Cluster Cosmology within the NIKA2 Sunyaev-Zeldovich Large Programme

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On behalf of the NIKA2 collaboration

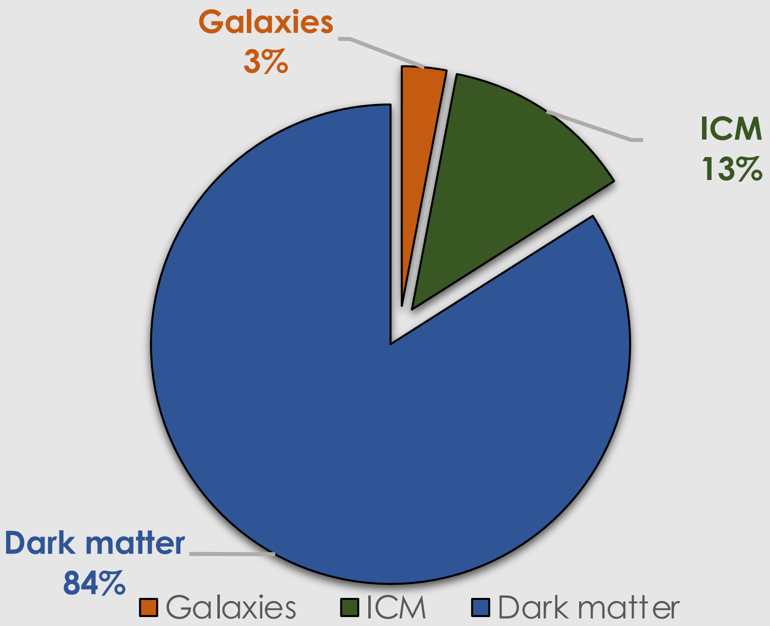
1. Galaxy clusters
2. Sunyaev-Zeldovich effect
3. Cosmology with galaxy clusters
4. The SZ large Program of NIKA2
5. The SZ-Mass scaling relation
    - Calibration method
    - Application to cosmology

Cosmology with galaxy clusters

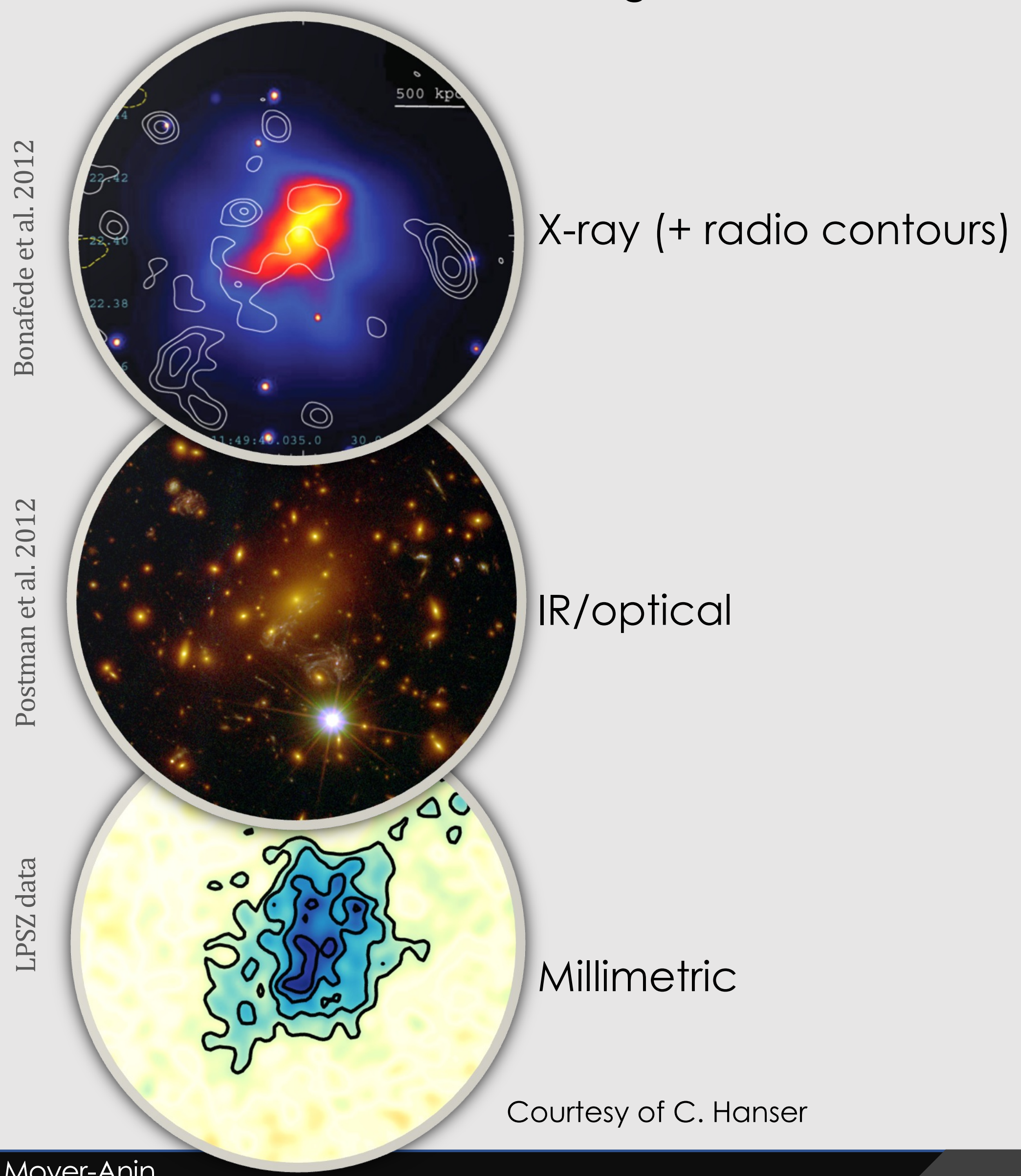
Galaxy clusters :

redshift z ≤ 2 (local probes)

Intra Cluster Medium (ICM) = Ionized gas



Observed at several wavelengths



Courtesy of C. Hanser

The Sunyaev-Zeldovich (SZ) effect

Inverse Compton scattering of CMB photons on cluster ionized gas

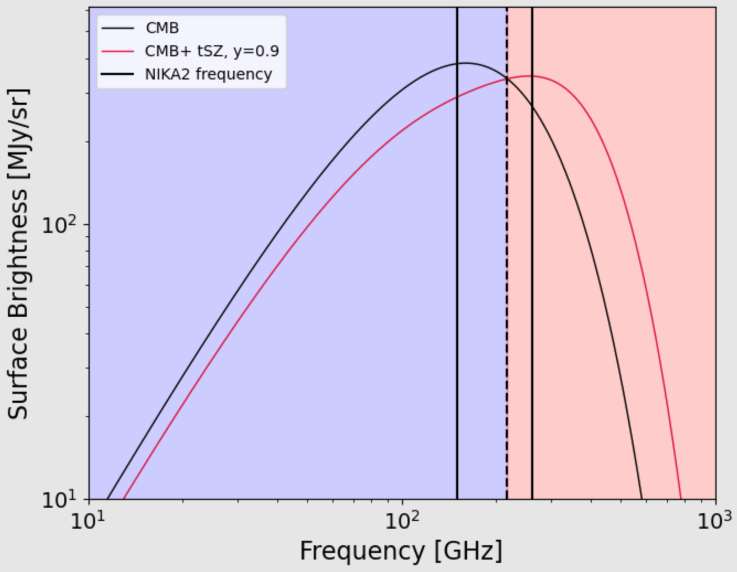
→ Energy transfer from electrons to photons

