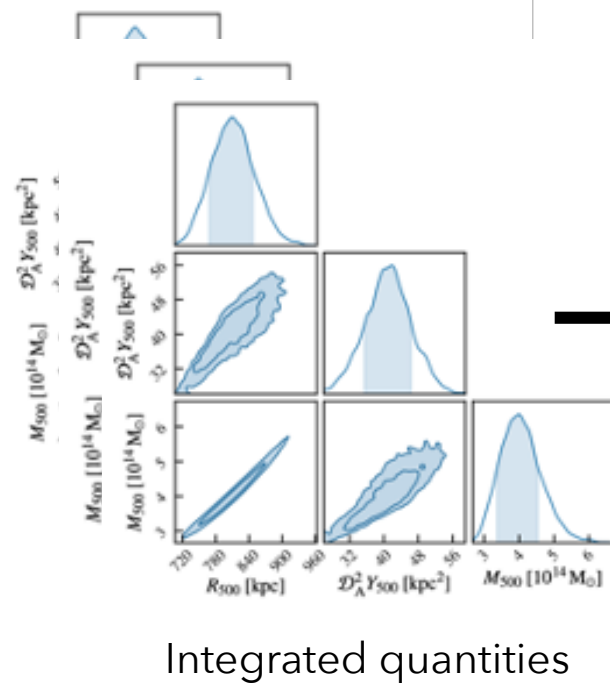
Standard self-similar model (based on gravitation) :

- Galaxy clusters are scaled versions of one another
- We can get normalized thermodynamical quantities → rescaled pressure profile :

$$\mathcal{P} = \frac{P}{P_{500}} \left(\frac{r}{R_{500}} \right)$$



+



Compute the mean pressure profile using the re-scaled individual profiles

Mean pressure profile estimate

Methods

- 1st approach : Take the median of the re-scaled profiles
- 2nd approach : Compute the best-fitting model θ for the mean profile using the posterior distribution $P(\theta | d_i)$ of the individual fit of each cluster d_i

Bayes theorem (applied twice)

$$P(\theta | d) = P(\theta)^{-(N-1)} \prod_i^N P(\theta | d_i) \implies \ln P(\theta | d) \propto \sum_i^N \ln P(\theta | d_i)$$

Likelihood

$$-2 \log \mathcal{L} = \sum_i \ln P(\theta | d_i) \text{ with } \theta = \{p_0, c_{500}, \alpha, \beta, \gamma\}$$

Problematic : we don't know for any arbitrary set of parameters θ the exact value of $P(\theta | d_i)$

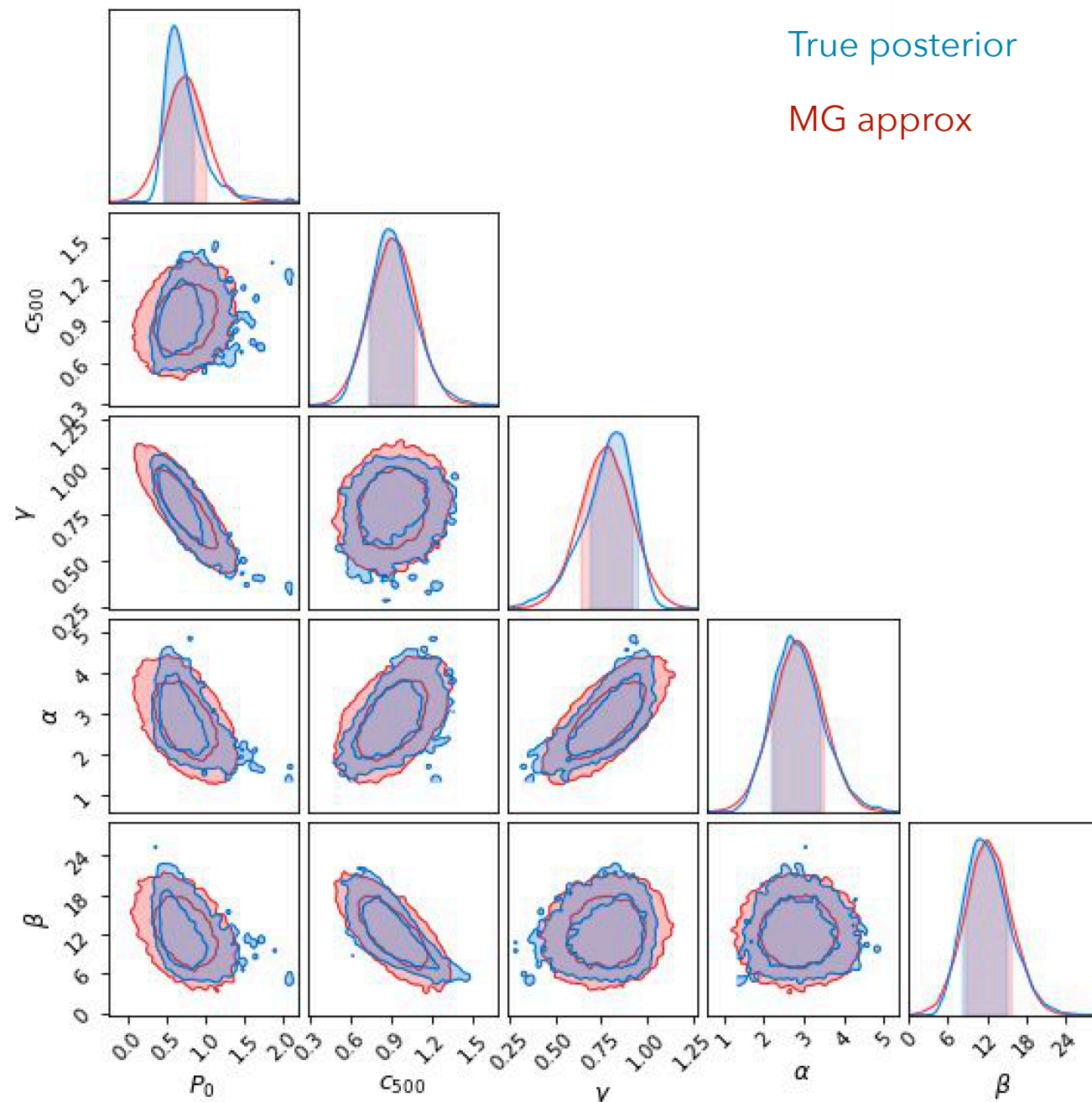
→ Very difficult to extrapolate

2nd approach

Idea

Consider posteriors as multivariate gaussians : $P(\theta | d_i) \approx \frac{1}{\sqrt{(2\pi)^k \det \Sigma_i}} \exp \left(-\frac{1}{2}(\theta - \mu_i)^T \Sigma_i^{-1}(\theta - \mu_i) \right)$

