TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Probing the Hubble constant from X-ray and millimetre observations of CHEX-MATE galaxy clusters

F. De Luca[1], H. Bourdin[1], P. Mazzotta[1], F. Oppizzi[1,2]
and the CHEX-MATE collaboration

1. Università Degli Studi di Roma Tor Vergata
2. Università Degli Studi di Padova

Illustration: M. Muñoz-Echeverría

Observing the Universe at millimetre wavelengths - Grenoble 26-30/06/2023

OVERVIEW

I. Introduction:

- Galaxy clusters in the context of the H_0 tension;

II. Method:

- Galaxy clusters as cosmological probes
  - Cosmological rulers;
  - Different inferences of thermodynamical profiles;
  - Hydrodynamical simulations;
- Data analysis
  - SZ signal;
  - X-ray signal;
- The samples

III. Results:

- Observed sample
  - η_T distribution;
- Simulated sample
  - New $\mathcal{B}$ bias;
- Cosmological inference
  - H_0 posterior;

IV. Discussion & Conclusion

INTRODUCTION

Galaxy clusters in the context of the H_0 tension

During the last decades, H_0 measurements became remarkably precise, especially for early-Universe (CMB-driven) and local Universe (SN1a-based) estimates.

However, the two methods start to disagree with a significant bias, at a level of 4σ with the latest measurements.

This bias survived several attempts of independent reanalyses or the inclusion of more sophisticated of systematics.

Indications of new physics beyond the concordance ΛCDM?

We need more observables, independent of these two methods, to explore the problem.

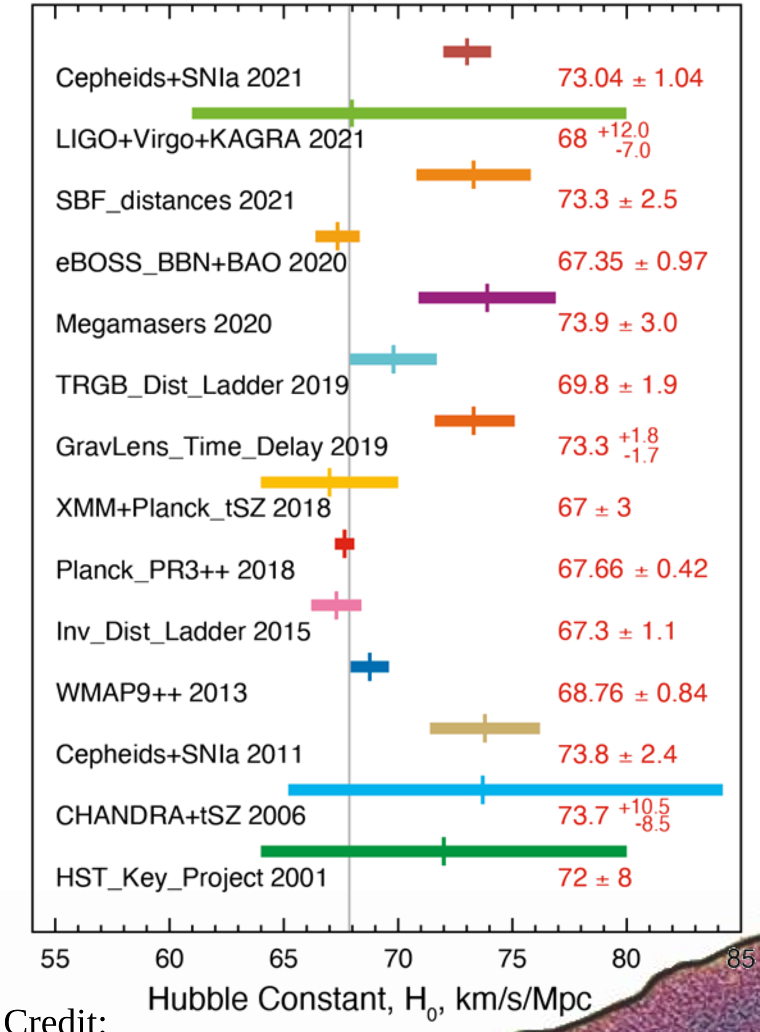


Image Credit:
NASA / LAMBDA
Archive Team

METHOD

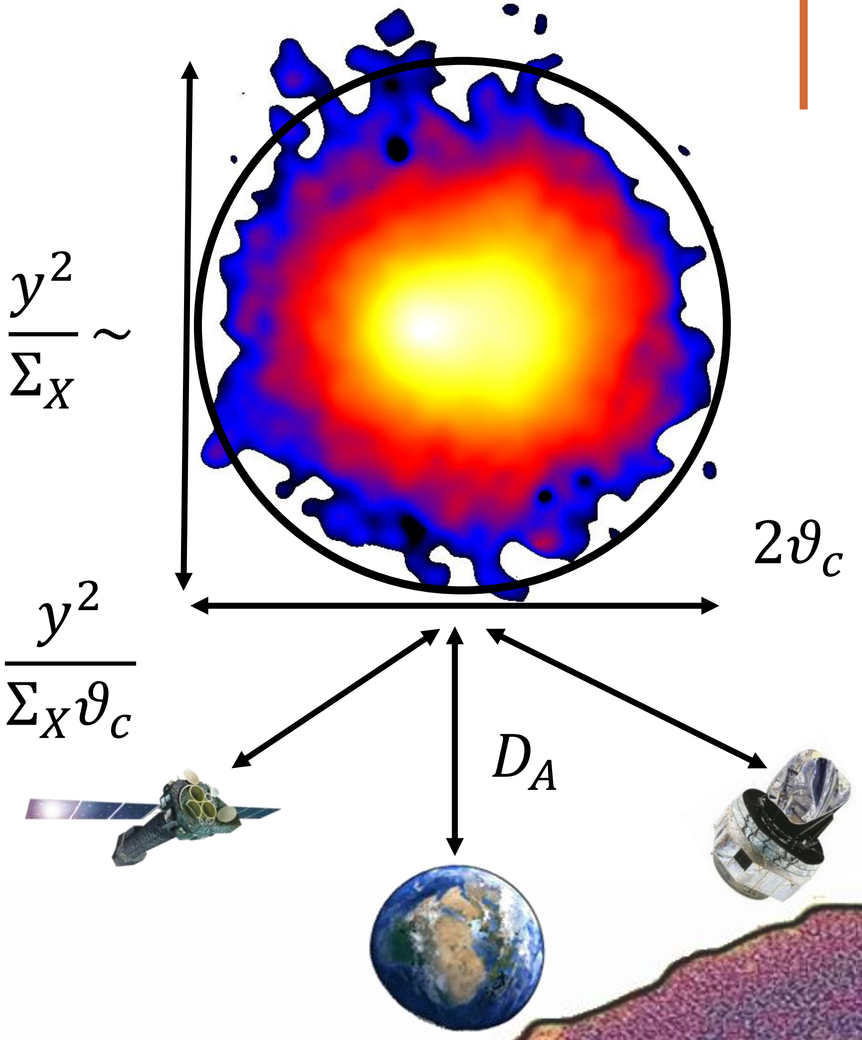
Galaxy clusters as cosmological probes: Cosmological rulers

It is possible to directly extract cosmological information by combining SZ and X-ray observables, as suggested by Cavaliere et al. (1977) and Silk & White (1978), with a distance-measuring technique.

