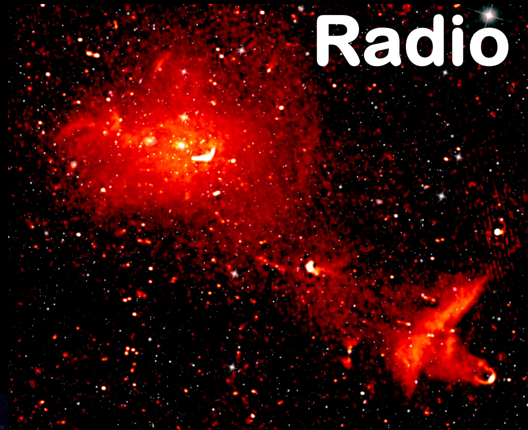
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INAF ISTITUTO NAZIONALE DI ASTROFISICA

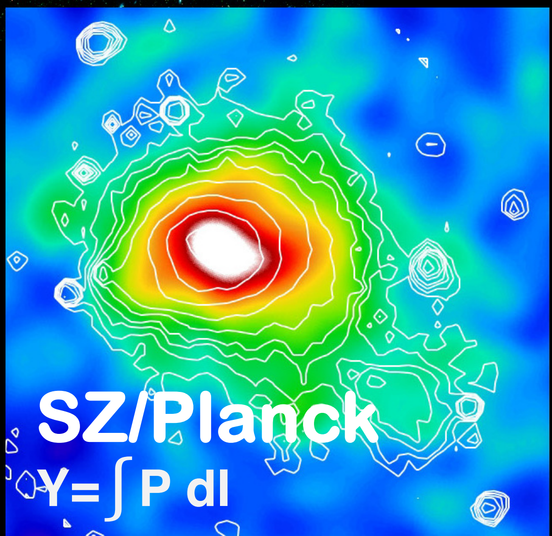
The Cluster XMM-Heritage project **CHEX-MATE:** current results and future prospects

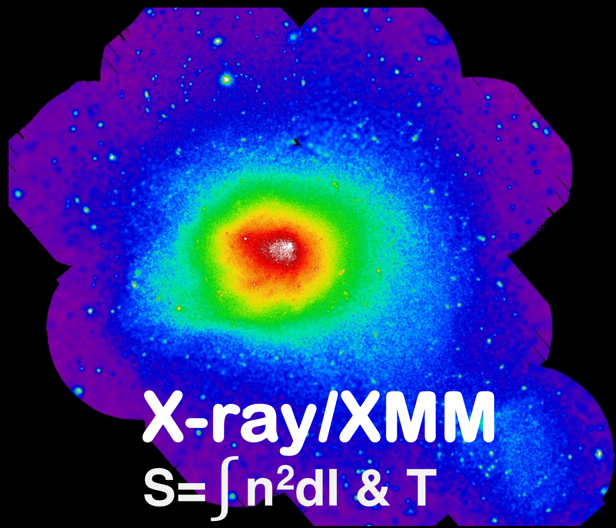
Stefano **Ettori**

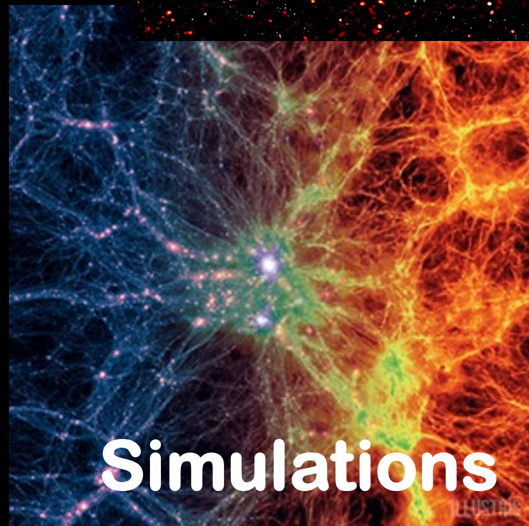
INAF-OAS Bologna

& **CHEX-MATE collaboration**









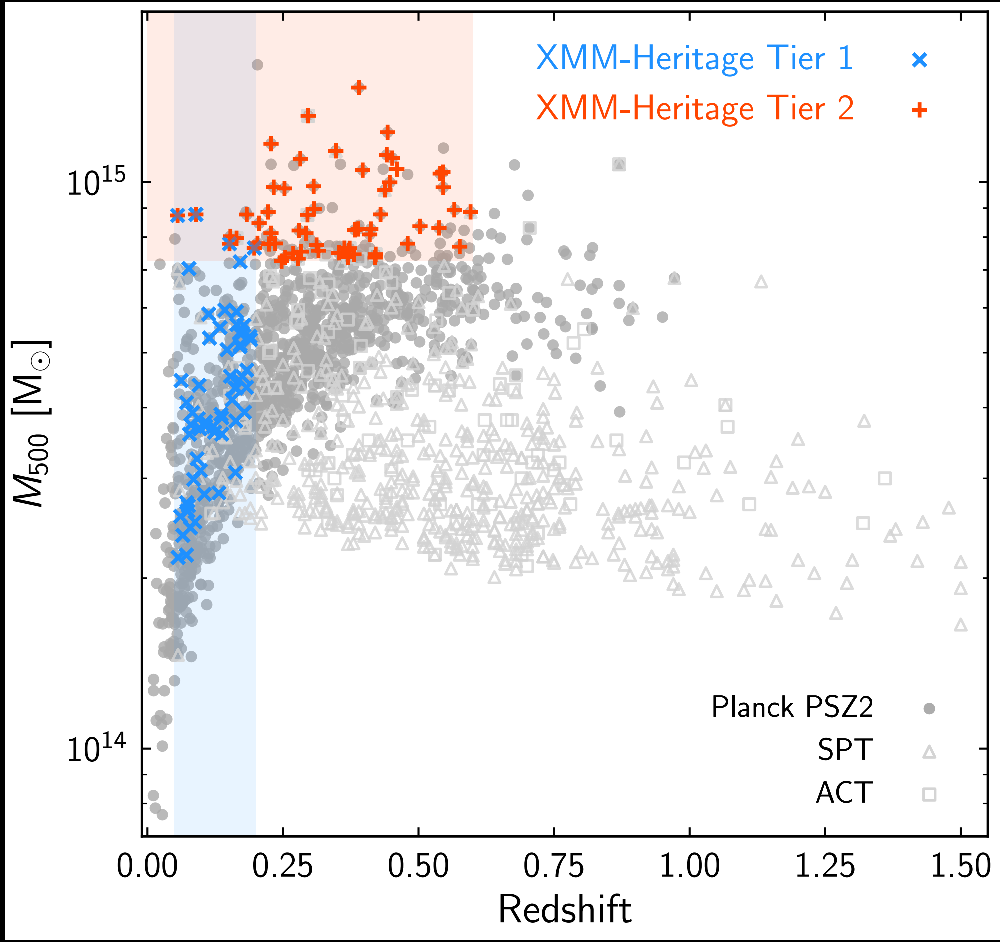
An XMM-Newton Multi-Year Heritage Program

Witnessing the culmination of structure formation in the Universe

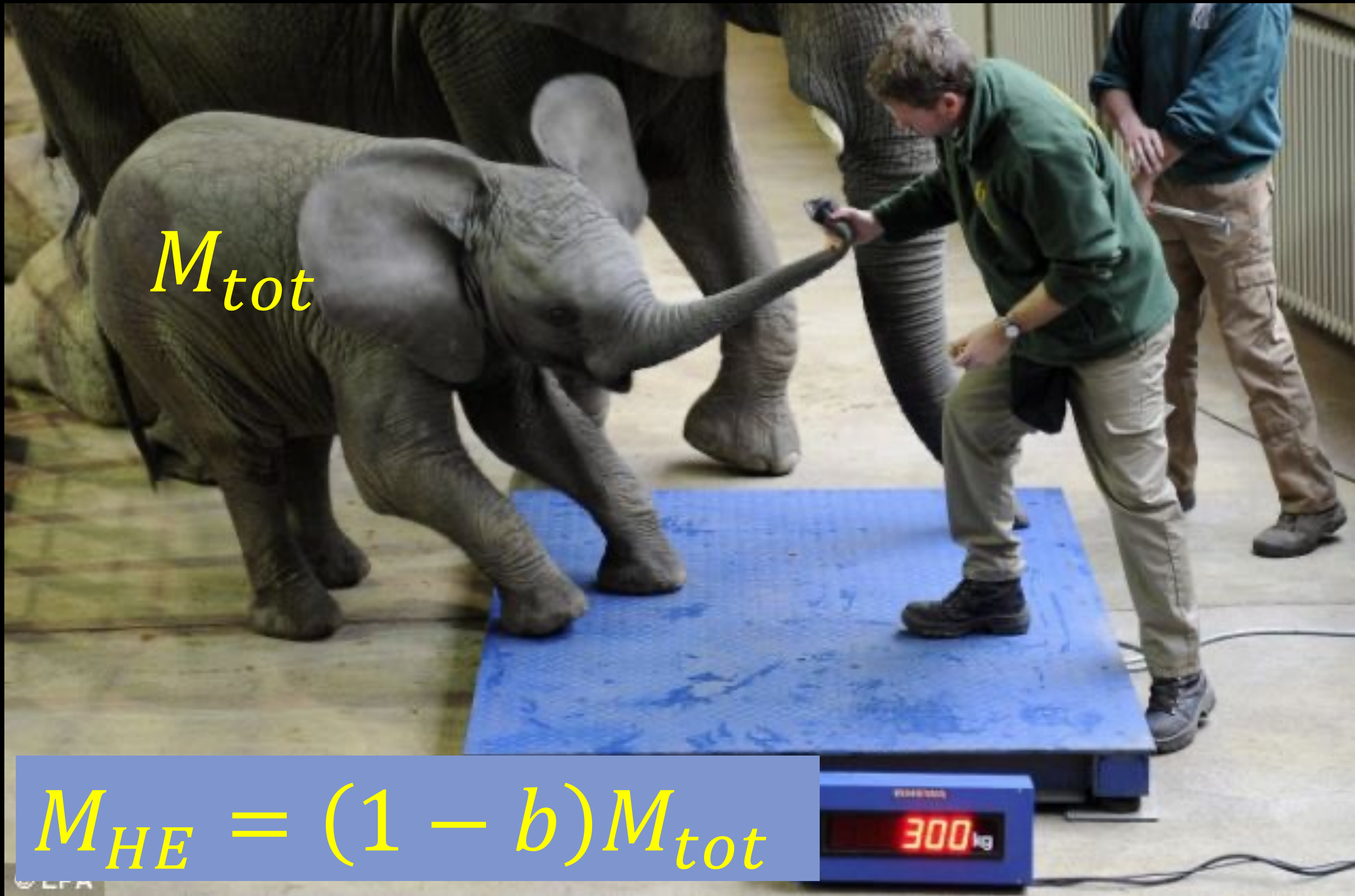
URL: xmm-heritage.oas.inaf.it

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*



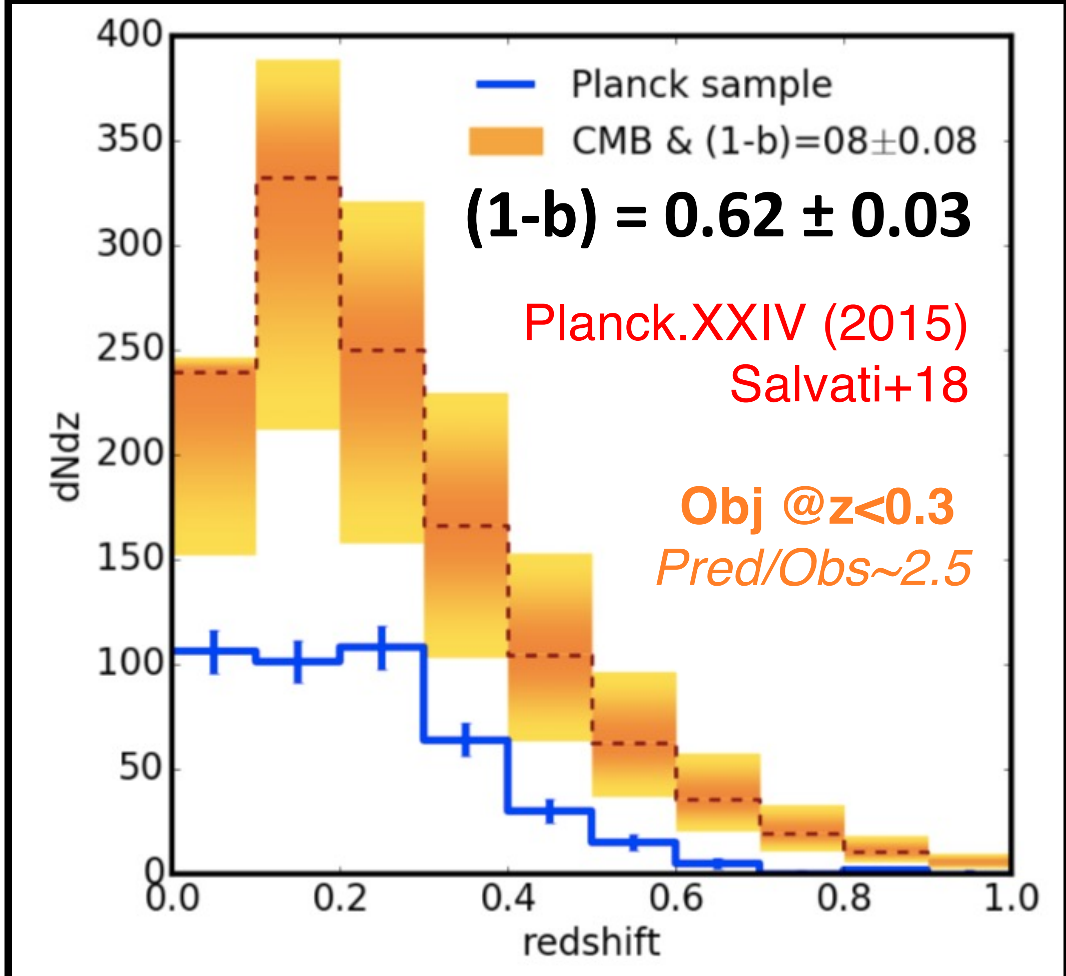
Big problem:
how to weigh Galaxy Clusters