→ We know exactly $P(\theta | d_i)$ for any arbitrary θ

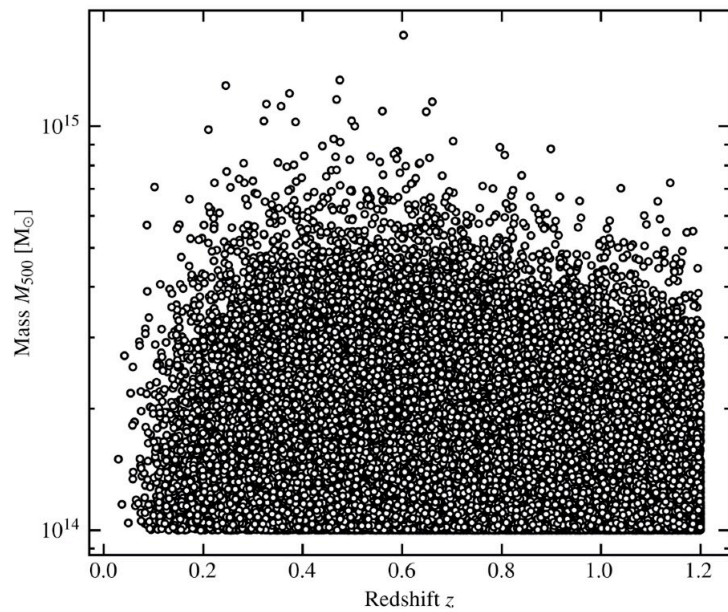


gNFW model : $\theta = \{p_0, c_{500}, \alpha, \beta, \gamma\}$

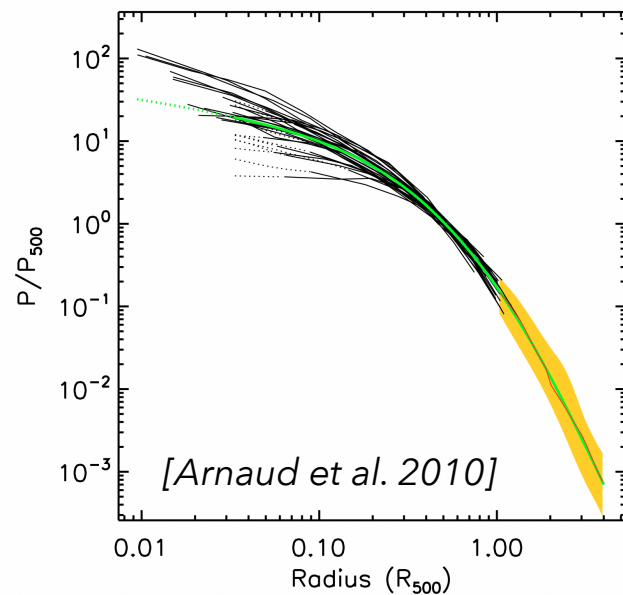
Good approximations of the posterior for all clusters

Validation on simulations

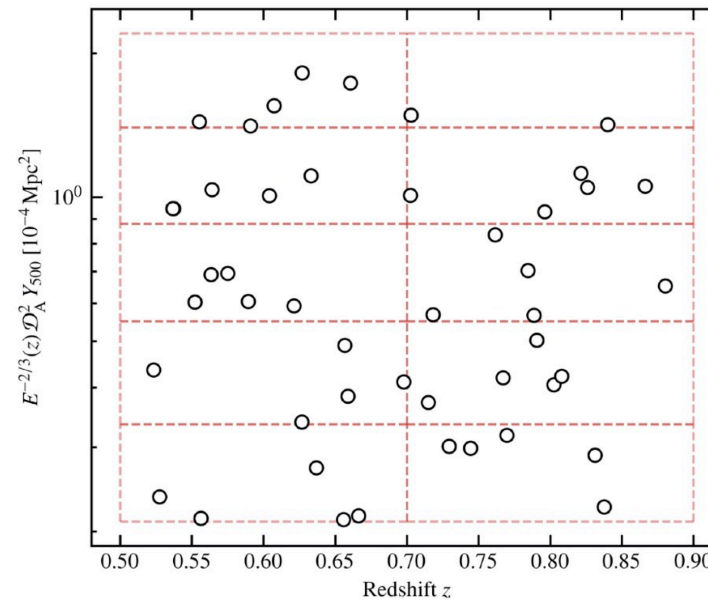
Simulations from A. Moyer (COSMO-ML)



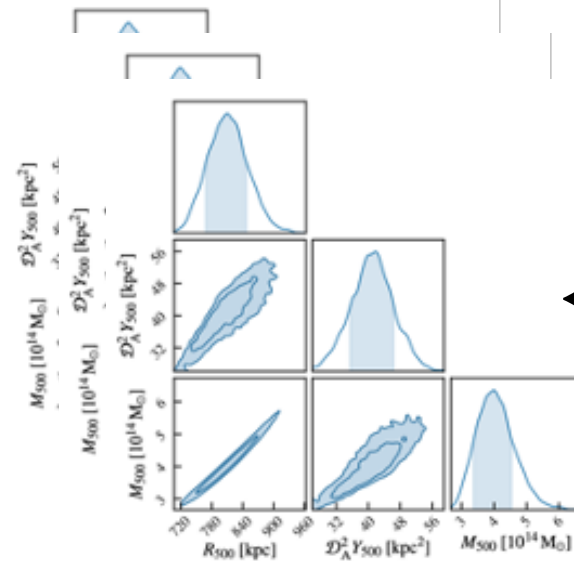
Draw random (z, M_{500}) points from a mass function



