The X-ray/SZ view of the virial region

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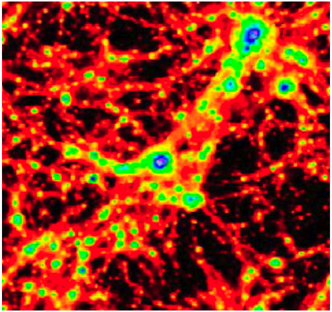
The outskirts of galaxy clusters

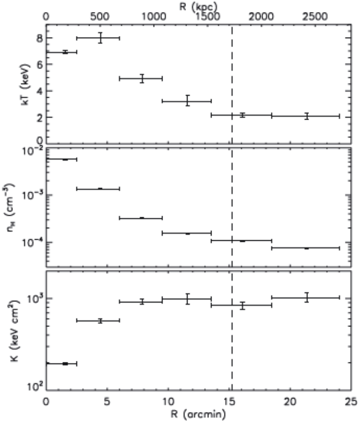
- 90% of the cluster volume beyond R_{500}, calibrate cluster mass measurements
- Where structure formation takes place
- The region where transition between virialized gas from clusters and infalling material from LSS occurs
- Estimate the global baryon budget



Vazza et al. 2011

Thermodynamic properties of cluster outskirts

- Recent *Suzaku* observations show steep temperature drops and flat density profiles in cluster outskirts
  $\rightarrow$ The entropy *flattens*
- Is the ICM convectively unstable? Important for structure formation processes



George et al. 2009

Thermodynamic properties of cluster outskirts

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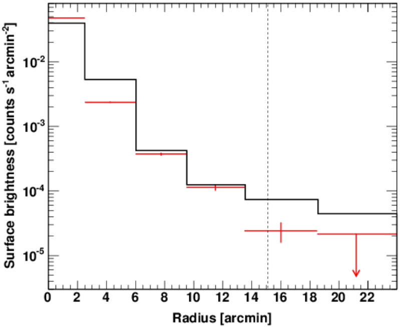
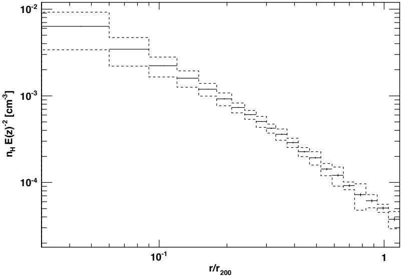
  $\rightarrow$ The entropy *flattens*
- Is the ICM convectively unstable? Important for structure formation processes
- But... In the outskirts systematic effects on X-ray spectroscopic information are hard to handle



Eckert et al. 2011

ROSAT density profiles

- We extracted deprojected density profiles for a sample of 31 nearby clusters ($0.04 < z < 0.2$)
- Stacked emission detected out to $1.2R_{200}$

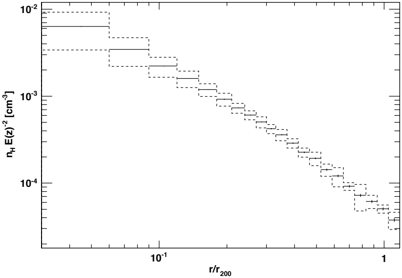


Eckert et al. 2012

ROSAT density profiles

- We extracted deprojected density profiles for a sample of 31 nearby clusters ($0.04 < z < 0.2$)
- Stacked emission detected out to $1.2R_{200}$
- The density **steepens** with increasing radius:

$\beta_{0.2-0.4}$	$\beta_{0.4-0.65}$	$\beta_{0.65-1.2}$
0.661 ± 0.002	0.710 ± 0.009	0.890 ± 0.026



Eckert et al. 2012

ROSAT density profiles

- We compared our mean density profile with 3 sets of numerical simulations:
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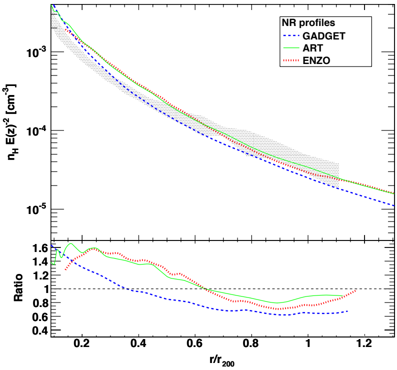
  ART, Nagai et al. 2007
  ENZO, Vazza et al. 2010



