Towards the first mean pressure profile estimate with the NIKA2 Sunyaev-Zeldovich Large Program

Corentin Hanser, Laurence Perotto

On behalf of the NIKA2 collaboration

mmUniverse 2023 conference

Outlines

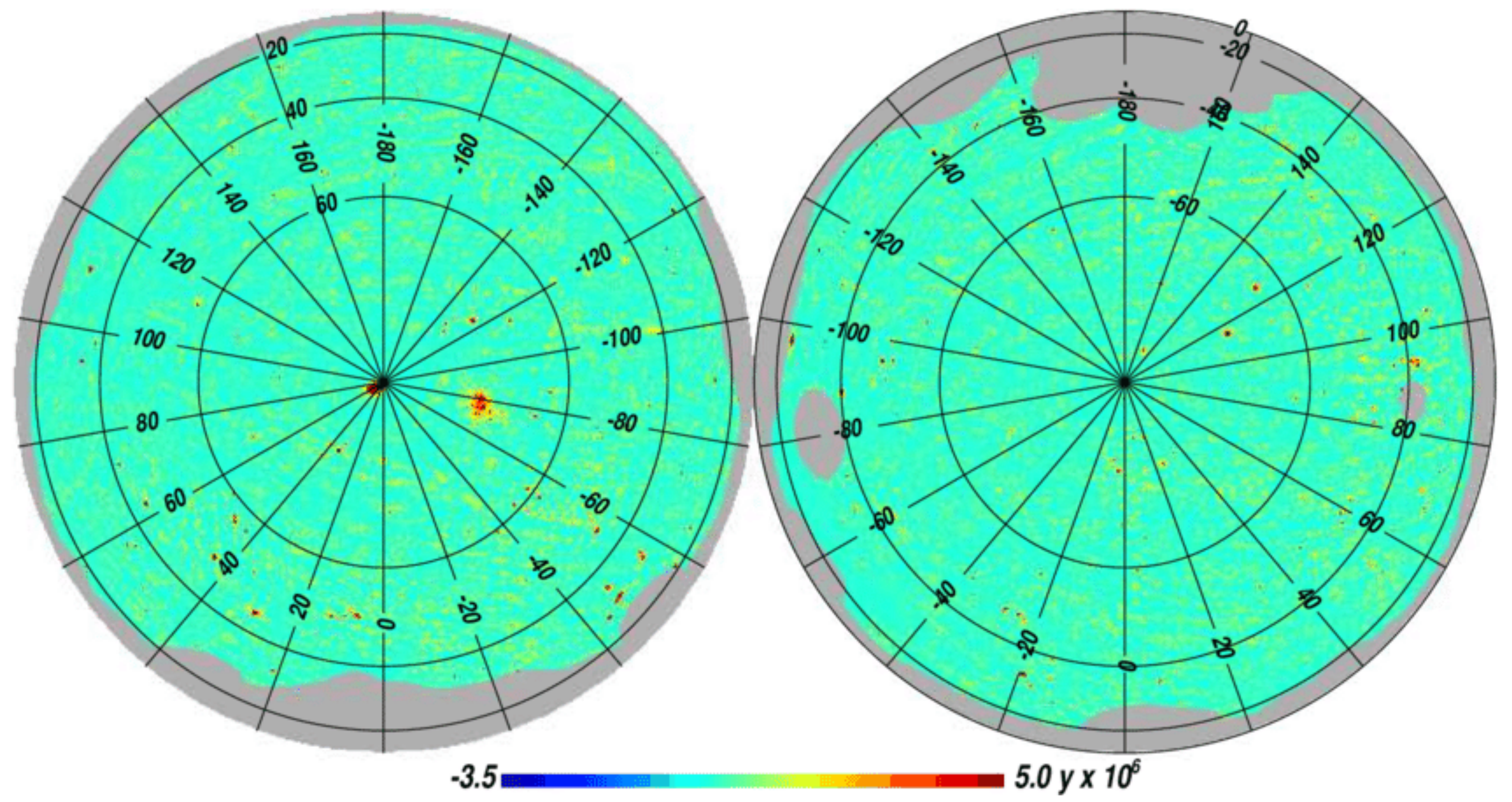
Cosmology with the SZ effect

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

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

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-Zel'dovich Large Program (LP-SZ)

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]

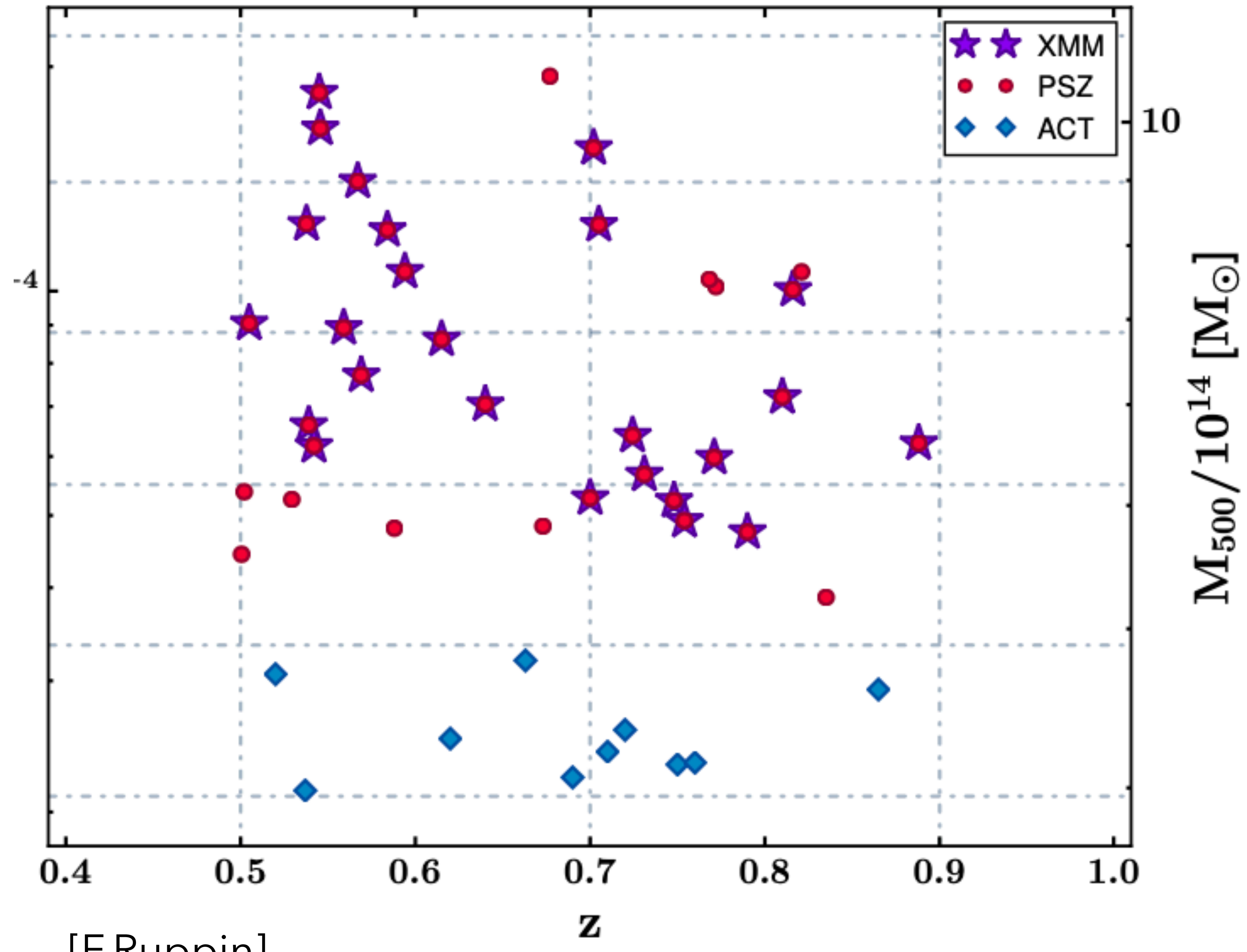
High angular resolution follow-up of 38 Planck and ACT galaxy clusters

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

→ Synergy between NIKA2 and XMM-Newton

→ Precise estimation of hydrostatic masses

(See L. Perotto's presentation)



[F.Ruppin]

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

Data quality

Objective 1 : Blind identification of problematics in individual observations

We suggest a list of criteria to define data quality

→ Study the Time Ordered Data after decorrelation (removing the correlated noise due to the atmosphere and instrumental effects)

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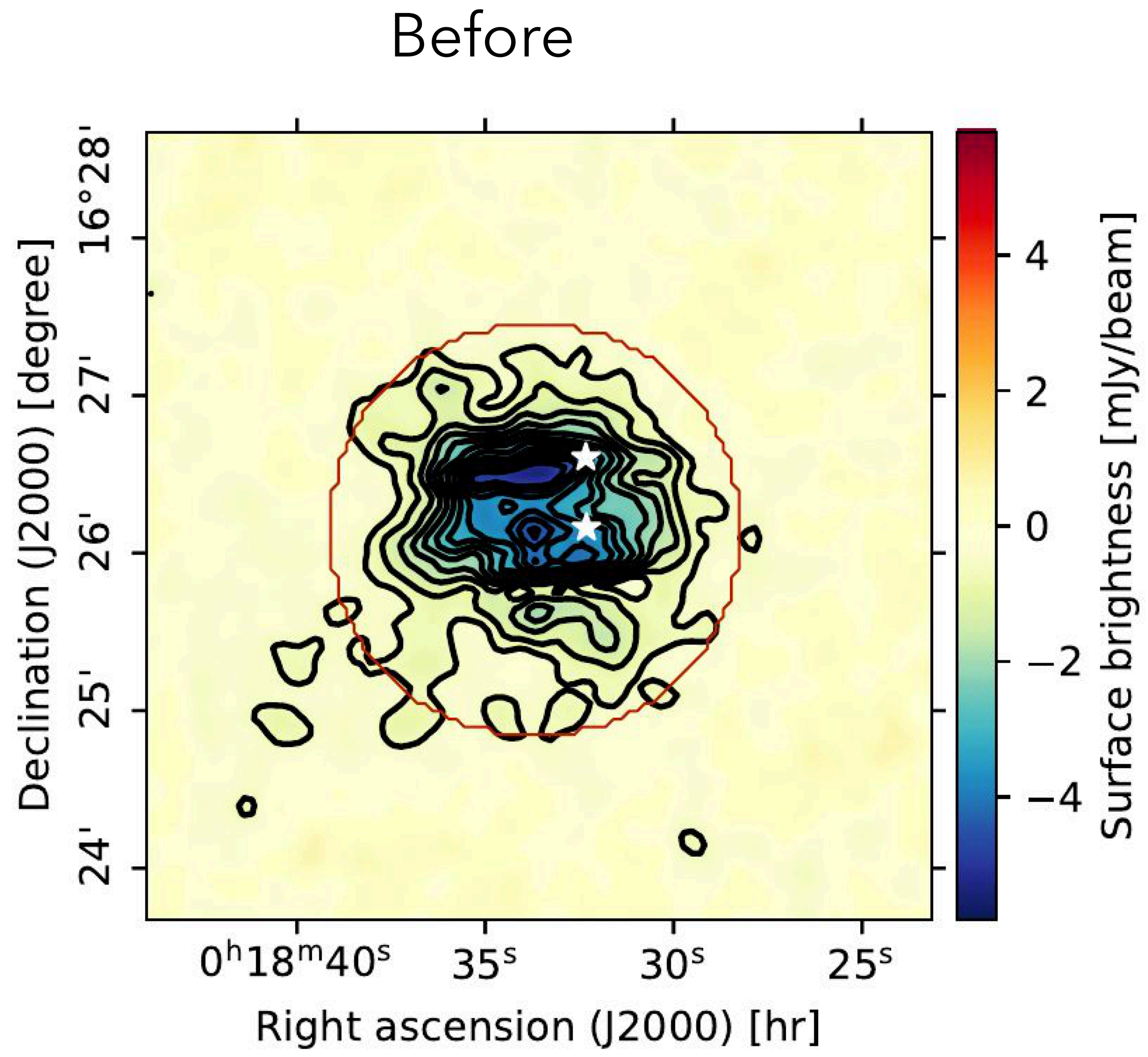

