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INAF

Hot Gas Accretion in Cluster Outskirts

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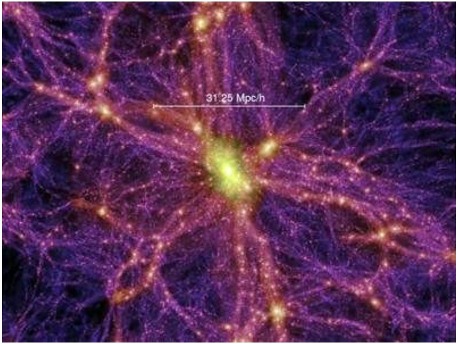
Outline

- Introduction: formation processes of galaxy clusters and current observational signatures
- The azimuthal median: a method to reconstruct cluster density profiles and estimate the clumping factor
- Accreting groups in A2142 and Hydra A: ram-pressure stripping and ICM physics

Cluster formation processes

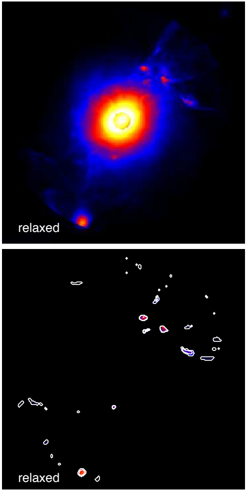
Galaxy clusters are the nodes of the cosmic web

- Clusters grow through accretion of substructures from filaments
- Most of the cluster mass ($\sim 80\%$) accumulates through accretion of small structures (major mergers carry a lot of mass but are very rare)
- Signatures of accretion processes should be found in the outskirts of clusters connected to filaments



The "clumping bias"

- The accretion flow on galaxy clusters is *clumpy* and *asymmetric*



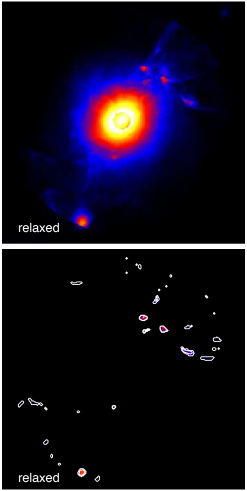
Vazza, DE et al. 2013

The "clumping bias"

- The accretion flow on galaxy clusters is *clumpy* and *asymmetric*
- X-ray signal biased towards high-density regions:

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

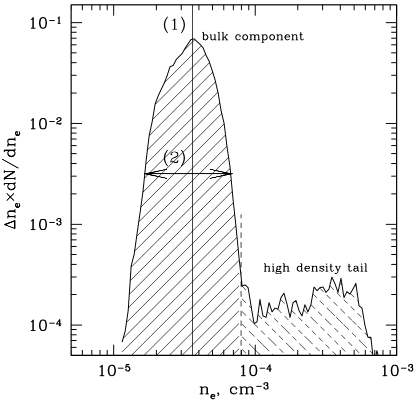
The gas density measured from X-ray observations is biased high in the presence of inhomogeneities



Vazza, DE et al. 2013

The azimuthal median method

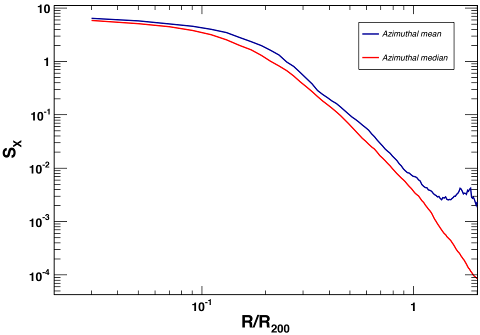
- In numerical simulations: the distribution of gas density values within a spherical shell is log-normal + skewed tail
- $\langle \rho^2 \rangle$ is biased high, but median(ρ^2) is not



Zhuravleva et al. 2013

The azimuthal median method

- In numerical simulations: the distribution of gas density values within a spherical shell is log-normal + skewed tail
- $\langle \rho^2 \rangle$ is biased high, but median(ρ^2) is not
- It is reasonable to think that the same is also true in projected 2D annuli $\rightarrow$ Use median(S_X) instead of $\langle S_X \rangle$ in concentric annuli