Eckert et al. 2012

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  GADGET-2, Roncarelli et al. 2006
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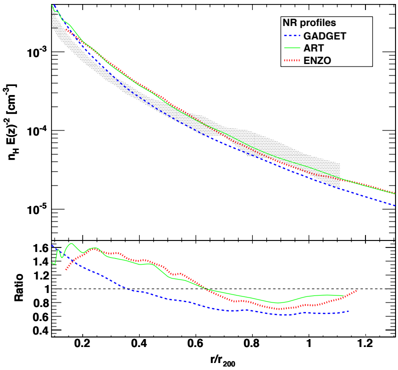
  ENZO, Vazza et al. 2010
- Non-radiative simulations predict *too steep* density slopes



Eckert et al. 2012

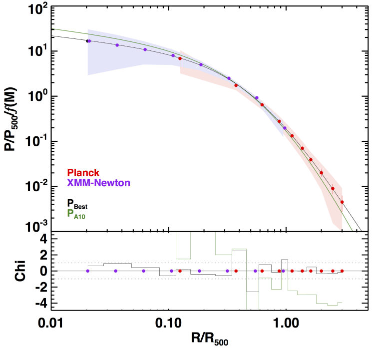
Planck breakthrough

- Recently: *Planck* measures the SZ effect beyond the virial radius
- Combined with *ROSAT*, we can reconstruct:

$$kT = \frac{P_{SZ}}{n_{X-ray}}, \quad K = P_{SZ} n_{X-ray}^{-5/3}$$

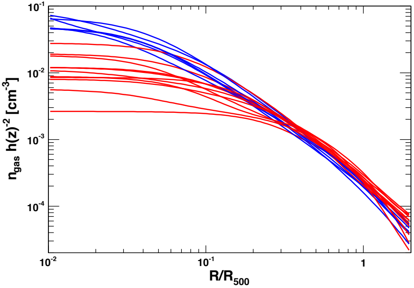
- Assuming hydrostatic equilibrium we can also reconstruct mass profiles:

$$\frac{dP}{dr} = -\rho \frac{GM(<r)}{r^2}$$

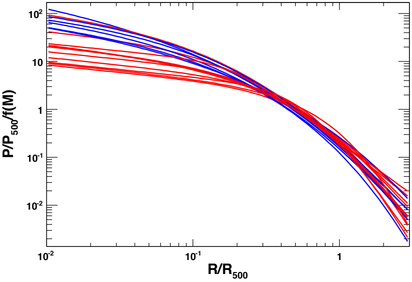


Planck Collaboration V 2012

Basic P and n_{gas} profiles



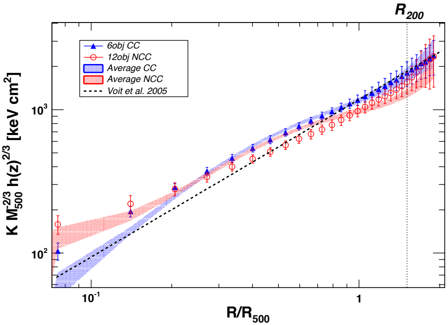
Eckert et al. 2012



Planck Collaboration V 2012

- 18 objects (6 CC, 12 NCC) are in common between the *ROSAT* and *Planck* samples
- The average P and n_{gas} profiles can also be combined (but caution about selection effects)

Average entropy profile



Eckert et al. 2013a

- CC clusters agree with the prediction from gravitational collapse (Voit et al. 2005)
- In NCC systems a deficit with respect to the prediction is observed

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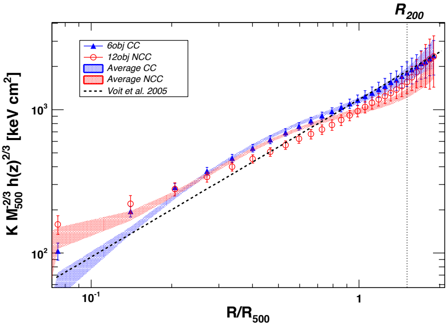

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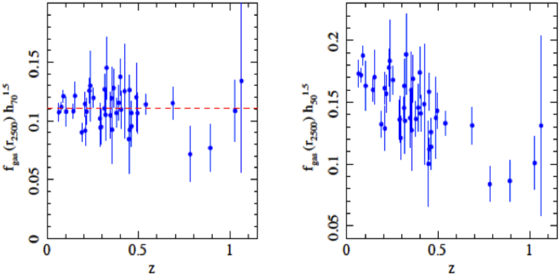
Gas clumping and/or non-thermal effects (turbulence, magnetic fields...) affect NCC more than CC

