UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

The XMM Cluster Outskirts Project (X-COP)

Dominique Eckert

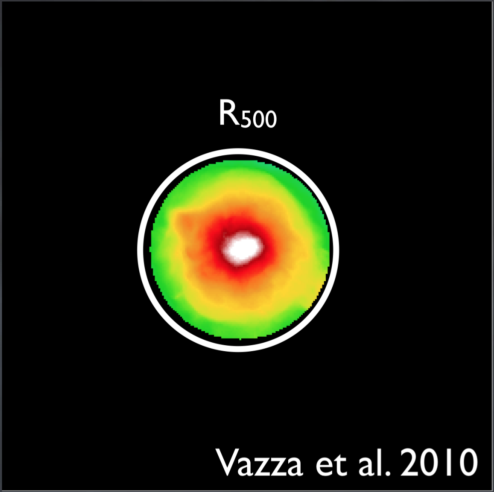
Department of Astronomy, University of Geneva

Main collaborators: V. Ghirardini, S. Ettori, E. Pointecouteau, S. Molendi, S. De Grandi, E. Rasia, F. Vazza, H. Bourdin, P. Mazzotta, ...

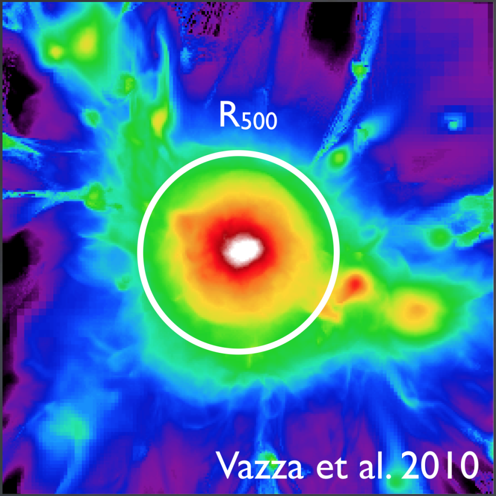
June 3, 2019

Cluster Outskirts: Introduction

Most current studies focus on the region inside R_{500}

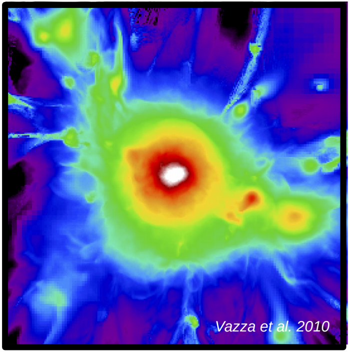


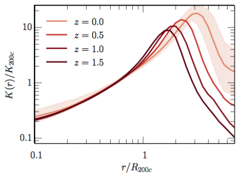
Most current studies focus on the region inside R_{500}



... But a wide range of interesting phenomena take place beyond that radius

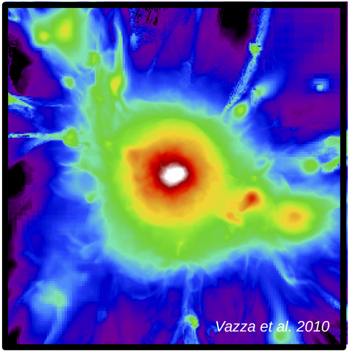
Cluster Outskirts: Introduction





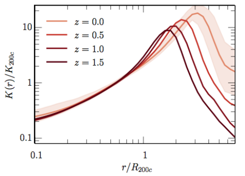
Lau et al. 2015

ICM entropy generation



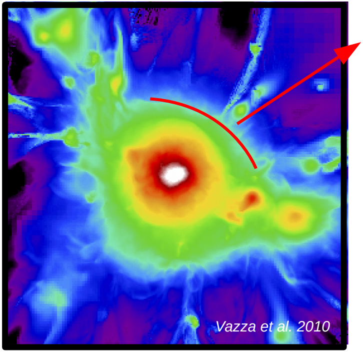
Vazza et al. 2010

Cluster Outskirts: Introduction

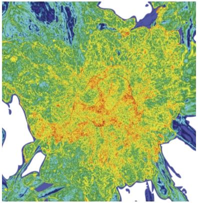


Lau et al. 2015

ICM entropy generation

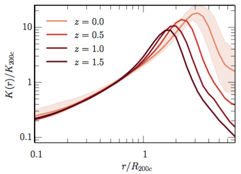


Vazza et al. 2010



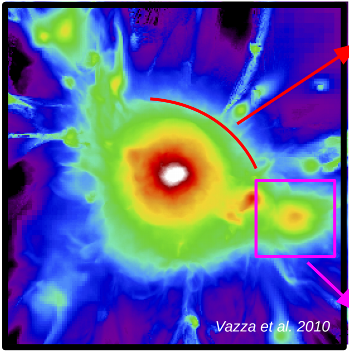
Miniati 2014

Non-thermal pressure
Turbulence, shocks, cosmic rays, ...

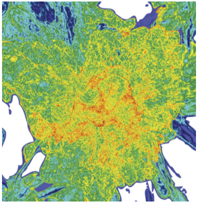


Lau et al. 2015

ICM entropy generation



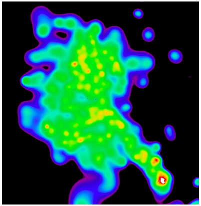
Vazza et al. 2010



Miniati 2014

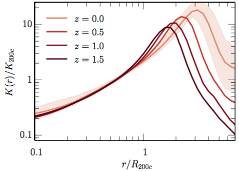
Non-thermal pressure
Turbulence, shocks, cosmic rays, ...