X-ray: $\Sigma_X(\theta) = \frac{1}{4\pi(1+z)^4} \int n_e^2 \, \Lambda_X \, D_A d\theta \propto n_e^2 D_A \theta_c$

SZ: $y(\theta) = \frac{k\sigma_T}{m_e c^2} \int n_e \, T_e \, D_A d\theta \propto n_e D_A \theta_c$

$$D_a(z, H_0) \sim \frac{y^2}{\Sigma_X \vartheta_c}$$



Key quantities: Σ_X, y, redshift

ϑ_c: characteristic scale of the cluster

METHOD

Galaxy clusters as cosmological probes: Cosmological rulers

Cosmological information in $D_a(z)$ can be derived from the thermodynamical profile of the ICM by combining multiwavelength surveys of galaxy clusters, as done in Kozmanyan[1] et al. (2019).

$$\Sigma_X(\theta) = \frac{1}{4\pi(1+z)^4} \int n_e^2\big(r(\theta)\big)\,\Lambda_X\,dr$$

$$T_X(\theta) = \frac{\int w\,T\big(r(\theta)\big)\,dr}{\int w\,dr}$$

$$y(\theta) = \frac{\sigma_T}{m_e c^2} \int \eta_T \cdot P_e\big(r(\theta)\big)dr$$

$$= \frac{\sigma_T}{m_e c^2} \int \eta_T \cdot n_e\big(r(\theta)\big) \cdot kT_{SZ}\big(r(\theta)\big)dr$$

$$w = n_e^2/T^{3/4}$$

$$\eta_T = {}^{T_X}\!/_{T_{SZ}} = \frac{T_X}{(P_e/n_e)}$$

Key quantities:
η_T, redshift

[1]DOI: 10.1051/0004-6361/201833879

METHOD

Galaxy clusters as cosmological probes:
Different inferences of thermodynamical profiles

In the ideal case: $\eta_T \equiv 1$. Source of departure from unity:

METHOD

Galaxy clusters as cosmological probes:
Different inferences of thermodynamical profiles

In the ideal case: $\eta_T \equiv 1$. Source of departure from unity:

Underlying cosmological framework ($\mathcal{C}$):

$$\mathcal{C} = \left(\frac{\overline{D_a}}{D_a}\right)^{1/2} \cdot \left(\frac{n_p/n_e}{\overline{n_p}/\overline{n_e}}\right)^{1/2} \cdot \left(\frac{1 + 4\, {n_{He}}/{n_p}}{1 + 4\, {\overline{n_{He}}}/{\overline{n_p}}}\right)^{1/2}$$

Contain H_0

Trace the
He abundance

METHOD

Galaxy clusters as cosmological probes:
Different inferences of thermodynamical profiles

In the ideal case: $\eta_T \equiv 1$. Source of departure from unity:

Underlying cosmological framework ($\mathcal{C}$):

$$\mathcal{C} = \left(\frac{\overline{D_a}}{D_a}\right)^{1/2} \cdot \left(\frac{n_p/n_e}{\overline{n_p}/\overline{n_e}}\right)^{1/2} \cdot \left(\frac{1+4\,{}^{n_{He}}/_{n_p}}{1+4\,{}^{\overline{n_{He}}}/_{\overline{n_p}}}\right)^{1/2}$$

Contain H_0

Trace the
He abundance

Emitting ICM distribution property ($\mathcal{B}$):

$$\mathcal{B} = \frac{C_\rho^{1/2}}{e_{LOS}^{1/2}}$$

e_{LOS}: Elongation along the line of sight

C_ρ: clumpiness

METHOD

Galaxy clusters as cosmological probes:
Different inferences of thermodynamical profiles

In the ideal case: $\eta_T \equiv 1$. Source of departure from unity:

Underlying cosmological framework ($\mathcal{C}$):

$$\mathcal{C} = \left(\frac{\overline{D_a}}{D_a}\right)^{1/2} \cdot \left(\frac{n_p/n_e}{\overline{n_p}/\overline{n_e}}\right)^{1/2} \cdot \left(\frac{1+4\,{}^{n_{He}}/_{n_p}}{1+4\,{}^{\overline{n_{He}}}/_{\overline{n_p}}}\right)^{1/2}$$

Contain H_0

Trace the He abundance

Emitting ICM distribution property ($\mathcal{B}$):

$$\mathcal{B} = \frac{C_\rho^{1/2}}{e_{LOS}^{1/2}}$$

$$\boxed{\eta_T = b_n \times \mathcal{C} \times \mathcal{B}}$$

b_n: all other possible systematics

e_{LOS}: Elongation along the line of sight

C_ρ: clumpiness

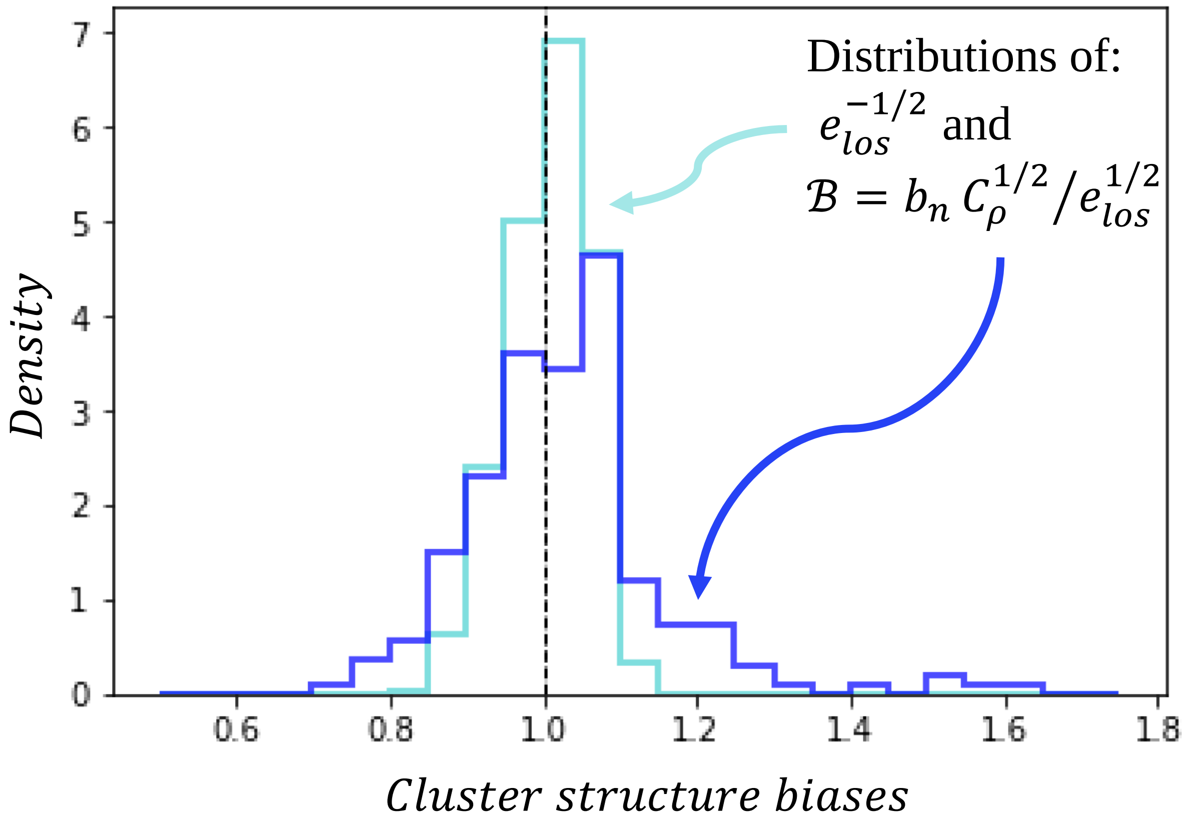
METHOD

Galaxy clusters as cosmological probes: Hydrodynamical simulations

We need hydrodynamical simulations to disentangle the cosmological information from the cluster structure bias.

For a simulated sample of galaxy clusters, the cosmological framework is set from the beginning: $\mathcal{C} \equiv 1$ and $\eta_T = b_n \mathcal{B}$.

