Status of the NIKA2 Sunyaev-Zeldovich Large Program

Preparation of the upcoming public data release

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On behalf of the NIKA2 collaboration

CMB France 2023

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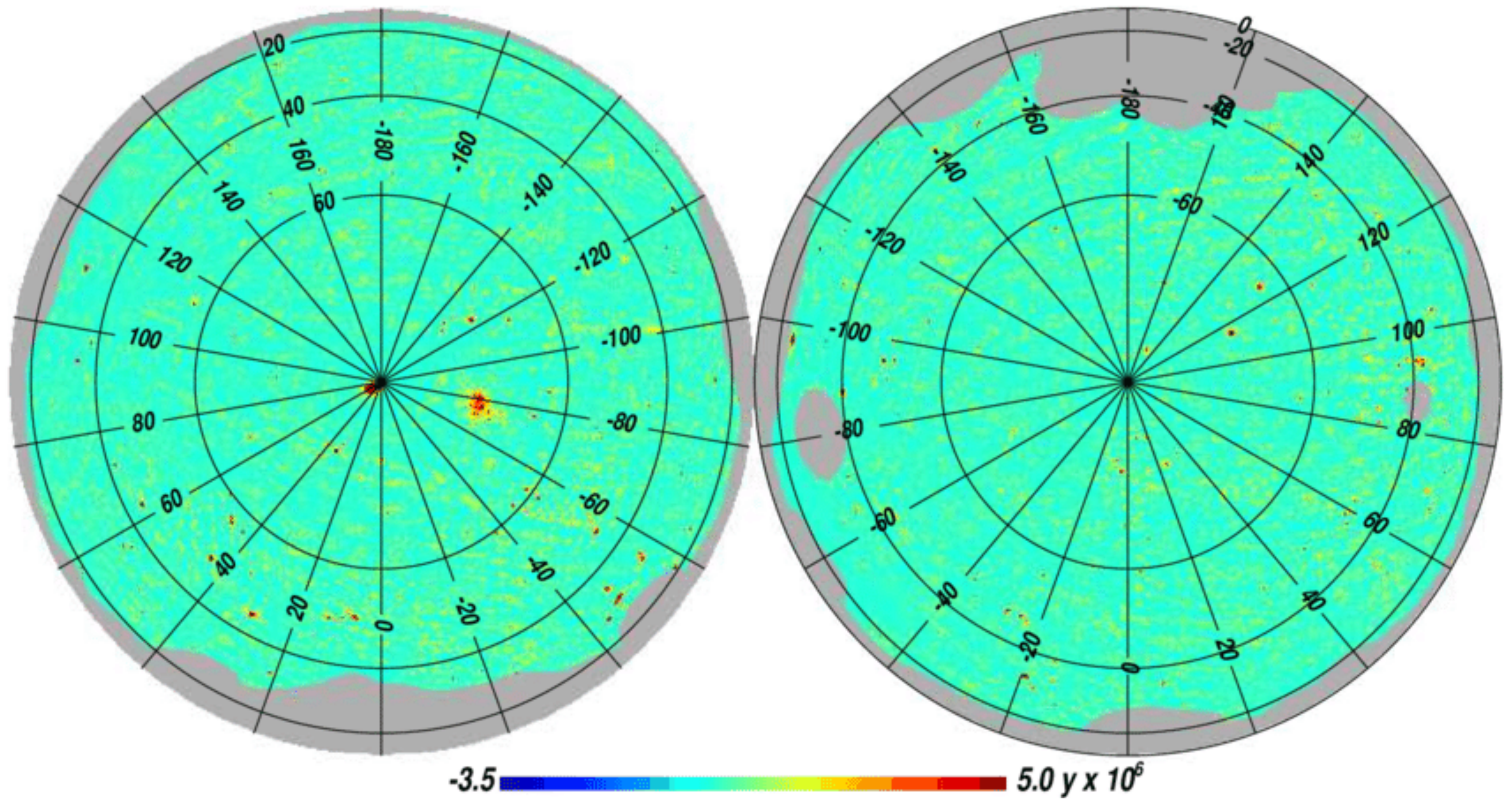
Summary

Cluster number count

Cluster abundance in intervals of mass and redshift depends on cosmological parameters

SZ power spectrum

Angular power spectrum of the SZ-map



Compton parameter map

Planck Collaboration XXII 2015

Compton parameter : $y \propto \int P_e dl$

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

Volume : background cosmology

Halo mass function

→ Highly sensitive to cosmology

Holder et al., 2001

Model cluster SZ signal

→ Mean pressure profile

Current mean pressure profile estimates don’t cover the whole mass and/or redshift and/or angular scale range

The NIKA2 Sunyaev-Zeldovich Large Program (LPSZ)

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

Observing band	150 GHz	260 GHz
FWHM [arcsec]	17.6 ± 0.1	11.1 ± 0.2
Field of view [arcmin]	6.5	6.5

Perotto et al. 2020

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Perotto et al. 2020

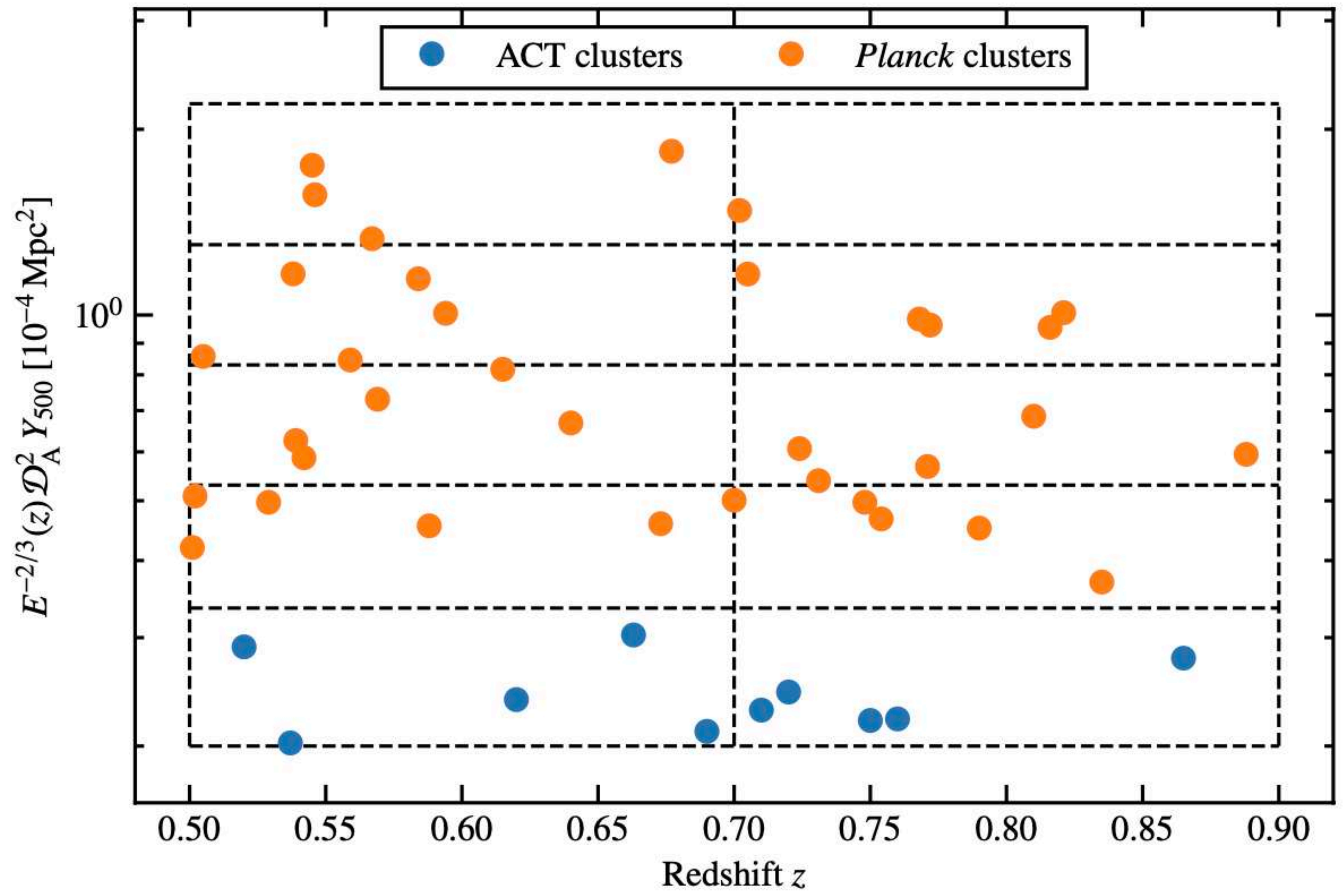
High angular resolution follow-up of 38 Planck and ACT galaxy clusters

Mayet et al. 2020 *Perotto et al. 2021*

→ 300 hours of guaranteed observation time

→ Synergy between NIKA2 and XMM-Newton

→ Precise estimation of pressure and mass profiles

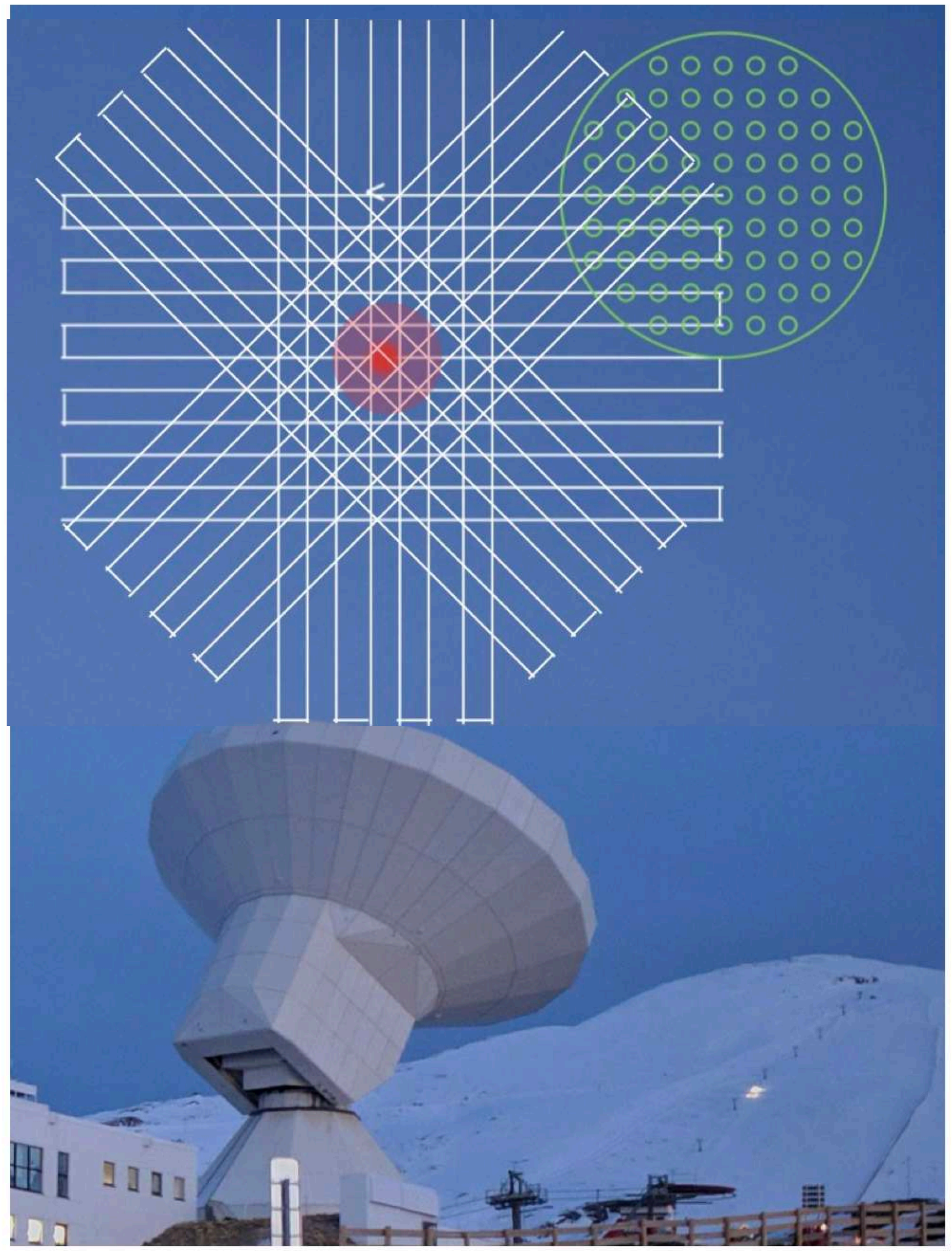


[F. Kéruzoré]

Precise characterization with NIKA2 high angular resolution of the mean pressure profile and SZ-M scaling relation with clusters at intermediate to high redshifts $0.5 < z < 0.9$

NIKA2 raw data

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



NIKA2 scan strategy

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

At a fixed time t the detectors see :

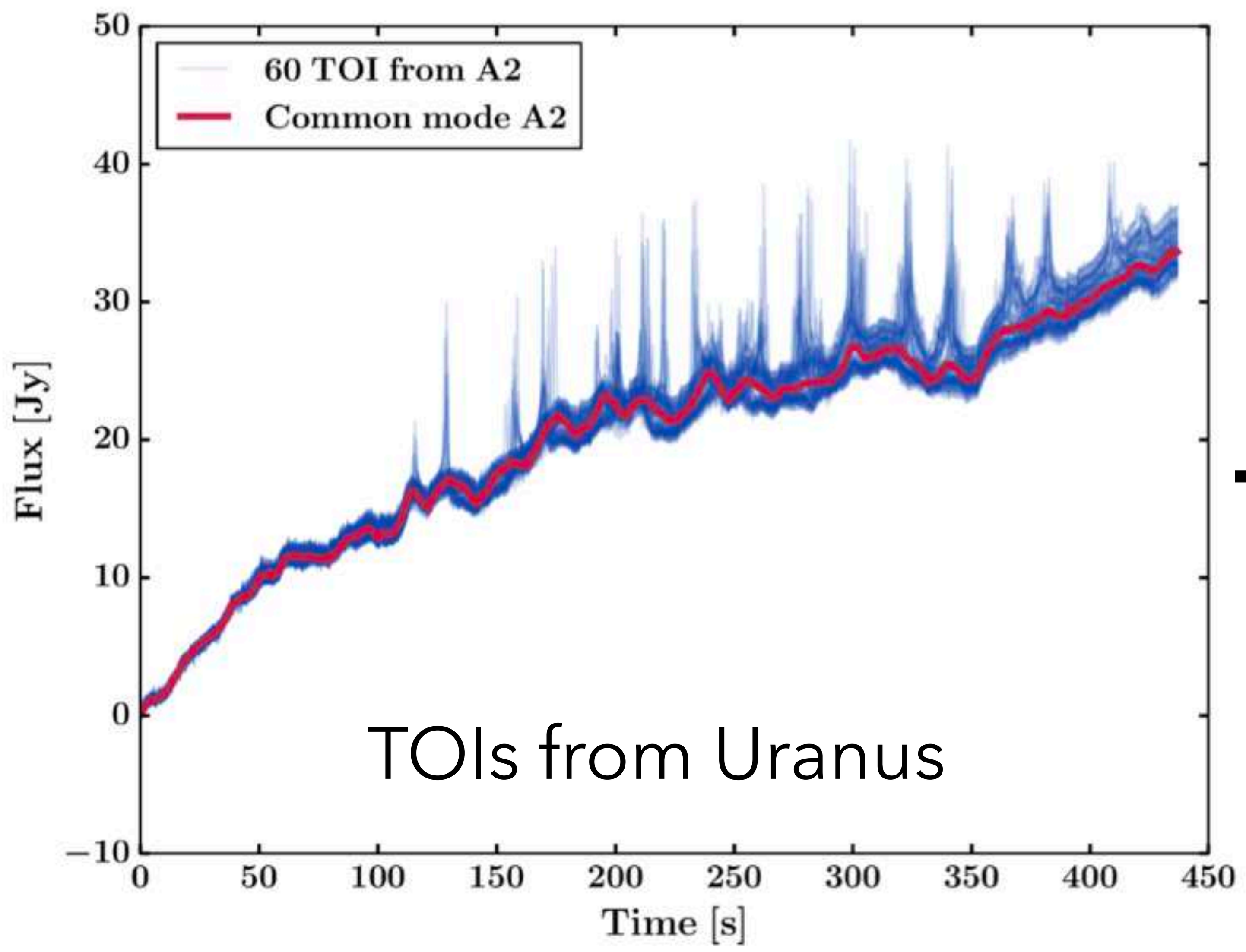
- -Different astrophysic signal $S_k(t)$
- -Same atmosphere $A(t)$
- -Correlated electronic noise $E_{B_k}(t)$
- -Intrinsic noise $WN_k(t)$

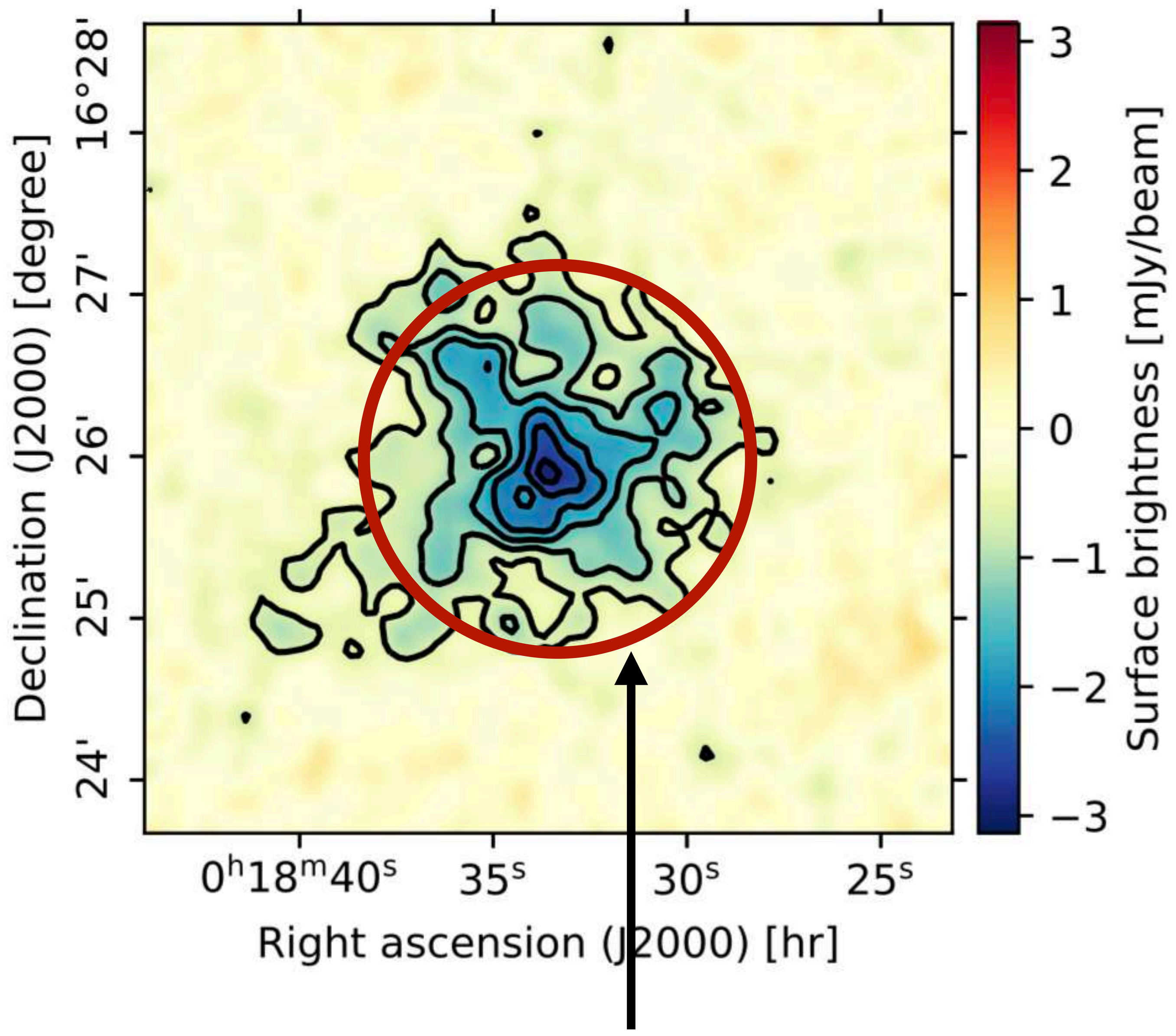
We estimate and subtract the correlated noise terms $A(t) + E_{B_k}(t)$ in a process called 'noise decorrelation'