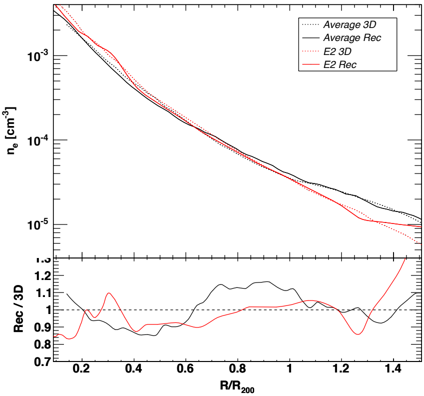
Eckert et al. subm, arXiv:1310.8389

The azimuthal median method

We used a sample of 20 systems simulated with the grid code `ENZO` to test the method

- The profiles obtained by deprojecting median(S_X) provide a good match to the true 3D gas density profiles
- The clumping factor can then be recovered through the expression:

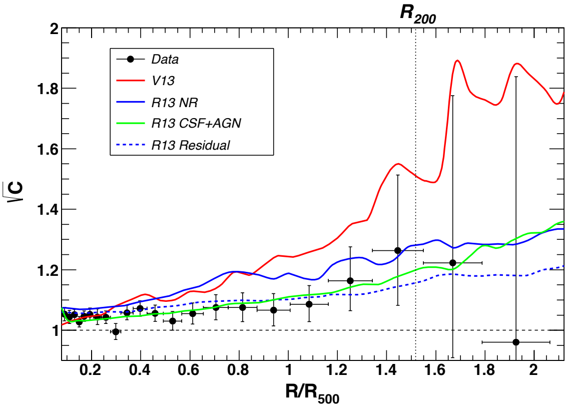
$$C = \frac{\mathrm{deproj}(\langle S_X \rangle)}{\mathrm{deproj}(\mathrm{median}(S_X))}$$



Eckert et al. subm

Results and comparison with numerical simulations

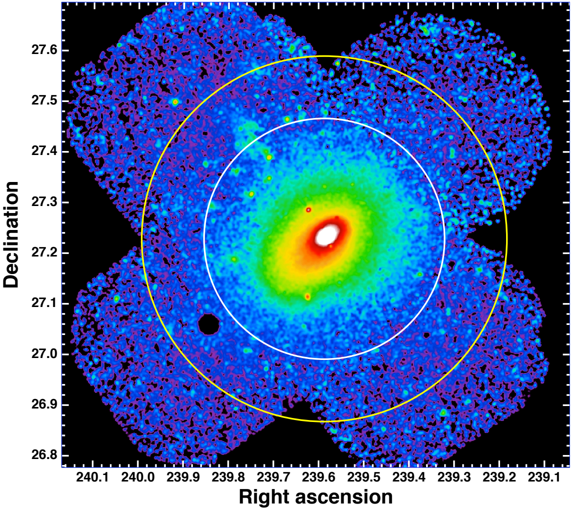
ROSAT/PSPC ENZO NR GADGET NR GADGET CSF+AGN



- Hydrodynamical simulations predict *too many* substructures in the outskirts
- Including AGN + SN feedback improves the match

Accreting substructures in A2142

We obtained 250 ks XMM observations of A2142 and Hydra A in AO-11 for to look for accreting substructures