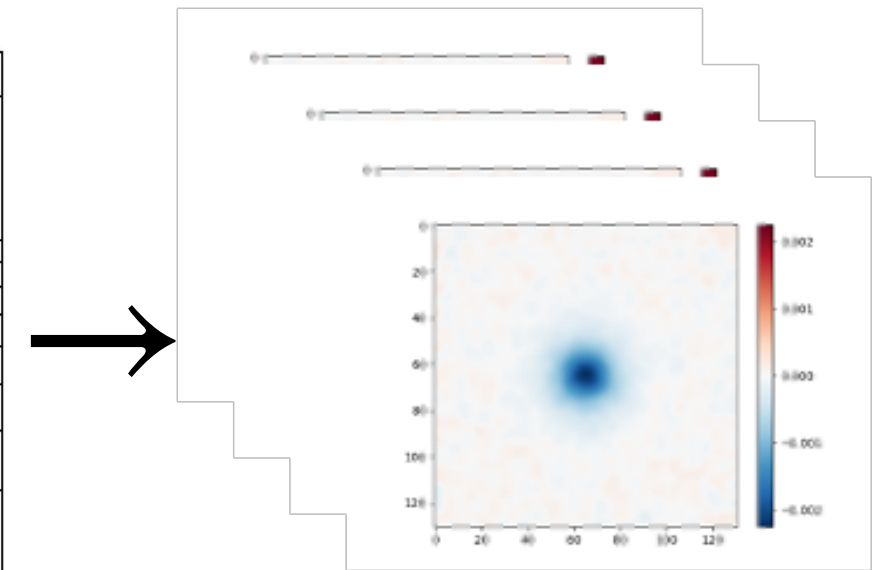
Estimate a mean pressure profile



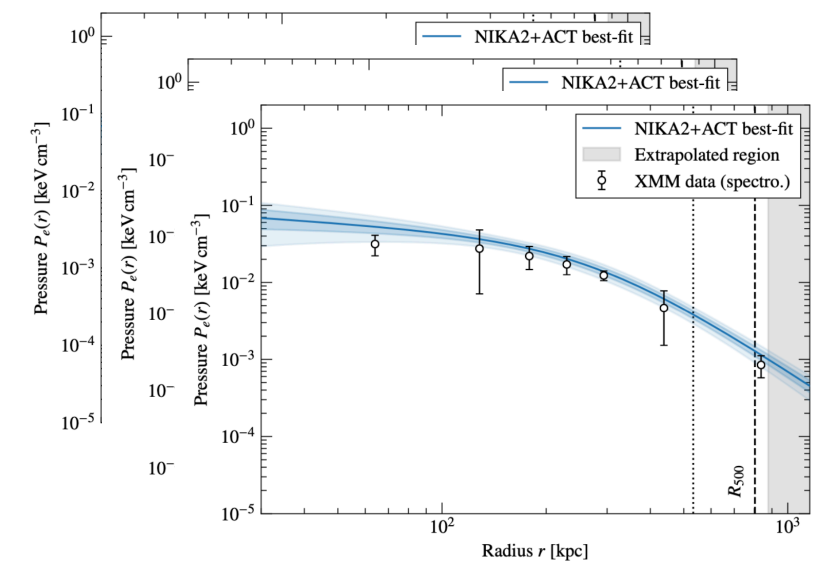
Select randomly a LPSZ-like sample



Get integrated quantities



Simulate SZ cluster maps (NIKA2-like) using a fixed universal pressure profile



Get thermodynamical properties

Knowing the input profile we can test our methods

Results

We test the 2 approaches on 49 simulated clusters

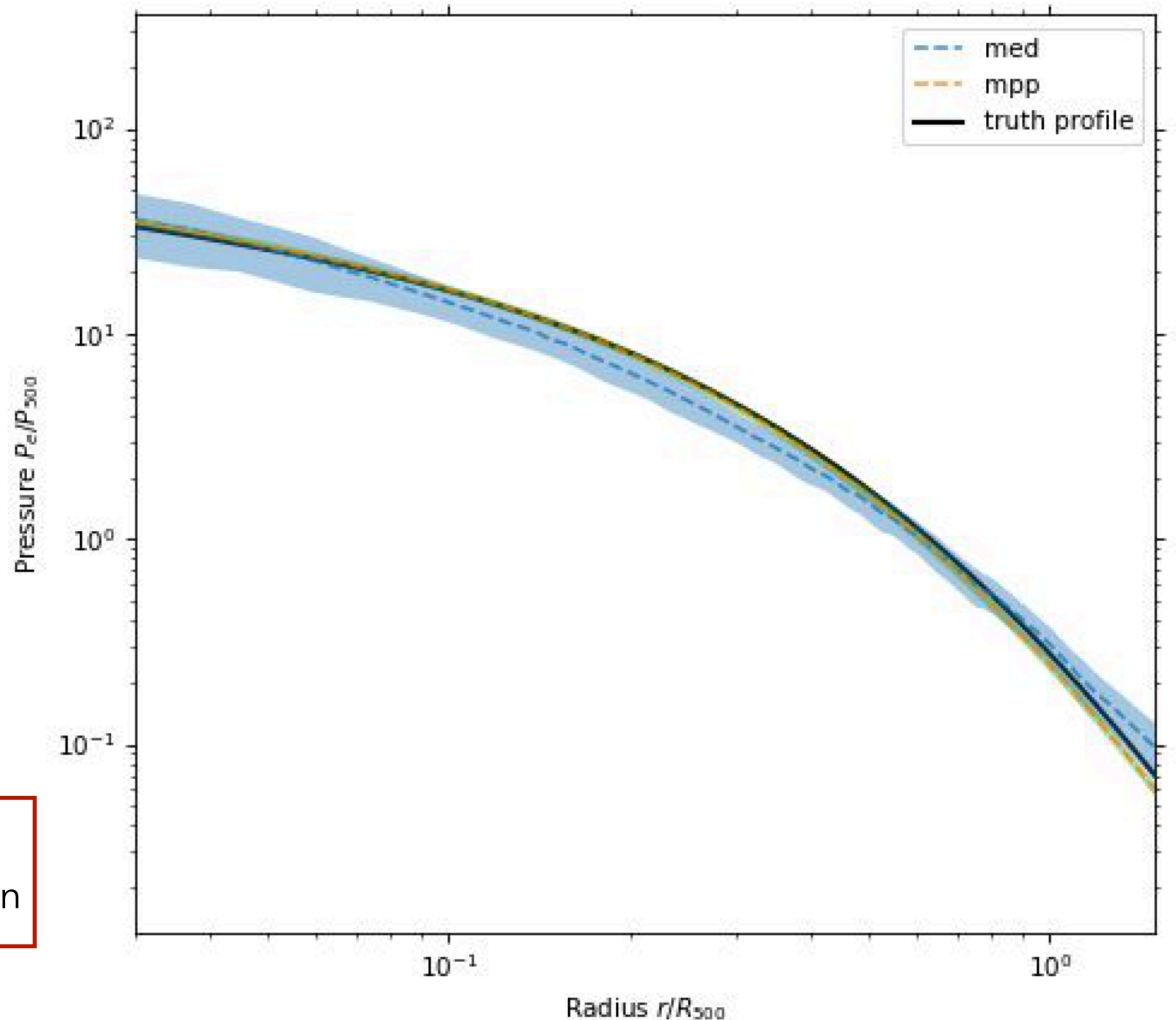
Truth : mean pressure profile from *Arnaud et al., 2010*