Goals of CHEX-MATE

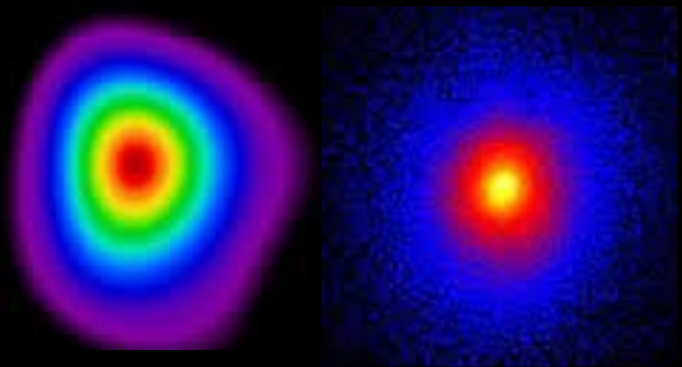
Selection for the 3 Msec *program:*

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

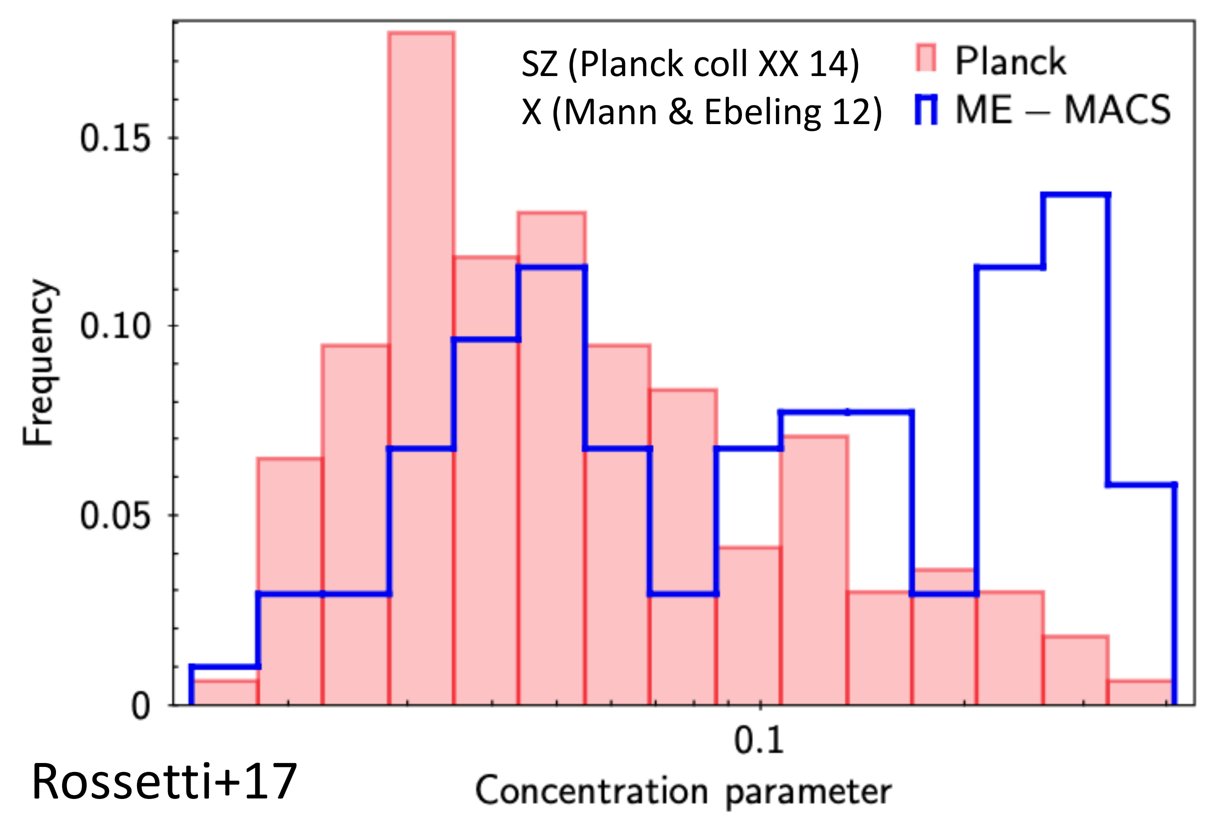


- What is the true mass scale?
- What are the properties of the »true» cluster population?
- How do these properties change over time?
- Provide a unique reference for evolution studies and numerical modelling
- Legacy for Next Generation missions
- **Exposure time**: *to map homogeneously the T profile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

SZ *vs* X-ray selection



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



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: **A. Bonafede**, **R. Cassano**, **D. Eckert**, **S. Ettori** (PI), **F. Gastaldello**, **R. Gavazzi**, **S. Kay**, **L. Lovisari**, **B. Maughan**, **S. Maurogordato**, **E. Pointecouteau**, **G.W. Pratt** (PI), **E. Rasia**, **M. Rossetti**, **J. Sayers**, **M. Sereno**, **K. Umetsu**

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**)

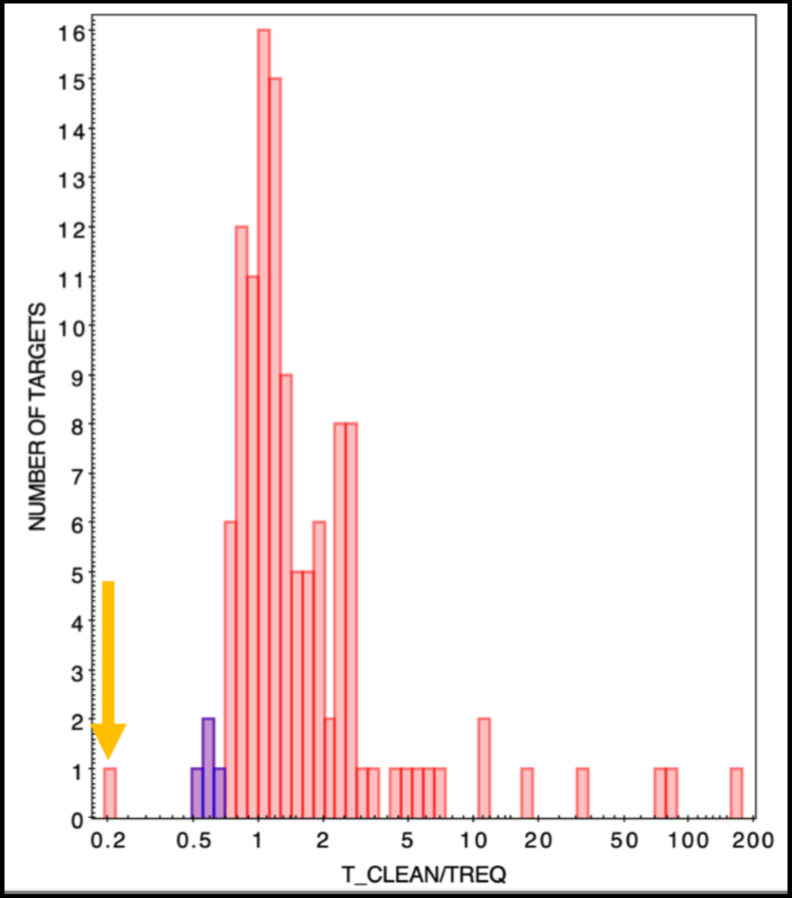
~80 collaborators from **12 countries** (France, Italy, Germany, Spain, Switzerland, UK, Australia, Chile, Japan, S.Africa, Taiwan, USA)

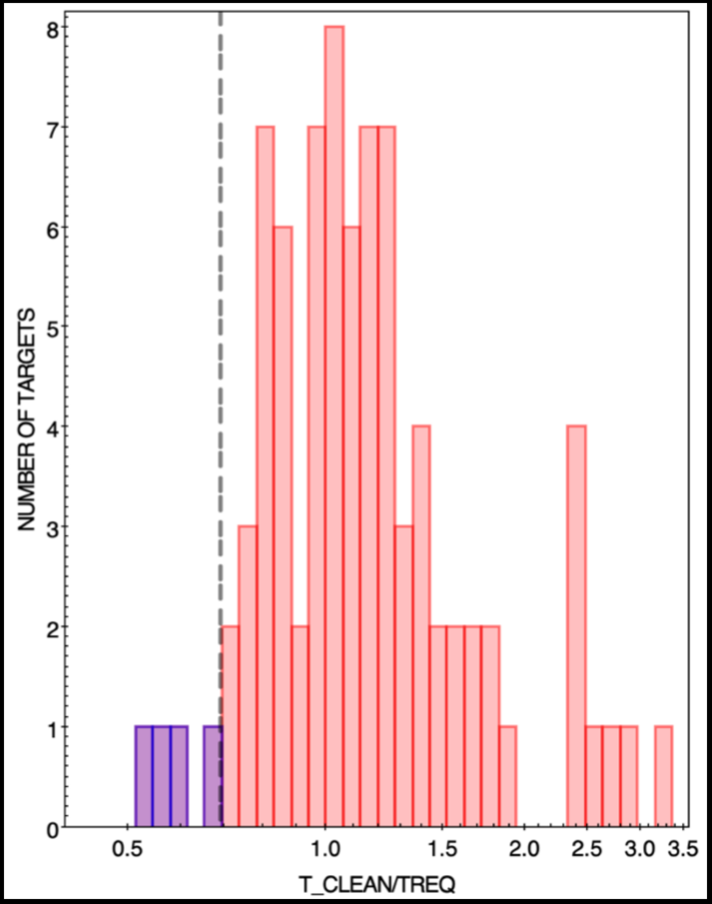
CHEX-MATE: *X-ray observations*

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: *publications*

1 2021A&A...650A.104C 2021/06 cited: 81
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: 37
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: 5
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 2023A&A...674A.179B 2023/06 cited: 18
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*

5 2023A&A...678A.181B 2023/10 cited: 3
CHEX-MATE: X-ray absorption and molecular content of the interstellar medium toward galaxy clusters
Bourdin, H.; De Luca, F.; Mazzotta, P. *and 14 more*

6 2023A&A...679A..51I 2023/11 cited: 5
CHEX-MATE: A non-parametric deep learning technique to deproject and deconvolve galaxy cluster X-ray temperature profiles
Iqbal, A.; Pratt, G. W.; Bobin, J. *and 21 more*

7 2024A&A...682A..45L 2024/02 cited: 12
CHEX-MATE: Characterization of the intra-cluster medium temperature distribution
Lovisari, L.; Ettori, S.; Rasia, E. *and 23 more*

8 2024A&A...686A...5B 2024/06 cited: 7
CHEX-MATE: A LOFAR pilot X-ray - radio study on five radio halo clusters
Balboni, M.; Gastaldello, F.; Bonafede, A. *and 24 more*

9 2024A&A...686A..68R 2024/06 cited: 15
CHEX-MATE: Robust reconstruction of temperature profiles in galaxy clusters with XMM-Newton
Rossetti, M.; Eckert, D.; Gastaldello, F. *and 25 more*

10 2024A&A...686A..97K 2024/06 cited: 6
CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D). I. Gas analysis method using X-ray and Sunyaev-Zel'dovich effect data
Kim, Junhan; Sayers, Jack; Sereno, Mauro *and 23 more*

11 2024A&A...687A..58D 2024/07 cited: 10
CHEX-MATE: Turbulence in the intra-cluster medium from X-ray surface brightness fluctuations
Dupourqué, S.; Clerc, N.; Pointecouteau, E. *and 15 more*

12 2024A&A...691A.340R 2024/11 cited: 2
CHEX-MATE: The intracluster medium entropy distribution in the gravity-dominated regime
Riva, G.; Pratt, G. W.; Rossetti, M. *and 26 more*

13 2025A&A...693A...2S 2025/01 cited: 3
CHEX-MATE: Dynamical masses for a sample of 101 Planck Sunyaev-Zeldovich-selected galaxy clusters
Sereno, Mauro; Maurogordato, Sophie; Cappi, Alberto *and 23 more*

14 2025A&A...695A.180B 2025/03
CHEX-MATE: Scaling relations of radio halo profiles for clusters in the LoTSS DR2 area
Balboni, M.; Ettori, S.; Gastaldello, F. *and 21 more*

15 2025arXiv250322316C 2025/03
CHEX-MATE: Multi-probe analysis of Abell 1689
Chappuis, L.; Eckert, D.; Sereno, M. *and 25 more*