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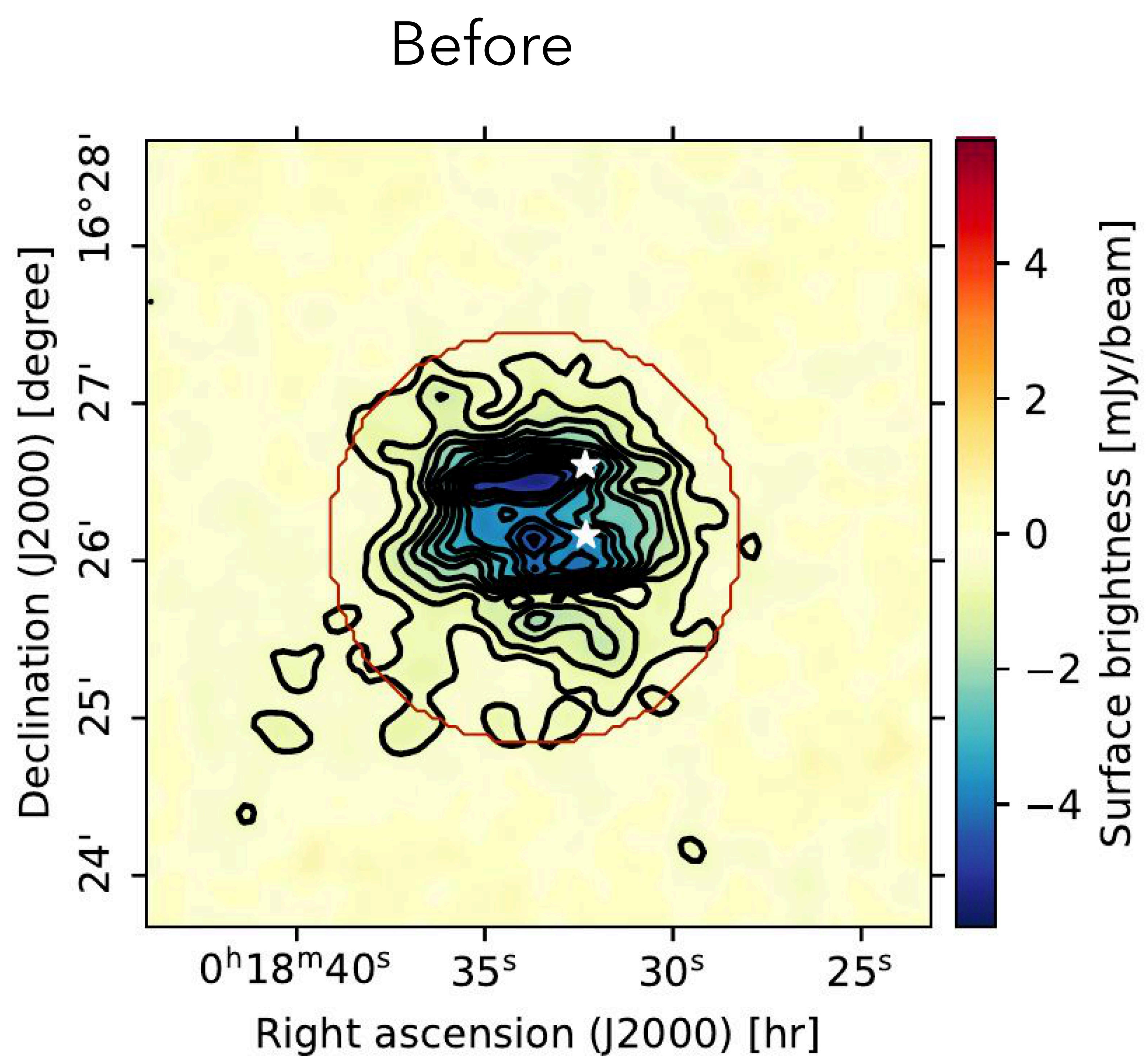
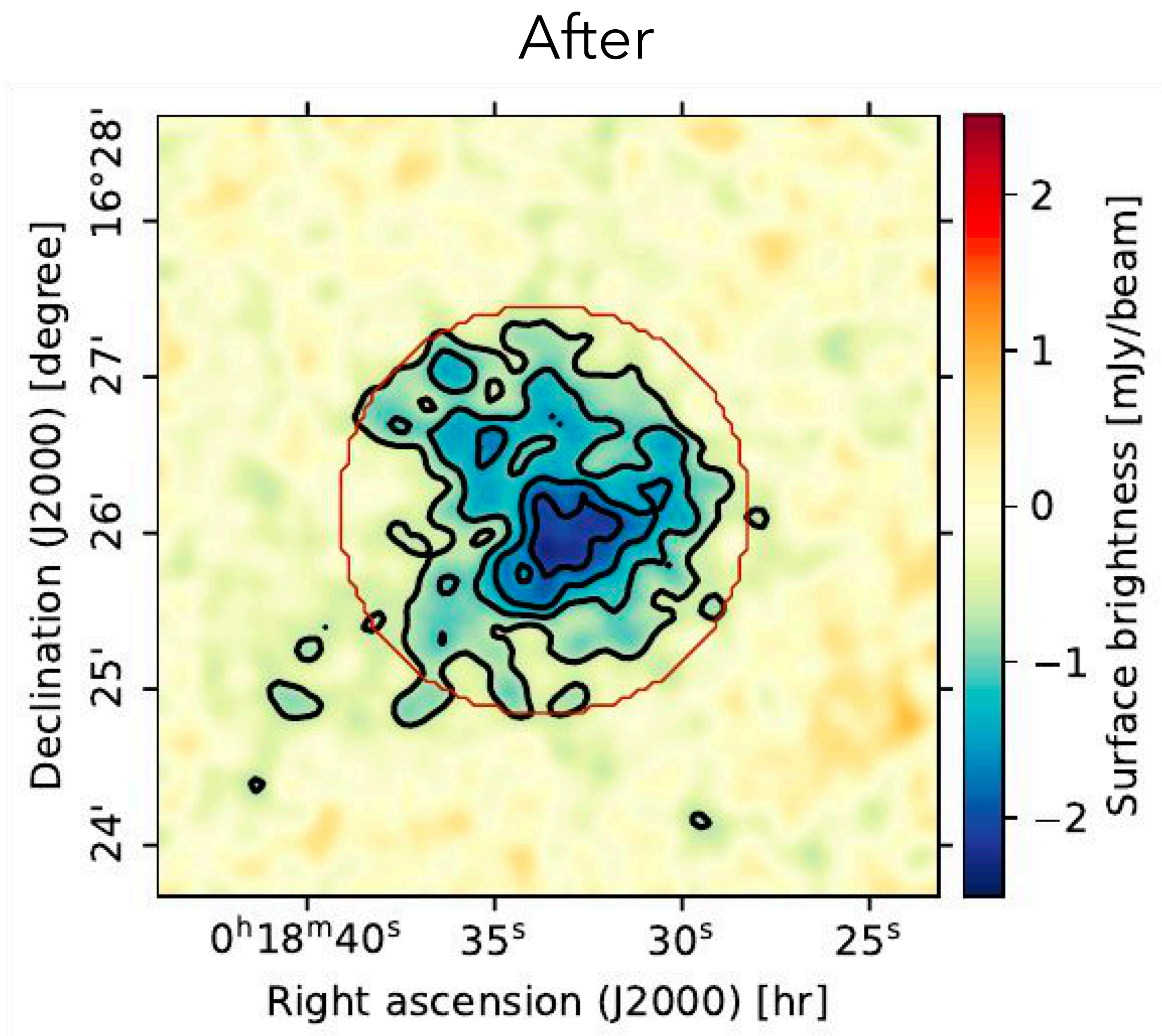


150 GHz maps →



Remaining issues are efficiently detected → allows to optimize the standard pipeline

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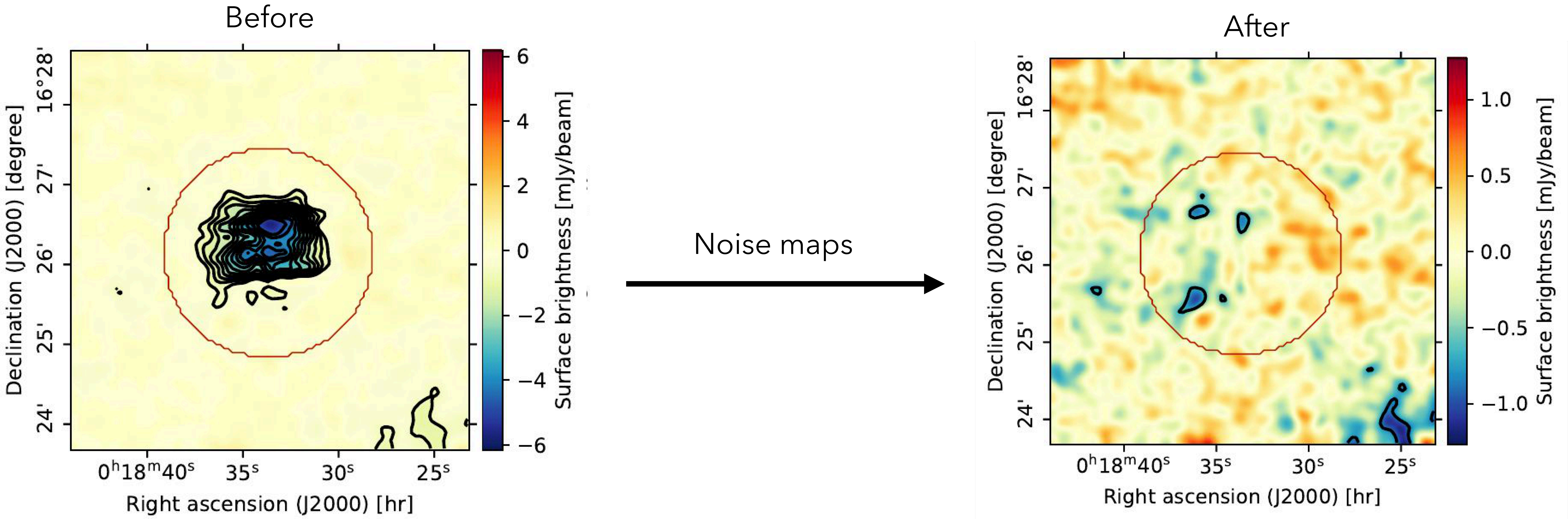