→ **Shift 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

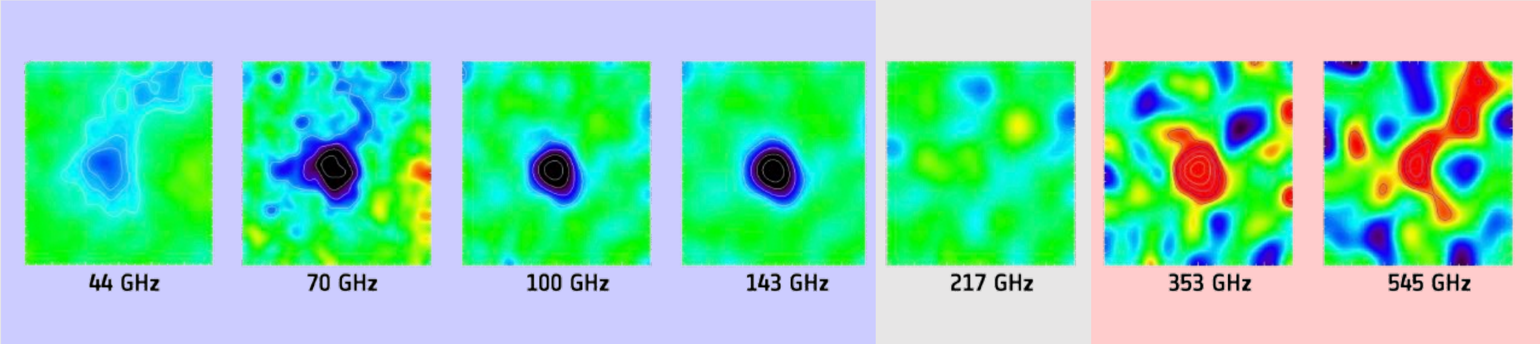
Positive Signal

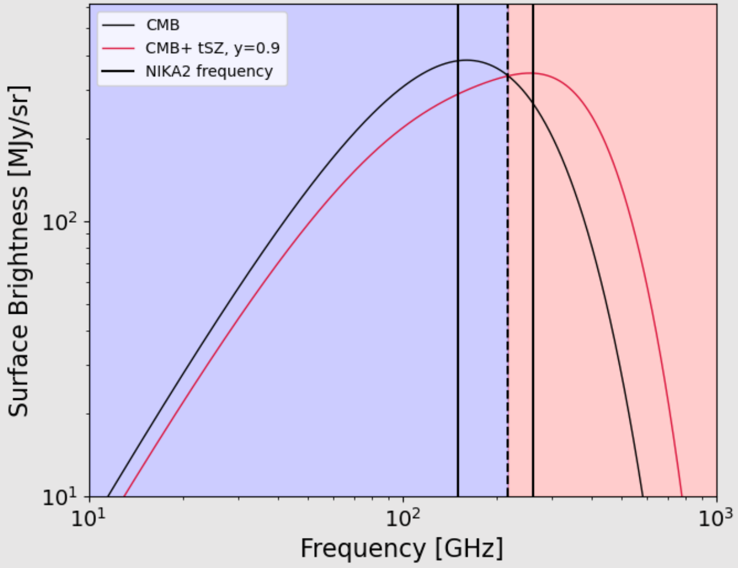
More intensity than expected from CMB

217 GHz

The Synyaev-Zeldovich (SZ) effect

Cluster observed by Planck





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 ρ_c

How to do cosmology with galaxy clusters?

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

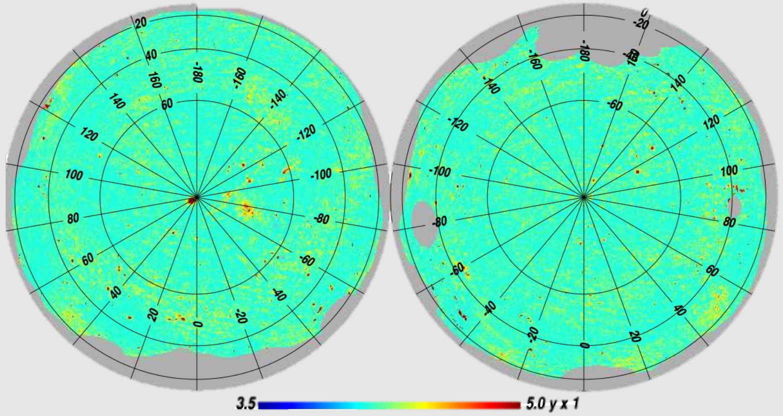
SZ Integrated quantity $Y_{SZ} \propto \int_0^{R_\Delta} y dS$