16 2025arXiv250503708P 2025/05
CHEX-MATE: exploring the kinematical properties of Planck galaxy clusters
Pizzuti, Lorenzo; Barrena, Rafael; Sereno, Mauro *and 19 more*

17 2025arXiv250523005S 2025/05
CHEX-MATE: The Impact of Triaxiality and Orientation on Planck SZ Cluster Selection and Weak Lensing Mass Measurements
Saxena, H.; Sayers, J.; Gavidia, A. *and 17 more*

- 20+ papers in prep
- tens more in the next ~3 years

CHEX-MATE: *publications*

1 ☐ 2021A&A...650A.104C 2021/06 cited: 81
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: 37
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: 5
CHEX-MATE: Pressure profiles of six galaxy clusters as seen by SPT and Planck
Oppizzi, F.; De Luca, F.; Bourdin, H. *and 11 more*

7 ☐ 2024A&A...682A..45L 2024/02 cited: 12
CHEX-MATE: Characterization of the intra-cluster medium temperature distribution
Lovisari, L.; Ettori, S.; Rasia, E. *and 23 more*

8 ☐ 2024A&A...686A...5B 2024/06 cited: 7
CHEX-MATE: A LOFAR pilot X-ray - radio study on five radio halo clusters
Balboni, M.; Gastaldello, F.; Bonafede, A. *and 24 more*

9 ☐ 2024A&A...686A..68R 2024/06 cited: 15
CHEX-MATE: Robust reconstruction of temperature profiles in galaxy clusters with XMM-Newton
Rossetti, M.; Eckert, D.; Gastaldello, F. *and 25 more*

10 ☐ 2024A&A...686A..97K 2024/06 cited: 6
CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D). I. Gas analysis method using X-ray and Sunyaev-Zel'dovich effect data
Kim, Junhan; Sayers, Jack; Sereno, Mauro *and 23 more*

11 ☐ 2024A&A...687A..58D 2024/07 cited: 10
CHEX-MATE: Turbulence in the intra-cluster medium from X-ray surface brightness

15 ☐ 2025arXiv250322316C 2025/03
CHEX-MATE: Multi-probe analysis of Abell 1689
Chappuis, L.; Eckert, D.; Sereno, M. *and 25 more*

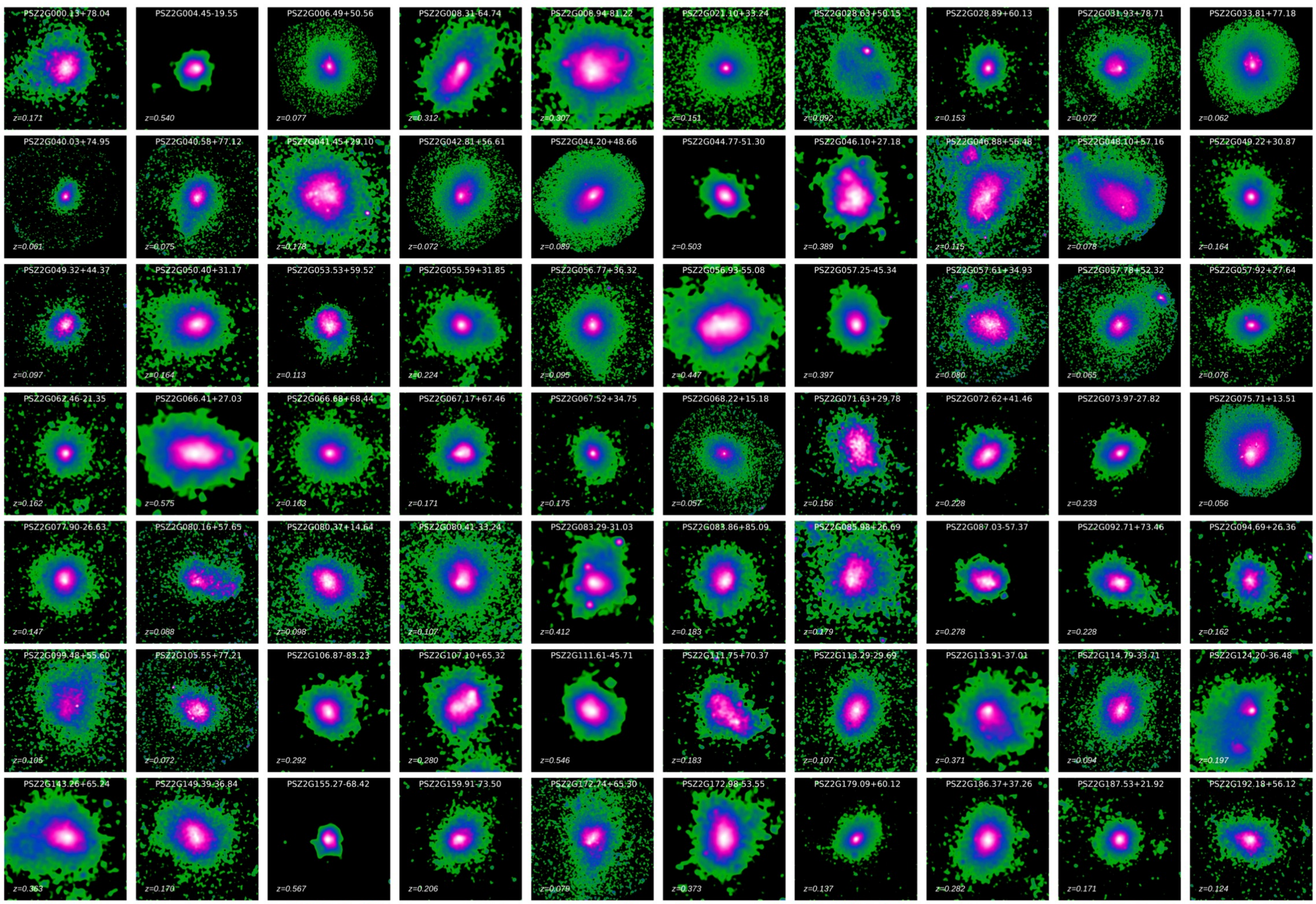
16 ☐ 2025arXiv250503708P 2025/05
CHEX-MATE: exploring the kinematical properties of Planck galaxy clusters
Pizzuti, Lorenzo; Barrena, Rafael; Sereno, Mauro *and 19 more*

17 ☐ 2025arXiv250523005S 2025/05
CHEX-MATE: The Impact of Triaxiality and Orientation on Planck SZ Cluster Selection and Weak Lensing Mass Measurements
Saxena, H.; Sayers, J.; Gavidia, A. *and 17 more*

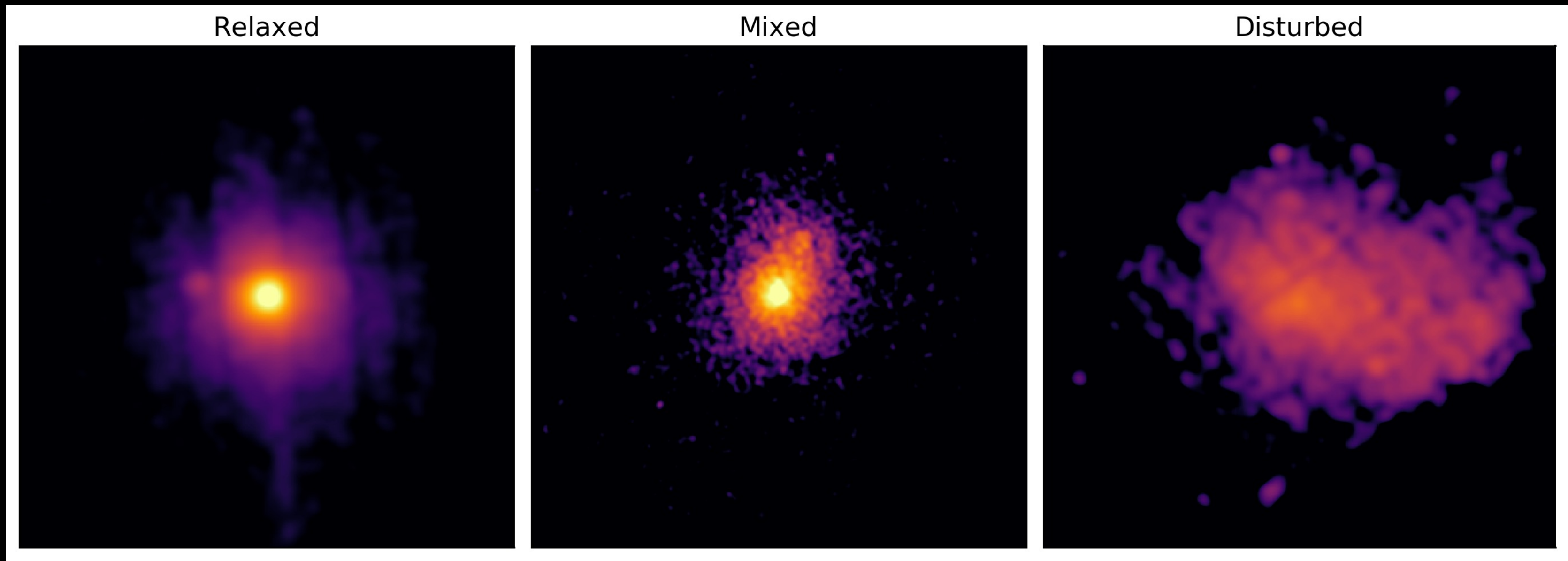
Talks @mmUniv:
- [Mon 4:15pm] **Gavidia** “A Multi-Probe Analysis of the 3D Shape and Non-Thermal Pressure of Galaxy Clusters”
- [Tue 2:25pm] **Echeverria** “Galaxy cluster mass measurements from a joint fit with the universal pressure profile”
- [Wed 1:55pm] **Saxena** “Impact of Halo Triaxiality and Orientation on SZ selection and WL mass bias”
- [Wed 2:10pm] **Ghiradrdini** “Cosmological constraints from the gas distribution”
- [Wed 2:25pm] **De Luca** “Constraining H_0 with X-ray and relativistic SZ data”
- [Thus 2:25pm] **Bartalucci** “Factors influencing density profile reconstruction in galaxy clusters”
- [Thu 2:45pm] **Campitiello** “The first census of ICM discontinuities”

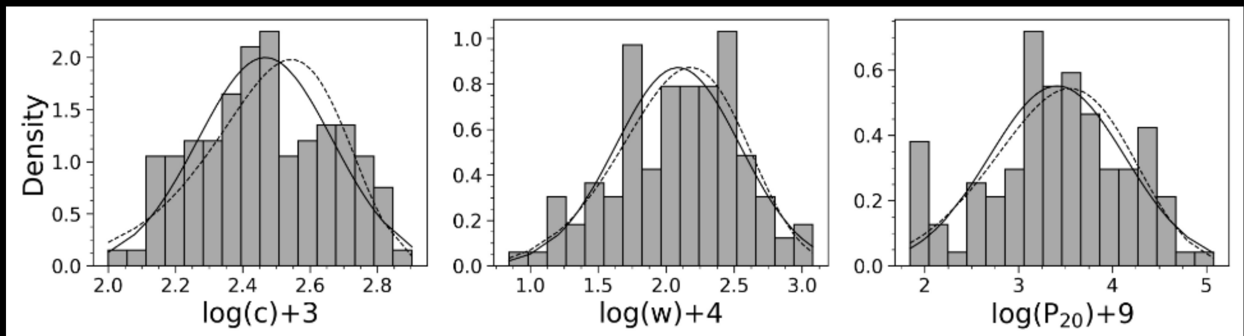
- 20+ papers in prep
- tens more in the next ~3 years

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



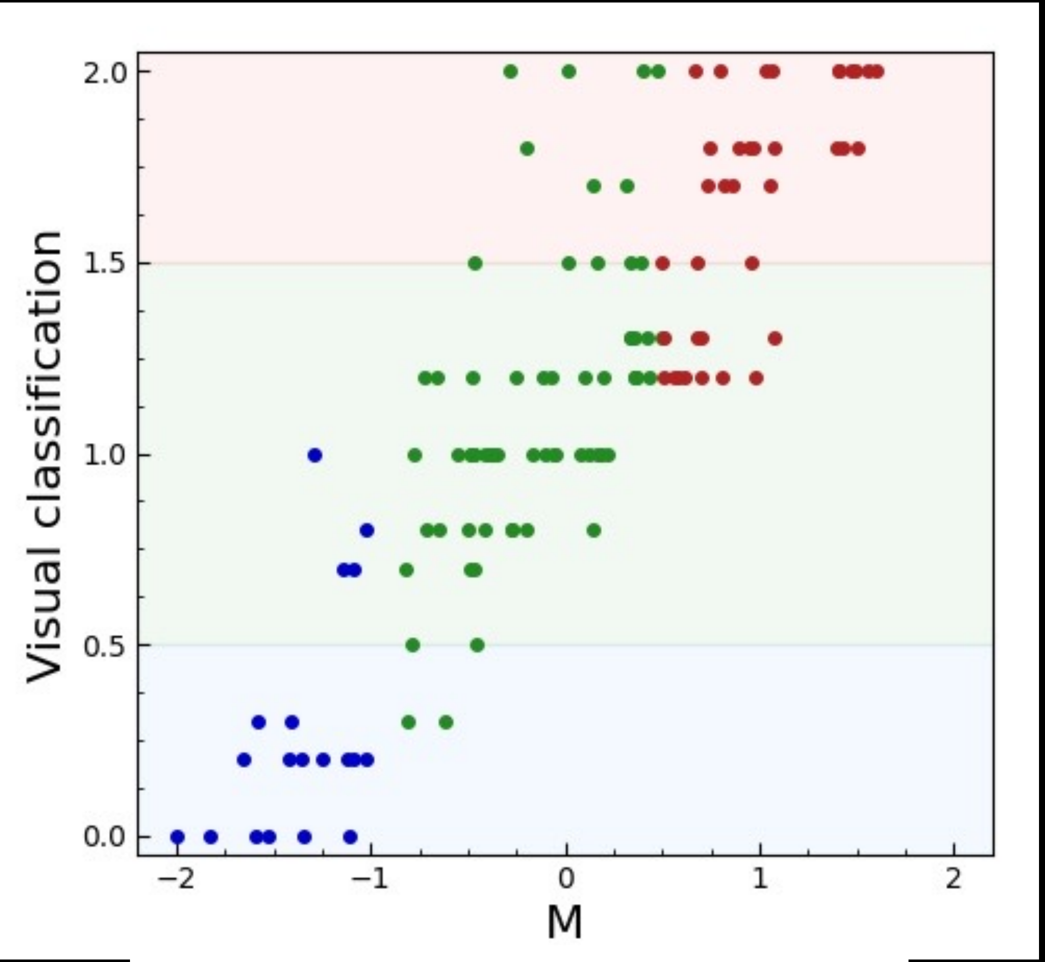
X-ray morphology
(Campitiello, Ettori et al. 2022)





