The Clusters' Gambit: winning simulations for CHEX-MATE

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UNIVERSITÉ DE GENÈVE

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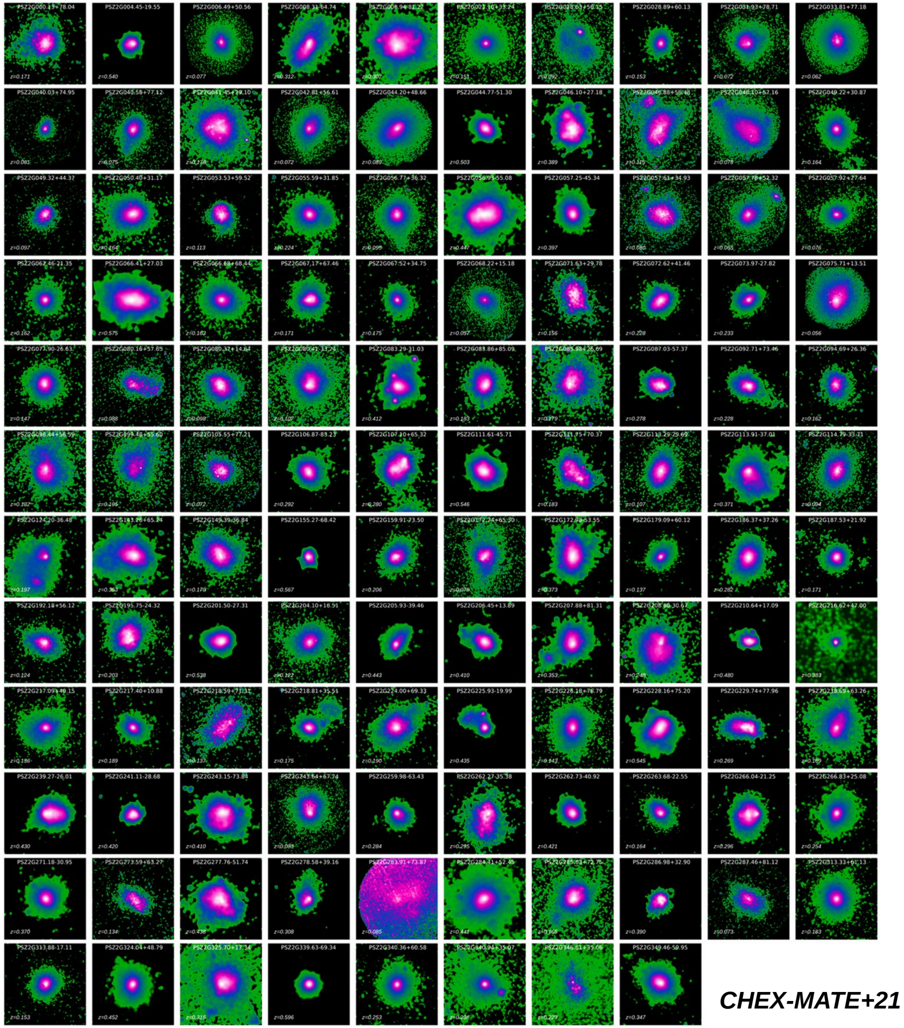
Outline

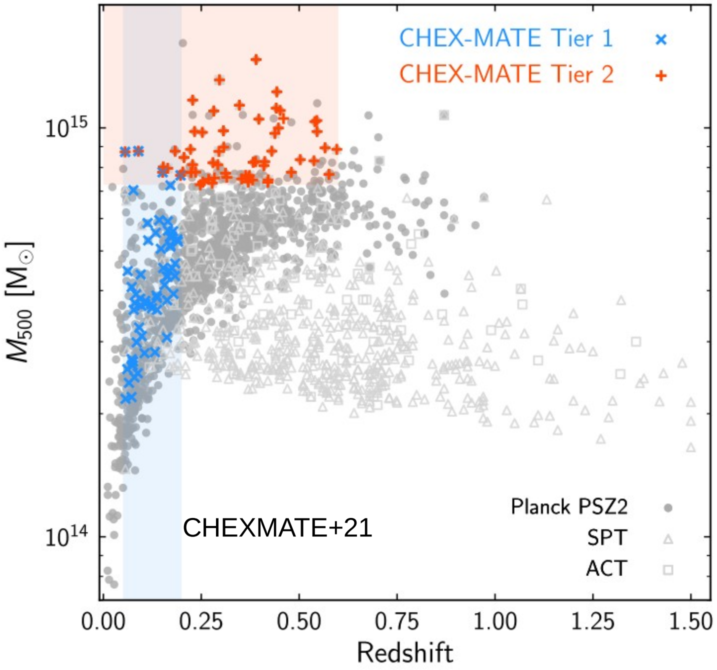
- ***CHEX-MATE intro***
- ***Aim: Testing observational techniques***
- ***Mock creation (E. Rasia, D. Eckert)***
- ***Mock processing and analysis***
- ***Population results kT, Mgas profiles and discussion***

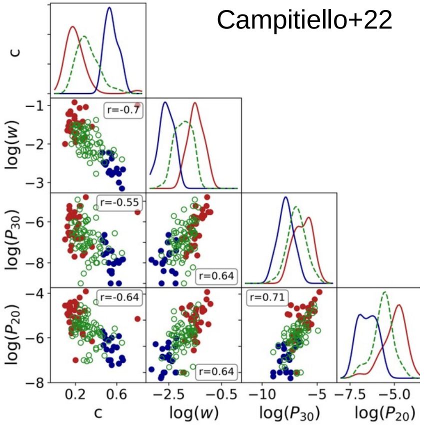


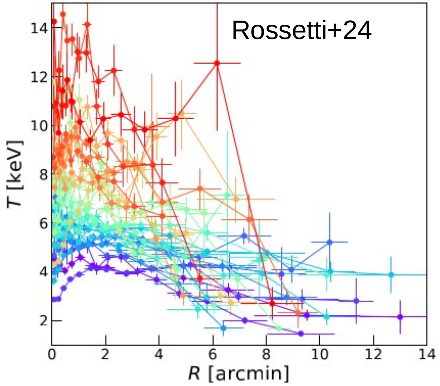
CHEX-MATE+21

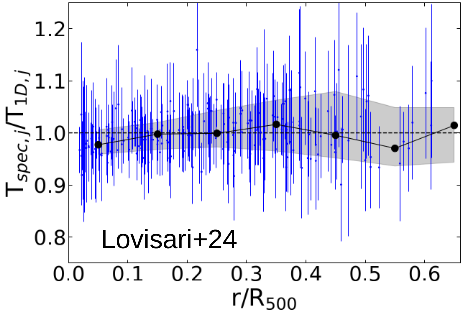
CHEX-MATE

- Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation (PI: S. Ettori, G.W. Pratt)
  - follow-up of 118 Planck clusters (SZ) with XMM-Newton

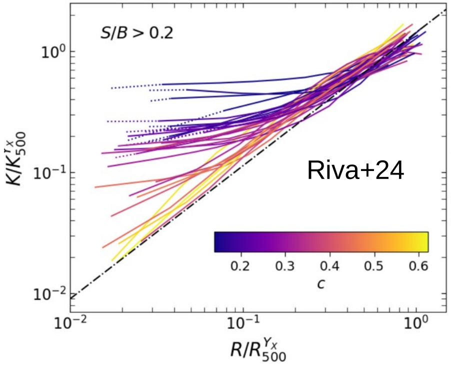


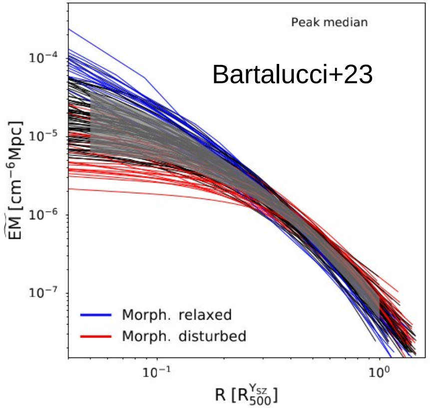


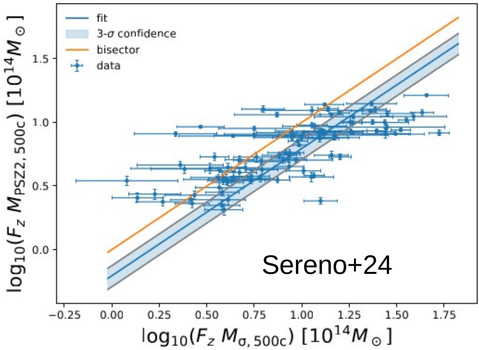




- Tier 1: 0.05<z<0.2, 2e14<M500c<9e14
  - Tier 2: z<0.6, M500c>7.25e14







CHEX-MATE

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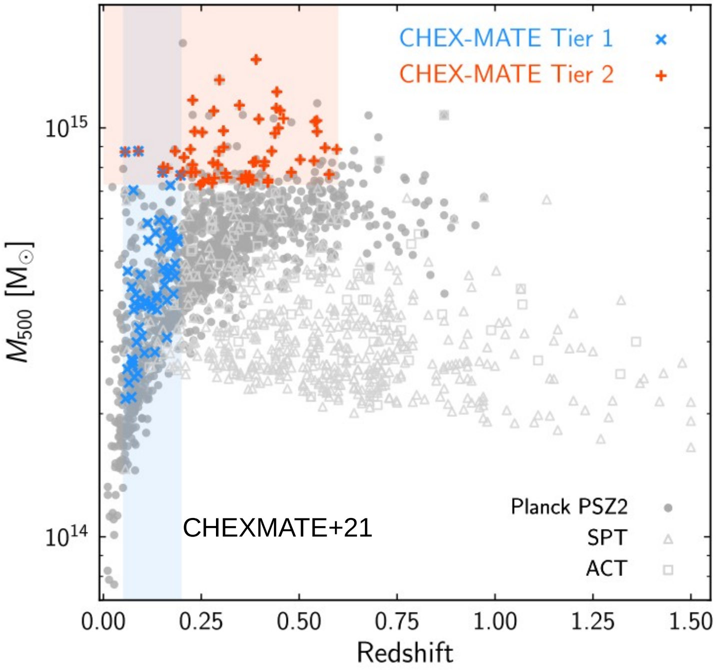

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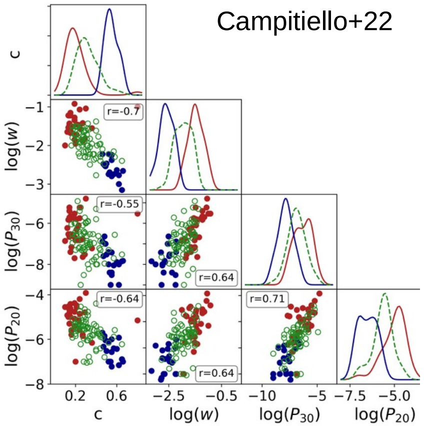
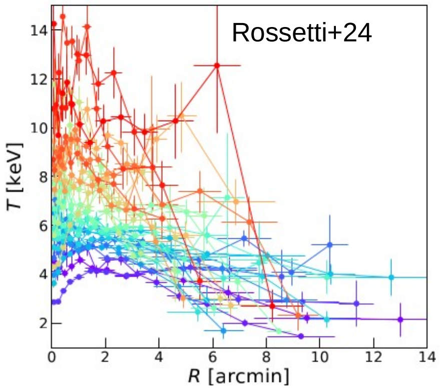
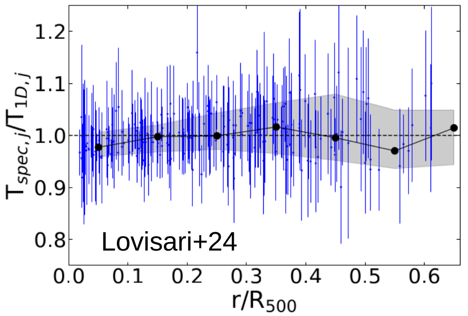
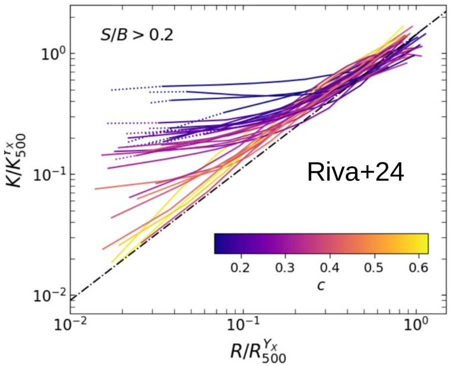
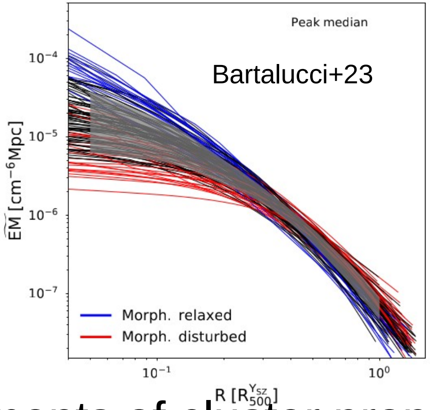
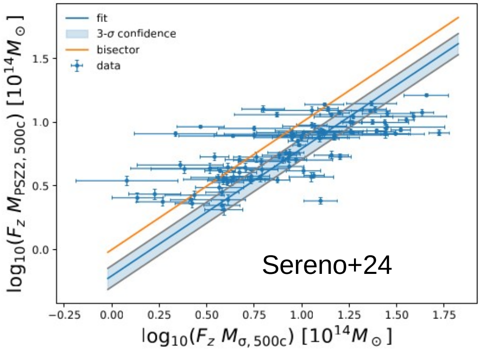