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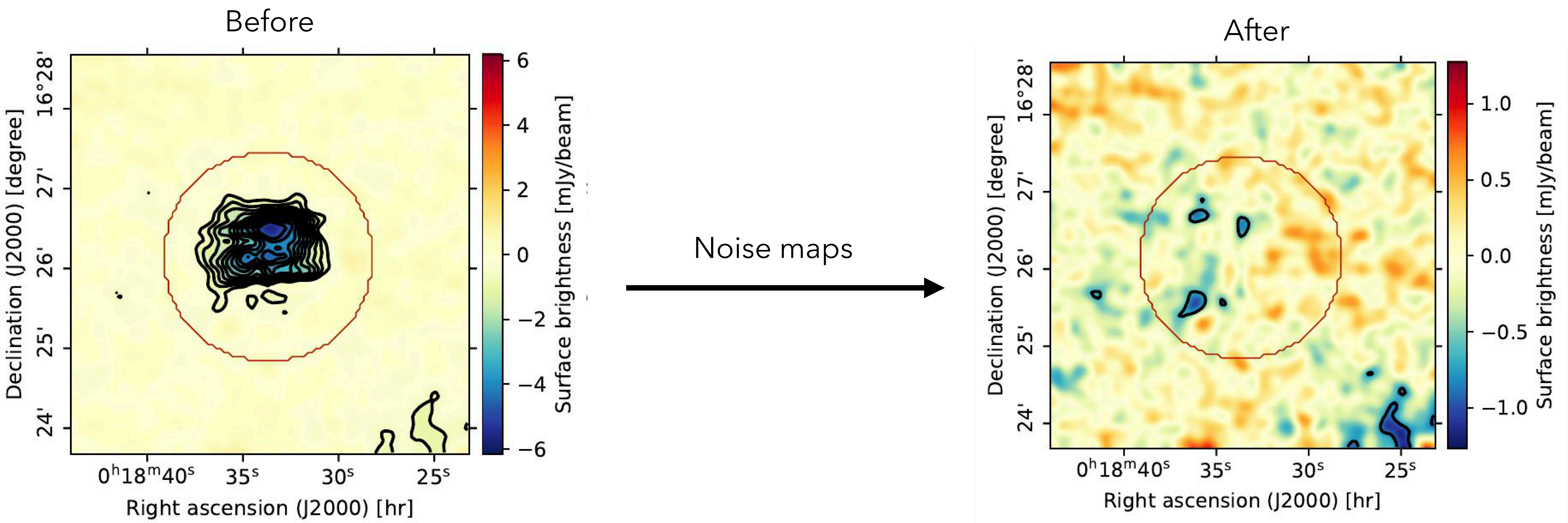

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Objective 2 : Robustness checks against systematic effects

→ perform null-tests as a function of the data quality score

NIKA2 150 GHz maps

Status of the LP-SZ
(see L. Perotto's presentation)

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

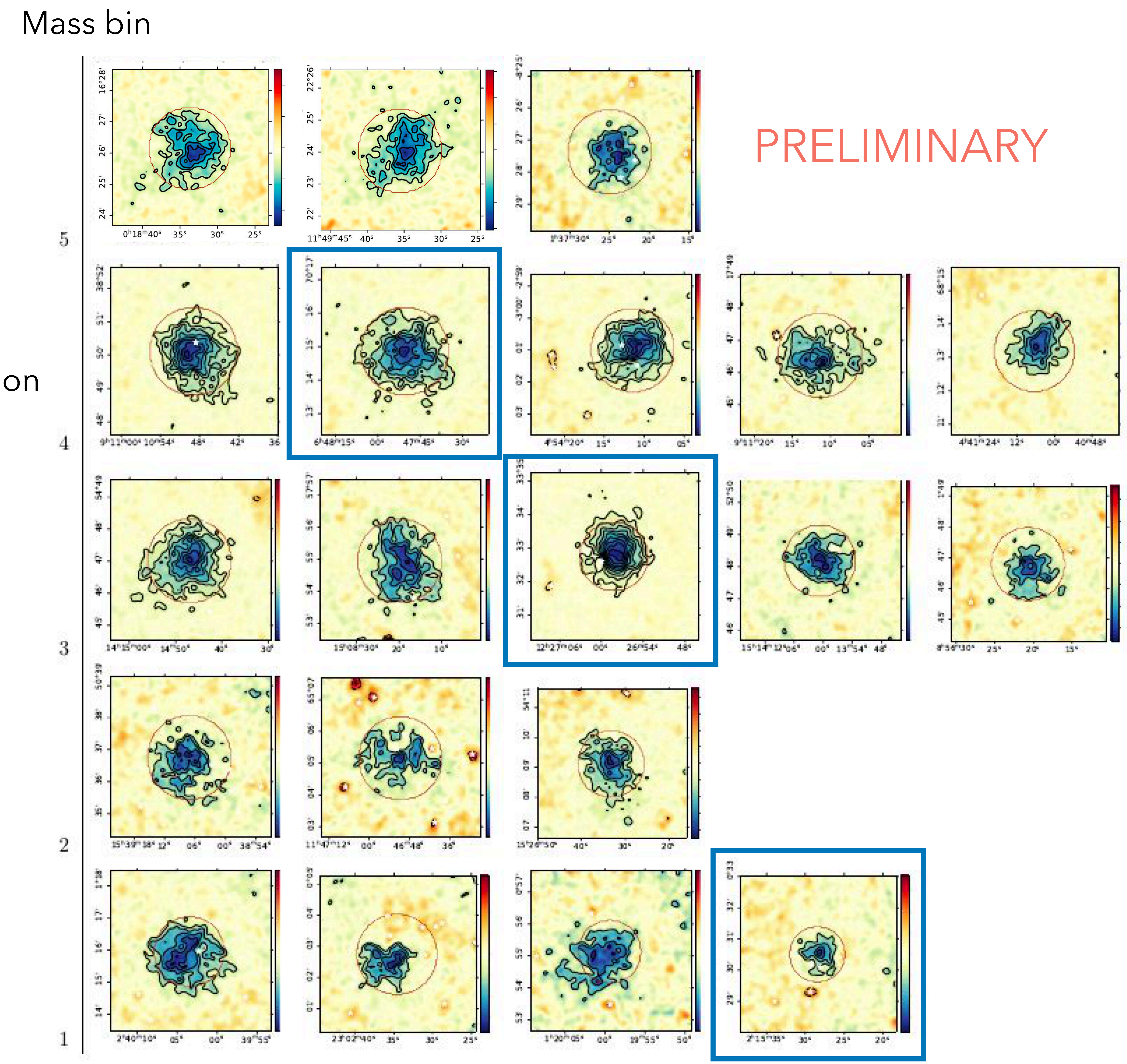
Study the systematics affecting the pressure and mass profiles reconstruction

Analysis already performed and published

Ruppin et al. 2018
Keruzore et al. 2020
Muñoz-Echeverría et al. 2023

High signal to noise measurements

→ Diversity of morphologies
→ Point sources contamination



Individual pressure profile estimate

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

LPSZ version of the PANCO2 public software (see F. Kéruzoré's presentation)

SZ signal

Spherical symmetry : 3D pressure profile

gNFW model :
Nagai et al. 2007

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

–> 5 parameters : P_0, 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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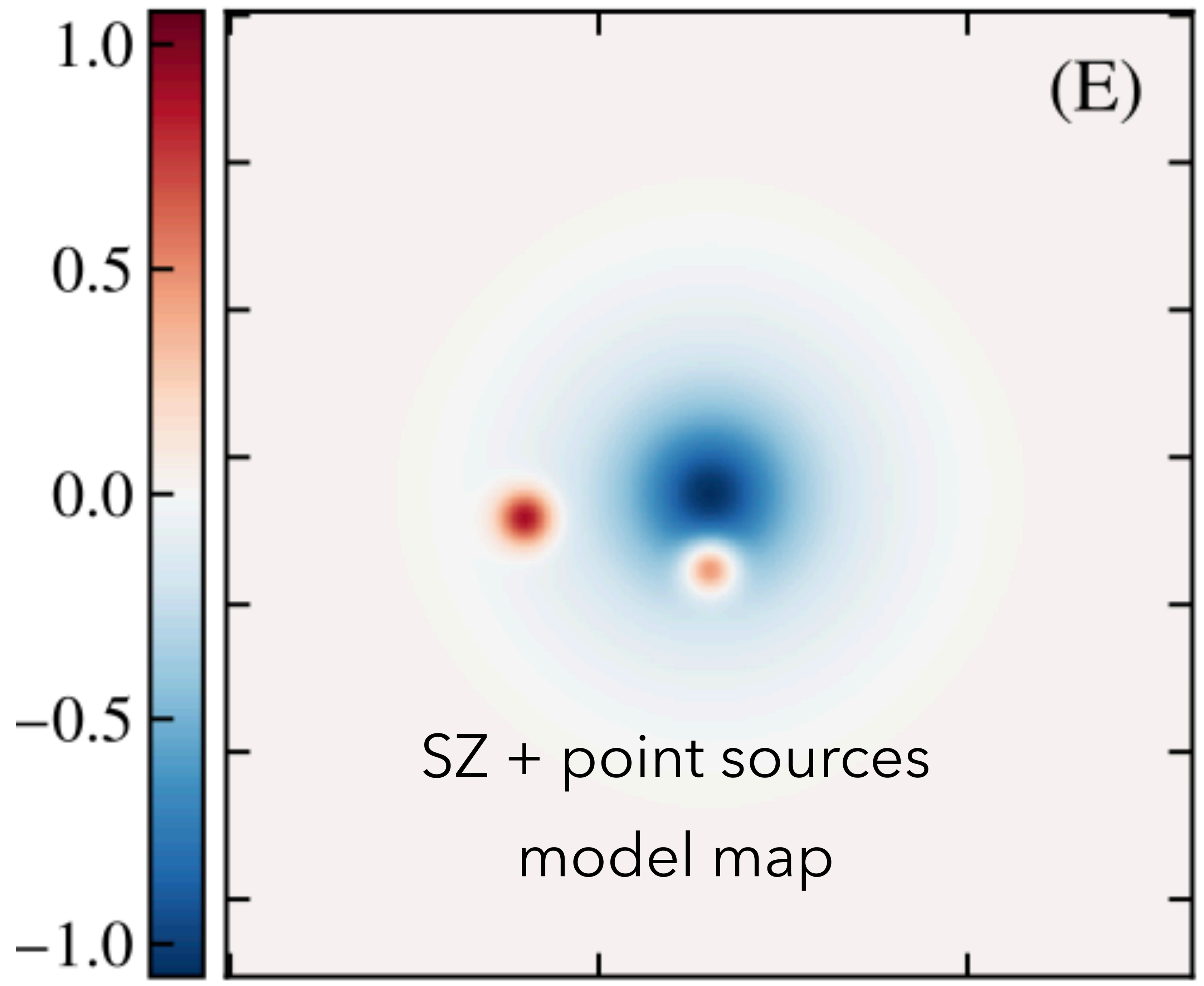
Forward modelling