Infalling substructures
Bulk motions



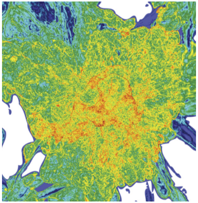
Eckert et al. 2017

Cluster Outskirts: Introduction

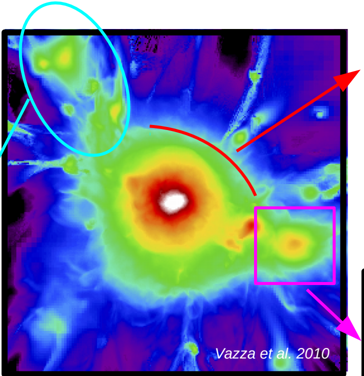


Lau et al. 2015

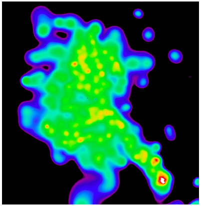
ICM entropy generation


Miniati 2014

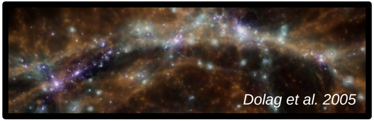
Non-thermal pressure
Turbulence, shocks, cosmic rays, ...


Vazza et al. 2010

Infalling substructures
Bulk motions

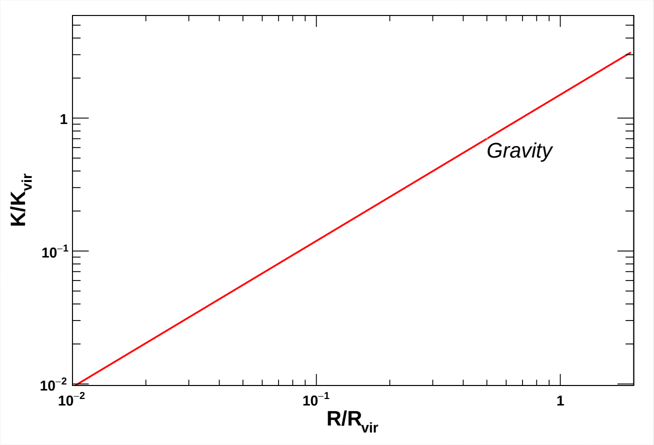

Eckert et al. 2017

Filaments and the WHIM


Dolag et al. 2005

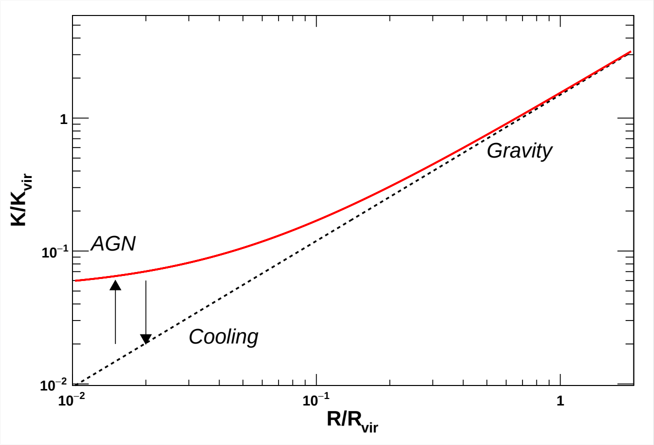
ICM entropy profiles

Gas entropy $K = kTn_e^{-2/3}$ encodes the formation history of the ICM



ICM entropy profiles

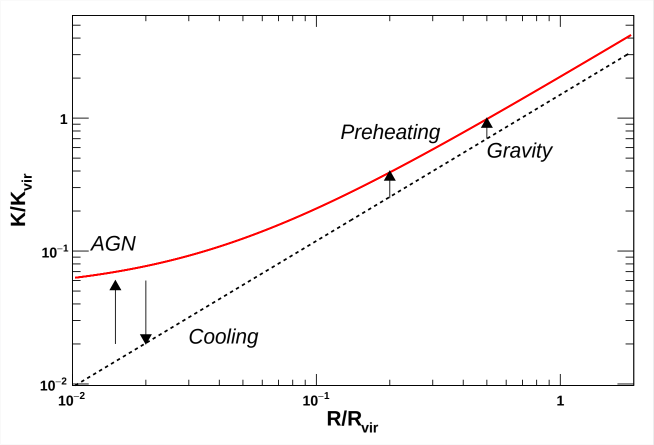
Gas entropy $K = kTn_e^{-2/3}$ encodes the formation history of the ICM



Deviations from baseline trace non-gravitational processes

ICM entropy profiles

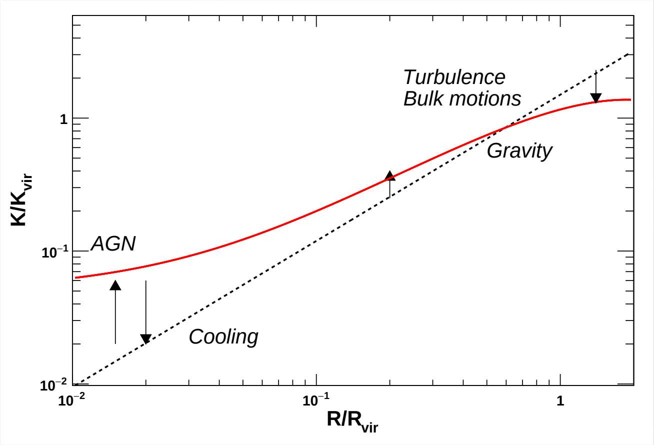
Gas entropy $K = kTn_e^{-2/3}$ encodes the formation history of the ICM



Deviations from baseline trace non-gravitational processes

ICM entropy profiles

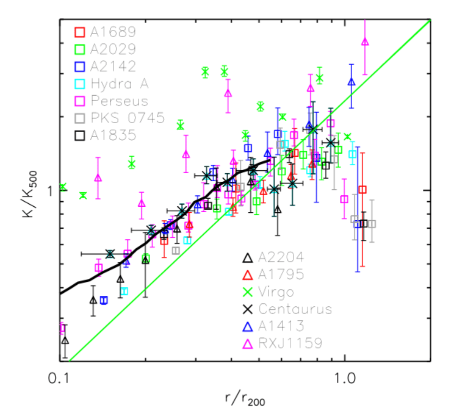
Gas entropy $K = kTn_e^{-2/3}$ encodes the formation history of the ICM



Deviations from baseline trace non-gravitational processes

A universal entropy flattening?

- Thanks to its low background *Suzaku* measured entropy profiles out to $R_{\rm vir}$ in a few clusters
- A deficit of entropy is often observed beyond R_{500}
- Possible interpretations: gas clumping, non-thermal pressure support, non-equilibrium electrons, ...