Med : Median of the profiles (1st method)

Mpp : best fit using the 2nd method

- Results in agreement with the input profile
- 2nd method gives more accurate results than taking the median only

Method 2 is validated on simulations
→ More accurate and precise than median



Conclusion

NIKA2 : a powerful instrument to study the tSZ effect

LPSZ main objectives :

Get a precise estimation of the mean pressure profile and the $Y_{500} - M_{500}$ scaling relation

First standard analysis on a LP-SZ sub-sample toward mean pressure profile

Characterization of the data quality : control the low frequency residual noise

Impact of point sources contamination : robust method without external data

Mean pressure profile estimate

New method to measure the mean pressure profile from a sample of cluster measurements

Validation of the method on a LPSZ-like cluster sample simulation

On going studies

Standard analysis

Sanity tests using scan selection in the standard pipeline

Robustness tests using various model of the pressure profile

- Binned model

Beyond the standard hypotheses

Morphological studies : preliminary results on an elliptical model

Mean pressure profile

Iterative method to jointly fit the mean pressure profile and P_{500} for all clusters

Deliver the first mean pressure profile results using the NIKA2-LPSZ clusters

Implication for SZ cosmology

Get cosmological constraints using the tSZ power spectrum (collaboration with B. Bolliet)

→ Improve the accuracy of the Planck SZ cosmology using the NIKA2-LPSZ mean pressure profile

Backups

Introduction to cosmology

Cosmological scenario :

- Starts with a homogeneous hot plasma of radiation and ionised matter
- Last scattering of photons and electrons → emission of the CMB radiation
- Large scale structures forms by gravitational collapse in the expanding universe

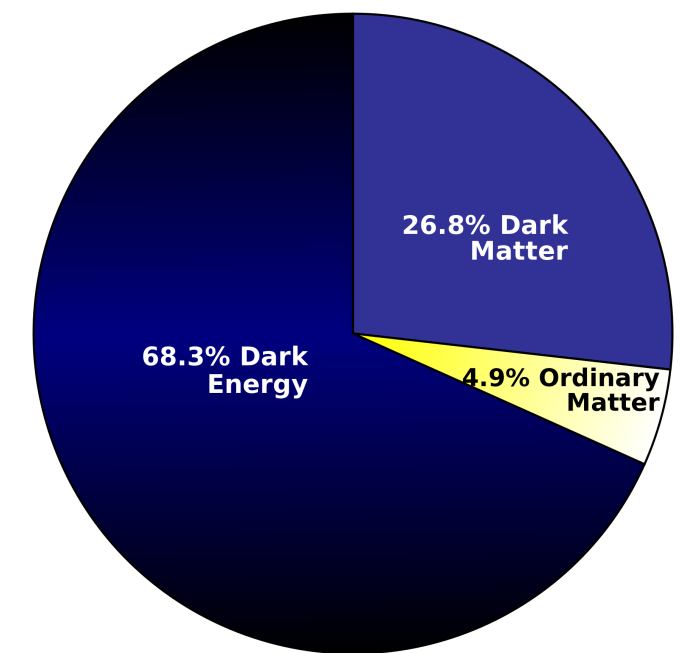
Two hypothetical components:

1. **Dark matter** : hypothetical form of matter explaining astrophysical observations as gravitational effects, formation and evolution of galaxies, ...
2. **Dark energy**: hypothetical form of energy that acts as a negative pressure, explaining the current accelerated expansion of the universe

Constraining the properties of dark matter and dark energy is one of the main goals of modern cosmology

Cosmic Microwave Background (CMB) : microwave radiation, the oldest print of the universe that we can observe

- Light emitted $\sim 380\,000$ years after the big bang (Universe becomes transparent)
- One of the most used observables to constrain cosmological parameters



Credit : ESA

SZ cosmology

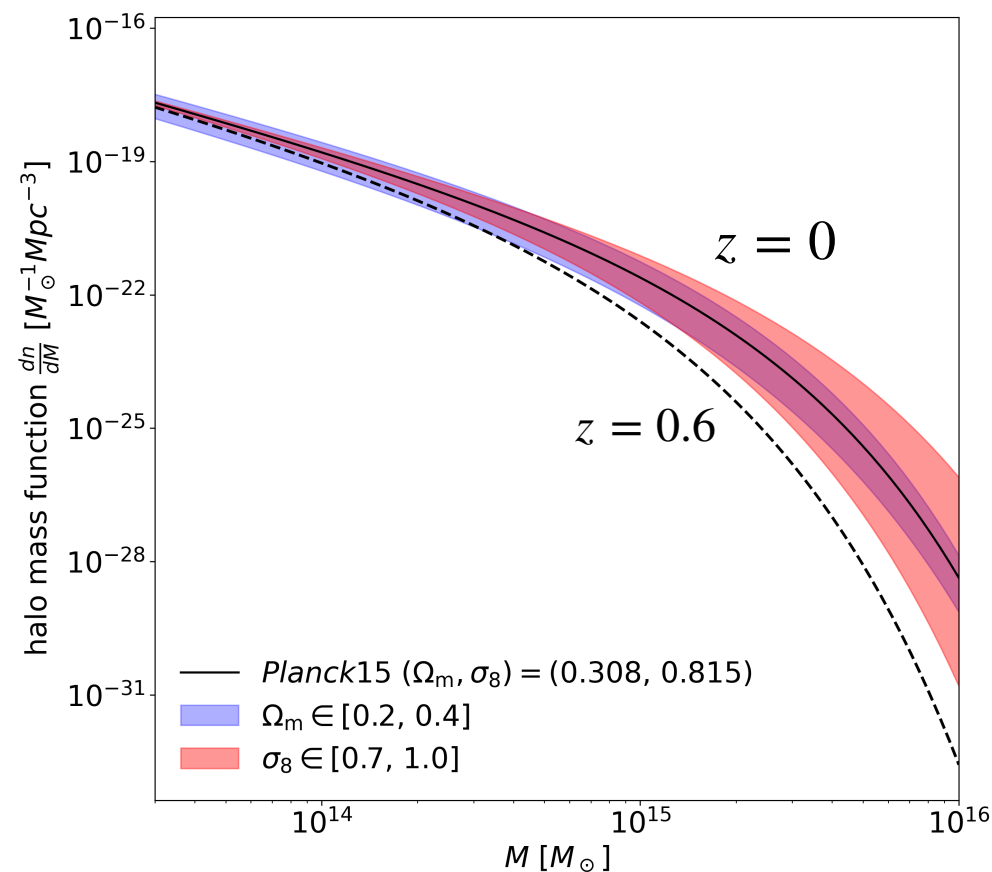
Cluster number count

The cluster abundance in intervals of mass and redshift :
 → Highly sensitive to cosmology

