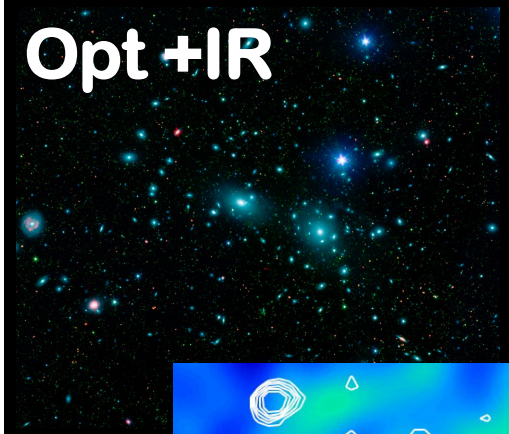
The Cluster XMM-Heritage project CHEX-MATE:

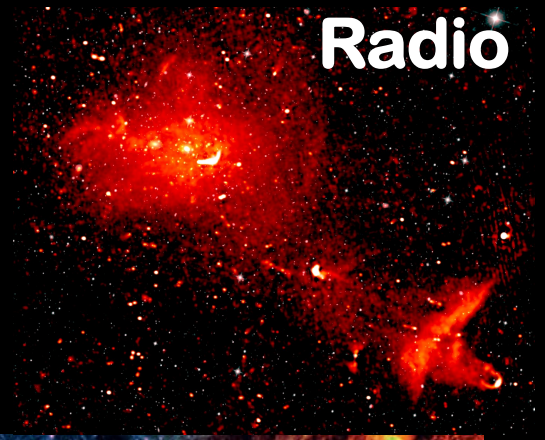
current results and future prospects

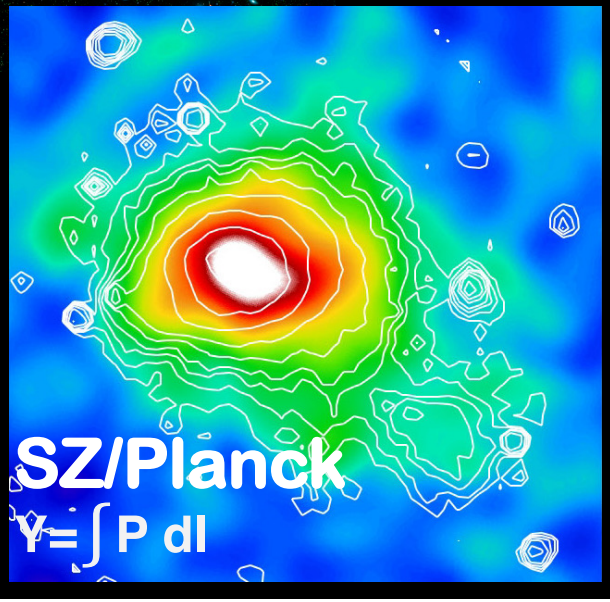
Stefano **Ettori**

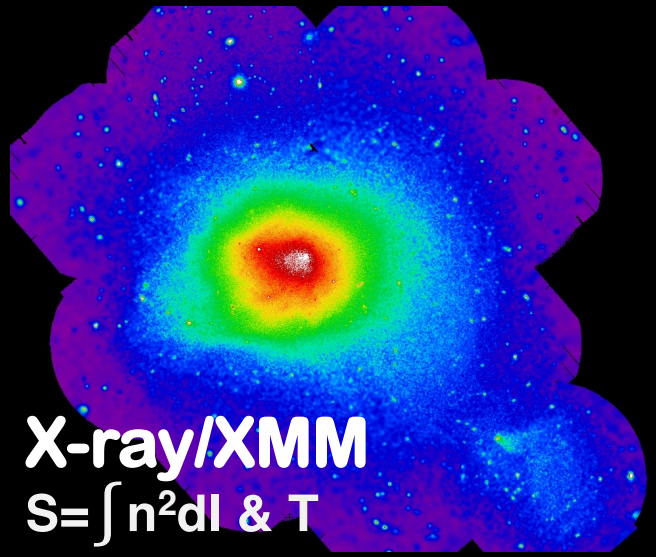
INAF-OAS Bologna

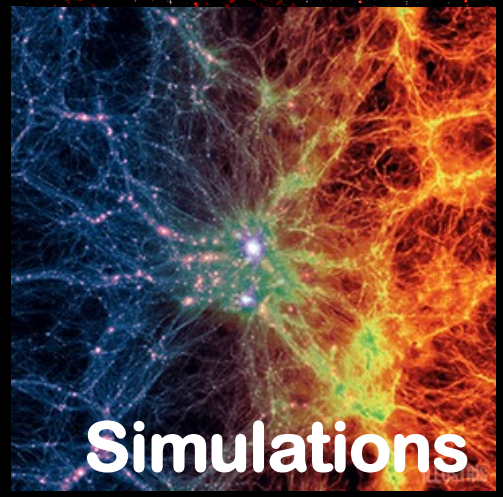
& **CHEX-MATE collaboration**



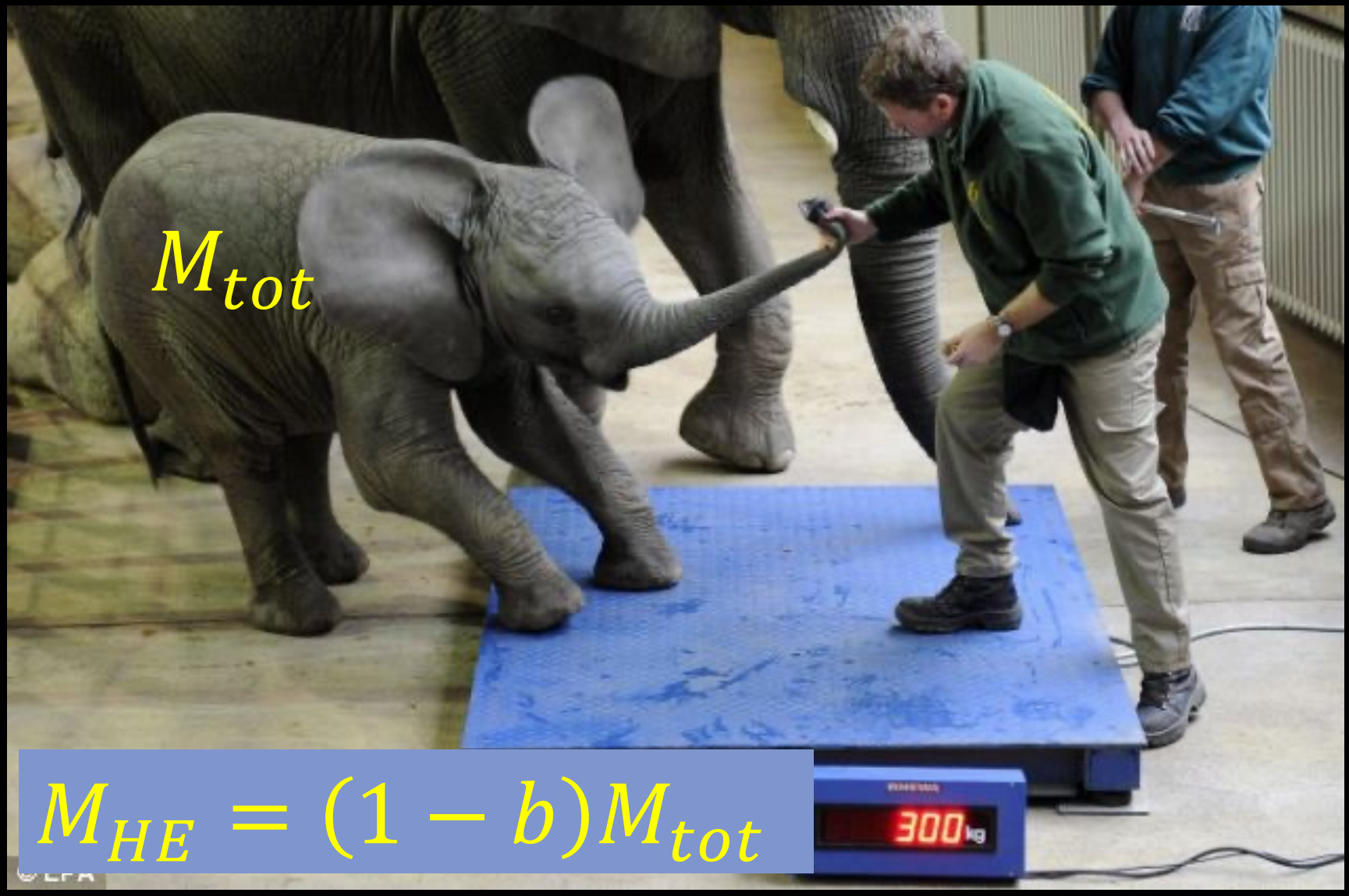








Big problem:
how to weigh Galaxy Clusters



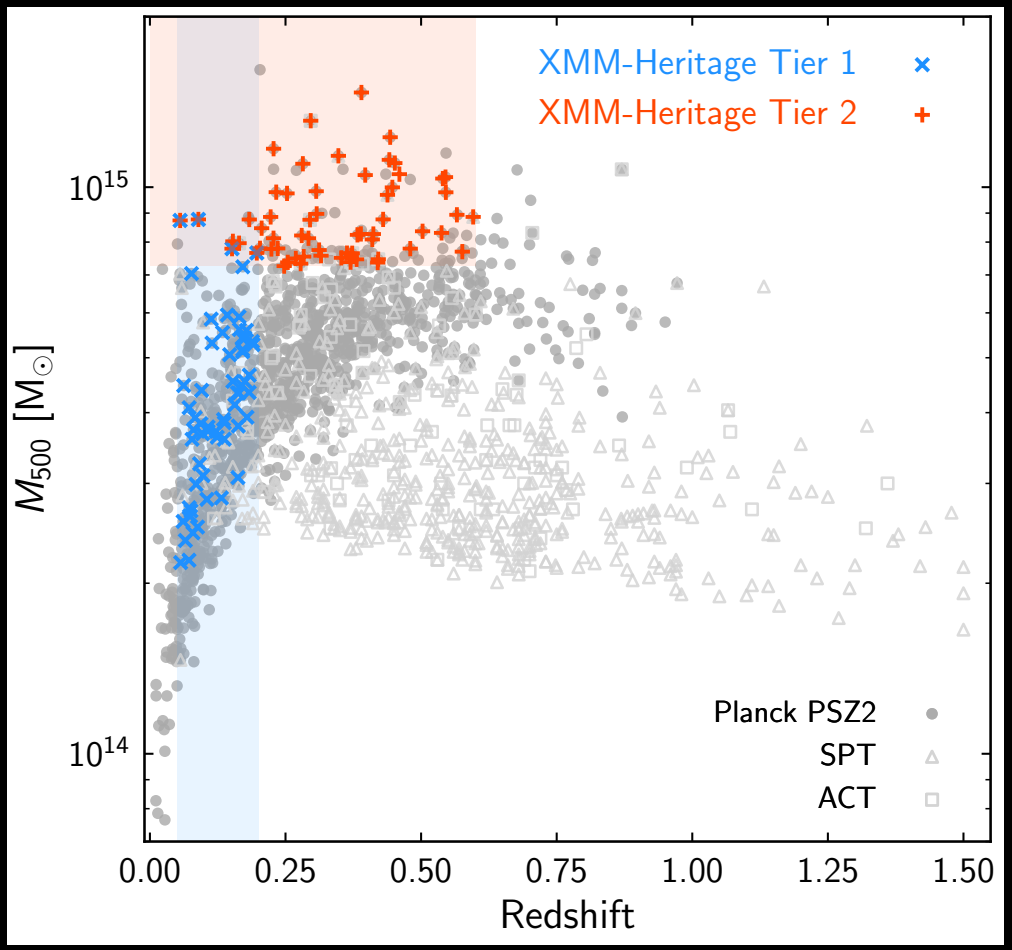
An XMM-Newton Multi-Year Heritage Program

Witnessing the culmination of structure formation in the Universe

URL: xmm-heritage.oas.inaf.it

CHEX-MATE (the Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation): **3 Msec** over the period 2018-22 to survey ***homogenously*** 118 Planck-SZ selected objects comprising an unbiased census of:

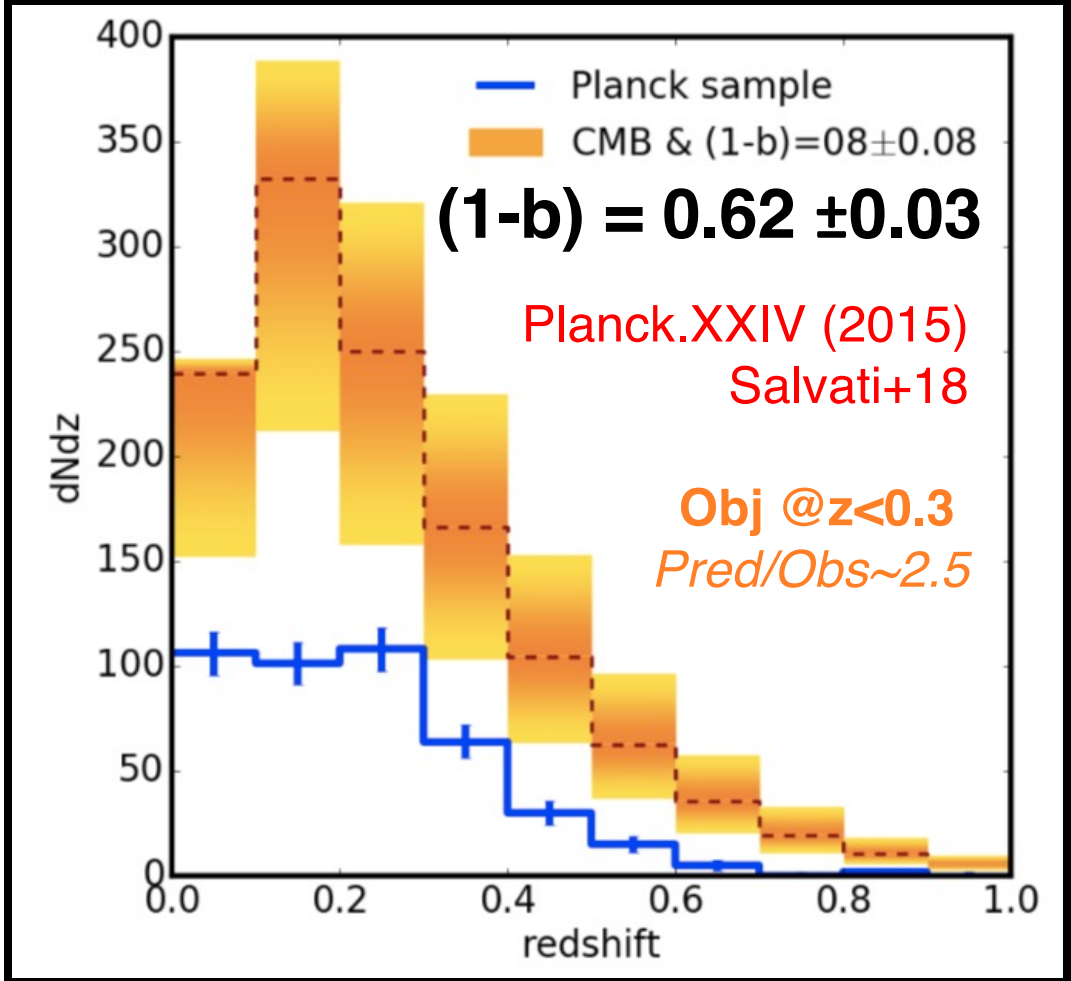
- *the population of clusters at the most recent time ($z < 0.2$)*
- *the most massive objects to have formed thus far in the history of the Universe*



Goals of CHEX-MATE

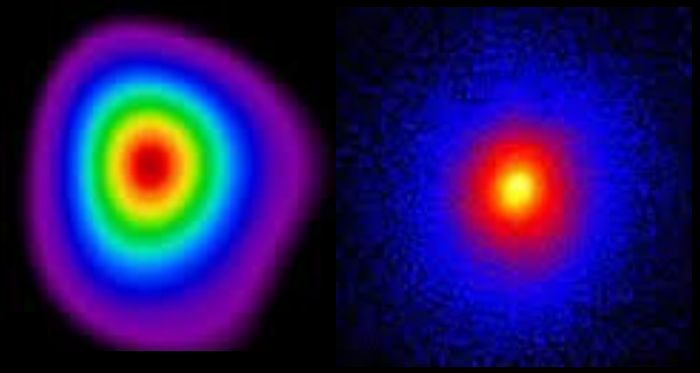
Selection for the 3 Msec *program:*

SNR>6.5; z ∈ [0.05, 0.6]; $M_{Tier\text{-}2}$>7.25e14



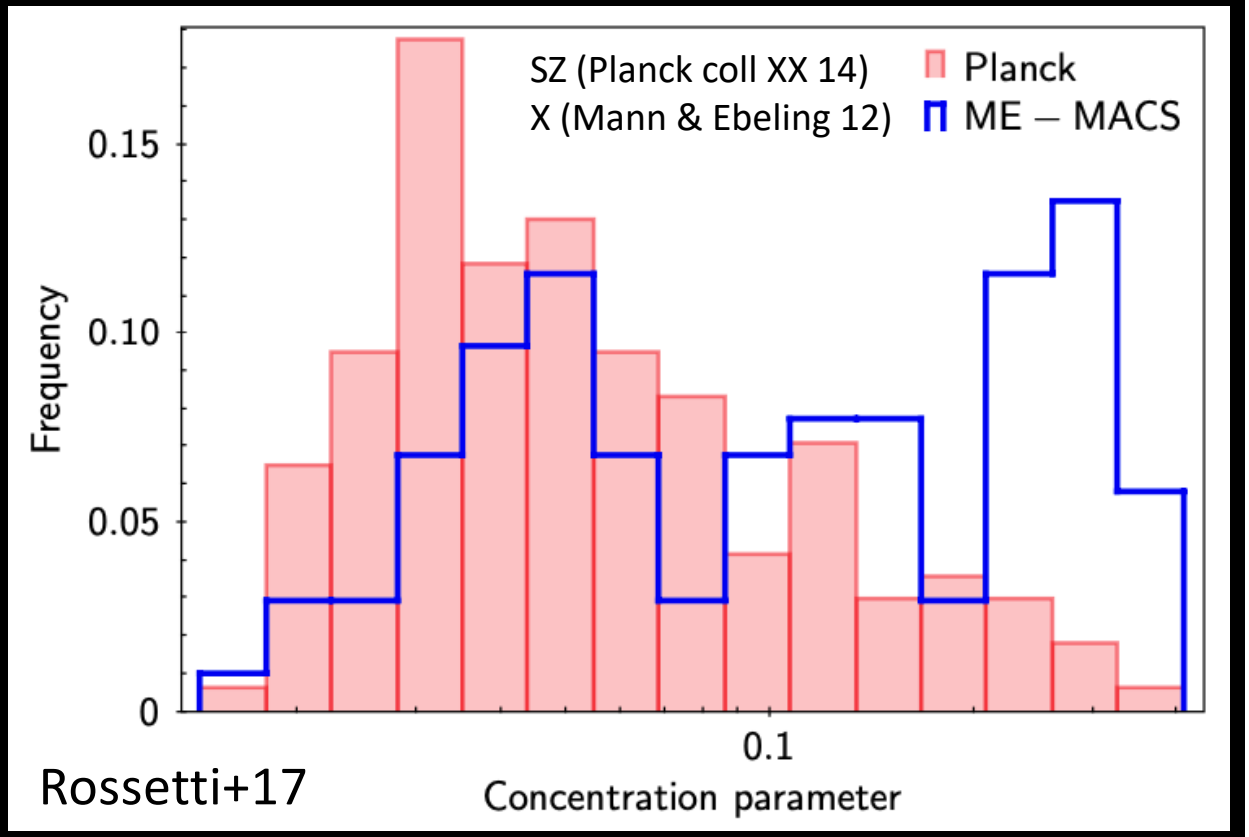
- What is the true mass scale?
- What are the properties of the »true» cluster population?
- How do these properties change over time?
- Provide a unique reference for evolution studies and numerical modelling
- Legacy for Next Generation missions
- **Exposure time**: *to map homogeneously the T profile in 8+ annuli at least up to R_{500} with a precision of ±15% in the in [0.8–1.2]R_{500} annulus*

SZ *vs* X-ray selection



A1835

$I_{SZ} \sim P_g$ $I_x \sim n_g^2$



X-ray selected objects: ~60% tends to be relaxed/CC systems

SZ selected objects: ~30% are relaxed/CC clusters; no z-evolution

An XMM-Newton Multi-Year Heritage Program

Witnessing the culmination of structure formation in the Universe

Steering Committee: **S. Ettori** (PI), **G. Pratt** (PI), **D. Eckert, F. Gastaldello, R. Gavazzi, S. Kay, L. Lovisari, B. Maughan, E. Pointecouteau, M. Rossetti, M. Sereno, *M. Arnaud***

WG-X-ray (*chairs:* **Pratt** & **Rossetti**)
WG-SZ (*chairs:* **Pointecouteau** & **Sayers**)
WG-lensing (*chairs:* **Gavazzi** & **Umetsu**)
WG-galaxies (*chairs:* **Maurogordato** & **Sereno**)
WG-radio (*chairs:* **Bonafede** & **Cassano**)
WG-hydrosims (*chairs:* **Kay** & **Rasia**)

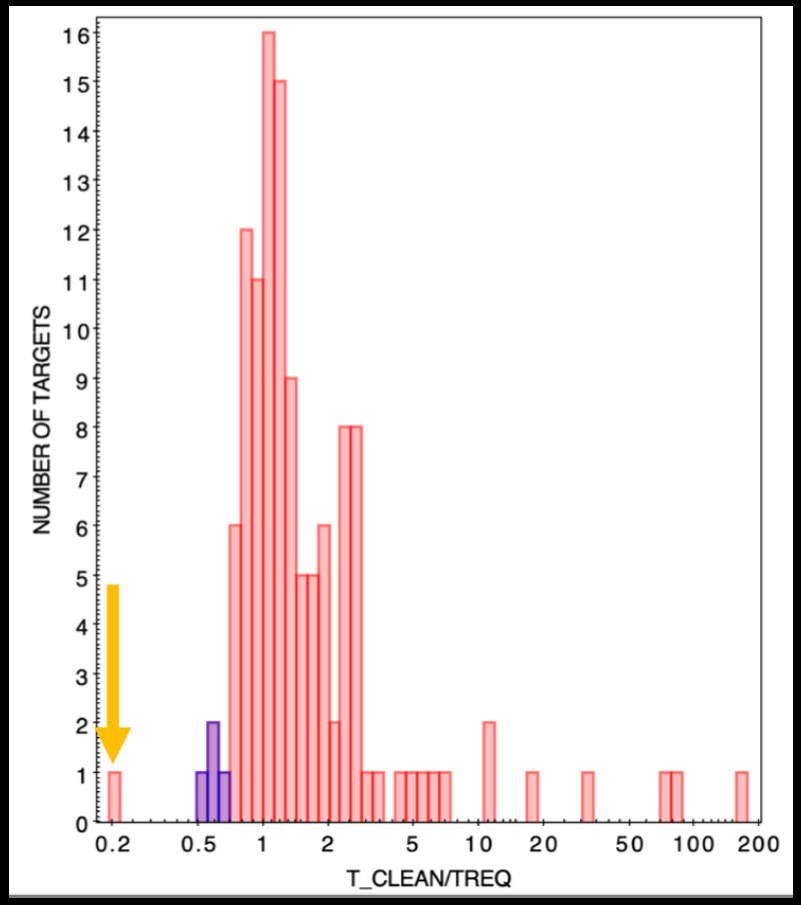
~80 collaborators from **12 countries** (France, Italy, Germany, Spain, Switzerland, UK, Australia, Chile, Japan, S.Africa, Taiwan, USA)