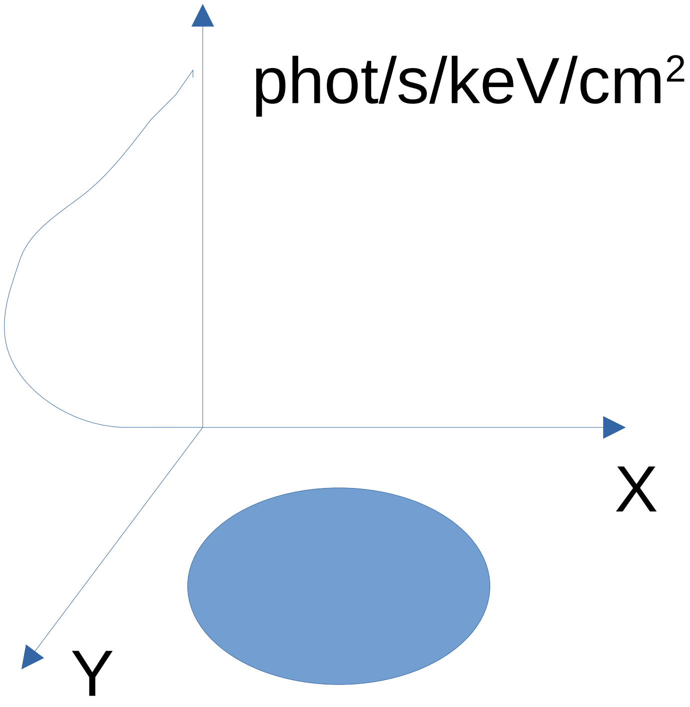




- CHEXMATE relies on precise and accurate measurements of cluster properties → ***simulations***

The XMM simulator

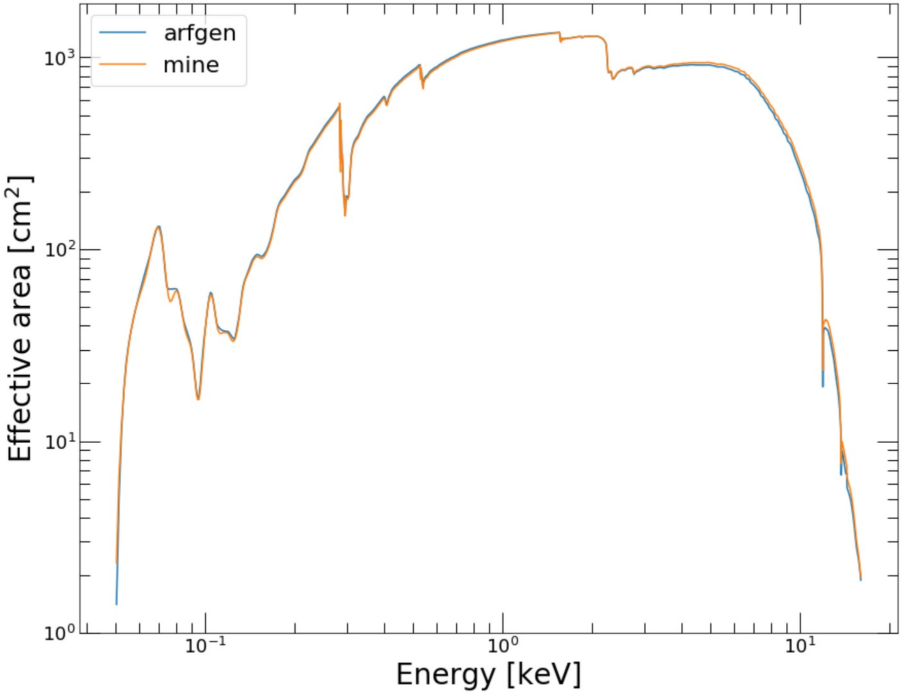
- The input data is in the form of model photon spectra for each pixel of an image :
  - For each particle a model spectrum is generated as phabs(apec) with $Z=0.3\ Z_{\odot}$
  - For every narrow energy channel, the emissivity of the particles is summed up and projected
  - For each energy channel we get a 2D model image over a field of 30x30 arcmin

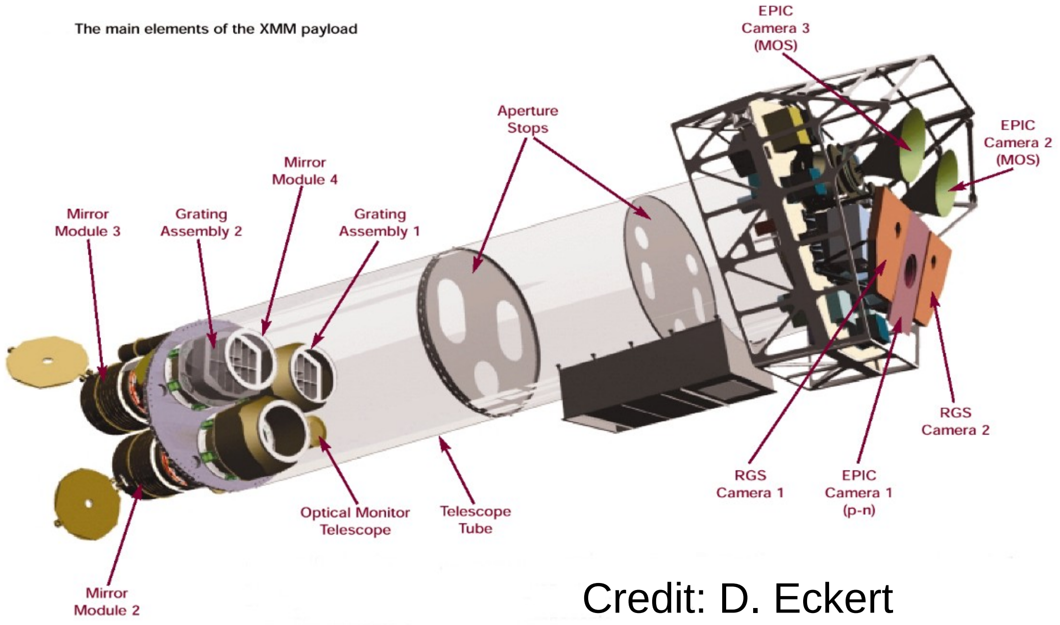


Credit: D. Eckert

XMM mock creation technique

- We construct effective area files for each point on a pre-defined grid including the telescope effective area curve, quantum efficiency, filter transmission, and vignetting



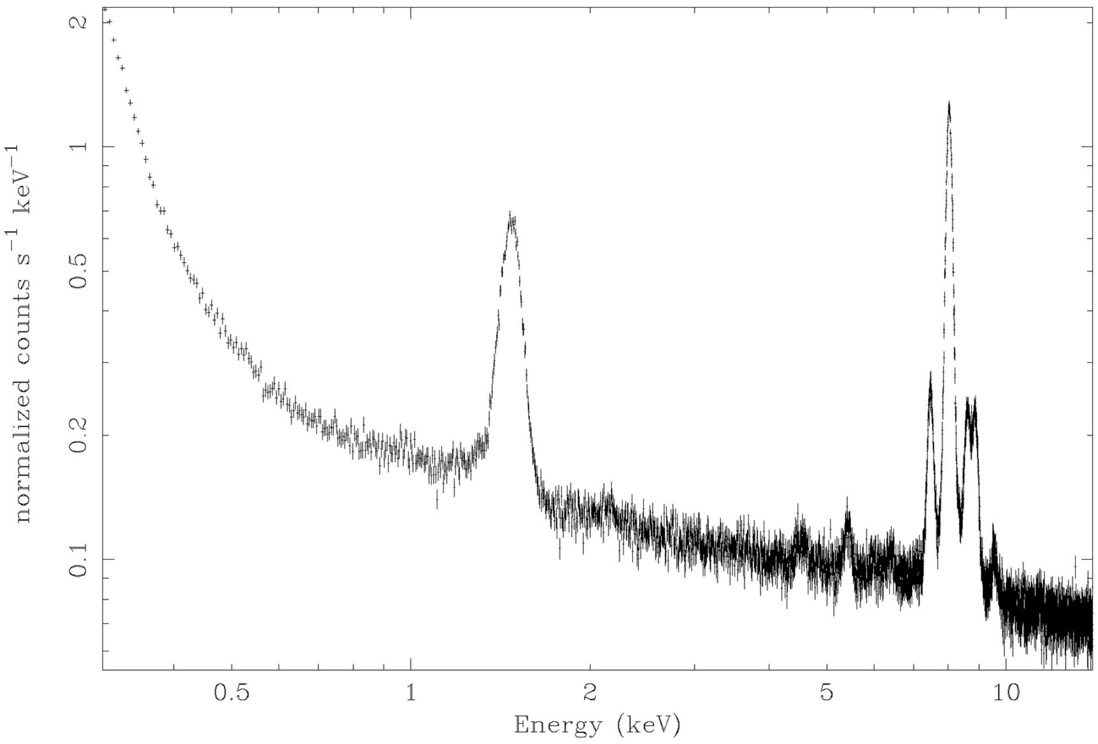


Credit: D. Eckert & ESA

Particle background

- The particle background spectrum is drawn from filter-wheel-closed data for each EPIC camera (MOS1, MOS2, PN)

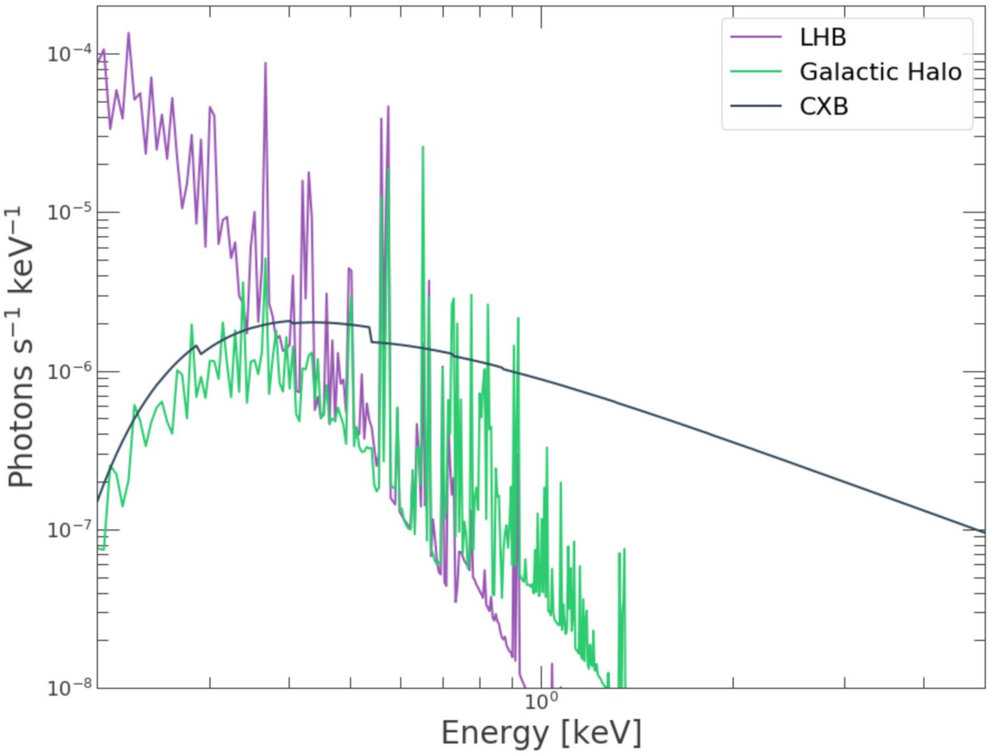
- The spectral shape and normalization are assumed to be constant over the detector