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

X-ray morphology
(Campitiello, Ettori et al. 2022)

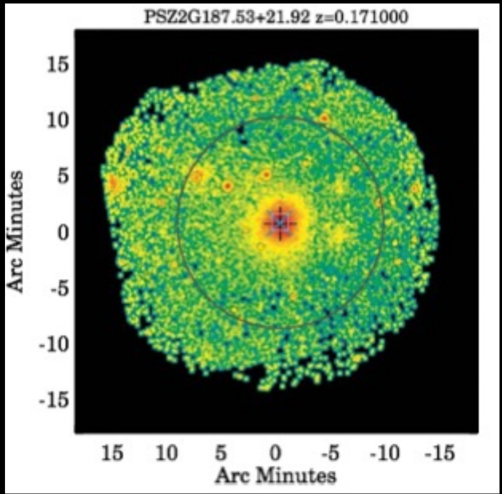


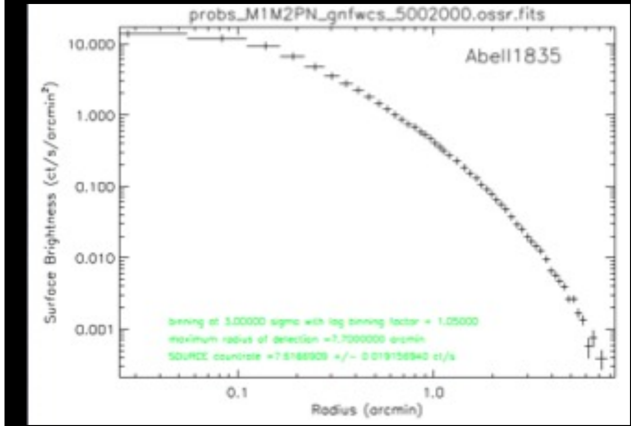
$$M = \sum \frac{\log_{10}(Par^{\alpha_{Par}}) - < \log_{10}(Par^{\alpha_{Par}}) >}{\sigma_{\log_{10}(Par^{\alpha_{Par}})}}$$

- All morphological info compressed 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

Properties of S_X

(Bartalucci, Molendi et al. 2023)

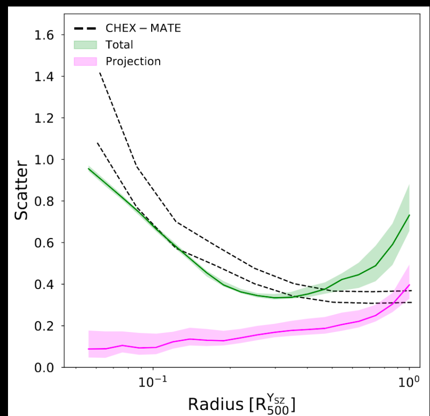


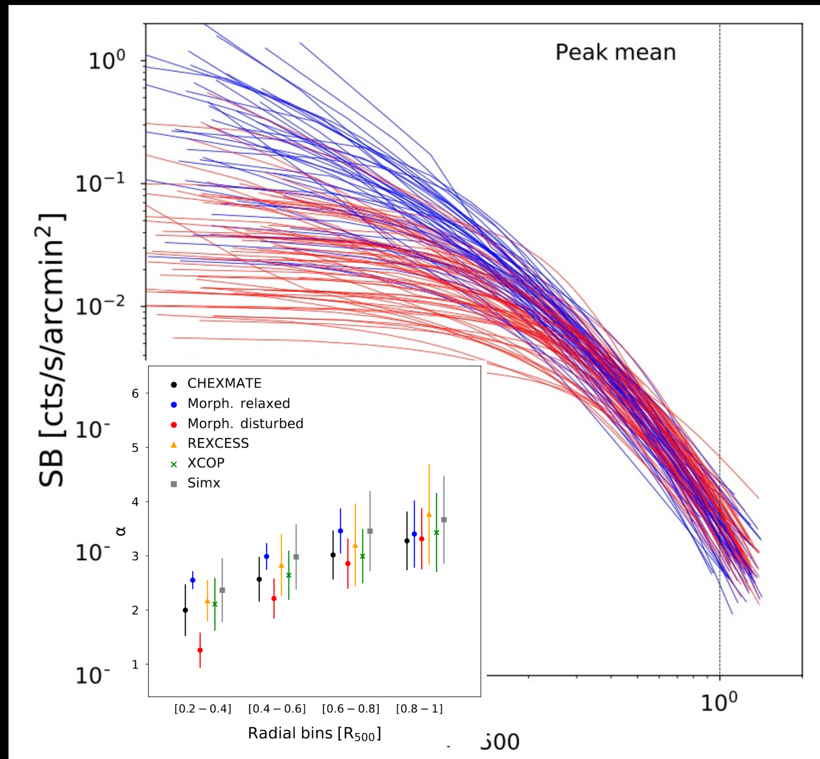


Data quality (116/118 obj):

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

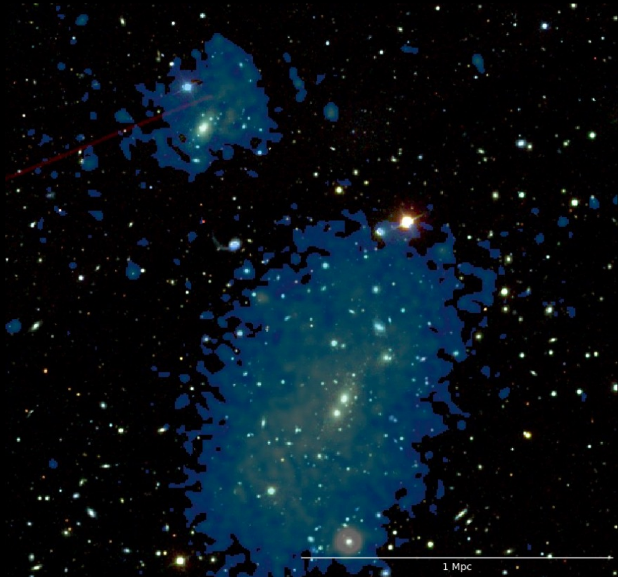
- EM profiles as clear proxy of the morphological state
- Hydro-sims (*the300*) show EM profiles slightly steeper than the CHEX-MATE ones
- Scatter in obs~sims $<0.6R_{500}$, with a min @$0.4R_{500}$

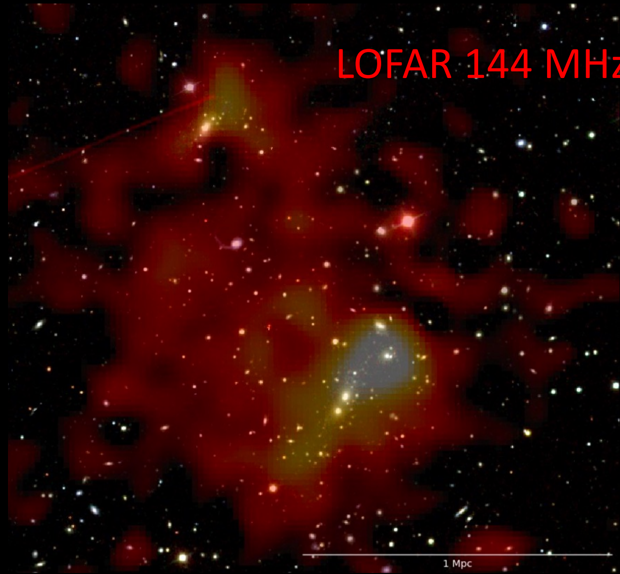


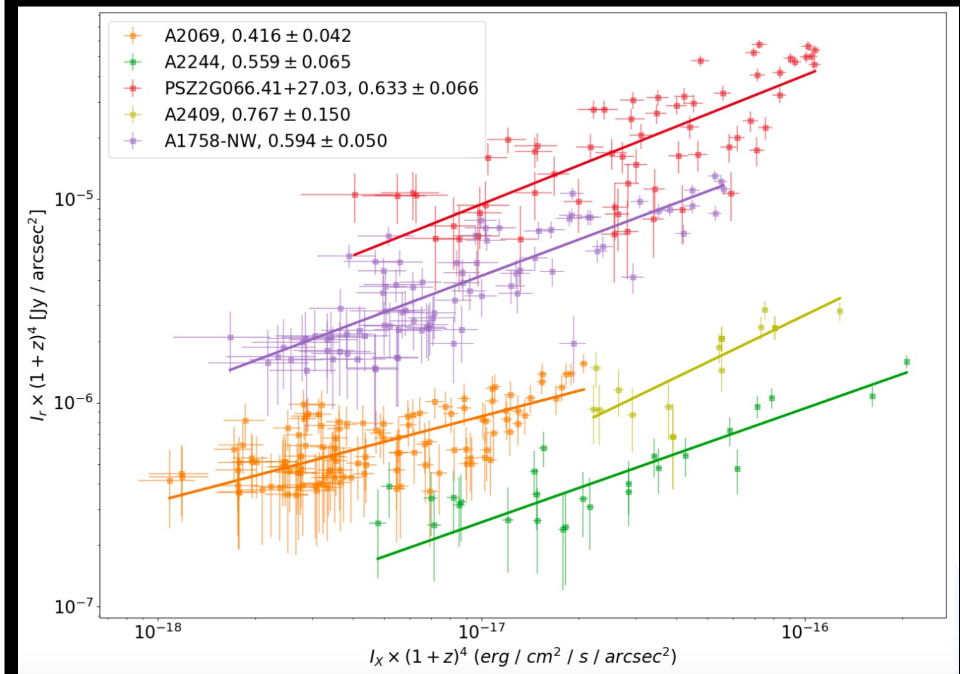


X-ray / radio correlation

(Balboni, Gastaldello et al. 2024)



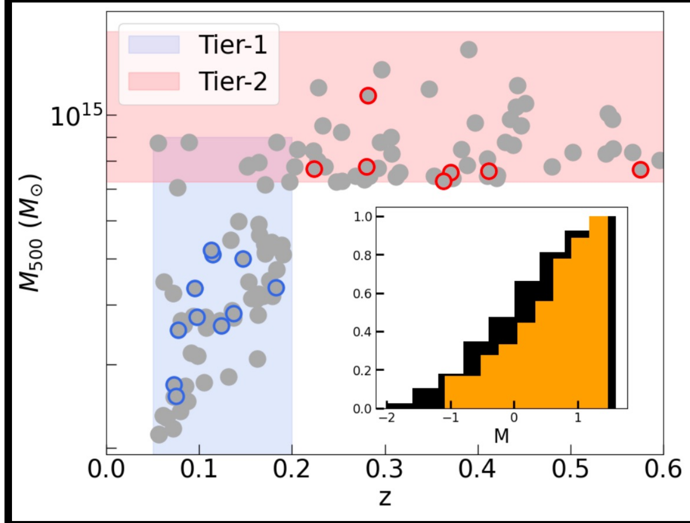


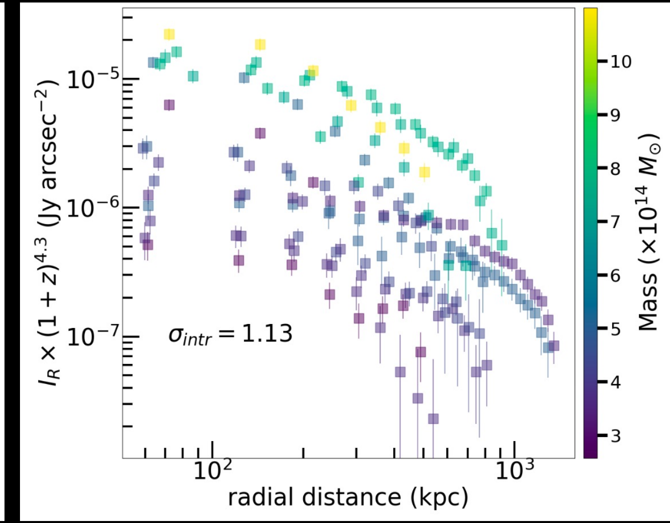


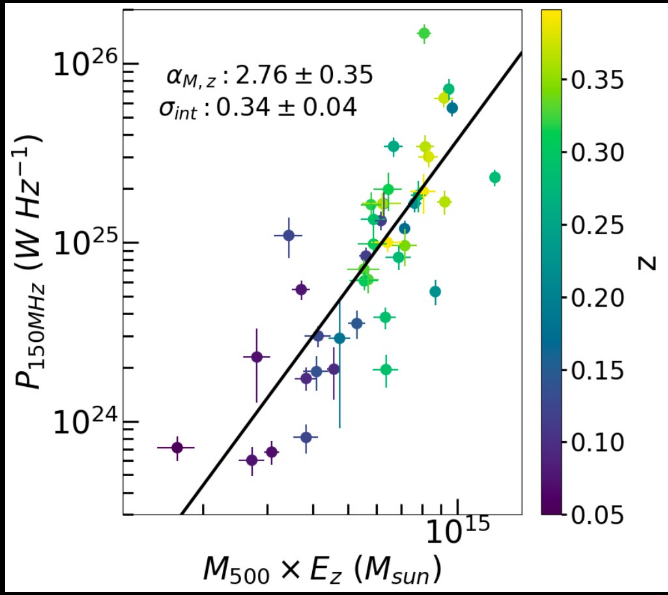
Same instruments/uniform coverage… $I_R \sim I_X^k$, with k<1 …sublinear correlation X-radio brightness ➔ weaker radial decline of the NT component w.r.t. the thermal one