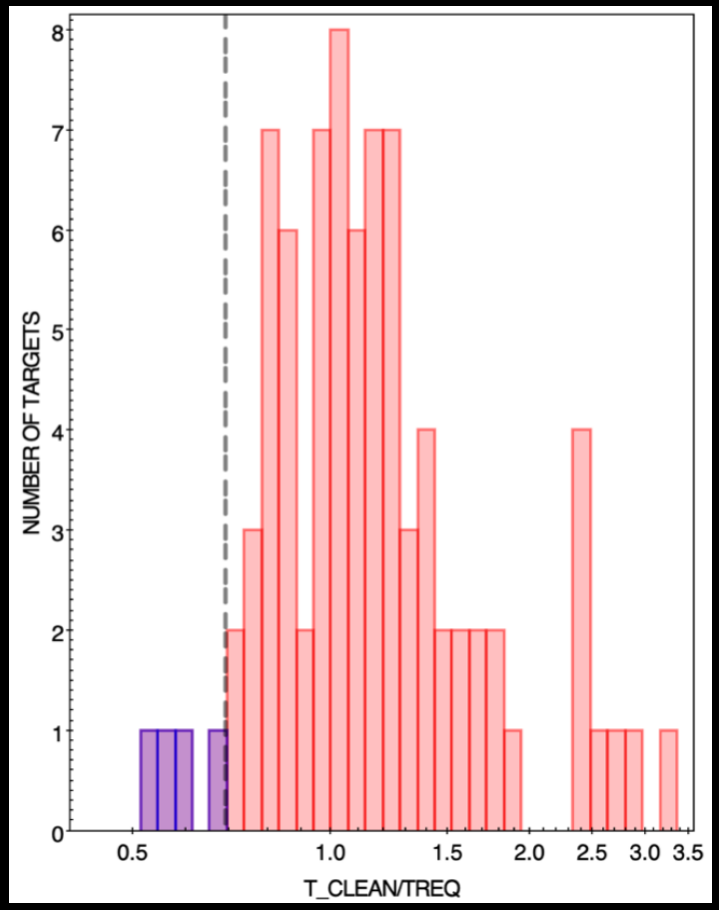
CHEX-MATE: *X-ray observations*

Observations started in 2018 and ended in ***May 2022***

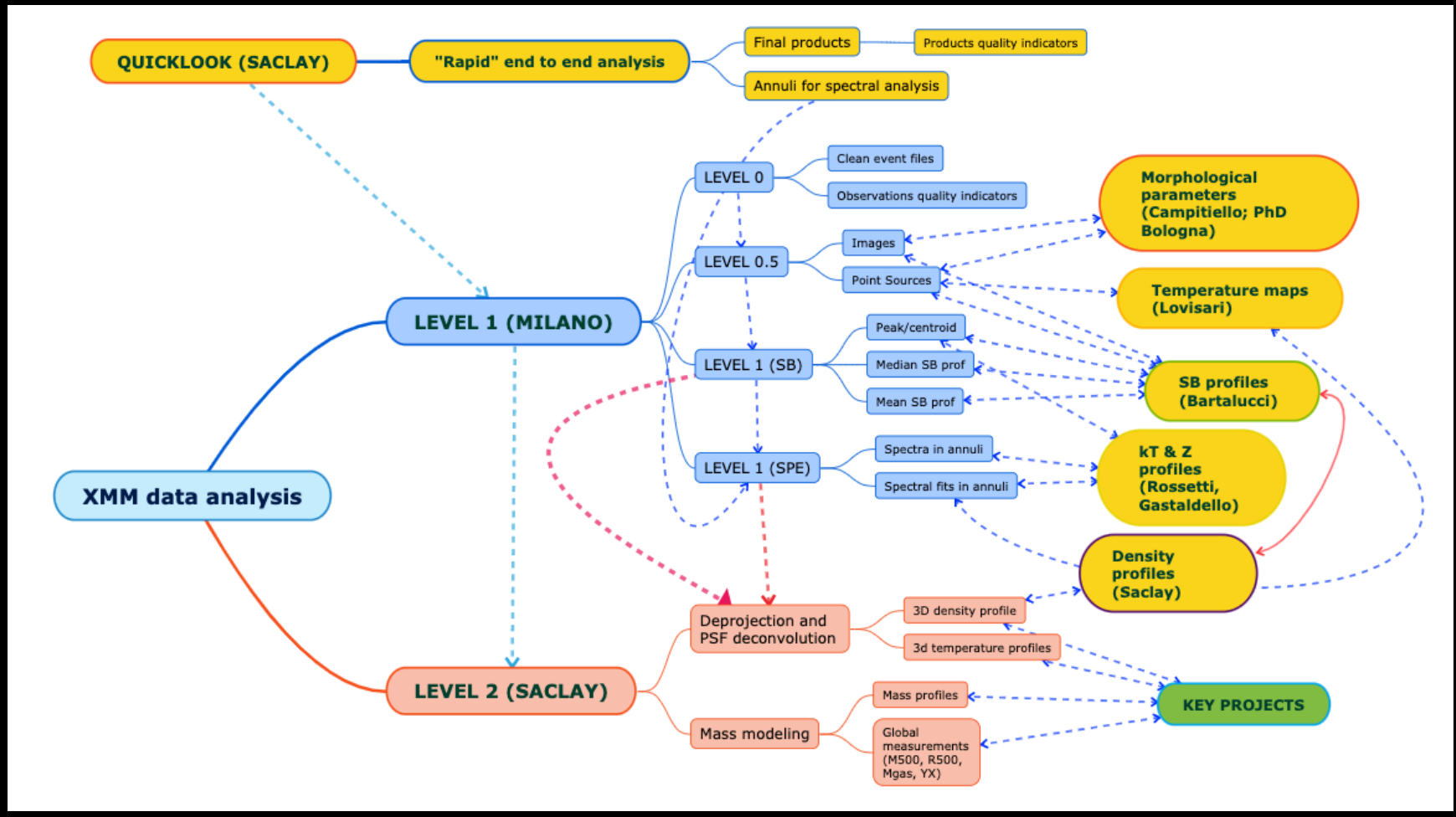
(Left) All exposures including archived ones (>4 Msec cleaned)

(right) our program (3.2 Msec tot; cleaned: 1.81 Msec; ~5 M-cts)





CHEX-MATE: *X-ray pipeline*



- All observations reduced up to images and good observations selected
- Mosaic images available for full sample
- Imaging and spectral analysis methods have been defined & implemented

CHEX-MATE: *publications*

1 ☐ 2021A&A...650A.104C 2021/06 cited: 30

The Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation. I. Programme overview

CHEX-MATE Collaboration; Arnaud, M.; Ettori, S. *and 66 more*

2 ☐ 2022A&A...665A.117C 2022/09 cited: 11

CHEX-MATE: Morphological analysis of the sample

Campitiello, M. G.; Ettori, S.; Lovisari, L. *and 17 more*

3 ☐ 2023A&A...672A.156O 2023/04 cited: 1

CHEX-MATE: Pressure profiles of six galaxy clusters as seen by SPT and Planck

Oppizzi, F.; De Luca, F.; Bourdin, H. *and 11 more*

4 ☐ 2023arXiv230503082B 2023/05

CHEX-MATE: Constraining the origin of the scatter in galaxy cluster radial X-ray surface brightness profiles

Bartalucci, I.; Molendi, S.; Rasia, E. *and 25 more*

CHEX-MATE: *ongoing projects*

Submitted papers

Paper title	Lead authors	KP	WG	Date of submission
CHEX-MATE: characterization of the ICM temperature distribution	L. Lovisari, S. Ettori	1	X/H	14/04/2023
CHEX-MATE: on the X-ray absorption and molecular content of the Interstellar Medium toward selected targets	H. Bourdin	1	X	09/06/2023
CHEX-MATE: A non-parametric deep learning technique to deproject and deconvolve galaxy cluster X-ray temperature profiles	A. Iqbal, G. W. Pratt, J. Bobin, M. Arnaud, E. Rasia	1	X/H	19/06/2023

Papers under internal review

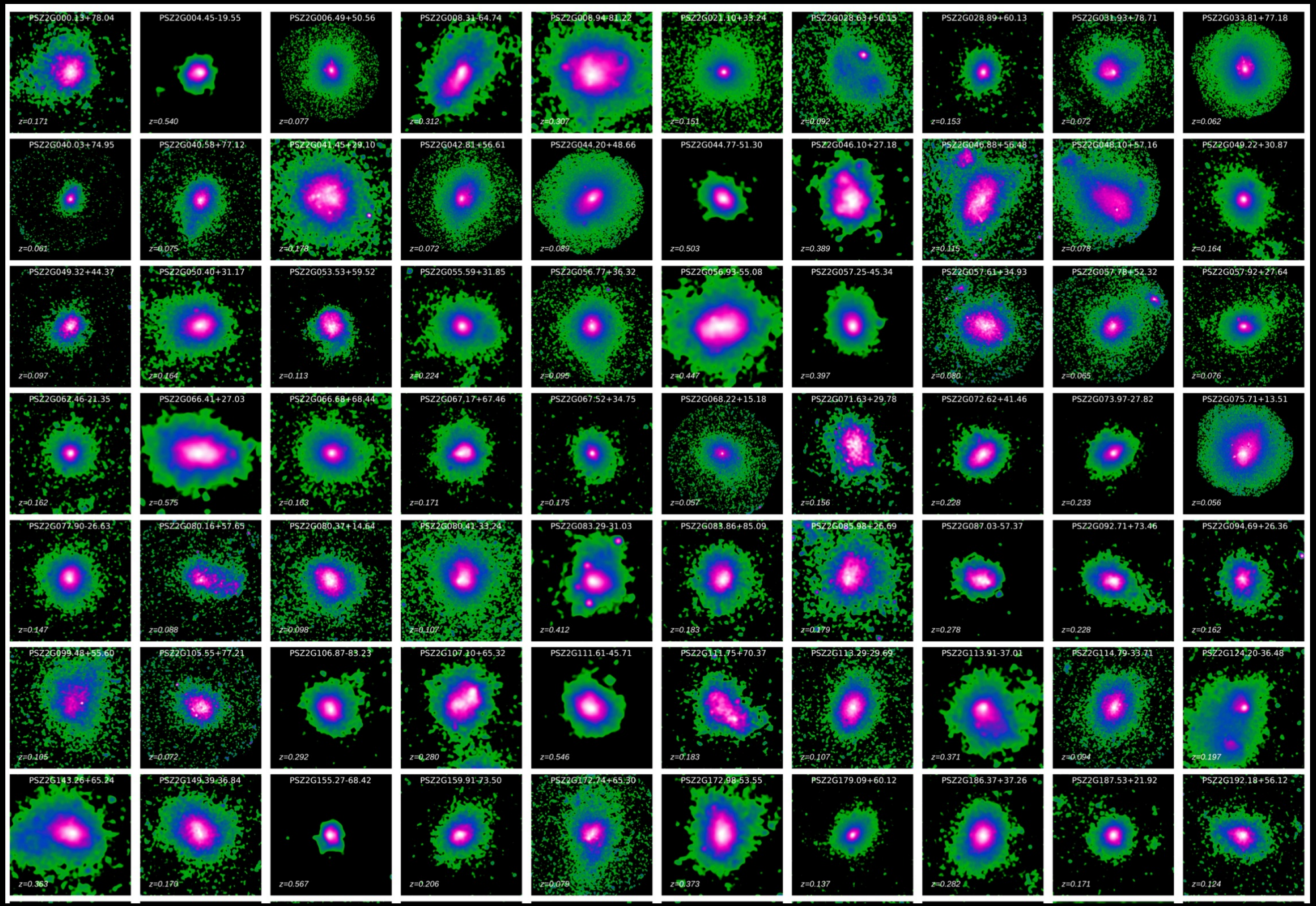
Paper title	Lead authors	KP	WG	Date of submission
CHEX-MATE: Relationship between X-ray and millimetre inferences of galaxy cluster pressure profiles	F. De Luca, H. Bourdin, F. Oppizzi, P. Mazzotta	1	SZ/X	14/10/2022
CHEX-MATE: Cluster Multi-Probes in Three Dimensions I. Gas Analysis Method using X-ray and SZE data	J. Kim, J. Sayers, M. Sereno	1	SZ/X	12/04/2023

Papers in preparation

Paper title	Lead authors	KP	WG	Expected submission
CHEX-MATE: the temperature profile of DR1 clusters	M. Rossetti, D. Eckert, F. Gastaldello	1	X	Q3 2023
CHEX-MATE: Factors influencing density profile reconstruction in galaxy clusters	R. T. Duffy, G. W. Pratt, M. Arnaud, E. Rasia	1	X	Q2 2023
CHEX-MATE: scaling relations wave 1 paper (final title TBC)	Z. Altria, B Maughan	2	SZ/X	Q3 2023
CHEX-MATE: ICM gas motions from the statistics of SXB fluctuations (final title TBC)	S. Dupourqué, N. Clerc, E. Pointecouteau	1	X	Q3 2023
CHEX-MATE: the abundance profiles of DR1 clusters	F. Gastaldello, M. Rossetti, G. W. Pratt, L. Lovisari, S. Ghizzardi	1	X	Q4 2023
CHEX-MATE-LOFAR: correlation between radio and X-ray properties for 5 clusters with radio halos	M. Balboni, F. Gastaldello, A. Bonafede, R. Cassano	6	X/R	Q2 2023
CHEX-MATE: the entropy profiles of the most massive galaxy clusters in the Universe in the range $0.2 < z < 0.6$	G. Riva, G. W. Pratt, M. Rossetti	1	X	Q4 2023
CHEX-MATE: the iron yield in the core of Tier 1 clusters	S. Ghizzardi	1	X/O	Q4 2023
CHEX-MATE: sampling edges and discontinuities in the distribution of the intracluster medium	G. Campitiello, S. Ettori, L. Lovisari	1	X	Q4 2023