Credit: D. Eckert

Sky background

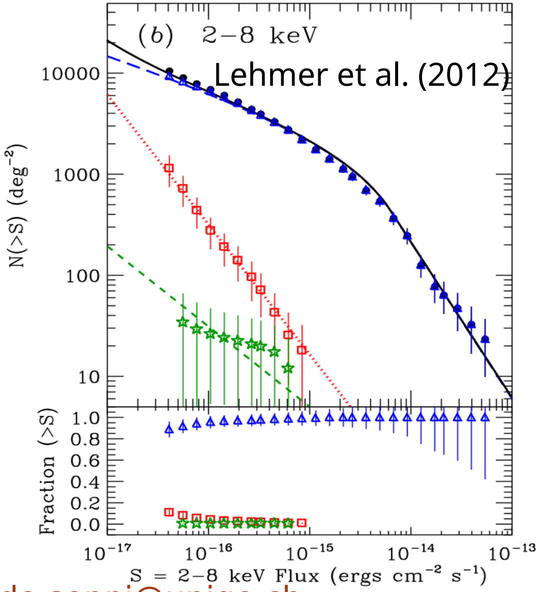
- The unresolved sky background is modeled as :
  - APEC at 0.11 keV for LHB
  - PhAbs(APEC) at 0.22 keV for GH
  - PhAbs(Power) with Γ=1.46 for CXB
- «typical» normalizations for extragalactic observations

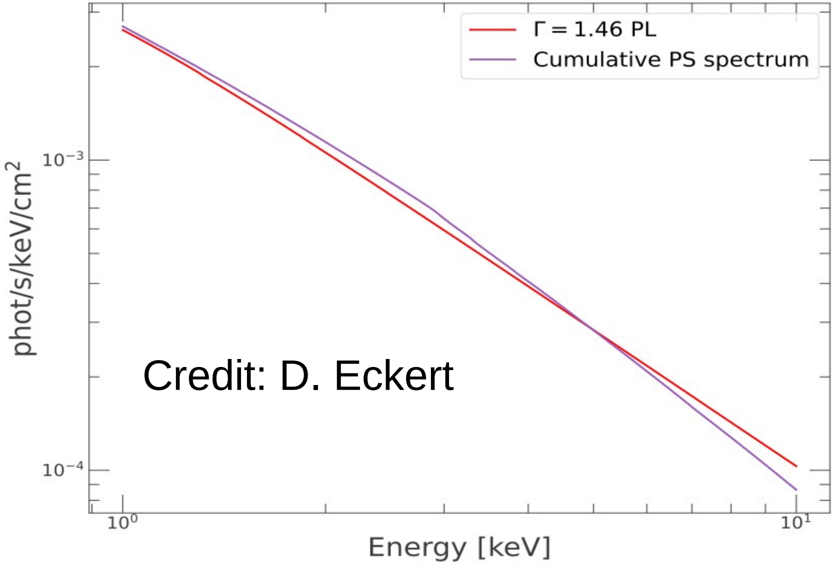


Credit: D. Eckert

Point sources

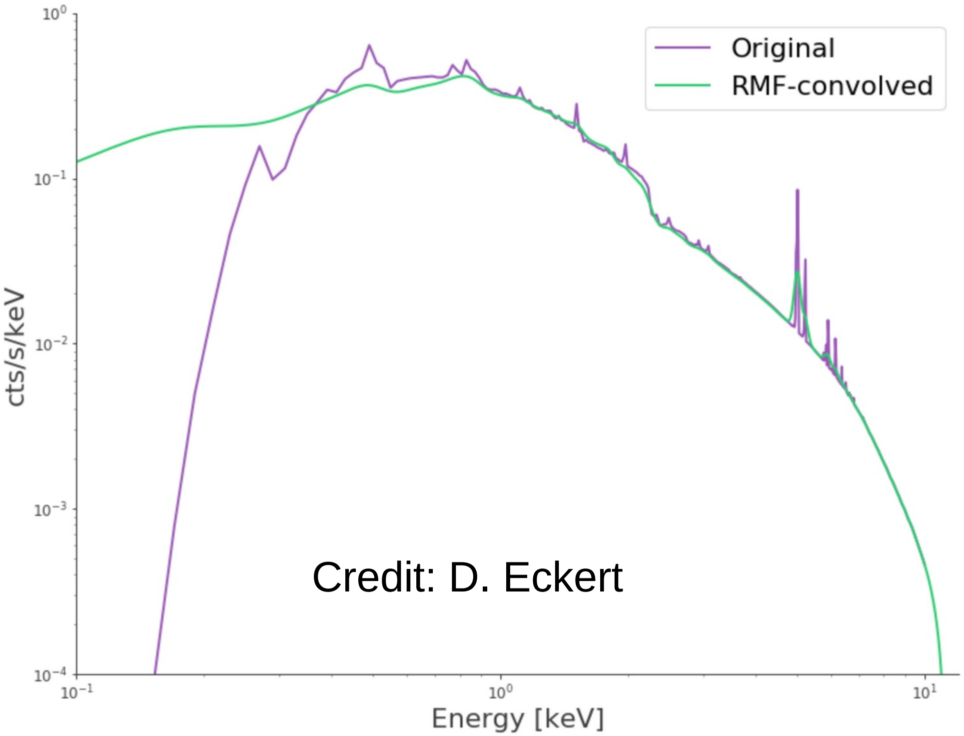
- Point sources with F(2-10 keV) > 1e-15 erg/cm2/s are randomly generated from the Lehmer et al. (2012) logN-logS
- The spectral shape is described as an absorbed power law, with the cumulative matching the CXB spectral shape: log $N_H \sim$ Uniform([20.5, 23]), log Γ ~ N(1.9, 0.2)





Event file generation

- For each narrow energy band, the model image (source + sky bkg + point sources) is converted into XMM pixels
- The narrow-band image is convolved with the PSF and the energy redistribution matrix (RMF)
- Individual events are generated as Poisson realizations of the total model
- An event file is also generated from the particle background model and merged with the photon events