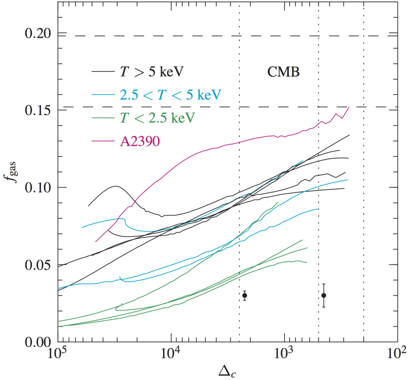
Gas fraction



Allen et al. 2008

- $f_{\rm gas}$ is used as a standard ruler for cosmology

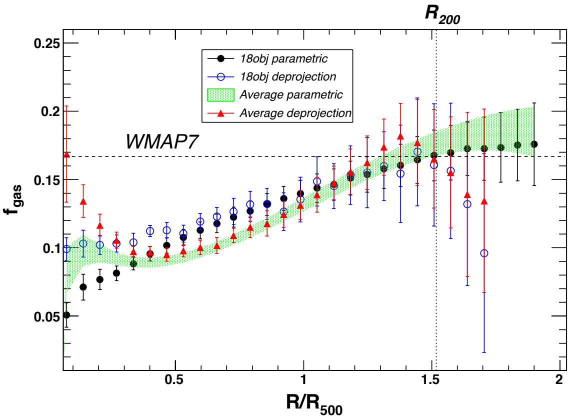
Gas fraction



Vikhlinin et al. 2006

- $f_{\rm gas}$ is used as a standard ruler for cosmology
- Because of non-gravitational energy input, f_{gas} rises with radius
- Only when reaching the virial radius, it is possible to know if $f_{gas} = \Omega_b/\Omega_m$

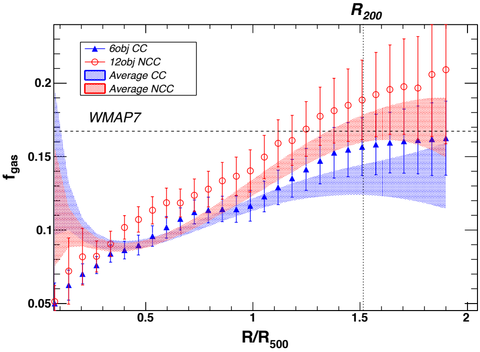
Gas fraction profiles



Eckert et al. 2013b

- We measure for the first time f_{gas} at R_{200} in a cluster sample
- f_{gas} **reaches the cosmic value** from WMAP7 at R_{200}
- Slight excess when considering the stellar content (1-2%); agreement with numerical simulations

Gas fraction in CC/NCC systems



Eckert et al. 2013b

- For CC profiles f_{gas} reaches the expected values $(\Omega_b/\Omega_m - 15\%)$
- For NCC profiles f_{gas} **exceeds** the cosmic value!

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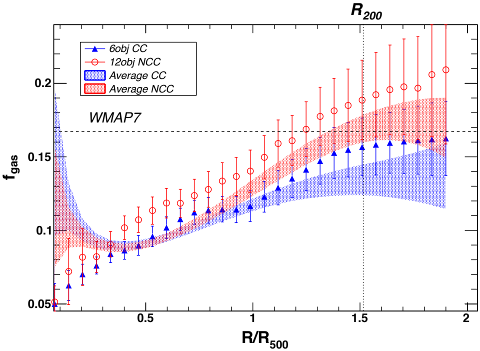

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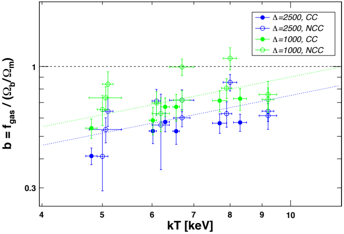
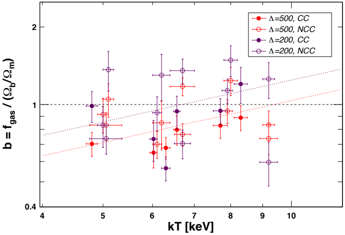
Gas clumping and/or breakdown of HE in NCC systems, only CC are suitable for cosmology