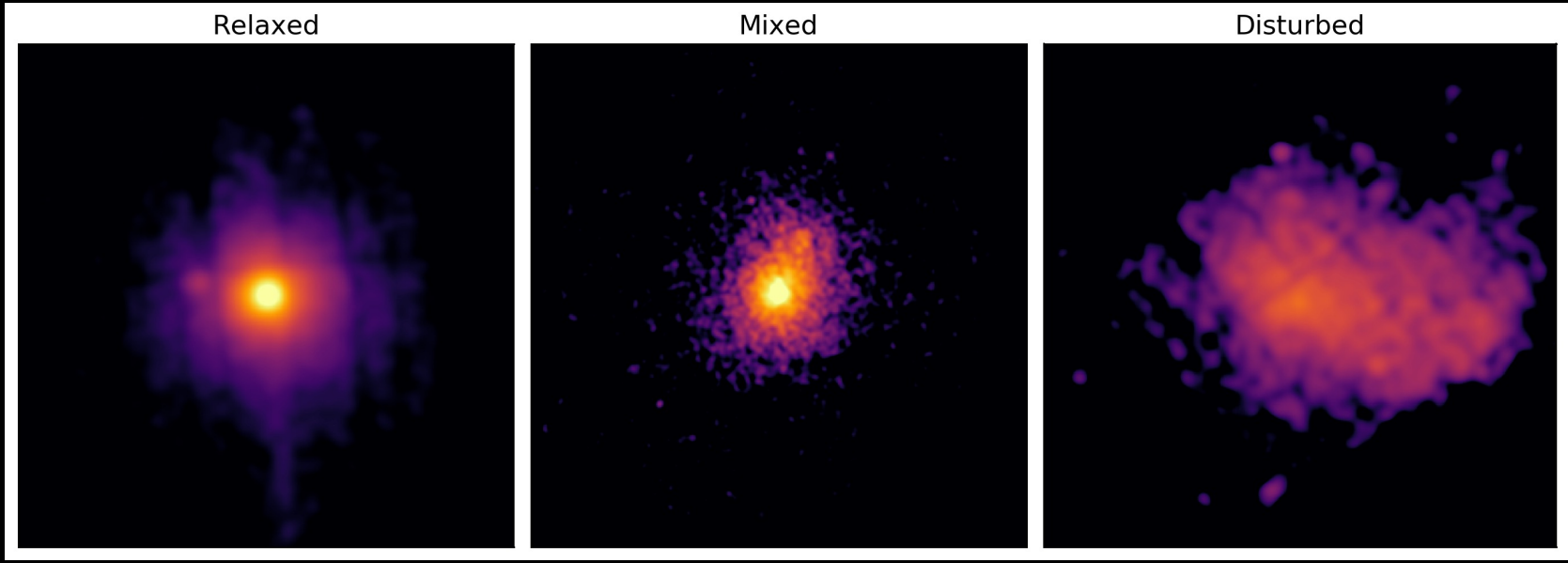
see talks by H. Bourdin (on n_H), I. Bartalucci (on S_X), F. De Luca (on H_0)

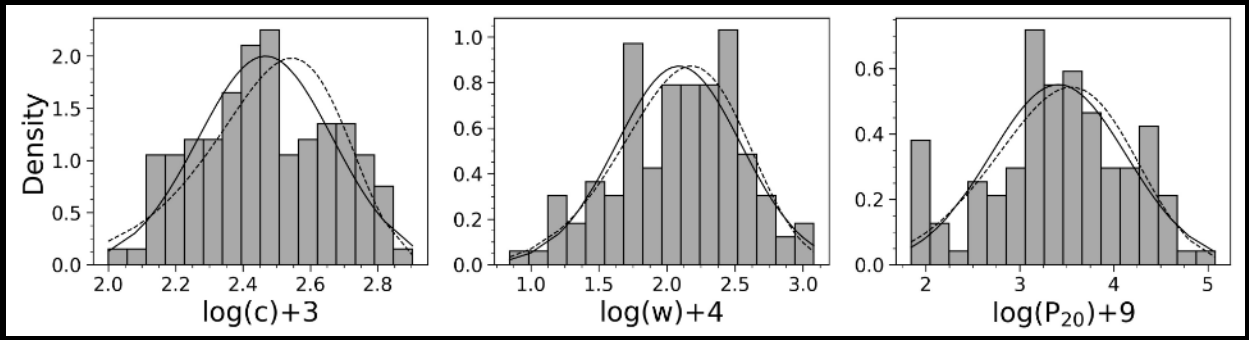
CHEX-MATE gallery *2021, A&A, 650, 104*



X-ray morphology

(Campitiello+22 A&A 665 117)

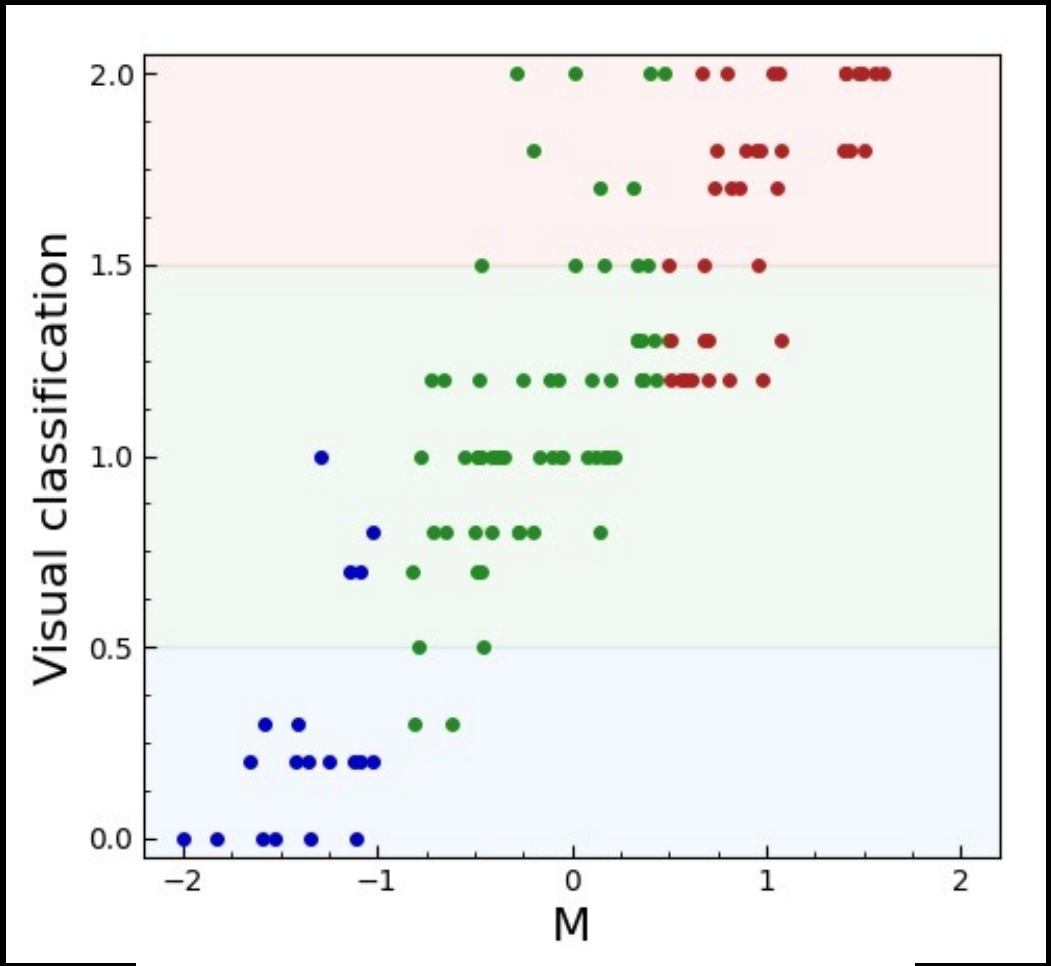




Distributions of morphological parameters is preferentially log-normal and do not show any bimodality

X-ray morphology

(Campitiello+22 A&A 665 117)

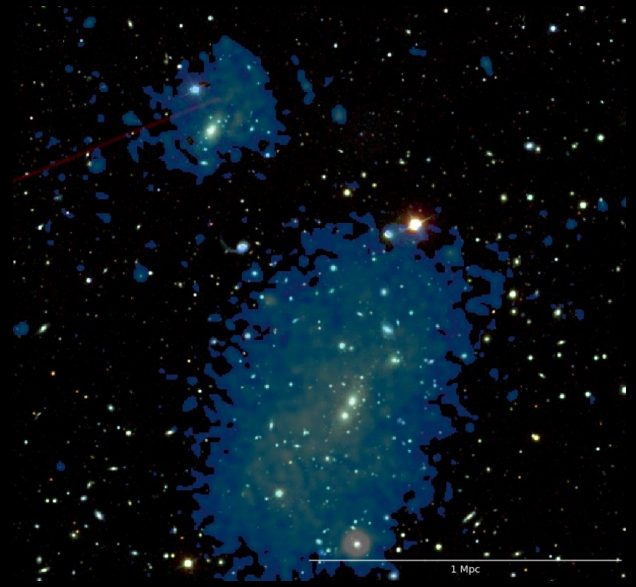


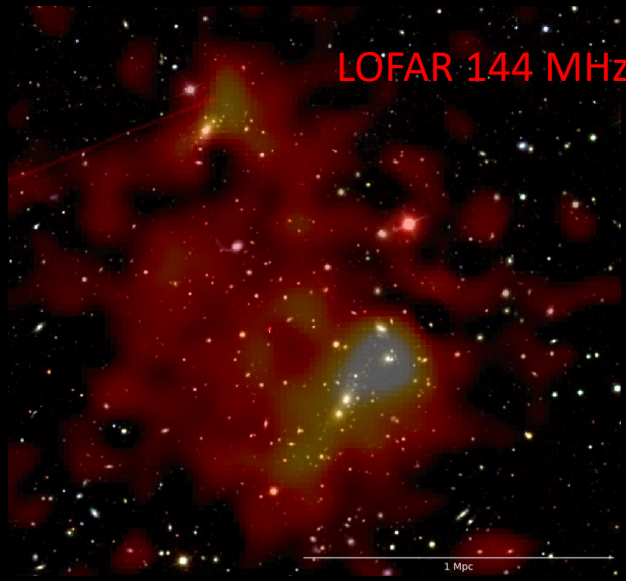
$$M = \sum \frac{\log_{10}(Par^{\alpha_{Par}}) - < \log_{10}(Par^{\alpha_{Par}}) >}{\sigma_{log_{10}(Par^{\alpha_{Par}})}}$$

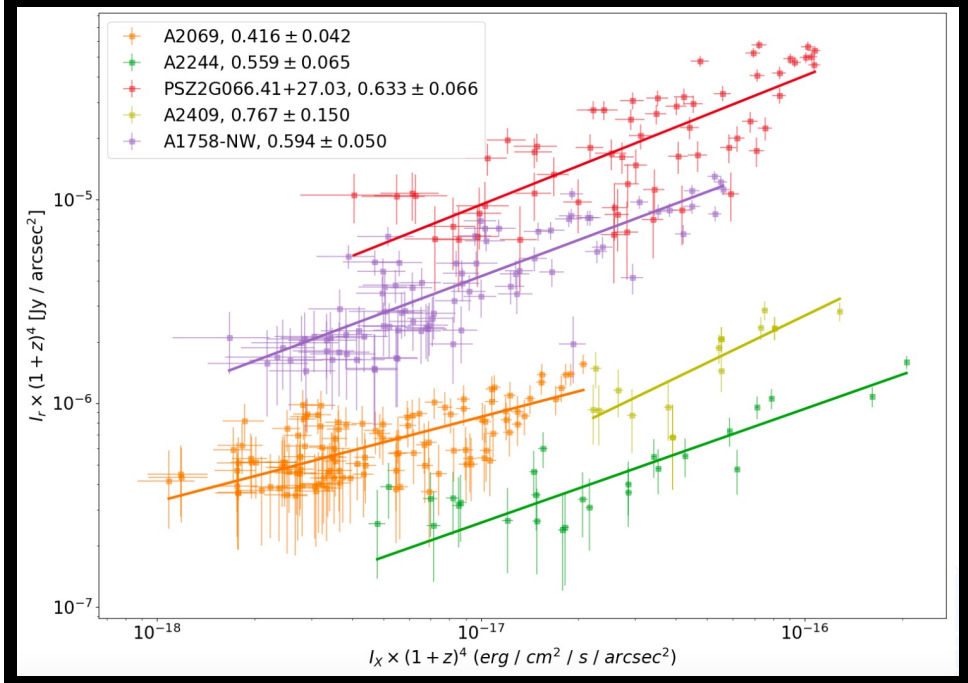
- We compress all morphological info into the parameter M
- *15 (13%) very relaxed & 27 (23%) very disturbed objects*
- We confirm that SZ selected sample contains more disturbed systems than X-ray selected ones