Noise decorrelation method

Baseline decorrelation method:

1. Mask the cluster signal in the TOIs (disk of radius r around the cluster center)
2. Compute the median of the TOIs outside the mask at each time t
3. Subtract the common mode from the TOIs and project them on a map





Decorrelation mask

$$TOI_k - CM_k = S_k + \boxed{\delta N_k}$$ Residual noise

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

→ Decorrelation failure inside the mask: too large mask and complex noise

→ Impact of other possible outlier scans

Method

New method of data quality assessment

Objective: Blind identification of problematics in individual scans (~3800 scans)

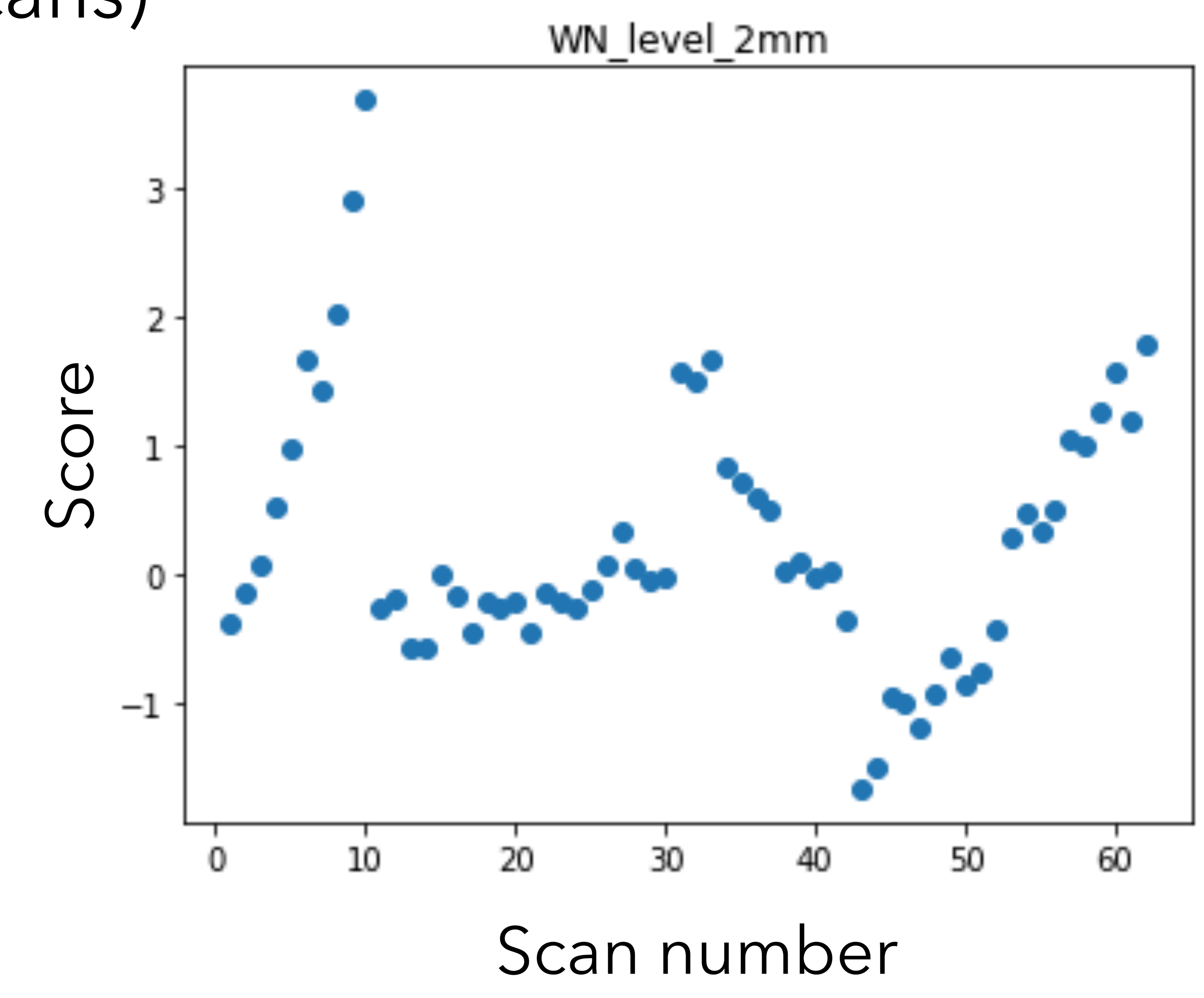
→ We identified a list of uncorrelated criteria to define data quality:

- Kid to kid correlation matrix : mean of the residual correlation
- Low frequency noise at large scales f_{knee}^{α}
- White noise at every scales B
- Integrated signal on the scan's map

→ Each scan gets a score per criterion: $score_s = \dfrac{c_s - med(c)}{\sigma(c)}$

→ We rank scans in function of their score: $max\{score_s\}_{crits}$

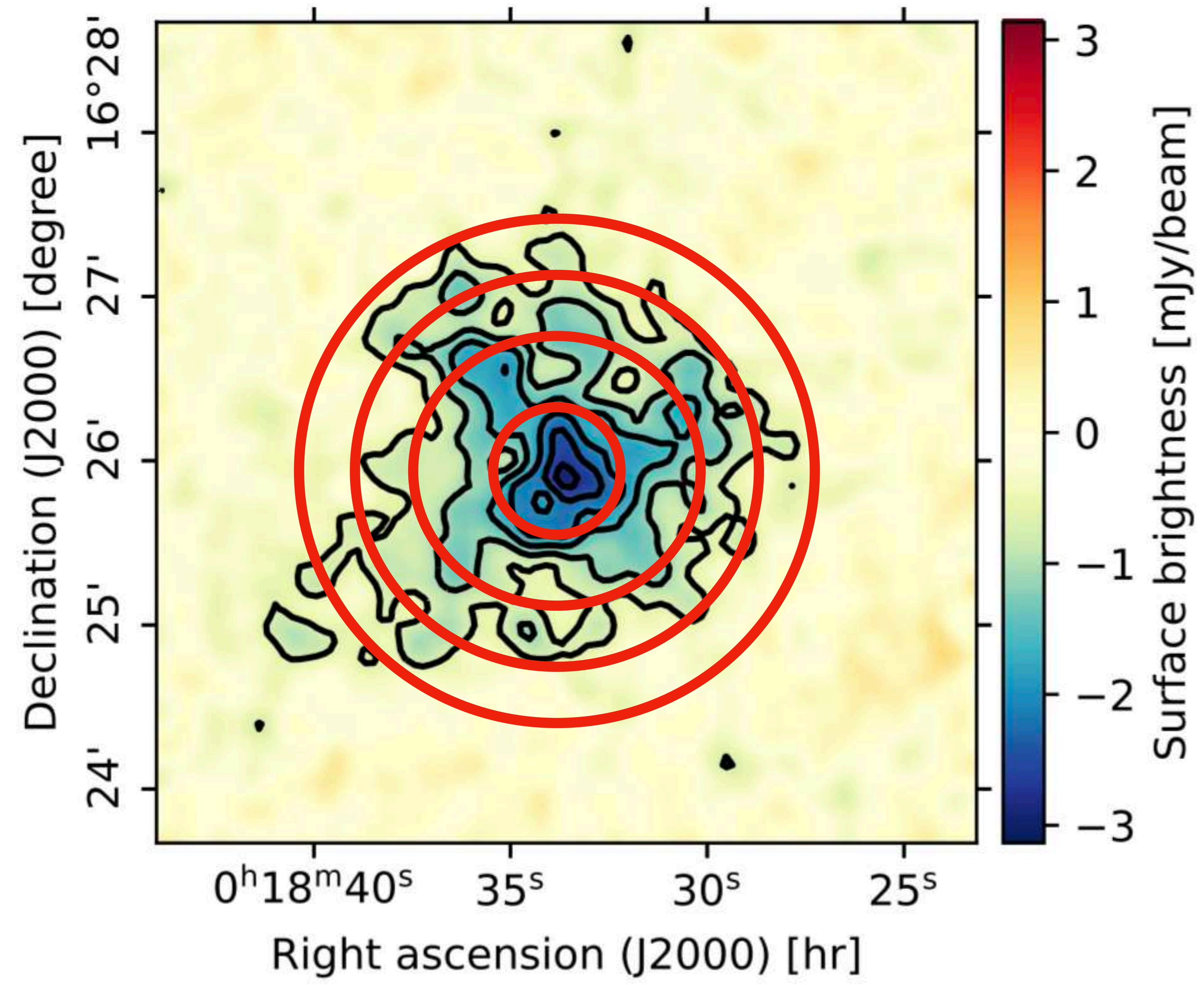
Example of criterion



Two parameters:

1. Mask radius as a function of θ_{500} (~2-3 arcmin) from Planck/ ACT catalogs
2. Threshold for scan selection $\sigma_{threshold}$

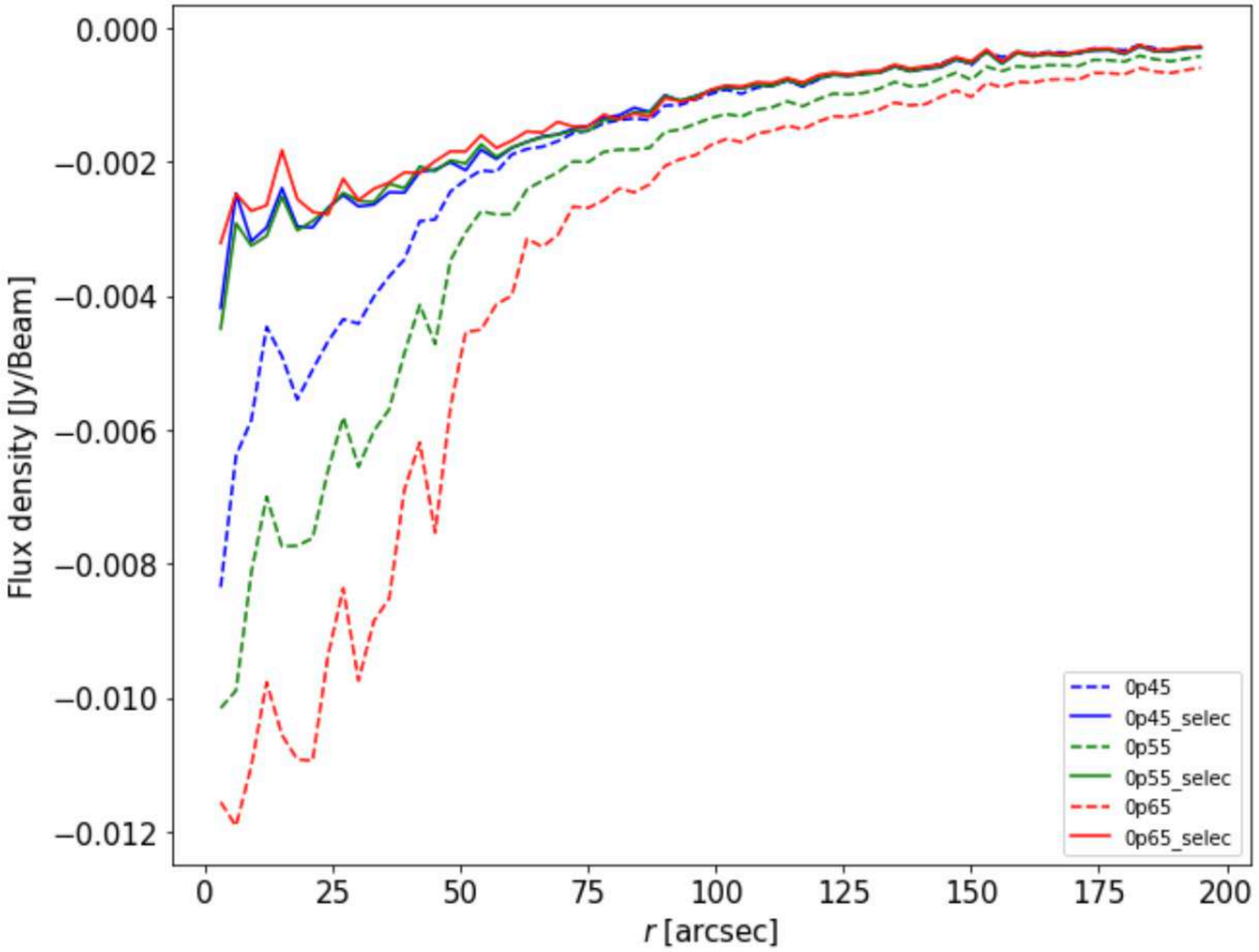
→ Spherical hypothesis: compare radial profiles →



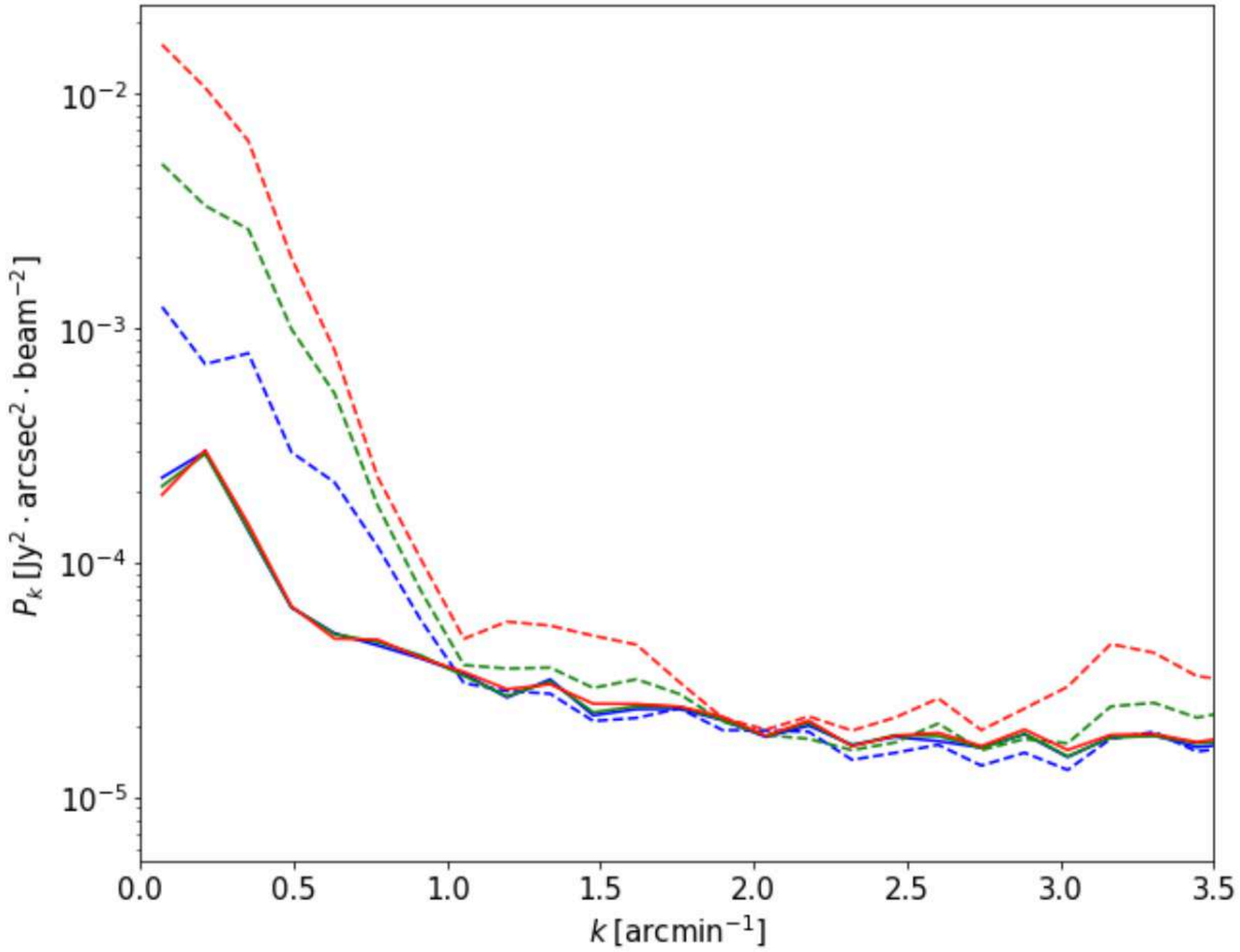
Parameters optimization

Mask radius as a function of θ_{500}: $\alpha \in [0.45, 0.55, 0.65]$
Two different thresholds: no selection VS $\sigma_{threshold} = 3.75$