Scatter of f_{gas}

The knowledge of the cluster-to-cluster scatter in f_{gas} is crucial to use it as a standard ruler





Eckert et al. 2013b

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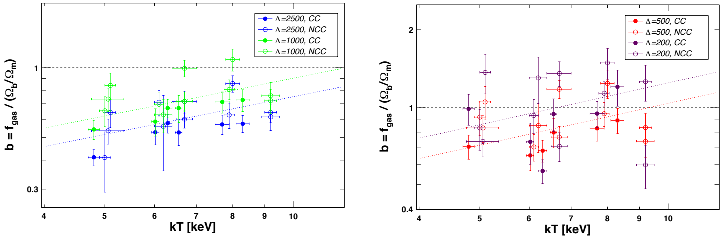

Eckert et al. 2013b

- $b = f_{gas}/f_{WMAP7}$ increases with cluster temperature, as $b \sim T^{0.5}$
- When correcting for this effect, $\sigma_{f,500} = (15 \pm 4)\%$

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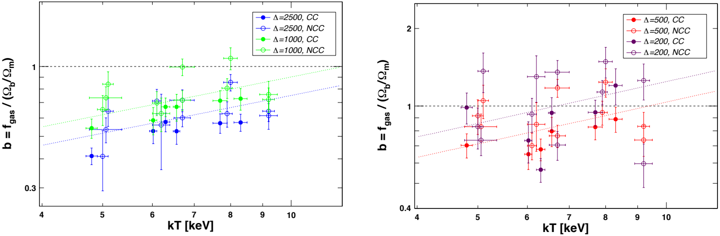

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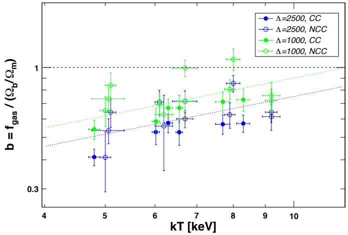

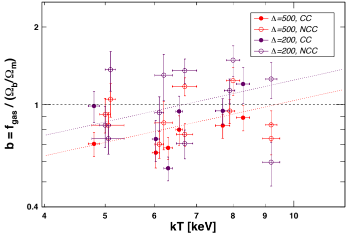

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CC clusters can be used efficiently for cosmology out to R_{500}

Summary

- We derived density profiles out to R_{200} from *ROSAT*, the gas density steepens beyond R_{500}
- By combining *Planck* and *ROSAT* data we measure for the first time thermodynamic quantities out to the virial radius in a substantial cluster sample
- No sign of entropy flattening, unlike several *Suzaku* results
- Evidence for deviations from self-similarity in cluster outskirts for NCC systems, CC systems agree with expectations
- The cause of the deviations (gas clumping, non-thermal pressure support) is still unknown, work in progress
- f_{gas} reaches the cosmic value at R_{200}, providing evidence that all the primordial gas is collapsed into clusters
- The scatter of f_{gas} is substantial in NCC systems, but negligible in CC

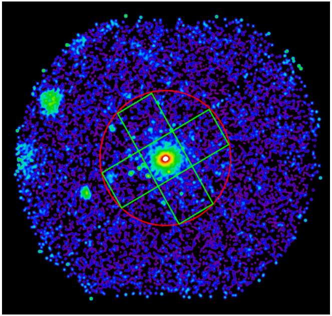
Backup Slides

ROSAT/PSPC observations

ROSAT had several advantages with respect to *Suzaku*

- Large FOV (25 times *Suzaku*)
- Low and stable instrumental bkg
- Better PSF ($25''$ on-axis)

... But limited spectral capabilities



Eckert et al. 2011

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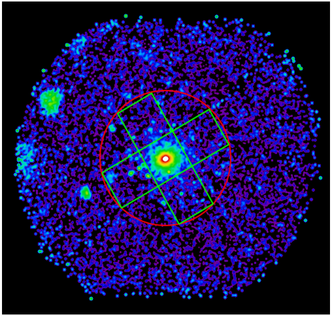
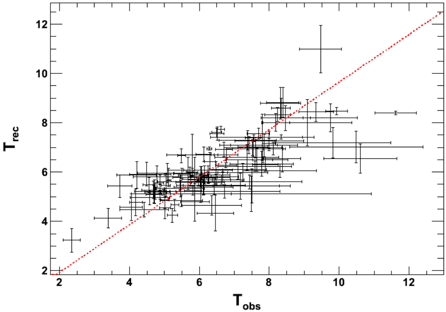