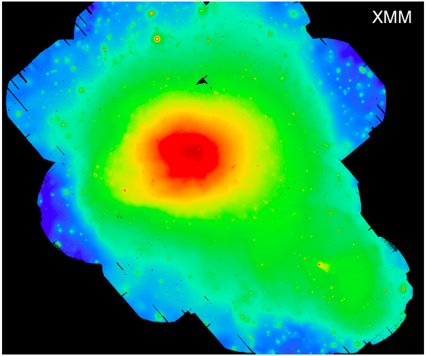
Walker et al. 2013

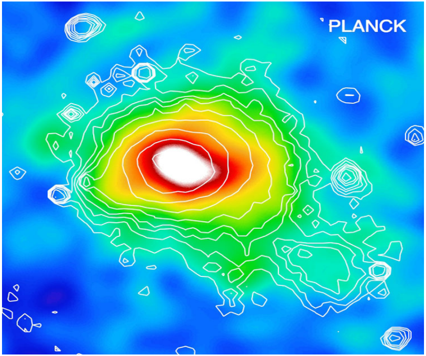
X-ray

$$\epsilon_X \sim \int n_e^2 T^{1/2} dl$$

Sunyaev-Zel'dovich

$$y \sim \int P_e dl$$

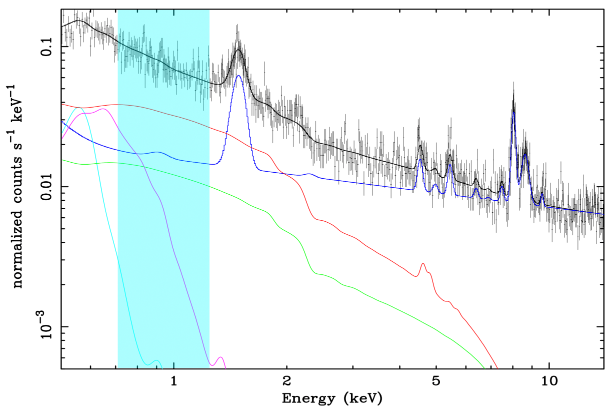




$$kT = P_{SZ}/n_X, K = P_{SZ} n_X^{-5/3}, \frac{dP_{SZ}}{dr} = -\rho_X \frac{GM(<r)}{r^2}$$

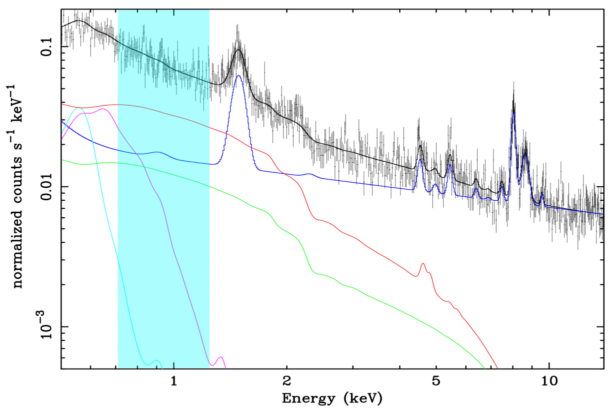
The X-COP strategy

XMM has a large FOV and collecting area... but also a high and variable background



The X-COP strategy

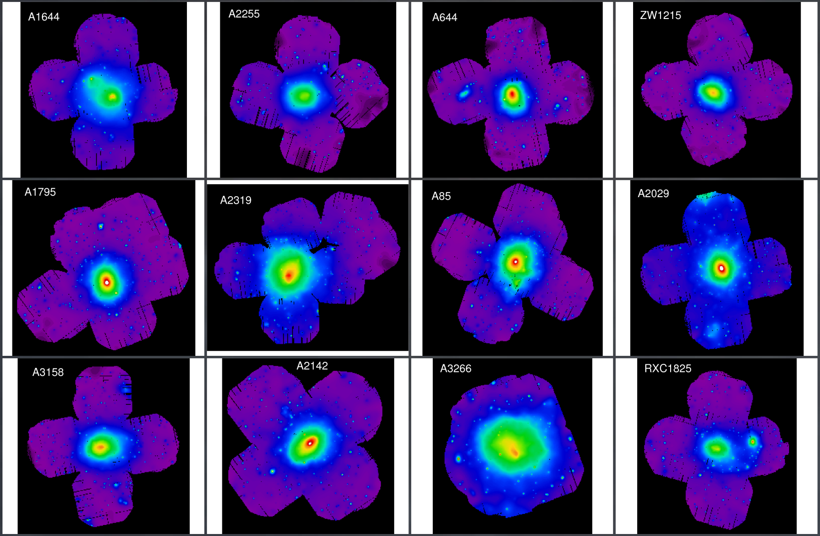
XMM has a large FOV and collecting area... but also a high and variable background



In the [0.7-1.2] keV band we reach an accuracy of $\sim 3\%$ on the subtraction of the XMM background

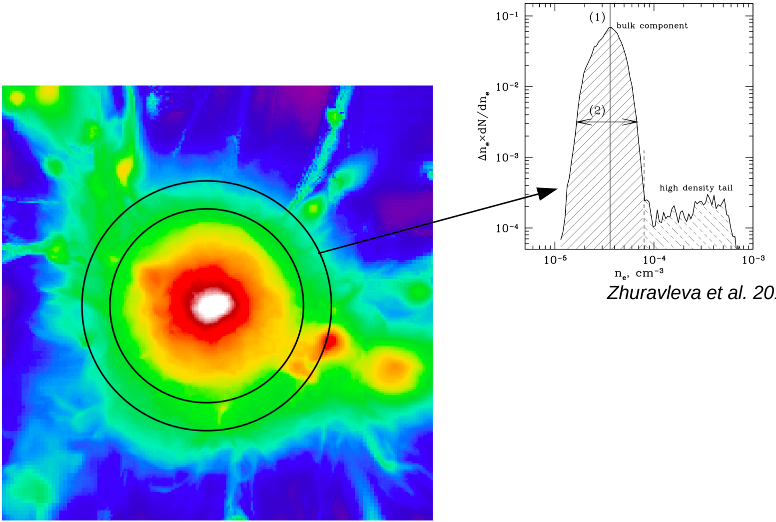
The X-COP project

X-COP (PI: Eckert) is a very large program on XMM to follow up Planck clusters with the highest S/N



