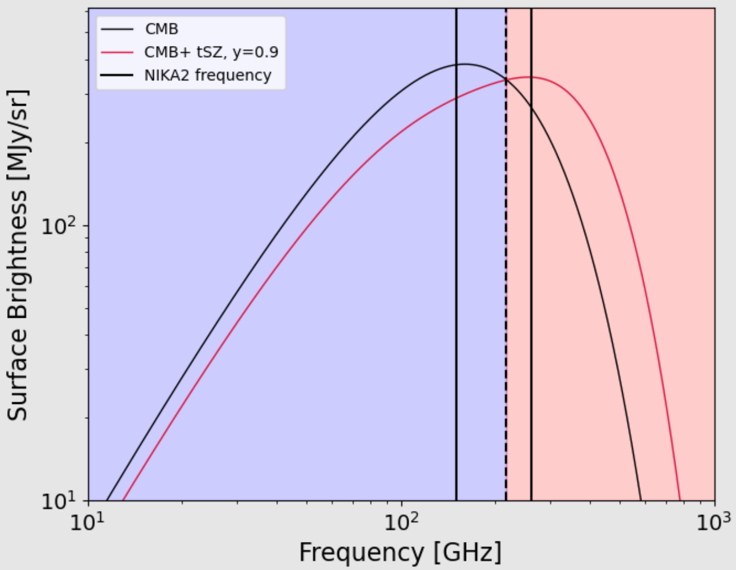
# The SZ large program of NIKA2: Scaling relation and application to cosmology

Alice Moyer-Anin
LPSC Grenoble

On behalf of the NIKA2 collaboration

1. SZ cluster cosmology
2. The SZ large Program of NIKA2
3. The SZ-Mass scaling relation
    - ➢ Calibration method
    - ➢ Application to cosmology

# The Sunyaev-Zeldovich (SZ) effect



**Inverse Compton scattering** of CMB photons on cluster ionized gas

→ Energy transfer from electrons to photons

→ **Distortion of CMB spectrum** to high frequencies

→ Effect amplitude caracterised by the Compton parameter

Intra-cluster electron pressure: $P_e(r)$

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

**Negative signal**

Less intensity than expected from CMB

**Positive Signal**

More intensity than expected from CMB

217 GHz

SZ output : Radial pressure profile $P_e(r)$

SZ Observable : $Y_{500} \propto \int y \, dS$ integrated up to $R_{500}$

$R_{500}$ : radius of a sphere of density 500 times $\rho_c$

# Cosmology with the Sunyaev Zeldovich (SZ) effect

y : compton parameter $y = \frac{\sigma_T}{m_e c^2} \int \mathbf{P_e}(\mathbf{r}) dl$

**Observable**

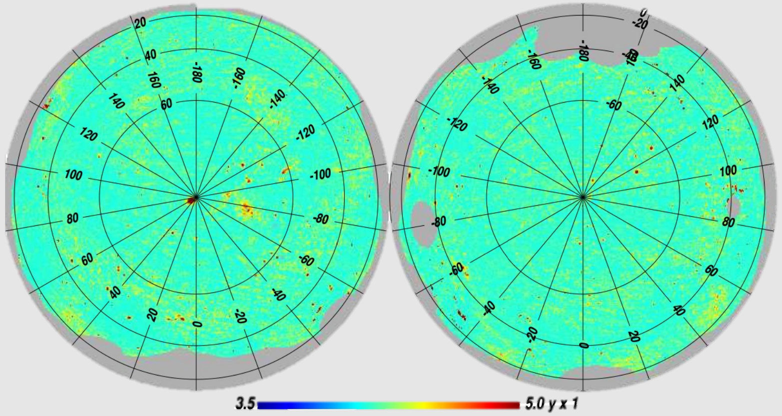
SZ Integrated quantity $Y_{SZ} \propto \int_0^{R_\Delta} y dS$

Universal pressure profile $P_{univ}(r)$

**Tools**

SZ-Mass scaling relation

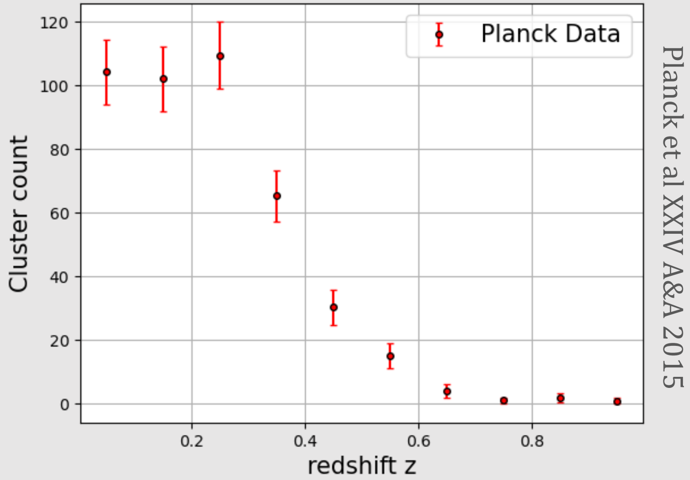
Y map



Planck Collaboration XXII 2015

**survey data**
(Planck, SPT, …)

cluster catalog with SZ observations



Planck et al XXIV A&A 2015

SZ power spectrum

Cluster number count

➔ Constraint on cosmology

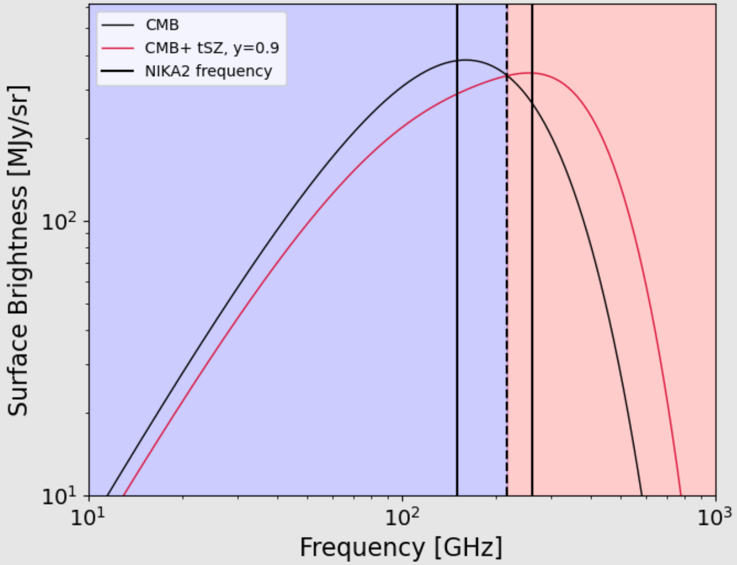
# SZ Large Program (LPSZ) of NIKA2

**NIKA2** high-resolution camera (KIDs)

- Installed at the IRAM 30-m telescope in Granada
- Operating since 2017

| $\nu$ observation | 150 GHz | 260 GHz |  |
|---|---|---|---|
| Resolution | 17.6'' ± 0.1'' | 11.1'' ± 0.2'' | Resolved substructures of clusters |
| Field of view | 6.5' | 6.5' | Full maps of the clusters |
| What we observe | negative SZ signal | point sources |  |