From Kozmanyan et al. (2019)



METHOD

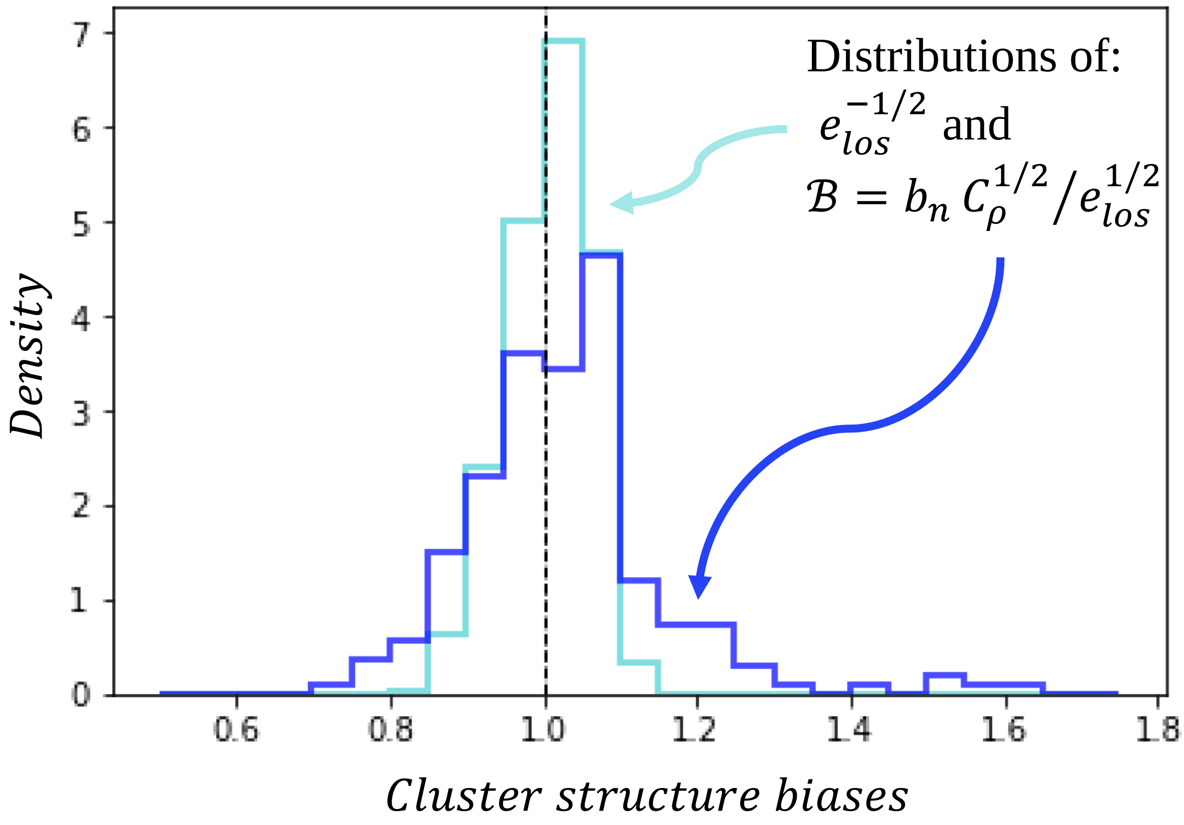
Galaxy clusters as cosmological probes: Hydrodynamical simulations

We need hydrodynamical simulations to disentangle the cosmological information from the cluster structure bias.

For a simulated sample of galaxy clusters, the cosmological framework is set from the beginning: $\mathcal{C} \equiv 1$ and $\eta_T = b_n \mathcal{B}$.

Thus, it is possible to use the $\mathcal{B}$ distribution in the H_0 derivation with a Bayesian approach:

From Kozmanyan et al. (2019)



$$P(H_0) = \int \mathcal{L}\left(\left\{\eta_T^{(i)}\right\} \mid H_0, \Omega_m, Y, \{\mathcal{B}_i\}\right) p(\{\mathcal{B}_i\}) p(H_0) p(\Omega_m) p(Y) d\Omega_m dY d\mathcal{B}_1 \ldots d\mathcal{B}_N$$

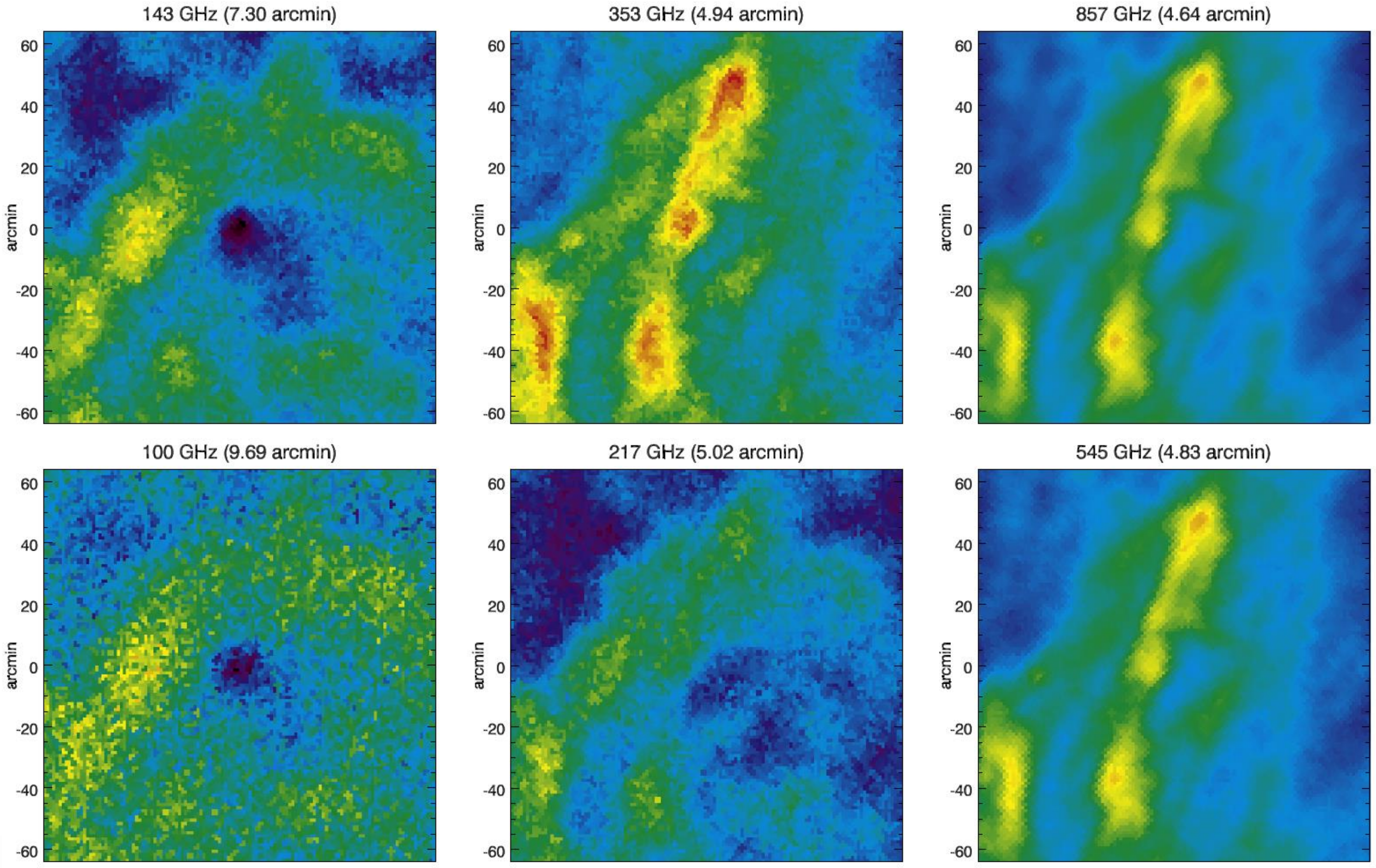
METHOD

Data analysis:
SZ signal

The SZ and X-ray signals are extracted with an optimised application of the Bourdin[2] et al. (2017) work.

- Instrument: *Planck*-HFI data;
- Wavelet denoising and reconstruction of HFI maps;
- Parametric component separation;
- Forward modelling of Nagai et al. (2006) pressure profile.

