The gas distribution in the outer regions of galaxy clusters

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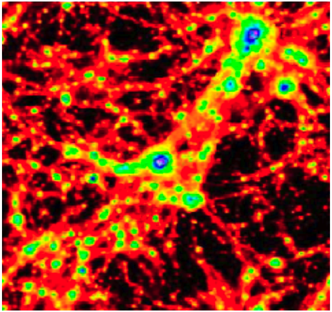
Introduction

Why study cluster outskirts?

- Where structure formation takes place
- The region where transition between virialized gas from clusters and infalling material from LSS occurs
- Calibrate X-ray mass measurements



Vazza et al. 2011

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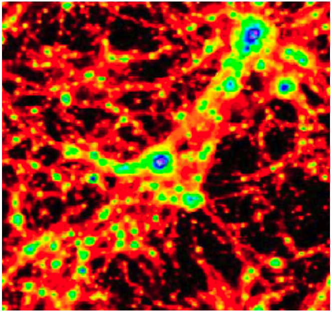


Vazza et al. 2011

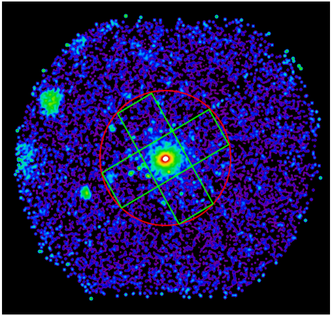
A breakthrough was achieved recently with Suzaku

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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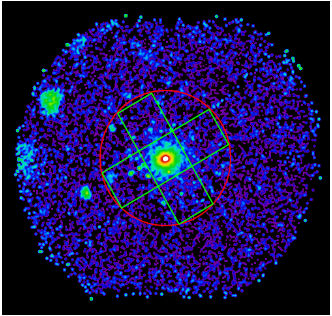
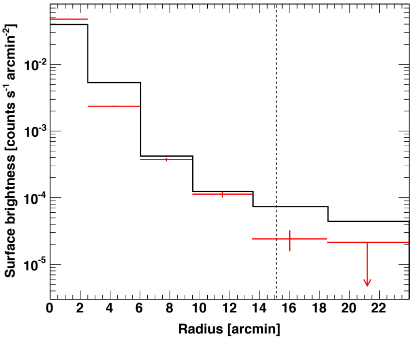


Eckert et al. 2011

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

The case of PKS 0745-191

- First cluster with T measurements at R_{200} (George et al. 2009)
- SB profile inconsistent with *ROSAT* (Eckert et al. 2011)
- Original analysis affected by incorrect bkg modeling, see the revised analysis by Walker et al. 2012



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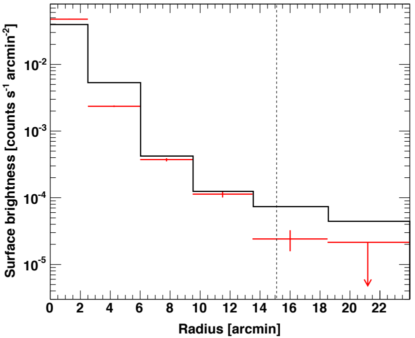
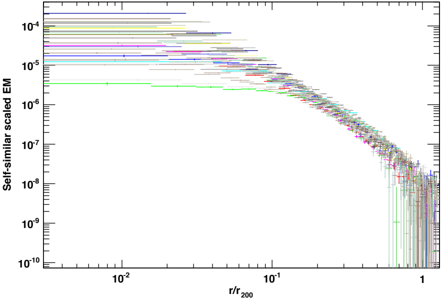


Eckert et al. 2011

Measurements in cluster outskirts are difficult, cross-check is important (see S. Molendi's talk)

ROSAT sample

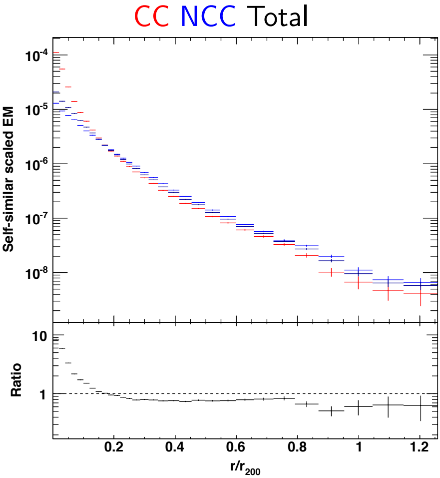
- We analyzed a sample of 31 nearby clusters ($0.04 < z < 0.2$), expanding on the works of Vikhlinin et al. 1999 and Neumann et al. 2005
- Emission-measure and deprojected density profiles for all clusters
- R_{200} values from scaling relations