L. Perotto et al., A&A 2020



---

## SZ Large Program (observations finished in 2023)

- Dedicated to cluster cosmology
- 38 observed clusters (ACT and Planck follow-up)
- observed both in **SZ** (NIKA2) and **X-ray** (XMM Newton)
  - Pressure profile
  - Density profile

$$M(r) \propto \frac{1}{n_e(r)} \times \frac{dP_e(r)}{dr}$$

hydrostatic mass

**Precise estimation of integrated quantity $Y_{500}$ and $M_{500}$**

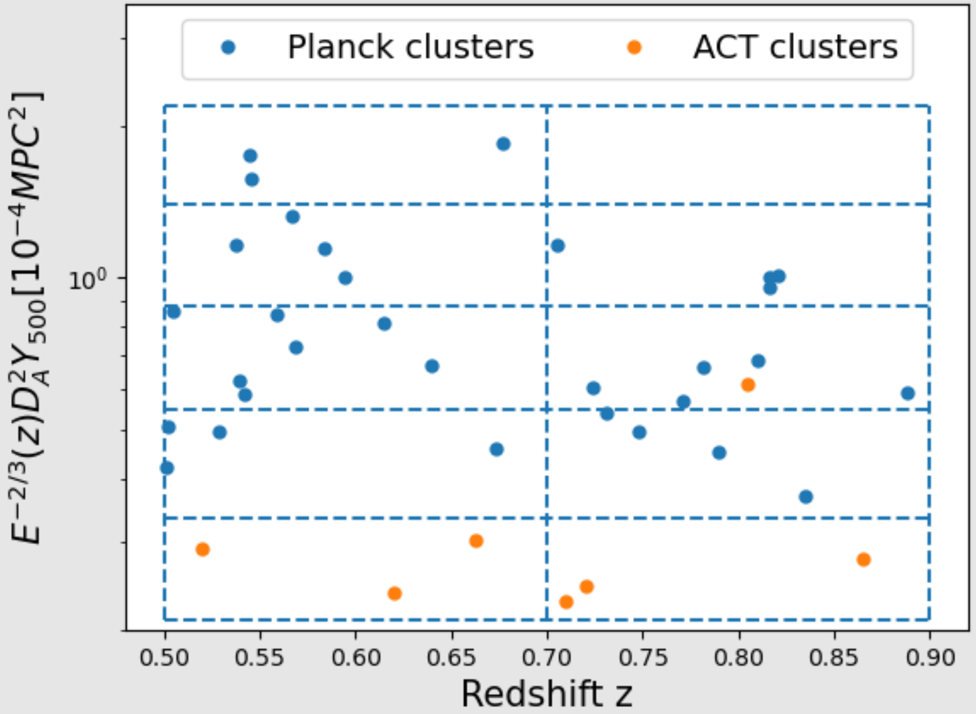
to calibrate scaling relation

# LPSZ data characteristics

- Intermediate to high redshift range: z ∈ [0.5,0.9]
- Direct measurement of $Y_{500}$ with SZ observations
- Consistent angular resolution across X-ray and SZ observations
- Hydrostatic mass estimated with SZ and X-ray data
- Box selection

→ insensitive to the underlying mass distribution

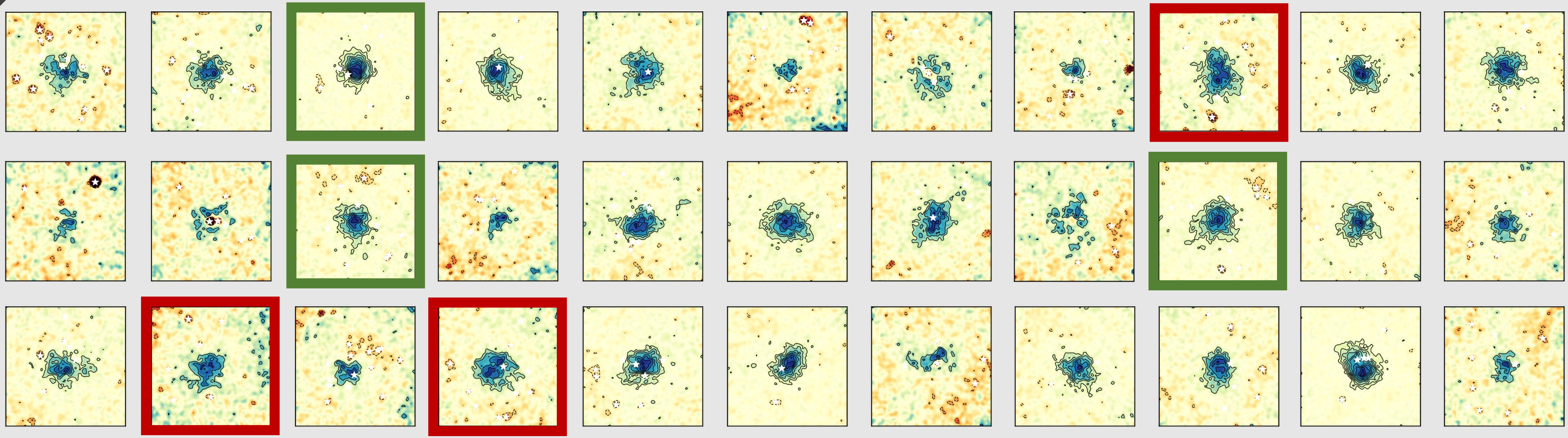
→ Suffisant range in $Y_{500}$ and $M_{500}$



→ First version of the maps

# LPSZ Clusters

## Clusters observed with NIKA2 at 150 GHz



preliminary

Various morphologies can be observed

Relaxed

Disturbed

Integrated quantities for all clusters: $Y_{500}$, $M_{500}$

# SZ-Mass scaling relation

Use LPSZ data to calibrate the SZ-Mass scaling relation → To be applied to large scale SZ survey

Power law linking $Y_{500}$ and $M_{500}$:

$$E_z^{-2/3}\left(\frac{D_A^2(z)Y_{500}}{10^{-4}\mathrm{Mpc}^2}\right) = 10^{\alpha}\left(\frac{M_{500}}{6\times 10^{14}M_{\odot}}\right)^{\beta} \longrightarrow$$