Flux density radial profiles



Noise angular power spectra



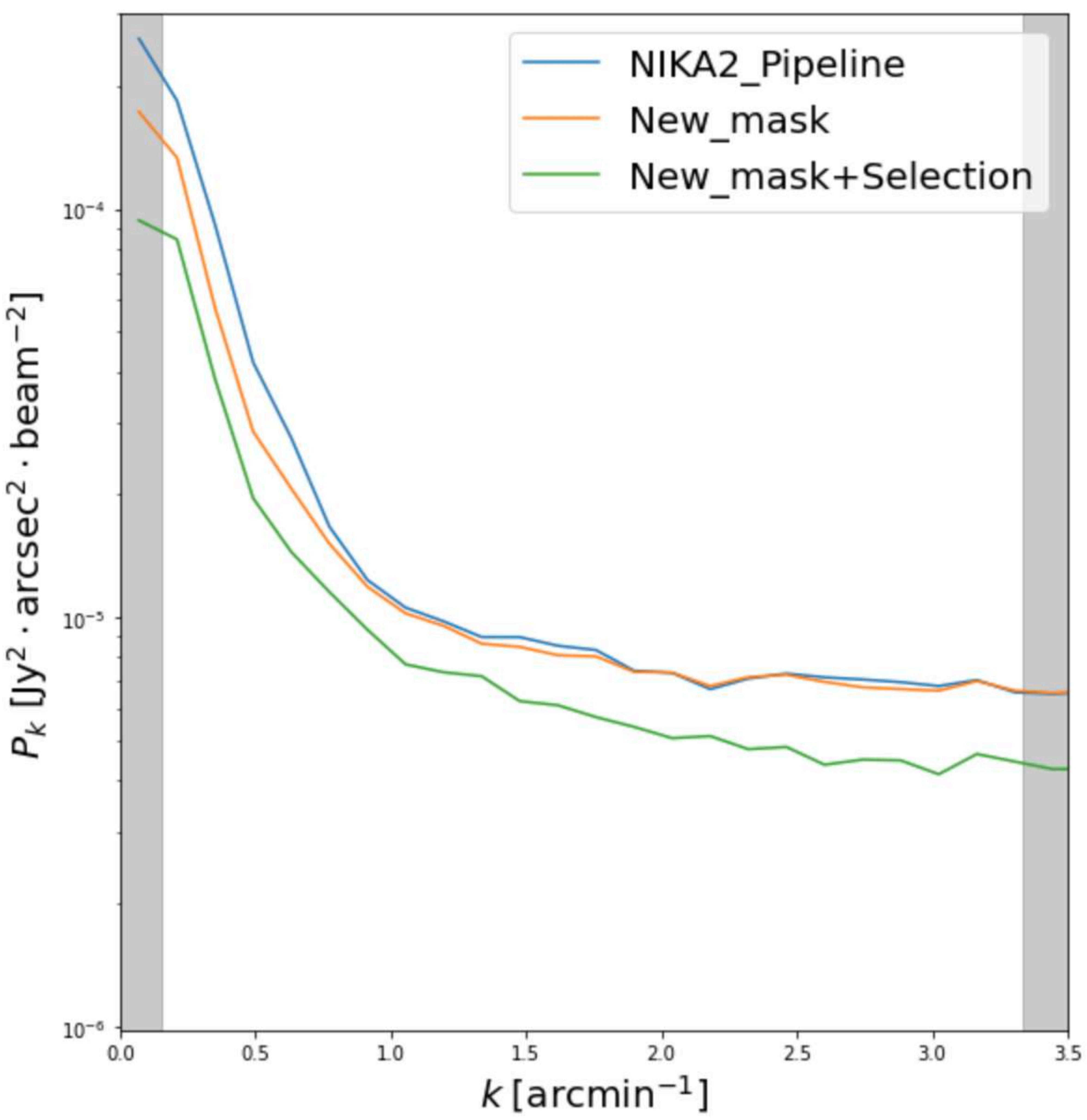
Compatible results between all analyses after scan selection until a certain value of the mask
Less residual noise in the map (especially at cluster's scales)

We did the same analysis for all clusters, varying different parameters and looking at the convergence of the profiles:
→ Mask size: $0.55 * \theta_{500}^{Planck/ACT}$; Max mask size: 75″; $\sigma_{threshold} = 3.75$

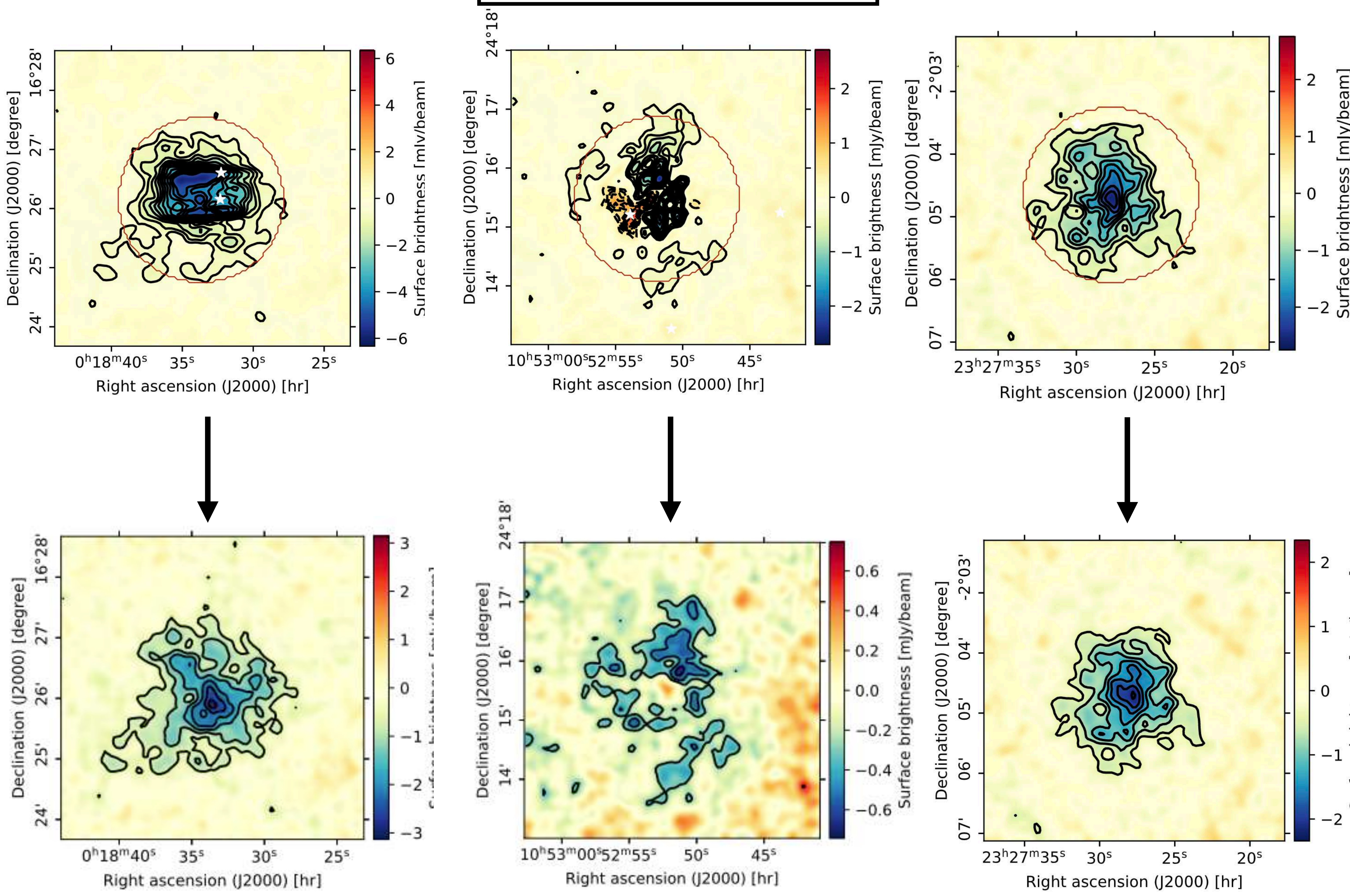
Impact on the whole sample

Look at the improvements with mask size optimisation and scan selection

Mean power spectrum



150 GHz data maps



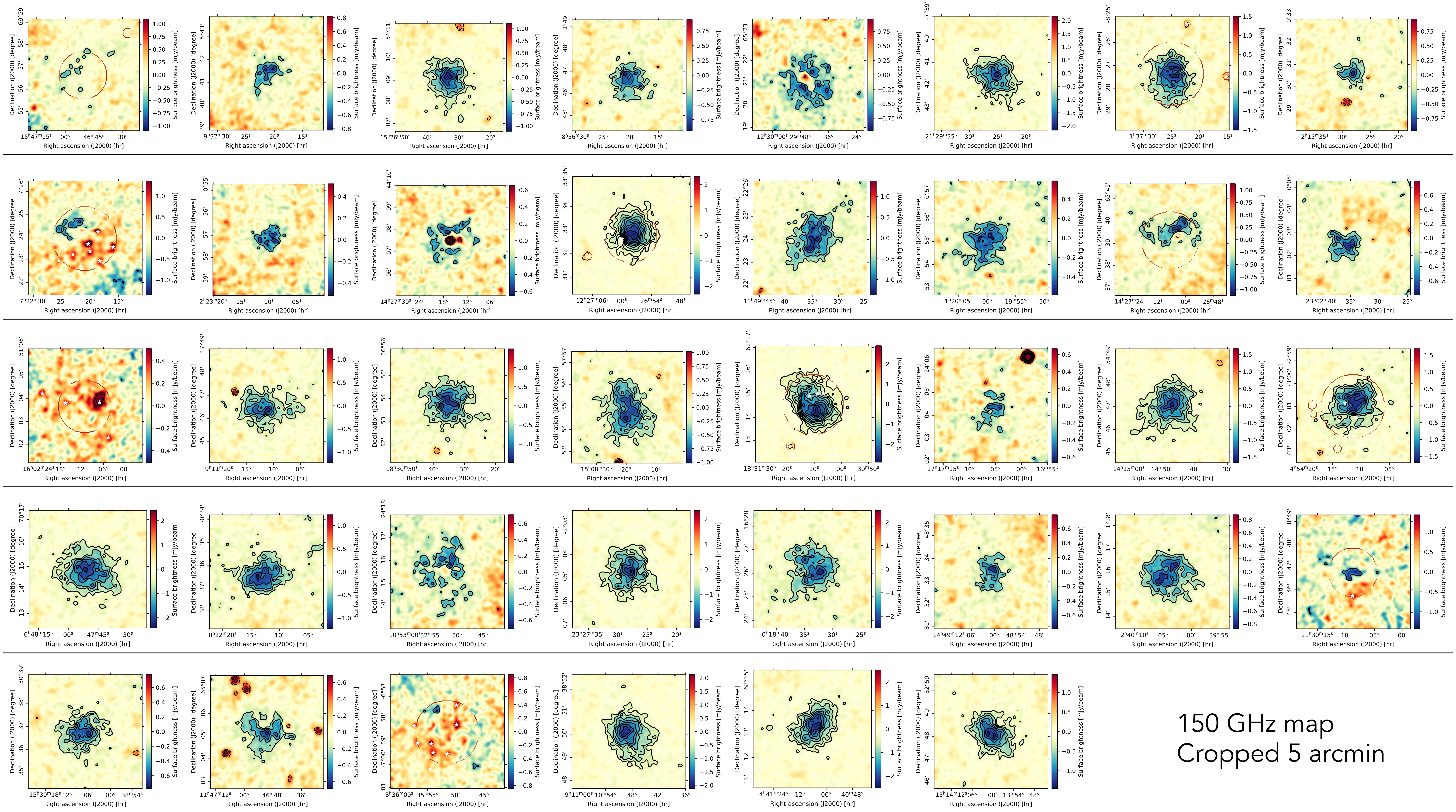
Both mask size and scan selection have a significant impact on the residual noise amplitude in the maps

→ Less noise at all scales

→ No more artefacts in the maps

NIKA2-LPSZ sample

NIKA2 150 GHz maps with signal-to-noise ratio contours starting from 3σ spaced with 1σ



150 GHz map
Cropped 5 arcmin

→ Final version of the NIKA2-LPSZ maps

Preliminary

Individual pressure profile estimate

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

LPSZ version of the PANCO2 public software

SZ signal

Spherical symmetry : 3D pressure profile

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

Nagai et al. 2007

–> 5 parameters : P_0, r_p, a, b, c

Binned model : $$P_e(r_i < r < r_{i+1}) = P_i \left(\frac{r}{r_i}\right)^{-\alpha_i}$$

–> 6 parameters : $P_0, P_1, P_2, P_3, P_4, P_5$

Points sources

Flux : free parameter in the MCMC

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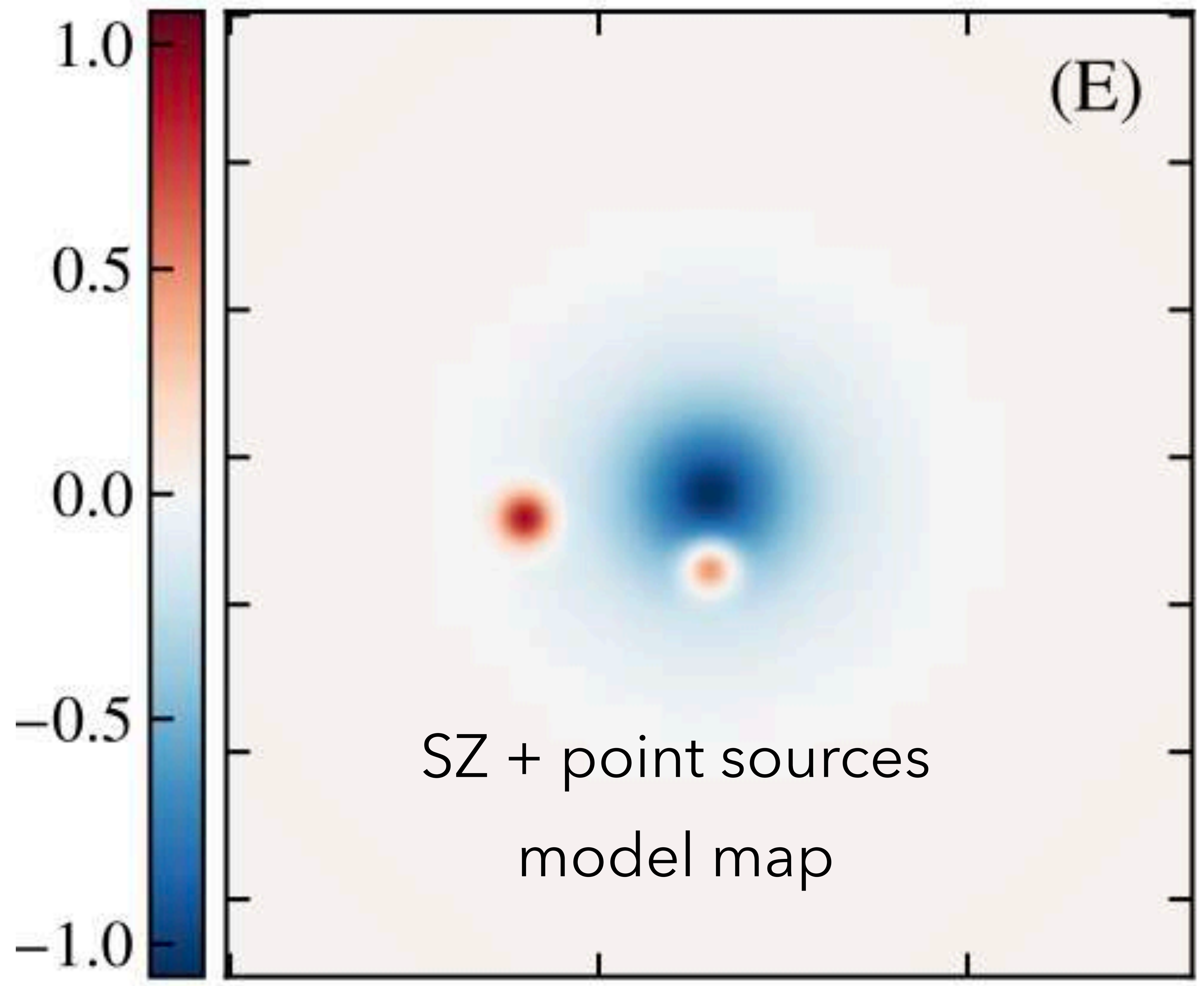
Flux : free parameter in the MCMC

Forward modelling

Integrate along the line of sight : $D_{th} \propto \int_{los} P_e(r)dr$

Convolved by the NIKA2 instrumental response

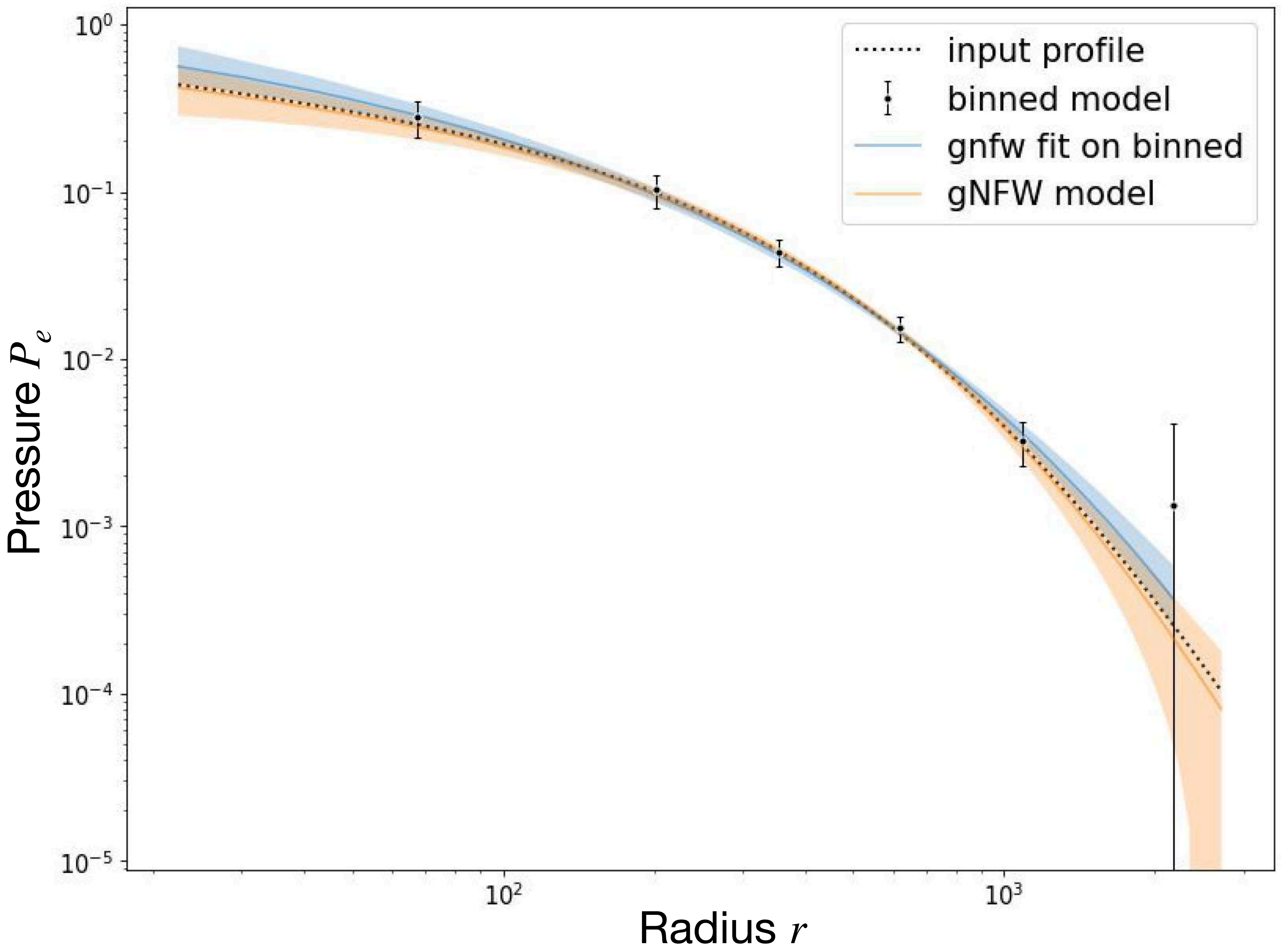


Likelihood : $$-2log\mathscr{L}(\theta) = \sum_{pixels} (D - D_{th}(\theta))^T C^{-1} (D - D_{th}(\theta)) + \left(\frac{Y_{500}^{meas.} - Y_{500}^{Model}}{\Delta Y_{500}^{meas.}}\right)^2$$