Mean pressure profile $P_{mean}(r)$

Tools

SZ-Mass scaling relation

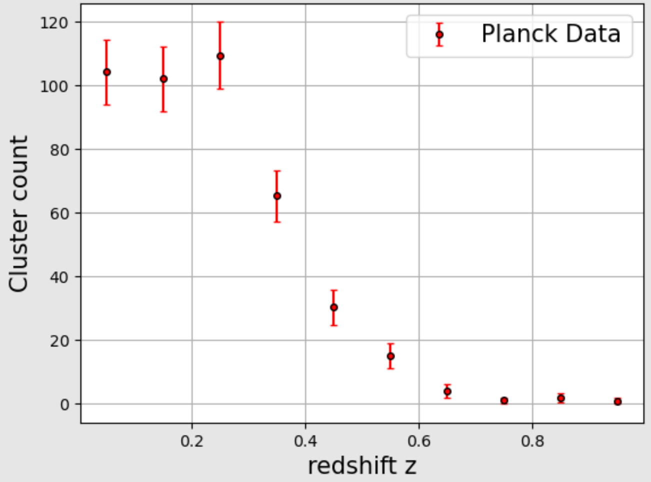
Y map



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

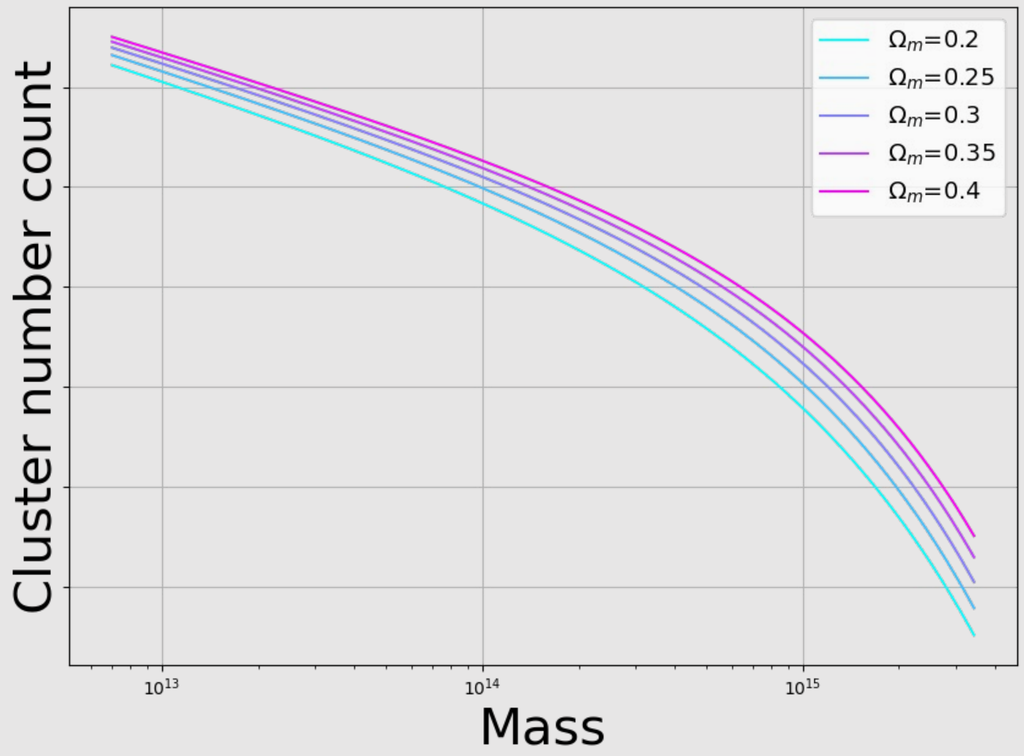
➔ Constraint on cosmology

Cosmological constraints

Cluster number count : $\frac{d^2N}{dMdz}$ depends on Ω_m and σ_8

Ω_m matter content in the Universe

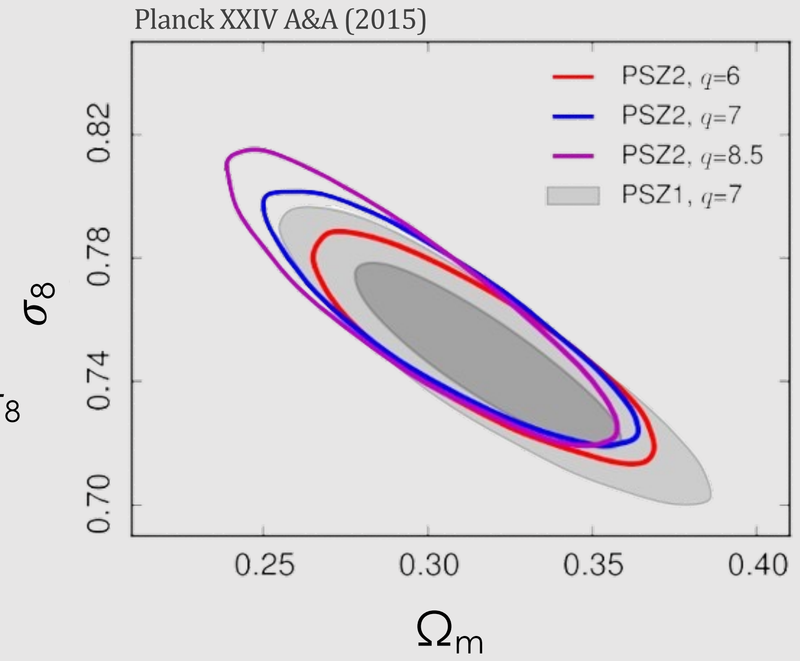
σ_8 matter distribution variance



Likelihood with data

→

Constraint on Ω_m and σ_8



We need a large number of cluster to constrain cosmology
→ Large scale survey ≠ LPSZ sample

The SZ Large program of NIKA2

NIKA2 high-resolution camera (KIDs)

Installed at the IRAM 30 m telescope in Granada

Operating since 2017

ν observation	150 GHz	260 GHz	
Resolution	17.6'' ± 0.1''	11.1'' ± 0.2''	Resolved inner parts of clusters
Field of view	6.5'	6.5'	Full maps of the clusters
mapping speed (arcmin$^2 \cdot$ mJy$^{-2} \cdot$ h^{-1})	1388±174	111±11	Good sensitivity

Adam *et al.* 2018
Perotto *et al.* 2020

SZ Large Program (observations finished in 2023)

Sample of 38 clusters fully observed →
To calibrate cosmological tools

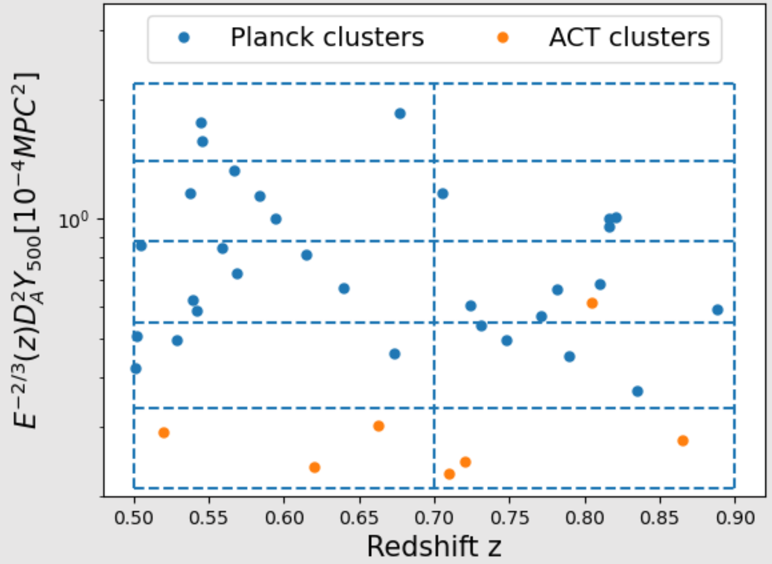
Clusters observed both in **SZ** (NIKA2) and **X-ray** (XMM Newton)

- Pressure profile
- Density profile

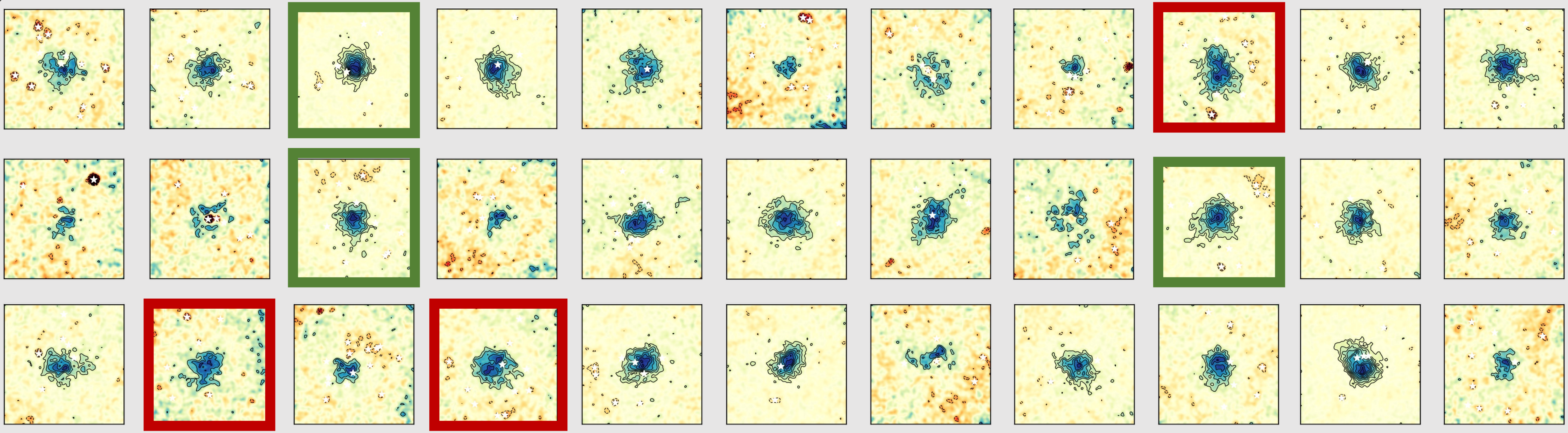
} Mass profile with hydrostatic equilibrium