Credit: D. Eckert

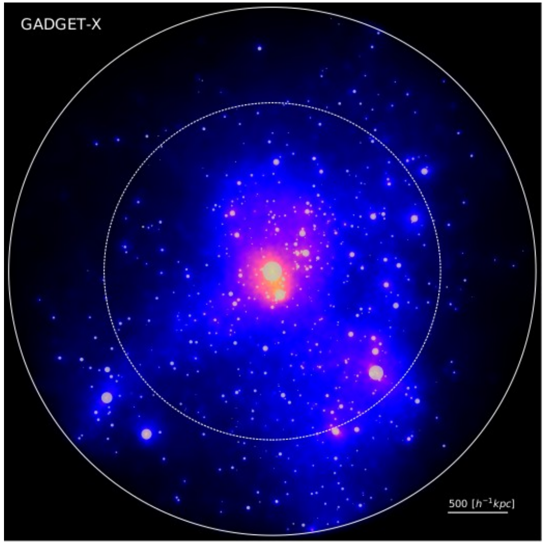
Hydro-simulations

The300

Cui+18

Zoom-in hydro run of the most massive MultiDark haloes

Mdm=1.9e9, Mgas=3.9e8

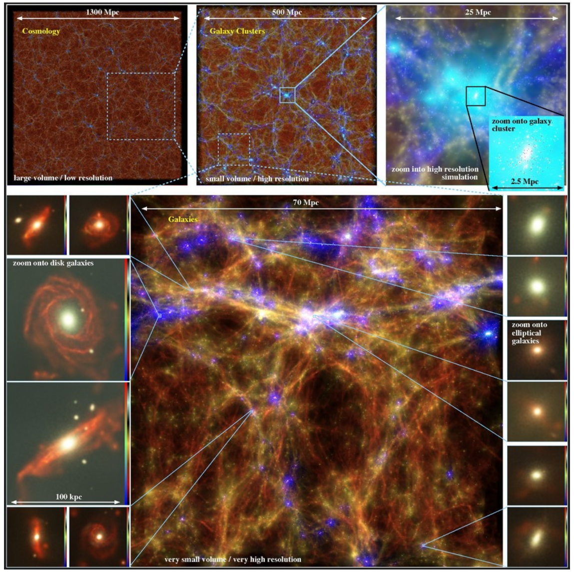


MAGNETICUM

Biffi, Dolag+

Clusters extracted from Box2, Box2b

Mdm=9.6e8, Mgas=1.9e8

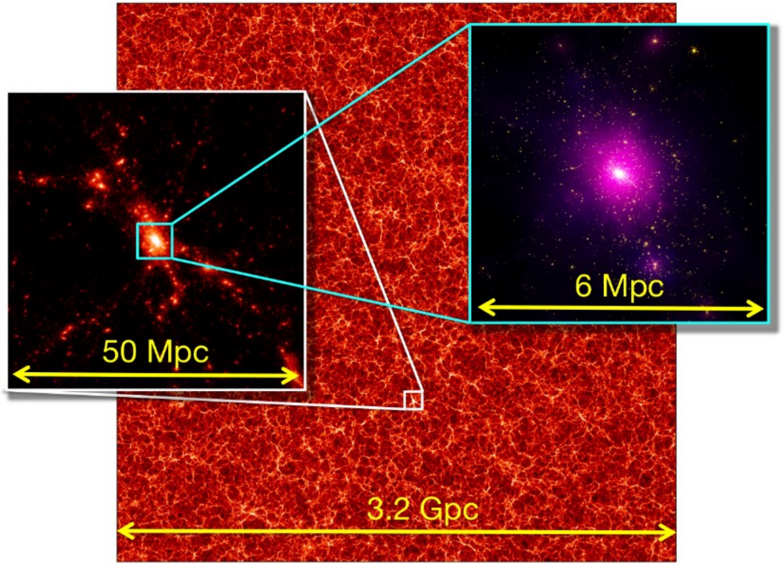


MACSIS

Barnes+17

Zoom-in hydro run of 390 massive haloes from parent DMonly

Mdm=6.5e9, Mgas=1.1e9

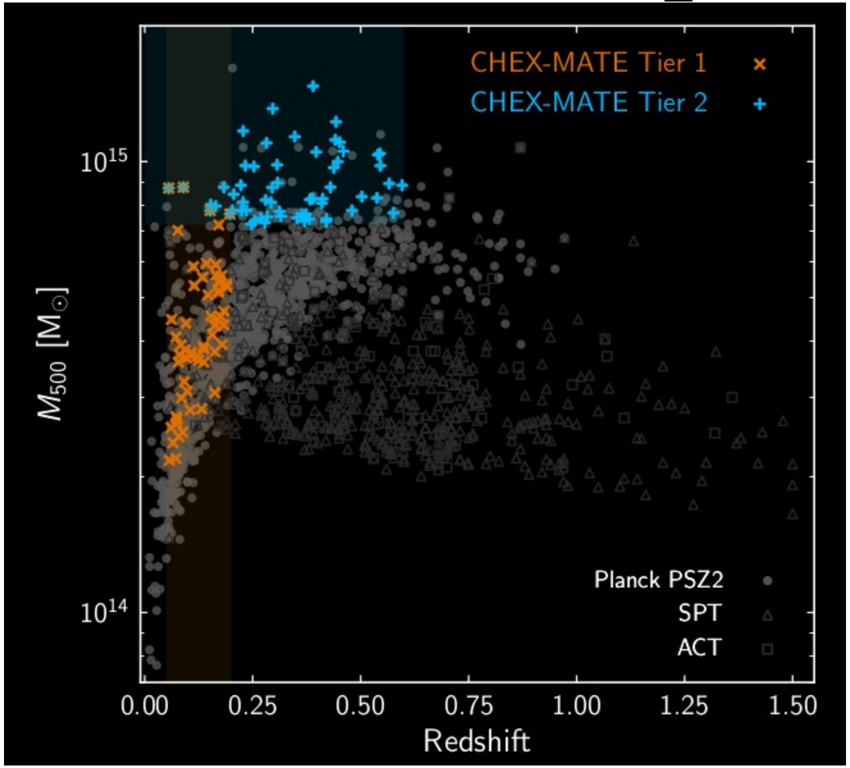


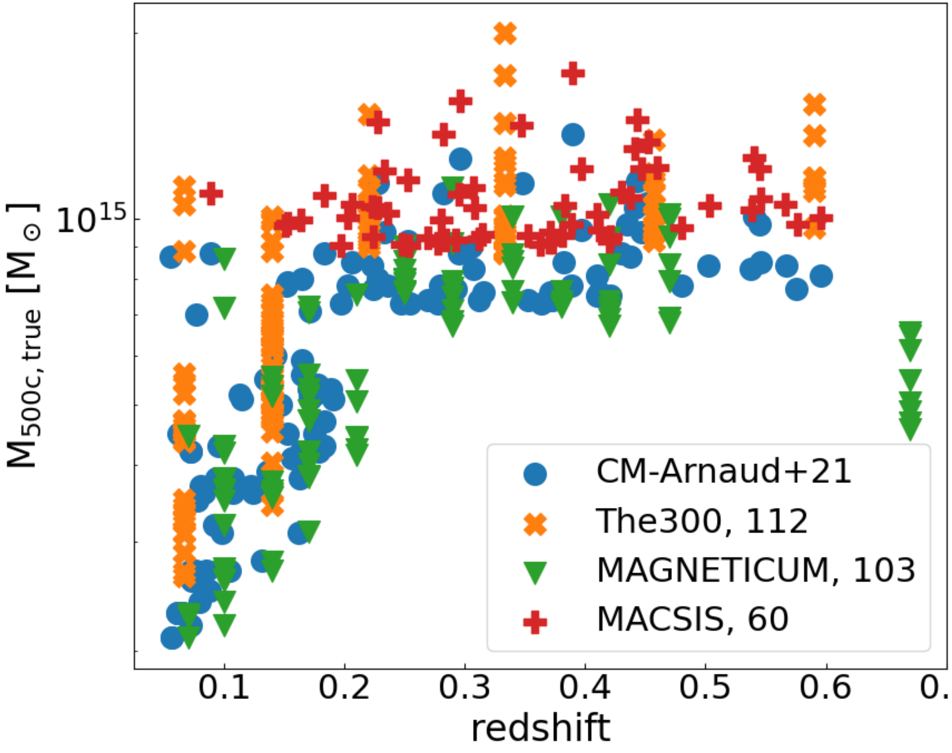
Match to ChexMate

Closest match in M-z

If multiple matches are found, choose the one with most similar morphology

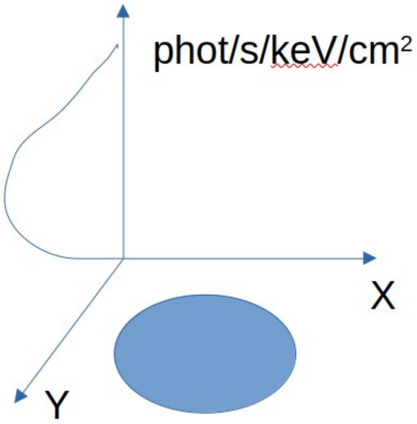
1-b_HE=0.8 for The300, MACSIS

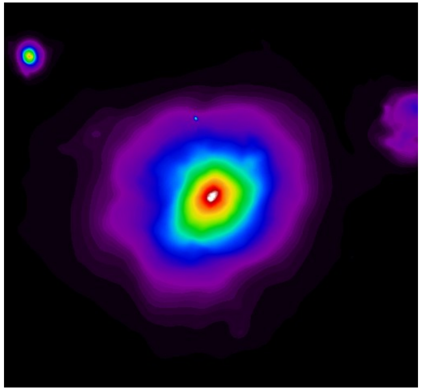




Forward Modeling XMM

xmm_simulator: github.com/domeckert/xmm_simulator





ARF + vignetting

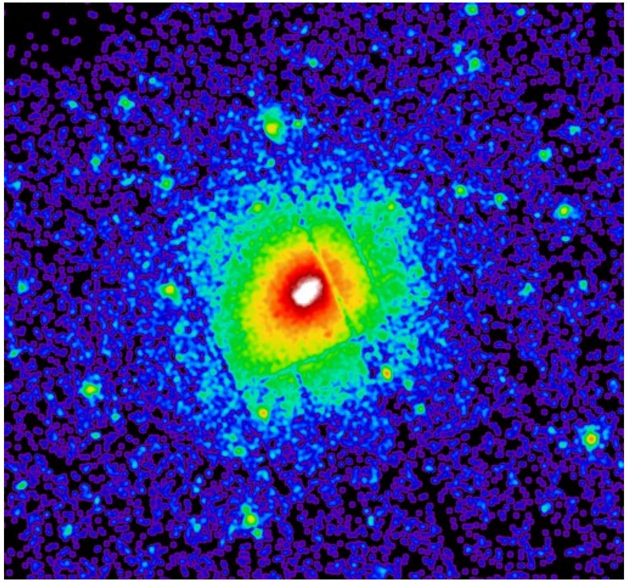
QPB from FWC data

SKY BKG:
LHB, GH, CXB

AGN:
Lehmer+13 logNlogS
NH: U(20.5, 23), Γ: N(1.9, 0.2)

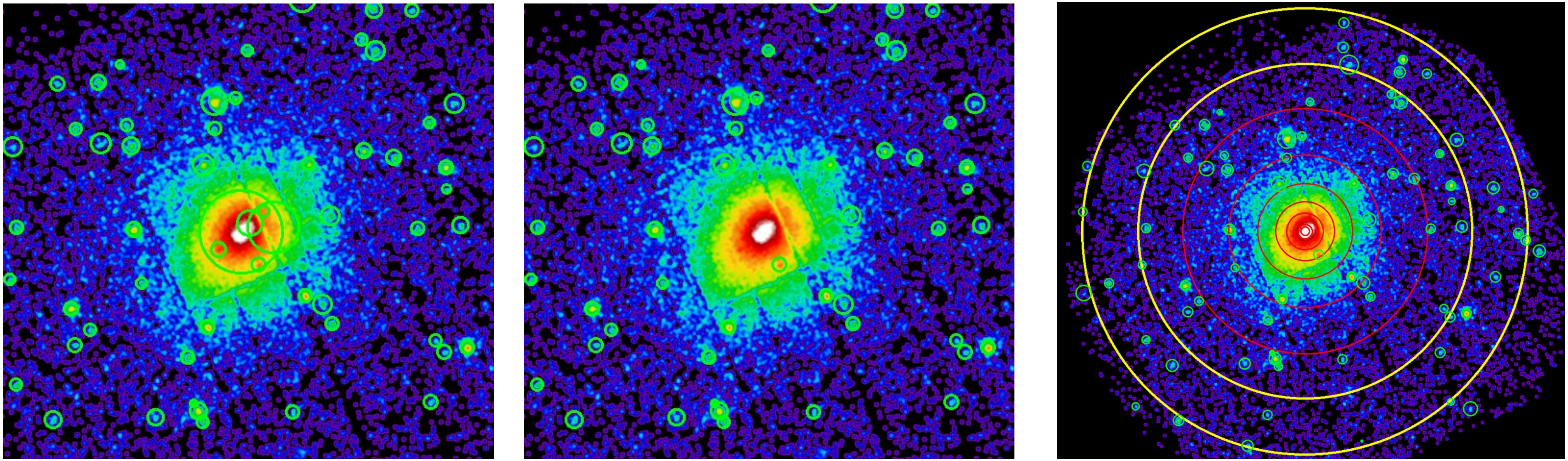
Mock EPIC

E = 0.7 – 1.2 keV
Texp = 25 ks



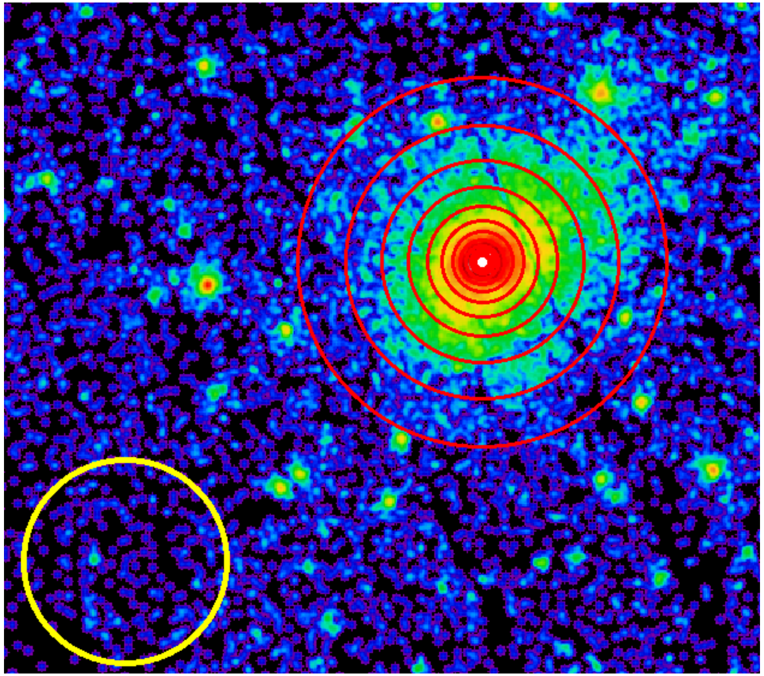
Mock processing

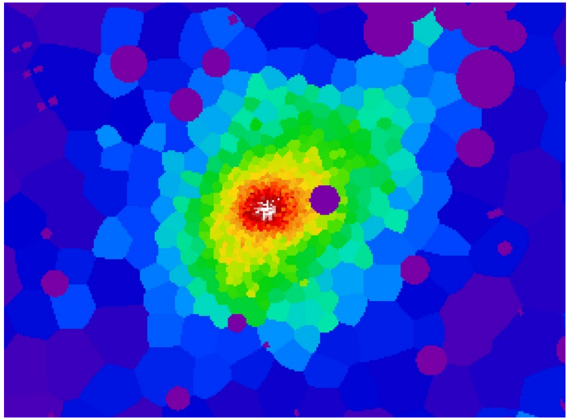
- SAS Wavelet source detection
- Manual handling of the region file
- Center is the peak of the X-ray emission
- Profile extraction in radial bins (bkg 1.5-2 R500)

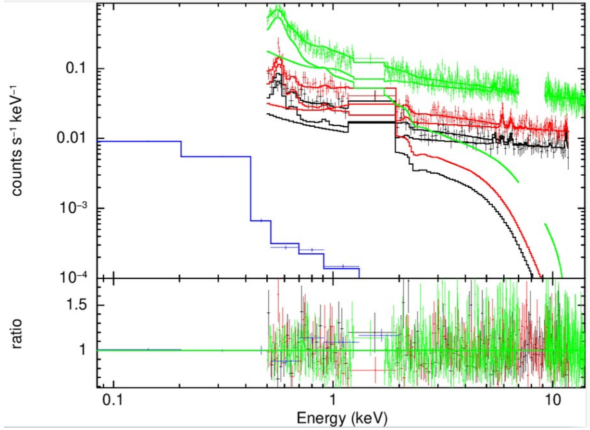


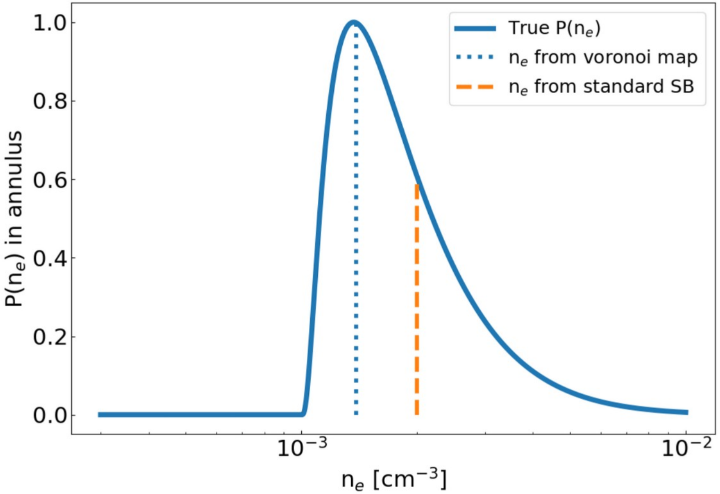
New improvements

- Visual inspection and BKG handling
- Median SB profile on voronoi maps (binsize: 25 cts)
- Cofitting a mock RASS BKG spectrum (crucial for Tx at R500!)