X-ray / radio correlation

(Balboni, Gastaldello et al. in prep)





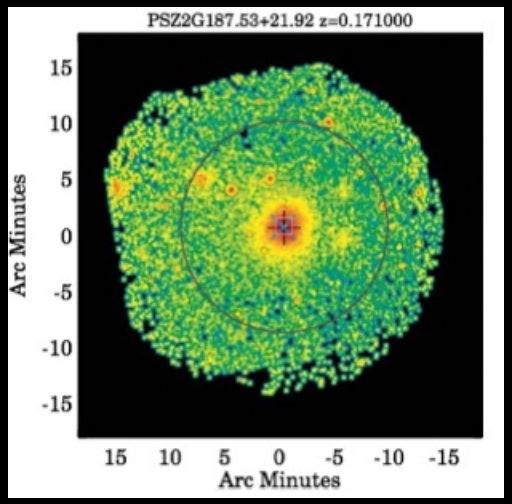


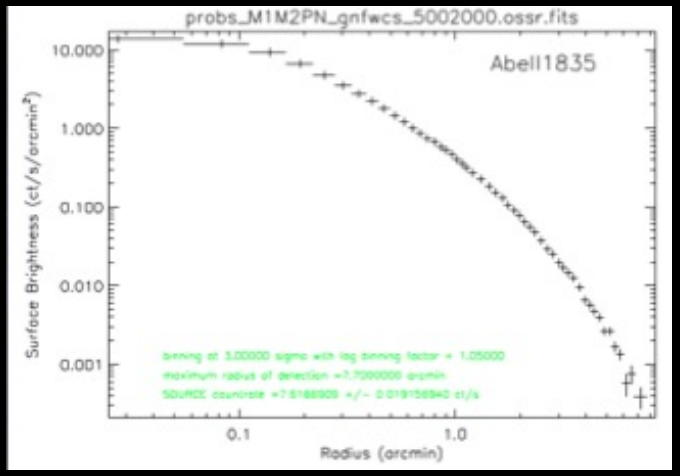
Same instruments/uniform coverage... $I_R \sim I_x^k$, with $k<1$

...sublinear correlation X-radio brightness ➔ weaker radial decline of the NT component w.r.t. the thermal one

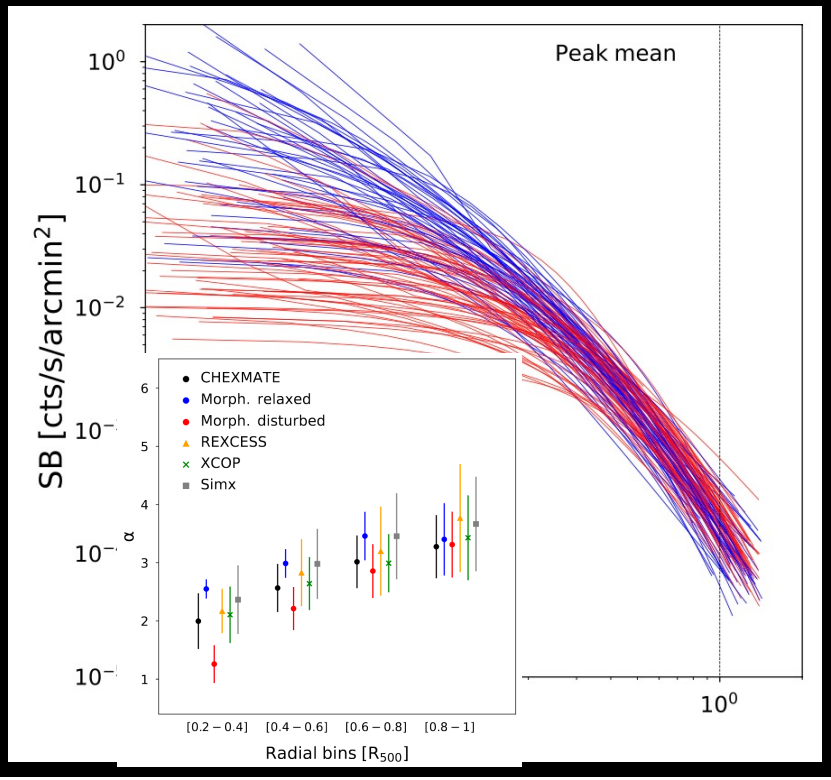
Properties of S_x

(Bartalucci+23 A&A 674 179)





Production of S_x: combining pipelines /expertize; improved bkg subtraction & pnt-src detection



Data quality (116/118 obj):

- ✓ 92% of the profile >R_{500}
- ✓ err(R_{500}) ~6%

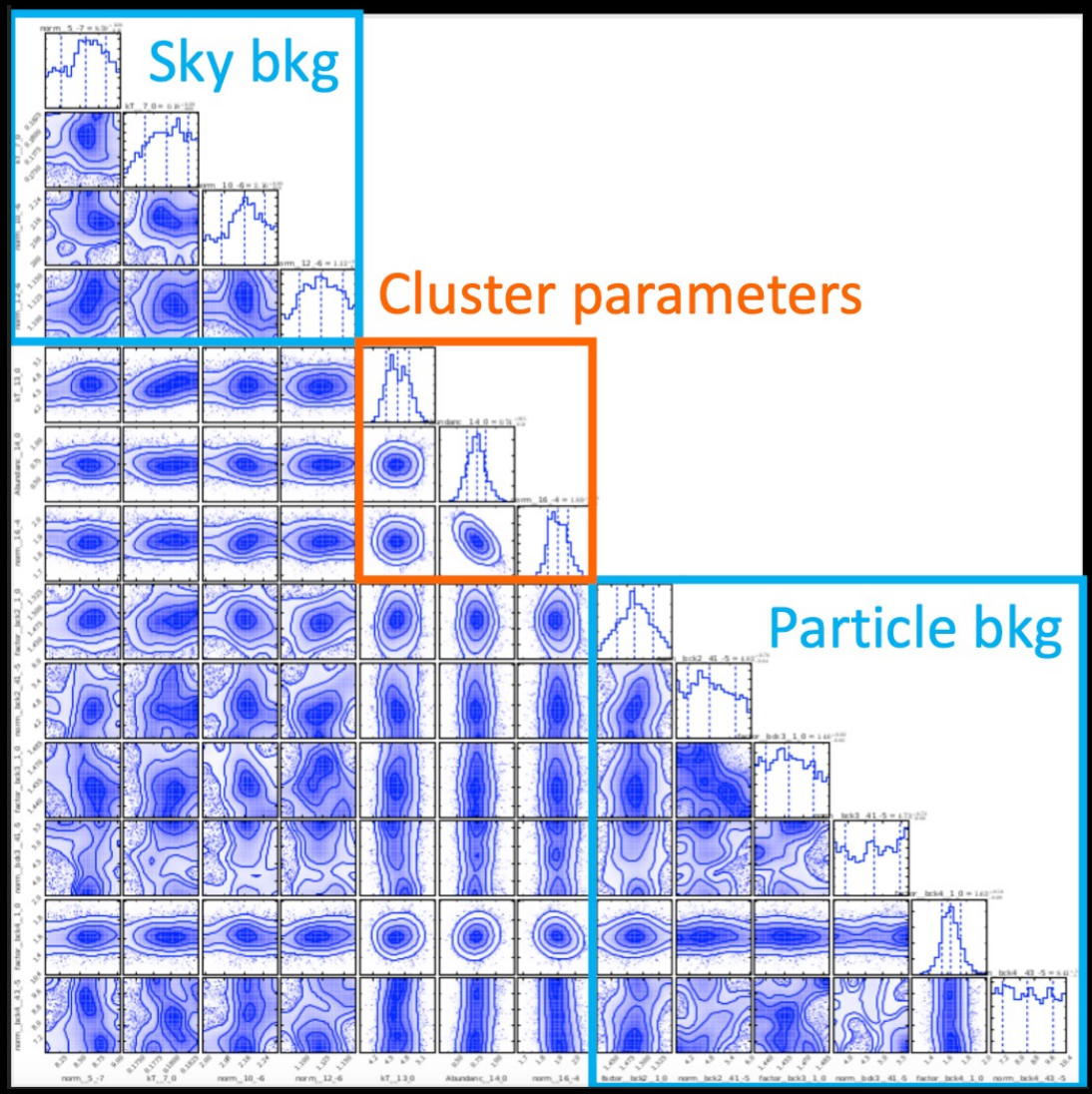
- EM profiles as clear proxy of the morphological state
- Hydro-sims (*the300*) show EM profiles steeper than the CHEX-MATE ones
- **Gas density reconstruction:** systematics studied in ***Duffy, Pratt et al***. in prep

Temperature profiles

(Rossetti, Eckert et al. in prep)

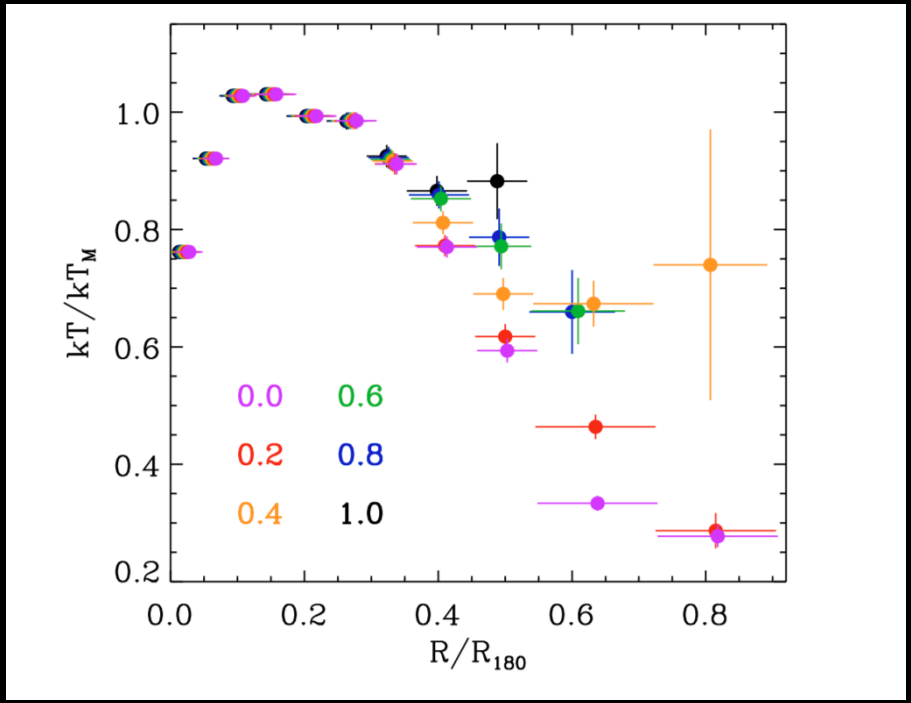
Data Release 1 (DR1; 30 obj; 16 T1, 14 T2) sample is ***(i) technical***, to test our pipeline and new methods under different analysis conditions (extension, background levels,..); ***(ii) representative*** of the original CHEX-MATE sample, in terms of its selection quantities (mass, redshift, *Planck* SNR).