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

Convolved by the NIKA2 instrumental response



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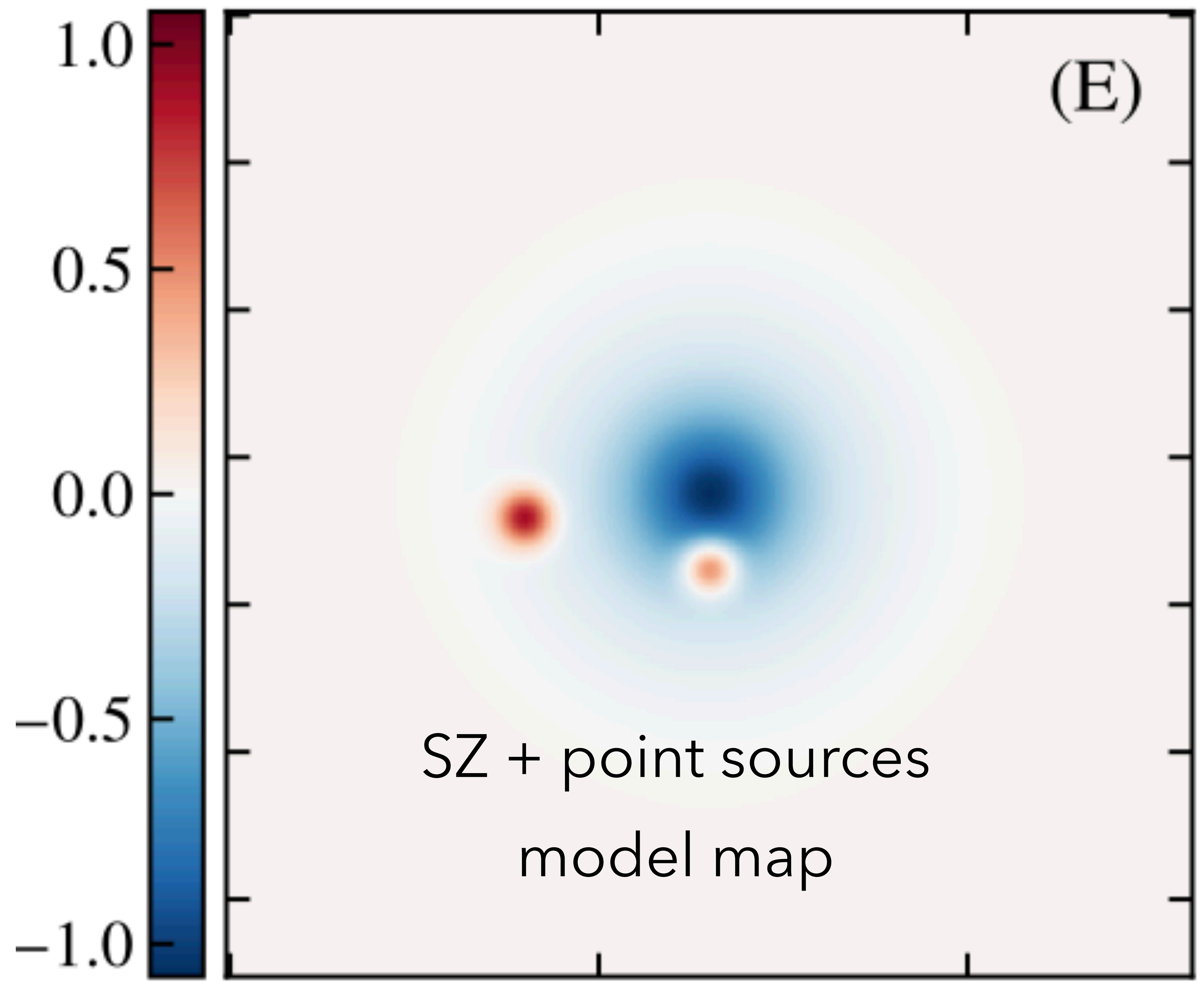
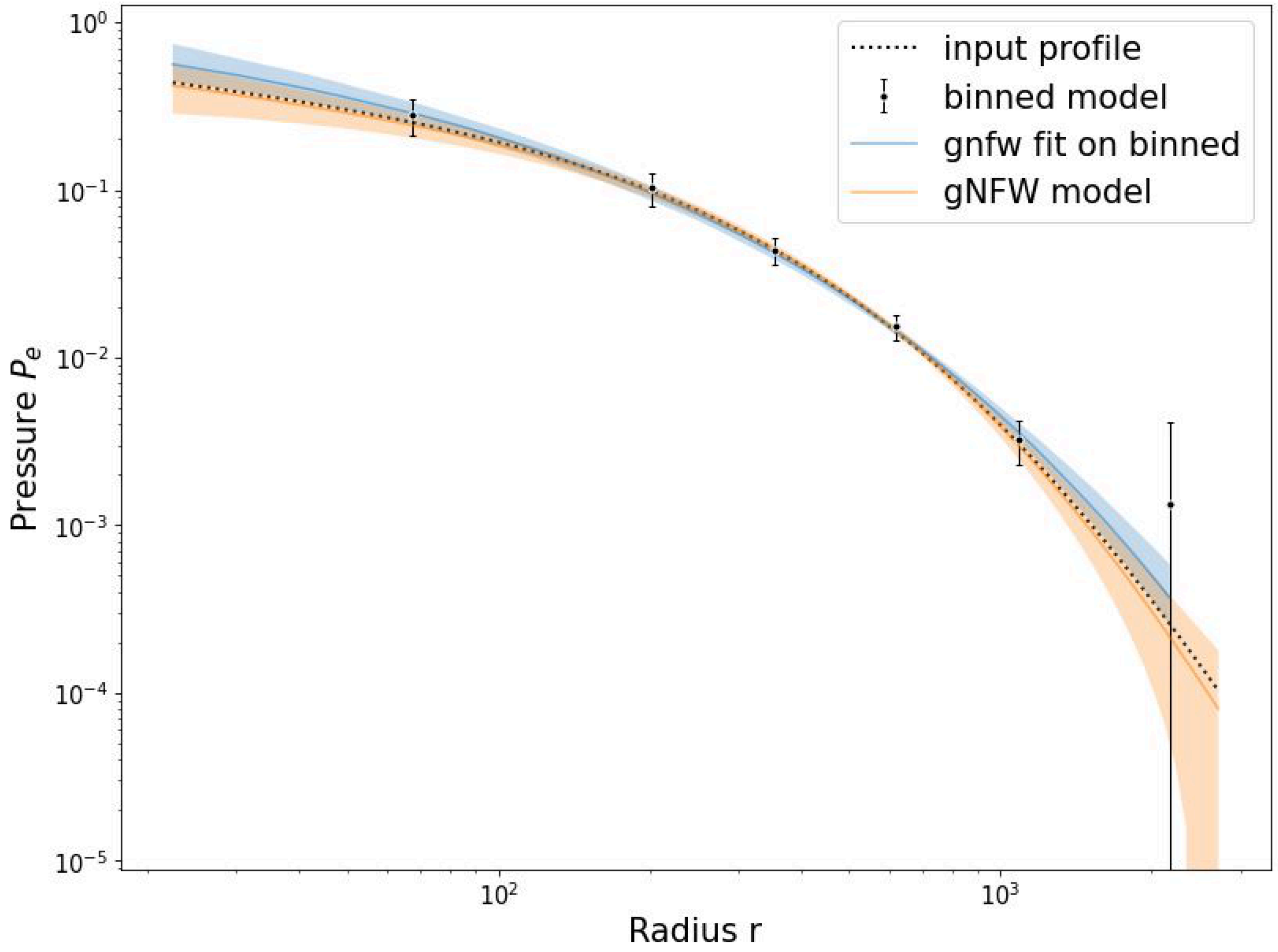


Likelihood : $$-2log\mathscr{L}(\theta) = \sum_{pixels} (D - D_{th}(\theta))^T C^{-1} (D - D_{th}(\theta)) + \left(\frac{Y_{500}^{meas.} - Y_{500}^{Model}}{\Delta Y_{500}^{meas.}}\right)^2$$

Thermodynamical properties

Results obtained on a simulation (see A. Moyer's presentation)

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



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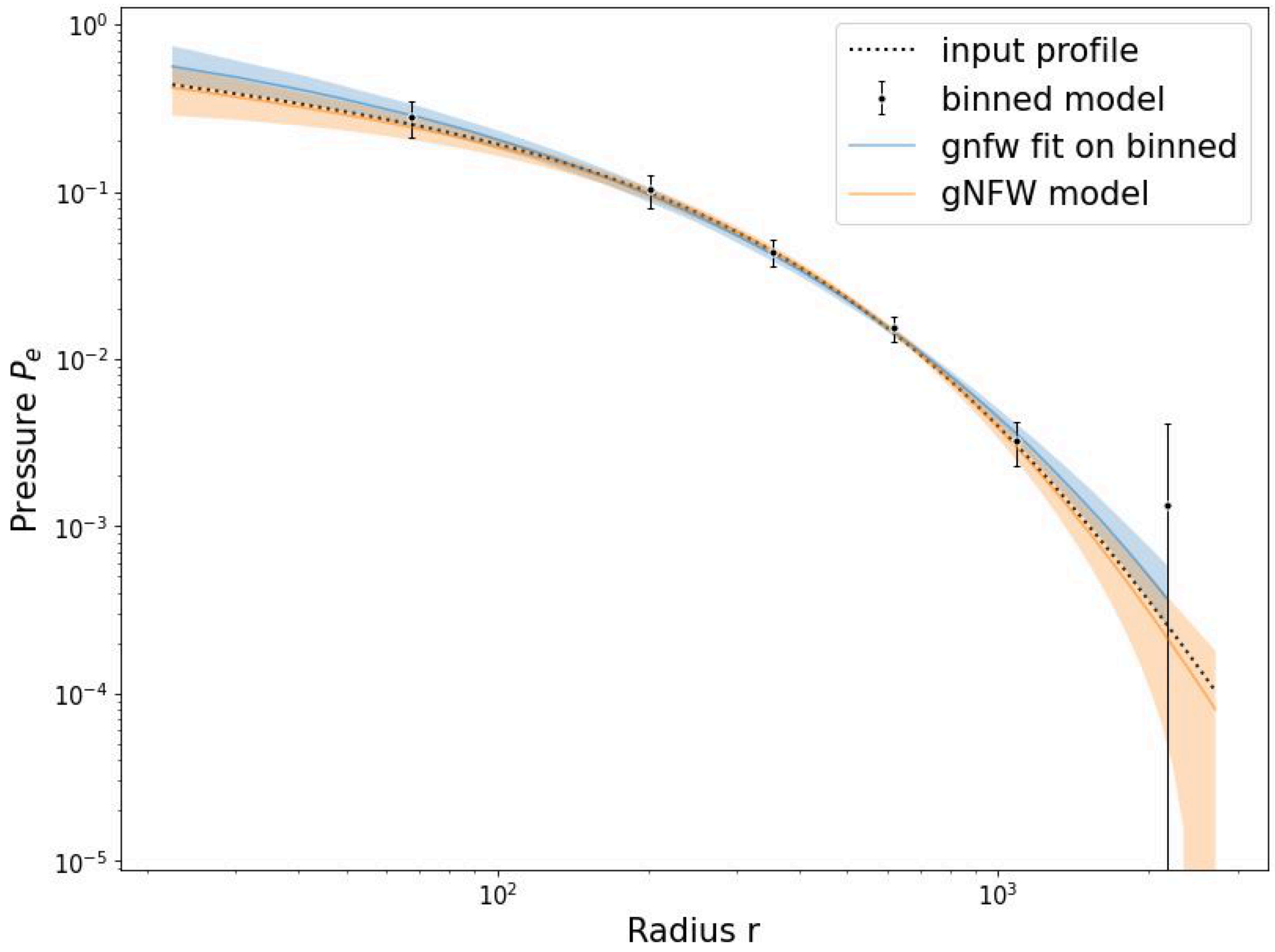