Gas clumping

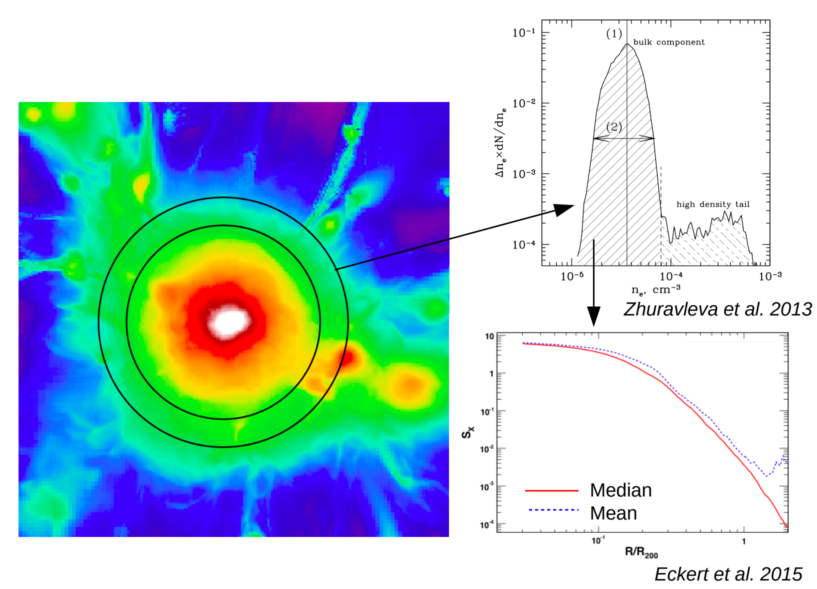
At large radii the gas distribution is clumpy and inhomogeneous



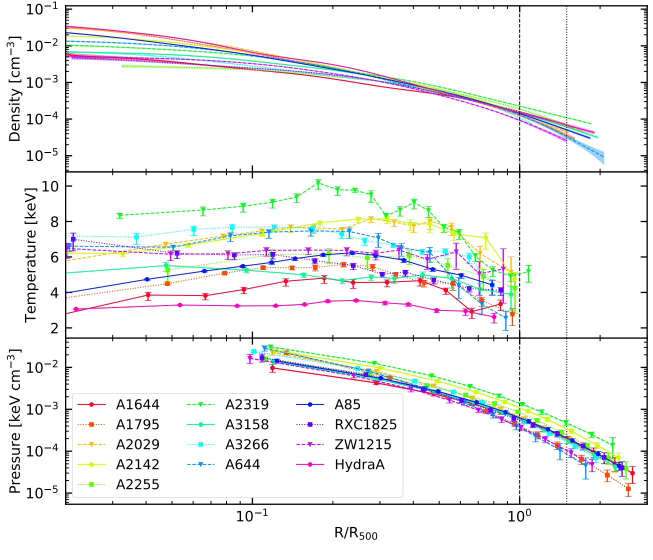
Zhuravleva et al. 2013

Gas clumping

At large radii the gas distribution is clumpy and inhomogeneous



X-ray and SZ profiles

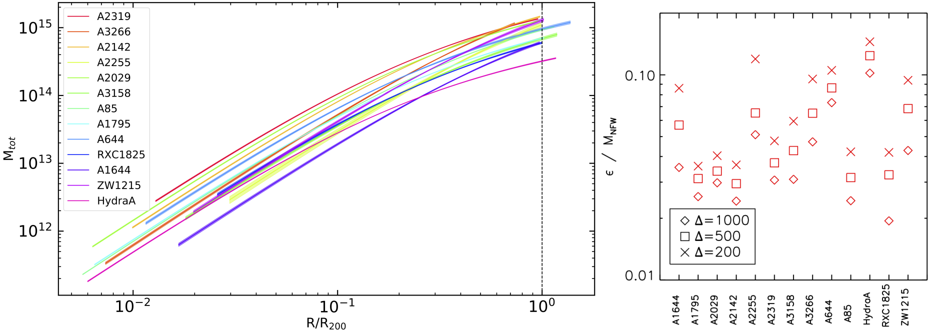


al. 2019

Our profiles extend to $1.8R_{500}$ (n), $2.3R_{500}$ (P), and $0.9R_{500}$ (T)