Thermodynamical properties

Results obtained on a simulation

→ Realistic LPSZ cluster sample simulation drawn from a spherical gNFW model (correlated noise + NIKA2 instrumental response)



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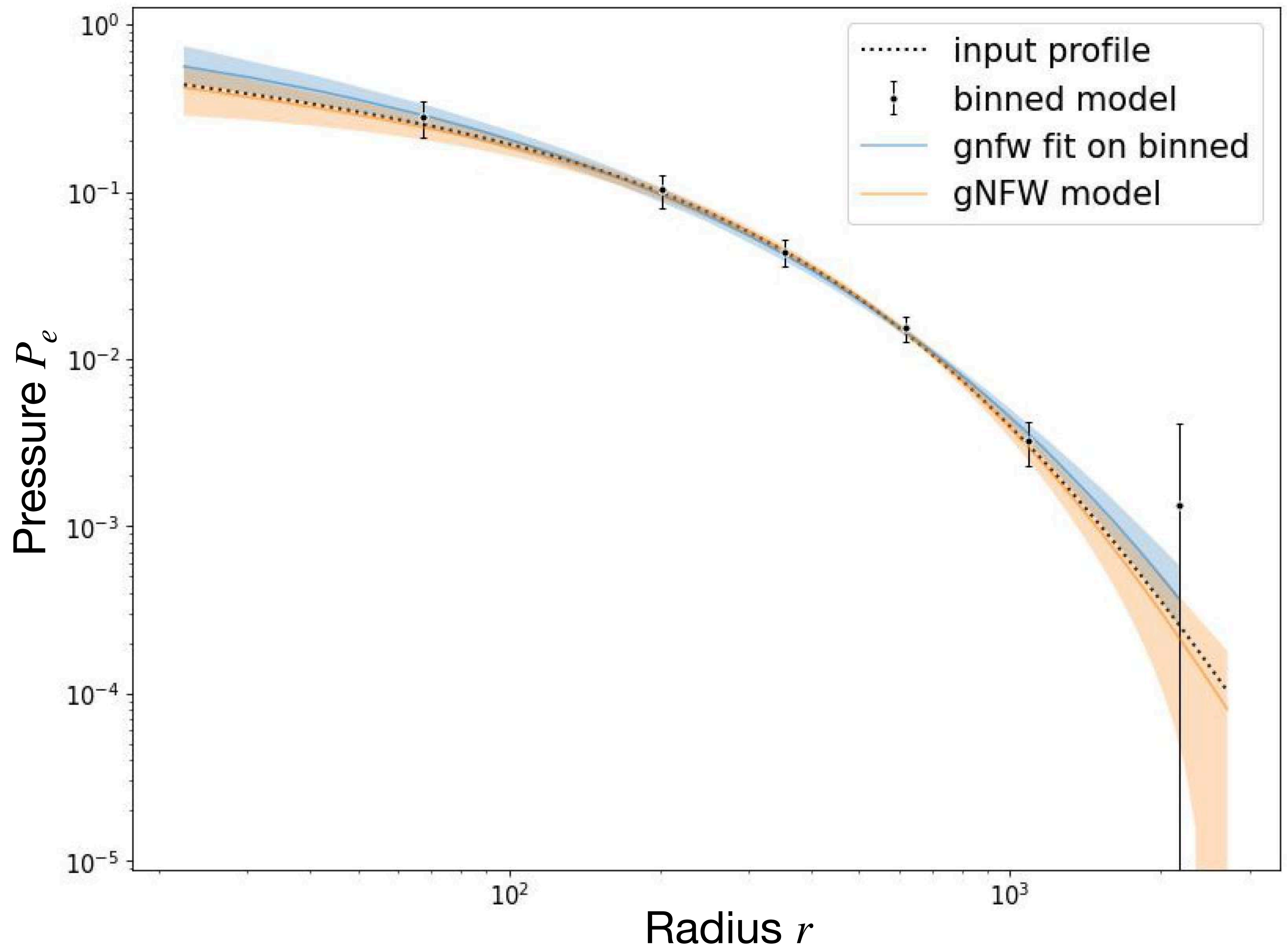

Compute the mass profile using SZ+X-ray data

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

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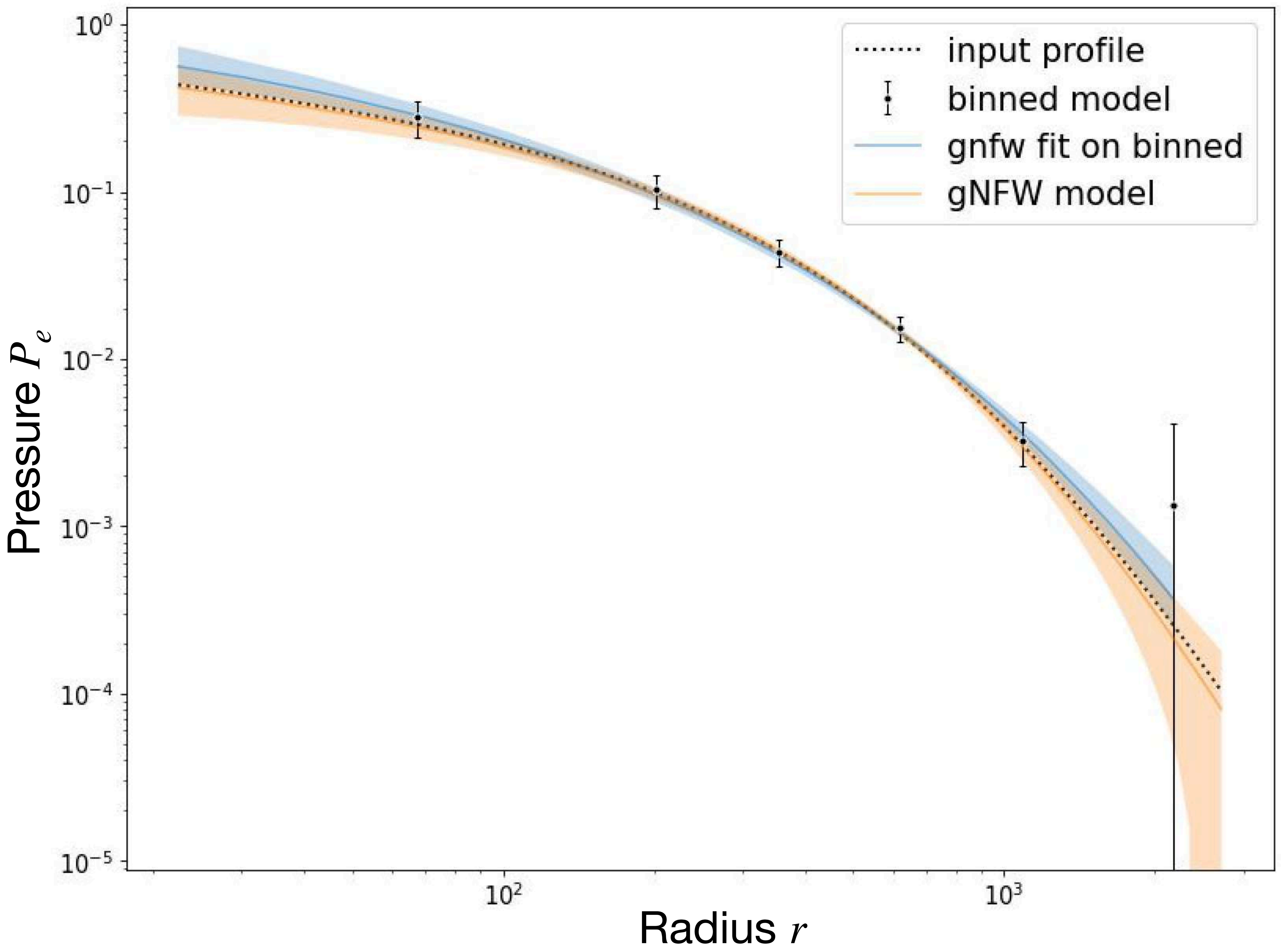

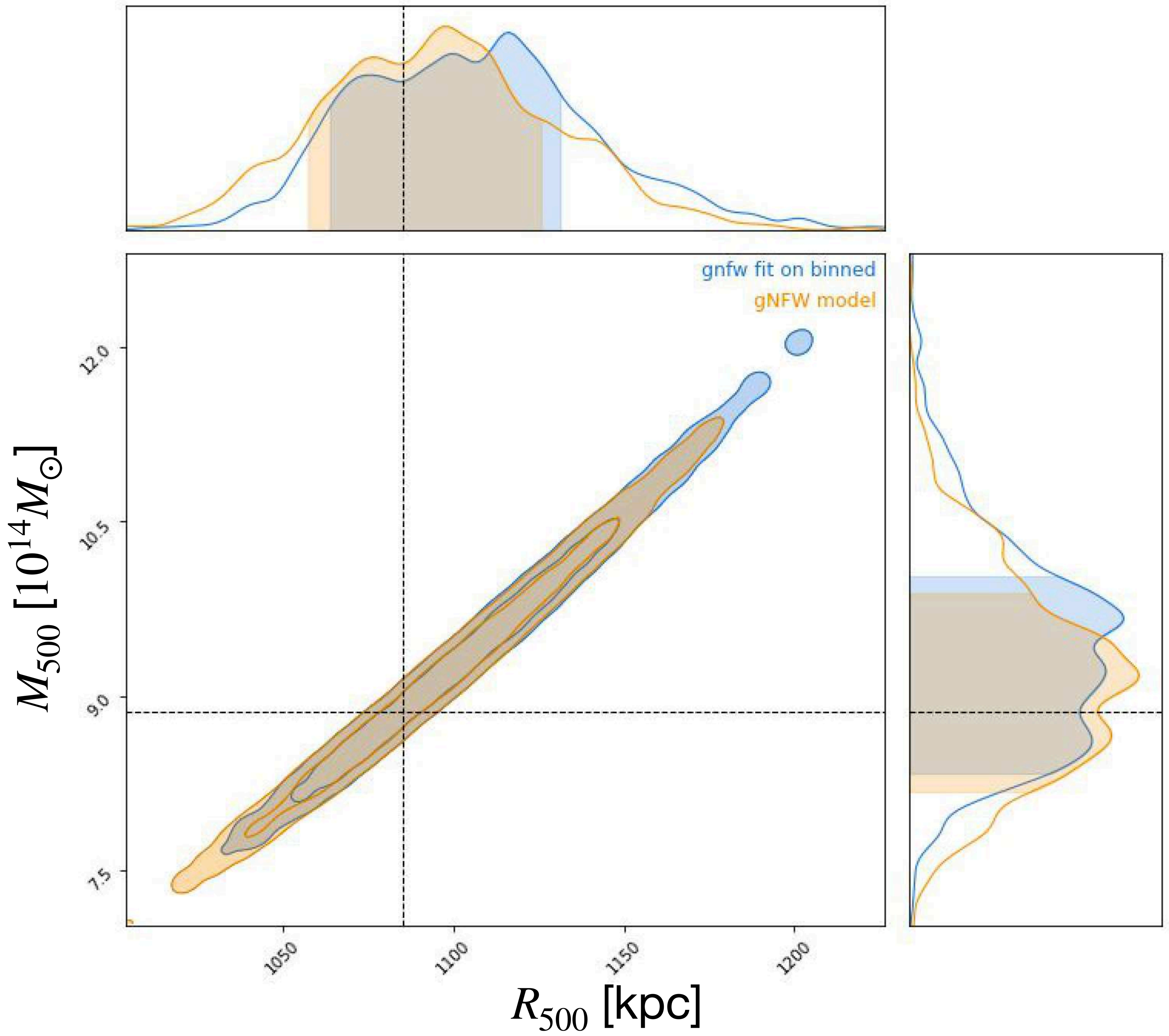

Compute the mass profile using SZ+X-ray data

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→

Get the integrated quantities

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

Both methods recover the input profile within 1σ

We now have everything to compute a universal pressure profile

Self similar approach

Standard self-similar model (based on gravitation, *Kaiser et al. 1986*) :

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

$$P(r) = P_{500}\, p(\frac{r}{R_{500}}),\; P_{500} \propto M_{500}^{2/3}$$

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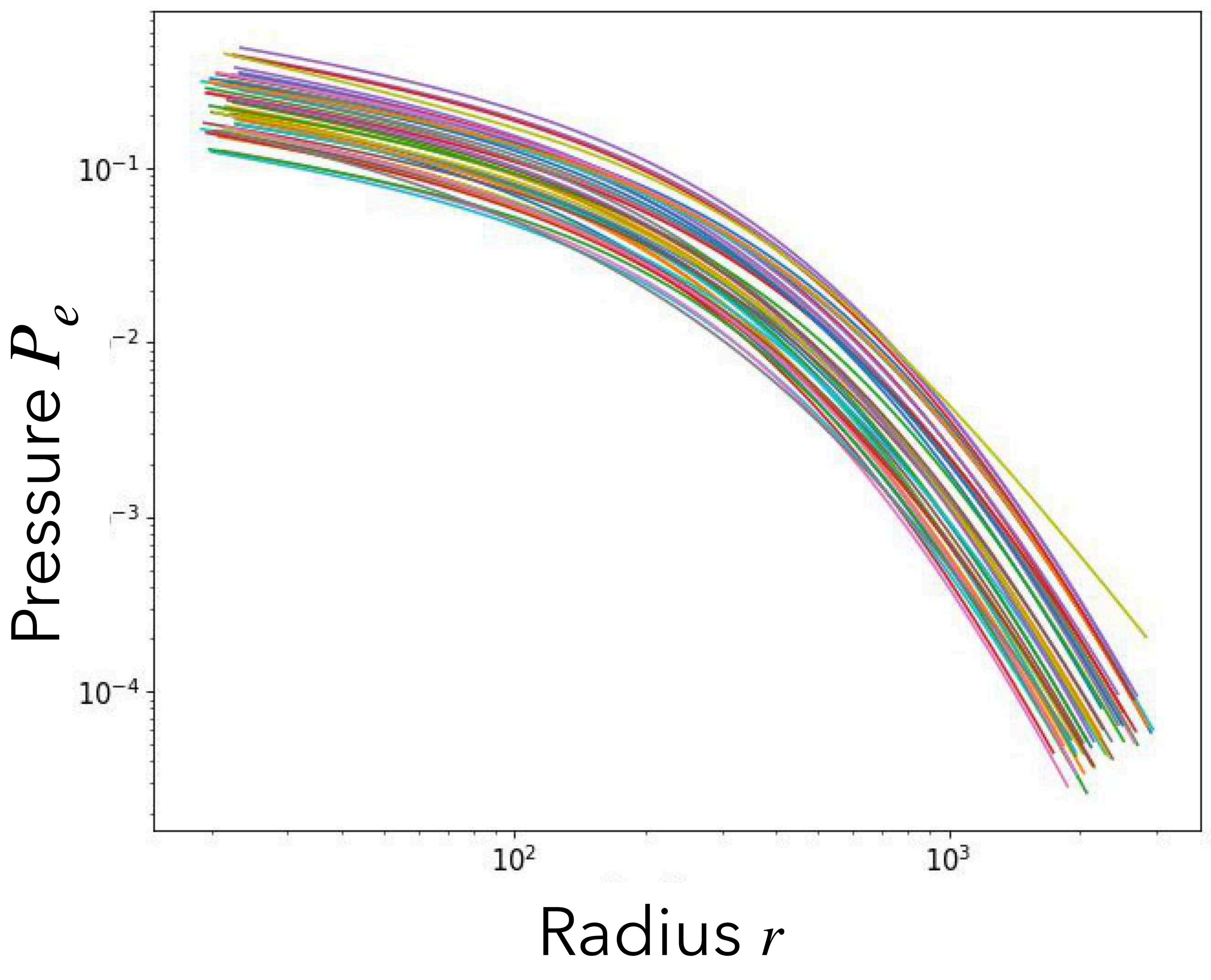
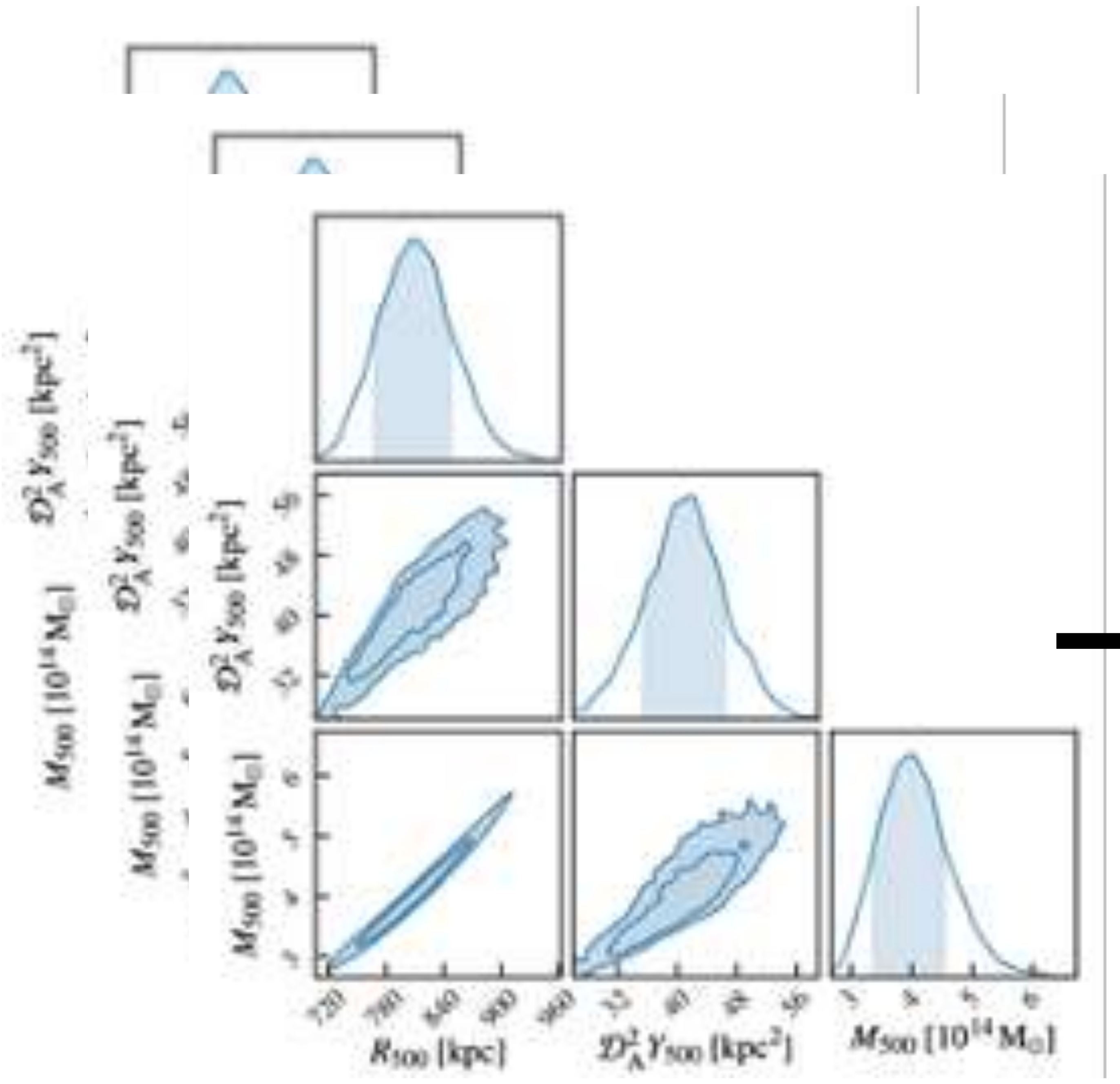
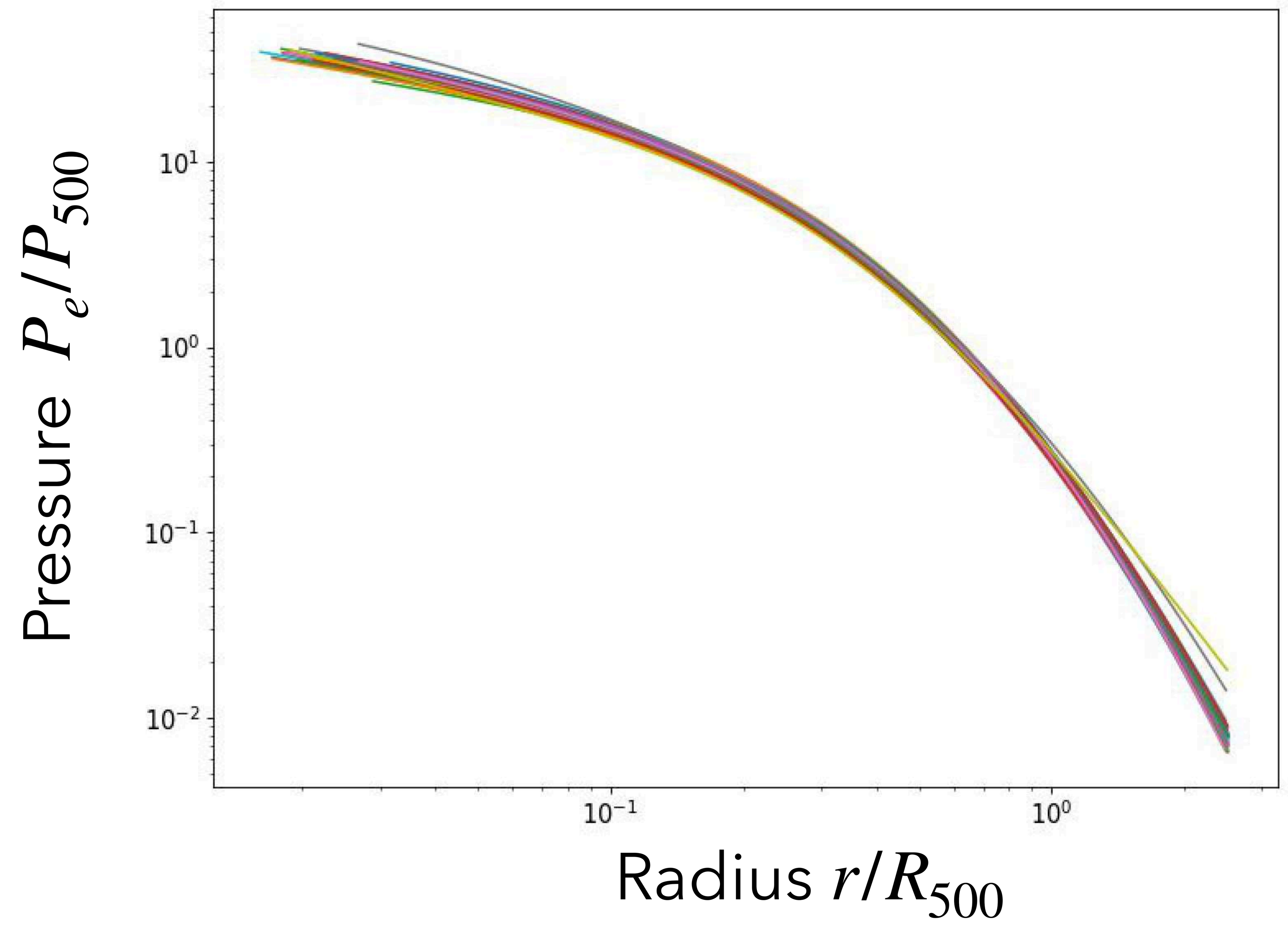