Compute the mass profile using SZ+X-ray data

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

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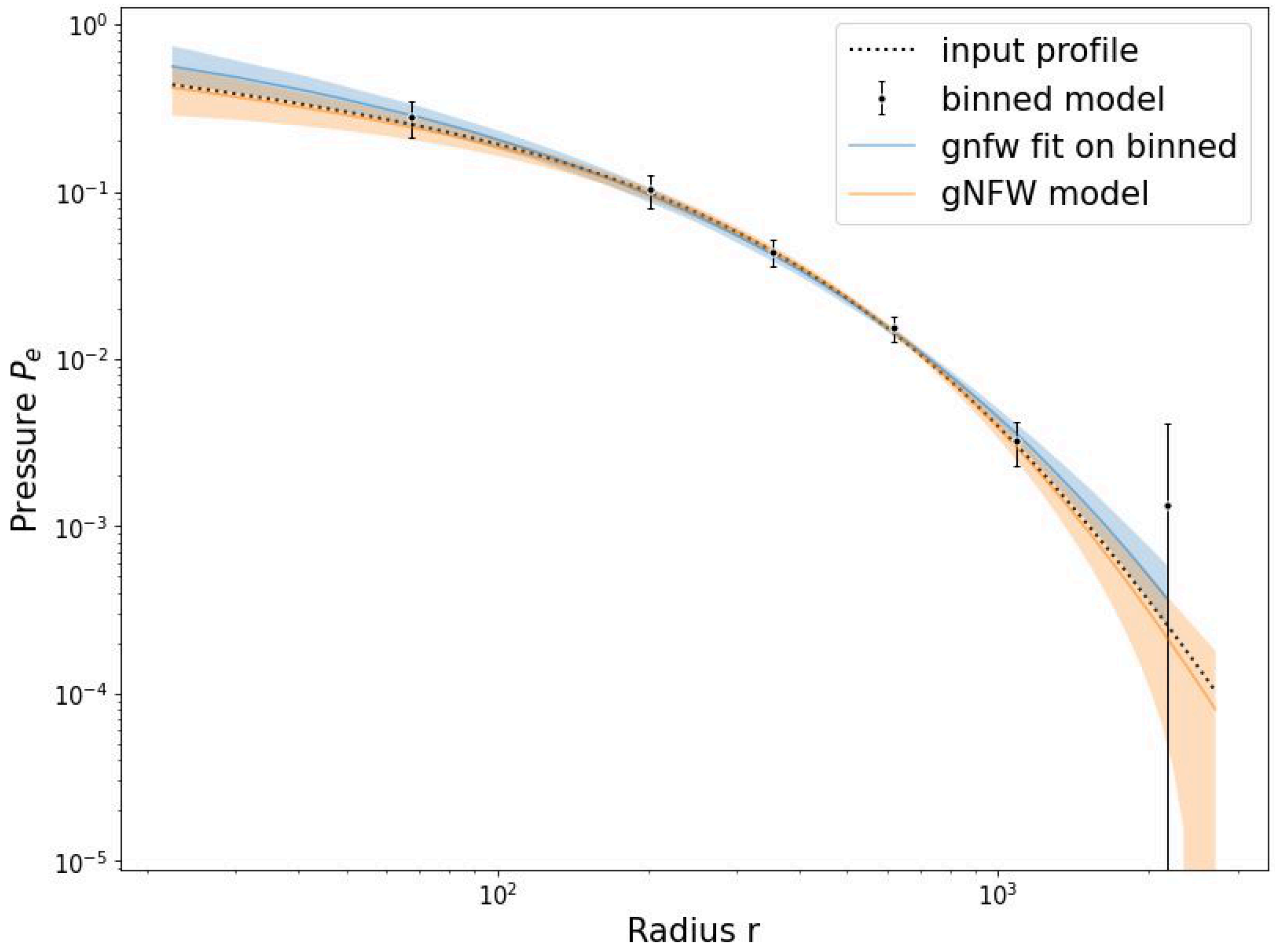

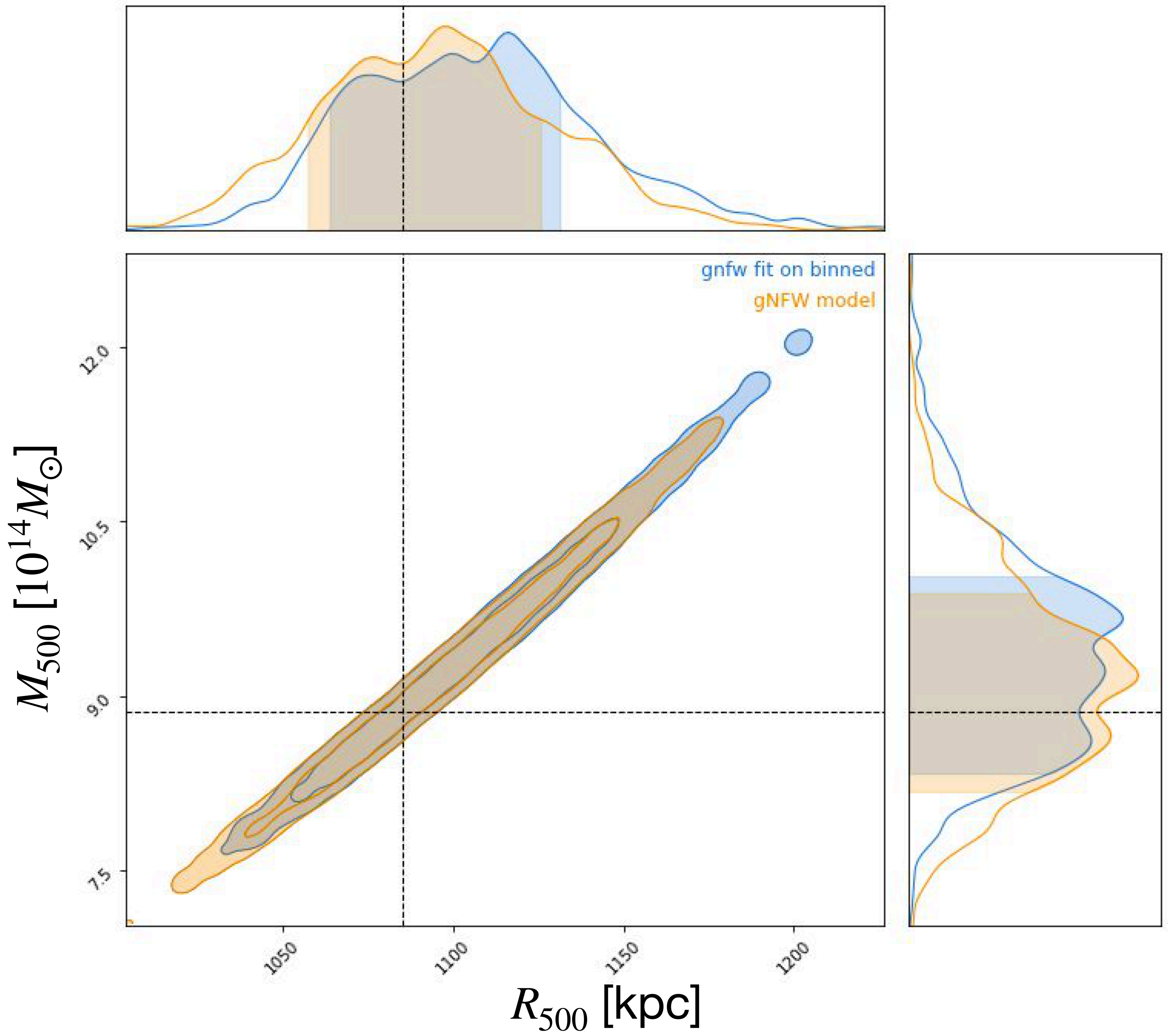

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→

Get the integrated quantities

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

Both methods recover the input profile within 1σ

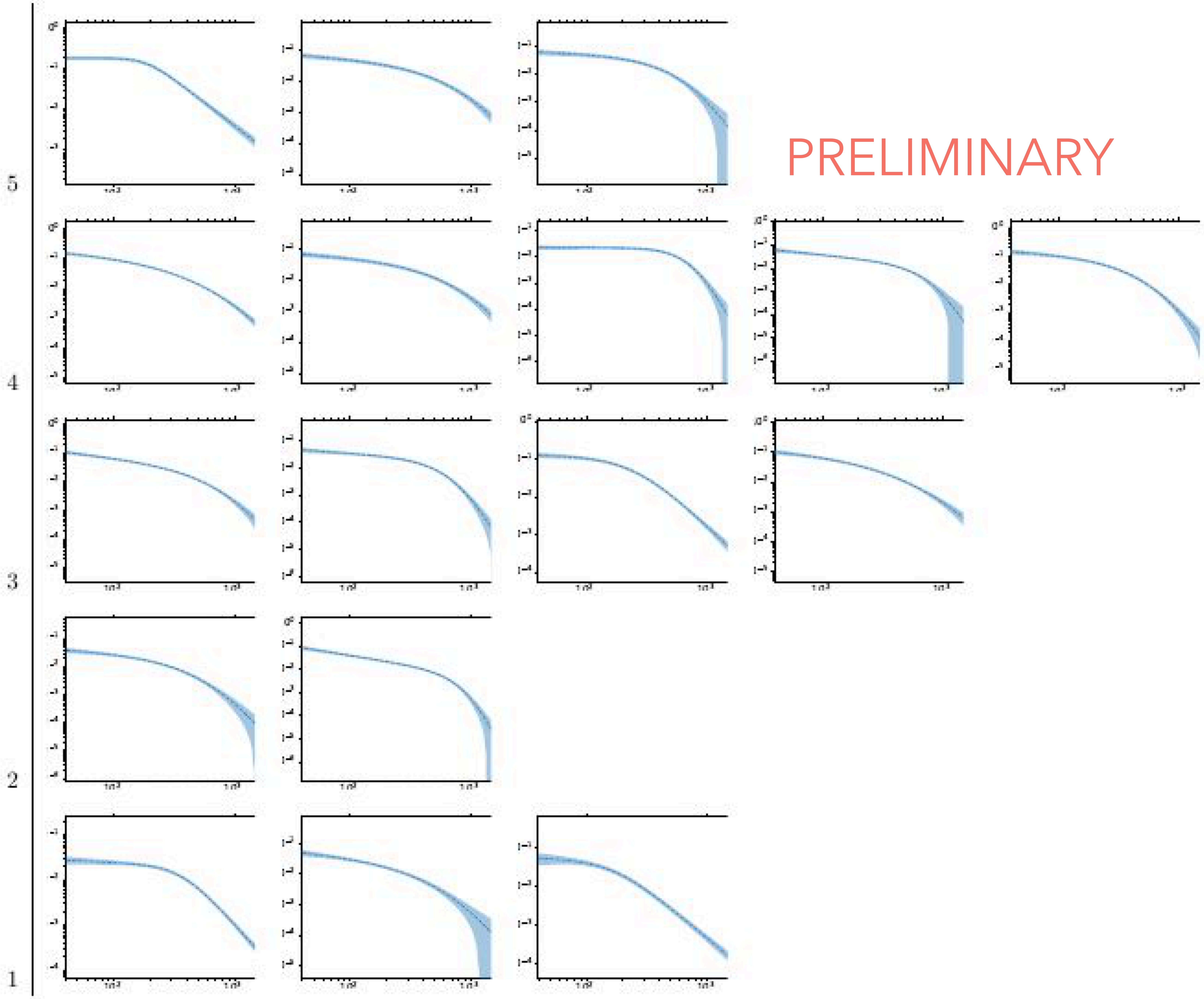
Use the 2 methods on data for robustness check against model dependency

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, ...)