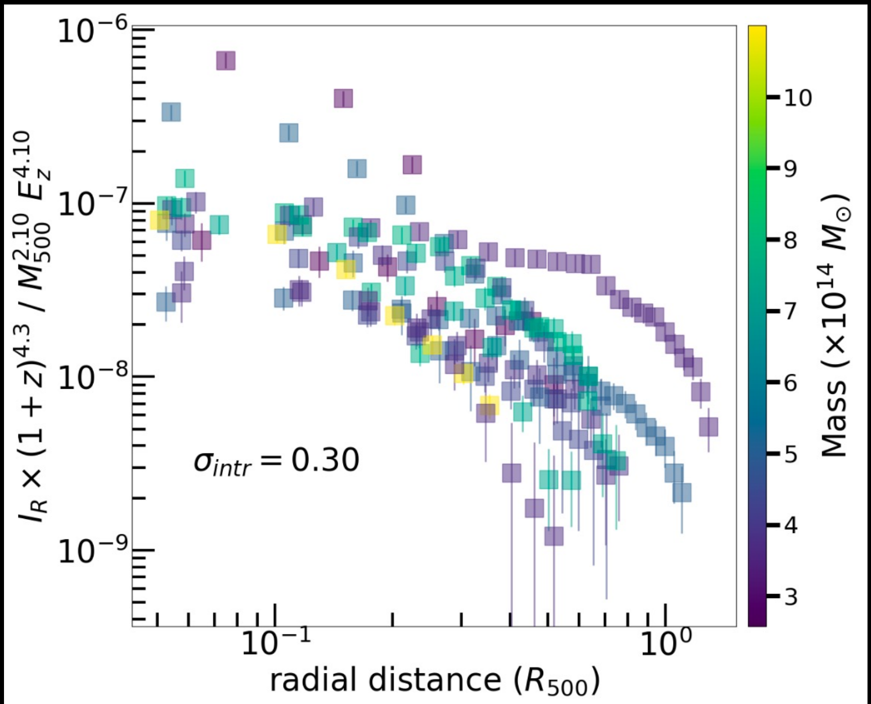
New radio scaling laws

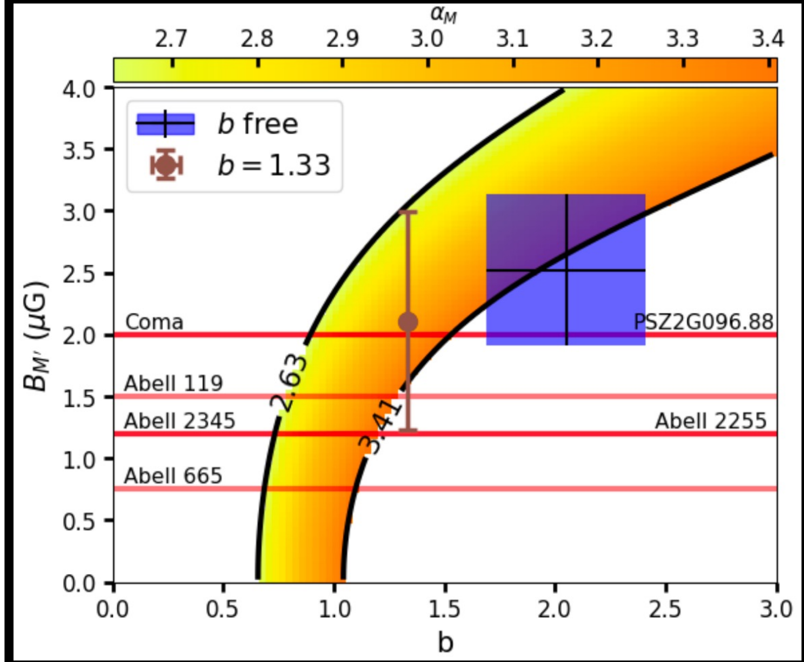
(Balboni, Ettori et al. 2025)



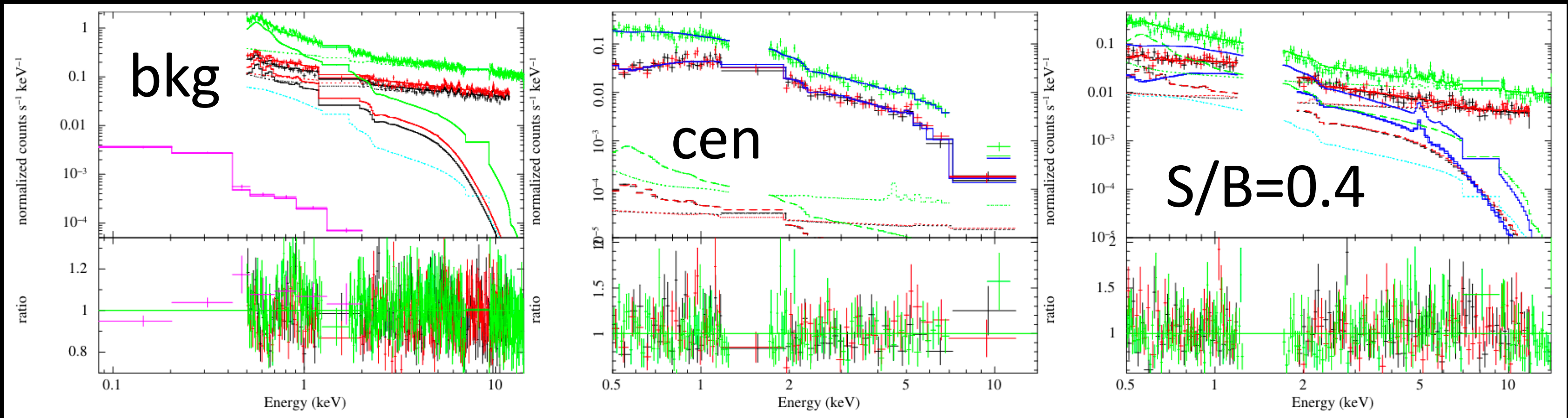






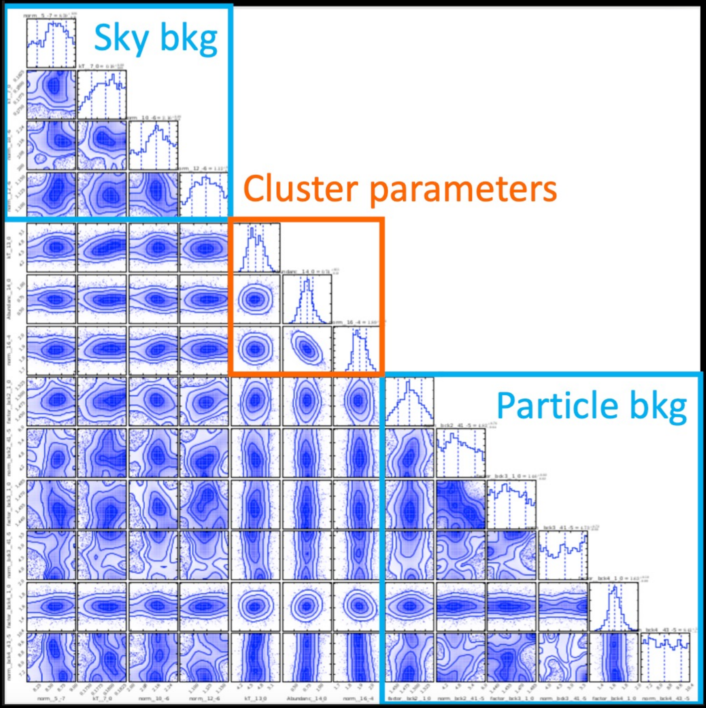


Temperature profiles
(Rossetti, Eckert et al. 2024)



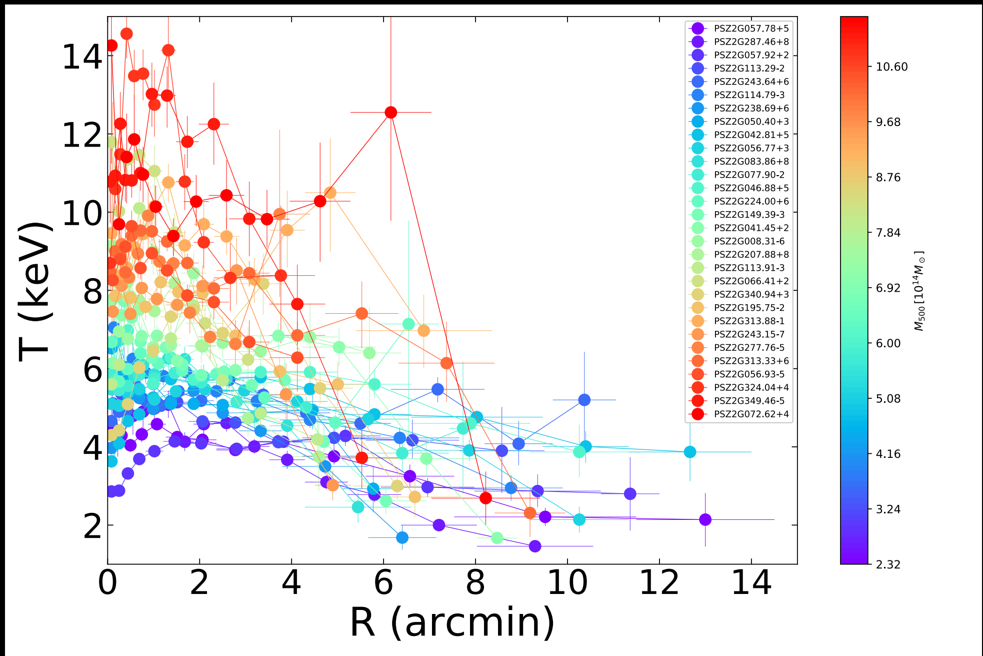
Data Release 1 (DR1; 30 obj; 16 T1, 14 T2)
the sample is ***(i) technical,*** to test our pipeline and new methods under different analysis conditions (extension, background levels,..); ***(ii) representative*** of the original CHEX-MATE sample, in terms of its selection quantities (mass, redshift, *Planck*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

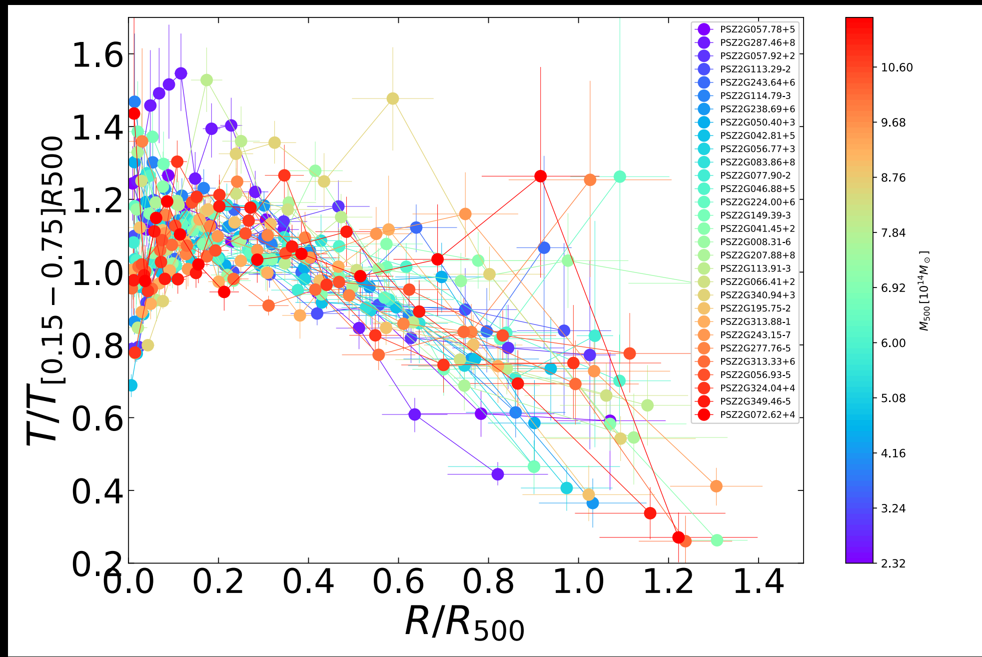
Model: *phabs(apec)*; aspl; nH fixed to Bourdin+23; modelled bkg (residual CXB/1 par; foregr em. of Galactic Halo/2 par; Local Hot Bubble / 2 pars)