**Assumptions:**

- sphericity
- Intra Cluster Medium = ideal gas
- hydrostatic equilibrium

} Not always followed

In fact $P\left(\log(Y_{500})|\log(M_{500})\right) = \mathcal{N}\left(\alpha + \beta\log(M_{500}), {\sigma_{int}}^2\right)$

three parameters

$\boldsymbol{\alpha}$ the intercept

$\boldsymbol{\beta}$ the slope

$\boldsymbol{\sigma_{int}}$ the intrinsic scatter

We need a precise and accurate estimation of $\alpha$, $\beta$ and $\sigma$

to obtain precise and accurate cosmological constraints

# SZ-Mass scaling relation

Use LPSZ data to calibrate the SZ-Mas scaling relation → To be applied to large scale SZ survey

Power law linking $Y_{500}$ and $M_{500}$:

$$E_z^{-2/3}\left(\frac{D_A^2(z)Y_{500}}{10^{-4}\mathrm{Mpc}^2}\right) = 10^{\alpha}\left(\frac{}{6\times}\right.$$

**Assumptions:**

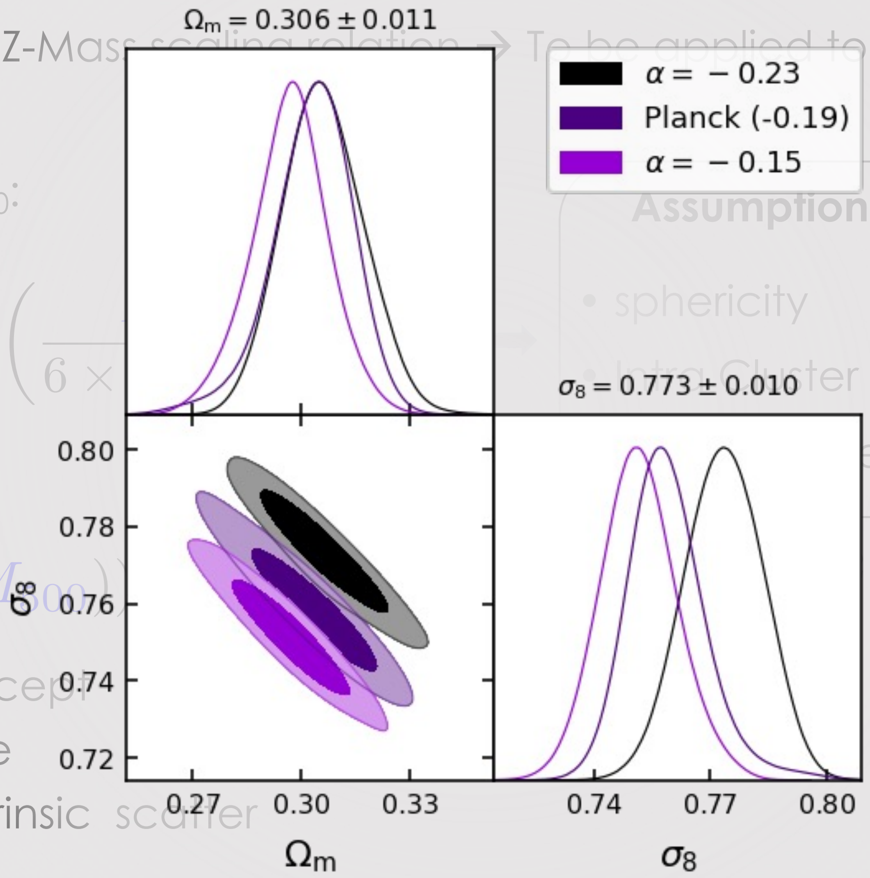
- sphericity
- Intra Cluster Medium = ideal gas
- equilibrium

Not always followed

In fact $P\left(\log(Y_{500})\right|\log(M_{500})$

three parameters

- $\alpha$ the intercept
- $\beta$ the slope
- $\sigma_{\text{int}}$ the intrinsic scatter



We need a precise and accurate estimation of $\alpha$, $\beta$ and $\sigma$

to obtain precise and accurate cosmological constraints

# Scaling relation estimation

Robust estimation

Error bars well defined

LPSZ selection function taken into account

**Solution** : LIRA+SBI

# Tools

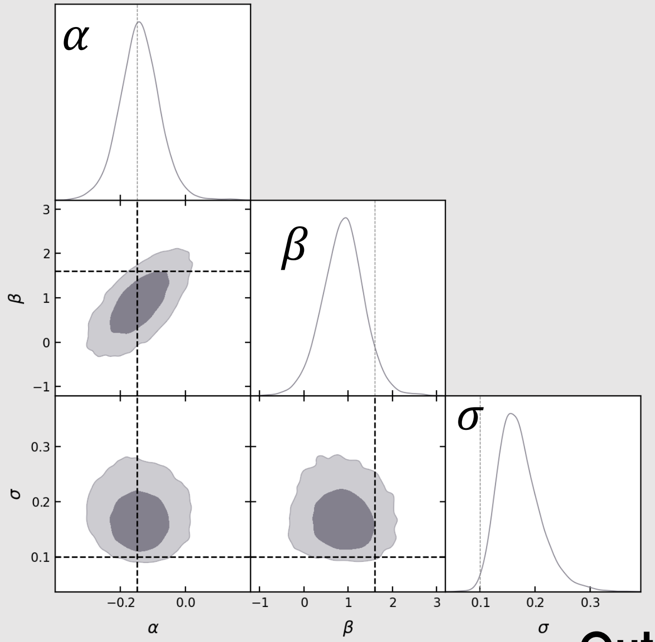
## **LIRA** M. Sereno MNRAS (2016)