- gNFW fit on data



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

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 $\rightarrow$ rescaled pressure profile p

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

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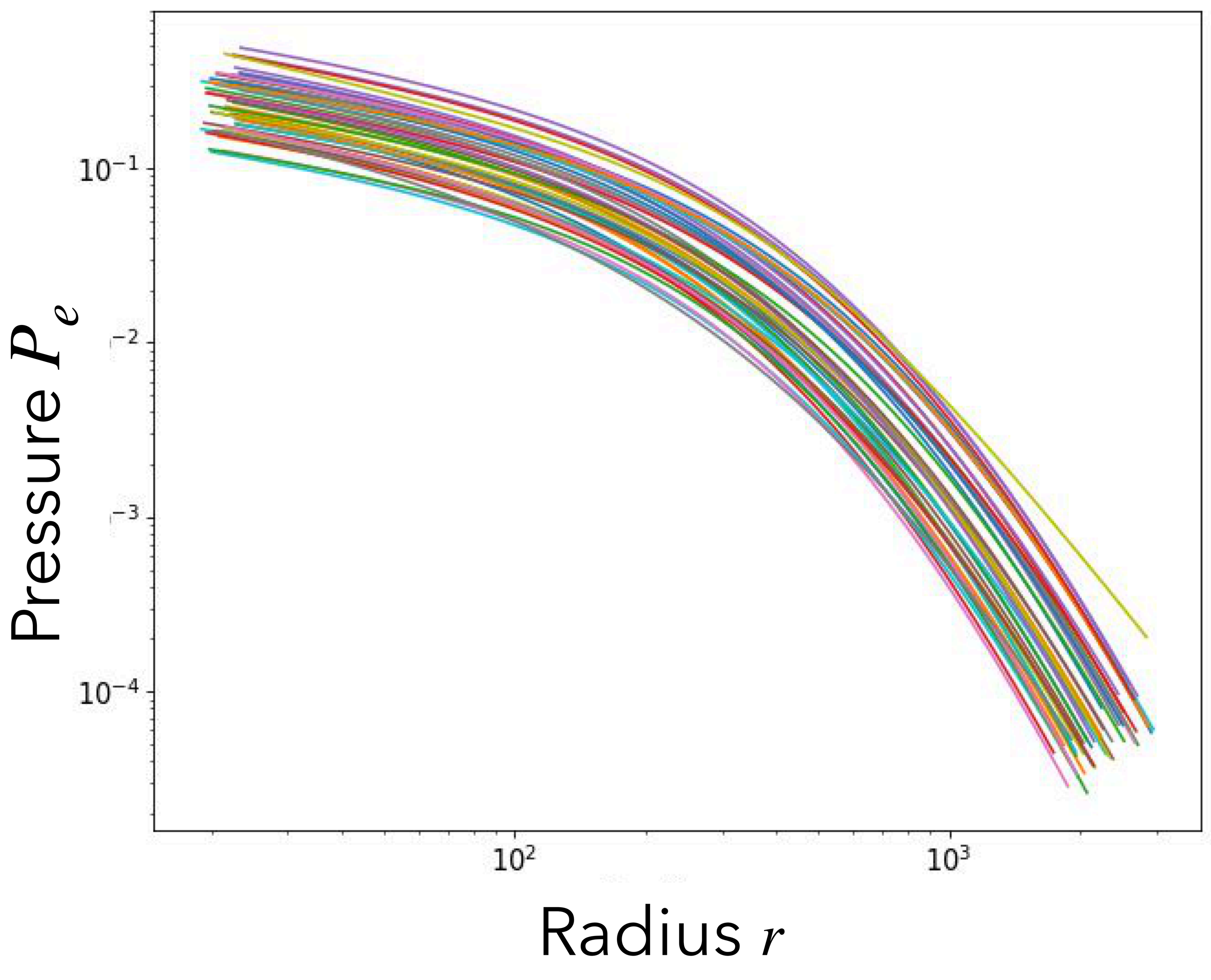

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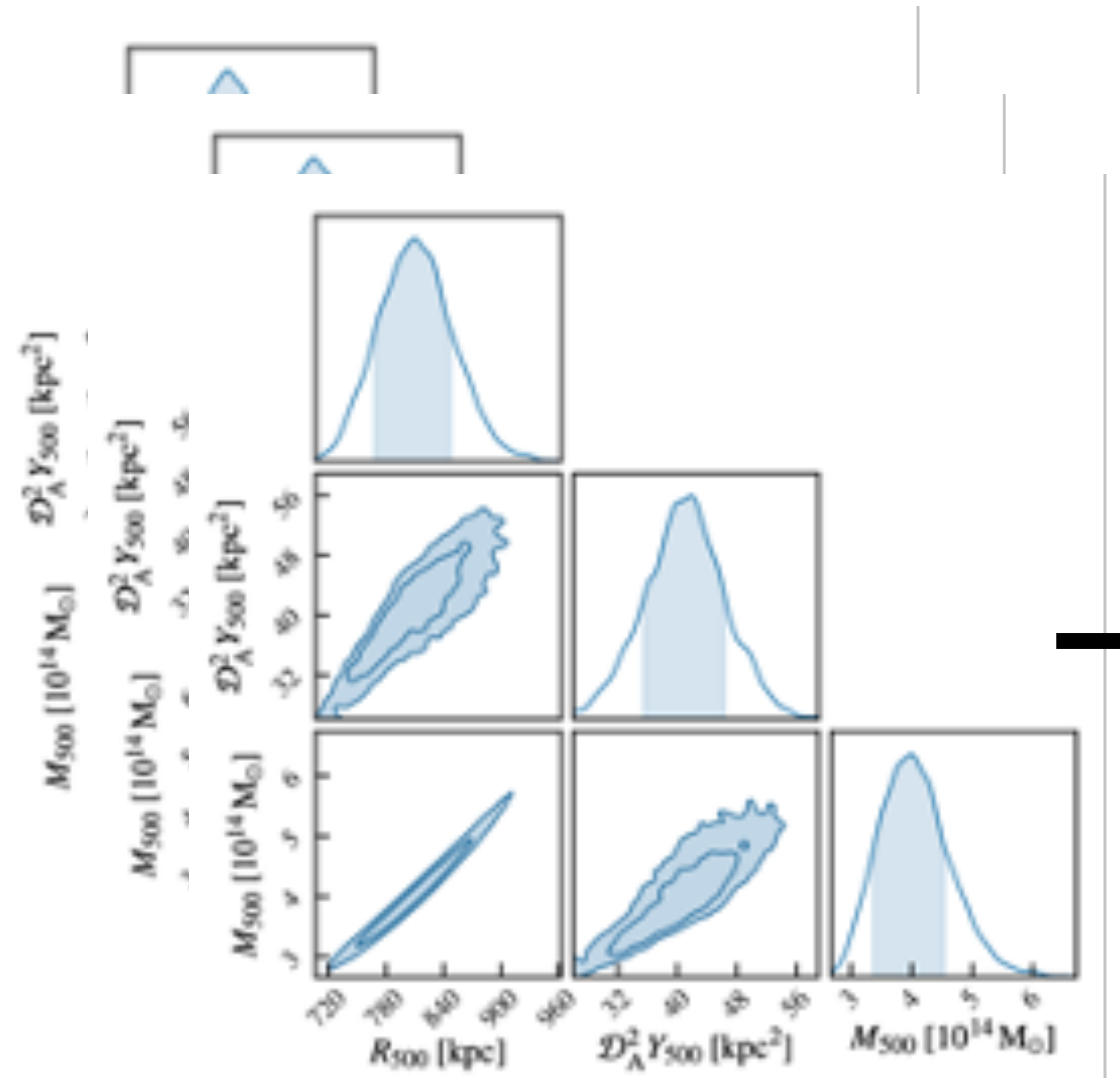

Integrated quantities

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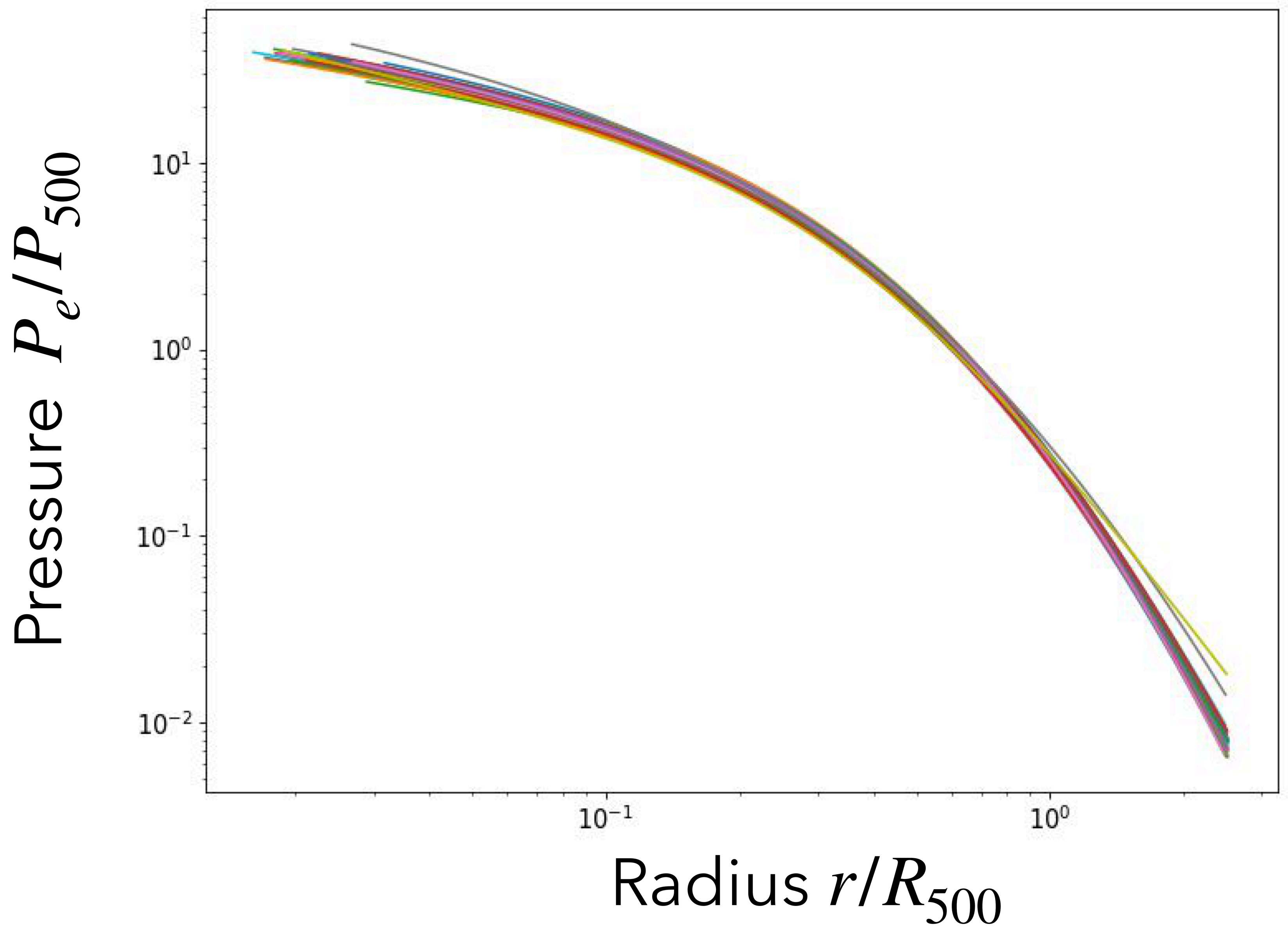

Compute the mean pressure profile using the re-scaled individual profiles

Mean pressure profile estimates

gNFW model

- 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

$$\ln \mathscr{L} = \sum_i \ln P(\theta \,|\, d_i) \qquad \text{with } \theta = \{p_0, c_{500}, \alpha, \beta, \gamma\} = \{P_0/P_{500}, R_{500}/r_p, \alpha, \beta, \gamma\}$$

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Account for the error 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 $P(\theta \,|\, d_i)$