[2]DOI: 10.3847/1538-4357/aa74d0



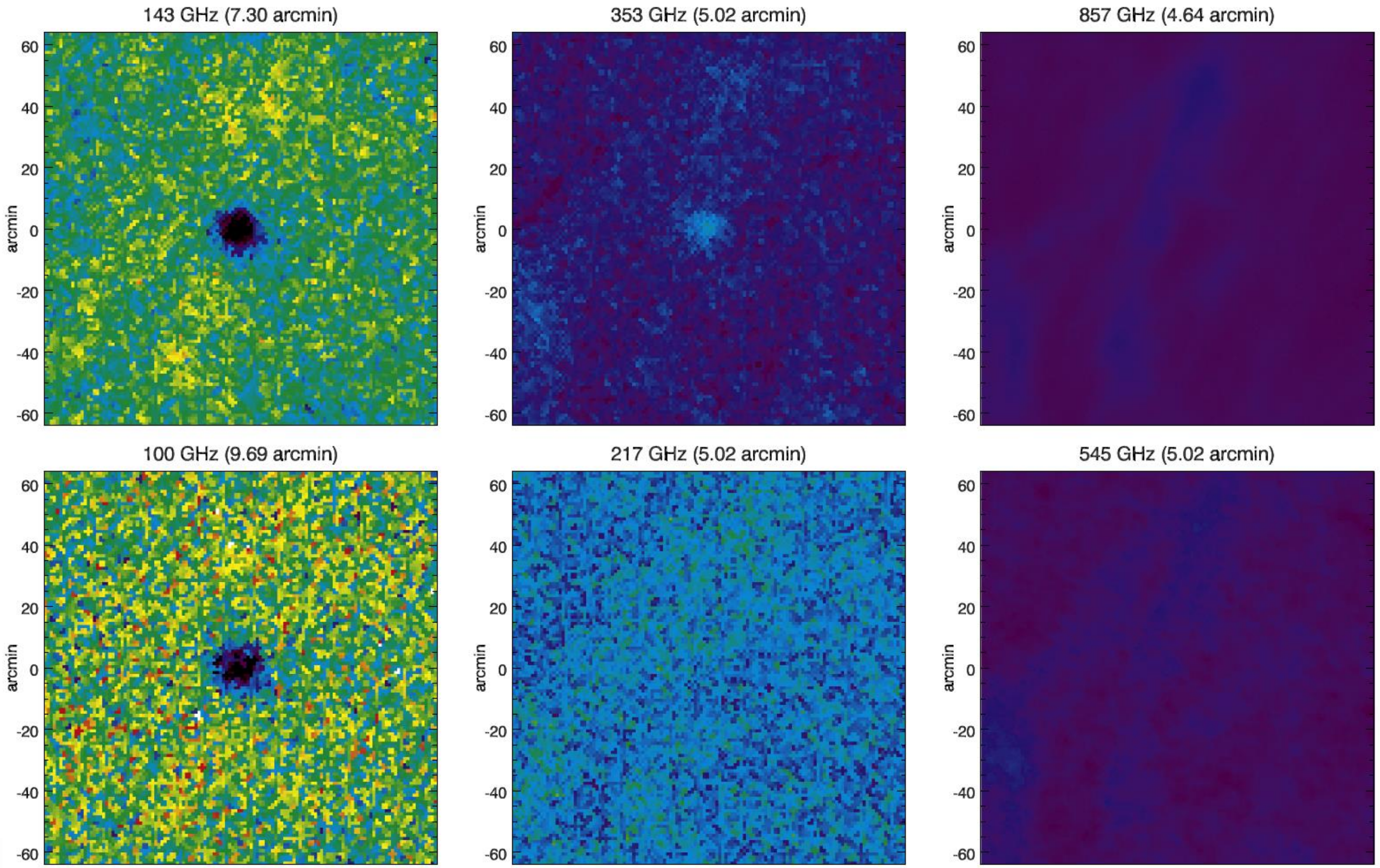
Planck-HFI frequency maps of A2163 from Bourdin et al. (2017).

METHOD

Data analysis:
SZ signal

The SZ and X-ray signals are extracted with an optimised application of the Bourdin[2] et al. (2017) work.

- Instrument: *Planck*-HFI data;
- Wavelet denoising and reconstruction of HFI maps;
- Parametric component separation;
- Forward modelling of Nagai et al. (2006) pressure profile.

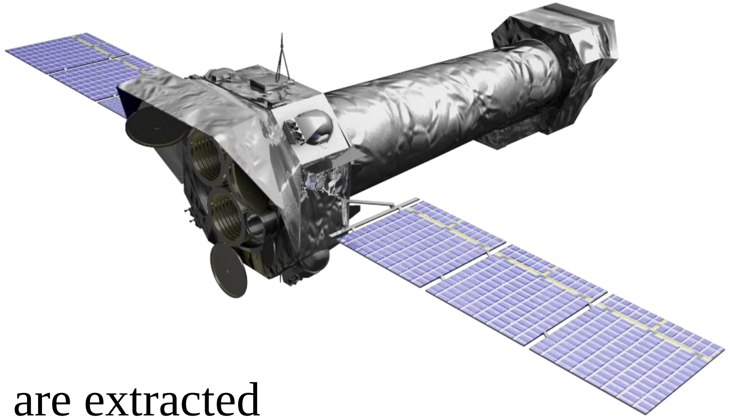


Filtered *Planck*-HFI SZ frequency maps of A2163 from Bourdin et al. (2017).