LInear Regression in Astronomy

**Main characteristics:**

- Gibbs sampling
- bayesian hierarchical methods

Can take into account redshift dependance



**Inputs:**
$Y_{500}$ and $M_{500}$
Covariance between $Y_{500}$ and $M_{500}$
Error on $Y_{500}$ and $M_{500}$

**Output:**
Pdf of $\alpha$, $\beta$ and $\sigma$

Box selection taken into account

## **SBI** A . Tejero-Cantero et. al. JOSS (2020)

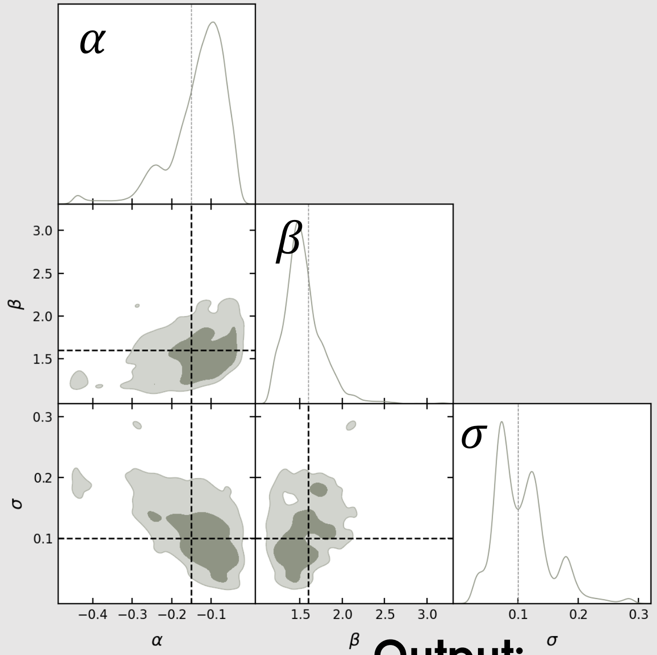
Simulation Based inference

**Main characteristics:**

- Based on Normalizing flow
- Likelihood free inference

**Training** with simulations

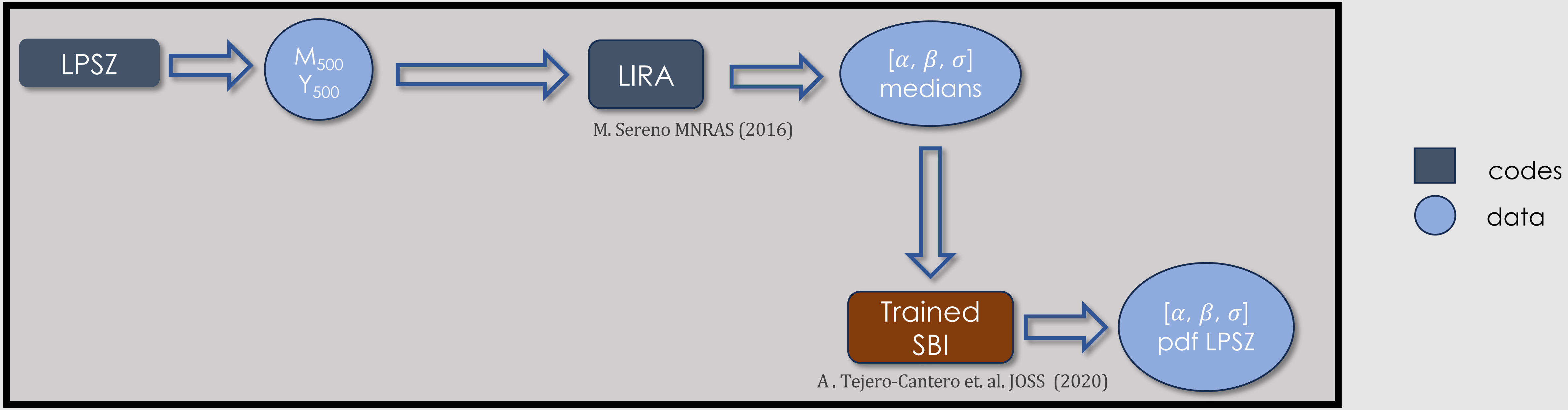
Gives $p(\theta\,|\,X)$ following X=LIRA outputs $\theta$=Scaling relation



**Input:**
$\alpha$, $\beta$ and $\sigma$ LIRA estimation

**Output:**
Pdf of underlying $\alpha$, $\beta$ and $\sigma$

# Method overview



LPSZ

$M_{500}$
$Y_{500}$

LIRA

M. Sereno MNRAS (2016)

$[\alpha, \beta, \sigma]$
medians

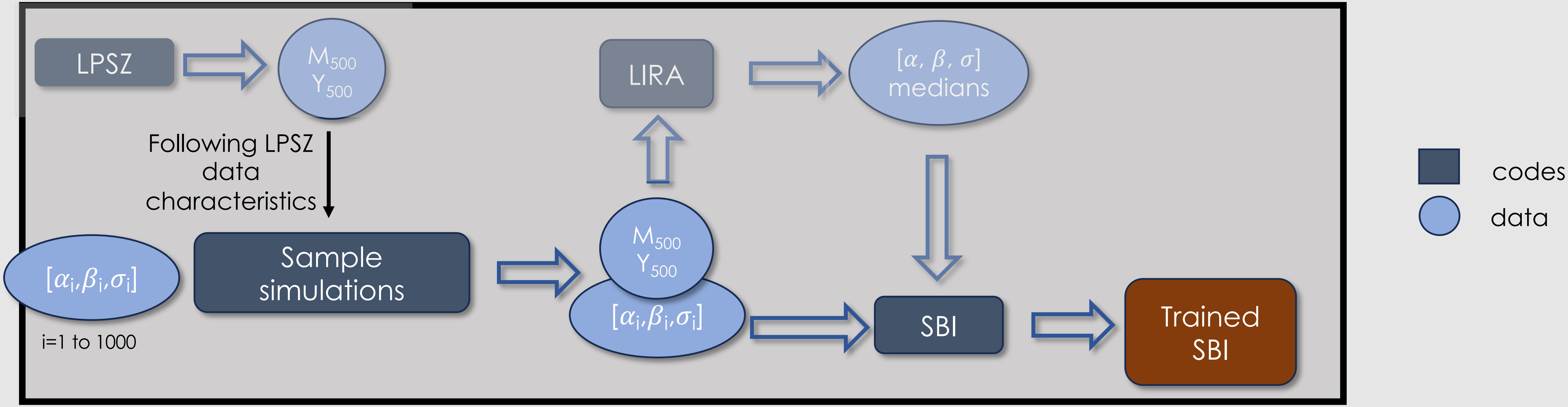
Trained
SBI

A . Tejero-Cantero et. al. JOSS (2020)

$[\alpha, \beta, \sigma]$
pdf LPSZ

■ codes
● data

# Method overview: Training



LPSZ

$M_{500}$ $Y_{500}$

Following LPSZ data characteristics

$[\alpha_i,\beta_i,\sigma_i]$

i=1 to 1000

Sample simulations

$M_{500}$ $Y_{500}$ $[\alpha_i,\beta_i,\sigma_i]$

LIRA

$[\alpha, \beta, \sigma]$ medians

SBI

Trained SBI

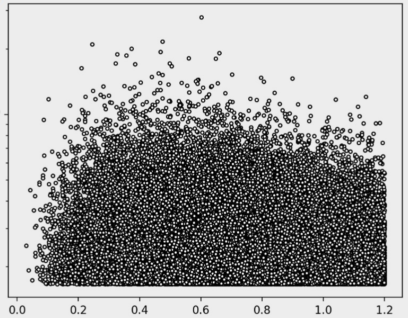
■ codes

● data

Pipeline developed to have unbiased result (selection function)