Integrated quantities



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

Mean pressure profile estimates

- Basic approach: Take the median of the re-scaled profiles
- Novel approach: Compute the best-fitting model θ for the mean profile using the likelihood distribution $\mathscr{L}_k(d_k \mid \overrightarrow{\theta}')$ of the individual fit of each cluster d_k

$$\ln \mathscr{L} = \sum_k \ln \mathscr{L}_k \qquad \text{with } \mathscr{L}_k(d_k \mid \overrightarrow{\theta}_{\mathrm{MPP}}) = \int d\overrightarrow{\theta}' \, \mathscr{L}_k(d_k \mid \overrightarrow{\theta}') \underbrace{\mathscr{N}(\overrightarrow{\theta}' \mid \overrightarrow{\theta}_{\mathrm{MPP}}, \Sigma_{\mathrm{int}})}_{\text{Intrinsic scatter}}$$

$$\overrightarrow{\theta} = \{p_0, c_{500}, \alpha, \beta, \gamma\} = \{P_0/P_{500}, R_{500}/r_p, \alpha, \beta, \gamma\}$$

The method accounts for the errors on R_{500}, P_{500} for each cluster

Problematic : we don't know for any arbitrary set of parameters θ the exact value of $\mathscr{L}_k(d_k \mid \overrightarrow{\theta}')$

→ Very difficult to extrapolate

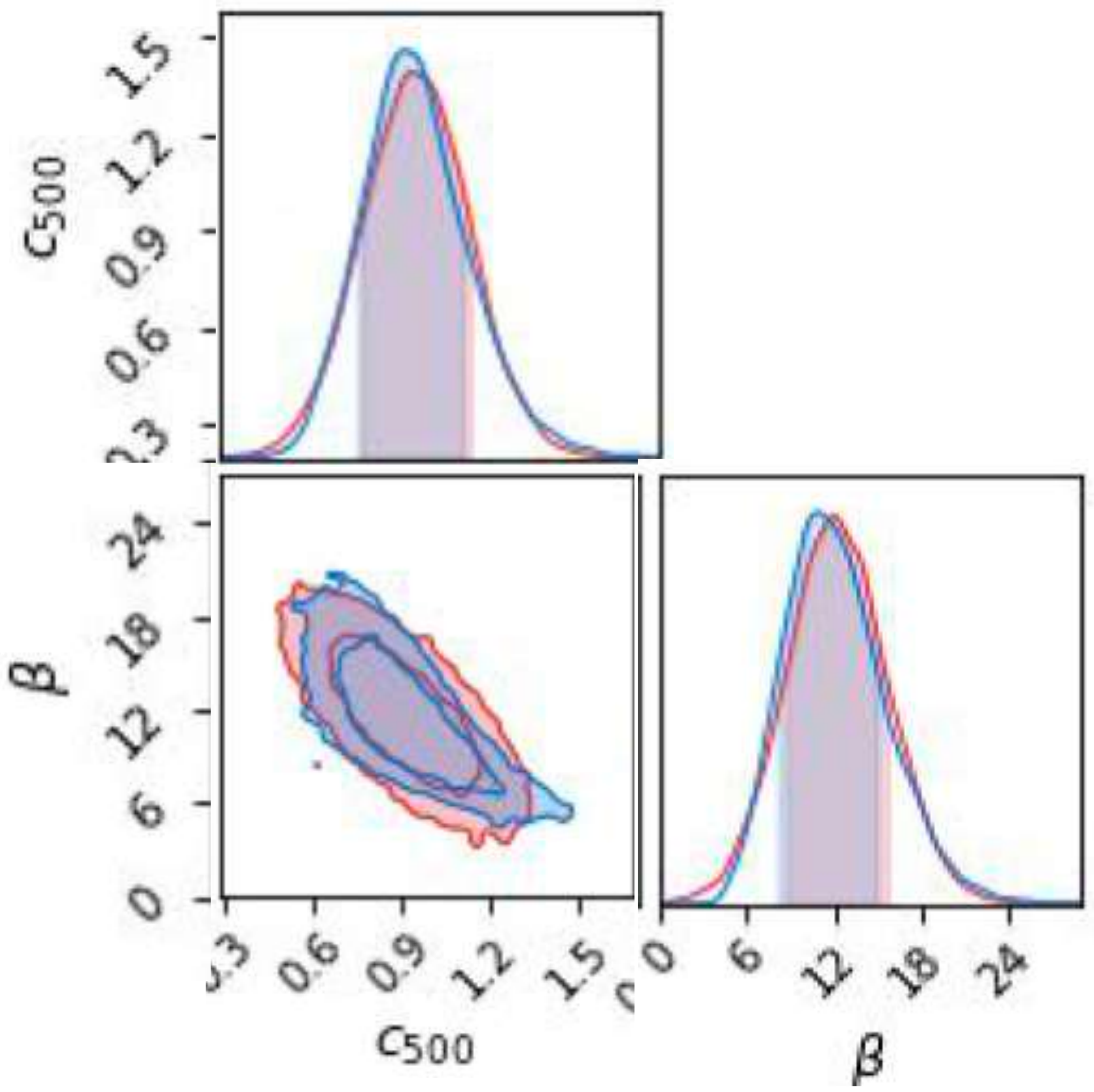
Novel method

Idea : Approximate by multivariate gaussians : $\mathscr{L}_k(d_k \mid \vec{\theta}) \approx \frac{1}{\sqrt{(2\pi)^D \det \Sigma_k}} \exp\left(-\frac{1}{2}(\vec{\theta} - \vec{\mu_k})^T \Sigma_k^{-1} (\vec{\theta} - \vec{\mu_k})\right)$

Results

True likelihood (from data)

MG approx



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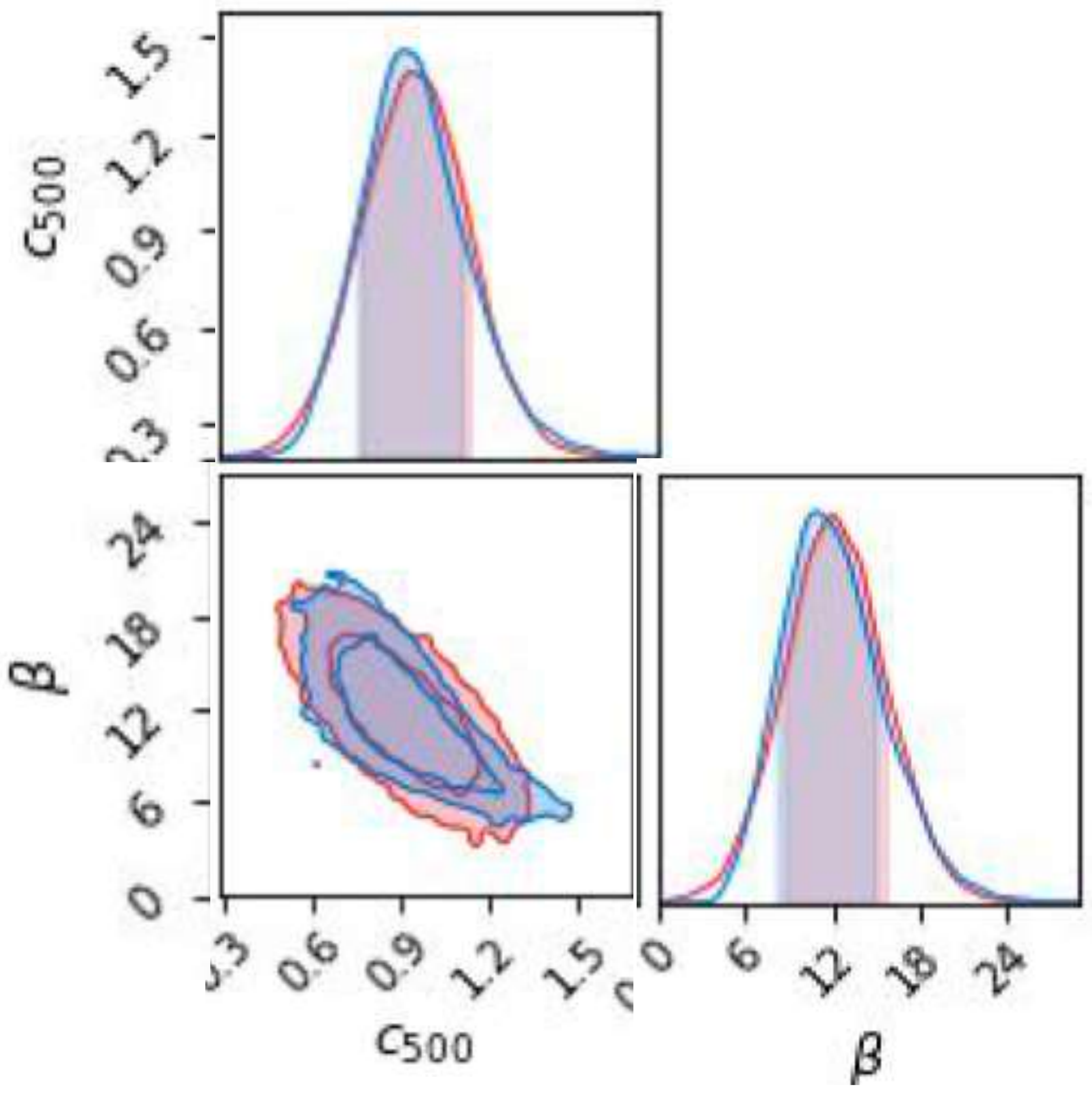
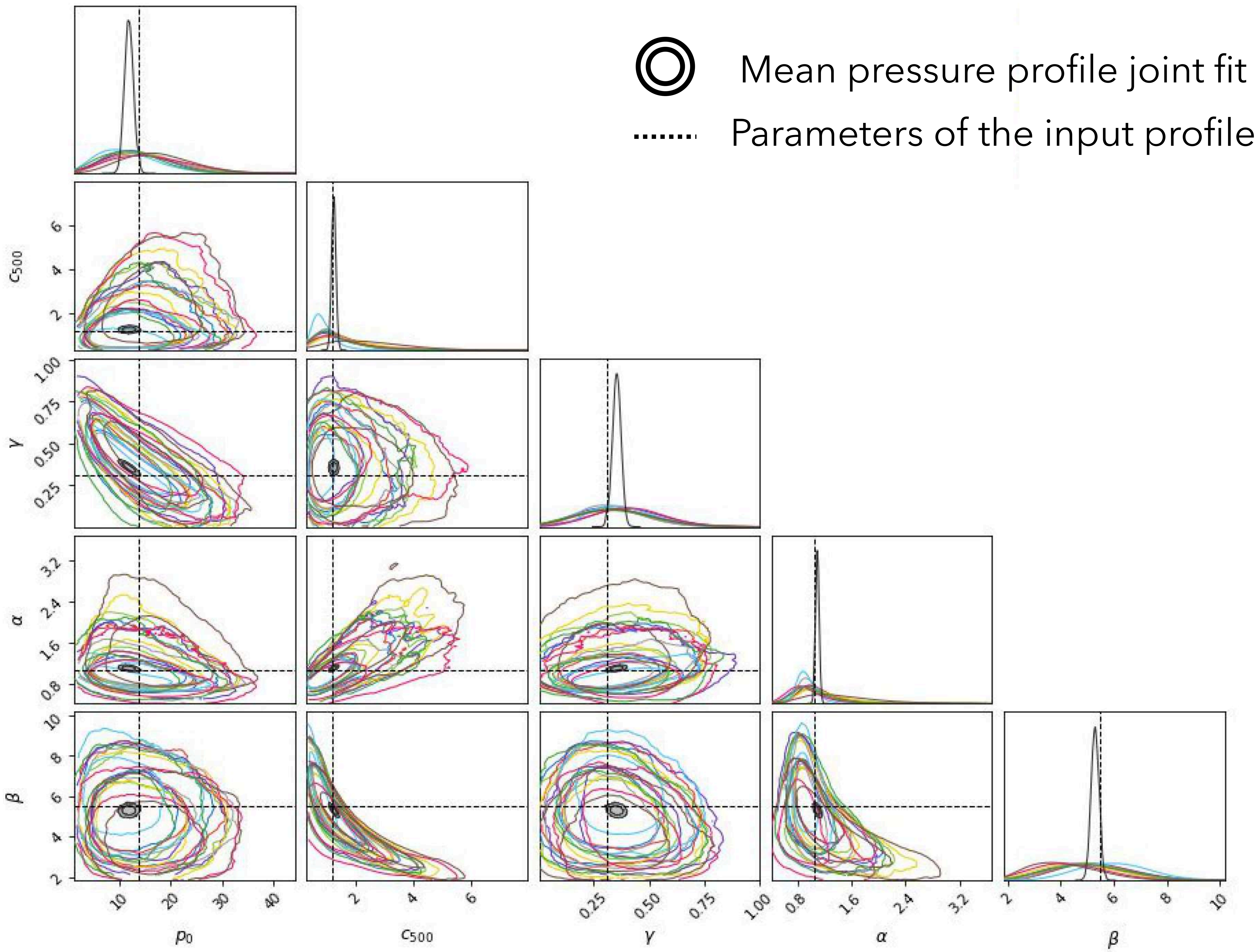