Model: *phabs(apec)*; aspl; nH fixed to Bourdin+23; modelled bkg (residual CXB/1 par; foreground emission of the Galactic Halo/2 par; Local Hot Bubble / 2 pars)

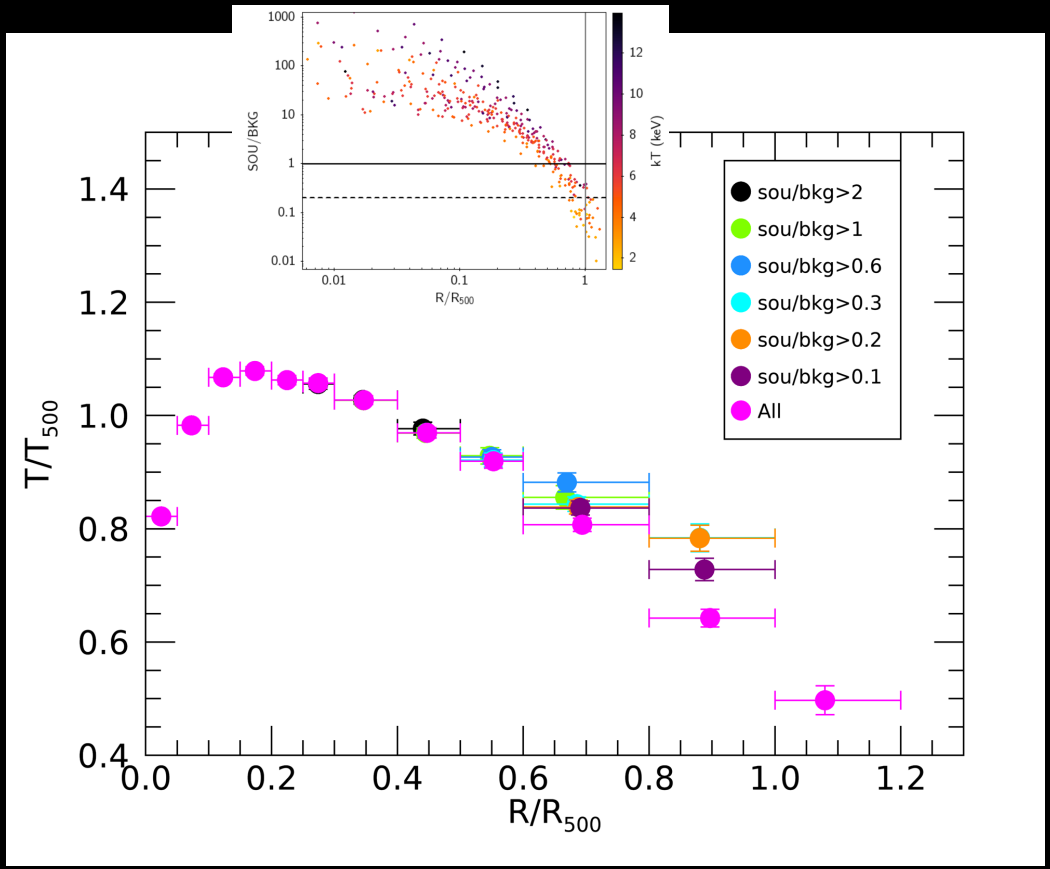


The DR1 temperature profiles

(Rossetti, Eckert et al. in prep)



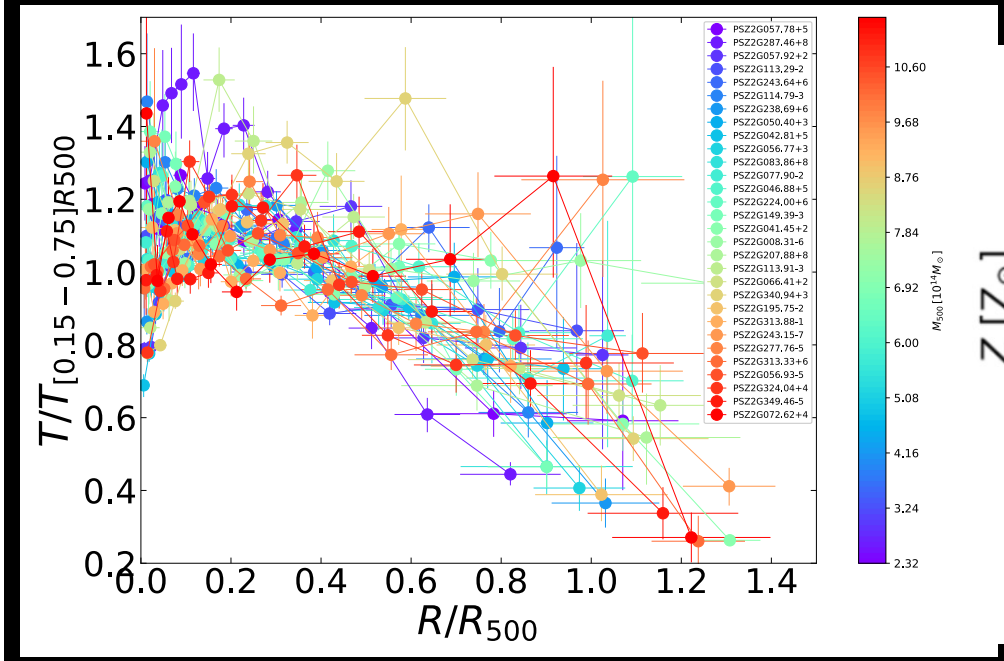
Leccardi & Molendi 08
S/B>0.6

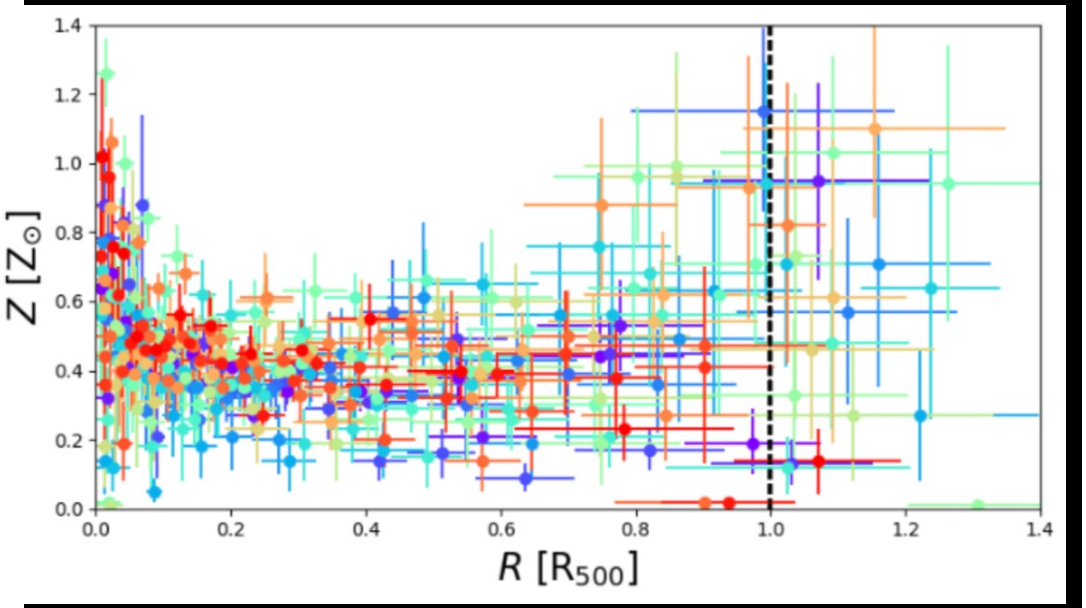


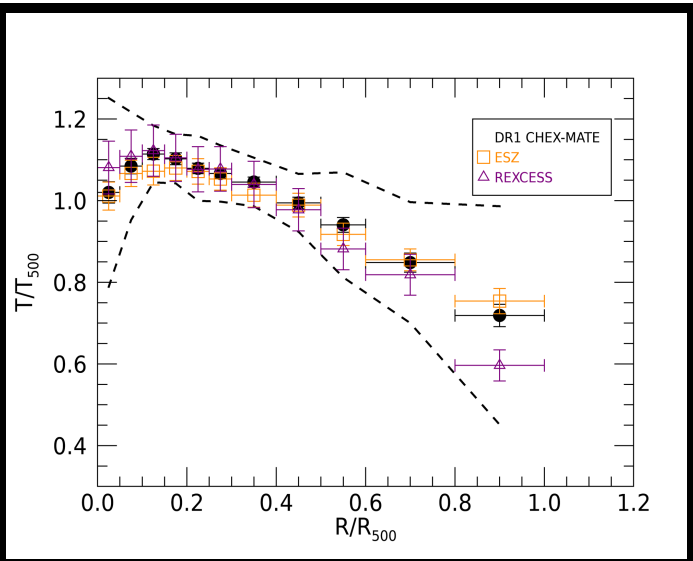
Now (2023) … S/B>0.2

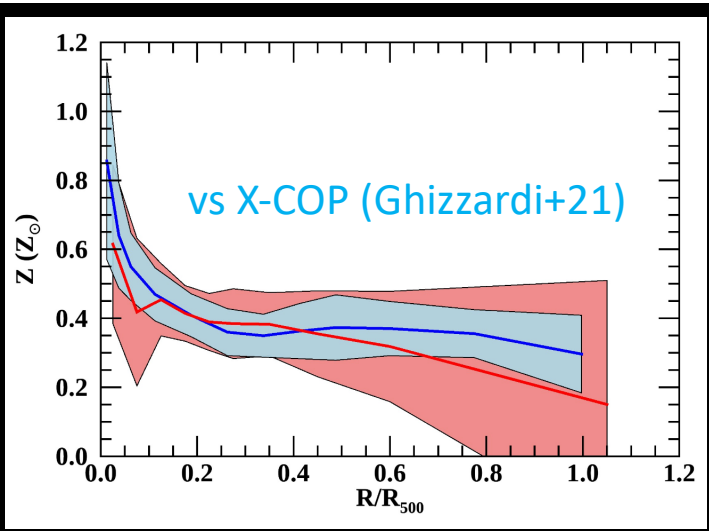
The DR1 T & Z profiles

(Rossetti+, Gastaldello+ in prep)