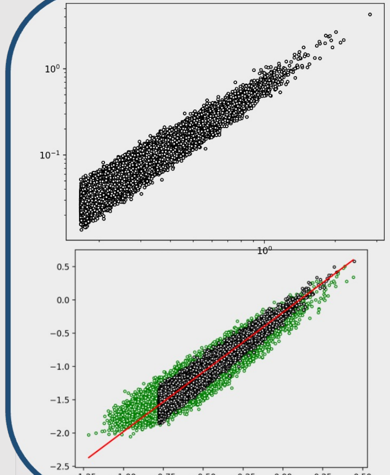
# Sample simulations

Goal : simulate [$Y_{500\_i}$ ,$M_{500\_i}$] sample similar to LPSZ data



**$M_{500}$-z catalog**

*Tinker et al 2010*



$Y_{500}$ attribution from $M_{500}$ and z

From chosen scaling relation

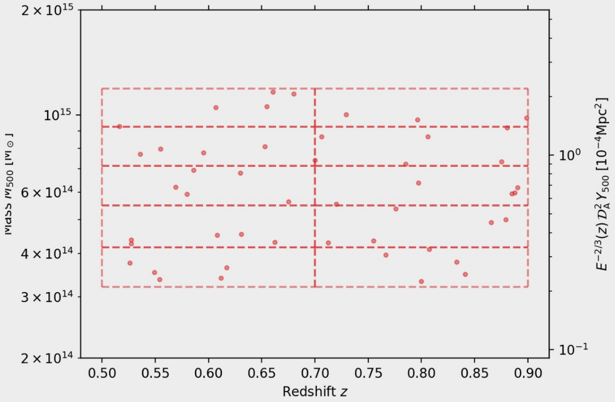
$\alpha$ β $\sigma$

Error bars simulation :

New value drawn inside error bar

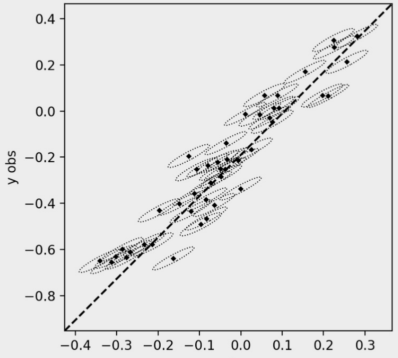
Errors, correlation between Y and M

× 10.000



**Box selection (LPSZ-like)**

Distribution inside boxes



**LPSZ-Like samples generated with known scaling relation**

Method from F. Kéruzoré PhD 2022

**Ready to be used by SBI**

# SBI training validation: Overall diagnostic

Multidimensional diagnostic : TARP (Tests of Accuracy with Random Points)

For a range of scaling relations

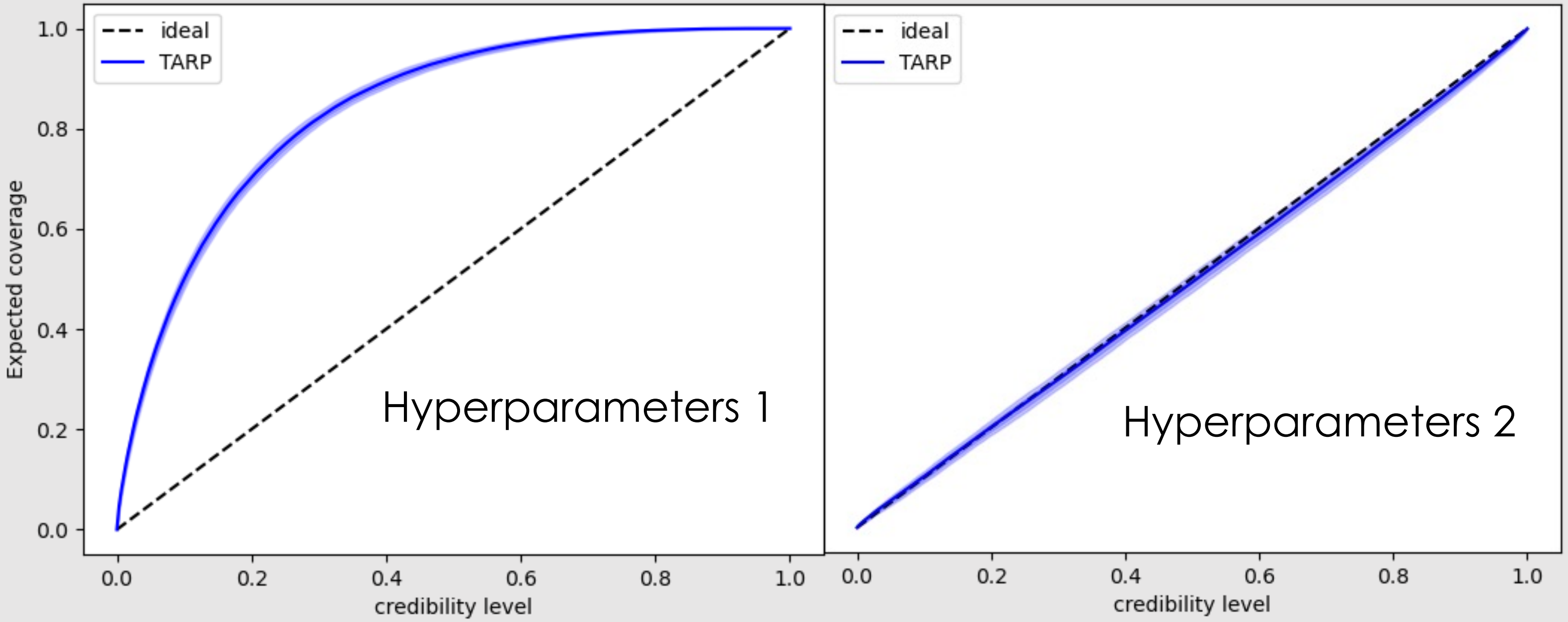
- necessary and sufficient condition for posterior accuracy