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→ We get $P(\theta | d_i)$

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

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 approximate $P(\theta \,|\, d_i)$ for any arbitrary θ

gNFW model : 2nd approach

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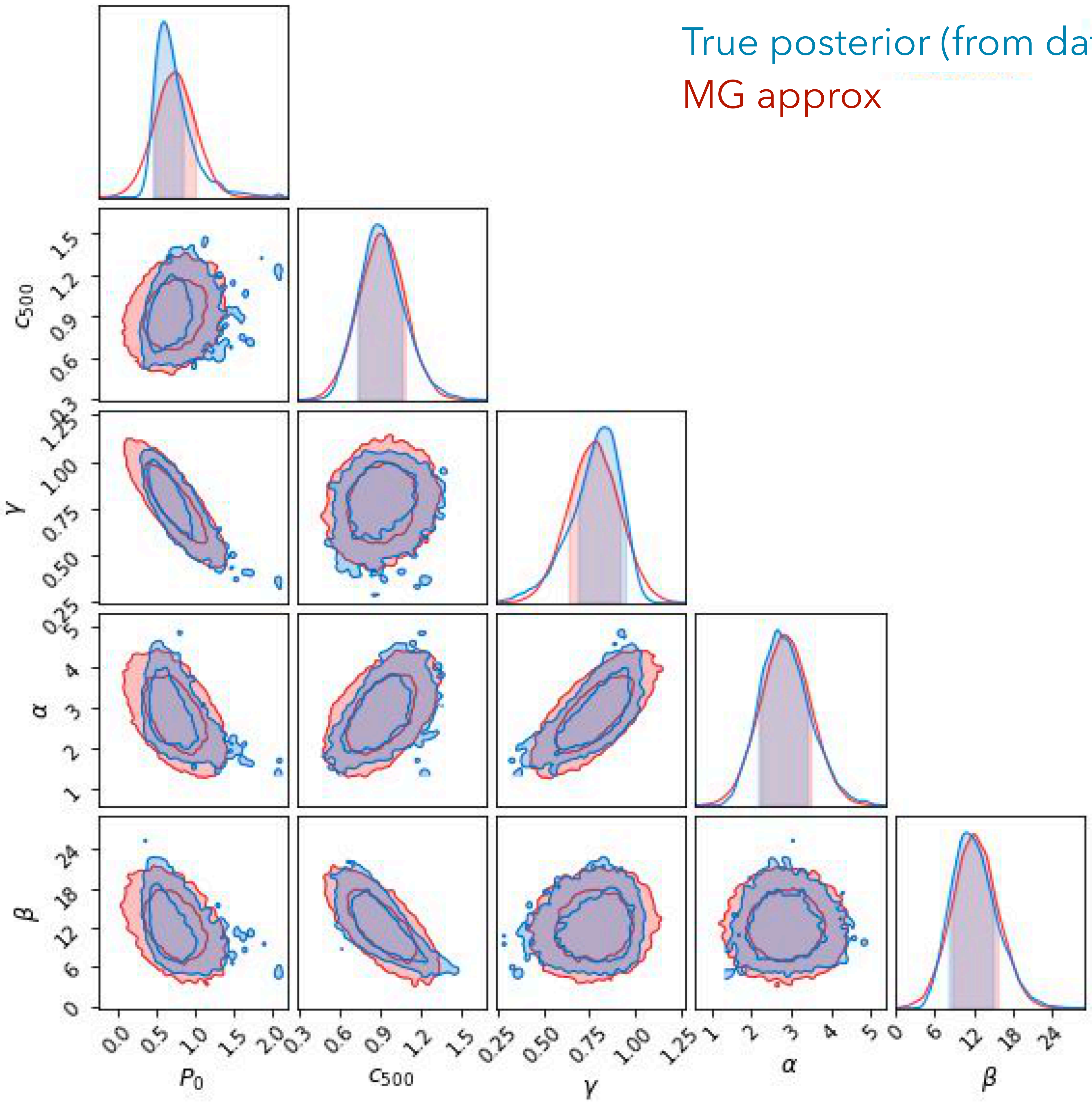


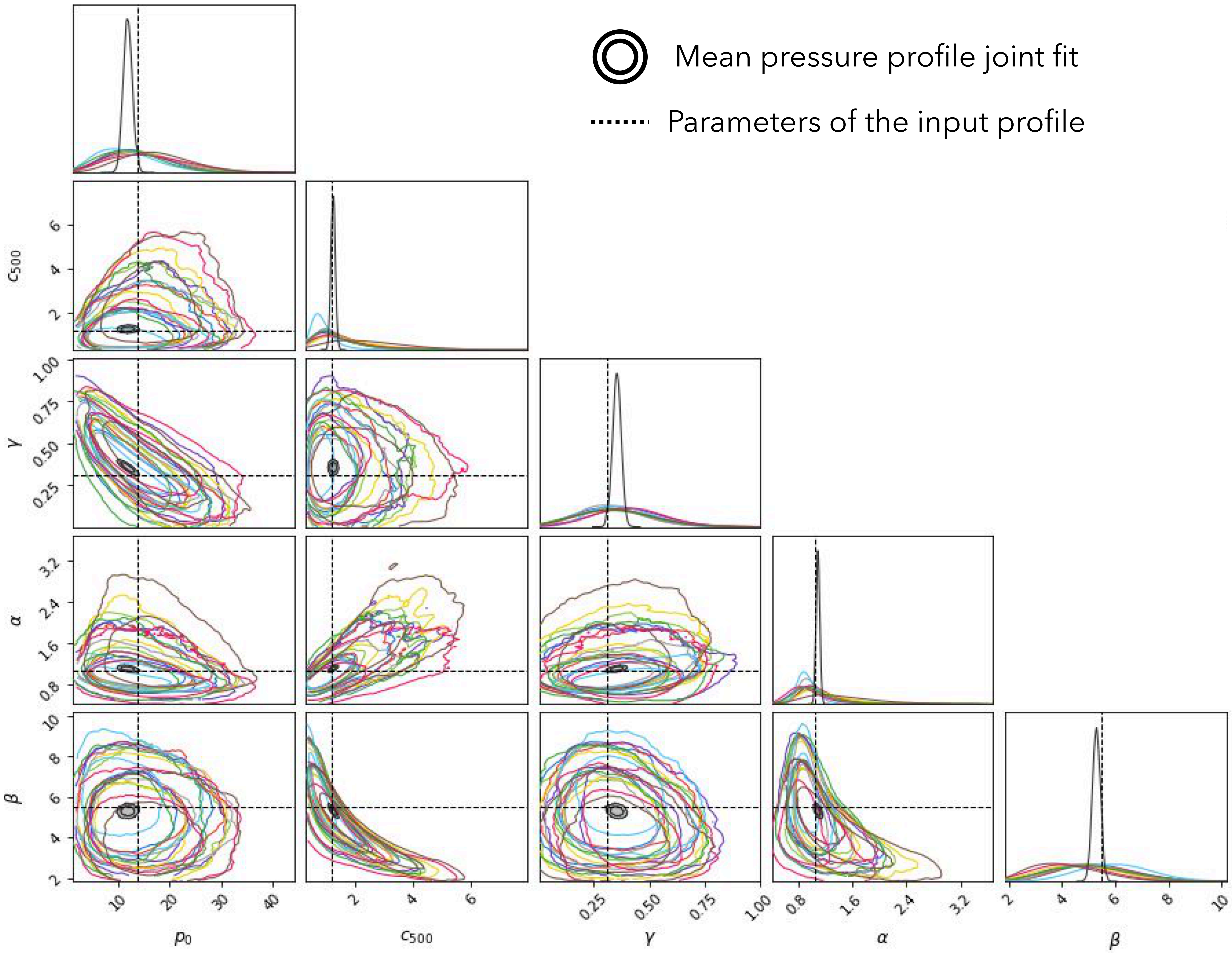
True posterior (from data)
MG approx

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

Good approximation of the posterior for all clusters

Results on simulations

Corner plot with all clusters' posteriors and the joint fit

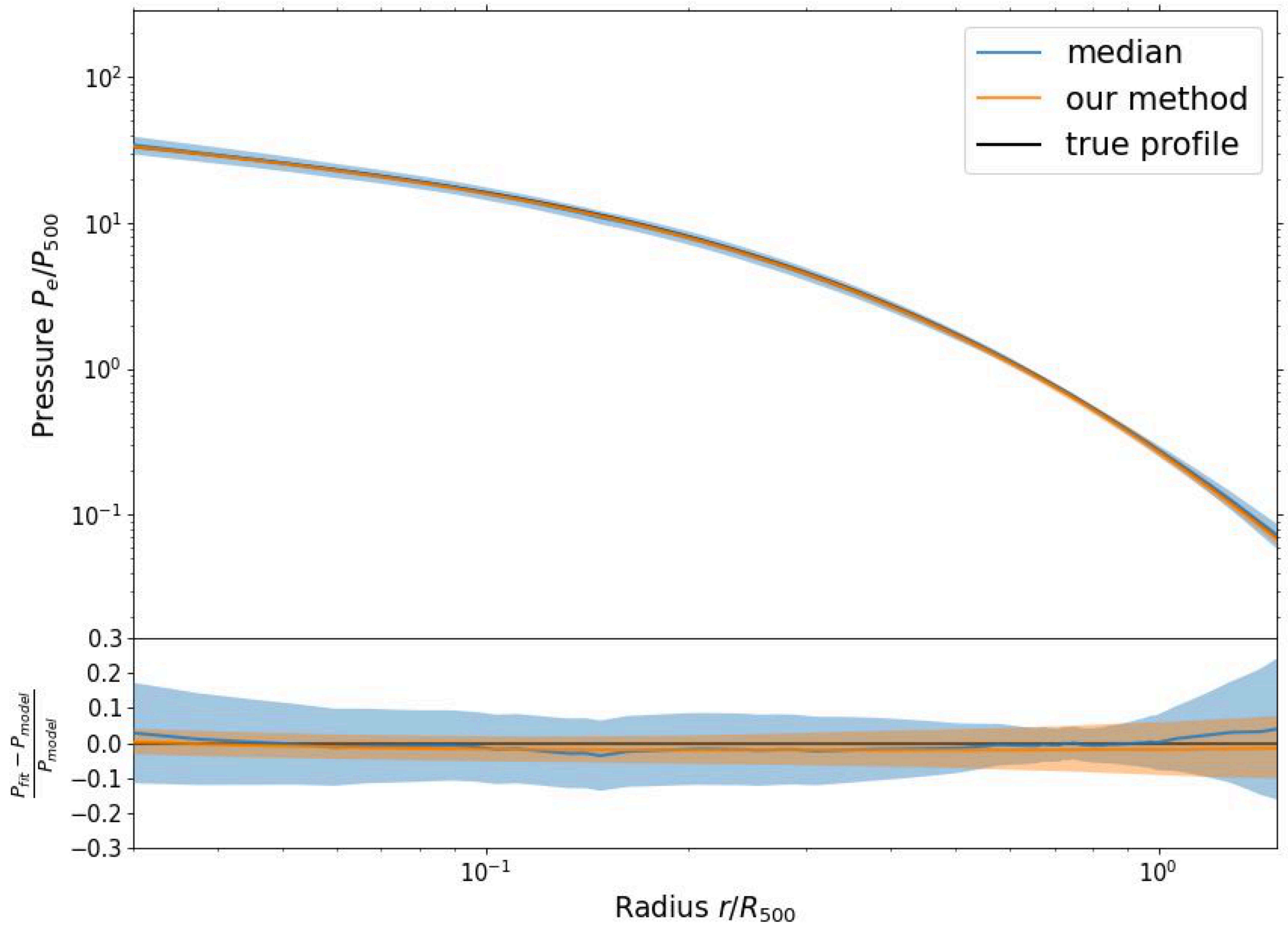


The input mean pressure profile parameters are recovered within 2σ

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

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

Conclusion

First standard analysis on a NIKA2 LP-SZ sub-sample

Study the systematics affecting the pressure and mass profiles reconstruction

- Characterisation of the data quality : sanity checks
- Robustness tests using various models of the pressure profile

Mean pressure profile estimate

We explore various methods to estimate the mean pressure profile
→ New method that use all individual information and propagate errors from integrated quantities
→ Validation using LPSZ realistic simulations

We have a first complete LPSZ standard pipeline from the raw NIKA2 data to the mean pressure profile that will be used on data

Forthcoming results

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

→ Study the implications on tSZ power spectrum cosmology (using CLASS_SZ, *B. Bolliet et al. 2018*)