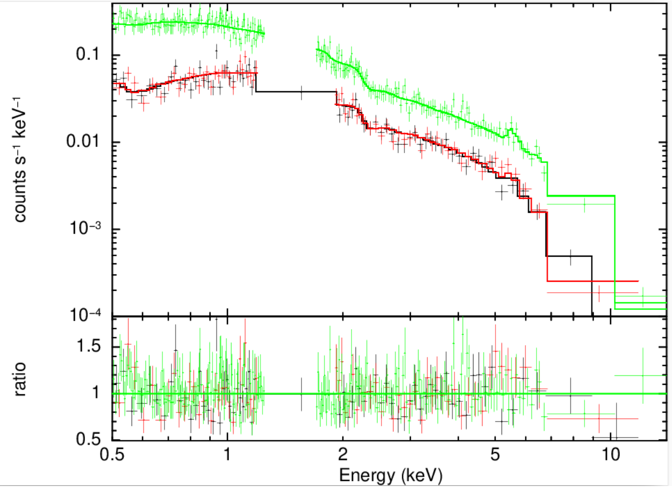




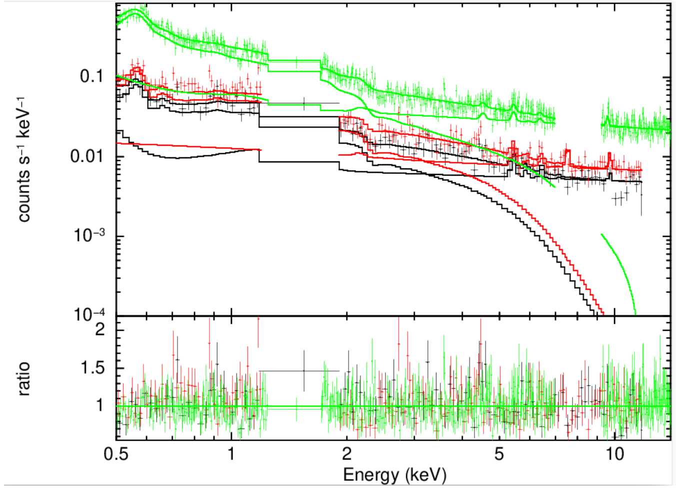
X-ray spectral analysis

- Spectral fitting for each bin
- 12 Bins: [0, 0.04-1.1]xR500
- X-COP pipeline: developed to analyze massive clusters (Eckert, Ghirardini)

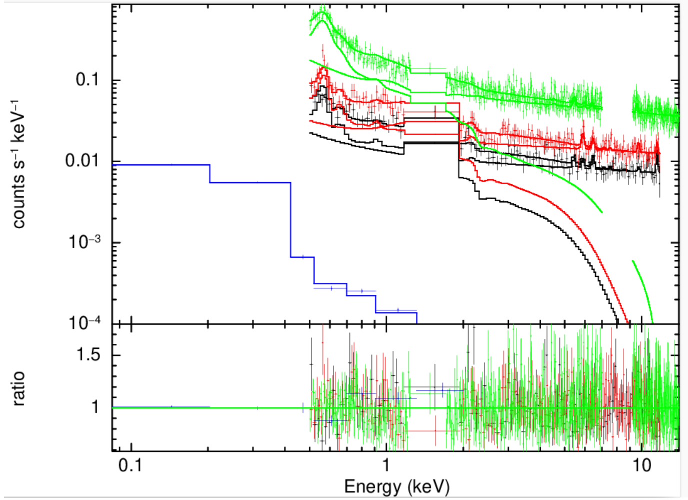
Core



Outskirts



BKG



X-ray analysis

- Density profile (Eckert+20):
Surface brightness allows profile reconstruction
Multi-scale decomposition for gas density

$$\epsilon(r) \propto n_e(r) n_p(r) \Lambda(T, Z)$$

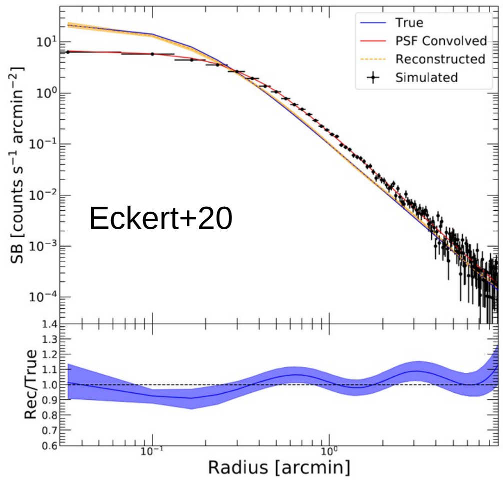
$$S(r) = \frac{1}{4\pi(1+z)^4} \int \epsilon(r) dl$$

- Mass and thermodynamical profiles (Eckert+22):
1) NFW: assume mass model and integrate Pressure
2) Non parameteric: Tx as combination of log-normal function
3) Forward Model: Assume P profile, solve HE locally

$$\frac{dP_{\rm gas}}{dr} = -\rho_{\rm gas} \frac{G M_{\rm TOT}(< r)}{r^2},$$

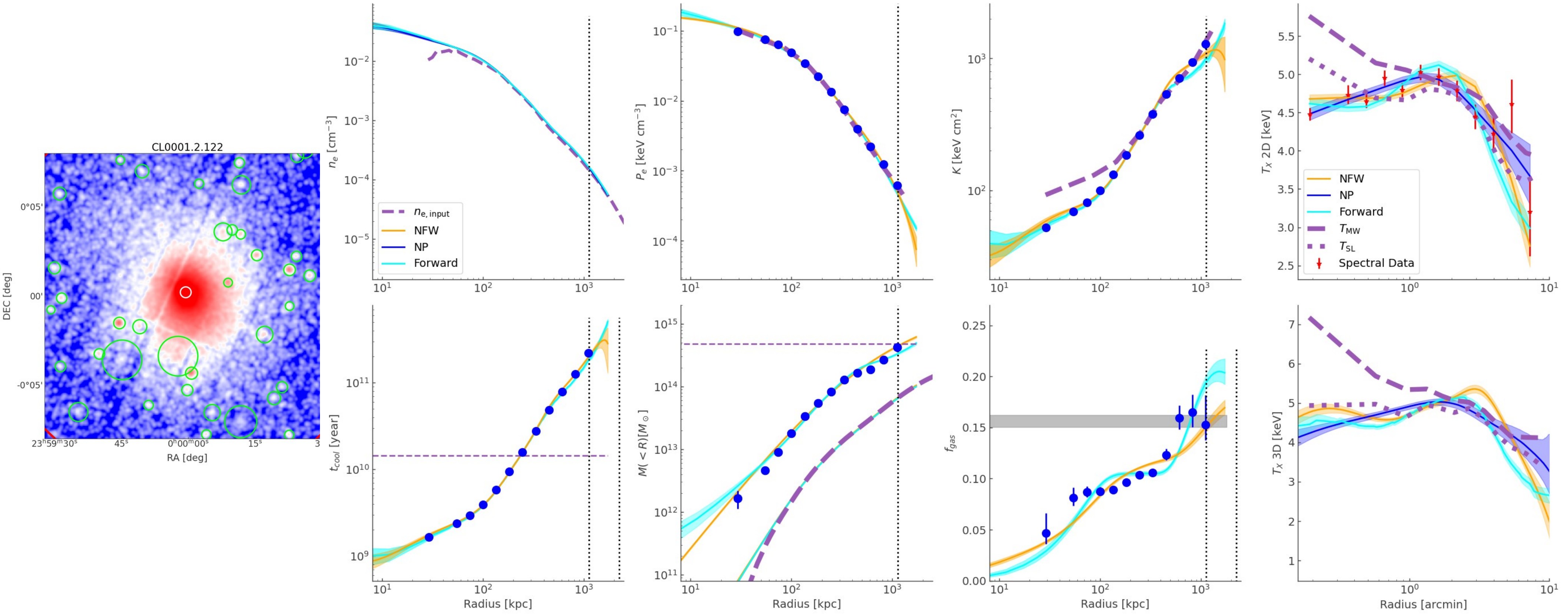
$$P_{\rm gas} = \frac{k_{\rm B}}{\mu m_{\rm p}} \rho_{\rm gas} T,$$

$$M(< r) = -\frac{r k_{\rm B} T(r)}{G \mu m_{\rm p}} \left(\frac{\partial \log T}{\partial \log r} + \frac{\partial \log n_{\rm gas}}{\partial \log r} \right)$$



X-ray analysis

- Spectral analysis: xcop-pipeline (Ghirardini+18, Eckert+19)
- X-ray modeling (ne, P, T): pyproffit (Eckert+20), hydromass (Eckert+22)



Tx profile measurement

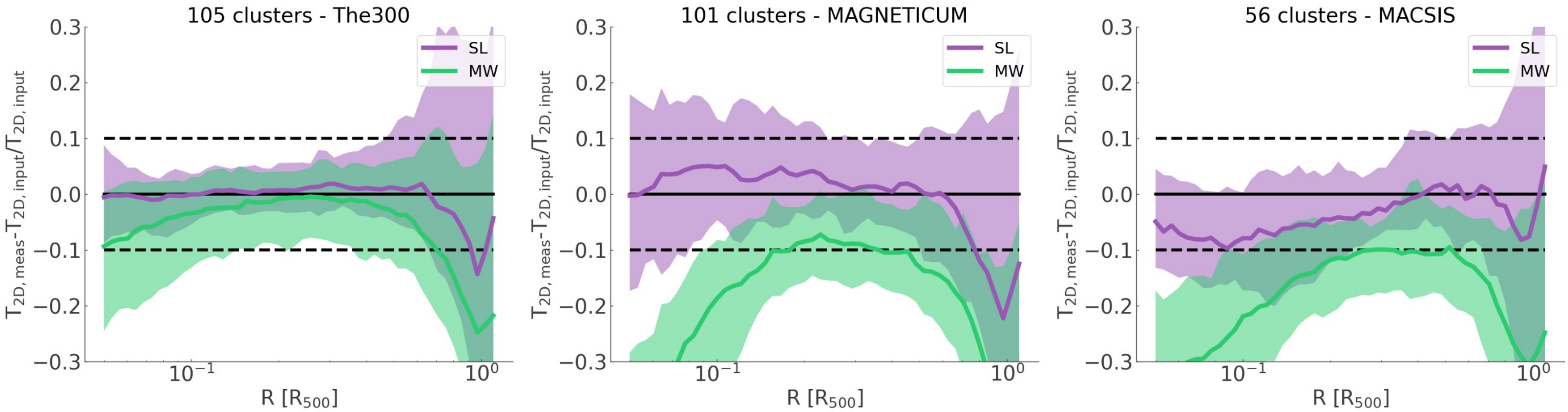
- ***2D temperature profiles***

$$T_{\rm mw} \equiv \frac{\int m T \, {\rm d}V}{\int m \, {\rm d}V}$$

$$T_{\rm sl} = \frac{\int W T \, {\rm d}V}{\int W \, {\rm d}V}$$

$$W = \frac{n^2}{T^{3/4}}.$$

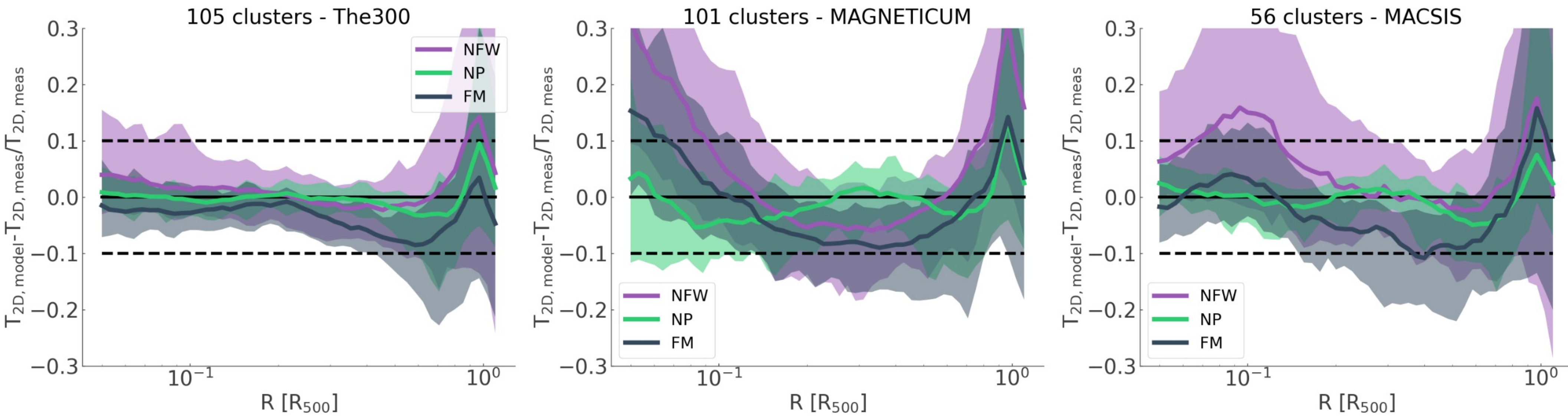
Measurements (from spectral fitting) vs Tx input
Good agreement for SL weights (Mazzotta+04, Rasia+)