Mass profiles

We reconstruct M_{HSE} by fitting jointly X-ray and SZ data

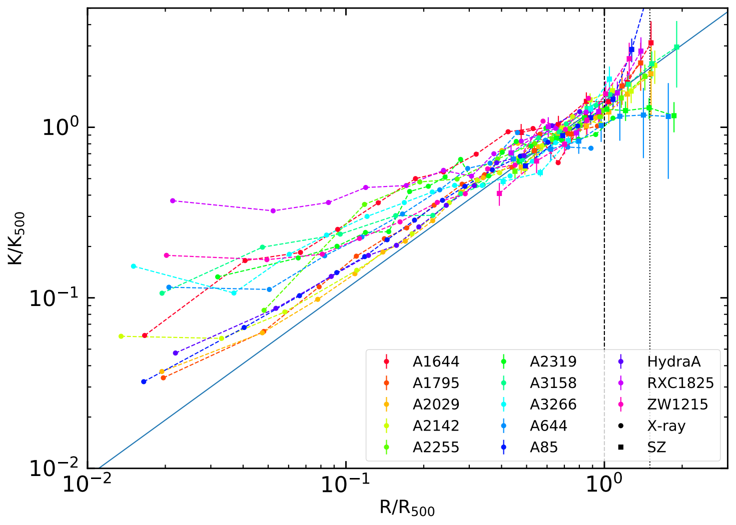


Ettori, DE et al. 2019

Our mass profiles can be used for

- Self-similar scaling
- Testing hydrostatic equilibrium
- Mass distribution

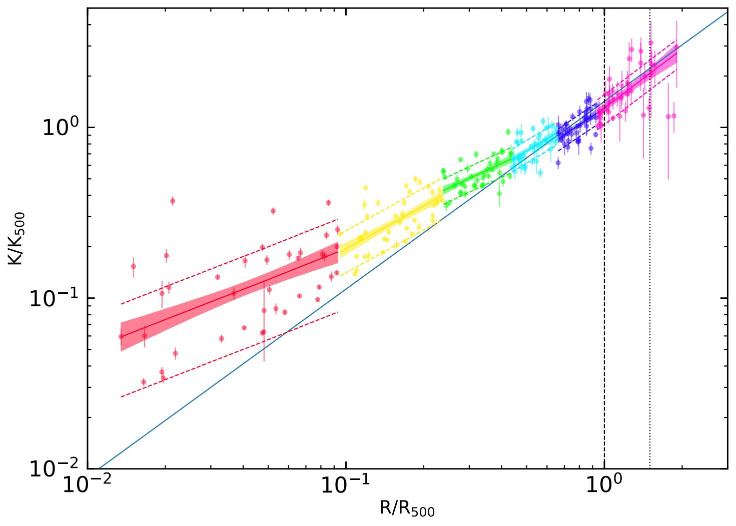
Entropy profiles



Ghirardini, DE et al. 2019

Except for one cluster (A2319) all clusters are consistent with gravitational heating once corrected for clumping

Entropy profiles

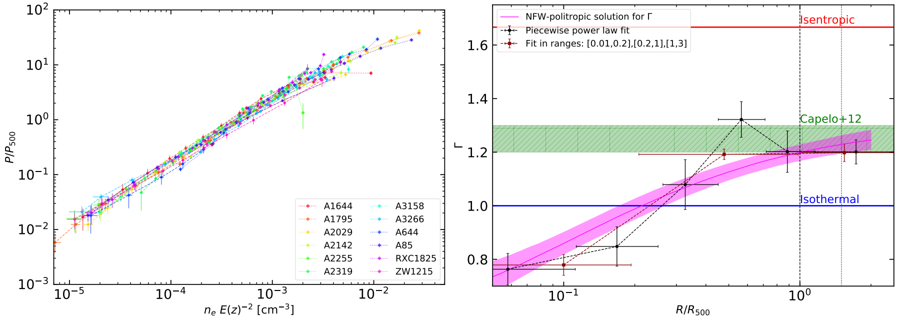


Ghirardini, DE et al. 2019

Slope beyond R_{500} of 1.25 ± 0.23 fitted over > 30 data points

Effective polytropic index

The effective polytropic index $\Gamma = \frac{d \log P}{d \log \rho}$ tells us about the equation of state

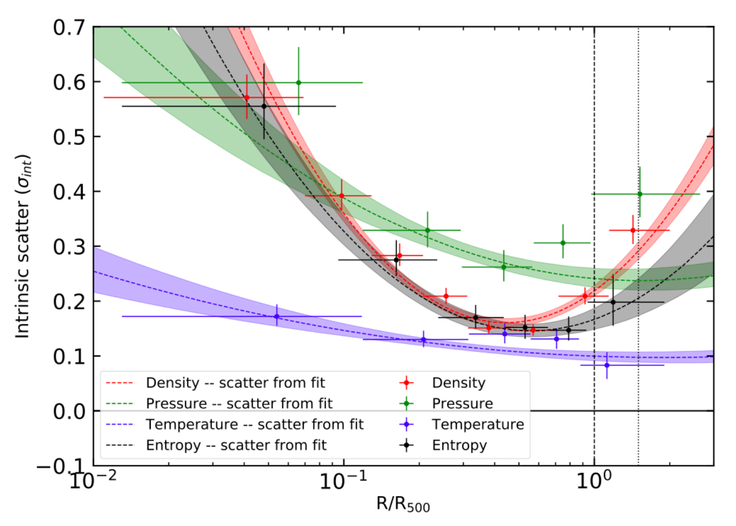


Ghirardini et al. in press

Beyond $R \sim 0.3 R_{500}$ (i.e. outside the cooling region) Γ is constant at ~ 1.2;

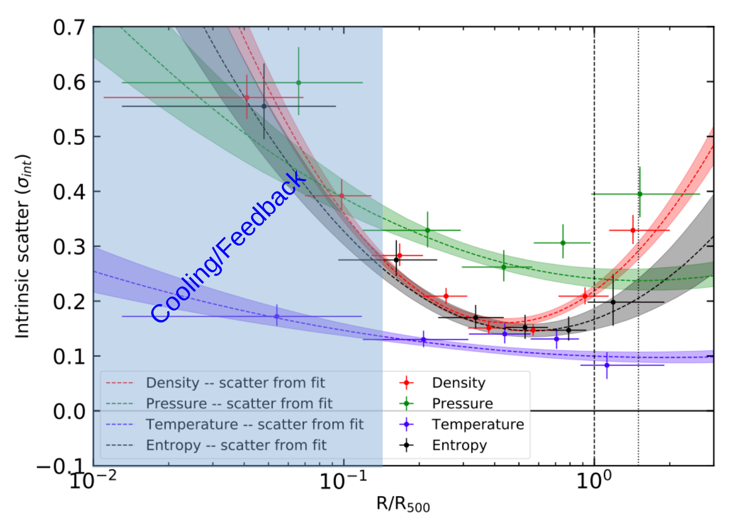
Agreement with predictions for ICM in hydrostatic equilibrium in NFW potential (Capelo et al. 2012)