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

M_{500} : integration up to R_{500}
R_{500} : radius of a sphere of density 500 times ρ_c



Clusters observed with NIKA2 at 150 GHz



Various morphologies can be observed Relaxed Disturbed

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

LPSZ products

LPSZ : Sunyaev Zeldovich Large Program of the NIKA2 collaboration

Catalog:

- Maps
- noise maps

- Thermodynamic profiles
- integrated quantities Y_{500} and M_{500}

} For each cluster in the sample

Mean pressure profile - C. Hanser *et al.*

- Precise estimation and study of the systematic effects
- Apply to Planck Y map to update cosmological contraints

SZ-Mass scaling relation - A. Moyer-Anin *et al.*

- Precise estimation and study of the systematic effects
- Apply to Planck cluster count to update cosmological contraints

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The SZ-Mass scaling relation

Y_{500} : integration up to R_{500}
M_{500} : integration up to R_{500}
R_{500} : radius of a sphere of density 500 times ρ_c

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

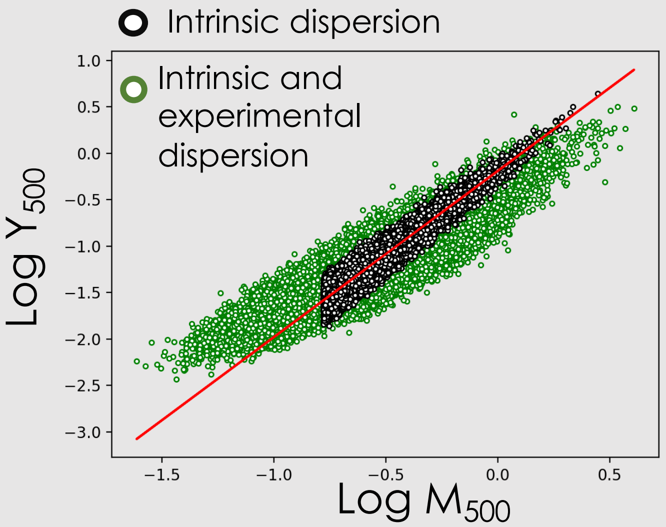
$$E_z^{-2/3} D_A^2(z) Y_{500} = 10^{\alpha} {M_{500}}^{\beta}$$

Assumptions:

- sphericity
- ICM = 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

α the intercept
β the slope
σ_{int} the intrinsic scatter

We need a precise and accurate estimation of α, β and σ

to obtain precise and accurate cosmological constraints

The SZ-Mass scaling relation

Y_{500} : integration up to R_{500}
M_{500} : integration up to R_{500}
R_{500} : radius of a sphere of density 500 times ρ_c

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

$$E_z^{-2/3} D_A^2(z) Y_{500} = 10^{\alpha} M$$

Not always followed

In fact $P\left(\log(Y_{500}) \,|\, \log(M\right.$

three parameters

α the interce
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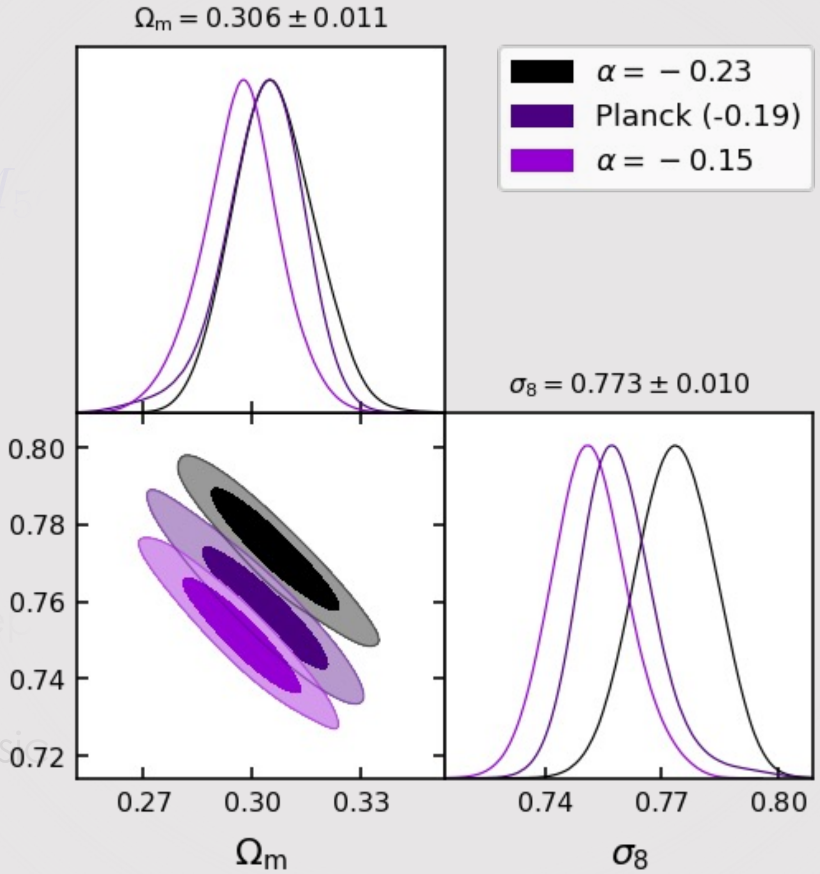
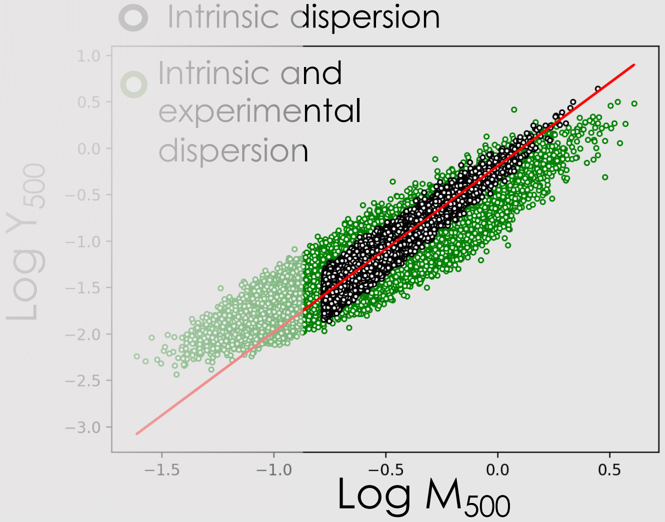




We need a precise and accurate estimation of α, β and σ

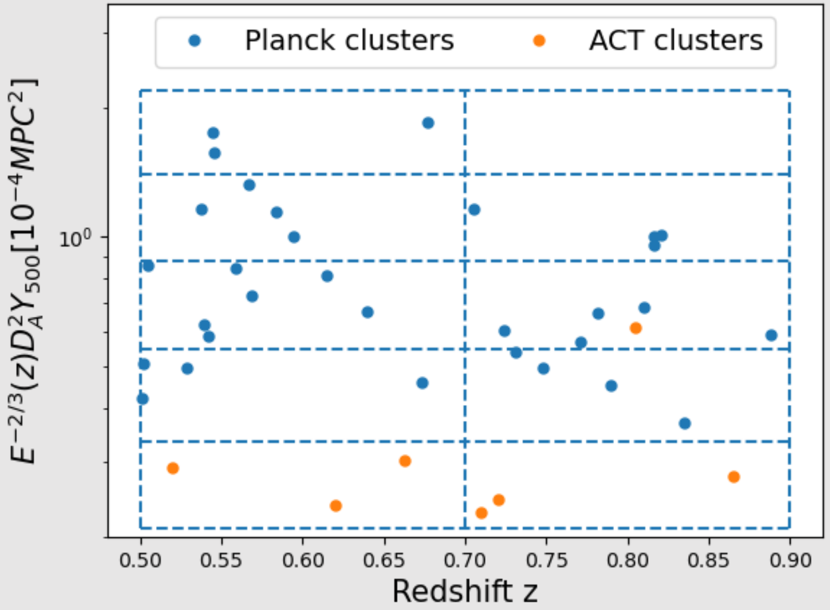
to obtain precise and accurate cosmological constraints