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



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Stacked emission-measure profiles

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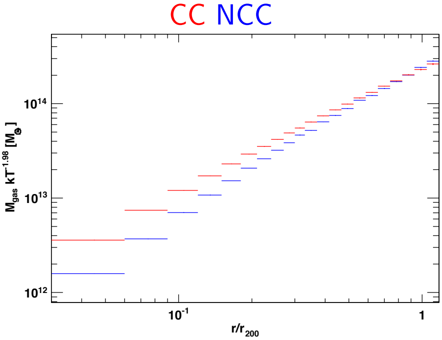
- Beyond $\sim 0.3R_{200}$ NCC profiles *exceed* CC
- When integrating out to R_{200} CC and NCC *include the same gas mass*



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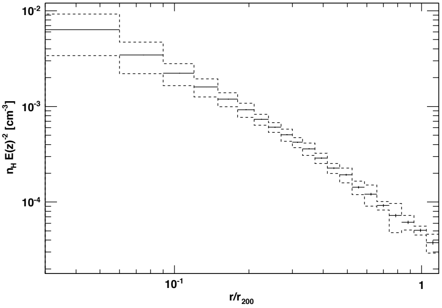
The same gas mass is redistributed between the central regions and the outskirts

Average density profile

- We extracted stacked deprojected density profiles for the full sample and the CC/NCC populations separately
- 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



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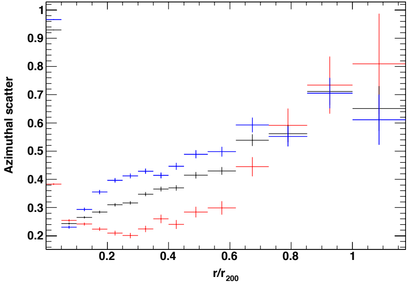
Azimuthal scatter profiles

- 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



Eckert et al. 2012

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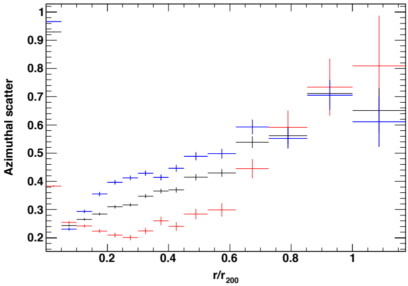

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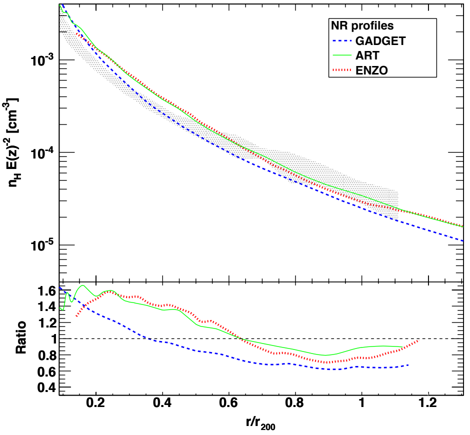
Even in "relaxed" clusters there is large asymmetry in the outskirts due to accretion occurring along preferential directions

Comparison with numerical simulations

- We compared our density profile with 3 different types of numerical simulations
- Non-radiative simulations are *too steep*, better agreement beyond R_{500}



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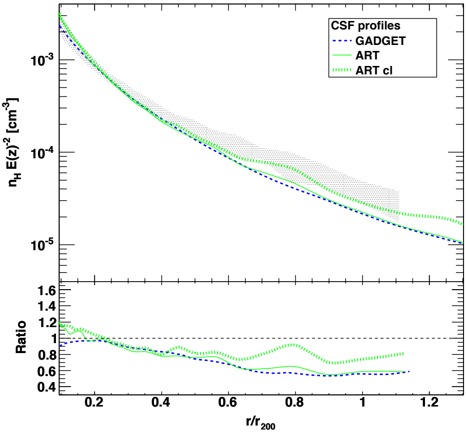
Comparison with numerical simulations

- We compared our density profile with 3 different types of numerical simulations
- Non-radiative simulations are *too steep*, better agreement beyond R_{500}
- Including cooling+star formation does not improve
- Clumping (Nagai & Lau 2011) leads to better agreement, but low gas fraction (∼10%)