Scatter in thermodynamic profiles



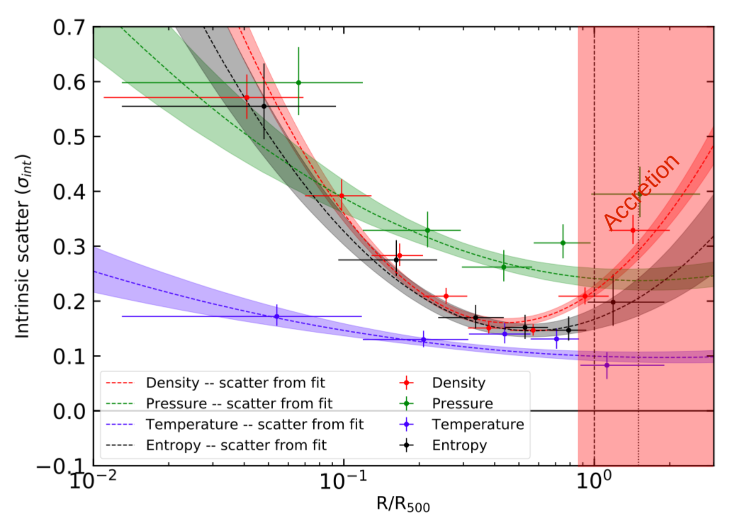
In the range $[0.2 - 0.8]R_{500}$ the cluster population behaves self-similarly

Scatter in thermodynamic profiles



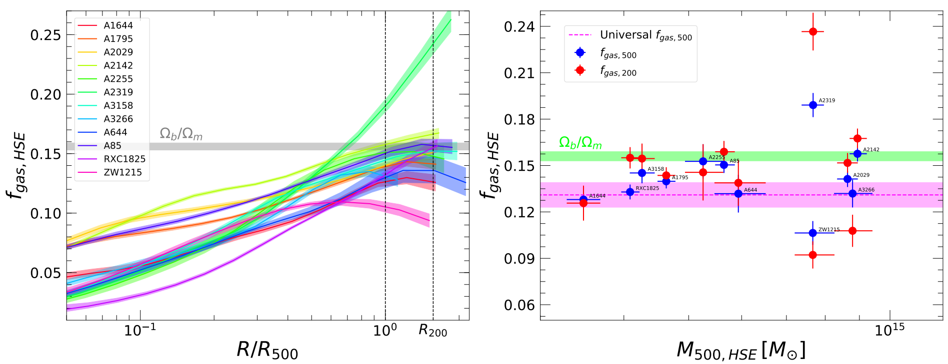
Cooling, AGN feedback and merger state have a large impact on cluster cores

Scatter in thermodynamic profiles



Beyond $\sim R_{500}$ accretion from the environment matters

Testing hydrostatic equilibrium with f_{gas}



Eckert et al. 2019

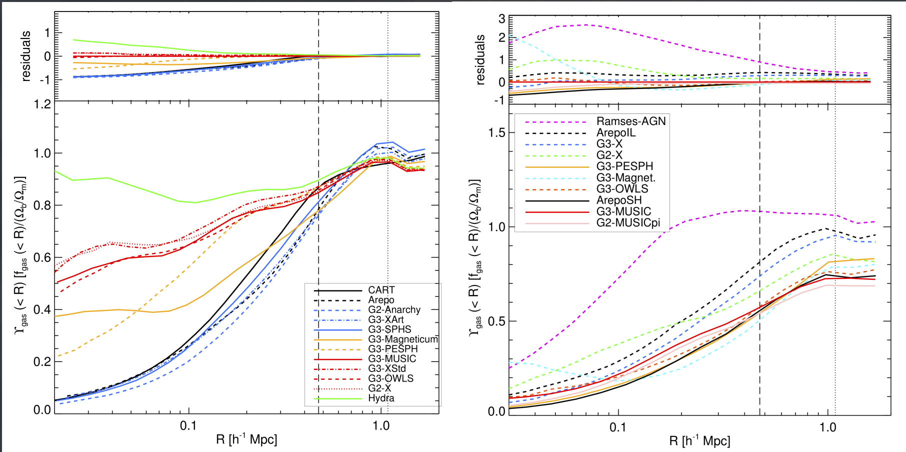
Median [percentiles] for the full sample:

- $f_{gas,500} = 0.141\ [0.131, 0.154]$
- $f_{gas,200} = 0.149\ [0.121, 0.161]$

Universal gas fraction

Comparison between 13 codes (Sembolini et al. 2016a,b)

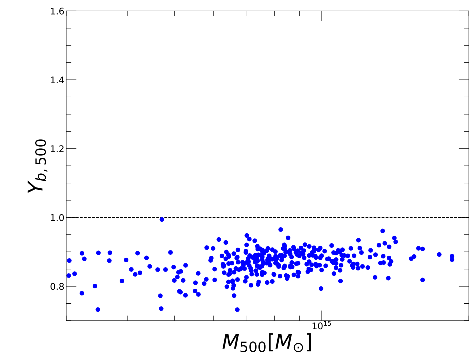
Non-radiative Radiative/AGN



The baryon fraction should be close to the cosmic value

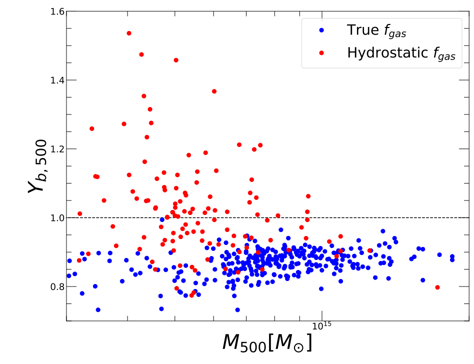
Universal gas fraction

We used a large set of ~ 300 simulated clusters (Rasia et al. in prep.) to determine the baryon depletion



Universal gas fraction

We used a large set of ~ 300 simulated clusters (Rasia et al. in prep.) to determine the baryon depletion



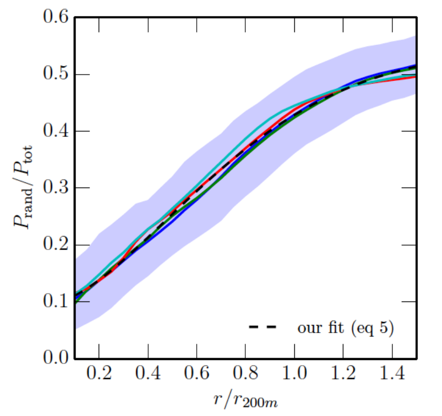
- The value of Y_{bar} is nearly independent of the adopted baryonic physics (Planelles et al. 2014)
- Considering the (well-measured) stellar fraction, we set $f_{gas} = Y_b \frac{\Omega_b}{\Omega_m} - f_{\star}$