LPSZ data characteristics

To span a large range in mass and redshift → **Box selection**

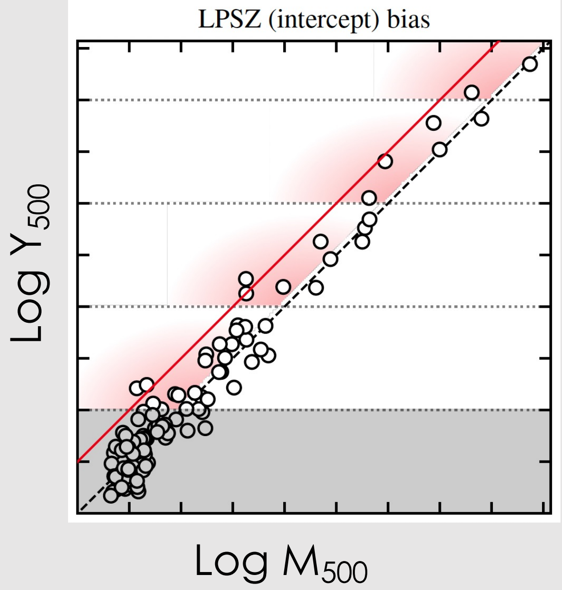
i.e force the sample to have 5 clusters inside each box

=threshold in Y_{500} and redshift



Problem: this selection has a strong impact on our data
several **thresholds** that are **difficult to process**

F. Kéruzoré PhD 2021



4 thresholds in Y_{500}

→ Effect on parameter α the intercept for example

Scaling relation estimation

Robust estimation

Error bars well defined

LPSZ selection function taken into account

Solution : LIRA+SBI

Tools

LIRA M. Sereno MNRAS (2016)

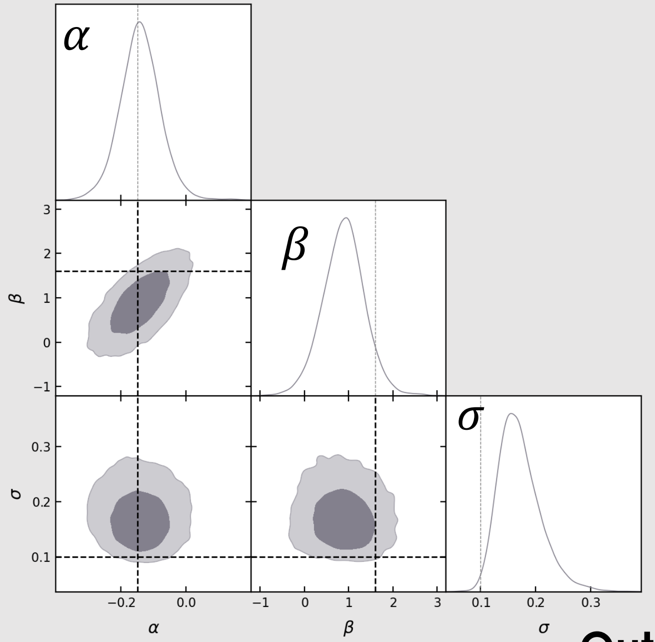
LInear Regression in Astronomy

Main characteristics:

Gibbs sampling

bayesian hierarchical methods

Can take into account redshift dependence



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

Output:
Pdf of α, β and σ

Box selection taken into account

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

Simulation Based inference

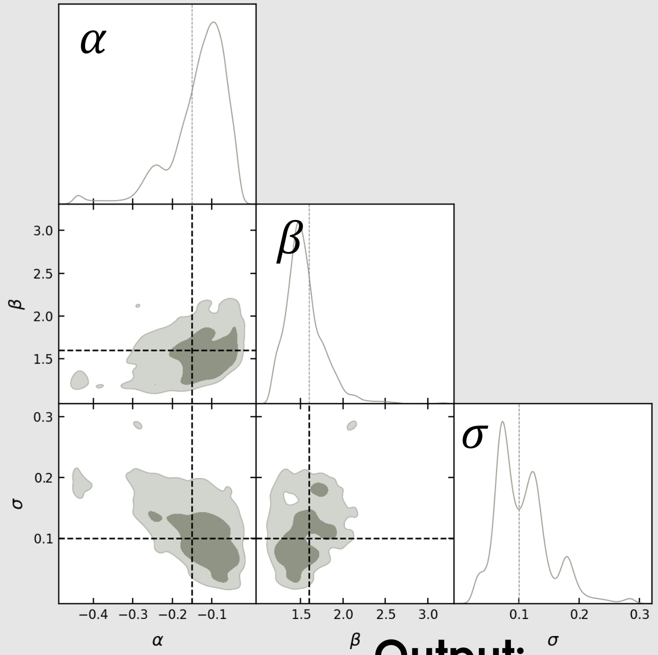
Main characteristics:

Based on Normalizing flow

Likelihood free inference

Training with sample simulations

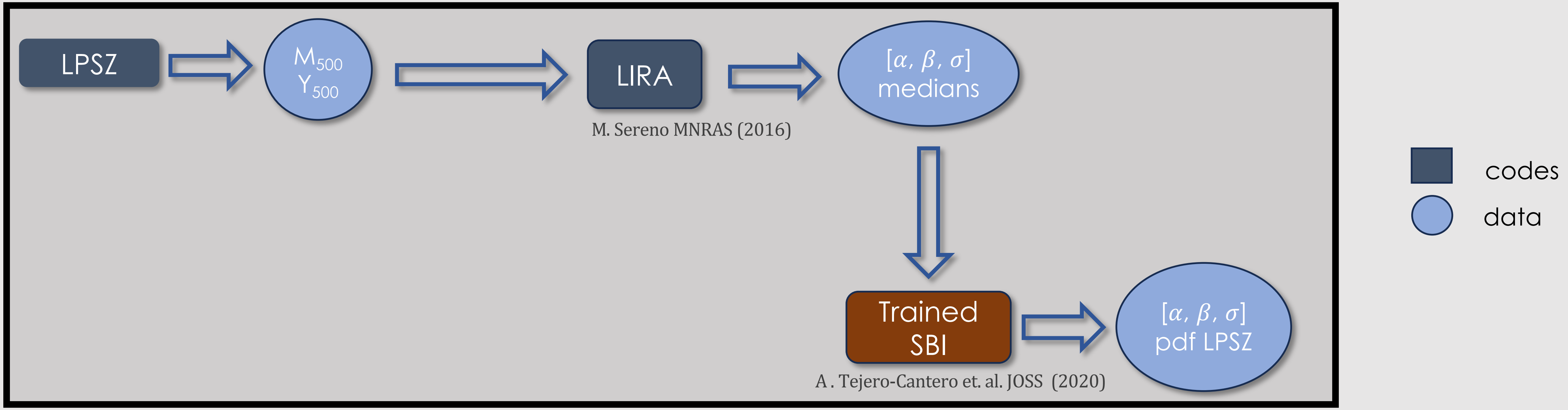
Gives p(θ | X) following X=LIRA outputs θ=Scaling relation