Eckert et al. subm

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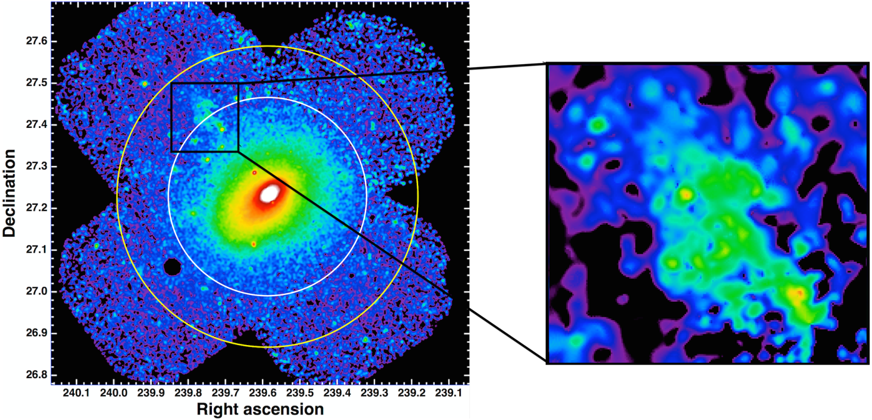
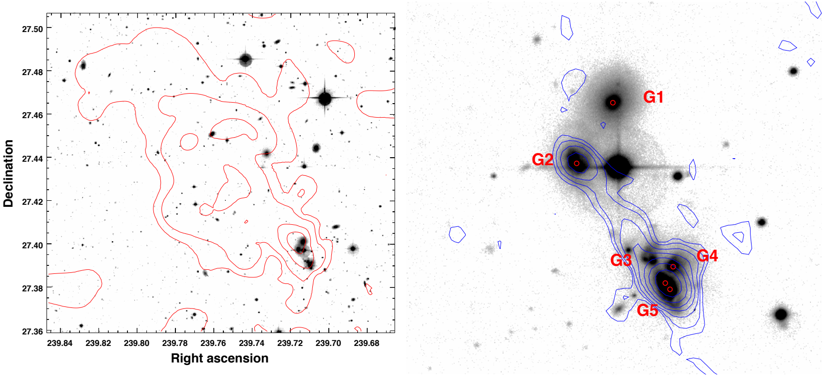


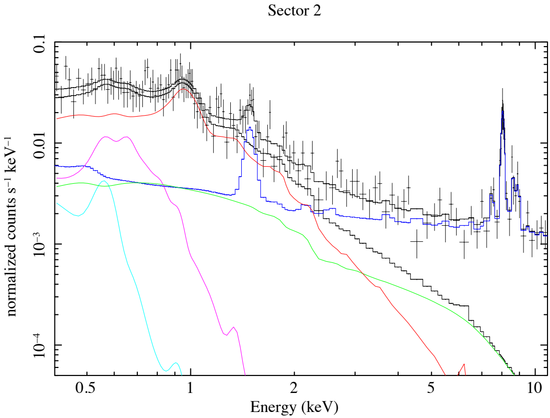
Eckert et al. subm

Tip of the substructure



The tip of the X-ray substructure is associated with an infalling galaxy group. The bulk of the gas is lagging behind

Spectral analysis



The gas is significantly cooler ($kT \sim 1.4$ keV) than the ambient ICM (~ 7 keV). Temperature typical of a galaxy group with mass of a few $10^{13} M_{\odot}$.

$\rightarrow$ Disruption of an infalling group within the DM halo of the main structure

Ram-pressure stripping properties

- This by far the largest stripped structure seen so far:
  - Projected distance > 800 kpc compared to 150 kpc for M86
  - Gas mass $\sim 2 \times 10^{12} M_{\odot}$ compared to $\sim 10^{10} M_{\odot}$ for M86

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- Assuming pressure equilibrium at the tip we can estimate the infall velocity:

$$P_{\rm ICM} + \rho_{\rm ICM} v^2 \approx P_{\rm group}$$

We find that $P_{\rm group} > P_{\rm ICM}$, such that we obtain $v \sim 1,200$ km s^{-1} for the infall velocity
$\Rightarrow$ the feature has been surviving in the cluster environment for at least 600 Myr

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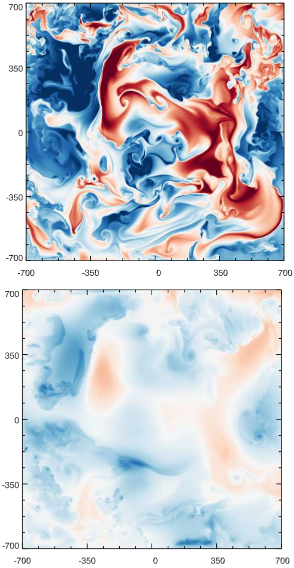
  $\Rightarrow$ the feature has been surviving in the cluster environment for at least 600 Myr
- For a typical group $P_{\rm ram}$ should exceed $P_{\rm th}$ throughout most of the volume, such that $> 90\%$ of the gas mass has been already stripped