[2]DOI: 10.3847/1538-4357/aa74d0

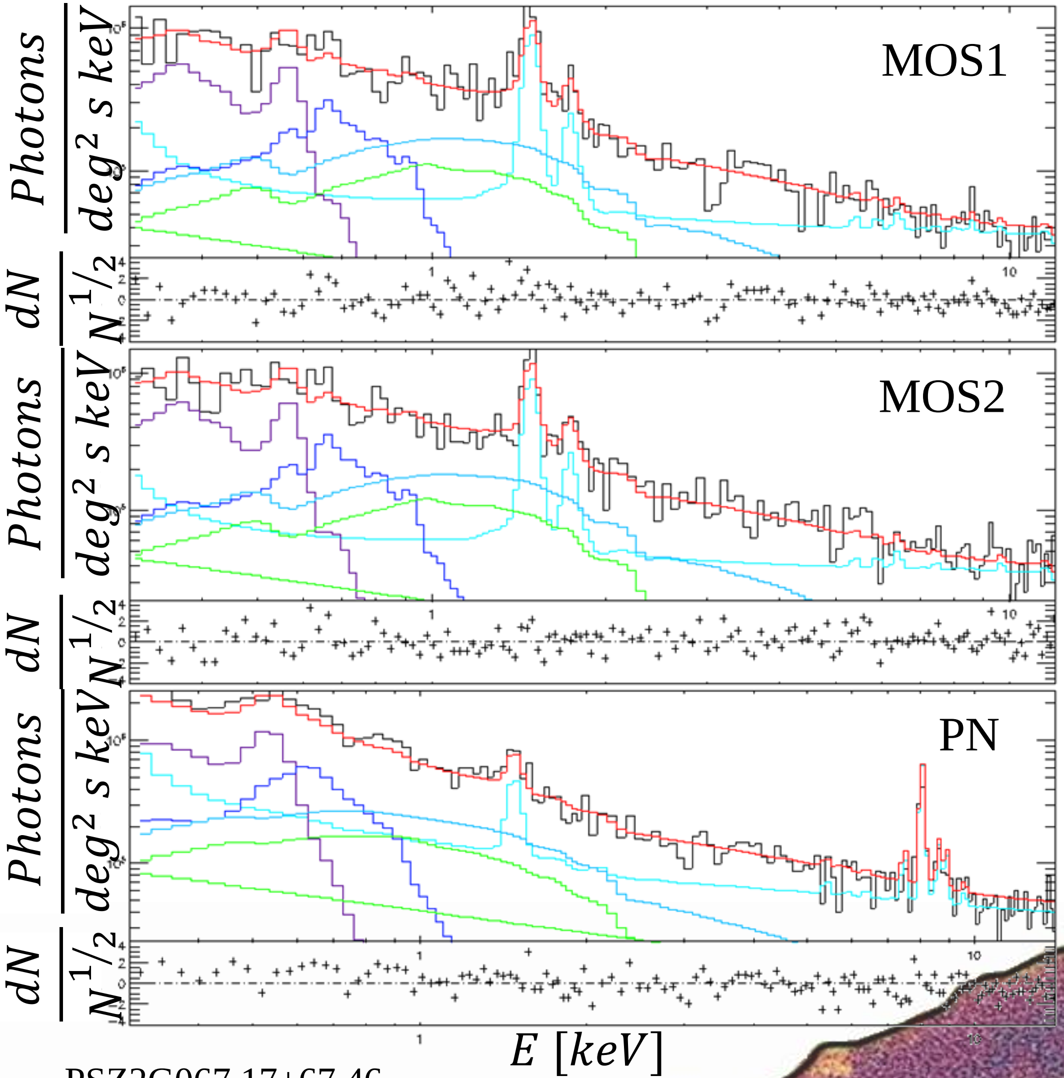
METHOD

Data analysis:
X-ray signal



The SZ and X-ray signals are extracted with an optimised application of the Bourdin[2] et al. (2017) work.

- Instruments: XMM-*Newton* telescope EPIC cameras;
- Parametric spectral modelling of the astrophysical (CXB and Galactic emission) and instrumental components;
- Forward modelling of density and temperature Vikhlinin et al. (2006) profiles.



PSZ2G067.17+67.46
Background spectral analysis

[2]DOI: 10.3847/1538-4357/aa74d0

The samples

For the Bayesian analysis, we need an observed and a simulated sample of clusters.

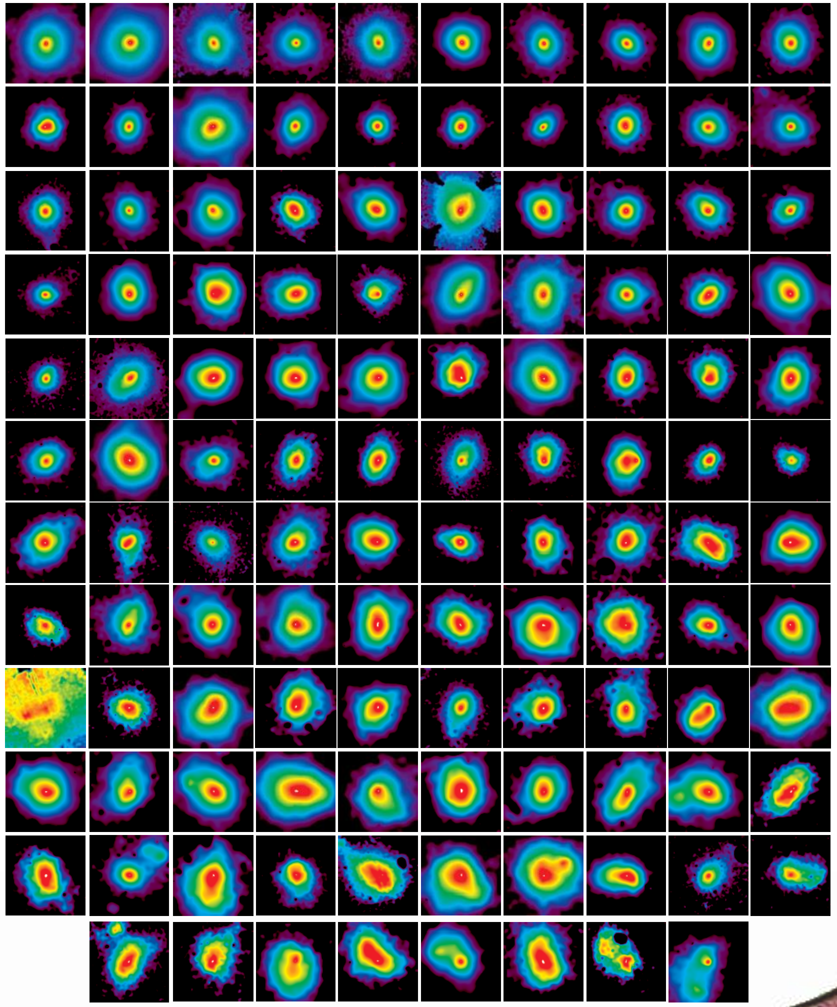
METHOD

The samples

For the Bayesian analysis, we need an observed and a simulated sample of clusters.

Observed sample: the **CHEX-MATE**[3] project.

- 117 clusters (over 118) extracted from PSZ2 catalogue within the cosmological mask and with *Planck* S/N > 6.5;
- Homogeneous and high-quality X-ray exposures: S/N=150;
- Temperature measurements with statistical 15% of accuracy at R_{500};
- Temperature profiles with more than 8 radial bins.



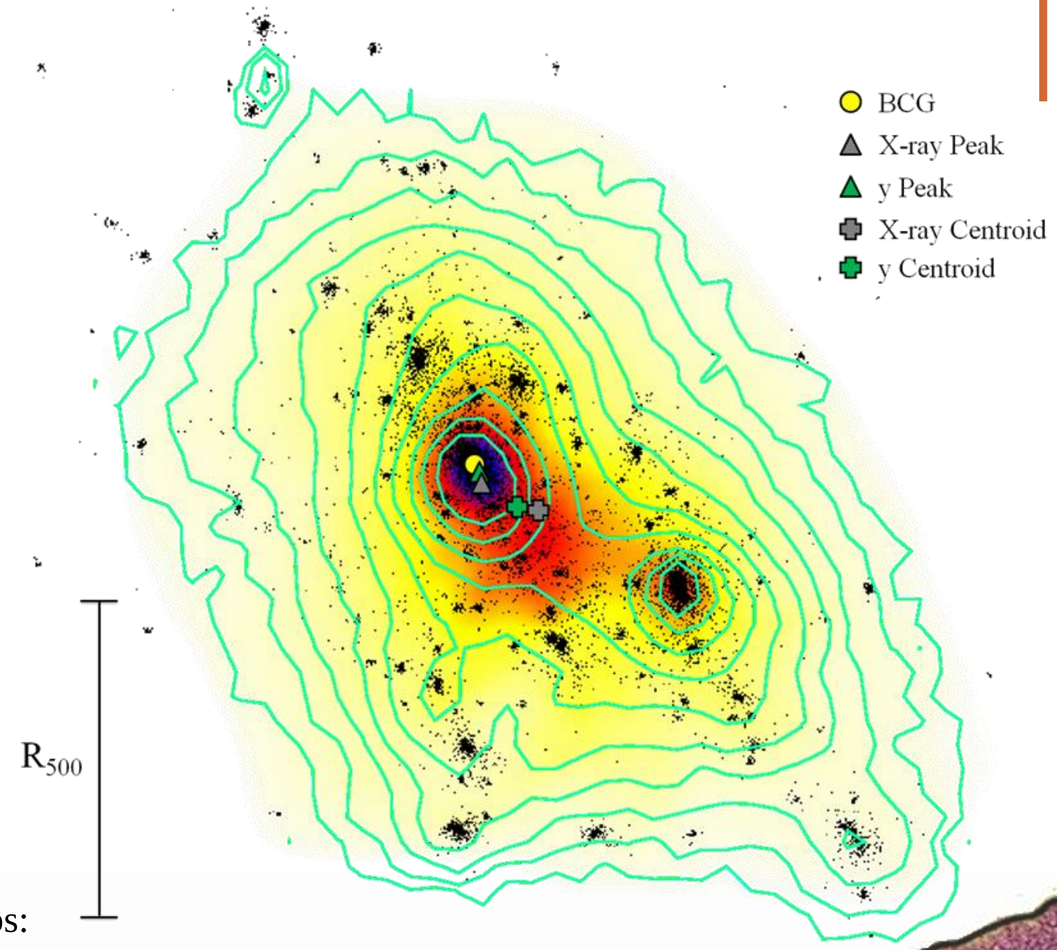
3: xmm-heritage.oas.inaf.it

The samples

For the Bayesian analysis, we need an observed and a simulated sample of clusters.