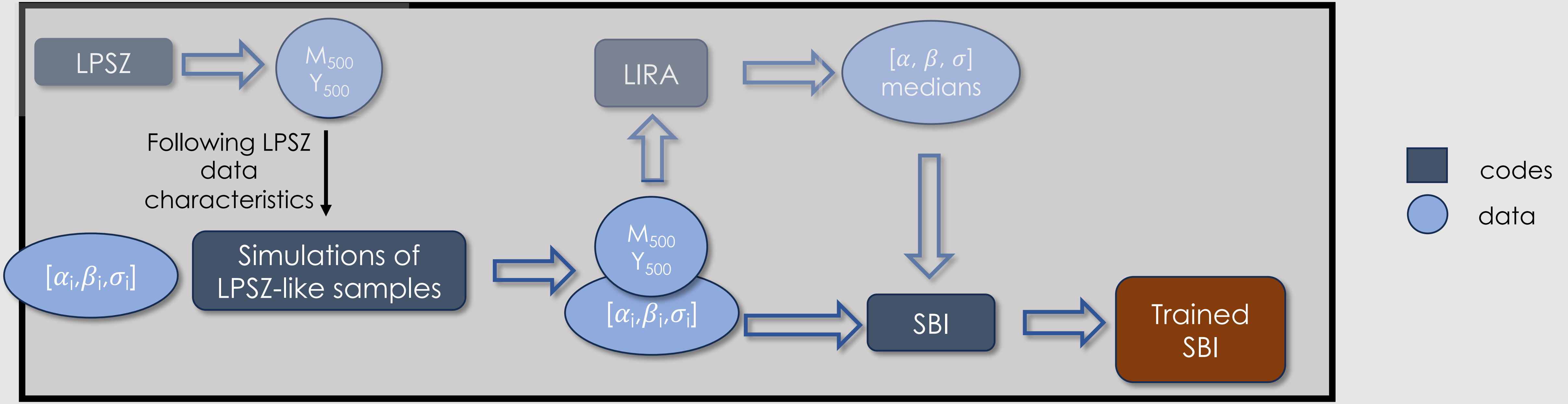
Input:
α, β and σ LIRA estimation

Output:
Pdf of underlying α, β and σ

Method overview



Method overview: Training



Pipeline developped to have unbiased result (selection function)

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

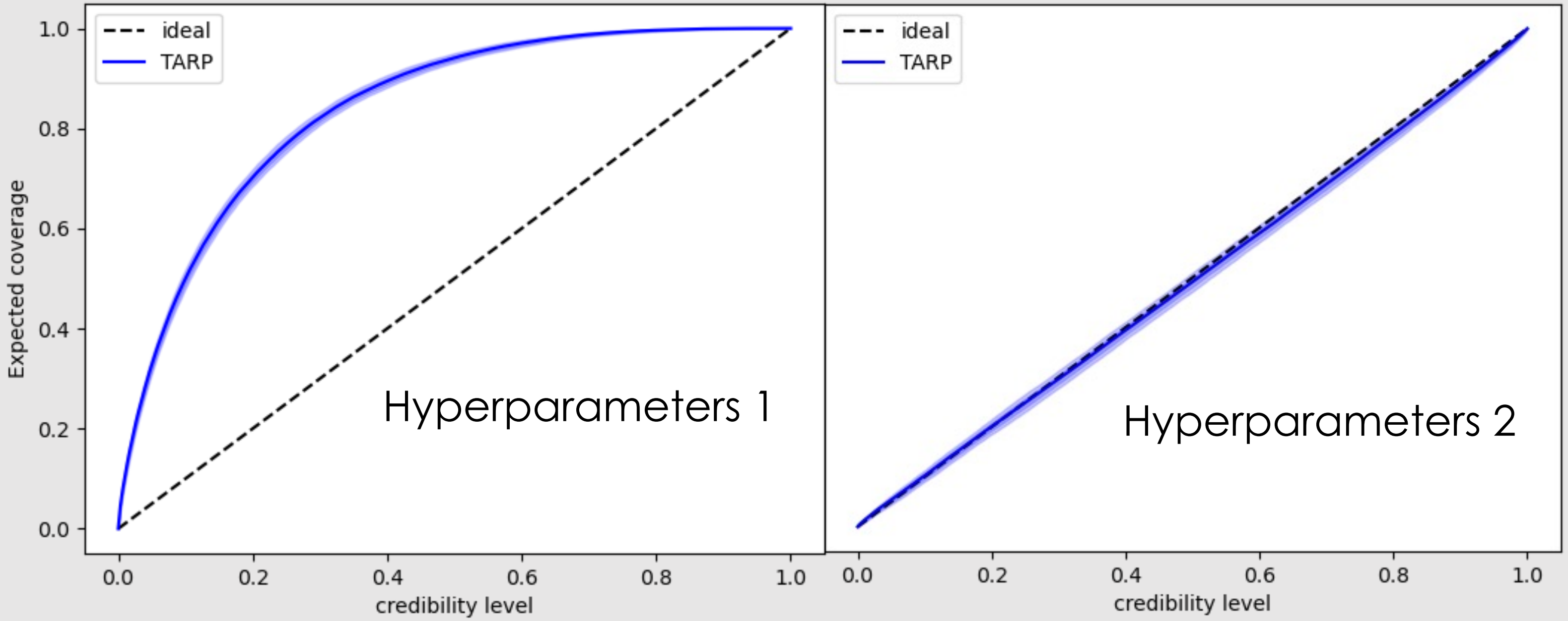
→ To identify the best SBI hyperparameters training

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

Learning rate = pace to change the model each time

…

Overall positive bias

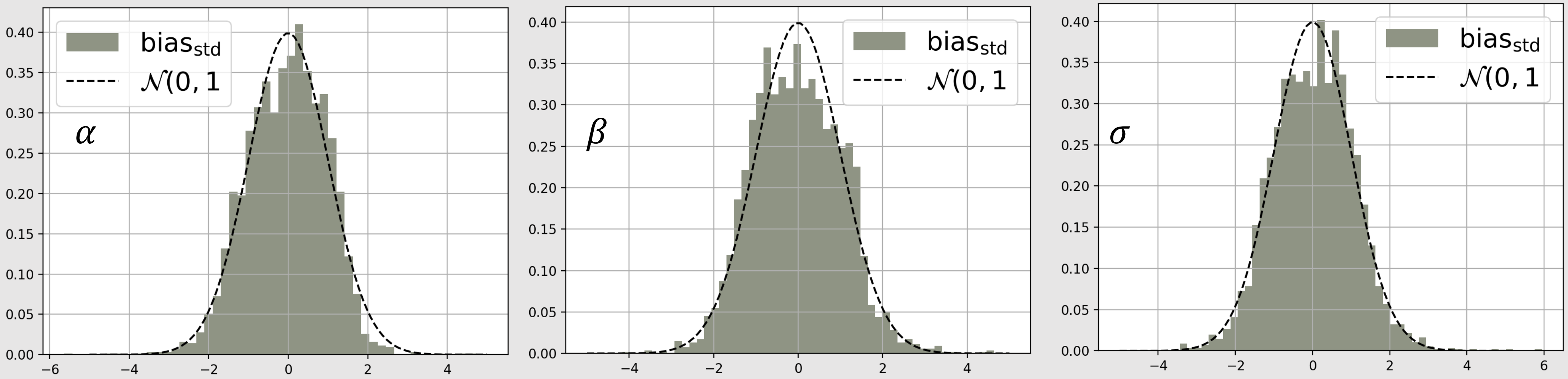


Well calibrated posterior

SBI training validation: 1D diagnostic

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

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



α, β and σ **unbiased** and with **coherent error bars**

Method validated for several scaling relations

Application to cosmology

Sample used: Planck 2015 cluster sample : large scale survey

Planck XXIV A&A (2015)