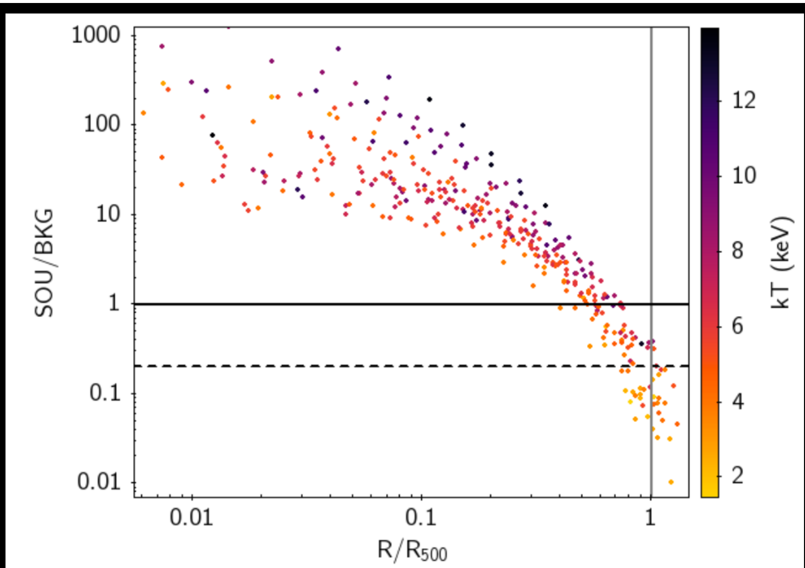


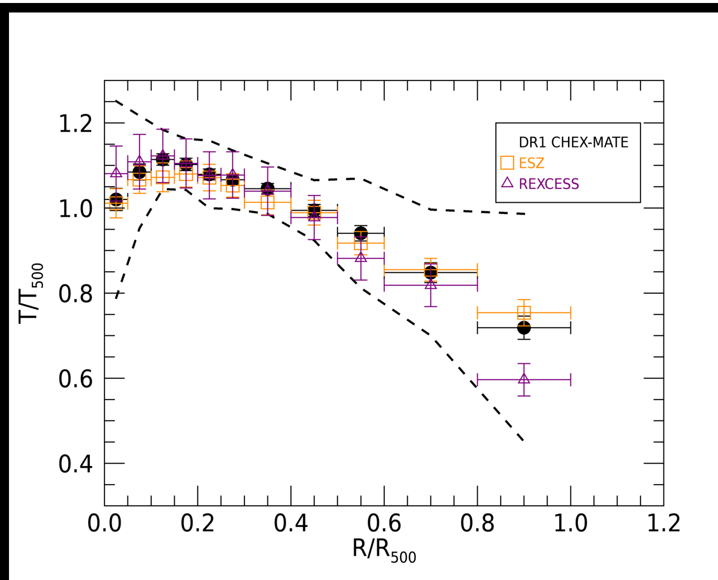
The DR1 temperature profiles

(Rossetti, Eckert et al. 2024)



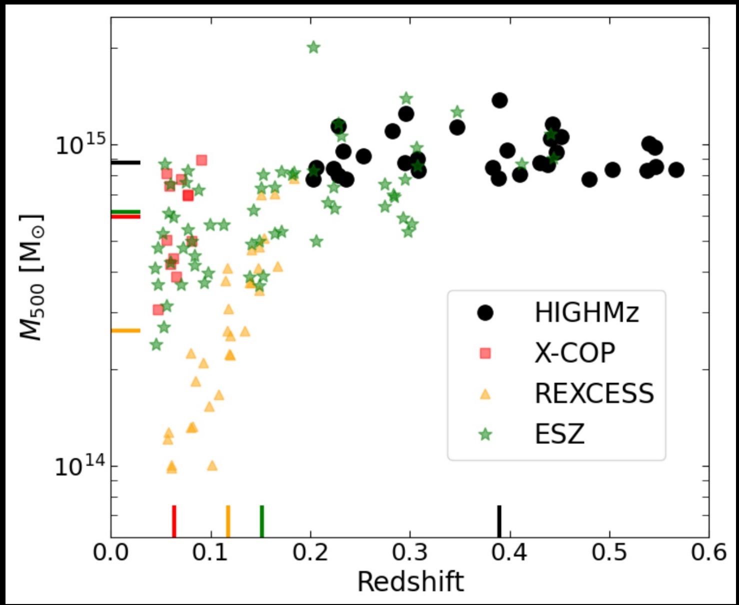


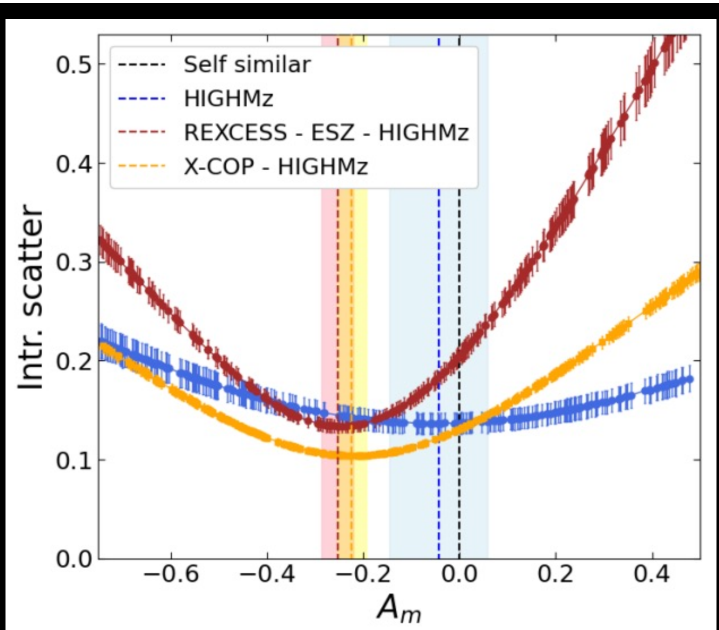


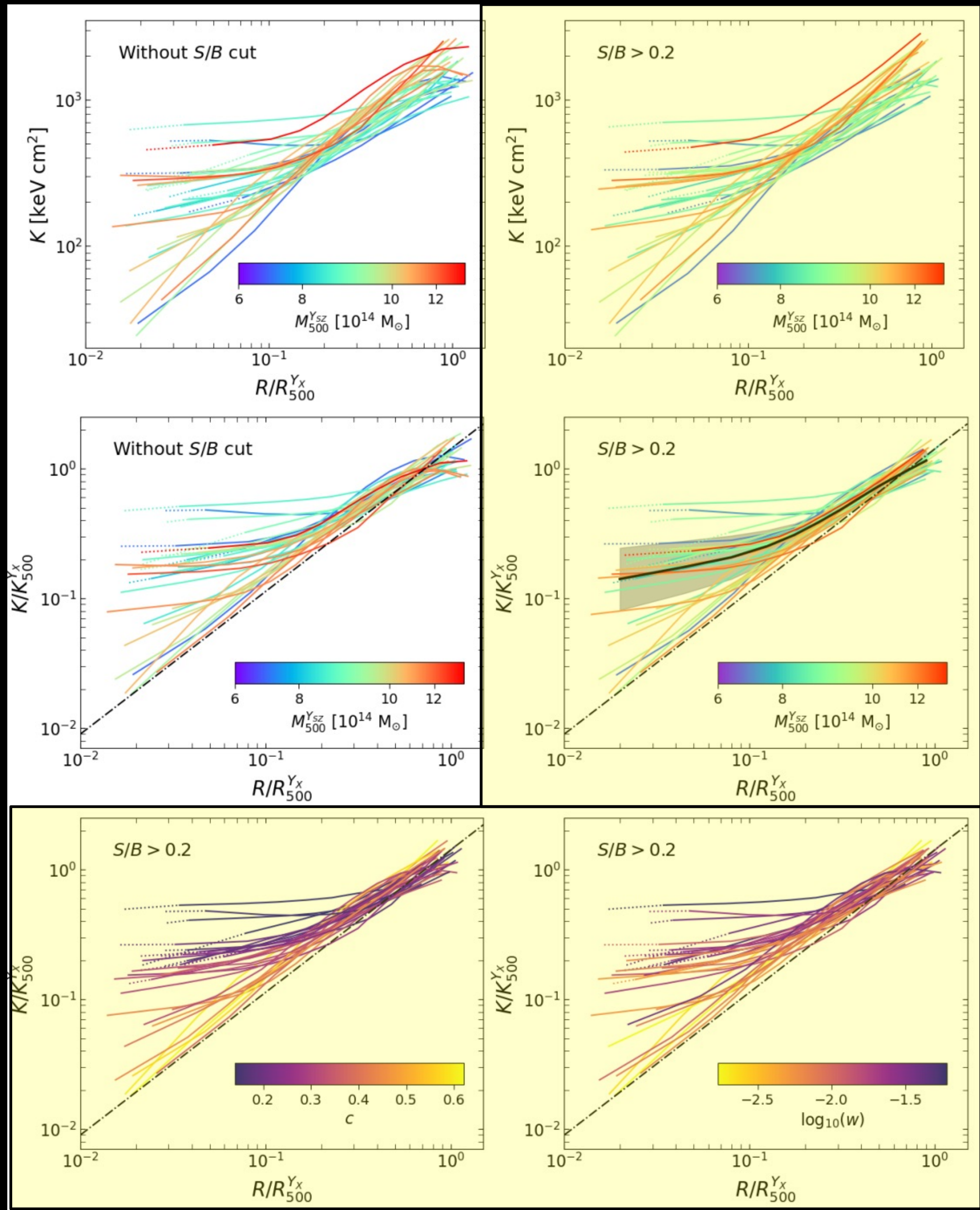


Entropy profiles at high-M

(Riva, Pratt et al 2024)