Tx profile modeling

- ***2D temperature profiles***

Models vs Measurements (from spectral fitting)
Core is off in MAGNETICUM (resolution? Non NFW?)
Overestimate at R500(?), within 1σ



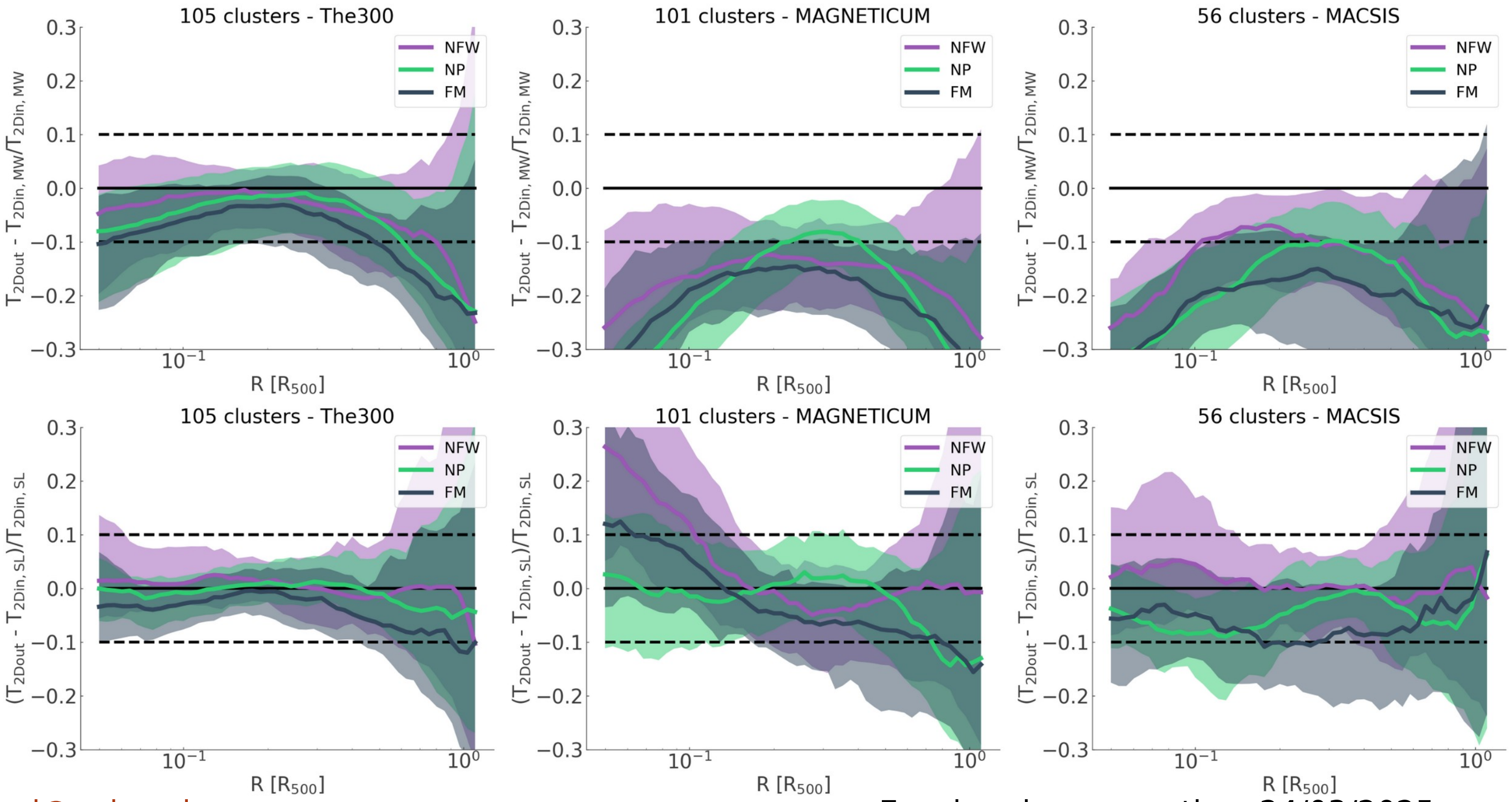
2D Temperature profiles

- Tout is closer to SL than MW for all simulations
- **The300**: best agreement
- **MAGNETICUM**: produces non-NFW profiles?
- **MACSIS**: NFW closer to 1:1 than NP

$$T_{\rm mw} \equiv \frac{\int m T \, {\rm d}V}{\int m \, {\rm d}V}$$

$$T_{\rm sl} = \frac{\int W T \, {\rm d}V}{\int W \, {\rm d}V}$$

$$W = \frac{n^2}{T^{3/4}}.$$



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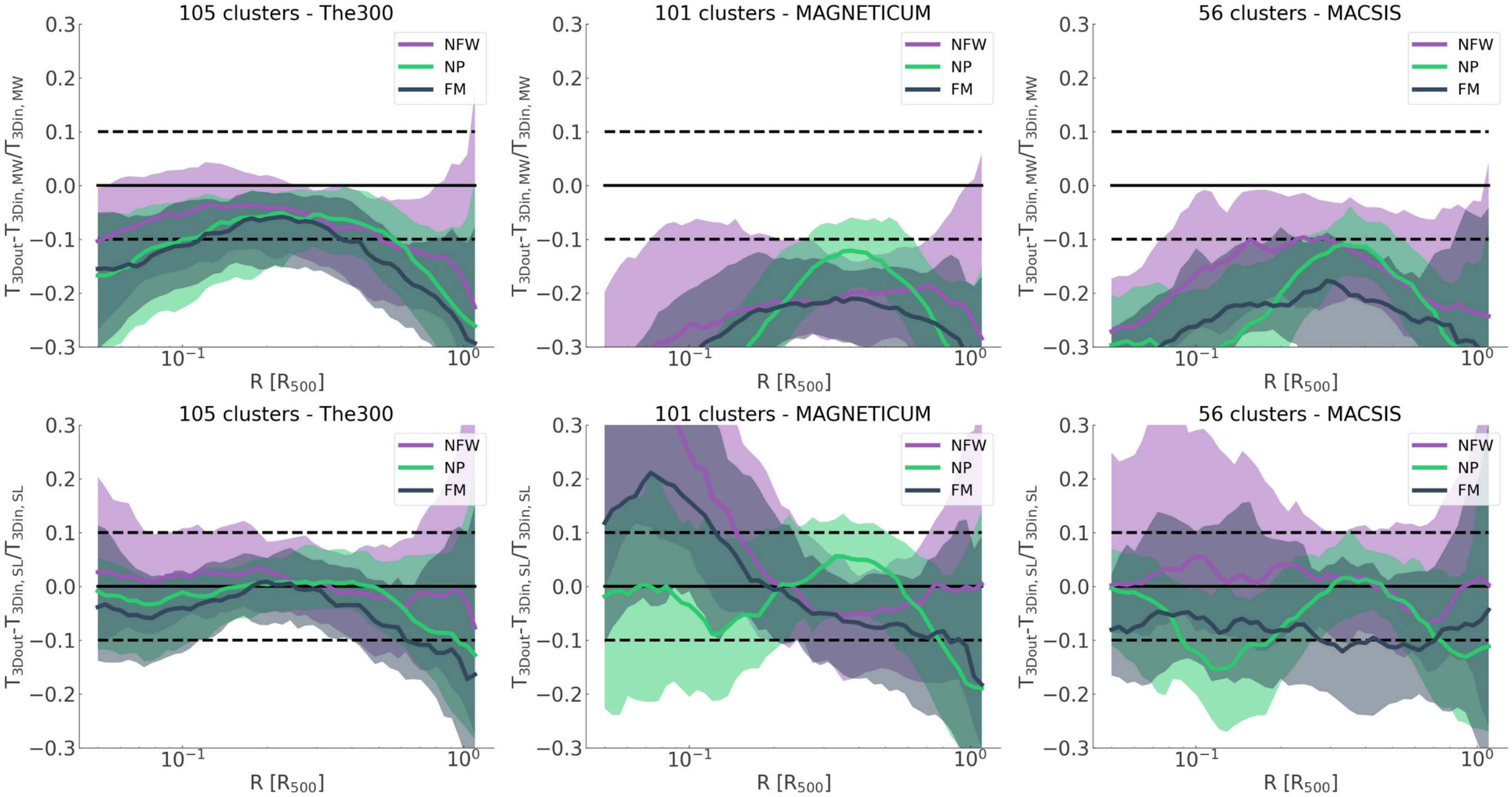
3D Temperature profiles

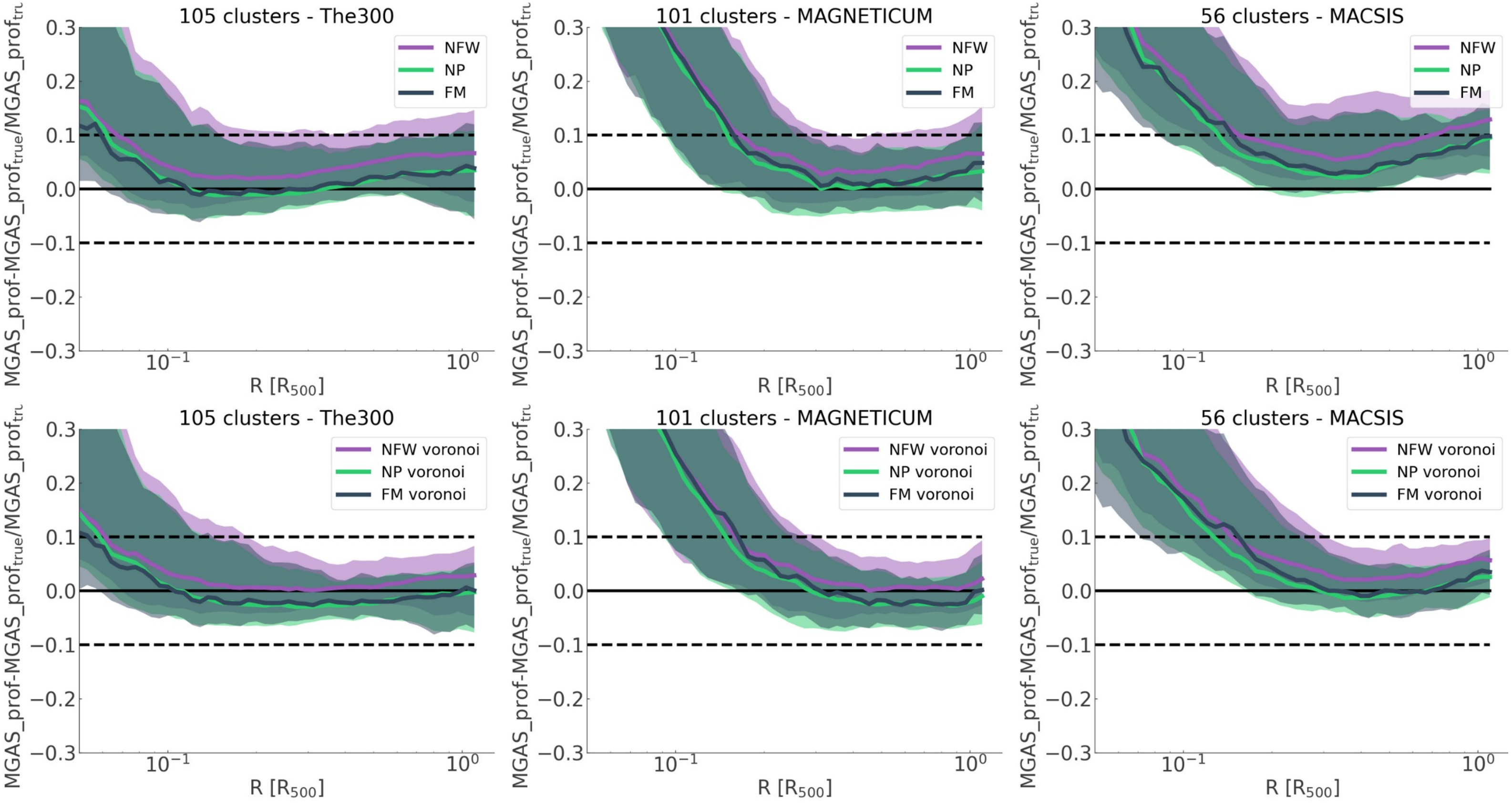
- Same trends as for the 2D temperature
- The deprojection is not affecting the comparison