Synthetic sample - **THE THREE HUNDRED**[4] project

- Gadget-X run. Hydrodynamic simulation with a cosmology consistent with Planck Collaboration et al. (2016);
- New $\mathcal{B}$ bias applying the X-ray-SZ pipeline on a simulated sample of 975 clusters from the snapshot at $z = 0$.



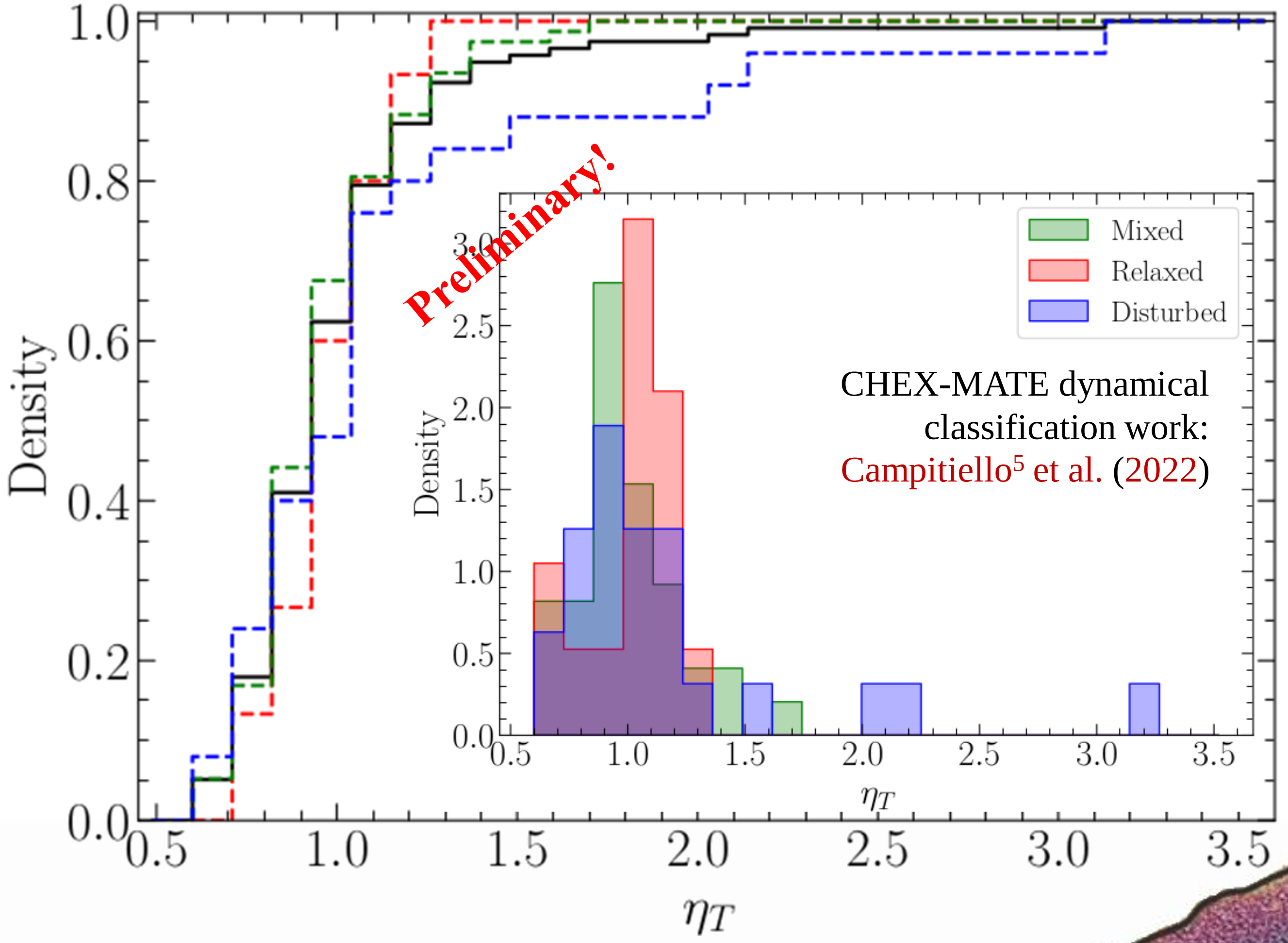
Mock maps:
Contours: X-ray
Colour map: tSZ
Black dots: Optical SDSS

4: the300-project.org

RESULTS

Observed sample: η_T distribution

- Median: $\eta_T = 0.98^{+0.23}_{-0.19}$ (± 16th, 84th percentiles);
- The distribution is compatible with the expected value ($\eta_T \equiv 1$);
- The analysis agree also with previous estimate available in the literature:
  - X-COP sample: $\eta_T = 0.9624 \pm 0.0013$;
  - Bourdin et al. (2017) low-redshift sample: $\eta_T = 1.01$ (median).



CHEX-MATE dynamical classification work: Campitiello[5] et al. (2022)

[5]DOI: 10.1051/0004-6361/202243470

RESULTS

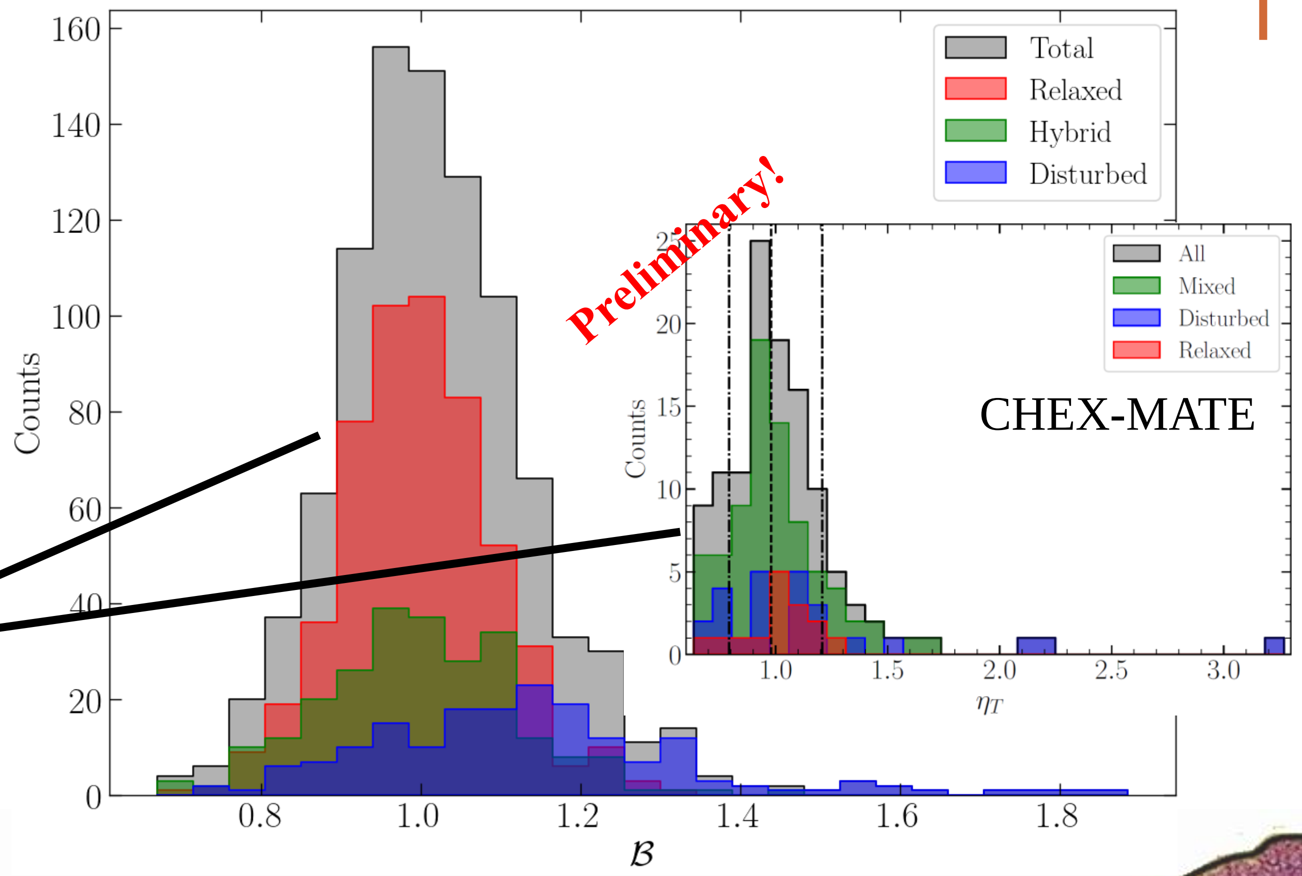
Simulated sample:
New $\mathcal{B}$ bias