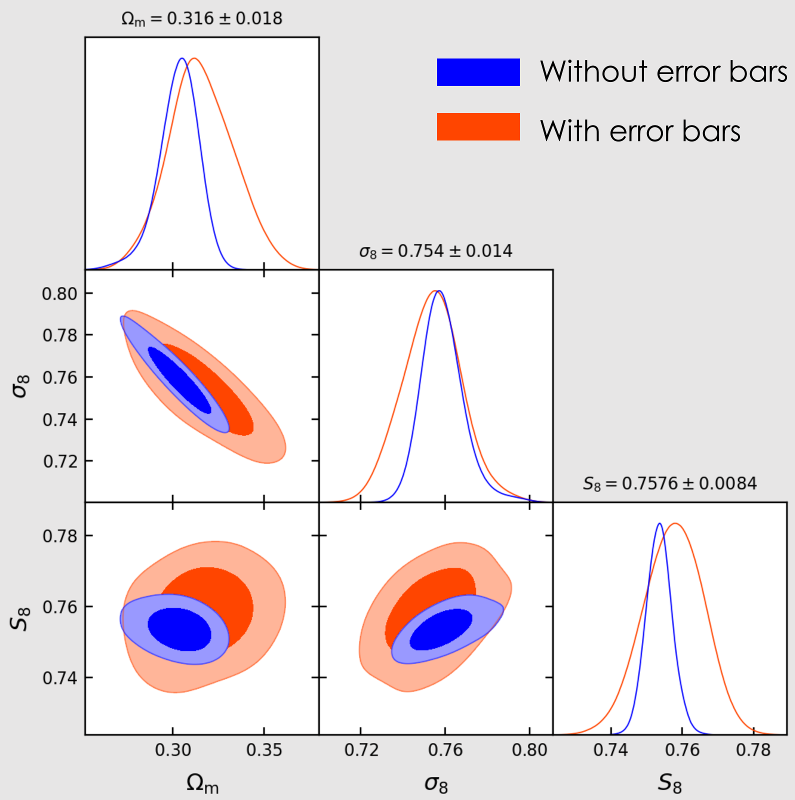
Analysed with Class-sz collaboration with B.Bolliet

B. Bolliet et. al. EPJ Web Conf. (2024)

Scaling relation used: Planck scaling relation (for now)

Planck XXIV A&A (2015)

α = -0.19 ± 0.02   β = 1.79 ± 0.08 σ = 0.075 ± 0.01



B fixed

Cosmological inference well beginned

→ First tests done with Planck scaling relation

→ Planck scaling relation error bars: taken into account

Red contours more accurate than blue contours

Error on scaling relation parameters must be propagated to cosmology

Conclusion

Accurate estimation of two tools for cosmology

→ mean pressure profile and SZ-Mass scaling relation

- ✶ Fully validated method to obtain LPSZ scaling relation
- ✶ Soon to be applied on LPSZ data
  - ○ Accurate pdf of α, β and σ
- ✶ Cosmological inference ready
  - ○ Error bars on scaling relation must be propagated to cosmological parameters

Thank you

Accurate estimation of two tools for cosmology

→ mean pressure profile and SZ-Mass scaling relation

✶ Fully validated method to obtain LPSZ scaling relation

✶ Soon to be applied on LPSZ data

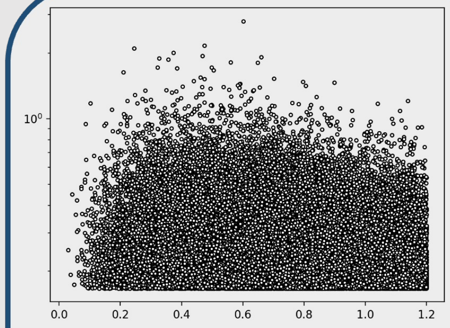
○ Accurate pdf of α, β and σ

✶ Cosmological inference ready

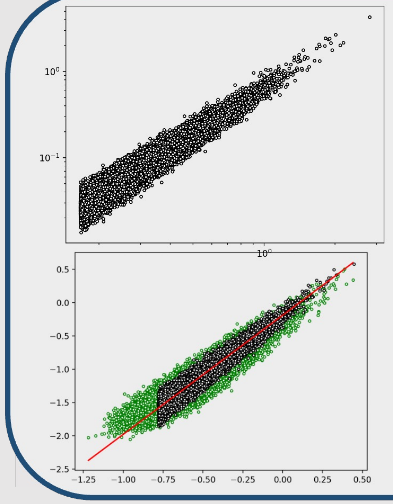
○ Error bars on scaling relation must be propagated to cosmological parameters

Sample simulations

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



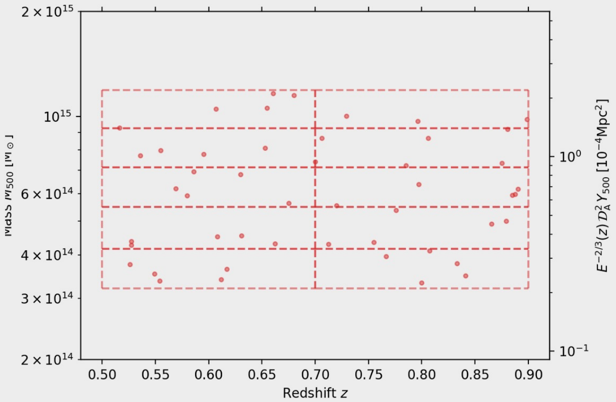
M_{500}-z catalog
Tinker et al 2010



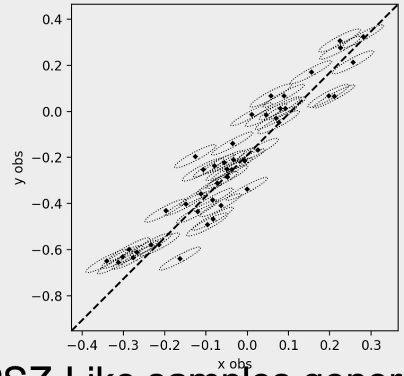
Y_{500} attribution from M_{500} and z
From chosen scaling relation
α β σ