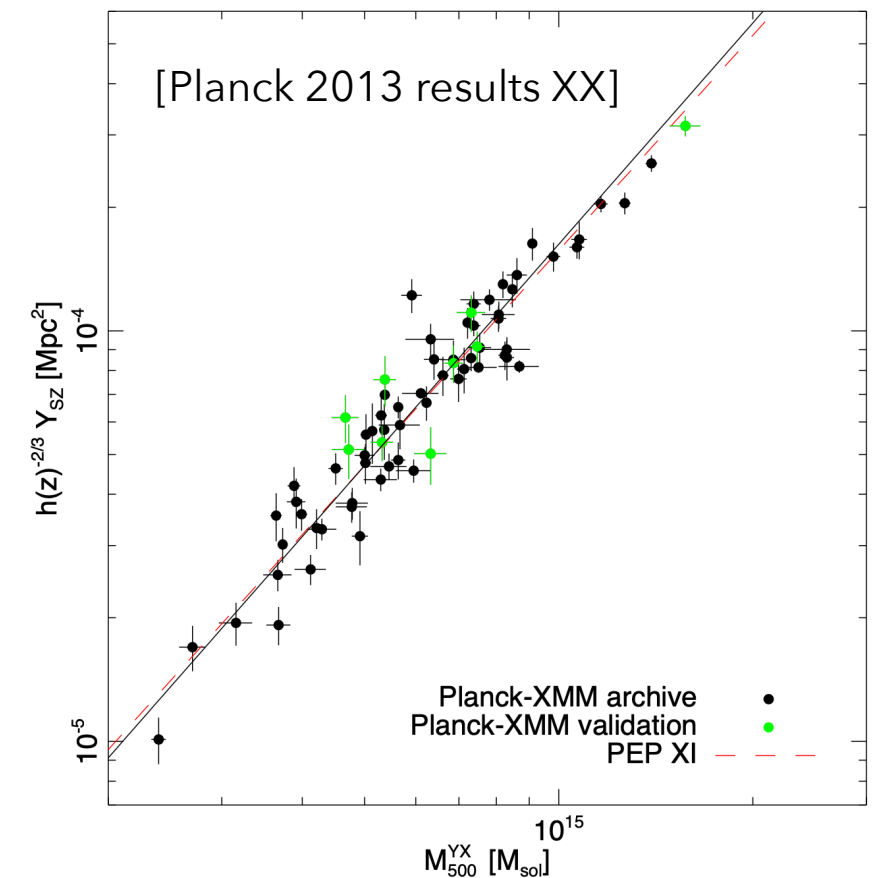
$$\frac{d^2 N}{dM dz} \sim \int d\Omega \int d\mathcal{O} \left[\frac{d^2 V}{dz d\Omega} \right] \left[\frac{dn}{dM} \right] P(\mathcal{O} | M)$$

Volume : background cosmology

Halo mass function → large variety (*Bolliet et al. 2018*)



SZ-M Scaling relation



We need a precise characterization of the scaling relation

SZ cosmology

SZ power spectrum

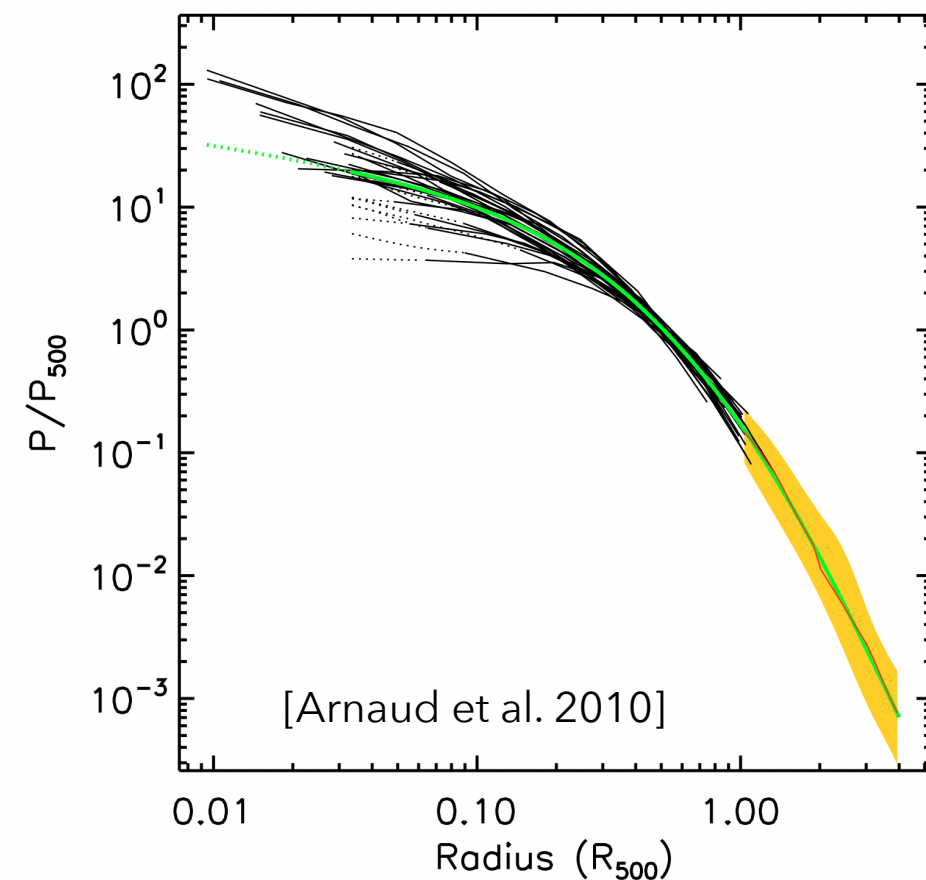
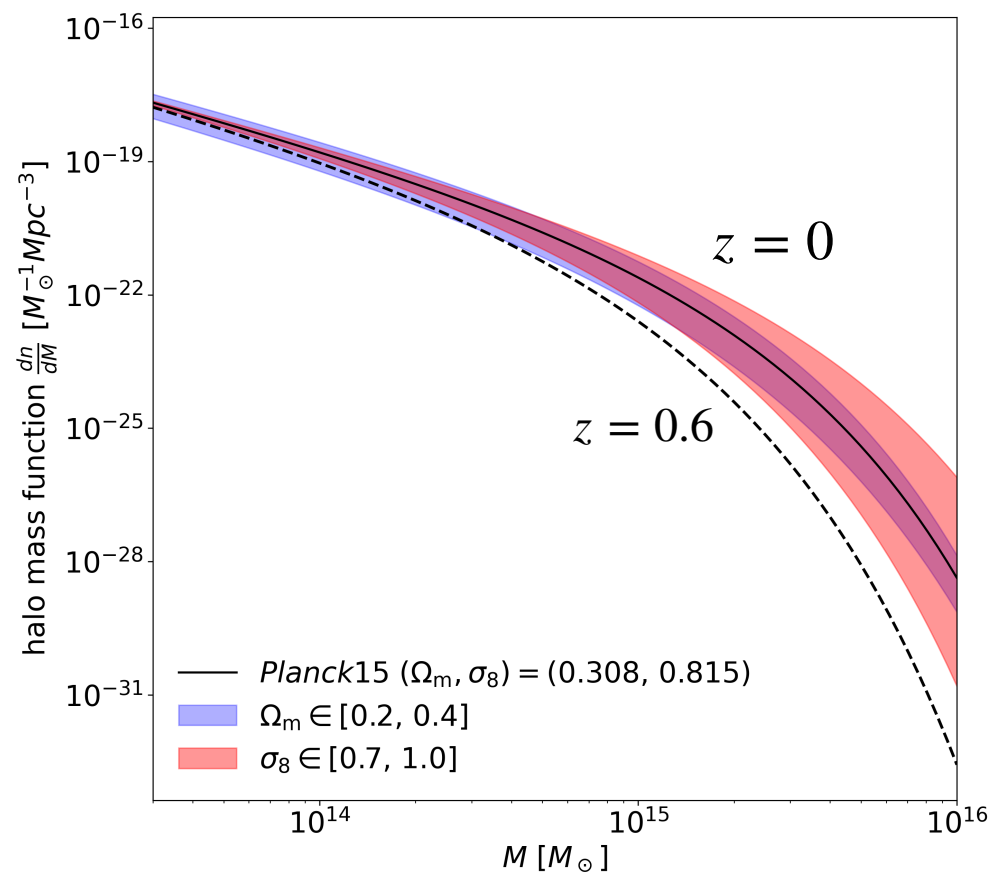
Angular power spectrum of the SZ-map :