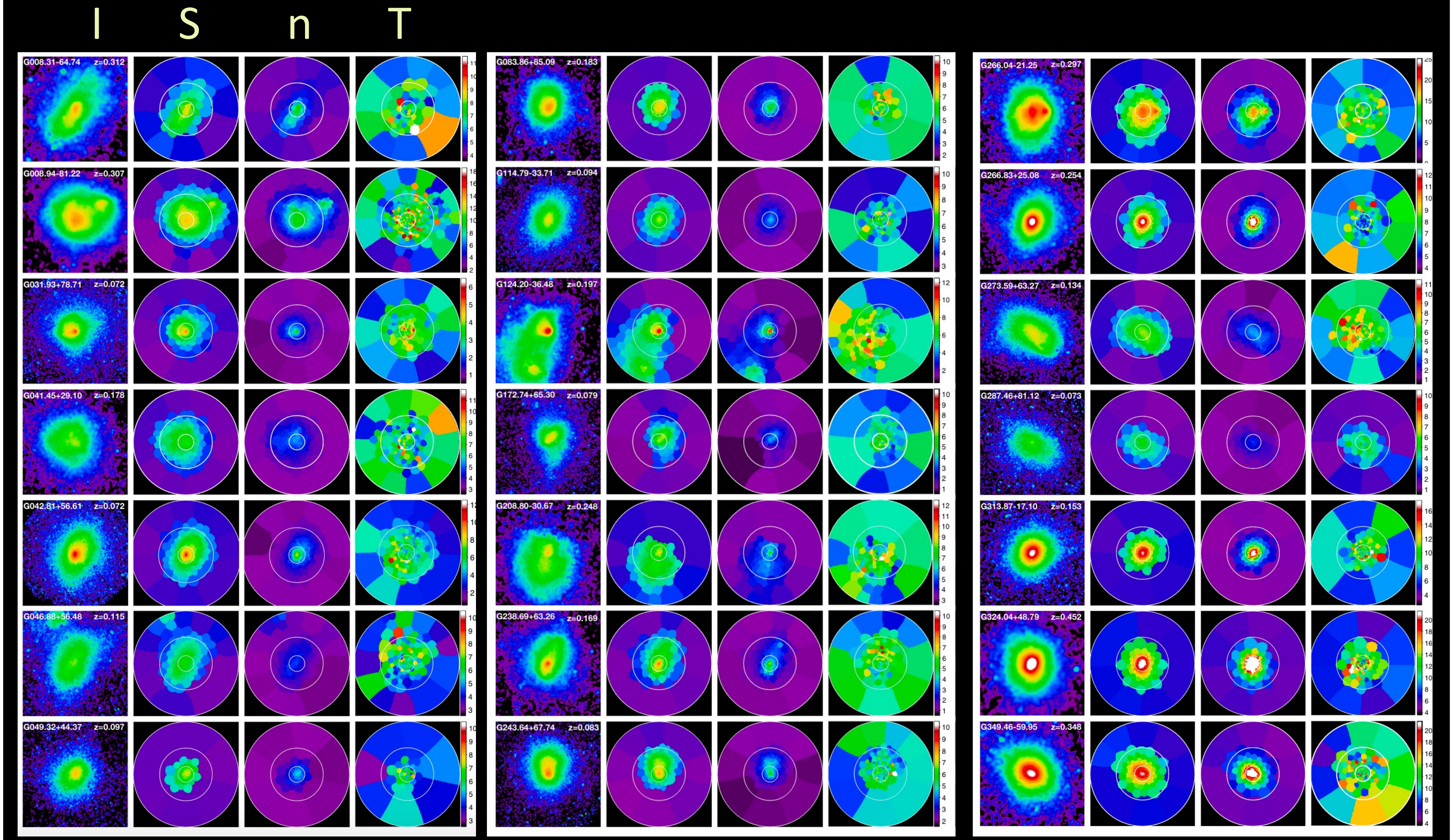




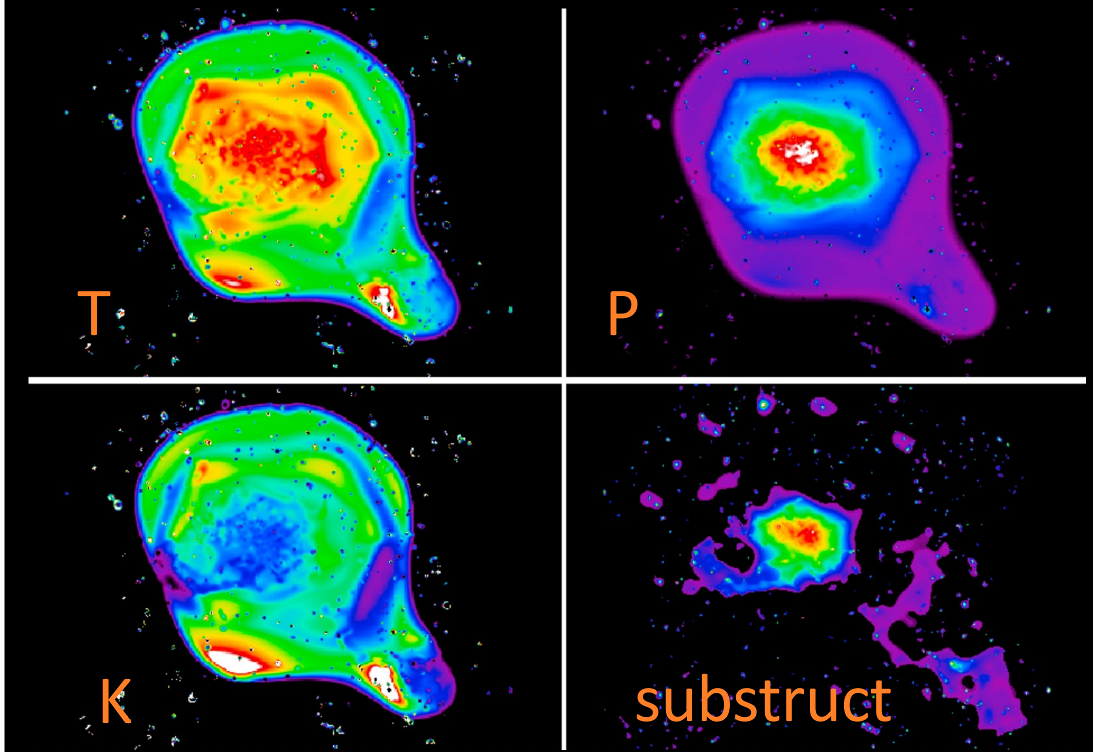


Temperature structure in the ICM

(Lovisari, Ettori et al. 2024, arXiv:2311.02176)



Temperature structure in the ICM



Coma (Schuecker+04)

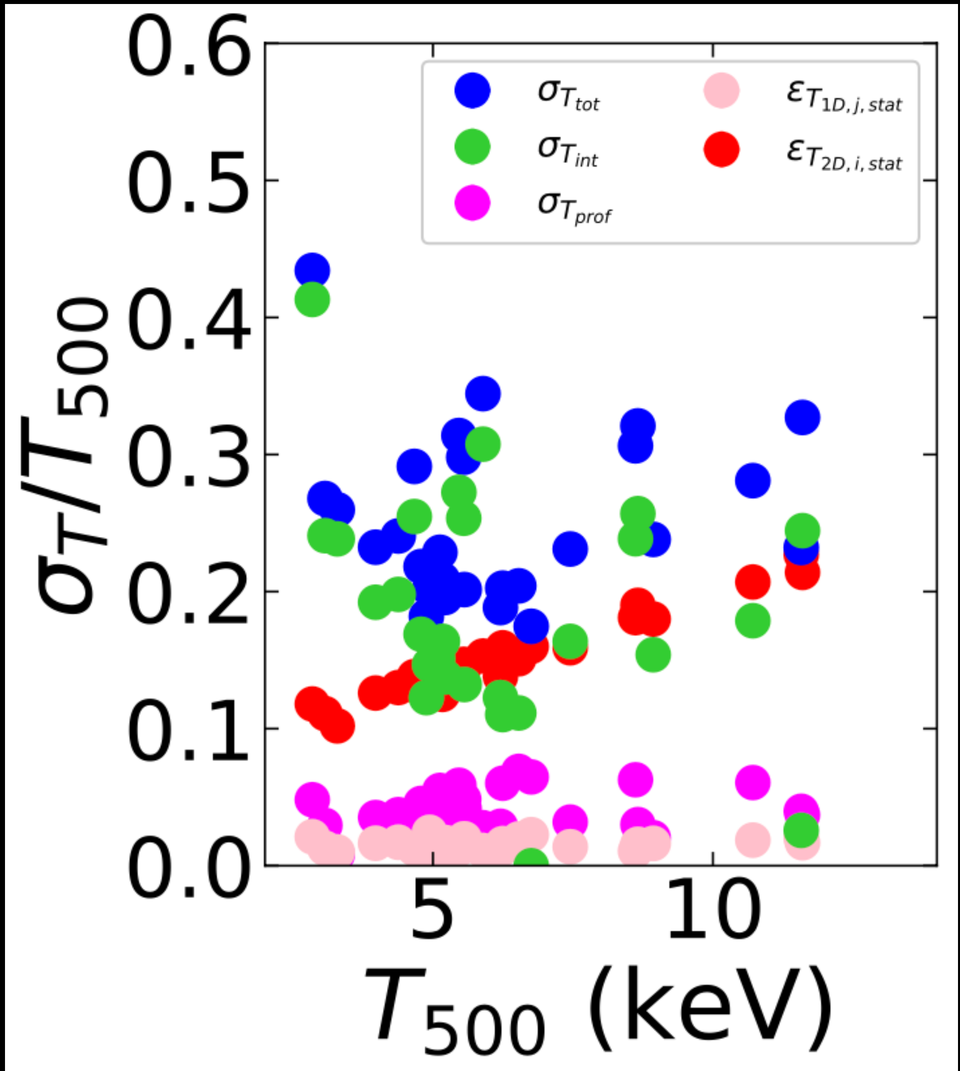
$$\frac{\delta T}{T} = (\Gamma - 1)\ \frac{\delta n}{n}$$

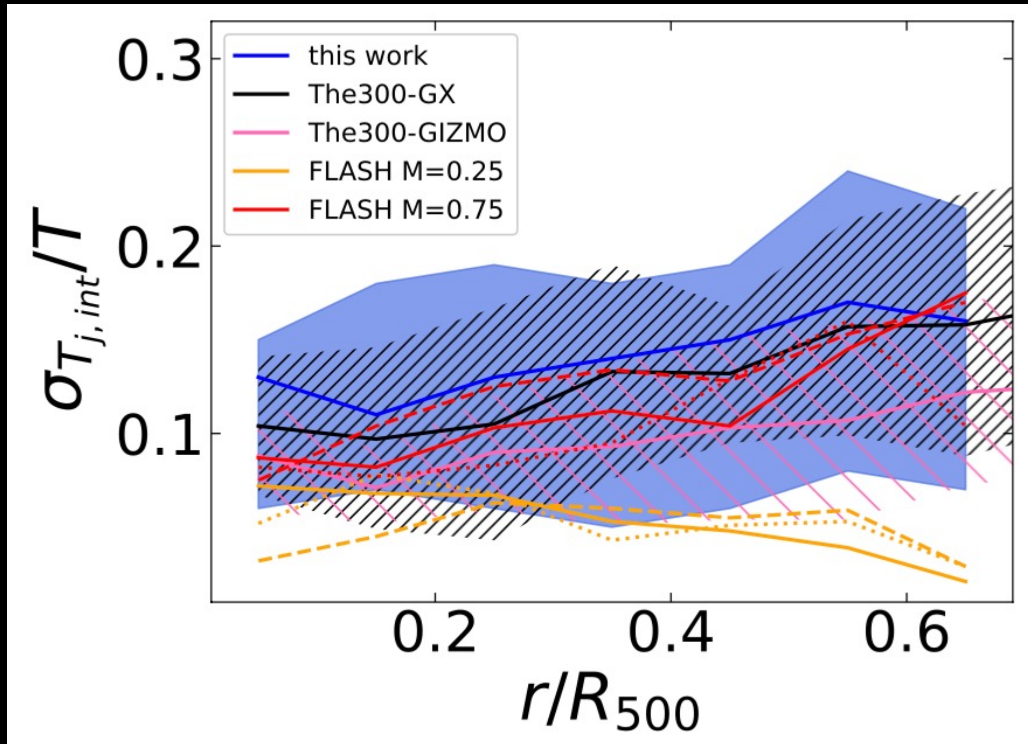
- Perturbations:
  Γ ~0: isobaric
  Γ ~5/3: adiabatic (weak shocks)
  Γ ~1: isothermal

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

Temperature structure in the ICM

(Lovisari, Ettori et al. 2024, arXiv:2311.02176)



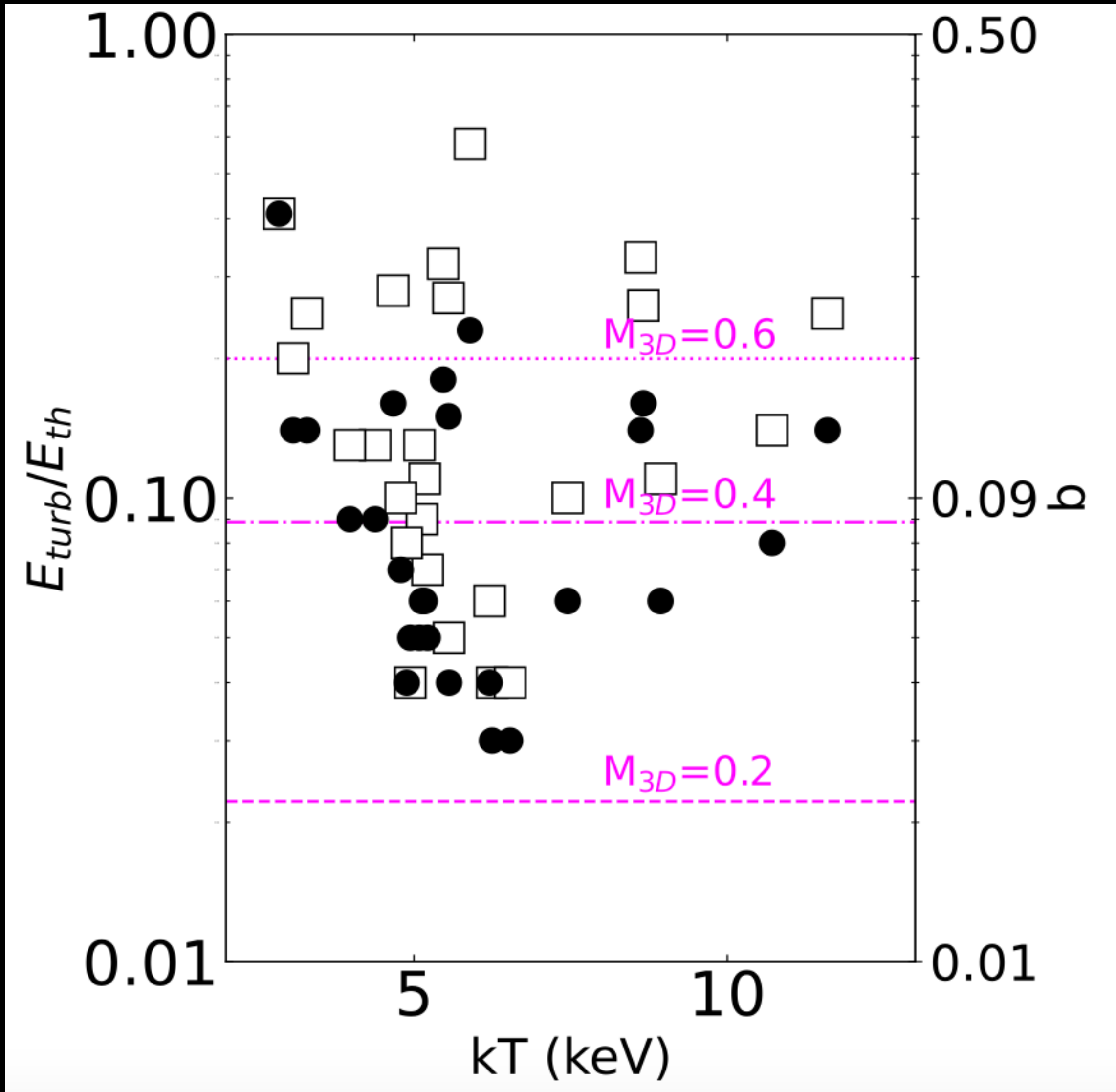


➔ **M =v/c$_s$ ~σ_T/T**

➔ **E$_{turb}$ / E$_{therm}$** = 0.5 γ (γ-1) M^2

Temperature structure in the ICM

(Lovisari, Ettori et al. 2024, arXiv:2311.02176)