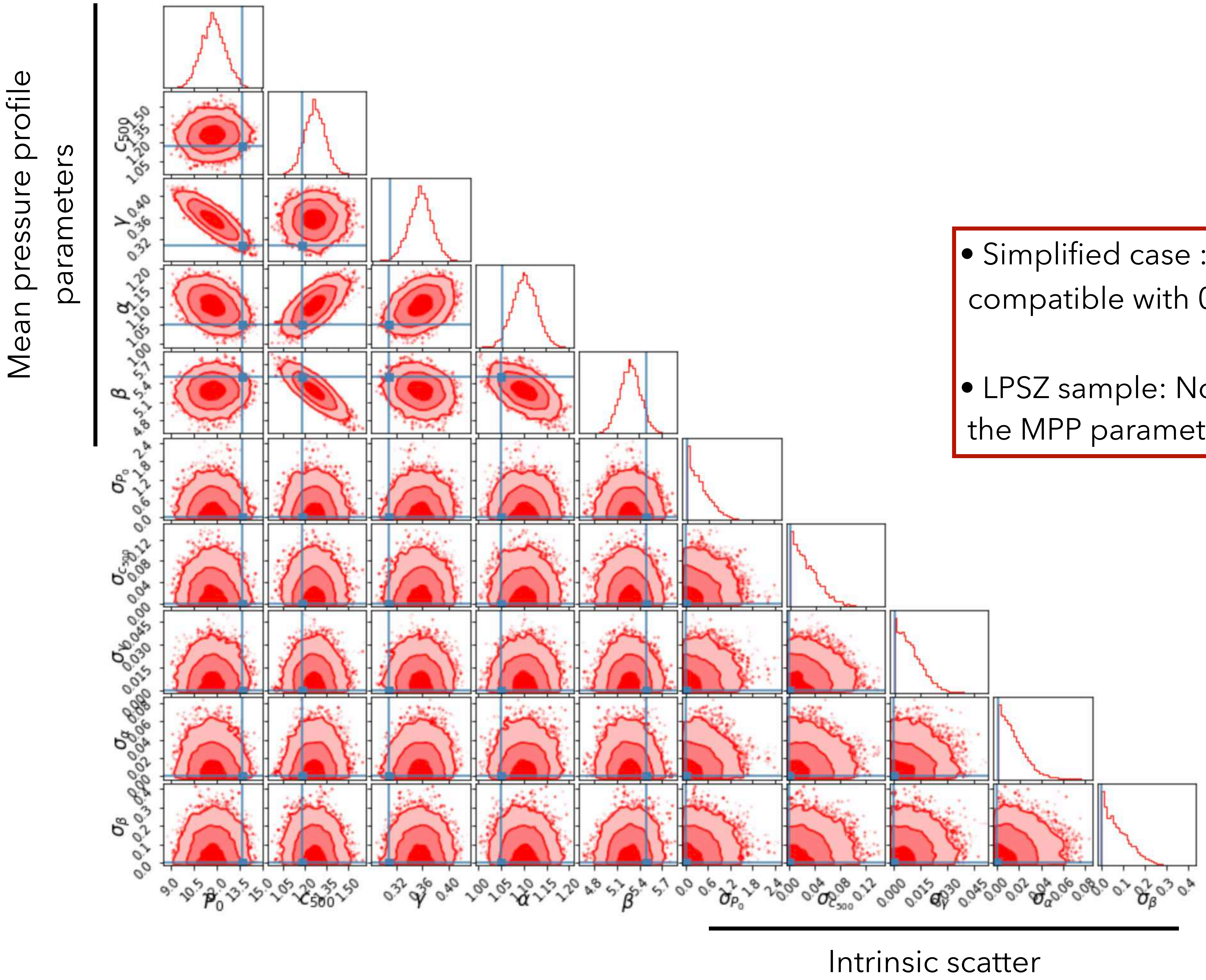


The input mean pressure profile parameters are recovered within 2σ

Small bias along the known $p_0 - \gamma$ degeneracy (*Nagai et al. 2007*)

Intrinsic scatter

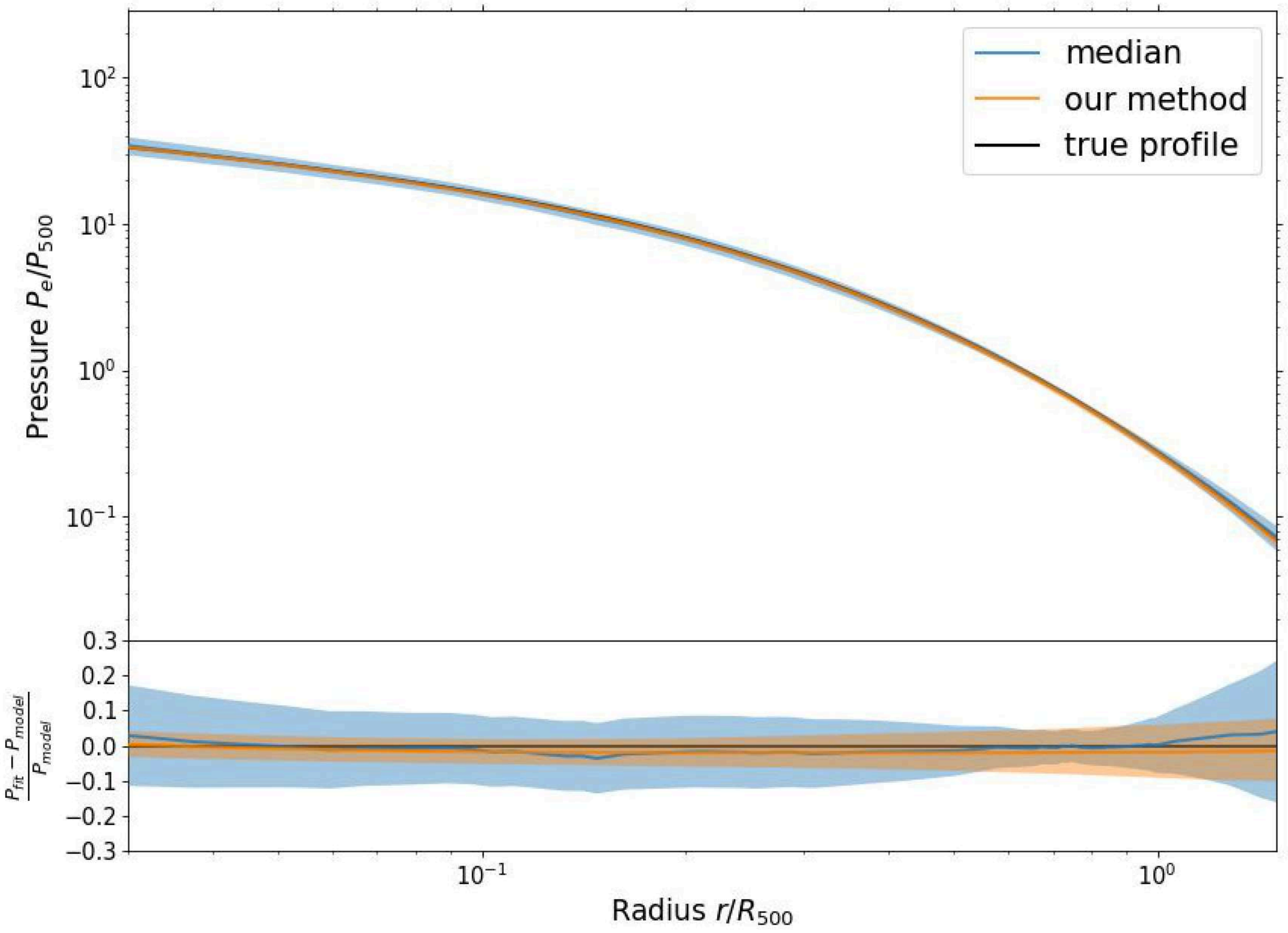
Simulations : no intrinsic scatter in input



- Simplified case : All intrinsic scatters are compatible with 0 at the 1σ level
- LPSZ sample: Non-zero scatter may impact the MPP parameters

Mean pressure profile

Results obtained with the 2 gNFW methods on simulations (no intrinsic dispersion)



The proposed method efficiently recovers the input profile within 1σ

Improvement on the median method : more precise constraints, takes into account errors on R_{500} + intrinsic scatter

The code will be delivered to the NIKA2 collaboration and will be used to compute the LPSZ mean pressure profile

Conclusion

First standard analysis on the NIKA2 LPSZ sample

Observations completed in January 2023

First complete characterization of the whole sample:

- Mapmaking: new tool for optimizing the decorrelation mask and flagging the outlier scans
  → Final cluster maps (to be part of the upcoming public data release)
- Standard pipeline to compute pressure and mass profiles validated on a realistic simulation of the LPSZ sample

Mean pressure profile estimate

- New method that use all individual information and propagate errors from integrated quantities

  → Validation using LPSZ realistic simulations

Perspectives

- Preparation of the upcoming public data release
  → First publication of the LPSZ mean pressure profile
- Study the implication on cosmology using Planck data

Back-ups

Noise decorrelation method

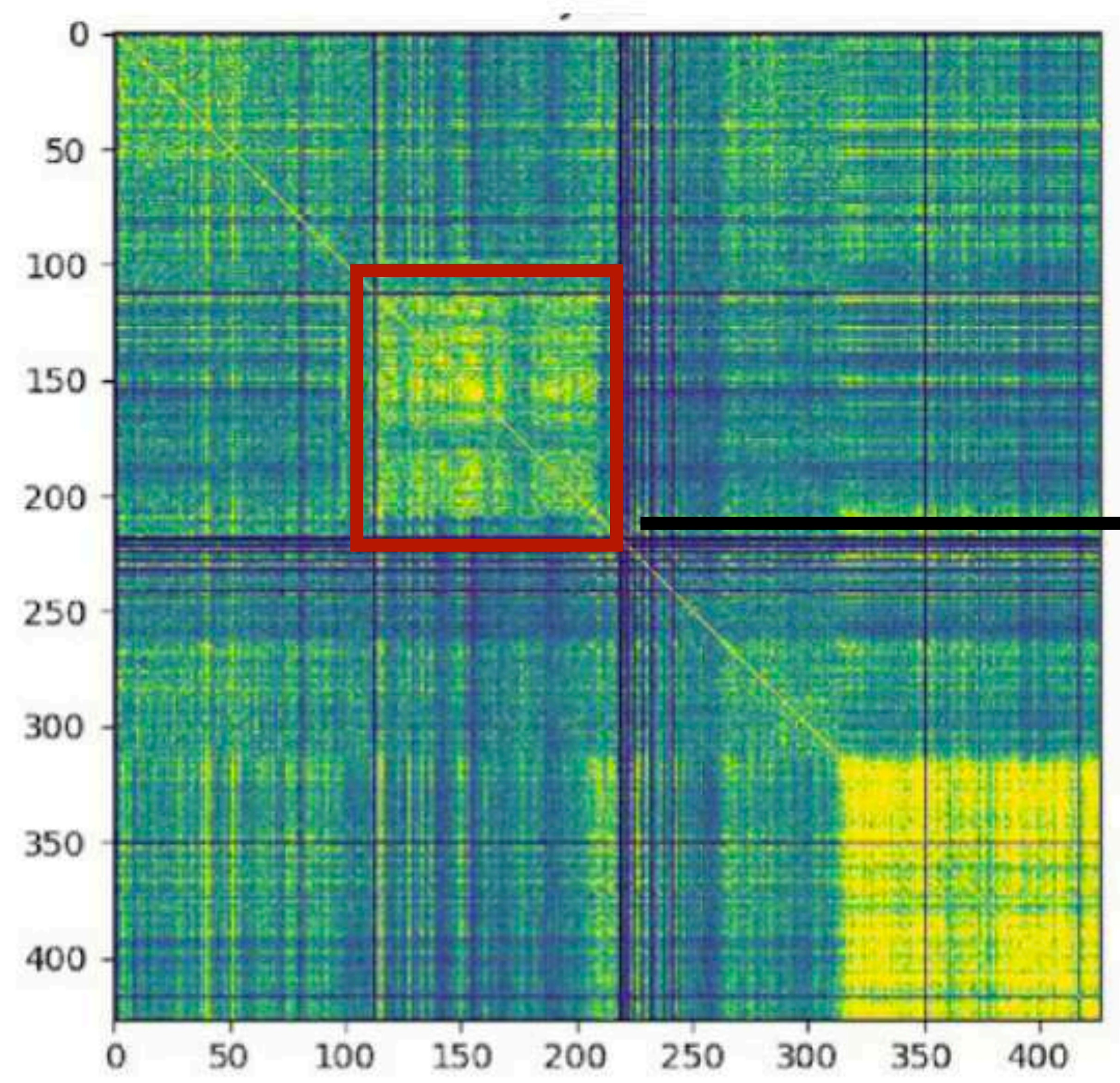
Baseline decorrelation method: Most Correlated KIDs (a.k.a Common Mode One Block)

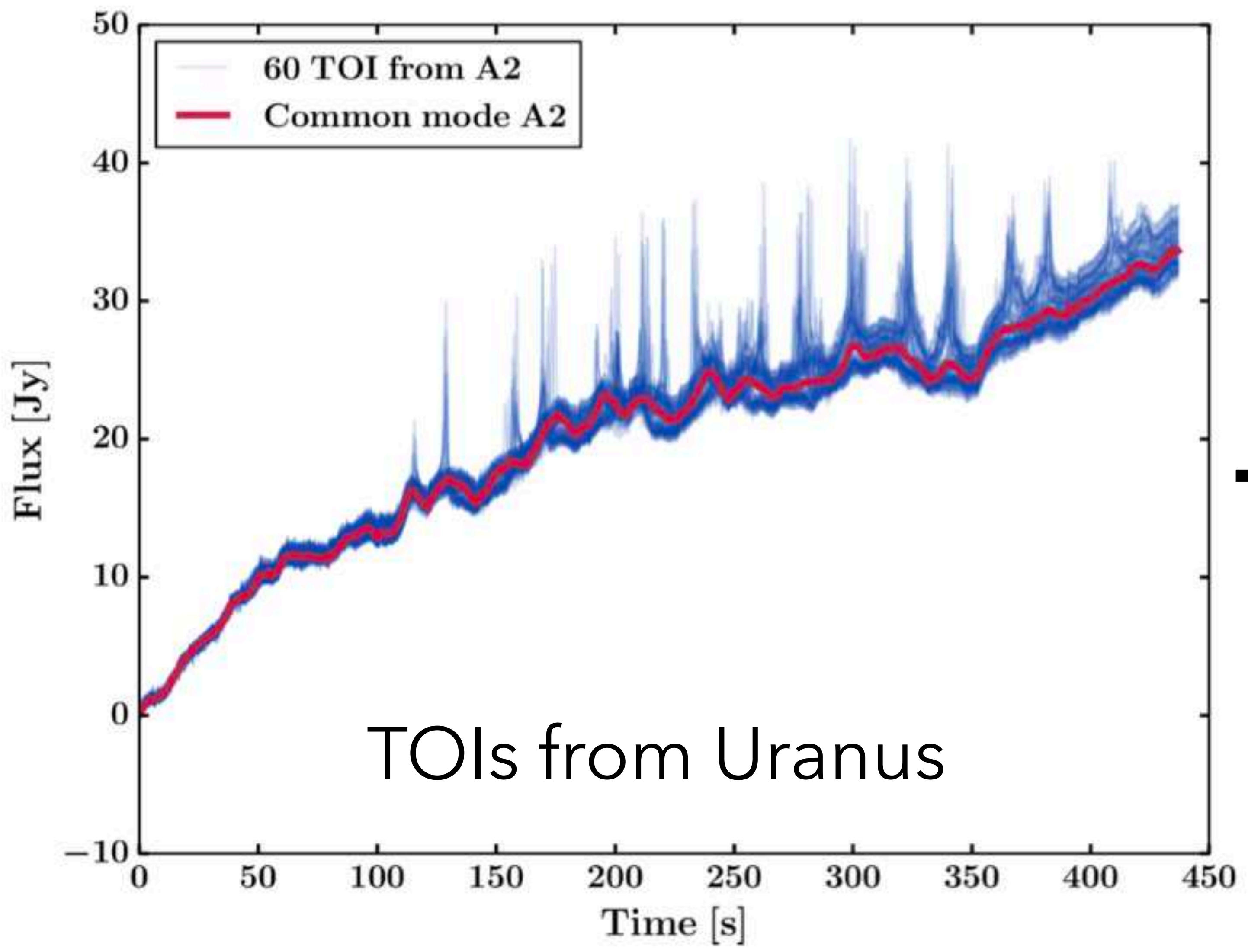
1. Compute the kid-to-kid correlation matrix and get blocks of most correlated kids

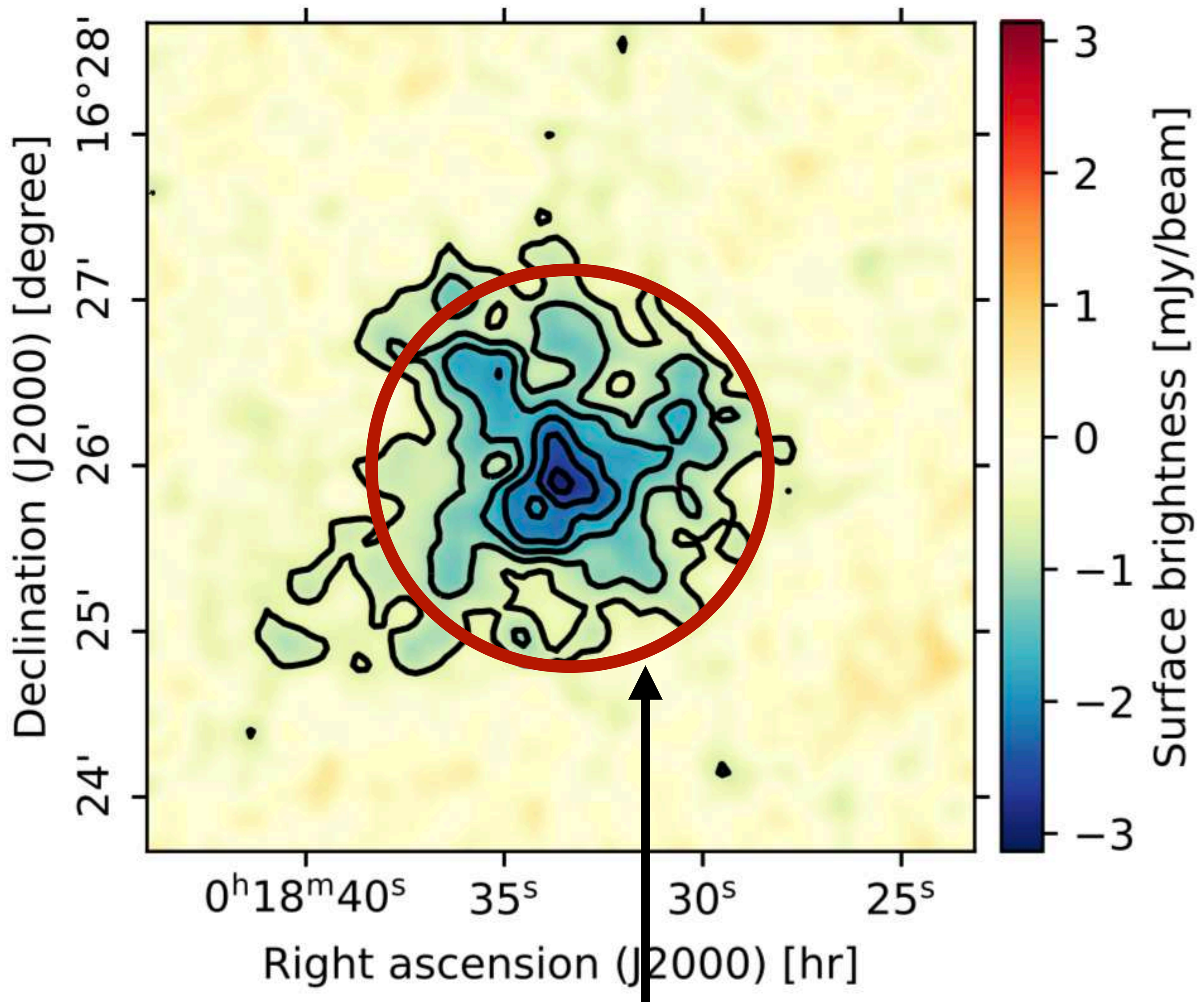
2. Mask the cluster (=mask each TOI) in each scan to prevent the signal from being removed
   –> Disk of radius r centered at the cluster's pointing center