With the simulated sample, we can:

- Derive a prior distribution $\mathcal{B}$ for the cosmological inference;
- Study, with more clusters, the effect of the dynamical and morphological state in η_T distribution.

Similar distribution of the observed CHEX-MATE sample!

THE THREE HUNDRED clusters



RESULTS

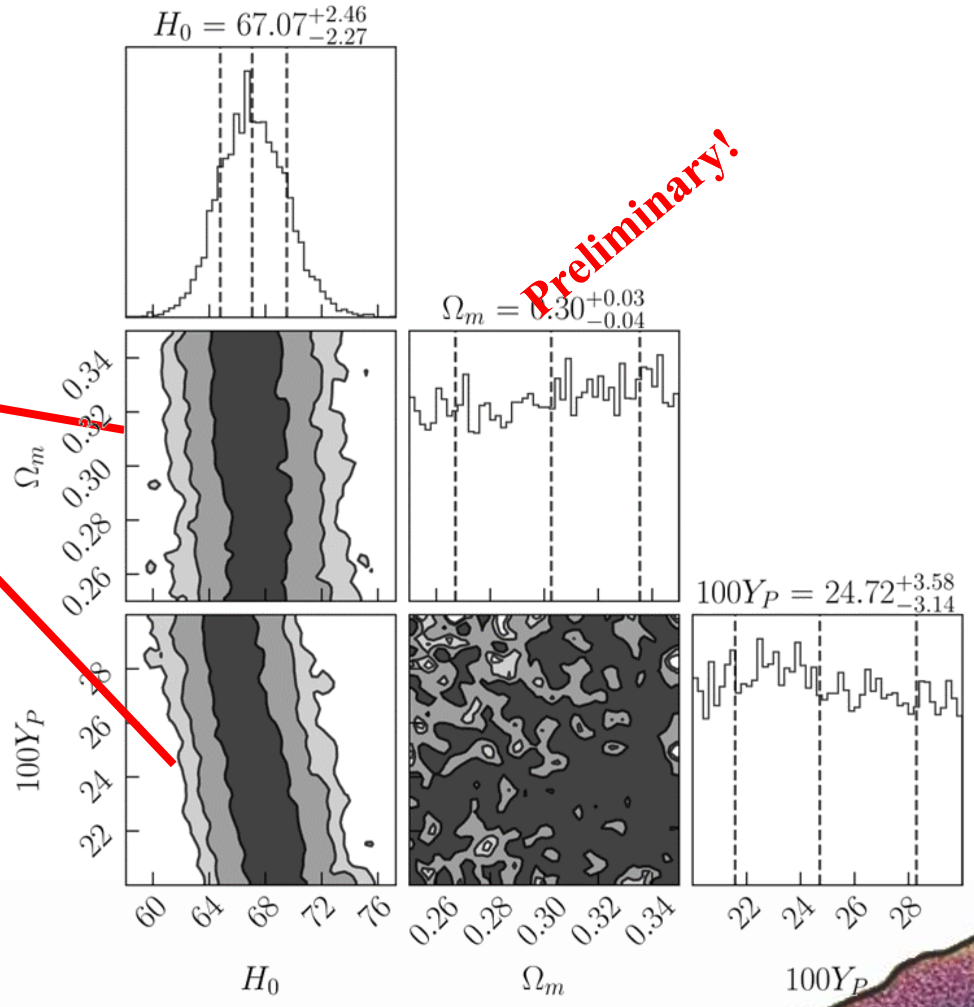
Cosmological inference

Using the $\mathcal{B}$ distribution from the synthetic sample, we can extract cosmological information from η_T.

The method is not sensitive enough to recover more than one free parameter (H_0) at a time ($\eta_T \propto D_A^{-1/2}$).

Bayesian prior setup of the MCMC runs

Parameter	Prior	Min	Max	μ	σ
H_0	Uniform	50	100		
$\mathcal{B}_i$	Uniform	0	1		
Ω_m	Uniform	0.25	0.35		
	Normal	0	1	0.3153	0.0073
Y_P	Uniform	0.20	0.30		
	Normal			0.243	0.024



RESULTS

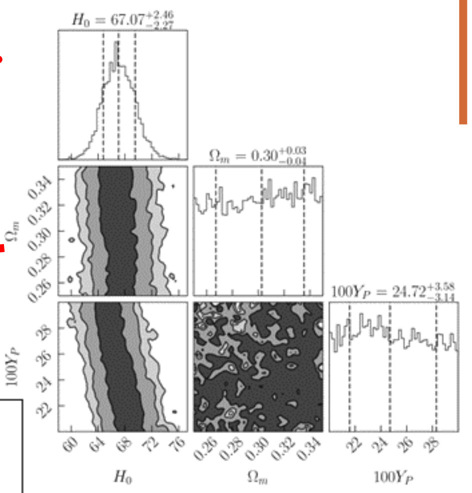
Cosmological inference

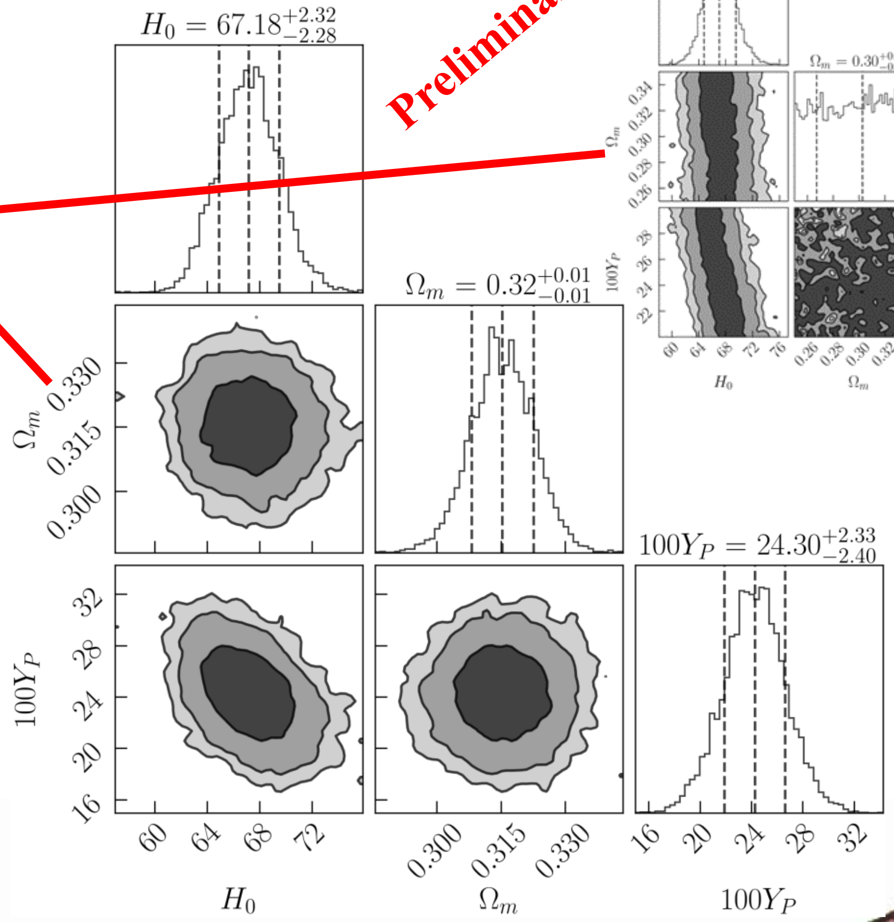
Using the $\mathcal{B}$ distribution from the synthetic sample, we can extract cosmological information from η_T.