Thermal conduction

- Thermal conduction “washes out" inhomogeneities



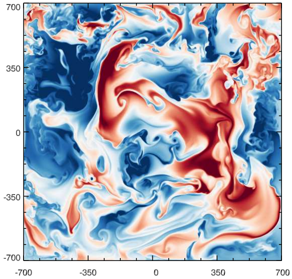
Gaspari & Churazov 2013

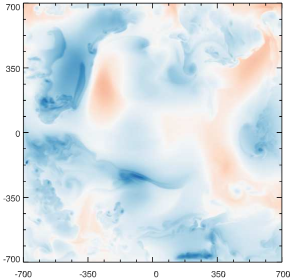
Thermal conduction

- Thermal conduction "washes out" inhomogeneities
- The thermal conduction timescale in a plasma is

$$t_{\rm cond} \sim \frac{\ell^2}{D_{\rm cond}} = \frac{3 n_e \ell^2 k_B}{2\kappa}$$

- In an unmagnetized plasma $\kappa = \kappa_{\rm Spitzer}$; for $n_e \sim 5 \times 10^{-5}$ cm^{-3} and $kT \sim 5$ keV we find $t_{\rm cond} \sim 1.4$ Myr





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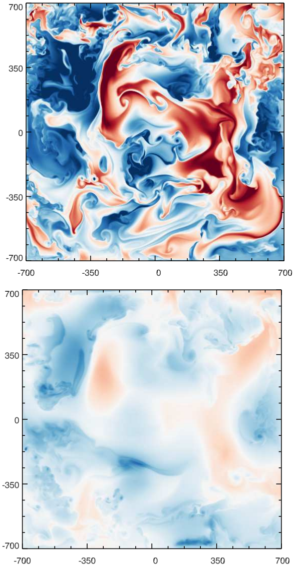
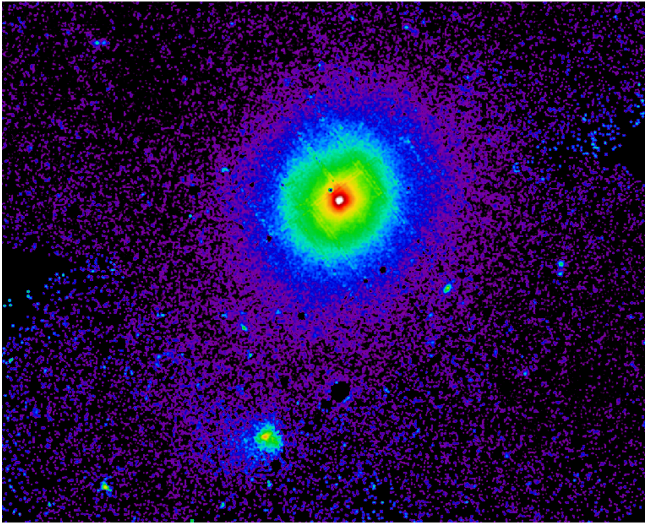
- In an unmagnetized plasma $\kappa = \kappa_{\rm Spitzer}$; for $n_e \sim 5 \times 10^{-5}$ cm^{-3} and $kT \sim 5$ keV we find $t_{\rm cond} \sim 1.4$ Myr
- Thermal conduction in the ICM is inhibited by a factor $\gtrsim 400$!