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

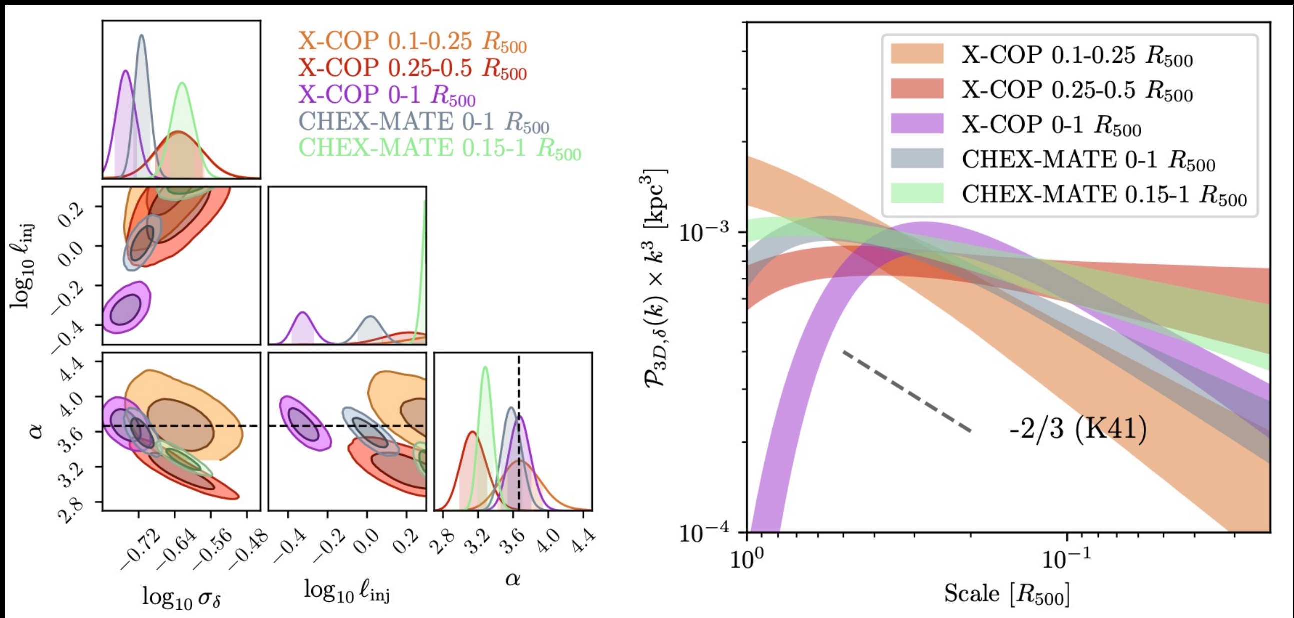
~0.06 [0.03-0.13]

0.11 [0.04-0.22]

In X-COP objects,
massive nearby GCs:
b<0.03 (0.17)
in 50 (80)%
(Ettori & Eckert 22)

S_X fluctuations in the ICM

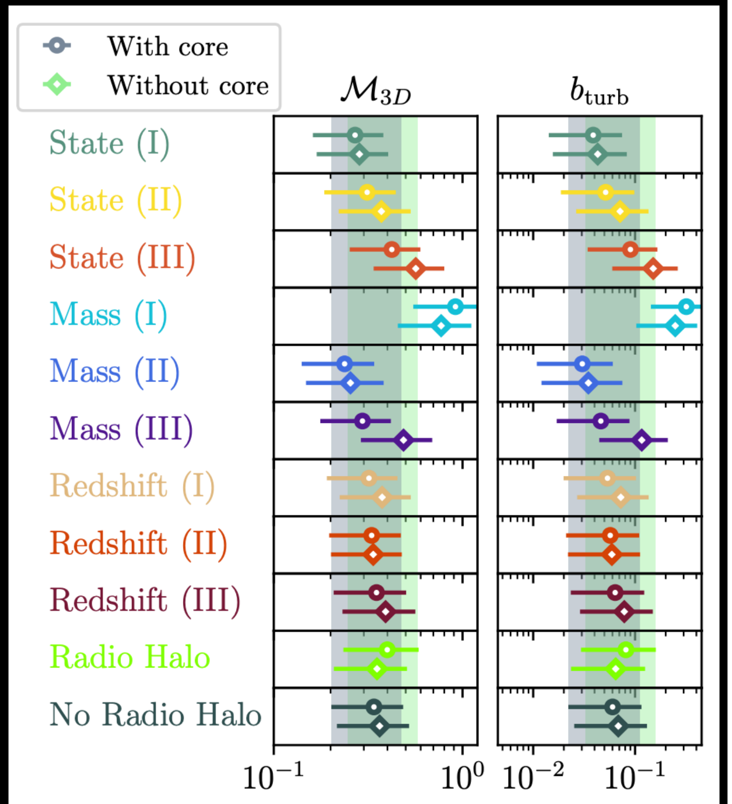
(Dupourqué, Clerc et al. 2024, arXiv:2403.03064)



$$\mathcal{M}_{3D} \approx \sqrt{3} \times (1 \pm 0.4)\, \sigma_\delta$$

$$\frac{P_{NT}}{P_{tot}} = \frac{M_{3D}^2 \gamma}{M_{3D}^2 \gamma + 3}$$

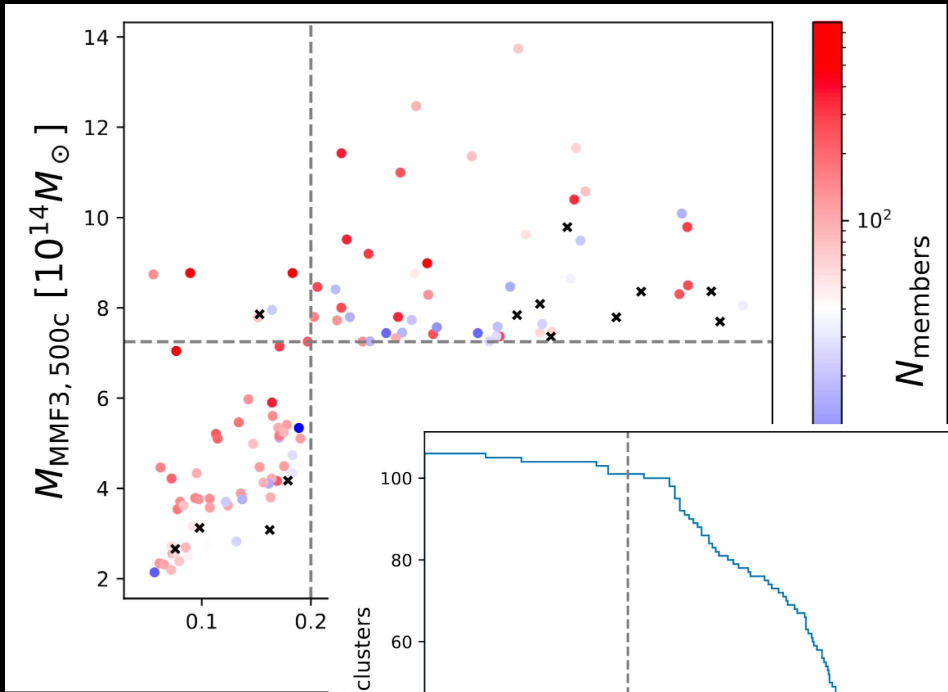
$$\sim b = 0.09 \ (\pm\ 0.06)$$

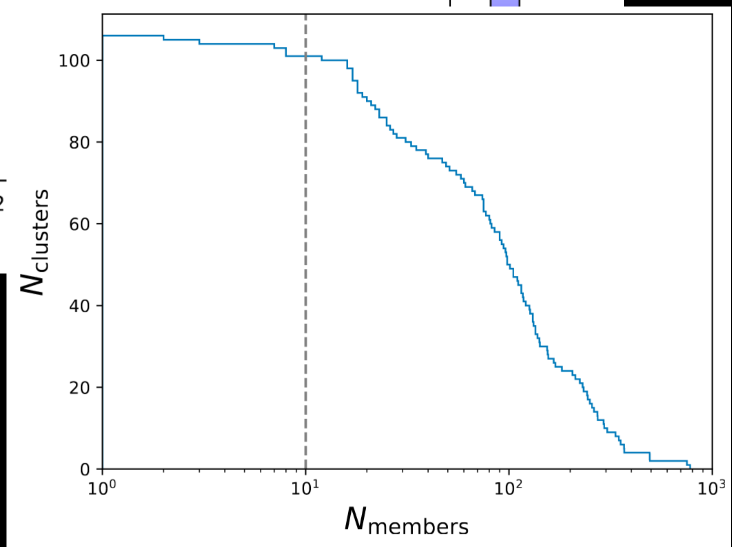


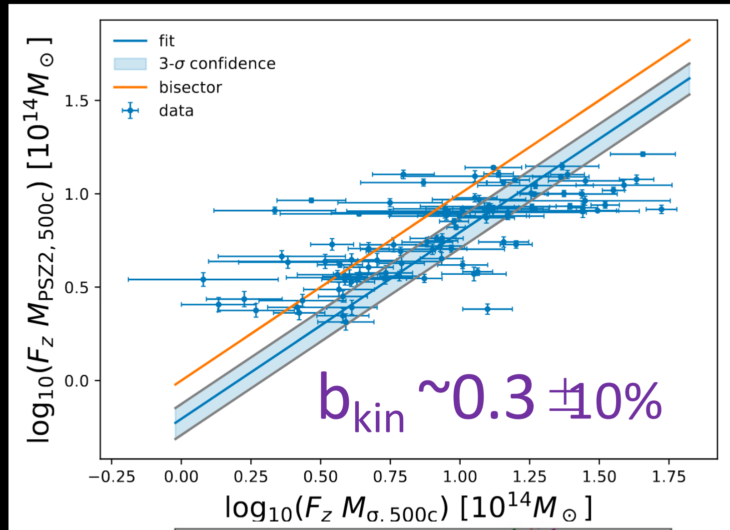
Dynamical masses

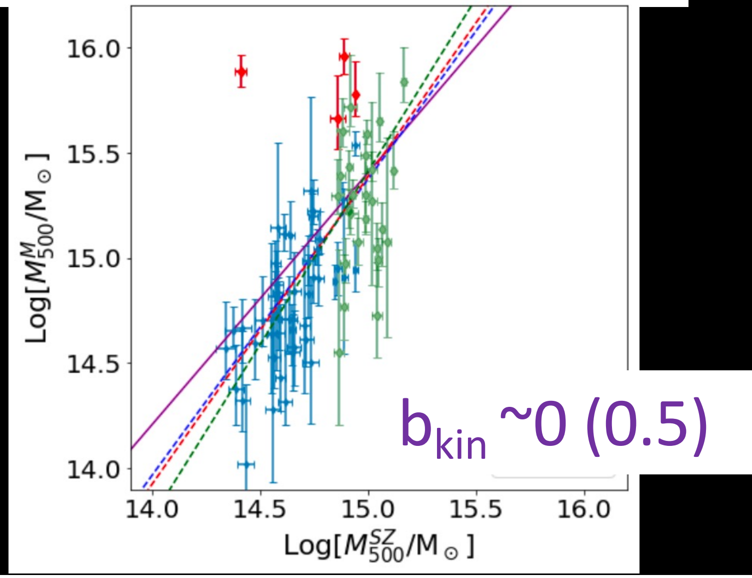
(Sereno+25, Pizzuti+25)

➔ redshifts recovered from NED, SDSS & DESI databases +CoMaLit compilation: robust estimate of velocity dispersions for 101 objects *(79 with >50 members)*









Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INAF ISTITUTO NAZIONALE DI ASTROFISICA

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

- **X-ray**: pipeline completed & running; ***next goal:*** M_{HE}
- **SZ**: Planck profiles available via 2 different methods (ref. Pointecouteau, Bourdin); **NEWS**: *NIKA2* data for ~20 obj (PIs: Bourdin, Adam, Macias-Perez); *ACT-DR6*: 44 obj
- **Lensing**: homogeneous analysis of Subaru/HSC, VST/OmegaCAM as part of the *Amalgam* program (62 obj; ref. Gavazzi, Umetsu); a few of these objects satisfy the SZ-X criteria for CLUMP-3D triaxial modelling (→ Kim+24)
- **Radio**: archived & proprietary LOFAR, GMRT, MeerKAT (*XLP approved*) maps (→ Balboni, Bonafede et al. 24, 25, in prep)
- **Hydro-sims**: tailoring of *the300* (ref. Rasia, De Petris) & MACSIS (ref. Kay) products

→ Stay tuned ←