Non-thermal pressure support

- In the presence of non-thermal pressure the HSE equation becomes

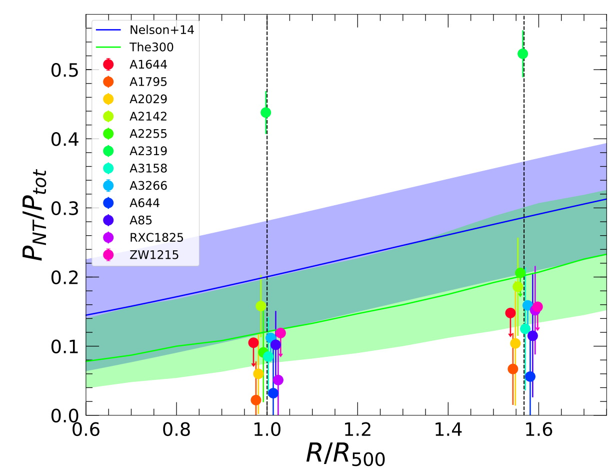
$$\frac{d}{dr}(P_T + P_{NT}) = -\rho \frac{GM}{r^2}$$

- We assume a parametric form for $P_{NT}/P_T(r)$ and solve for the parameters assuming universal f_{gas}
- Scatter and uncertainties in universal f_{gas} are propagated to NT pressure



Nelson et al. 2014

Non-thermal pressure support vs simulations

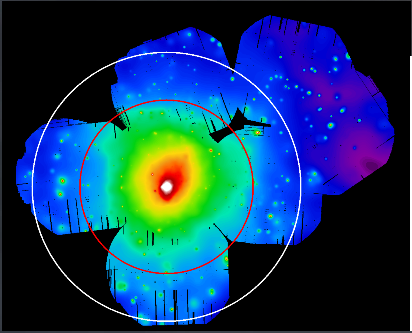


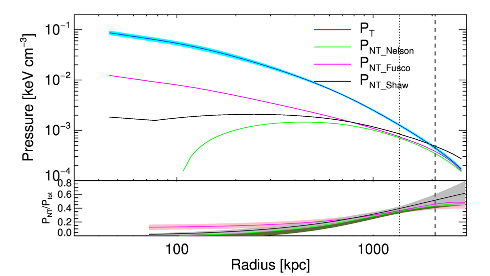
Eckert et al. 2019

With one exception (A2319) the level of NT pressure is *lower* than predicted

Median $P_{NT,500} = 6\%$, $P_{NT,200} = 10\%$

A2319 is a head-on merger with 3:1 mass ratio

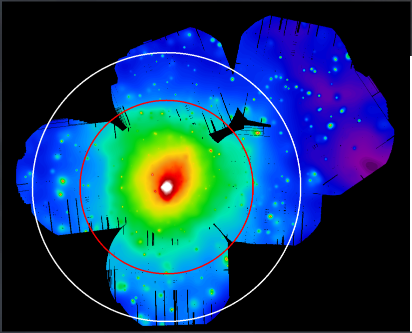


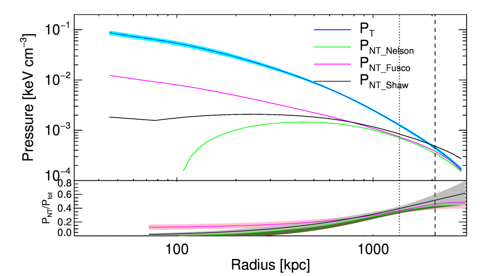


Ghirardini, Ettori, DE et al. 2018

The case of A2319

A2319 is a head-on merger with 3:1 mass ratio



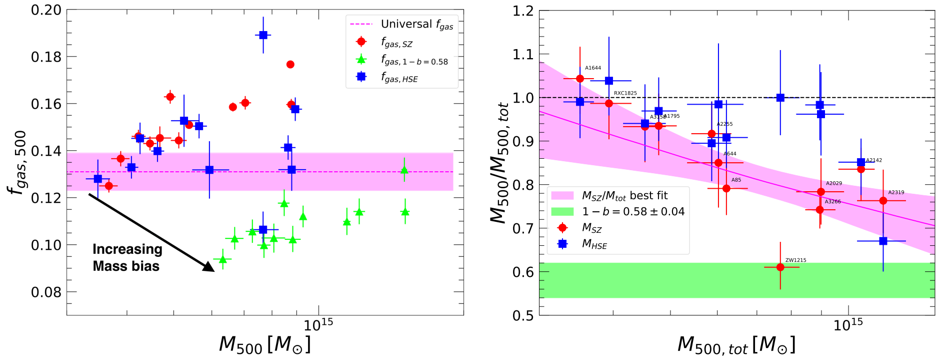


Ghirardini, Ettori, DE et al. 2018

A2319 is probably in a transient phase of high NT pressure ($\sim 40\%$)

Non-thermal pressure and hydrostatic bias

We compared our masses corrected for NT pressure with hydrostatic masses

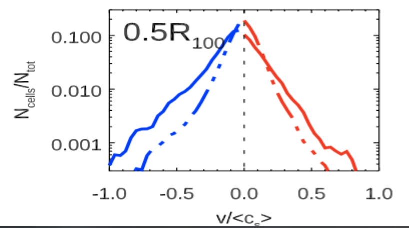


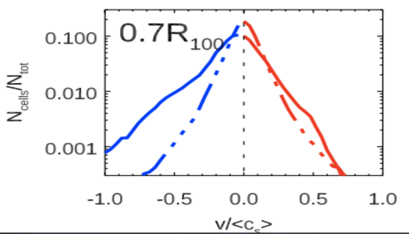
Eckert et al. 2019

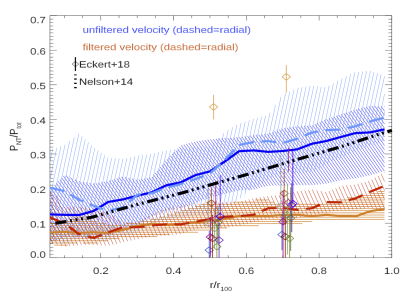
- On average we measure $M_{HSE}/M_{tot} = 0.94 \pm 0.04$
- *Planck* masses are slightly biased low, $M_{SZ}/M_{tot} = 0.85 \pm 0.05$
- $1 - b = 0.58 \pm 0.04$ would imply a very low $f_{gas} = 10.5\%$

A low hydrostatic bias?