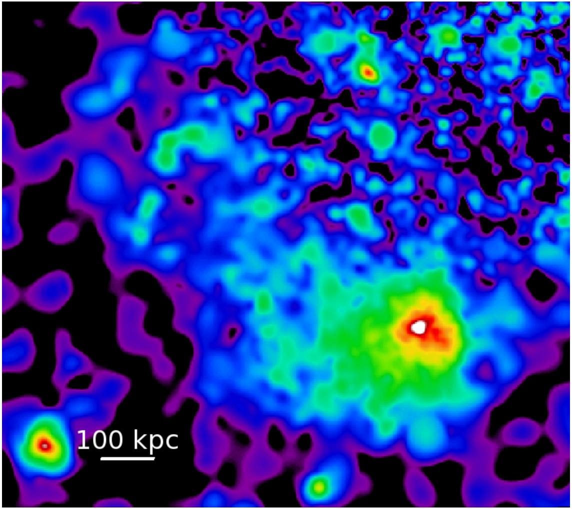
Gaspari & Churazov 2013

...And more: Hydra A

Another galaxy group 1.1 Mpc South of the cluster core

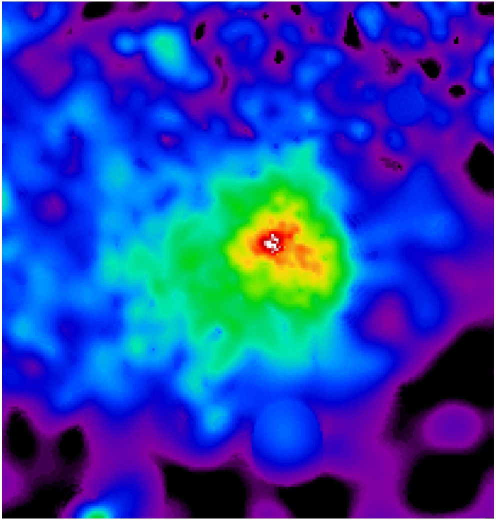


Around the group



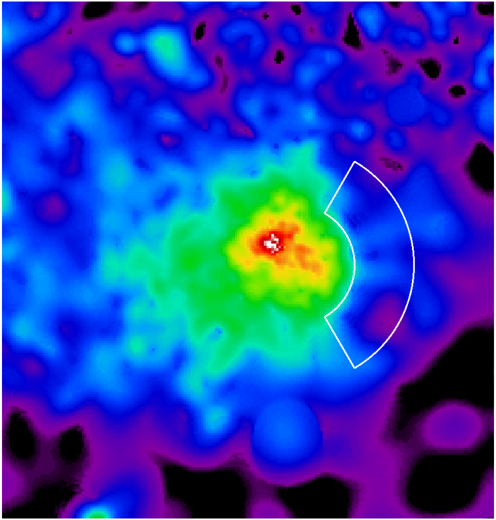
Very extended diffuse emission around the group not associated with the cluster

Cold front



The cold front is not pointing towards the cluster!

Cold front



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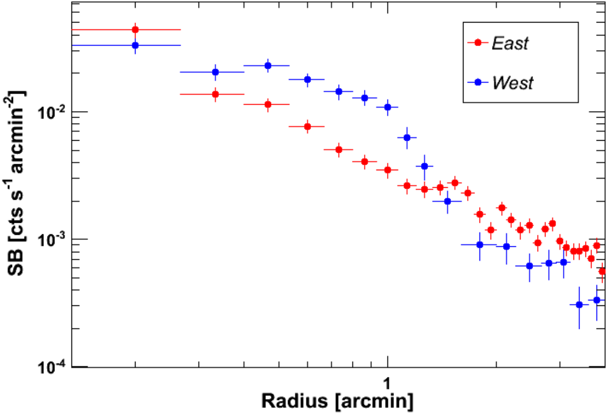
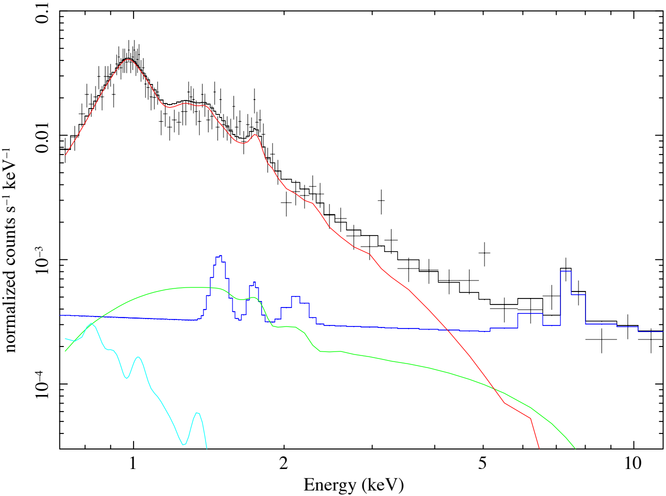
Cold front