Eckert et al. 2011

→ **Excellent instrument to study the gas distribution in low-SB regions**

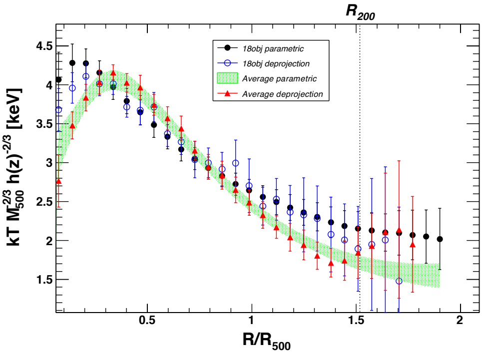
Validation of the method

- We collected available X-ray T profiles and compared with our method
- Combining SZ pressure with X-ray density we are able to reproduce the observed X-ray temperatures within $< 10\%$



Eckert et al. 2013a

Average temperature profile

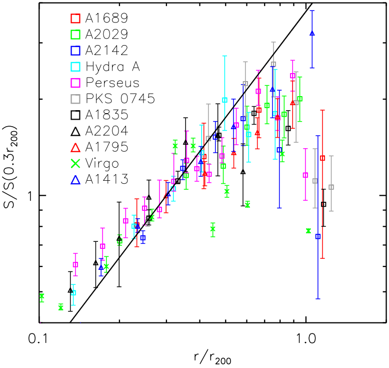


Eckert et al. 2013a

- Average temperature from the mean profiles agrees very well with the average of the 18 individual objects
- Two different deprojection methods (parametric fitting, geometrical deprojection) also yield similar results

A general entropy flattening in relaxed clusters?

- *Suzaku* detected the ICM at large radii in ∼10 clusters
- Is the ICM convectively unstable?



Walker et al. 2012

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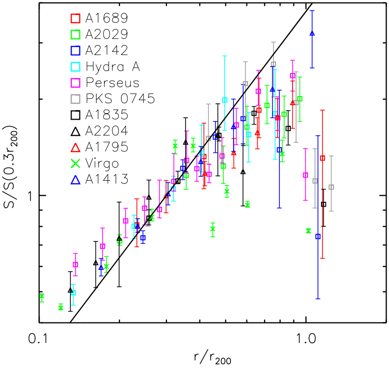
- Walker et al. (2012) fix the normalization of the profiles at $0.3R_{200}$ instead of using the self-similar normalization K_{500} (Pratt et al. 2010)



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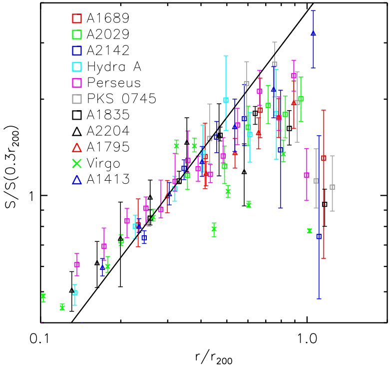


Walker et al. 2012

Our results are at odds with this interpretation

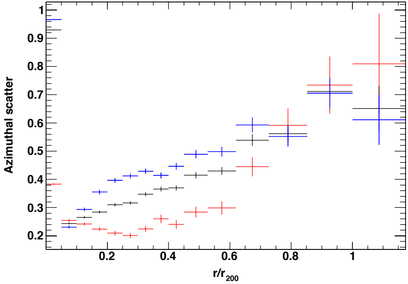
Azimuthal scatter profiles

- Azimuthal scatter (Vazza et al. 2011) in $N = 12$ sectors: quantifies deviations from azimuthal symmetry

$$\Sigma^2(r) = \frac{1}{N} \sum_{i=1}^{N} \frac{(SB_i(r) - \langle SB(r) \rangle)^2}{\langle SB(r) \rangle^2}$$

- In the central regions $\Sigma_{CC} \ll \Sigma_{NCC}$
- Beyond $\sim R_{500}$ all populations exhibit a large level of scatter $(60-80\%)$