3. For each block compute a common mode (CM = median of the TOIs)

4. Subtract the common mode from the TOIs and project them on a map







$$TOI_k - CM_k = S_k + \boxed{\delta N_k}$$ Residual noise

Decorrelation mask

But the residual correlated noise is one of the main systematic effects affecting NIKA2 maps
Trade-off between the filtering of the signal and the number of KIDs outside the mask to compute the CM

Mask size optimisation

Two parameters:

1. Mask radius as a function of θ_{500} (~2-3 arcmin) from Planck/ ACT catalogs
2. Threshold for scan selection $\sigma_{threshold}$

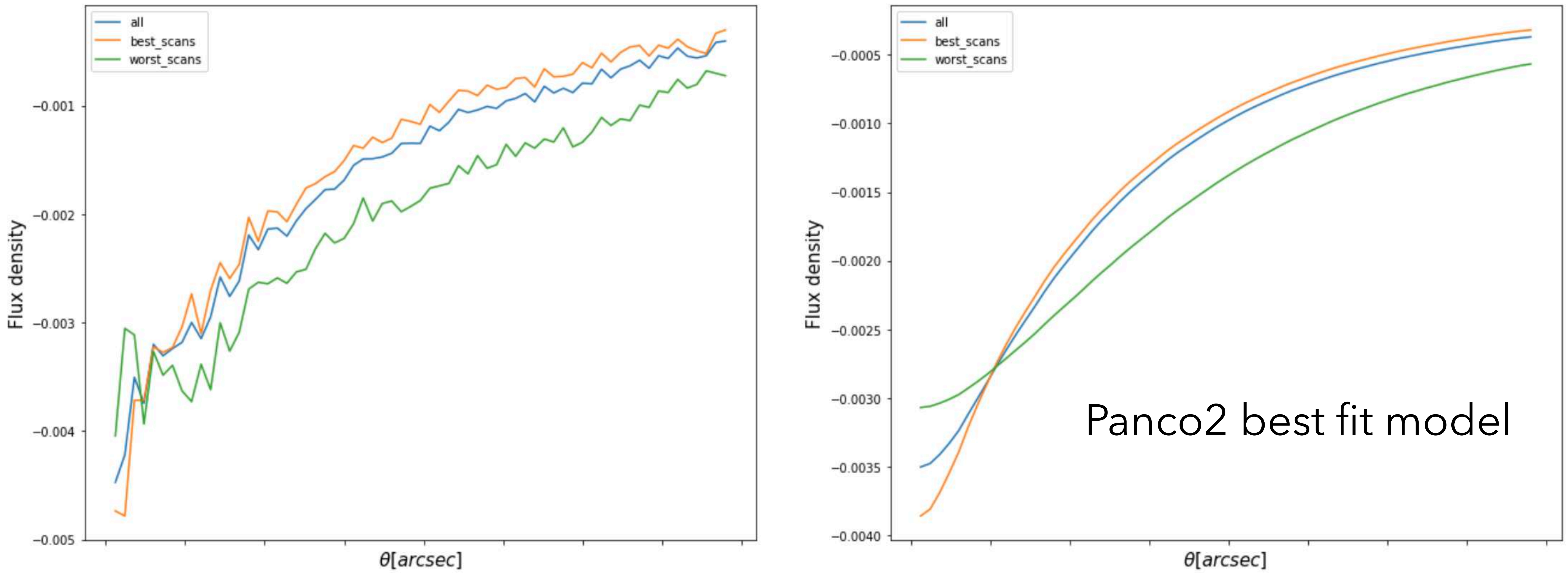
Our scientific goal: cluster pressure profiles computed with panco2 *(F. Kéruzoré et al. 2023)*

38 clusters → Many analyses to do:1 analysis with panco2 = several hours

Inputs in panco2: Processed data map + Transfer function (TF)

- Compare a combination of these 2 quantities: deconvolved data map
- Sphericity hypothesis: compare radial profiles

Flux density profiles for 3 different analyses with panco2



We can compare directly the flux density profiles

Identification of outlier scans

Objective: Blind identification of problematics in individual scans

–> We suggest a list of criteria to define data quality

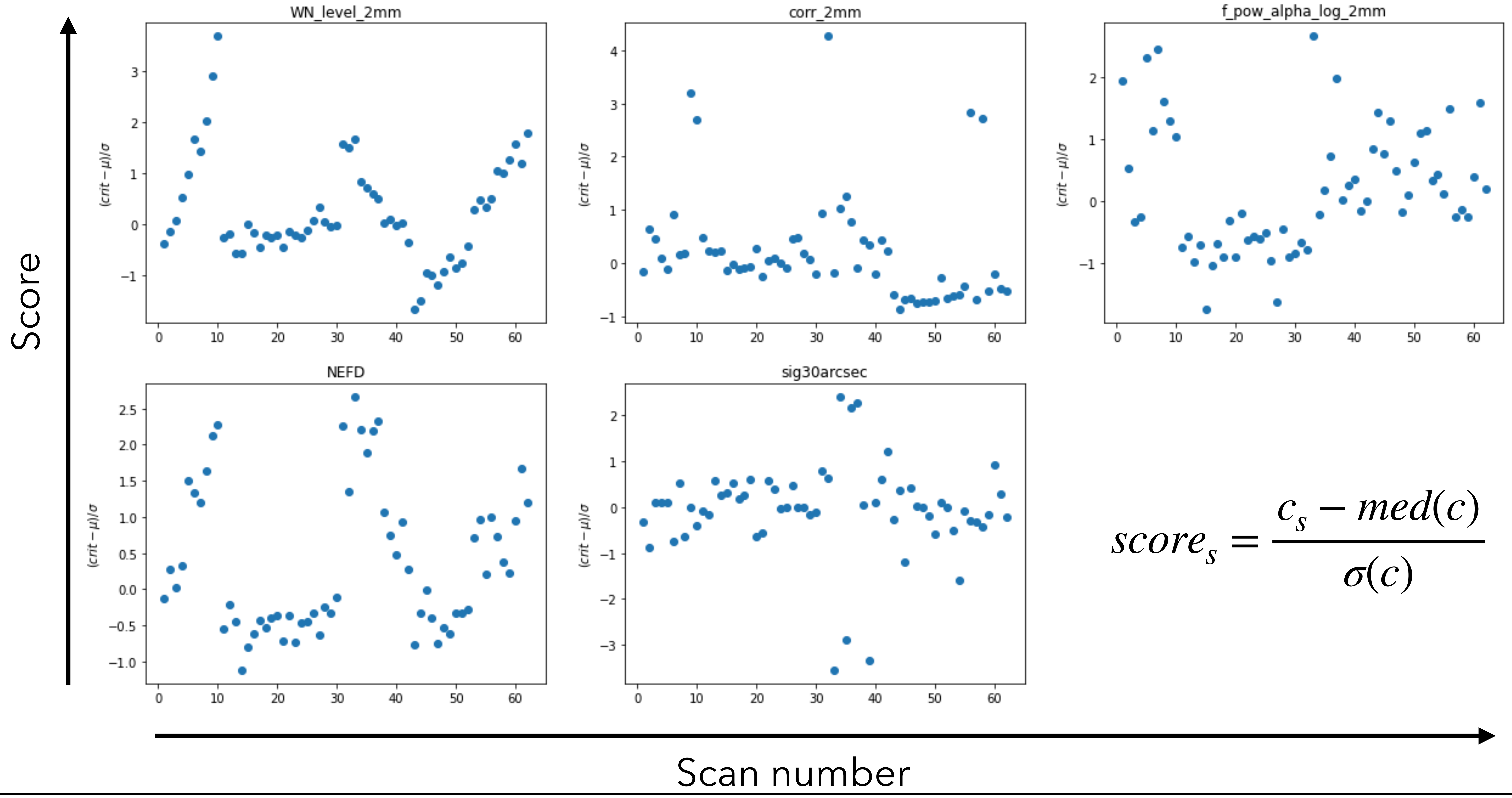
Kid to kid correlation matrix : mean of the residual correlation

Low frequency noise at large scales f_{knee}^{α}

White noise at every scales B

Integrated signal over a sphere of radius R = 30'' on the scan's map

NEFD : Noise equivalent flux density



$$score_s = \frac{c_s - med(c)}{\sigma(c)}$$

Low frequency noise

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

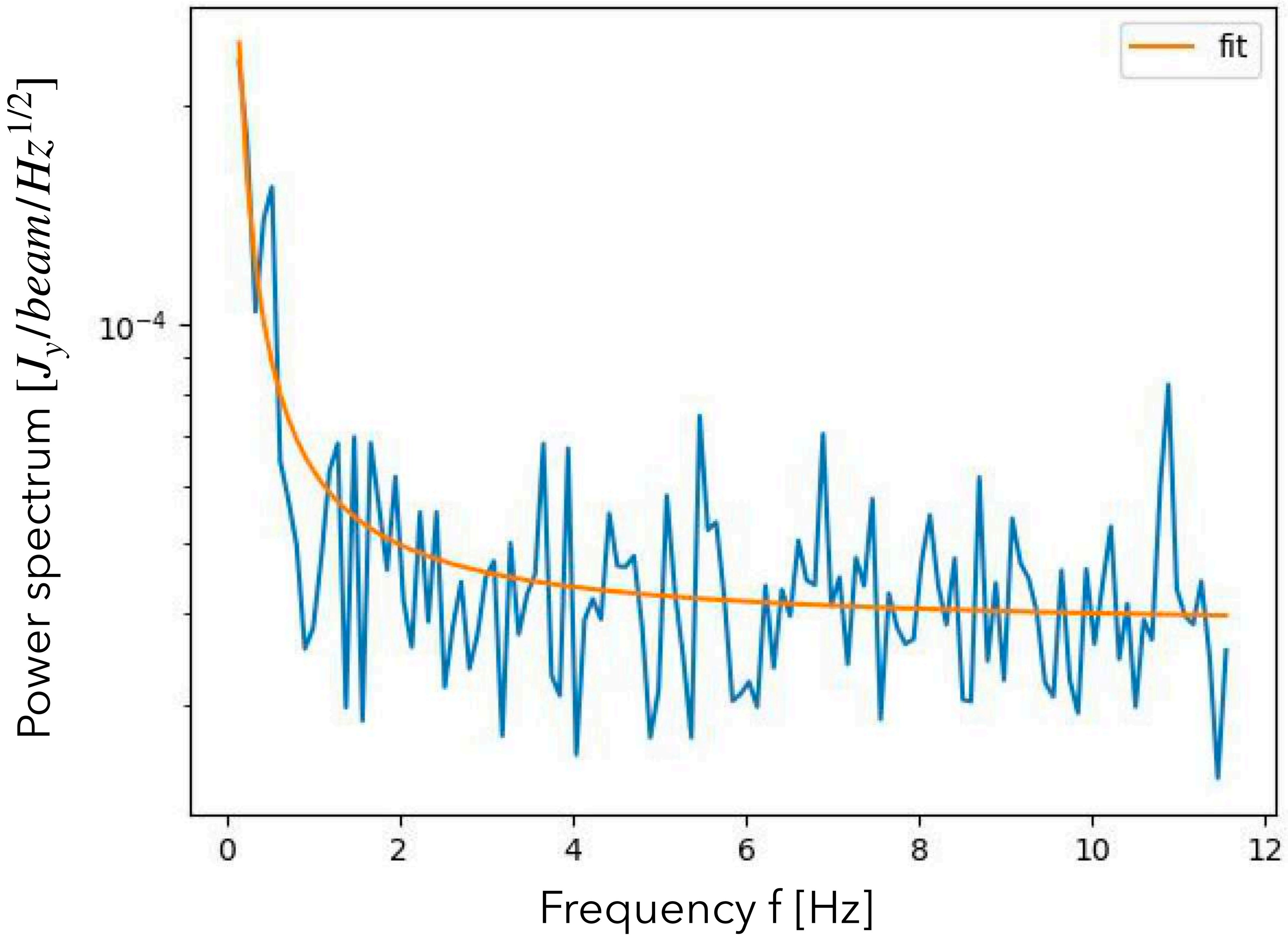
Fit : iMinuit library

$$\chi^2 = \sum_i \left(\frac{P_{data}(f_i) - P_{model}(f_i)}{\sigma_{P_i}}\right)^2$$

–> We bin the power spectrum : $P_{data}(f_i) = med(P_{data}(f)_{bin_i})$

$$\sigma_{P_i} = mad(P_{data}(f)_{bin_i})$$

–> Binning choice : linear or logarithmic



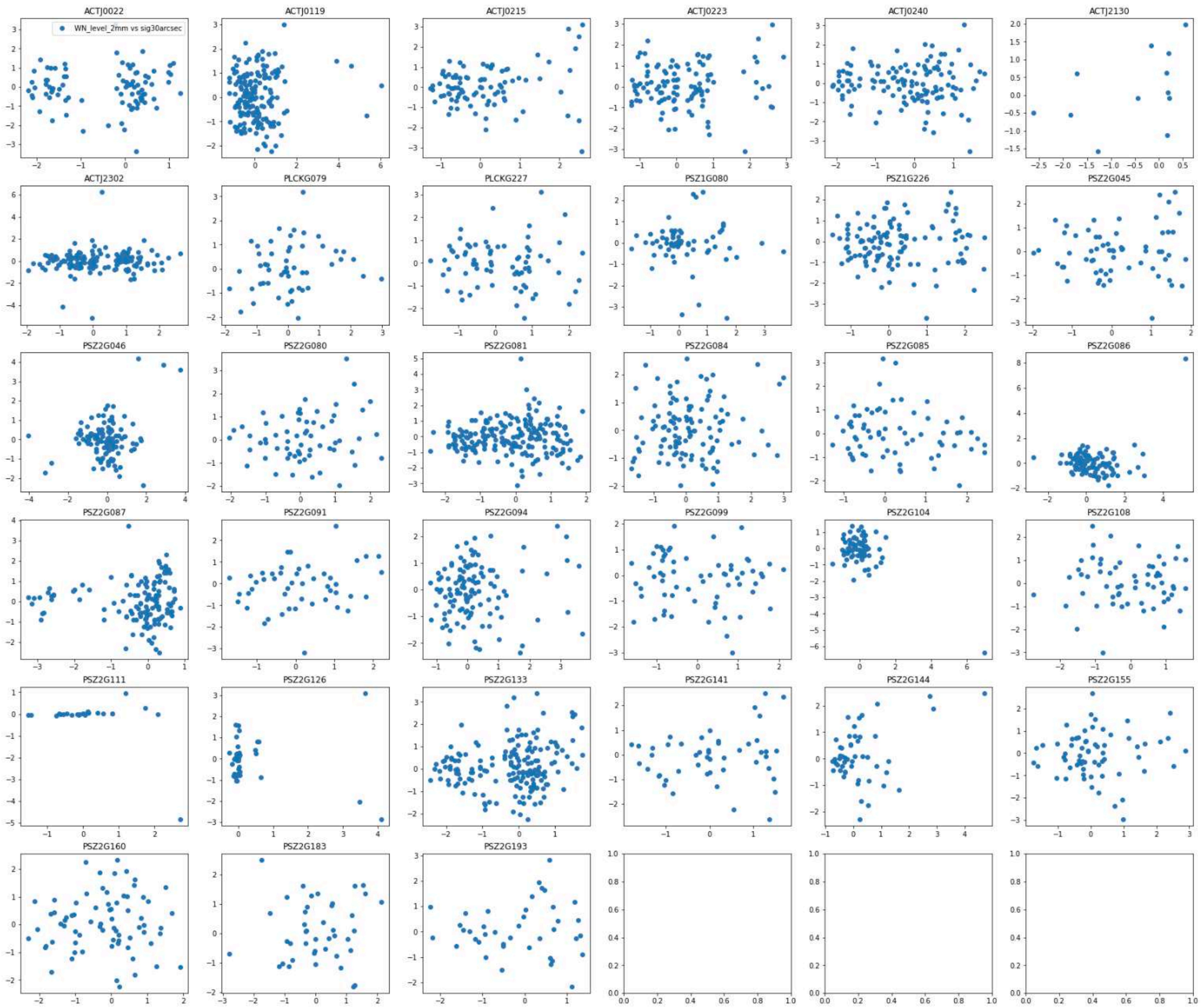
Power spectrum of one TOI from one KID (blue) and associated fit (yellow)

Criteria:
- f_{knee}^{α} Low-frequency noise at large scales
- B White noise at every scales

Methodology

Method :

- Select independent data quality criteria
- Compute a score for each criterion c per scan s
- Find a threshold to discriminate outliers

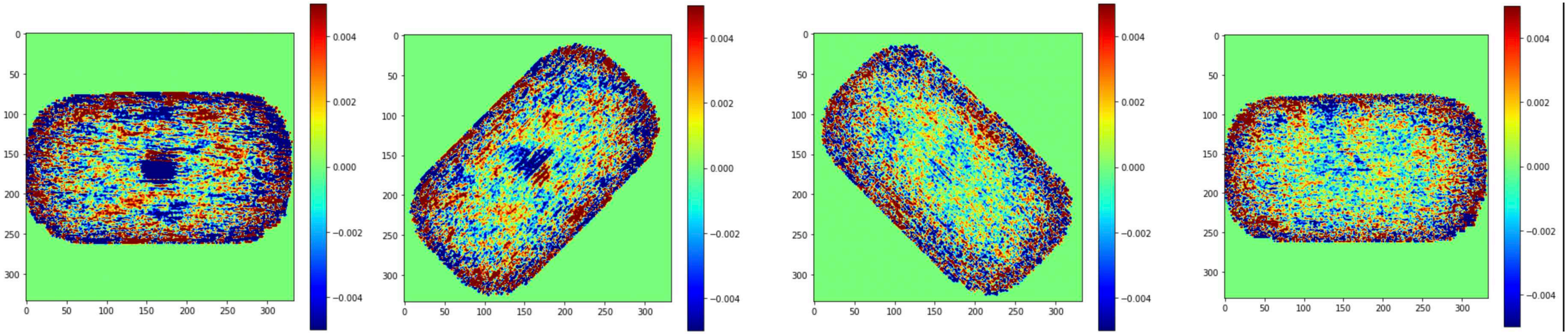


We verified that 4 out of the 5 criteria are uncorrelated

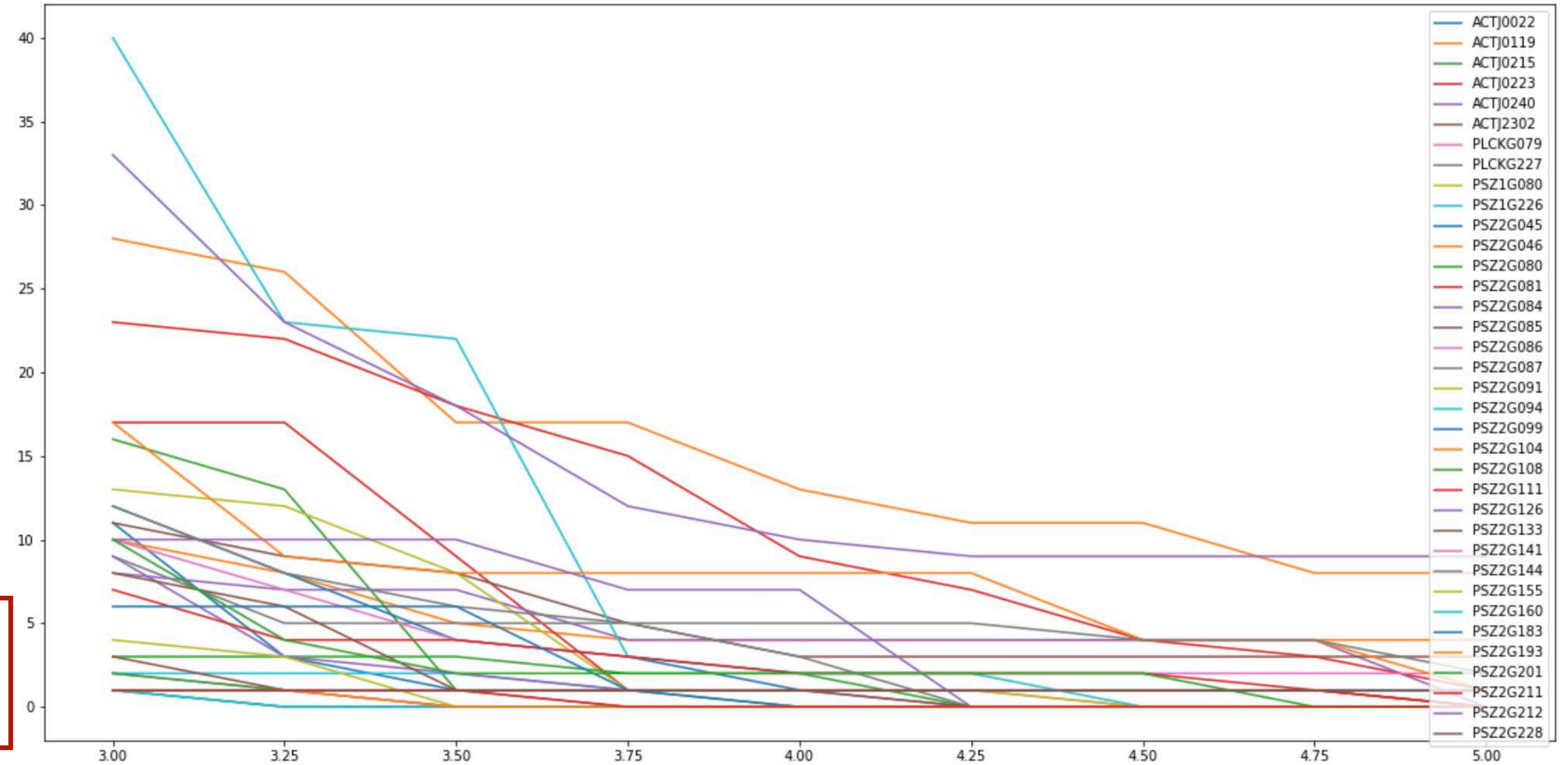
Scan ranks

Ranking the scans as a function of the score: Considering the highest score over the criteria per scan $max\{score_s\}_{crits}$