→ To identify the best SBI hyperparameters training

batch size = Number of data seen before updating the neural network

Learning rate = pace to change the model each time

…



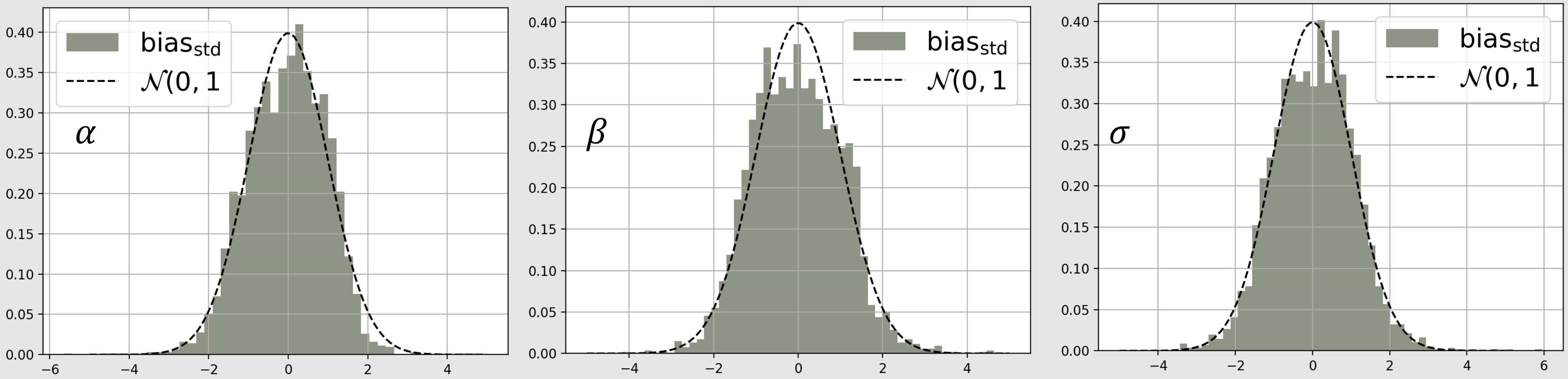
**Overall positive bias**

**Well calibrated posterior**

# SBI training validation: 1D diagnostic

One dimension diagnostic: $\mathrm{bias}_{\mathrm{std}} = \dfrac{\alpha_{\mathrm{SBI}} - \alpha_{\mathrm{True}}}{\mathrm{std}_{\mathrm{SBI}}}$ For a range of scaling relations

If $\mathrm{bias}_{\mathrm{std}} \in [-2, 2]$ means input values within 2 $\sigma$ error bars of SBI outputs



$\alpha$, $\beta$ and $\sigma$ **unbiased** and with **coherent error bars**

**Method validated for several scaling relations**

# Application to cosmology

Sample used: Planck 2015 sample
Planck XXIV A&A (2015)

Analysed with Class-sz B. Bolliet et. al. EPJ Web Conf. (2024)
collaboration with B.Bolliet

Planck scaling relation and error bars

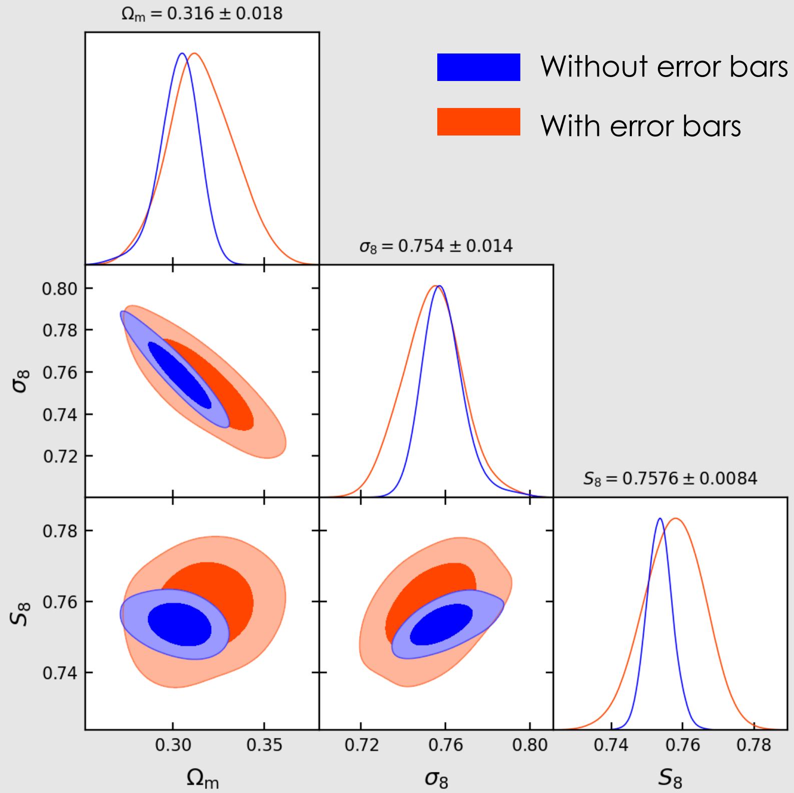
$\alpha$ = -0.19 ± 0.02 β = 1.79 ± 0.08 $\sigma$ = 0.075 ± 0.01

Cosmological inference well underway

→ First tests done with Planck scaling relation

→ Planck scaling relation error bars: taken into account

→ Tests done with different scaling relations



B fixed

Red contours more accurate than blue contours

**Error on scaling relation parameters must be propagated to cosmology**

# Conclusion

- Fully validated method to obtain the SZ-Mass scaling relation from the LPSZ sample
- Soon to be applied on LPSZ data

  ➔ Accurate pdf of $\alpha$, $\beta$ and $\sigma$
- Cosmological inference ready

  ➔ Error bars on scaling relation must be propagated to cosmological parameters

# Conclusion

- Fully validated method to obtain the SZ-Mass scaling relation from the LPSZ sample
- Soon to be applied on LPSZ data
    - ➔ Accurate pdf of $\alpha$, $\beta$ and $\sigma$
- Cosmological inference ready
    - ➔ Error bars on scaling relation must be propagated to cosmological parameters