Volume : background cosmology

Halo mass function \rightarrow large variety (Bolliet et al. 2018)

$$C_l^{tSZ} \sim \int dz \int dM \left[\frac{d^2 V}{dz d\Omega} \frac{dn}{dM} \right] |y_l(M, z)|^2$$

Mean pressure profile



We need a precise characterization of the mean pressure profile

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

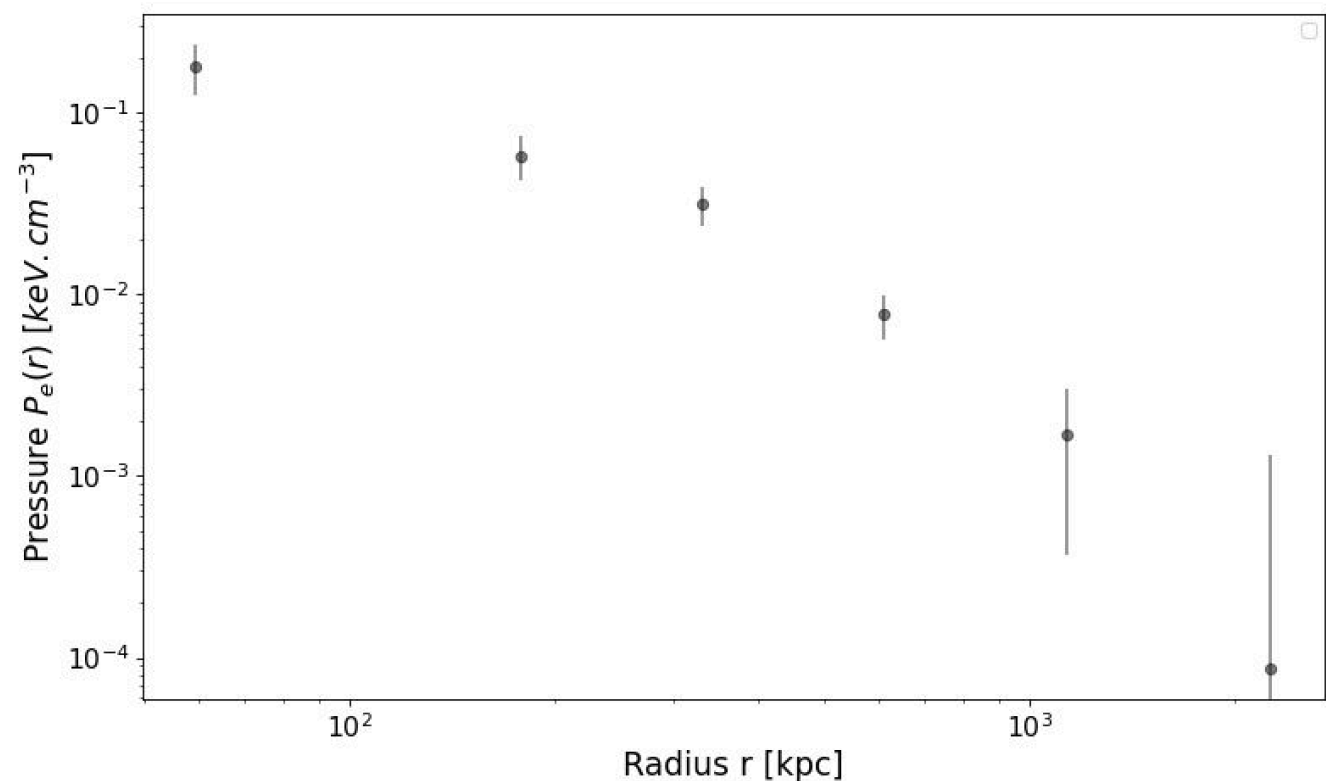
gNFW model :
$$P_e(r) = P_0 \left(\frac{r}{r_p} \right)^{-c} \left[1 + \left(\frac{r}{r_p} \right)^a \right]^{\frac{c-b}{a}}$$

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

Radially binned model :