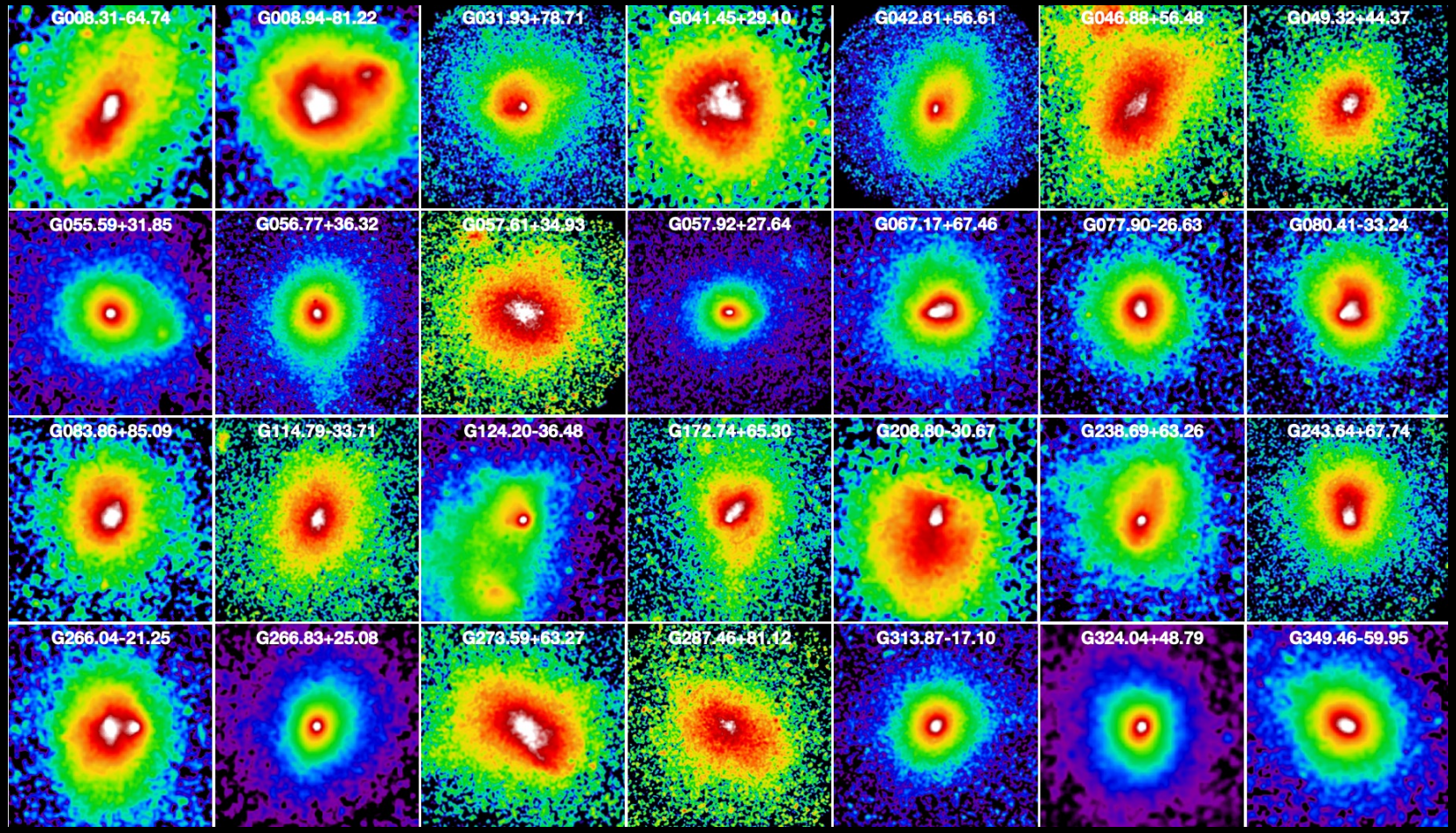






Temperature structure in the ICM

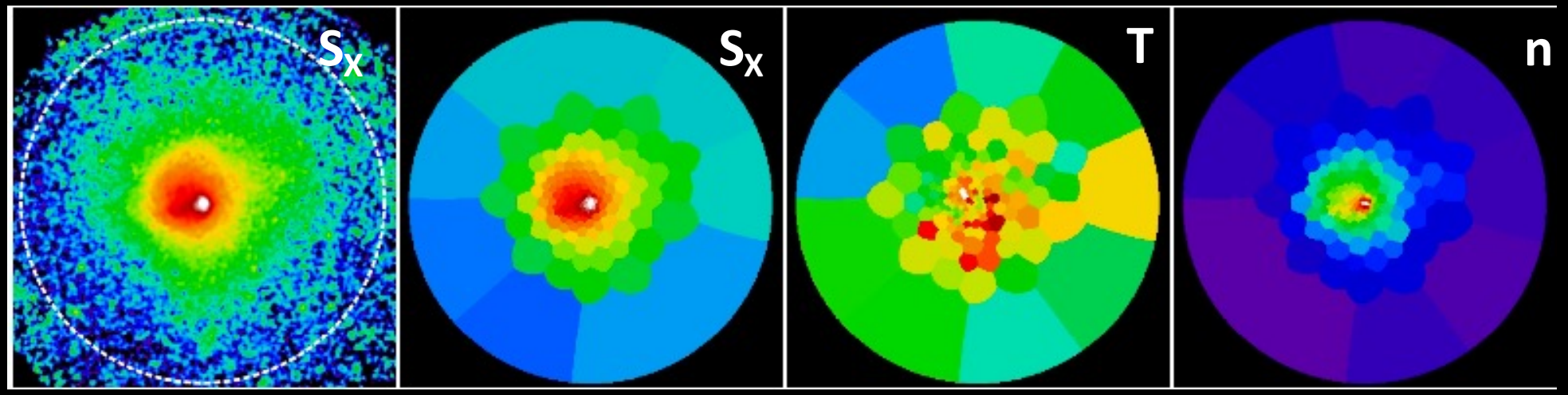
(Lovisari, Ettori et al. subm)



For a pilot sample of 28 CHEX-MATE clusters, we (i) investigate how the thermodynamical maps can be used to investigate the fluctuations in the ICM and (ii) complement the information about the dynamical state of the clusters coming from the standard morphological analysis of the X-ray images presented in Campitiello et al. (2022)

Temperature structure in the ICM

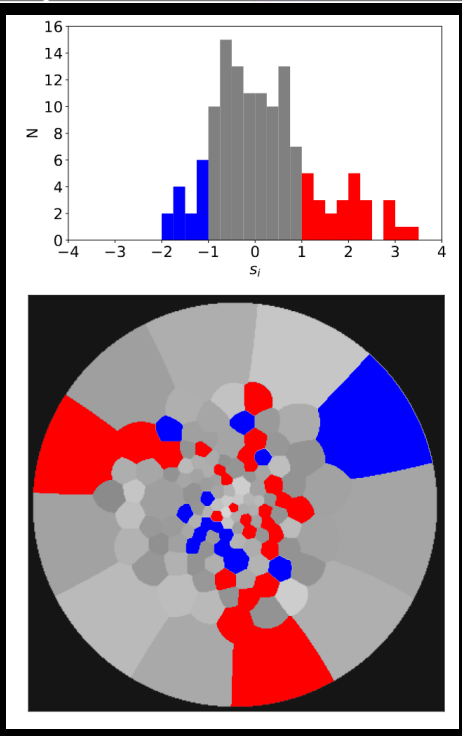
(Lovisari, Ettori et al. subm)



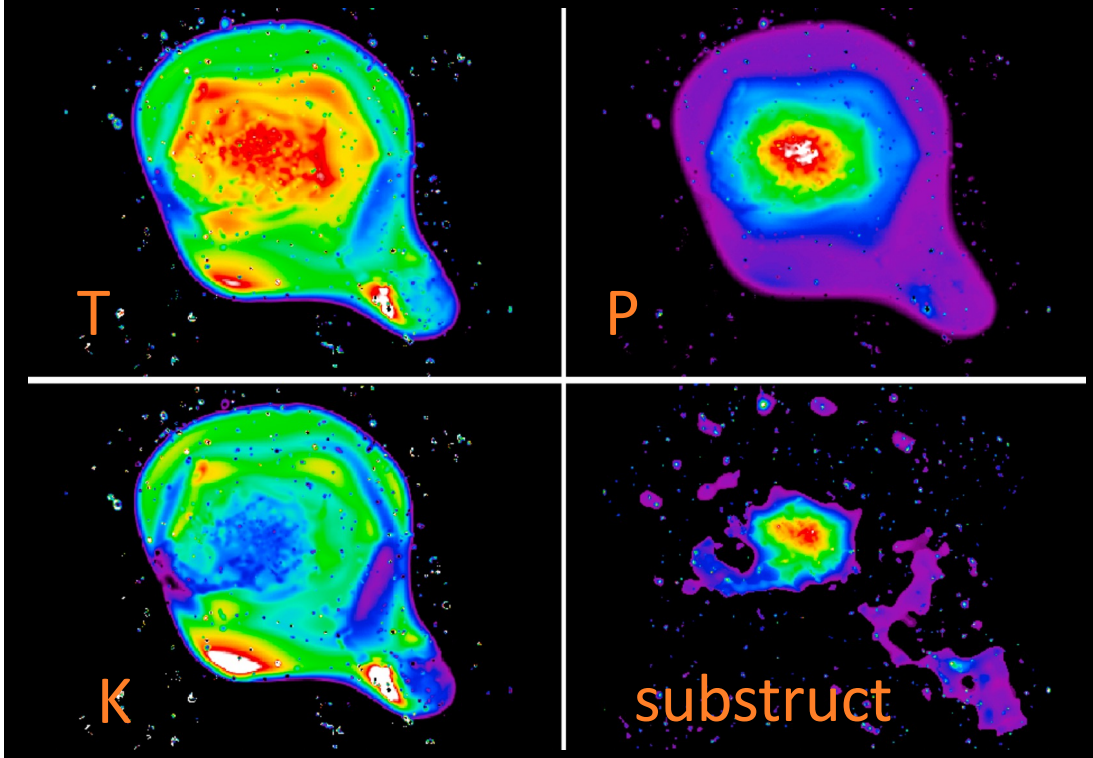
2D maps are obtained through Voronoi tessellation method with a S/N=30 (50); curvelet technique provides similar results.

Temperature distribution: skewed towards high values; log-normal; no evidence that N_{reg} deviating >1σ from the azimuthal value correlates with the dynamical state.

The removal of these regions leads to local temperature variations up to 10-20% & an average increase of ~5% in the overall cluster temperatures.



Temperature structure in the ICM



Coma (Schuecker+04)

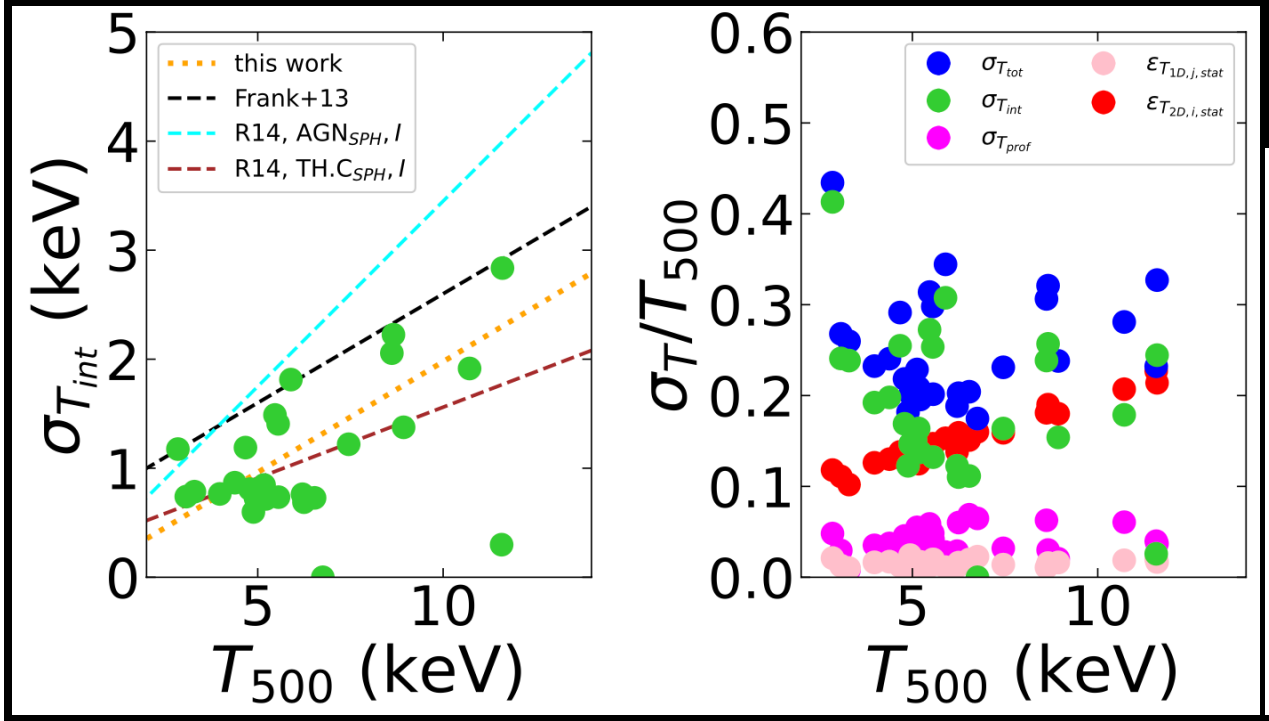
$$\frac{\delta T}{T} = (\Gamma - 1)\,\frac{\delta n}{n}$$

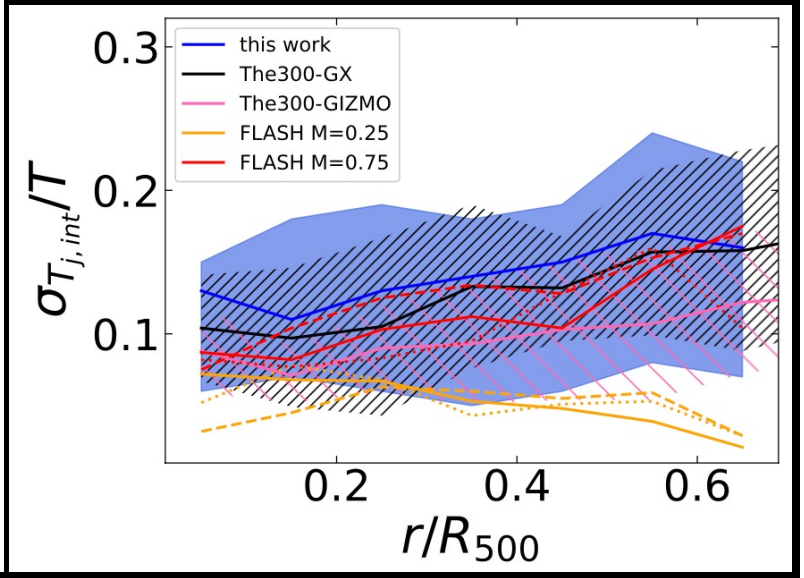
- Perturbations:
  - Γ ~0: isobaric
  - Γ ~5/3: adiabatic (weak shocks)
  - Γ ~1: isothermal

- **M = v/c_s**
  ~ dominant pertubations
  δK → low M; δP → high M
  (Gaspari+, Zhuravleva+)

Temperature structure in the ICM

(Lovisari, Ettori et al. subm.)