Gas Mass profiles

$$M_{gas} = 4\pi\mu_e m_p \int_0^{R_{500c}} n_e(r) r^2 dr$$

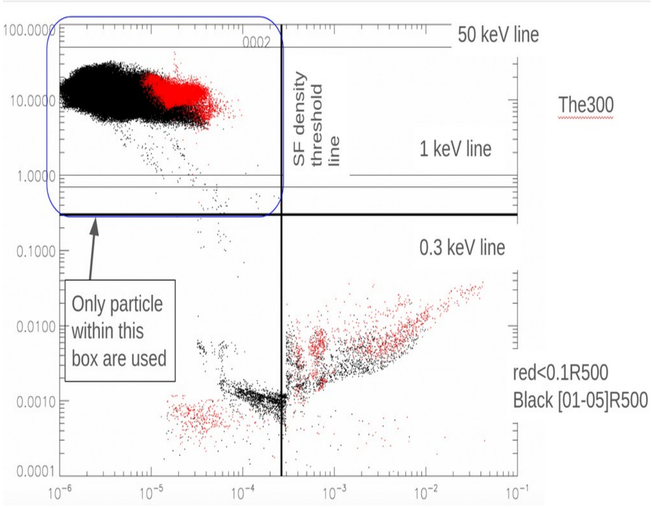
- Excellent recovery of gas density
  - Voronoi result closer to 1:1
- Discrepancy in the core due to resolution

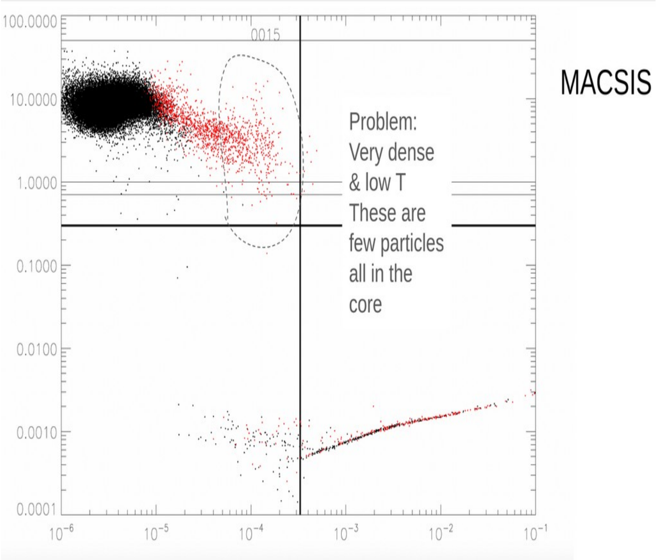


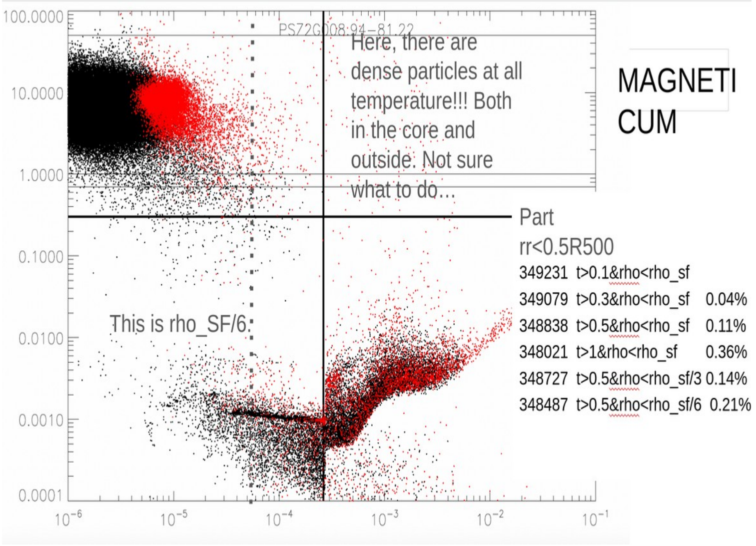
Intrinsic differences

- Our work is testing a method:
  we don't expect differences between individual simulations

- The gas particles distribution in the density-temperature plane IS different:
  The300 is regular, MACSIS has lowT, highN in the core, MAGNETICUM has many dense particles



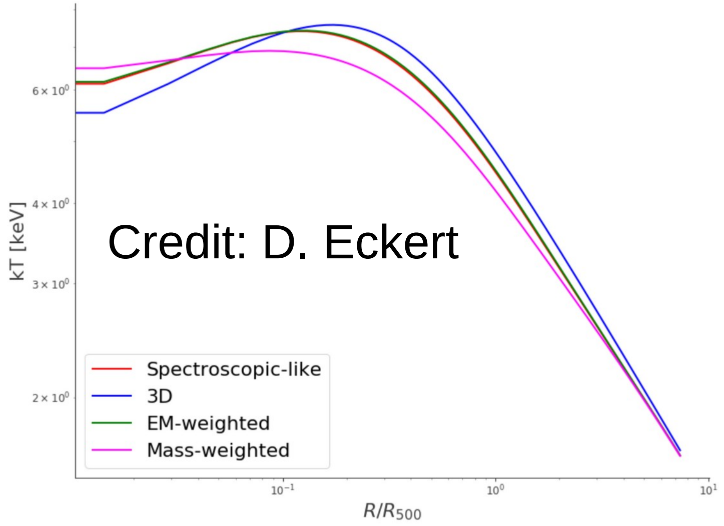


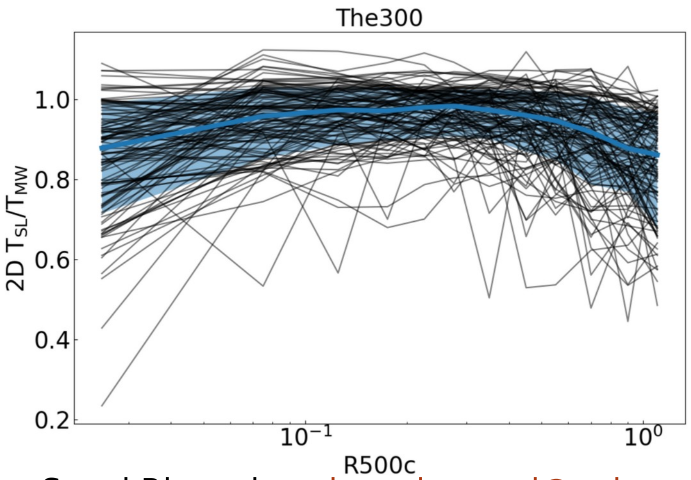


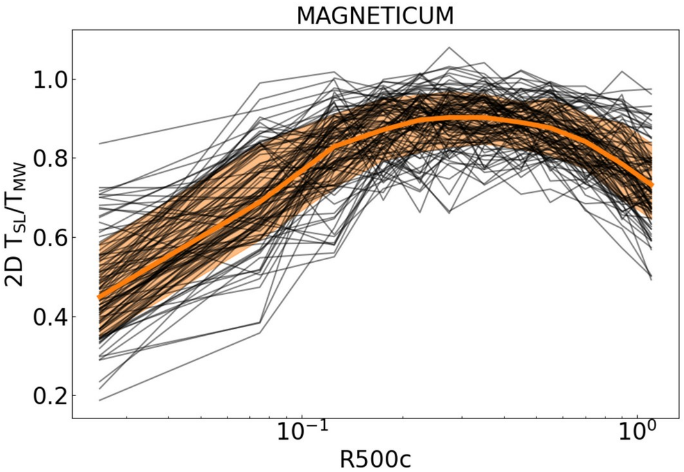
Credit: E. Rasia

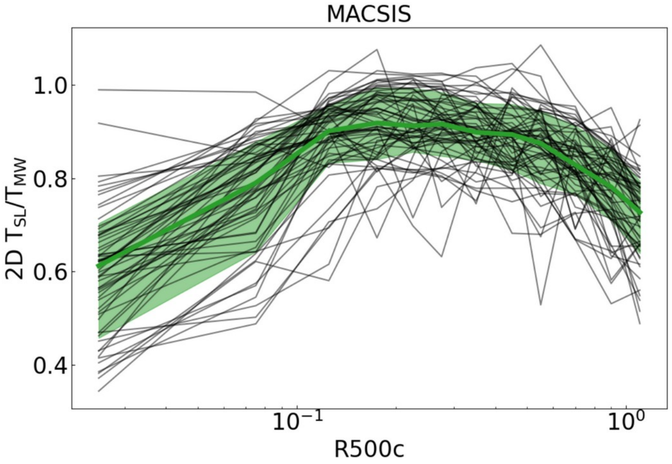
Temperature interpretation

- Core: 2D projection includes hotter gas in front and behind the center (TMW>TSL)
- In the outskirts the projection includes colder gas (TSL>TMW)
- We do NOT see that: multi-Tx and azimuthal variations dominate over projection effects