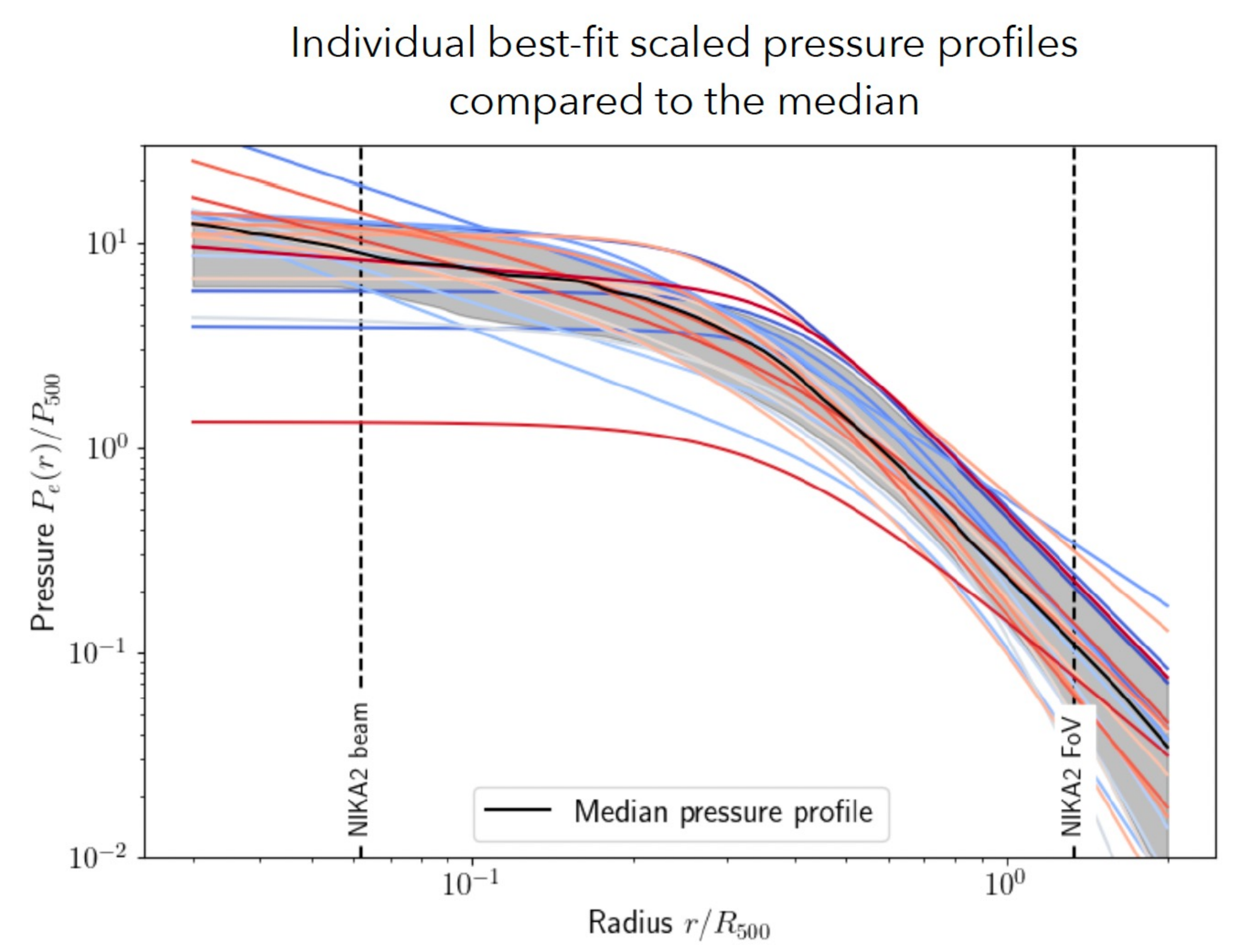
**Thank you**

# Universal pressure profile

gNFW model :

*Nagai et al. 2007*

$$P_e(r) = P_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$$

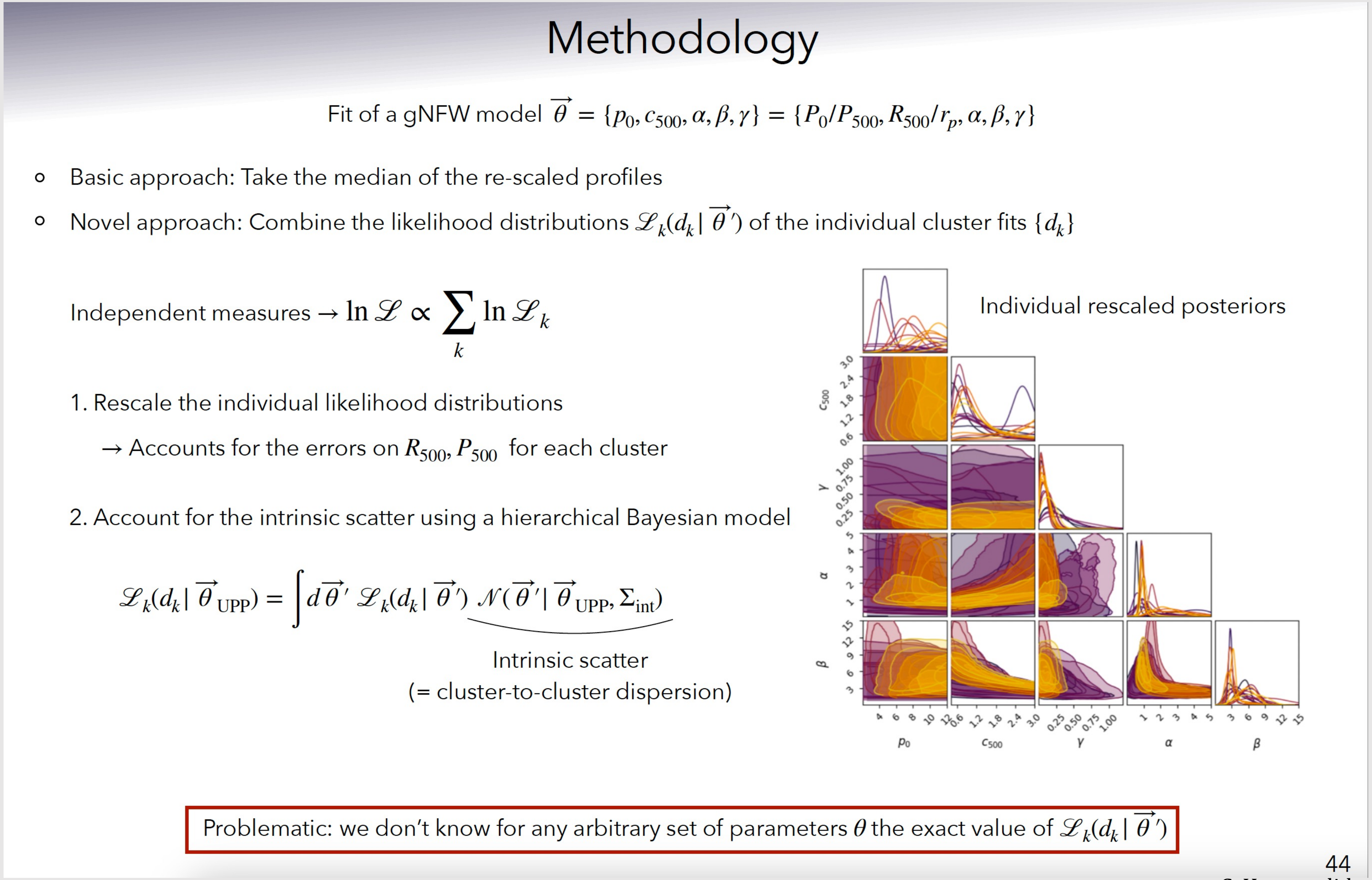


Individual best-fit scaled pressure profiles compared to the median

C. Hanser *et al.* In prep

# Universal pressure profile

C. Hanser *et al.* In prep



## Methodology

Fit of a gNFW model $\overrightarrow{\theta} = \{p_0, c_{500}, \alpha, \beta, \gamma\} = \{P_0/P_{500}, R_{500}/r_p, \alpha, \beta, \gamma\}$

- Basic approach: Take the median of the re-scaled profiles
- Novel approach: Combine the likelihood distributions $\mathscr{L}_k(d_k | \overrightarrow{\theta}')$ of the individual cluster fits $\{d_k\}$