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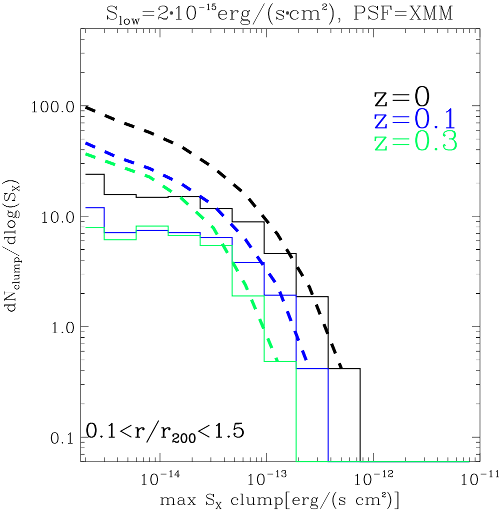
XMM program

- 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})



Vazza, DE et al. in prep

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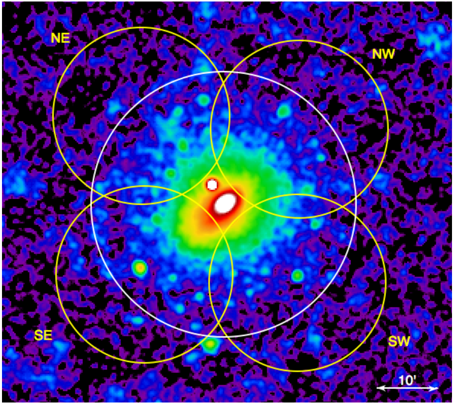
- According to ENZO simulations we should detect ~ 40 clumps per cluster ($z = 0.1,\ F_{lim} = 2 \times 10^{-15}$ ergs s^{-1} cm^{-2})
- Our program will give strong constraints on the amount of clumping in cluster outskirts

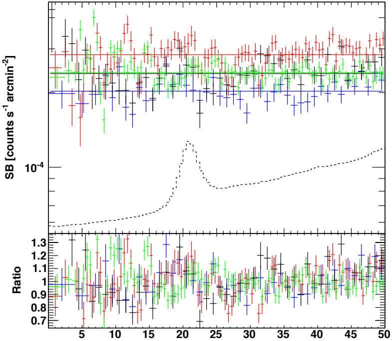


Conclusion

- We analyzed a sample of 31 clusters observed with *ROSAT*/PSPC
- Emission detected out to $\sim 1.2 R_{200}$, EM profiles steepen beyond R_{500}
- NCC profiles exceed CC beyond $0.3 R_{200}$, we explain this by redistribution of the same gas mass within the cluster volume
- Beyond R_{500} all clusters exhibit a high level of asymmetry (sector-to-sector scatter $\Sigma \gtrsim 60\%$)
- Simple NR and CSF simulations are too steep to reproduce the data, clumping slightly improves the agreement
- We obtained an *XMM* program to map the outskirts of 2 clusters (A2142 and Hydra A) with high azimuthal scatter to look for accreting clumps

Backup Slides

- 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



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Intrinsic vs statistical scatter

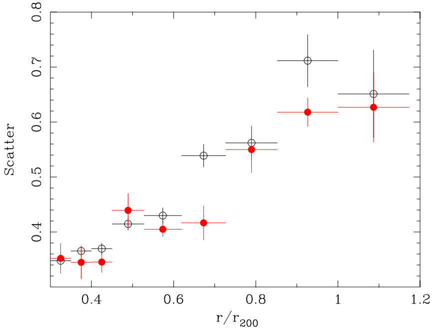
- The total azimuthal scatter is the sum of the intrinsic and statistical scatter:

$$\Sigma^2 = \Sigma_{int}^2 + \Sigma_{stat}^2$$

- Method 1: subtraction of the statistical scatter

$$\Sigma_{stat}^2 = \frac{1}{N} \sum_{i=1}^{N} \frac{\sigma_i^2}{\langle SB \rangle^2}$$

- Method 2: ML estimator (Maccaccaro et al. 1988)
- Good agreement between the 2 methods



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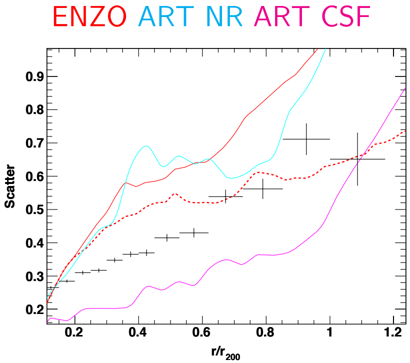
Observed scatter vs simulations

- We compared the observed azimuthal scatter profile with simulations
- NR simulations predict *too large* scatter, including cooling predicts *too low* scatter
- Cooling makes clusters more spherical (Lau et al. 2011), too much because of "cooling catastrophe"



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