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

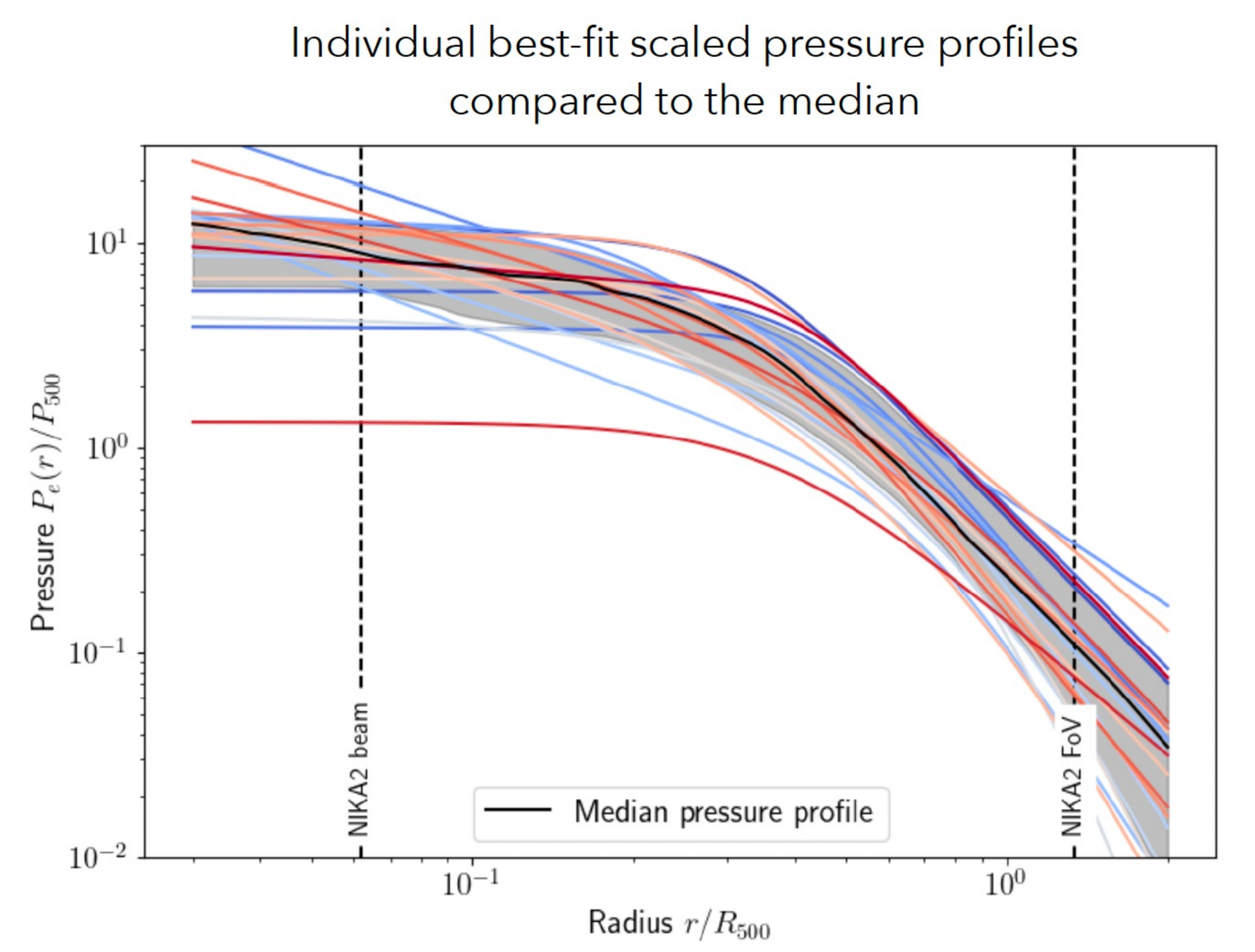
Method from F. Kéruzoré PhD 2022

Ready to be used by SBI

Mean pressure profile

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

Nagai et al. 2007



C. Hanser *et al.* In prep

Mean pressure profile

C. Hanser *et al.* In prep

Methodology

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

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

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

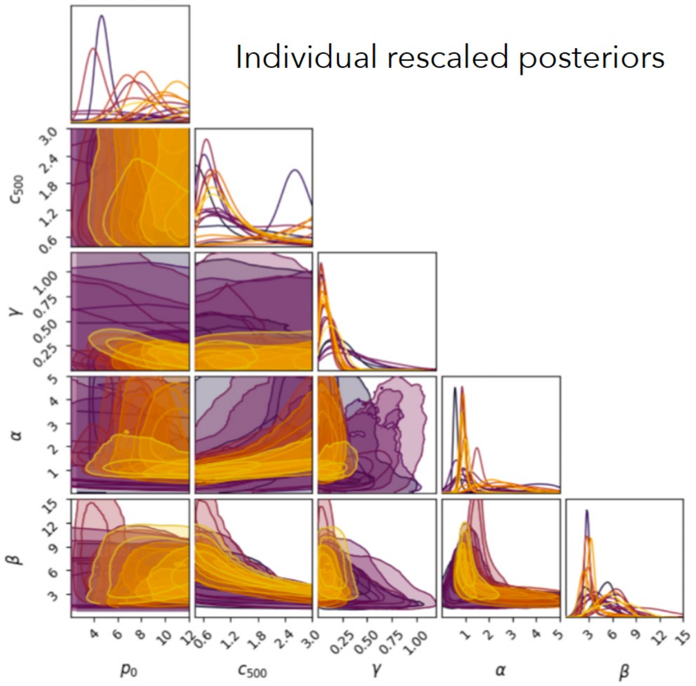
1. Rescale the individual likelihood distributions

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

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

$$\mathscr{L}_k(d_k | \vec{\theta}_{\rm UPP}) = \int d\vec{\theta}\,' \, \mathscr{L}_k(d_k | \vec{\theta}\,') \underbrace{\mathscr{N}(\vec{\theta}\,' | \vec{\theta}_{\rm UPP}, \Sigma_{\rm int})}_{\text{Intrinsic scatter}}$$

Intrinsic scatter
(= cluster-to-cluster dispersion)



Individual rescaled posteriors

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

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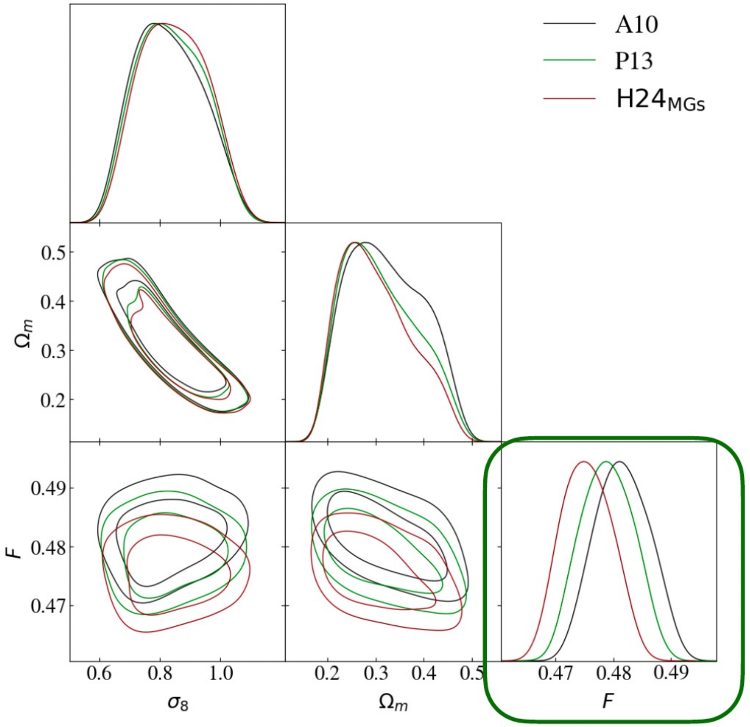
C. Hanser slide

Study of the UPP impact on the C_ℓ^{tSZ}

PRELIMINARY

- Fixed Halo-Mass function (*Tinker et al, 2008*)
- Fit of 5 parameters for ΛCDM (τ^{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 ± 0.004
$\mathrm{H24_{MGs}}$	0.475 ± 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

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C. Hanser slide