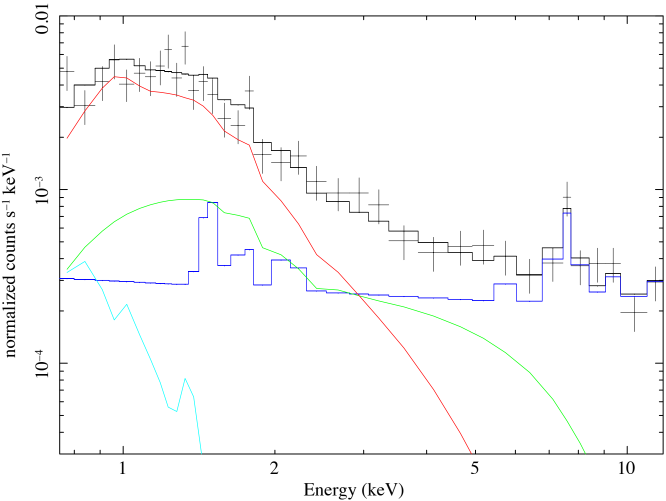
The cold front is not pointing towards the cluster!

Suzaku spectral analysis



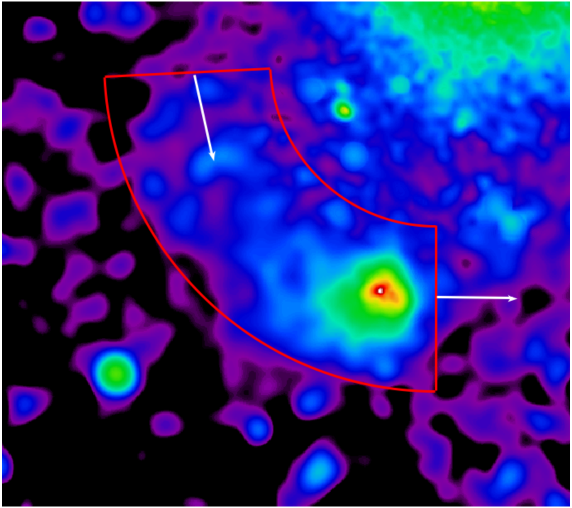
The temperature of the group is 1.26 ± 0.03 keV, ~ 2 times smaller than in the surrounding ICM

Suzaku spectral analysis



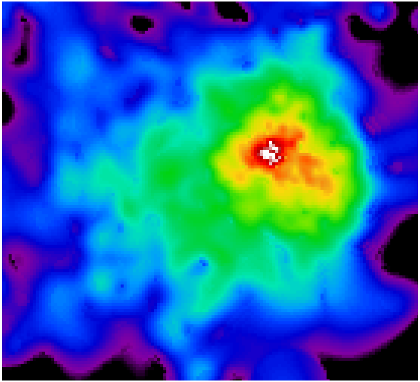
The temperature is constant along the trail out to >500 kpc from the group

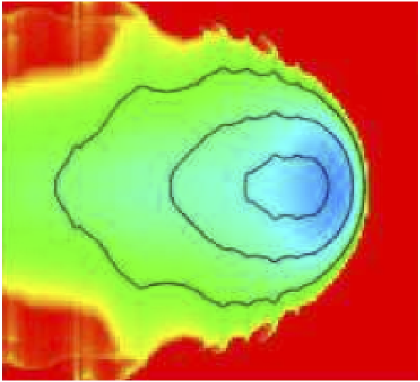
A bent ram-pressure stripped tail



Mpc-scale stripped tail bent because of a large impact parameter

A bent ram-pressure stripped tail





Heinz et al. 2003

XMM AO-13 VLP, total 1.2 Ms: Construct a sample of 13 clusters at $0.04 < z < 0.1$ with high-S/N *Planck* detection and XMM mapping of the entire azimuth

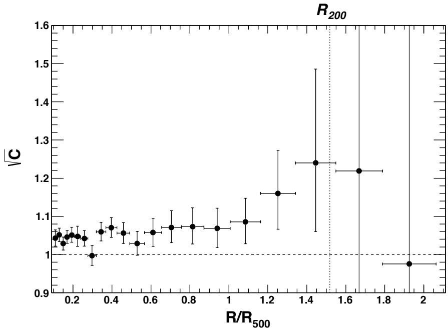
Cluster	Redshift	Mass [10^{14} $M_\odot$]	*Planck* S/N
A2319	0.0557	5.83	30.8
A3266**	0.0589	4.56	27.0
A2142*	0.090	8.15	21.3
A2255	0.0809	3.74	19.4
A2029	0.0766	7.27	19.3
A3158	0.059	3.65	17.2
A85	0.0555	5.32	16.9
A1795	0.0622	5.53	15.0
A644	0.0704	3.88	13.9
RXC J1825	0.065	2.62	13.4
A1644	0.0473	2.93	13.2
ZwCl 1215	0.0766	3.59	12.8
A780*	0.0538	1.89	-