CC NCC Total



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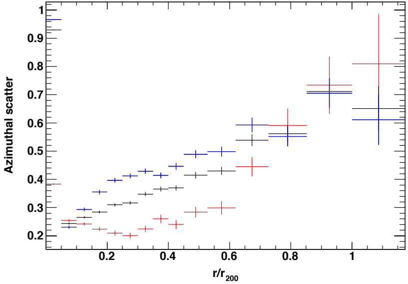
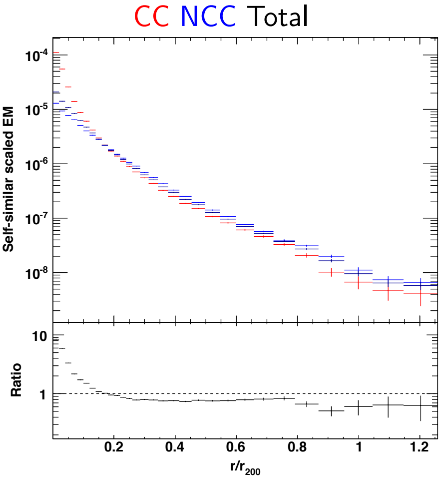


Eckert et al. 2012

Even in “relaxed" clusters there is large asymmetry in the outskirts due to accretion occurring along preferential directions

Stacked emission-measure profiles

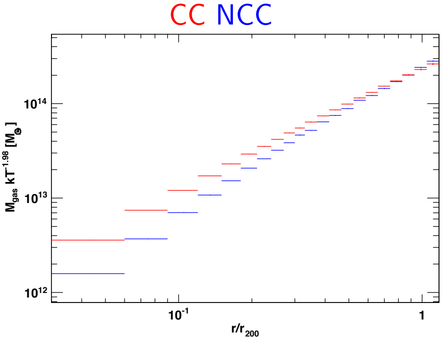
- We stacked self-similar scaled EM profiles and divided the sample into CC and NCC
- Beyond $\sim 0.3 R_{200}$ NCC profiles *exceed* CC



Eckert et al. 2012

Stacked emission-measure profiles

- We stacked self-similar scaled EM profiles and divided the sample into CC and NCC
- Beyond $\sim 0.3 R_{200}$ NCC profiles *exceed* CC
- When integrating out to R_{200} CC and NCC *include the same gas mass*

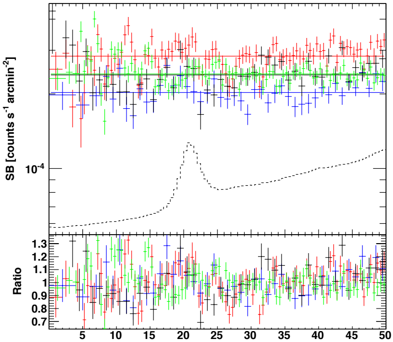


Eckert et al. 2012

The same gas mass is redistributed between the central regions and the outskirts

Systematics in ROSAT analysis

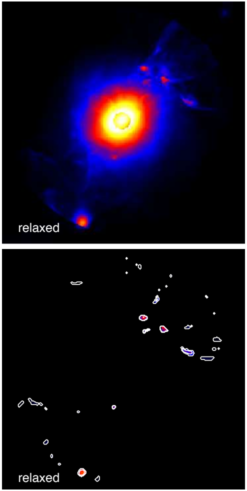
- Bkg dominated by cosmic components, total non-cosmic ~20% of the total bkg
- SB analysis of 5 blank fields from the center of the observation, fit with a constant
- Excess scatter in the data of 6% of the background value, includes both systematic error and cosmic variance
- A systematic error of 6% is propagated when subtracting the bkg



Eckert et al. 2012

Gas clumping

- Possible interpretation: gas clumping
- The accretion flow on galaxy clusters is *clumpy* and *asymmetric*

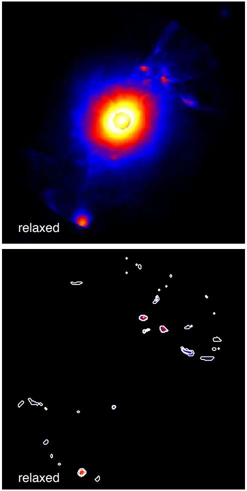


Vazza, DE et al. 2012

Gas clumping

- Possible interpretation: gas clumping
- The accretion flow on galaxy clusters is *clumpy* and *asymmetric*
- X-ray signal biased towards high-density, cool regions; in cluster outskirts