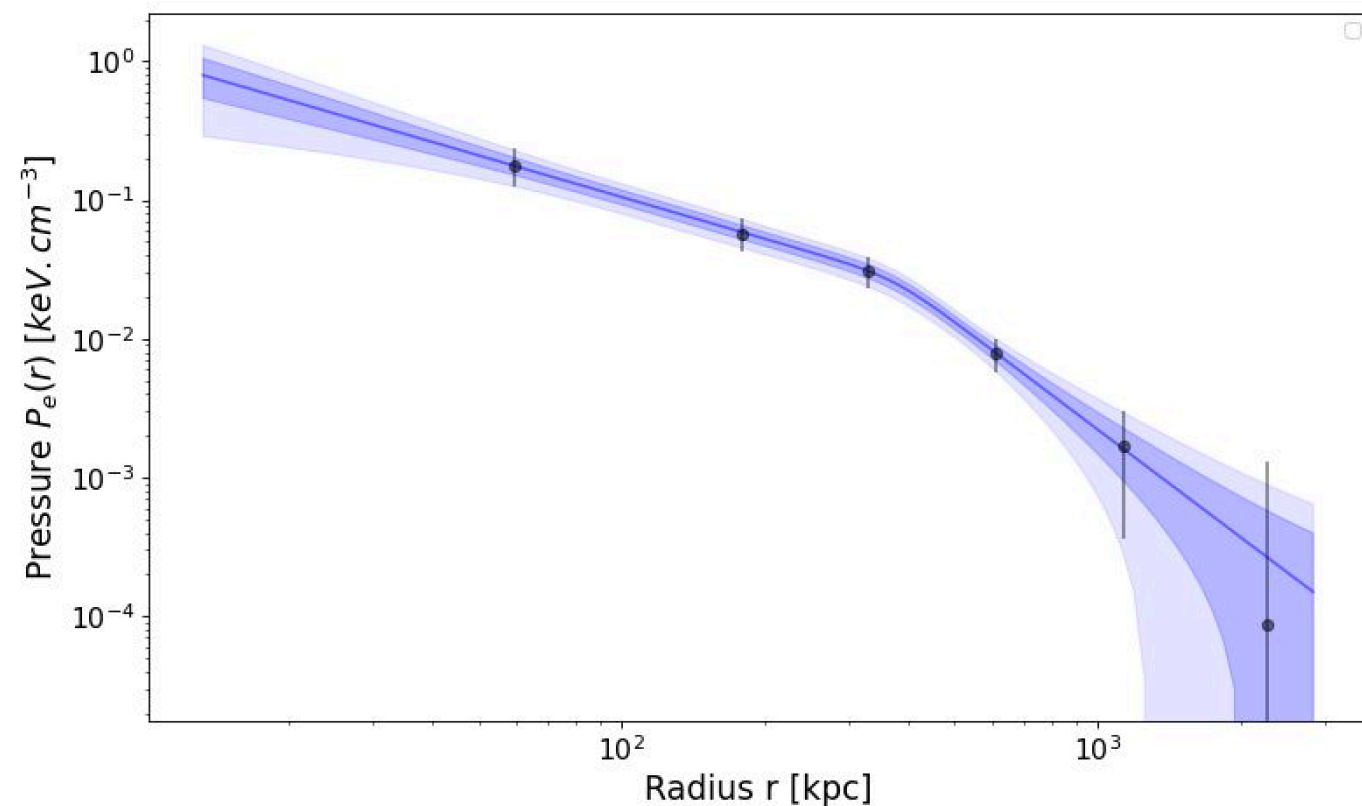
Choose a binning : N points logarithmically spaced from NIKA2 beam ($< 100kpc$)

to NIKA2 FoV (up to $2Mpc$)

→ N parameters : P_i amplitude of the pressure at R_i

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

→ gNFW, ...



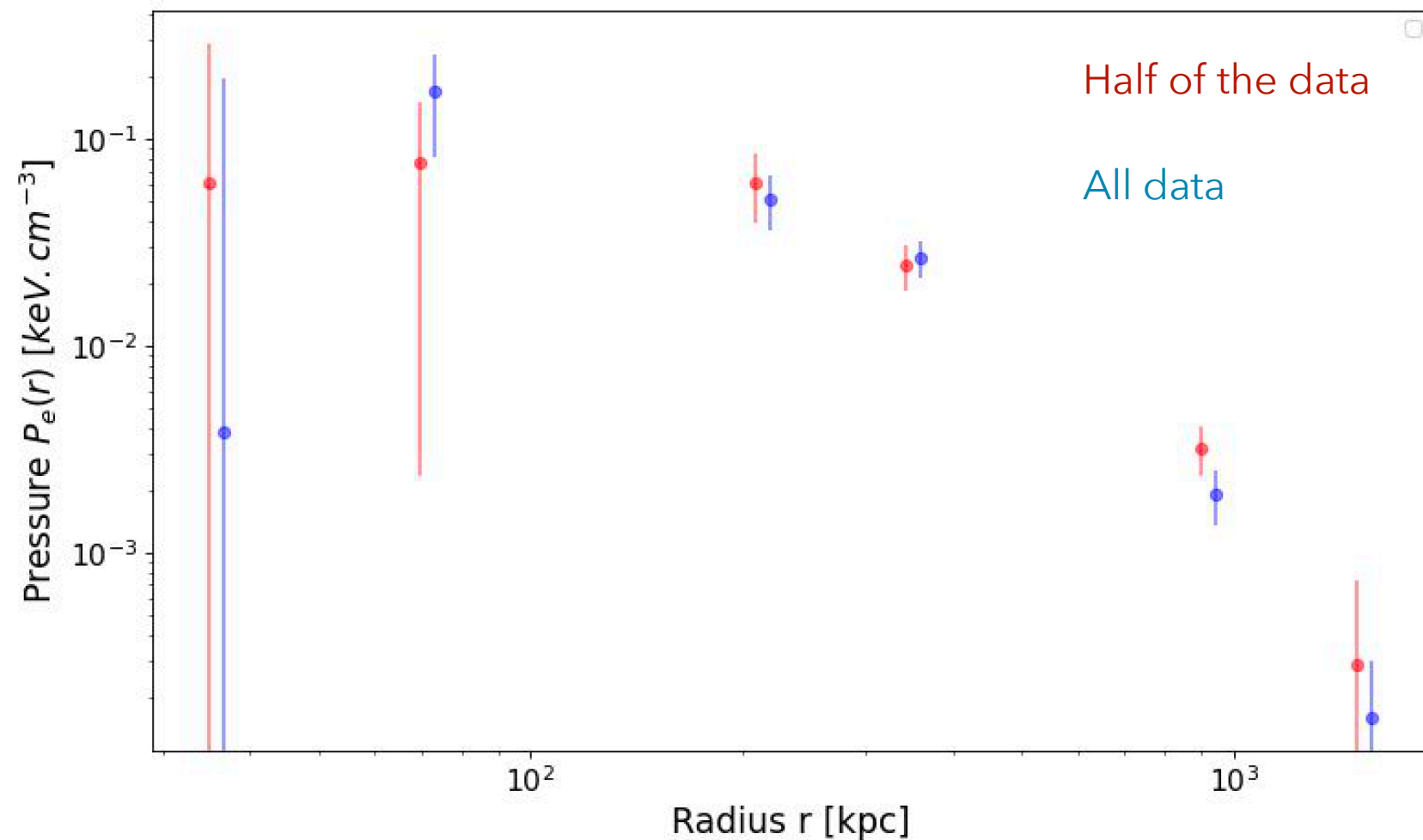
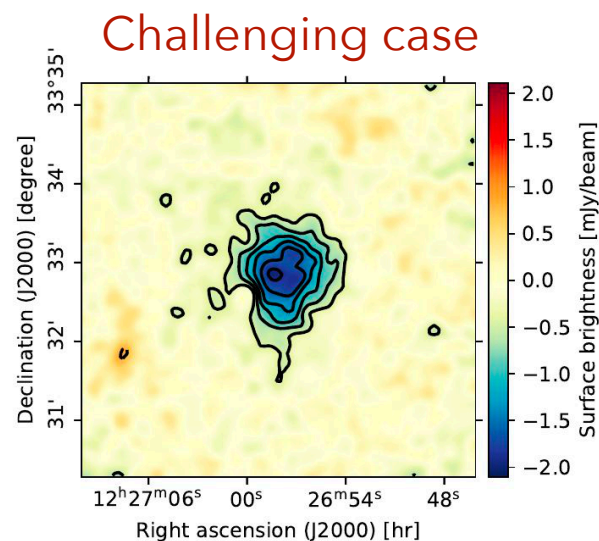
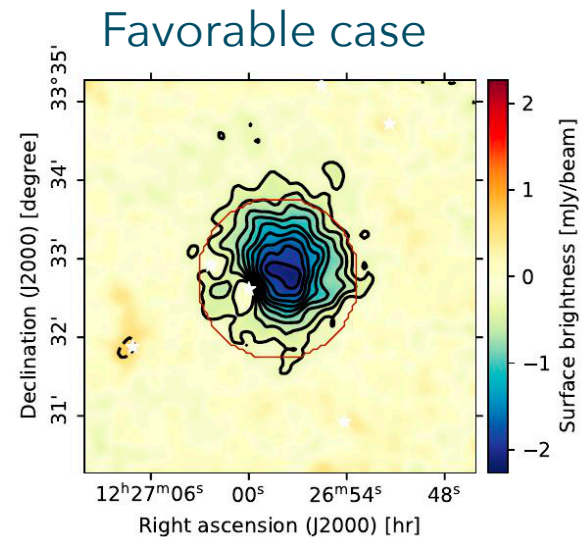
Check the robustness of the radially binned model