Summary and conclusions

- We developed a new method to study matter accretion in cluster outskirts in a statistical way
- Our observational results indicate that accretion may be less active to the present day than predicted by cosmo simulations
- We found spectacular accreting structures in the outskirts of A2142 and Hydra A associated with infalling galaxy groups
- The X-ray gas trails behind the core of the structures because of ram-pressure stripping over Mpc scales
- Ram-pressure stripping is efficient already at large distance from the cluster core
- The long survival of the gas brings direct evidence that thermal conduction is strongly suppressed in the ICM
- In Hydra A the bent morphology allows us to follow the trajectory of the group
- Upcoming XMM data for 10 more clusters: stay tuned!

Results

- We applied this method to a sample of 31 clusters observed with ROSAT/PSPC (Eckert et al. 2012)
- The recovered clumping factors are mild at all radii



Eckert et al. subm

Results

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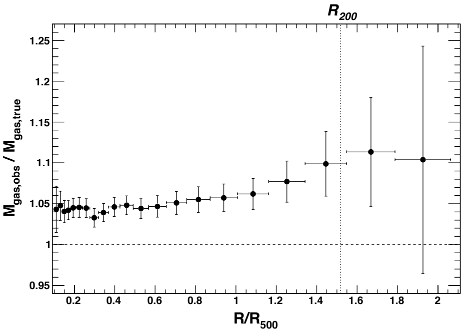
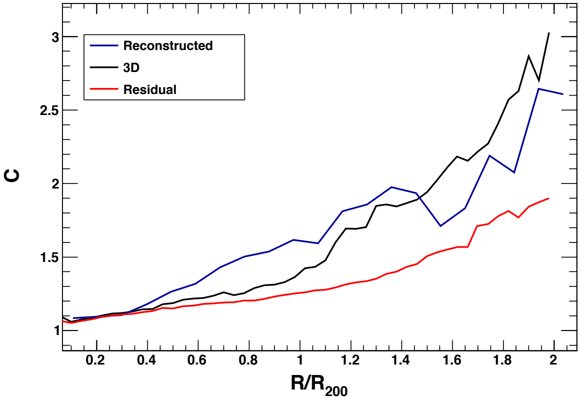
- The recovered clumping factors are mild at all radii
- The bias in gas mass is of the order of 5-10%



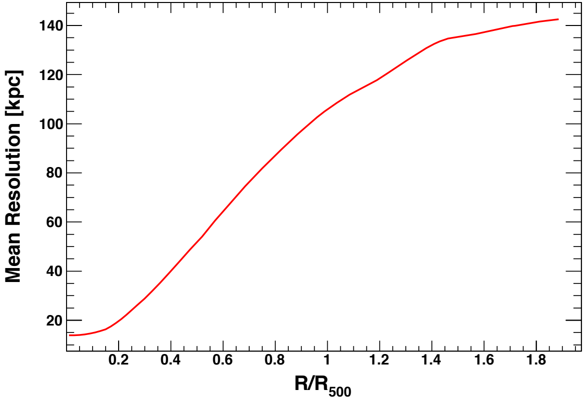
Eckert et al. subm

Reconstructed vs 3D clumping factor



Our method is able to reproduce the 3D clumping factor as measured in numerical simulations