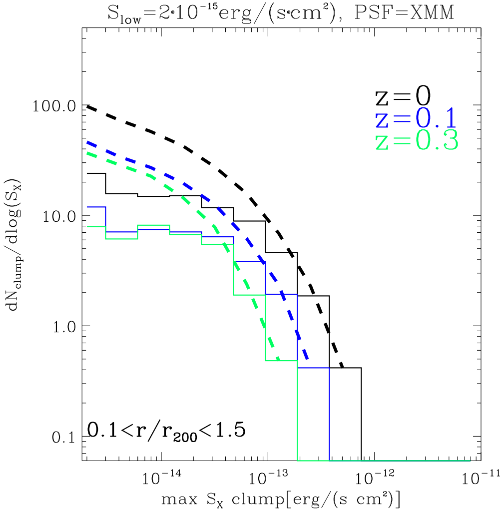
$$C = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} > 1$$



Vazza, DE et al. 2012

XMM program

- We obtained 250 ks with XMM to detect clumps in A2142 and Hydra A
- According to ENZO simulations we should detect ~ 40 clumps per cluster ($z = 0.1,\ F_{lim} = 2 \times 10^{-15}$ ergs s^{-1} cm^{-2})



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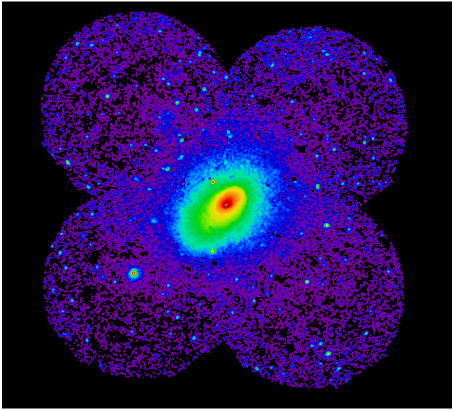
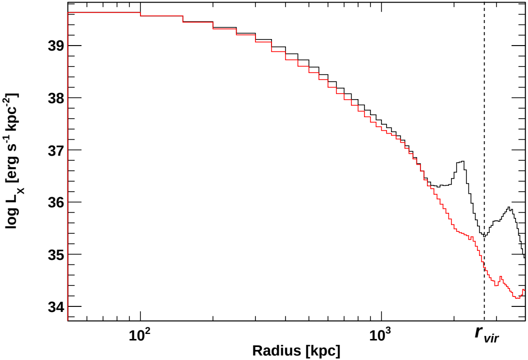
- According to ENZO simulations we should detect $\sim$ 40 clumps per cluster ($z = 0.1,\ F_{lim} = 2 \times 10^{-15}$ ergs s^{-1} cm^{-2})
- Our program will give strong constraints on the amount of clumping in cluster outskirts



Eckert et al. in prep.

Correcting for the clumping bias

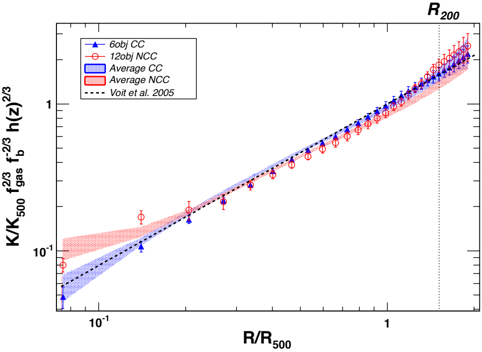
Mean in annuli Median in sectors



- The mean of an inhomogeneous gas distribution is biased high
- Idea: divide the SB in relatively narrow sectors and take the median
- This method allows to recover an unbiased density profile and determine the clumping factor (in prep.)

Correcting for gas depletion

Following Pratt et al. (2010) we rescale the entropy profiles by the gas fraction to compensate for gas motions



Eckert et al. 2013a

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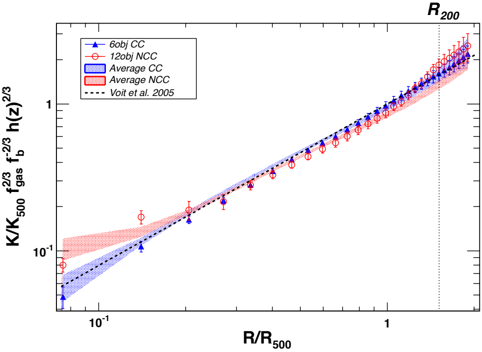

Eckert et al. 2013a

When correcting for gas depletion, the total entropy agrees perfectly with the self-similar prediction out to R_{vir}