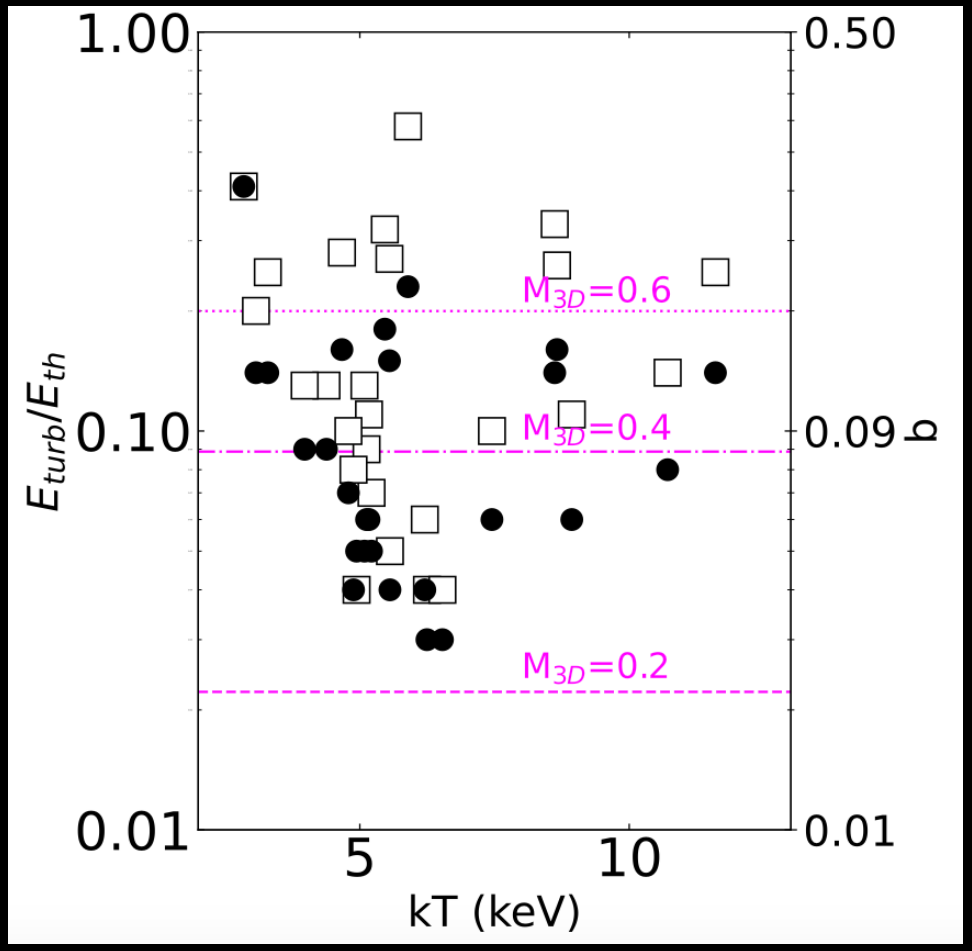


➔ M =v/c_s ~σ_T/T

➔ E_{turb} / E_{therm} = 0.5 γ (γ-1) (3 M_{1D}^2) = 0.5 γ (γ-1) M^2

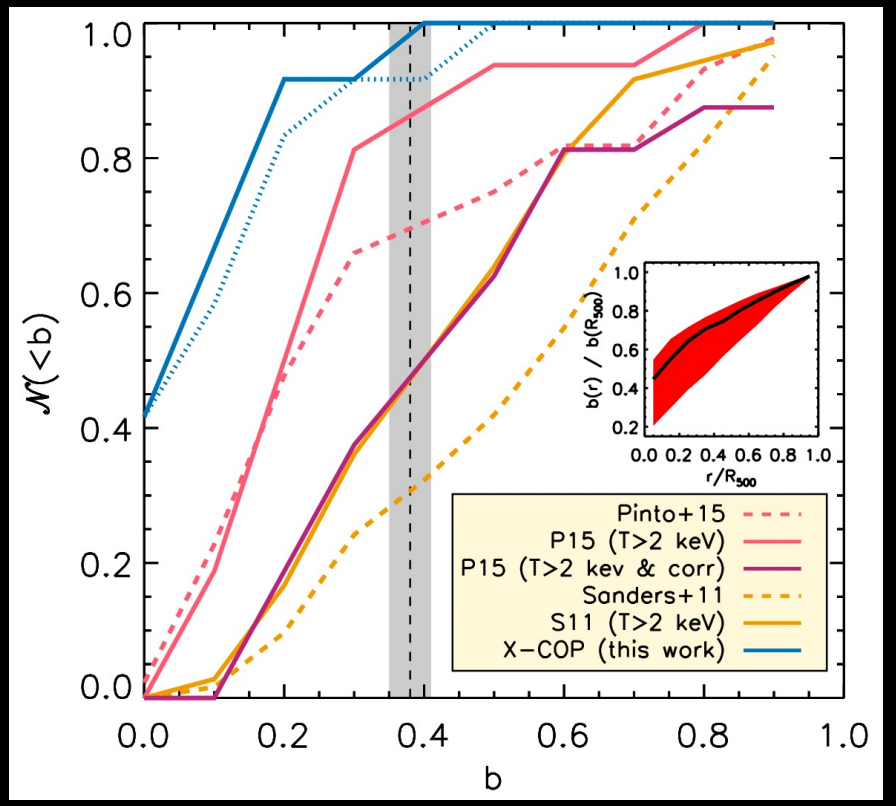
Temperature structure in the ICM

(Lovisari, Ettori et al. subm.)



Ettori & Eckert 22

➔ ***See my talk on Friday***

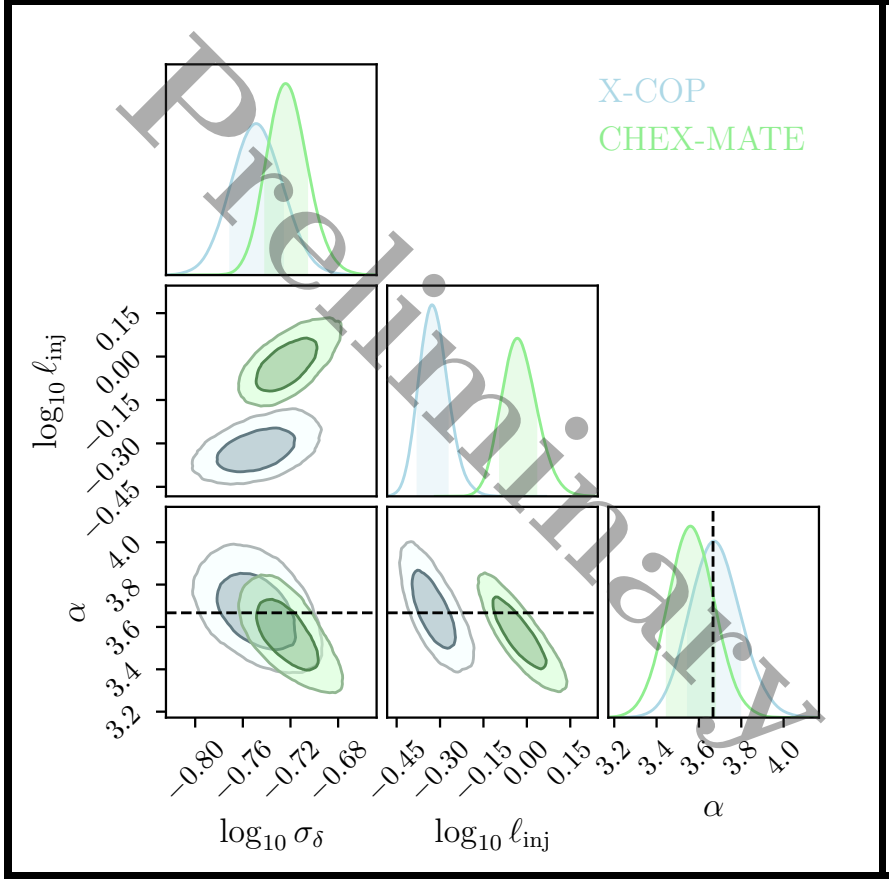


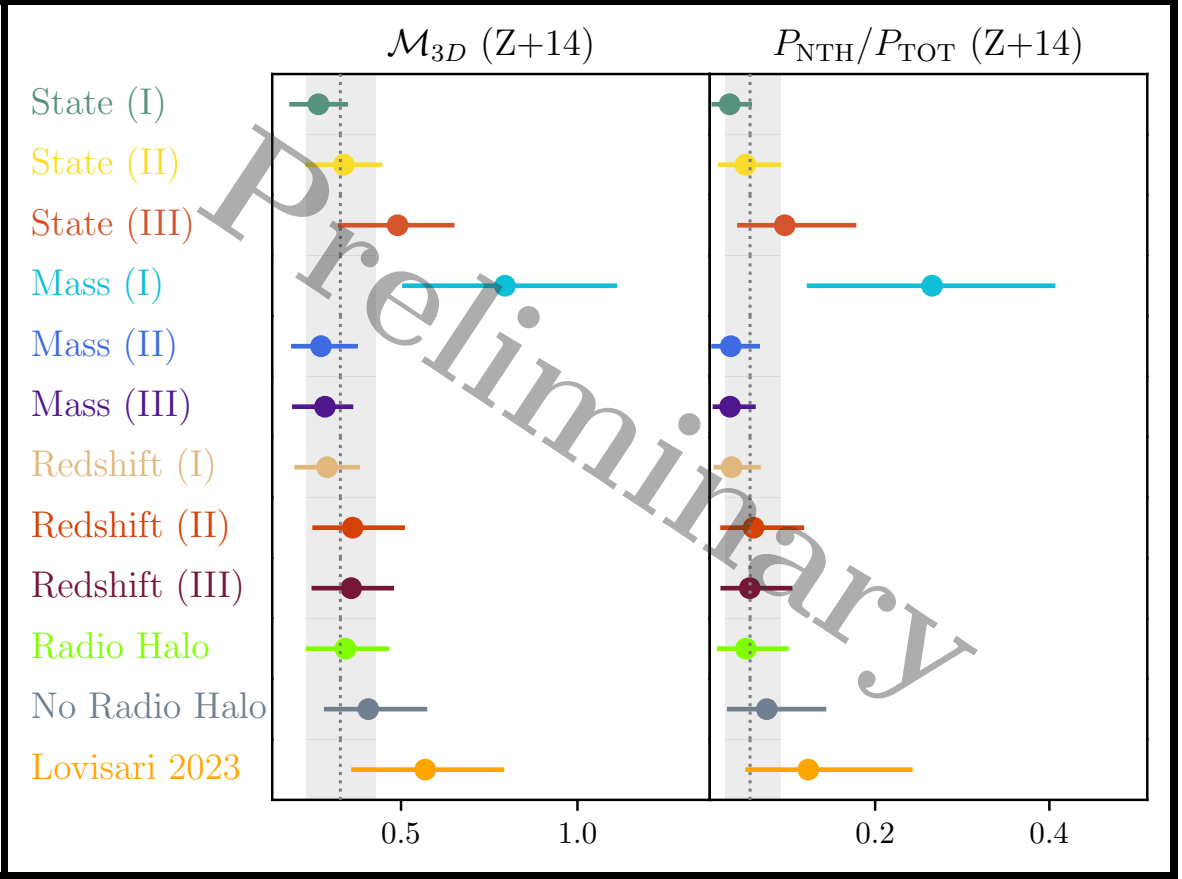
$$\mathbf{b} = 1 - M_{HE}/M_{tot} = (E_{th}/E_{turb} + 1)^{-1}$$

~0.06 [0.03-0.13] / 0.11 [0.04-0.22]

S_X fluctuations in the ICM

(Dupourqué, Clerc et al. in prep.)





CHEX-MATE: *final remarks on a truly multi-λ survey of GCs*

- X-ray observations: pipeline completed & running...
- SZ: Planck profiles available via 2 different methods (ref. Pointecouteau, Bourdin); Oppizzi+23 present a novel algorithm to derive the P profiles by combining Planck HFI + SPT (*6 obj in common with CHEX-MATE*)
- Lensing: homogeneous analysis of Subaru/HSC, VST/OmegaCAM developed in the context of the *Amalgam* program (62 obj; ref. Gavazzi, Umetsu); a subsample of several objects (e.g. A1914, A2261, RXJ1347) optimized for WL analysis has been identified. In most cases, these clusters satisfy the SZ-X criteria for CLUMP-3D triaxial modelling (ref. Kim, Sayers, Sereno)
- Optical: robust estimate of velocity dispersions as further mass proxy; redshifts recovered from SDSS-DR16 & NED databases +CoMaLit compilation: *only 30/118 objects with <25 candidate members* (ref. Maurogordato, Sereno)
- Radio: LOFAR, MeerKAAT, GMRT maps archived & proprietary (ref. Balboni, Bonafede, Cassano, Gastaldello)
- Hydro-sims: access & tailoring of *the300* products (ref. Rasia) +other cosmological & constrained datasets (ref. Gaspari, Vazza)