The method is not sensitive enough to recover more than one free parameter (H_0) at a time ($\eta_T \propto D_A^{-1/2}$).

Bayesian prior setup of the MCMC runs

Parameter	Prior	Min	Max	μ	σ
H_0	Uniform	50	100		
$\mathcal{B}_i$	Uniform	0	1		
Ω_m	Uniform	0.25	0.35		
	Normal	0	1	0.3153	0.0073
Y_P	Uniform	0.20	0.30		
	Normal			0.243	0.024





RESULTS

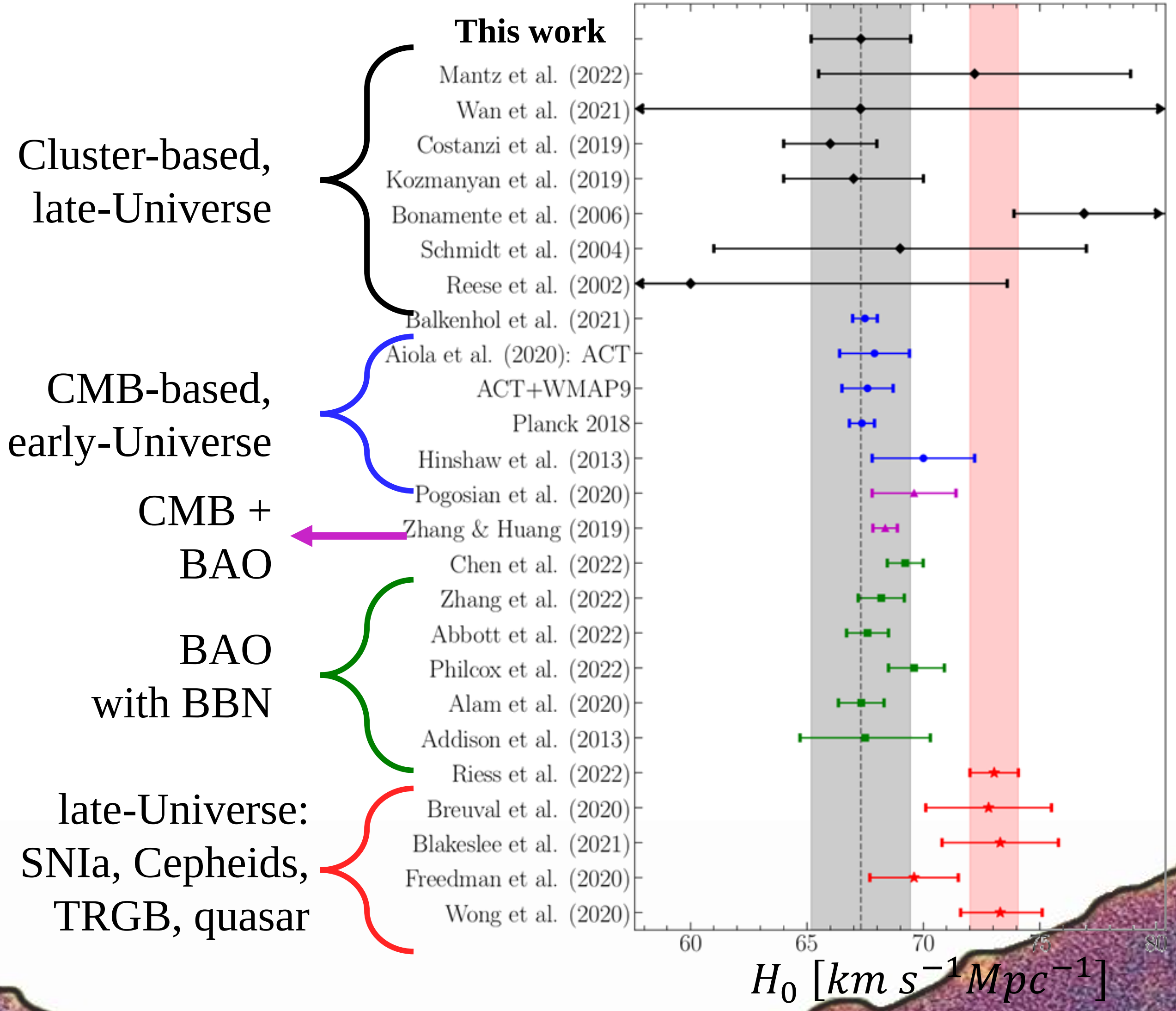
Cosmological inference: H_0 posterior

With the Kozmanyan et al. (2019) method, we have a **preliminary** measure for the CHEX-MATE clusters:

$$H_0 \sim 67.2 \pm 2.3 \; km \; s^{-1} \; Mpc^{-1}$$

Compatibly with the precedent estimates based on multiwavelength cluster studies or with early-Universe and LSS estimates.

More in tension with late-Universe SNIa, Cepheids, TRGB, quasars.



DISCUSSION & CONCLUSION

Potential systematics

- Astrophysical uncertainties: (N_H, X-ray/millimetre contaminants, relativistic SZ effect, etc.);
- X-ray temperature cross-calibration (see Wan et al. 2021):
  - Cross-calibration depends on the cluster temperature (higher at higher temperatures);
  - Temperatures from *Chandra* and XMM are known to disagree;
  - XMM EPIC cameras give different results if not jointly used;
- Hydrodynamical simulations:
  - Are we sure that our synthetic samples are accurate representations of real clusters?

✓ Our results on η_T or H_0 are compatible with precedent estimates from *Planck* and XMM and with Wan et al. (2021);

✓ Our method for H_0 is mainly driven by the thermodynamical state at intermediate-large scales, where the temperature is lower;

✓ Different hydrodynamical simulations (Rasia et al. 2015 and THE THREE HUNDRED Gadget-X run) give compatible estimates for H_0;

✓ More tests can be done for new runs (as Gadget-Simba) or using new hydrodynamical simulations with different physics.

DISCUSSION & CONCLUSION

- ✓ The CHEX-MATE Project allows accurate characterisation of the thermodynamical state of galaxy clusters with its sample definition and observational strategy;
- ✓ Accurate mass selection function with 117 clusters in total, double compared to Kozmanyan et al. (2019) and a factor of 10 more than Wan et al. (2021) or the X-COP sample;
- ✓ Need hydrodynamical simulation priors, but it is not restricted to only relaxed sample;
- ✓ Our local estimate for H_0 agrees with the precedent constraints based on XMM, *Chandra*, and *Planck*;
- ✓ The uncertainty on H_0 is continually decreasing with the cluster size;

Future prospective:

- Possibility to extend the analysis to larger samples (e.g. early-SZ+CHEX-MATE ~ 160 objects).
- For 200 clusters: 2% uncertainty level;
- Combination with other X-ray or millimetre instruments (e.g. SPT, Chandra);
- Inclusion of more systematics in the model, such as the relativistic SZ effect or temperature cross calibration;
- Possible combination with other cluster probes, such as the f_{gas} (e.g. $f_{gas} \propto D_A^{3/2}$)

THANKS FOR THE ATTENTION!

Illustration: M. Muñoz-Echeverría