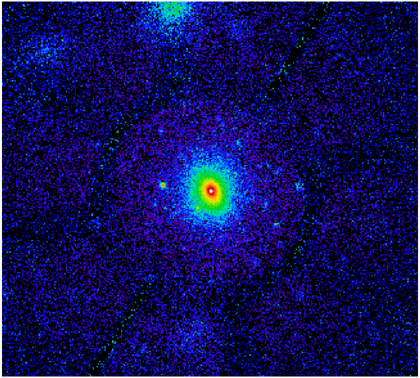
Resolution in the sample



The mean resolution of our maps is ~ 100 kpc at R_{500}

Application to X-ray observations

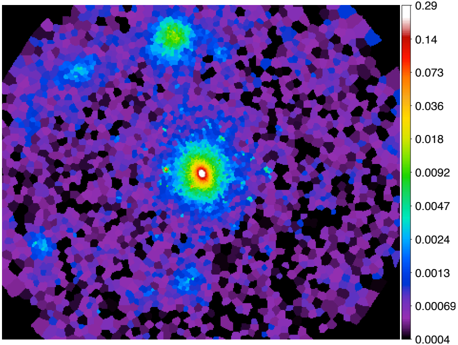
- In practice: measuring the median is difficult because of Poisson noise



Eckert et al. subm

Application to X-ray observations

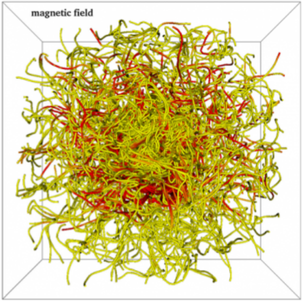
- In practice: measuring the median is difficult because of Poisson noise
- We use an algorithm based on Voronoi tessellation to create a binned S_X map
- The median is then computed from the binned image



Eckert et al. subm

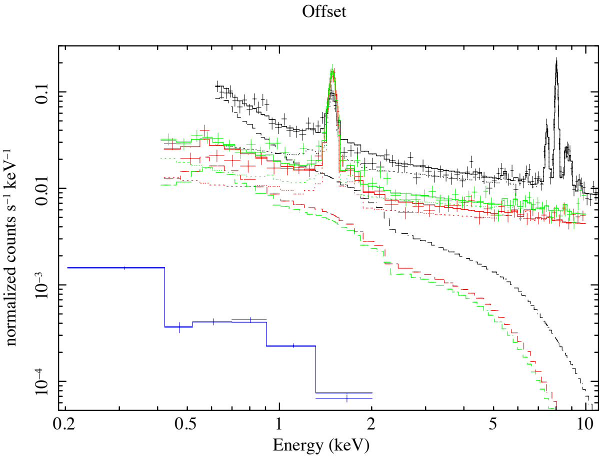
Magnetic field configuration

- In the ICM the gyro-radius is $\sim 2 \times 10^8$ cm (for $B \sim 1\mu$G)
- This is 12 orders of magnitude smaller than the electron mean free path ($\lambda \sim 1$ kpc)!
- Conduction is possible only along the field lines
- In a chaotic magnetic field configuration:
  Conduction is inhibited by $\sim \ell_B/\lambda$, where ℓ_B is the B-field coherence length (Chandran & Cowley 1998)



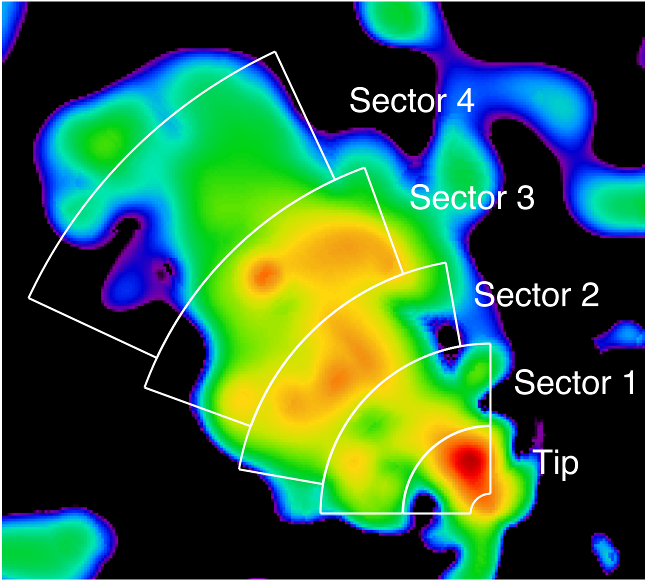
Gaspari & Churazov 2013

Background modeling



Local background measurement + NXB modeling through closed-filter data

Regions for spectral analysis A2142



The temperature is flat at $1.3 - 1.5$ keV over > 600 kpc

Regions for spectral analysis Hydra A