Back-ups

Chosen criteria

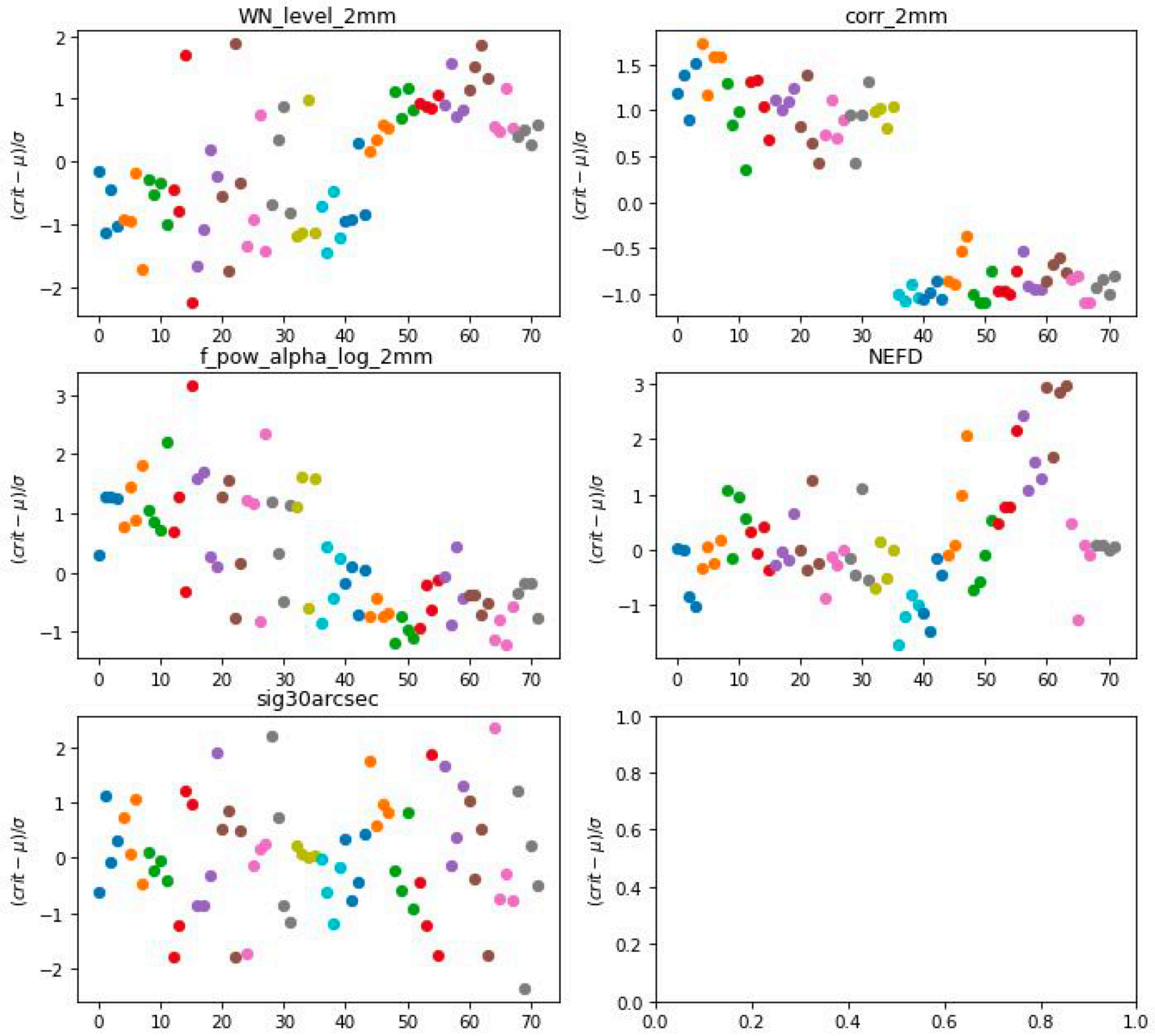
Kid to kid correlation matrix : mean of the residual correlation

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 map

NEFD : Noise equivalent flux density



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

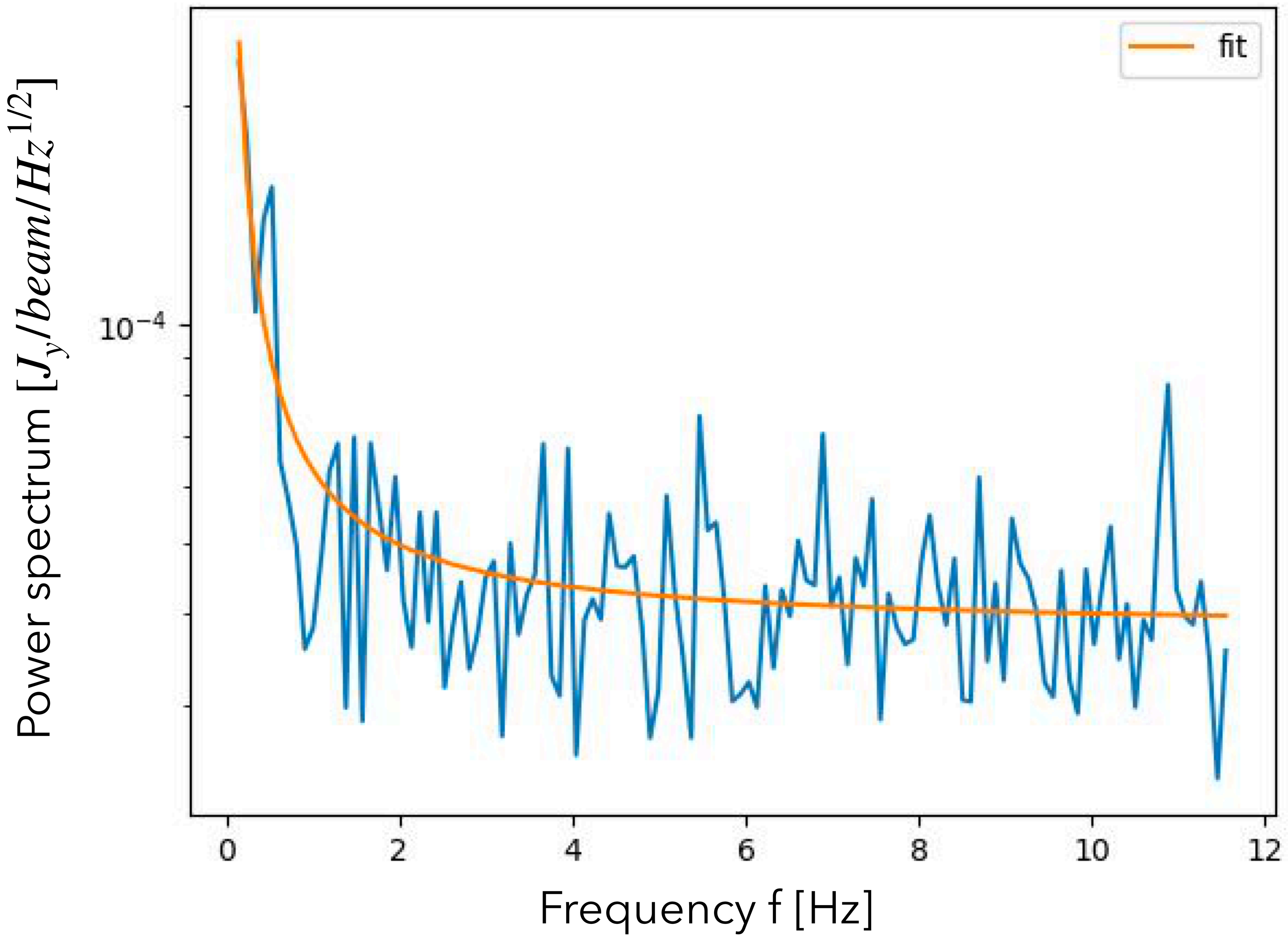
Fit : iMinuit library

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

–> 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

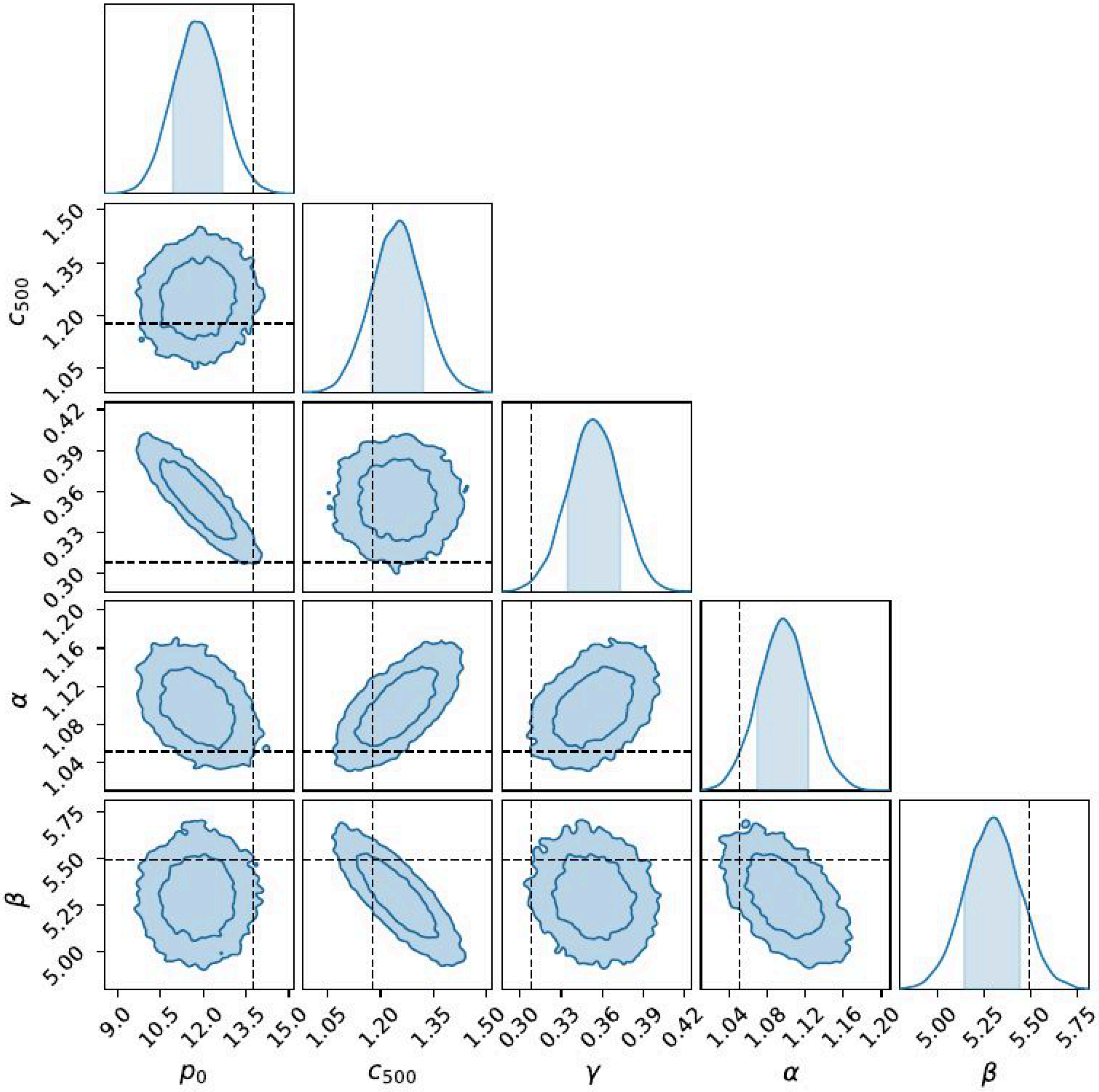


Power spectrum of one TOI from one KID (blue) and associated fit (yellow)

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

- B White noise at every scales

Corner plot mean pressure profile (simulations)



Corner plot mean pressure profile : gamma fixed