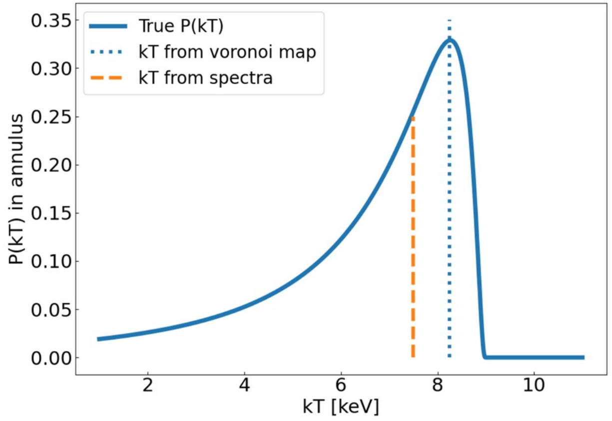


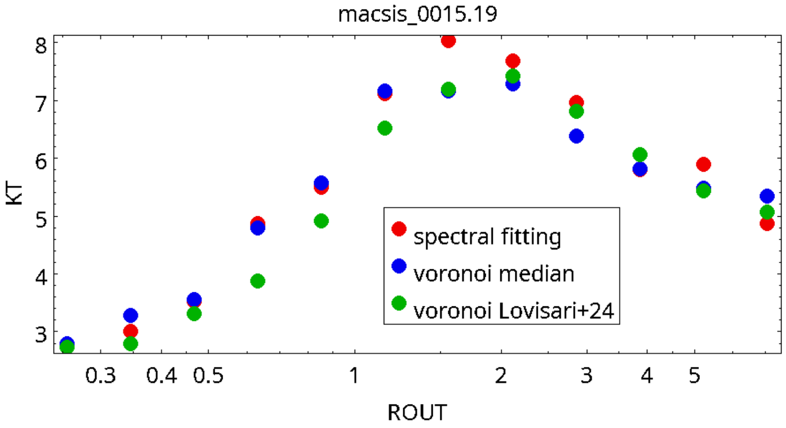




Tx distribution in annuli

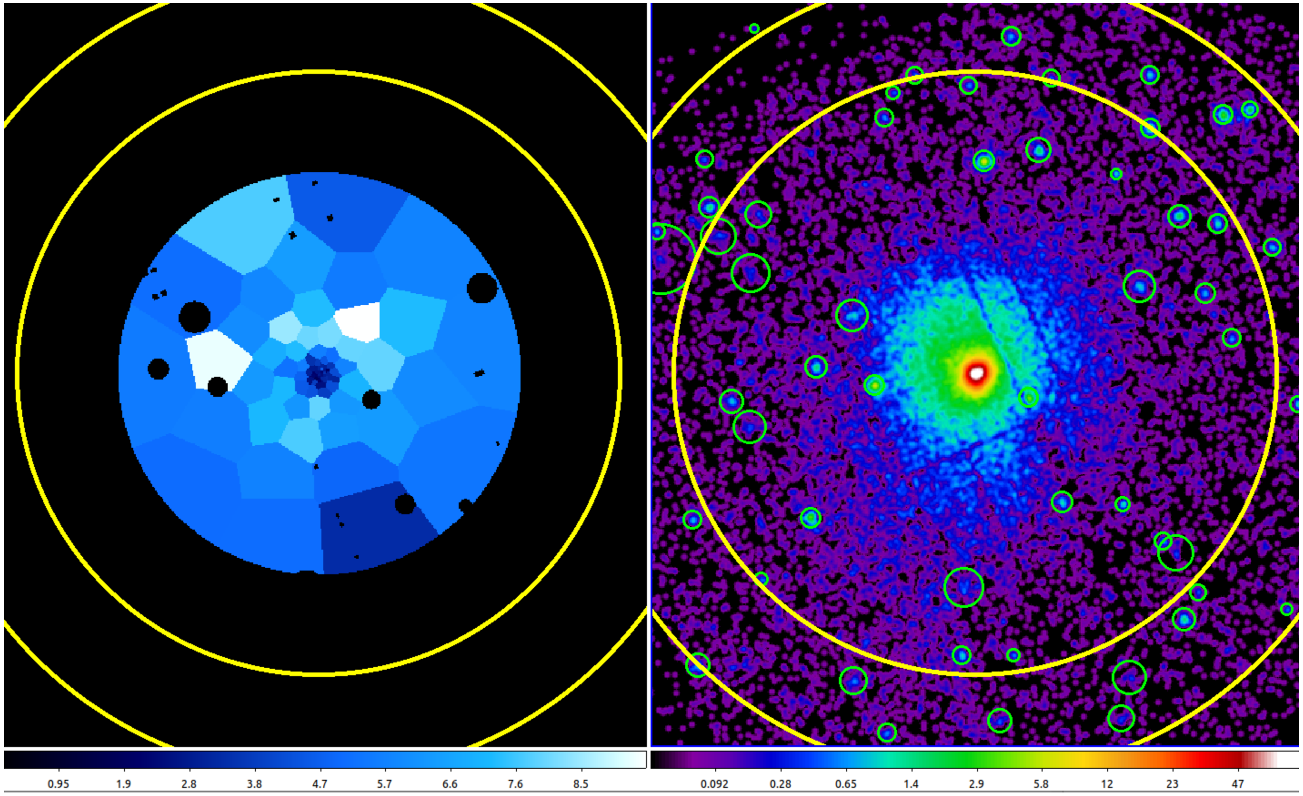
Investigate Tx distribution in annuli
Tx from spectral fit may be biased toward low kT





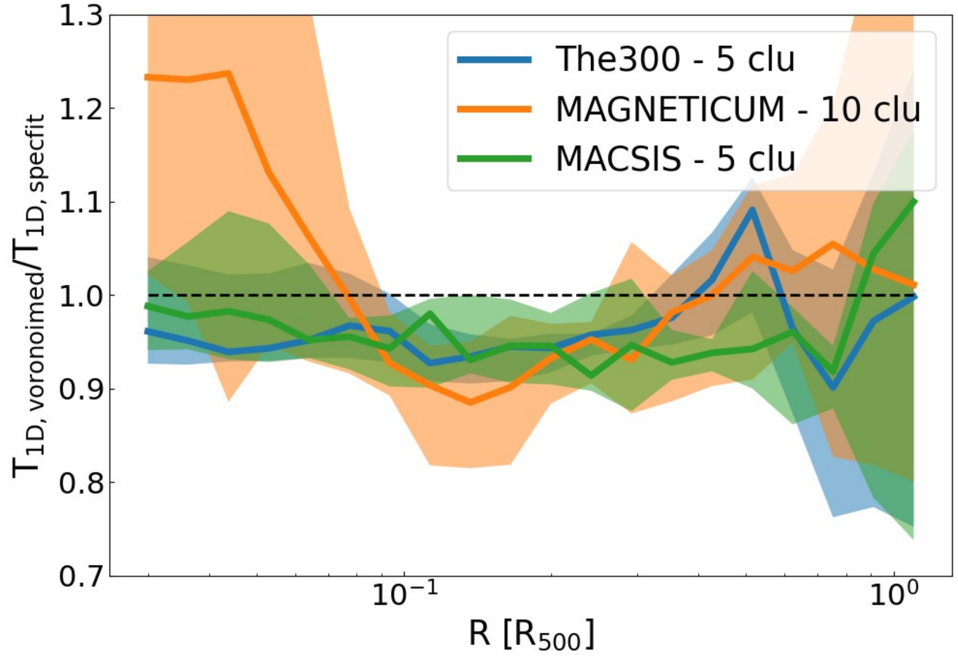
Use voronoi maps to probe median Tx in radial bins

Macsis_0015.019: z=0.24, R500c=6.7’

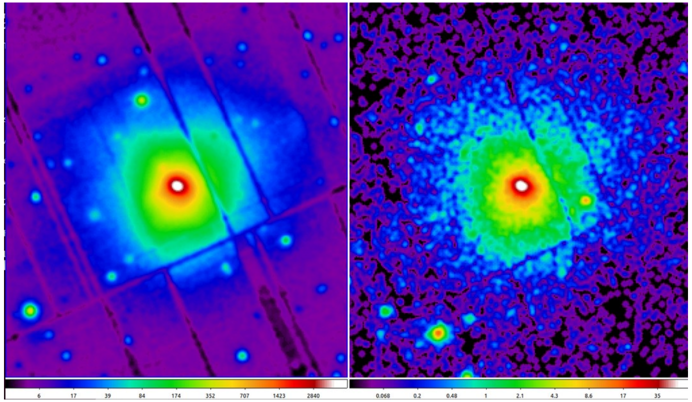


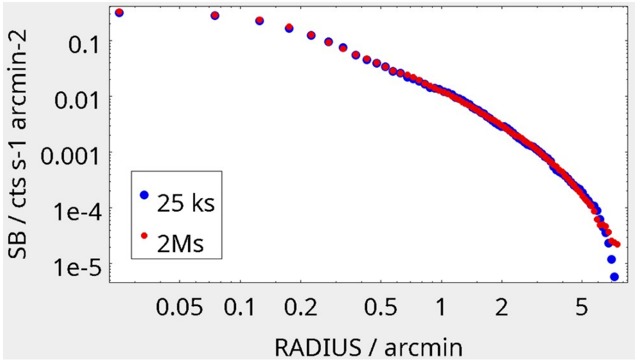
Investigate Tx

Ongoing: production of all voronoi maps
Preliminary kT from voronoi seems lower than the spectral fit (opposite to expectation)



Next: produce and analyze a deeper mock (2 Ms) and compare it to the standard 25 ks





Summary

- End to end pipeline to generate and analyze CHEX-MATE like data

- ***Results:***

TSL is reconstruction is the most accurate and precise

The300 (MAGNETICUM) behaves best (worst)

Excellent reconstruction of gas mass

Investigation on Tx:

should we worry about multi-T, azimuthal variations more than hydrostatic equilibrium?

- Article in prep (Q2 2025?)

CHEX-MATE: Unveiling true Thermodynamical Gas Profiles of Galaxy Clusters Using Simulations

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ABSTRACT

Context. context
Aims. aims
Methods. method
Results. results
Conclusions. conclusions

Key words. X-rays: galaxies: clusters - Galaxies: clusters: intracluster medium - Surveys - Cosmology: large-scale structure of Universe - Methods: data analysis

1. Introduction

RS: Clusters Clusters of galaxies are the end point of the structure formation process throughout the history of the Universe and are located in the nodes of the cosmic web (Mo & White 2002; Springel 2005). Therefore, they encode precious cosmological information about dark matter, driving the shaping of the large scale structure of the Universe, dark energy, driving its accelerated expansion at late times (Allen et al. 2004; Kravtsov & Borgani 2012; Clerc & Finoguenov 2022; Ghirardini et al. 2024). Massive galaxy clusters benefit from high signal to noise ratio observations at various wavelengths. In the optical band they are seen as a collection of their galaxy members (Rykoff et al. 2014; Abbott et al. 2020). However, only 1% of their total mass resides in the galaxy population. Instead, about 90% is in form of dark matter. Since dark matter is not directly detectable, its gravitational effect shows up as peaks in weak lensing convergence maps (Miyazaki et al. 2018). Finally, the majority of baryons is located in the hot gas that constitutes the intra-cluster medium (ICM), heated up by the process of gravitational collapse to high temperatures around 10^8 K. This allows us to detect clusters in the millimeter band via the Sunyaev-Zeldovich (SZ) effect (Staniszewski et al. 2009; Planck Collaboration et al. 2014a), and in X-rays thanks to direct emission via thermal bremsstrahlung (Böhringer et al. 2004; Pratt et al. 2019). SZ surveys such as the Atacama Cosmology Telescope (ACT, Hilton et al. 2021), the South Pole Telescope (SPT, Bleem et al. 2020), and Planck (Planck Collaboration et al. 2014b) are sensitive to most massive clusters up to high redshift. X-ray surveys from ROSAT (Böhringer et al. 2004), XMM-XXL (Pierre et al. 2016), and eROSITA (Predehl et al. 2021; Bulbul et al. 2024) are better suited to detect the low mass cluster population, but their sensitivity quickly drops at high redshift. The combination of multi-wavelength data is essential to obtain a clear view of galaxy clusters in the Universe.

RS: CHEXMATE The Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX-MATE[1], CHEX-MATE Collaboration et al. 2021) is a Heritage program to follow-up a sample of 118 galaxy clusters selected from Planck via the SZ effect with X-ray observations using XMM-Newton. The program covers three mega-seconds in total exposure time, with a median exposure time of 40 ks per object. The goal is to study the final products of structure formation, focusing on the most recent objects formed in time (Tier-1: $0.05<z<0.2$, $2\times10^{14}<M_{500c}/M_\odot<9\times10^{14}$), and the most massive clusters in the Universe (Tier-2: $z<0.6$, $M_{500c}>7.25\times10^{14}$ $M_\odot$). CHEX-MATE aims to combine the deep XMM observations with archival and follow-up lensing and SZ data to tackle some open questions in cluster science, such as their mass calibration using different observables, understand and quantify the impact of different selection processes, study the evolution of cluster properties throughout cosmic time. Campitiello et al. (2022) analyzed the dynamical state of CHEX-MATE clusters from the X-ray images, by combining morphological parameters such as surface brightness concentration, centroid shift, and power ratios into a dynamical state indicator and found that CHEX-MATE is more disturbed than X-ray selected samples. Bartalucci et al. (2023) studied the surface brightness profiles and found a large spread in cluster cores following the clusters' dynamical state, with steep (flat) profiles corresponding to relaxed (disturbed) clusters. Moving towards the outer region the profiles are less dependent on the dynamical state, with a minimal scatter between 0.4-$0.8R_{500c}$. A key data product in CHEX-MATE is the temperature profile, as presented by Rossetti et al. (2024) for a subsample of 30 clusters up to R_{500c}, highlighting the potential for cutting-edge science once the whole sample is analyzed in a statistical way. A pilot study of the entropy profiles is provided by Riva et al. (2024), who found a correlation between the dynamical state and the en-