Example of PSZ2G111: worst scans (left) and best scans (right)



X-axis: $\sigma_{threshold}$
Y-axis: Number of scans removed

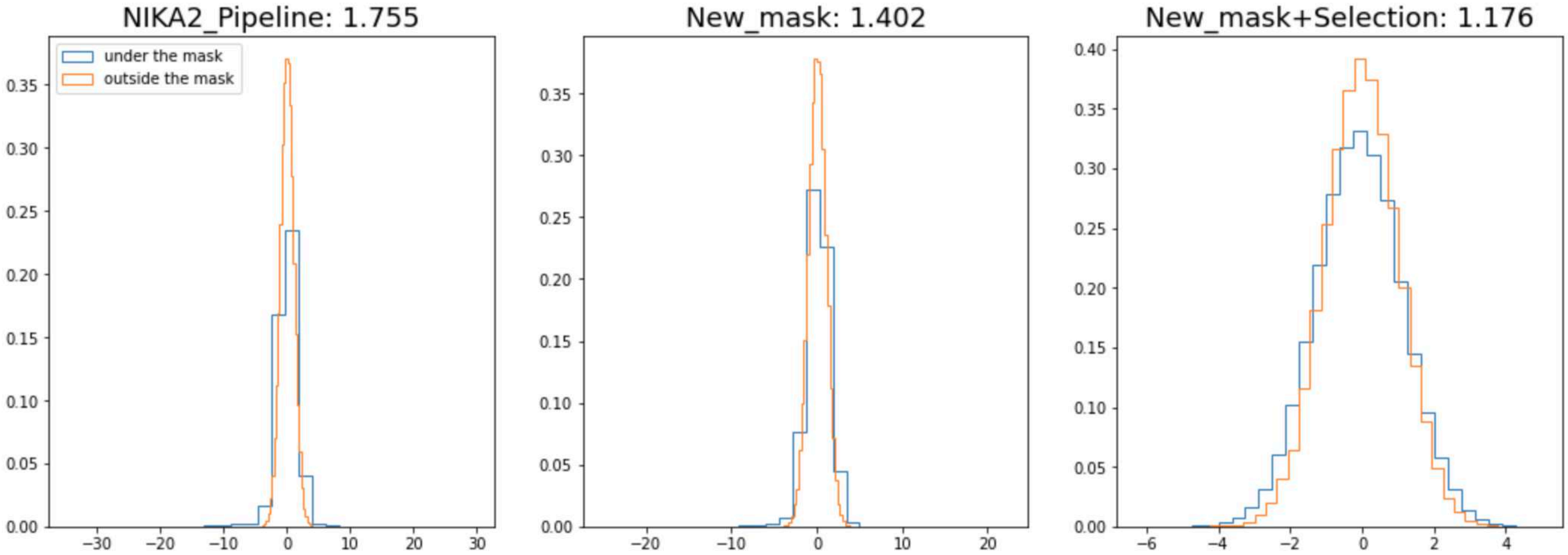


We want to remove the outliers only
→ Optimise the mask and the threshold

Improvements on the whole sample

Mean excess variance under the mask

→ Make a histogram of the pixels under the mask
→ Make a histogram of the same volume of pixels outside the mask
→ Compute the ratio of the scatters: σ_{in}/σ_{out}



Pressure profiles of the NIKA2-LPSZ sub-sample

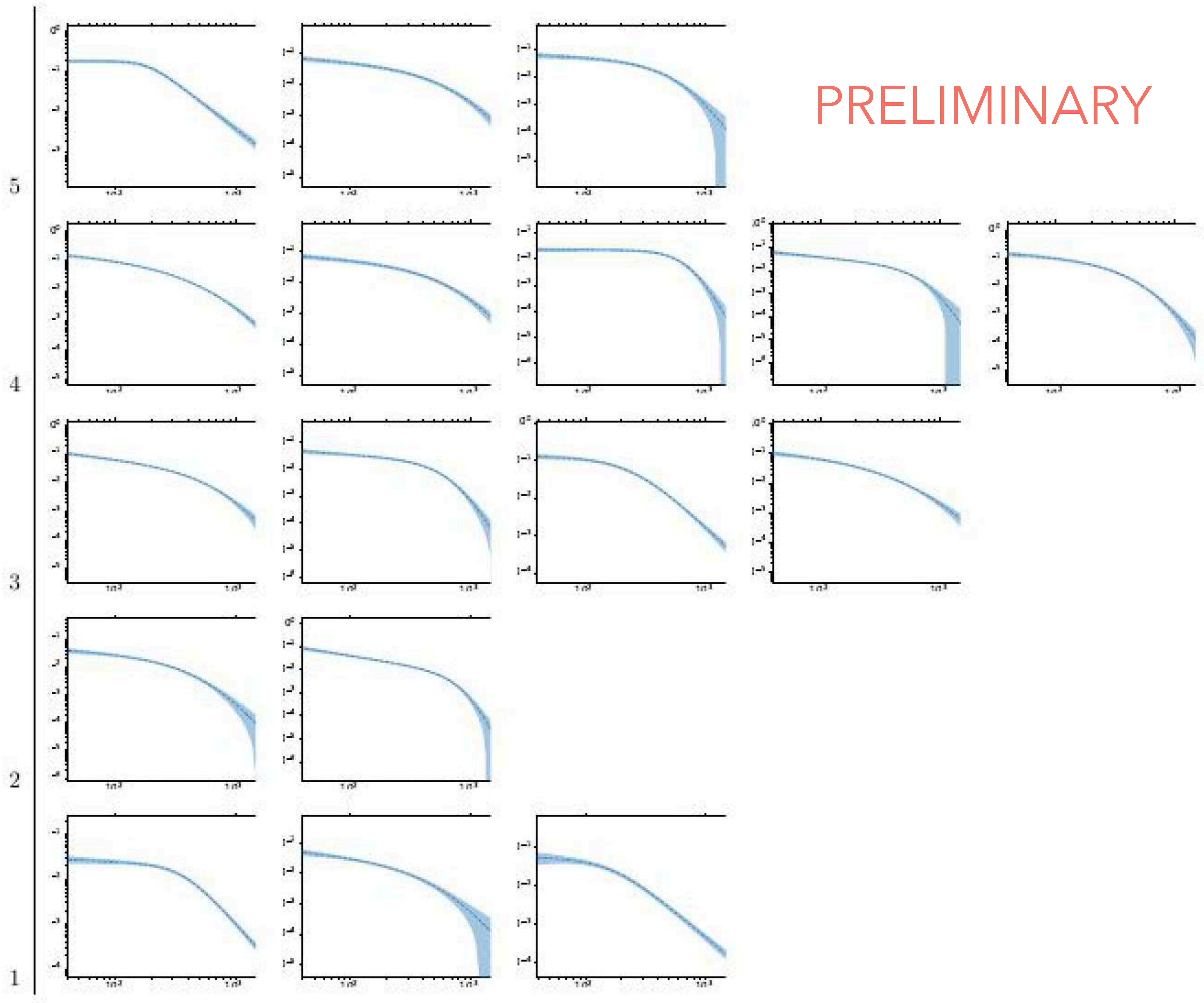
We have designed a first standard analysis pipeline

→ On-going studies on the systematics affecting the profiles reconstruction (point sources, model, …)

Preliminary study on 20 clusters

- gNFW fit on data

First measurement of the pressure profiles on a NIKA2-LPSZ sub sample



Pressure profiles and integrated quantities will be part of the upcoming data release

Mean pressure profile estimates

- Basic approach: Take the median of the re-scaled profiles
- Novel approach: Compute the best-fitting model θ for the mean profile using the likelihood distribution $\mathscr{L}_k(d_k | \overrightarrow{\theta}')$ of the individual fit of each cluster d_k

$$\ln \mathscr{L} = \sum_k \ln \mathscr{L}_k \qquad \text{with } \mathscr{L}_k(d_k | \overrightarrow{\theta}_{\text{MPP}}) = \int d\overrightarrow{\theta}' \, \mathscr{L}_k(d_k | \overrightarrow{\theta}') \underbrace{\mathscr{N}(\overrightarrow{\theta}' | \overrightarrow{\theta}_{\text{MPP}}, \Sigma_{\text{int}})}_{\text{Intrinsic scatter}}$$

$$\overrightarrow{\theta} = \{p_0, c_{500}, \alpha, \beta, \gamma\} = \{P_0/P_{500}, R_{500}/r_p, \alpha, \beta, \gamma\}$$

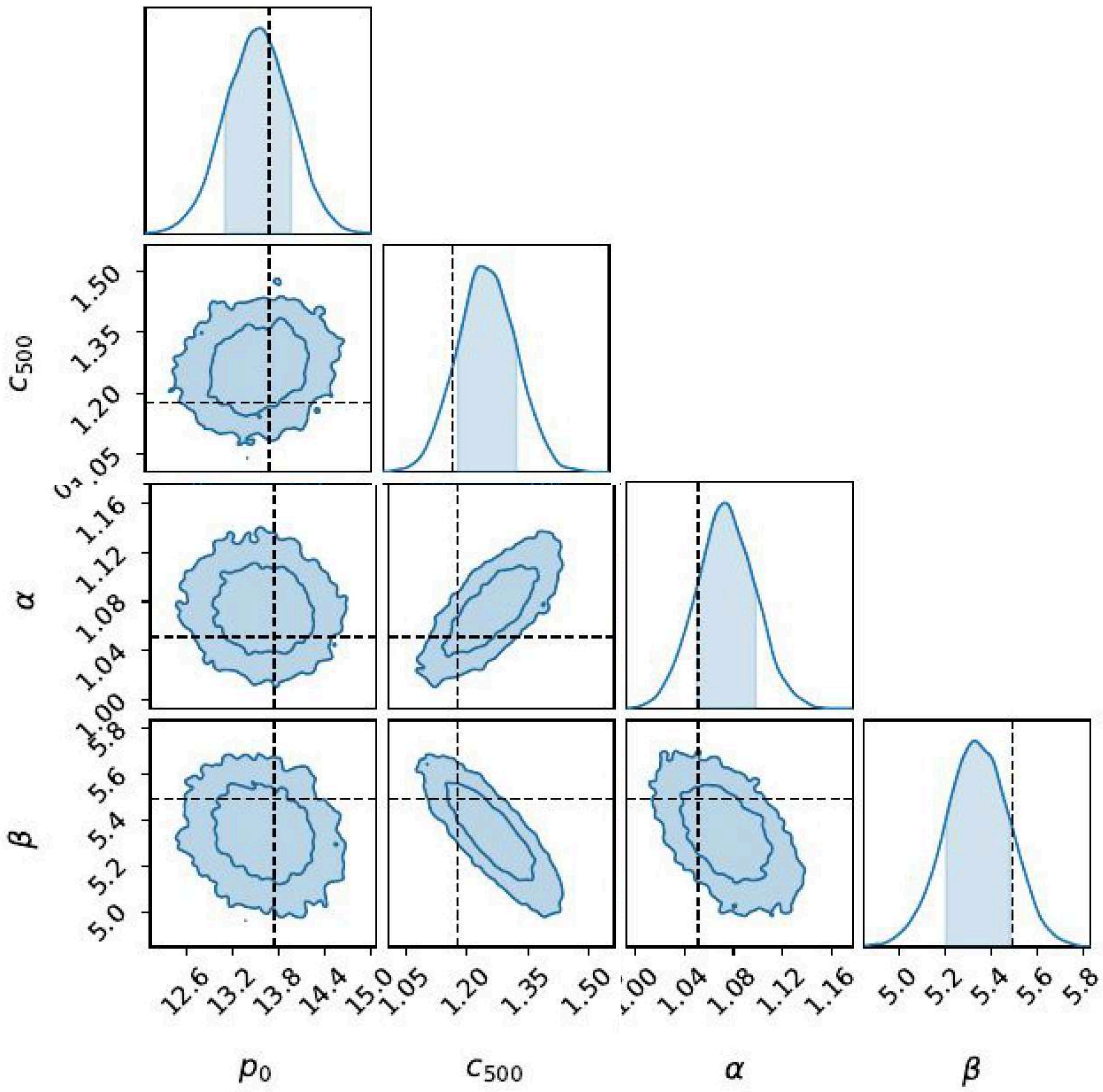
The method account for the errors on R_{500}, P_{500} for each cluster

→ We compute $R^j_{500} P^j_{500}$ for each set of parameters $\{P_0, r_p, \alpha, \beta, \gamma\}^j$ in the MCMC chains

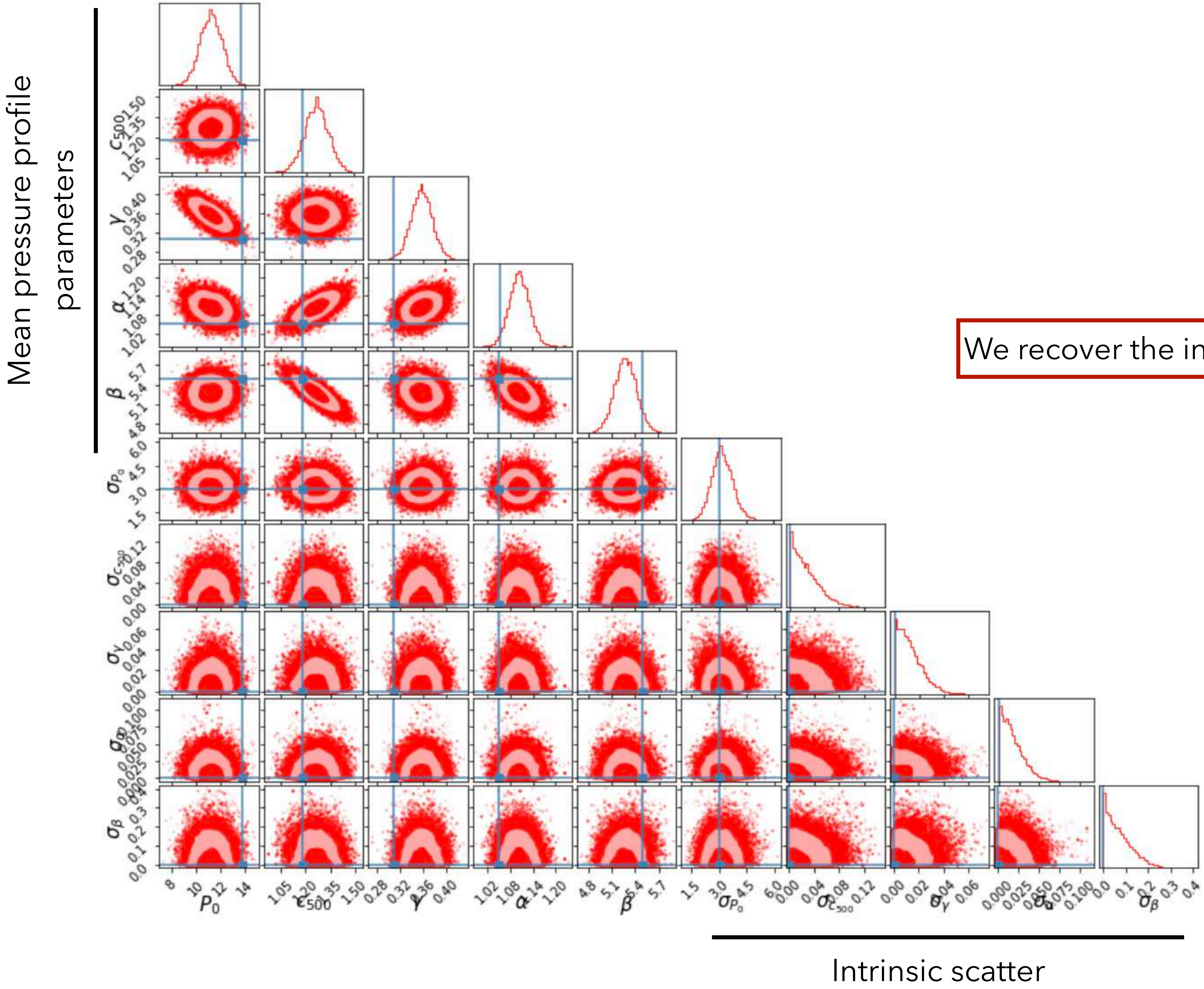
→ We compute the corresponding re-scaled parameters

→ We get $\mathscr{L}_k(d_k | \overrightarrow{\theta}')$

Corner plot mean pressure profile : gamma fixed



Simulations : intrinsic scatter on p_0 only



We recover the intrinsic scatter for p_0