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



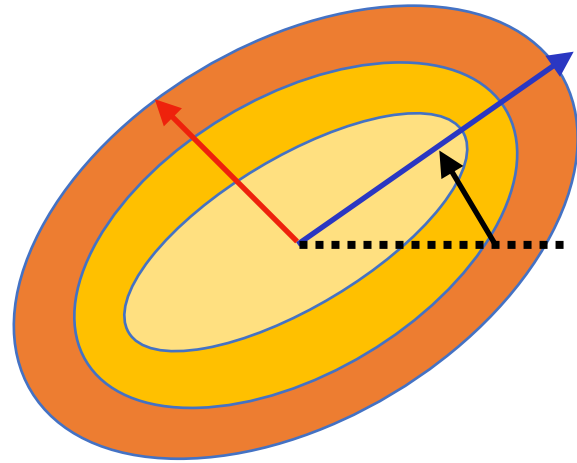
→ Results in agreement

Robust method against noise residuals

Beyond the standard hypotheses : 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

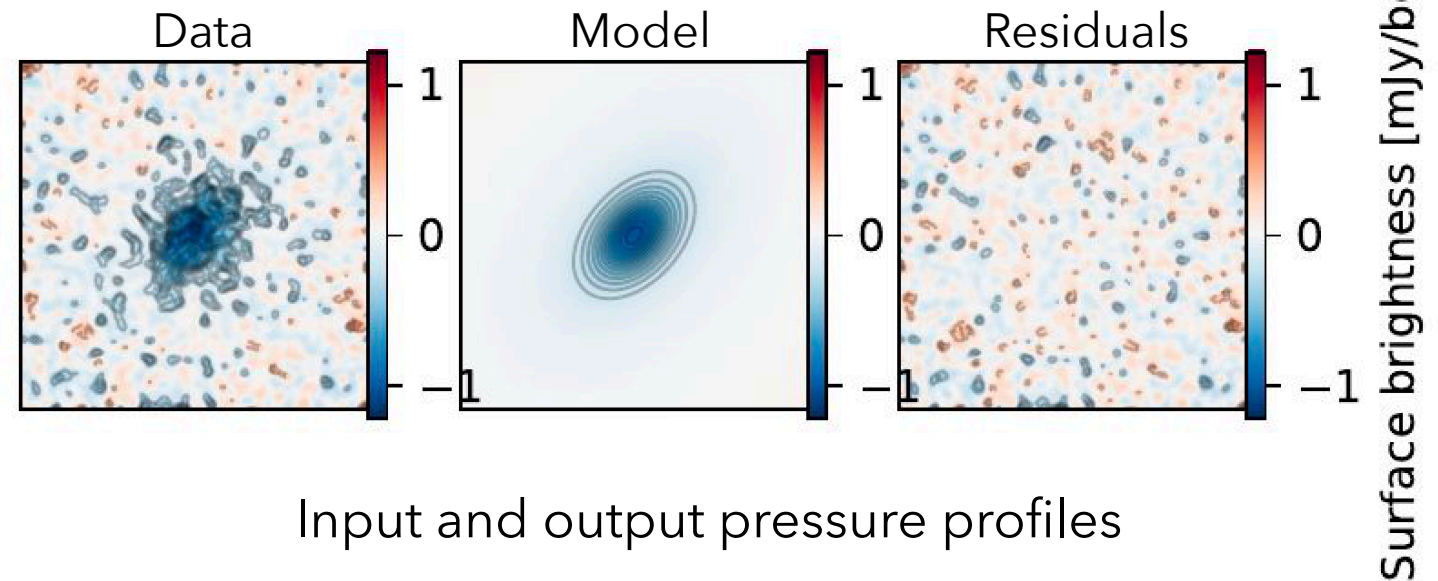
$$R_{ell} = R_c / e(\phi), \quad e(\phi) = \sqrt{\frac{\cos^2(\phi - \phi_0)}{a_x^2} + \frac{\sin^2(\phi - \phi_0)}{a_y^2}}$$

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