NT pressure in simulations is usually calculated as $P_{NT} = \frac{1}{3}\rho\sigma^2_{\rm gas}$



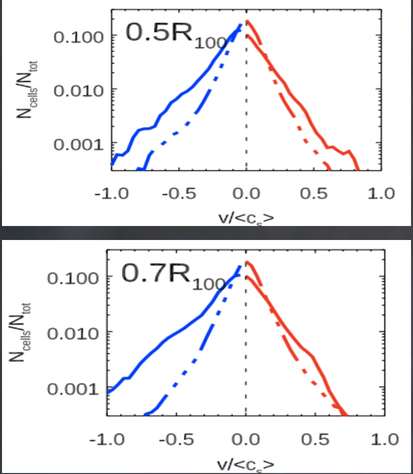


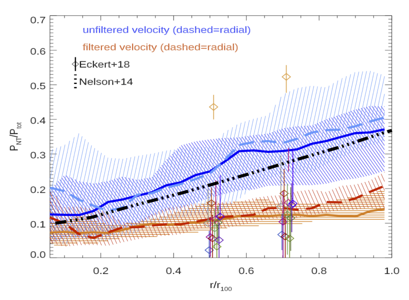


Vazza, DE et al. 2018

A low hydrostatic bias?

NT pressure in simulations is usually calculated as $P_{NT} = \frac{1}{3}\rho\sigma_{\rm gas}^2$



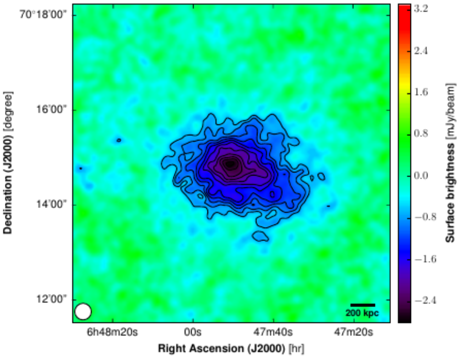


Vazza, DE et al. 2018

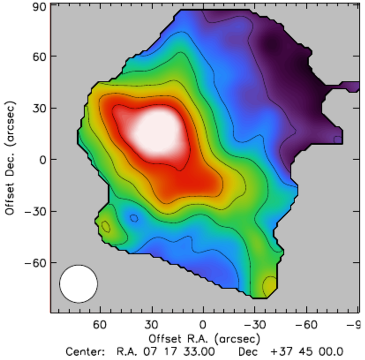
The velocity distribution in spherical shells has a tail extending towards **negative values**

Prospects for NIKA-2

Combining Chandra/XMM data with NIKA-2 we can use the X/SZ method out to high redshift



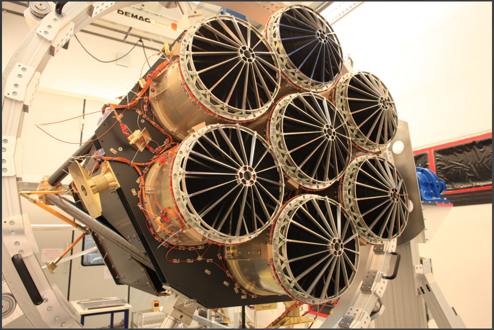
Ruppin et al. 2018

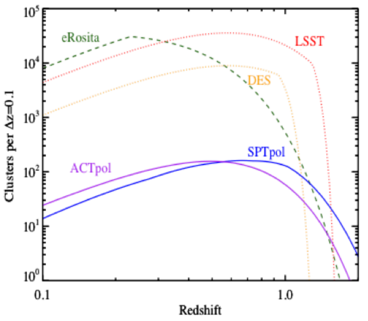


Adam et al. 2018

The future: the eROSITA all-sky survey

eROSITA is the next-generation X-ray survey instrument

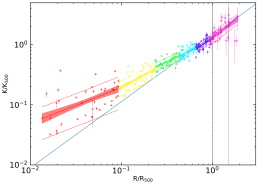




eROSITA will detect 100,000 clusters out to $z \sim 1.5$! Synergies with SZ instruments are obvious

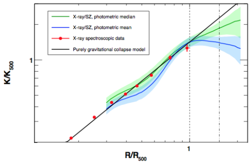
Take home message

All X-COP clusters but one follow gravitational collapse predictions



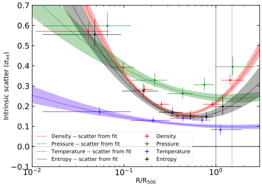
Ghirardini et al. X-COP1

Regular outskirts when clumping is taken into account



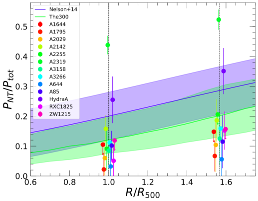
Tchernin et al. 2016

The scatter in density and temperature is positively correlated



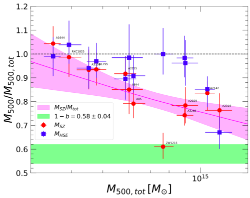
Ghirardini et al. X-COP1

The level of NT pressure is just 6% at R_{500}



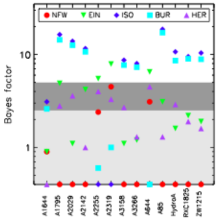
Eckert et al. X-COP3

The gas fraction of X-COP clusters implies a mild HSE bias $M_{HSE}/M_{tot}=0.94$



Eckert et al. X-COP3

NFW is the best-fit mass model in 9/13 cases ; cores disfavored



Ettori et al. X-COP2