Independent measures → $\ln \mathscr{L} \propto \sum_k \ln \mathscr{L}_k$

Individual rescaled posteriors

1. Rescale the individual likelihood distributions

→ Accounts for the errors on $R_{500}, P_{500}$ for each cluster

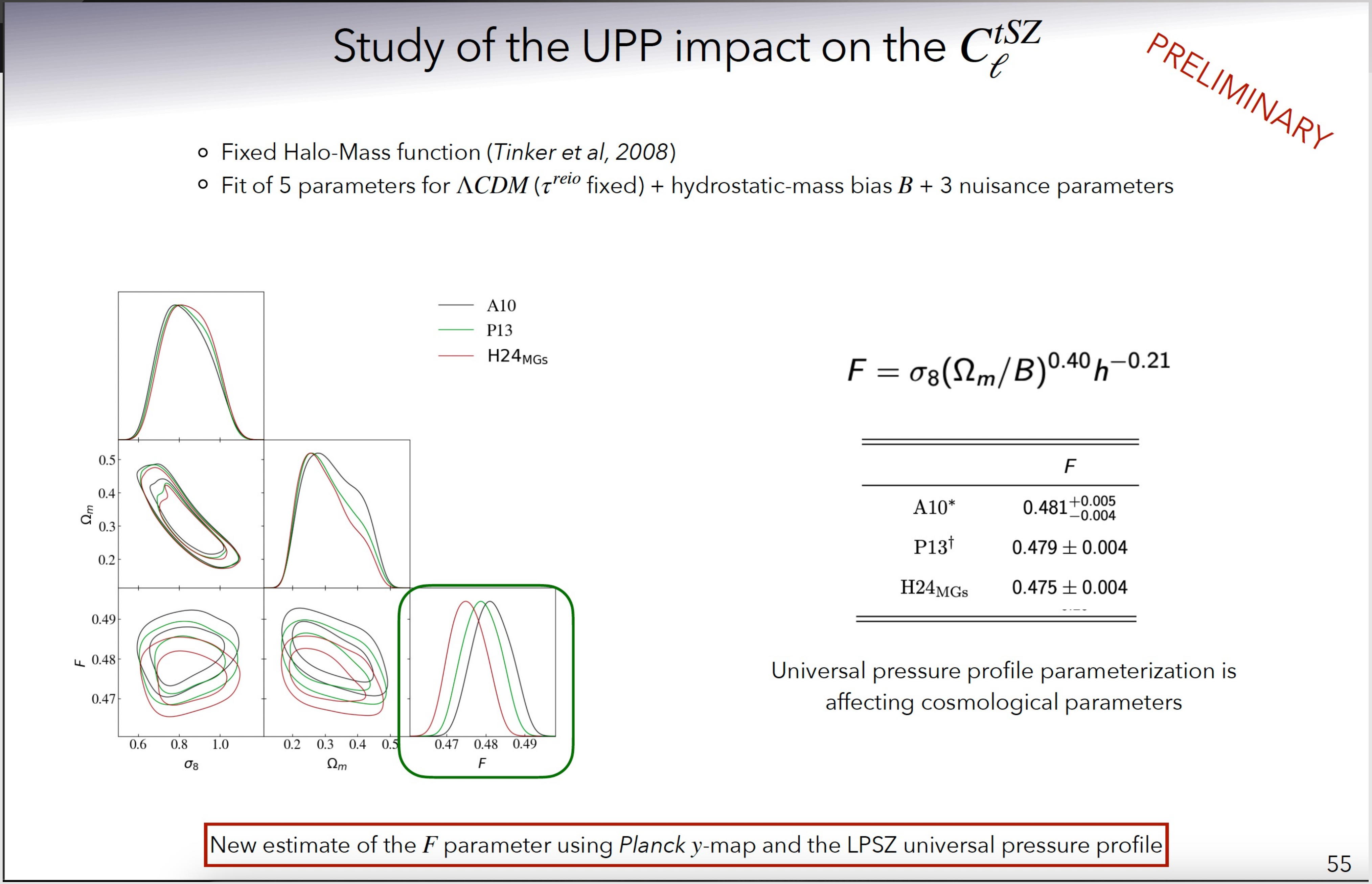
2. Account for the intrinsic scatter using a hierarchical Bayesian model

$$\mathscr{L}_k(d_k | \overrightarrow{\theta}_{\mathrm{UPP}}) = \int d\overrightarrow{\theta}' \, \mathscr{L}_k(d_k | \overrightarrow{\theta}') \underbrace{\mathscr{N}(\overrightarrow{\theta}' | \overrightarrow{\theta}_{\mathrm{UPP}}, \Sigma_{\mathrm{int}})}_{}$$

Intrinsic scatter
(= cluster-to-cluster dispersion)

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

C. Hanser slide



# Study of the UPP impact on the $C_\ell^{tSZ}$

PRELIMINARY

- Fixed Halo-Mass function (*Tinker et al, 2008*)
- Fit of 5 parameters for $\Lambda CDM$ ($\tau^{reio}$ fixed) + hydrostatic-mass bias $B$ + 3 nuisance parameters

$$F = \sigma_8(\Omega_m/B)^{0.40}h^{-0.21}$$

| | $F$ |
|---|---|
| A10* | $0.481^{+0.005}_{-0.004}$ |
| P13† | $0.479 \pm 0.004$ |
| H24$_{\rm MGs}$ | $0.475 \pm 0.004$ |

Universal pressure profile parameterization is affecting cosmological parameters

New estimate of the $F$ parameter using *Planck* $y$-map and the LPSZ universal pressure profile

C. Hanser slide

# SZ scaling relation

$$E_z^{-2/3}\left(\frac{D_A^2(z)Y_{500}}{10^{-4}\mathrm{Mpc}^2}\right) = 10^{\alpha}\left(\frac{M_{500}}{6\times10^{14}M_{\odot}}\right)^{\beta}$$

**different SZ-Mass scaling relations:**

| | **Planck 2013** | **Chandra-Planck (2024)** | **NIKA2-LPSZ** |
|---|---|---|---|
| Data | XMM-Newton<br>Planck | Chandra<br>Planck | XMM-Newton<br>NIKA2 + Planck |
| redshift | [0,0.45] | [0,0.35] | [0.5,0.9] |
| sample size | 71 | 146 | 38 |
| resolution | X : 6.6''<br>SZ : ~6 ' | X : 0.2''<br>SZ : ~6' | X : 6.6''<br>SZ : 17.6'' |
| mass estimation | X-only Mass | X-only Mass | SZ-X Mass |

*Planck 2013 results XX A&A* *G. Aymerich et al. A&A 2024*

## NIKA2-LPSZ

Aim: obtain a **scaling relation**
a **mean pressure profile**

- At larger redshift
- With controlled systematics
  including cluster morphology