# Gas Accretion and Non-Equilibrium Phenomena in the Outskirts of Galaxy Clusters


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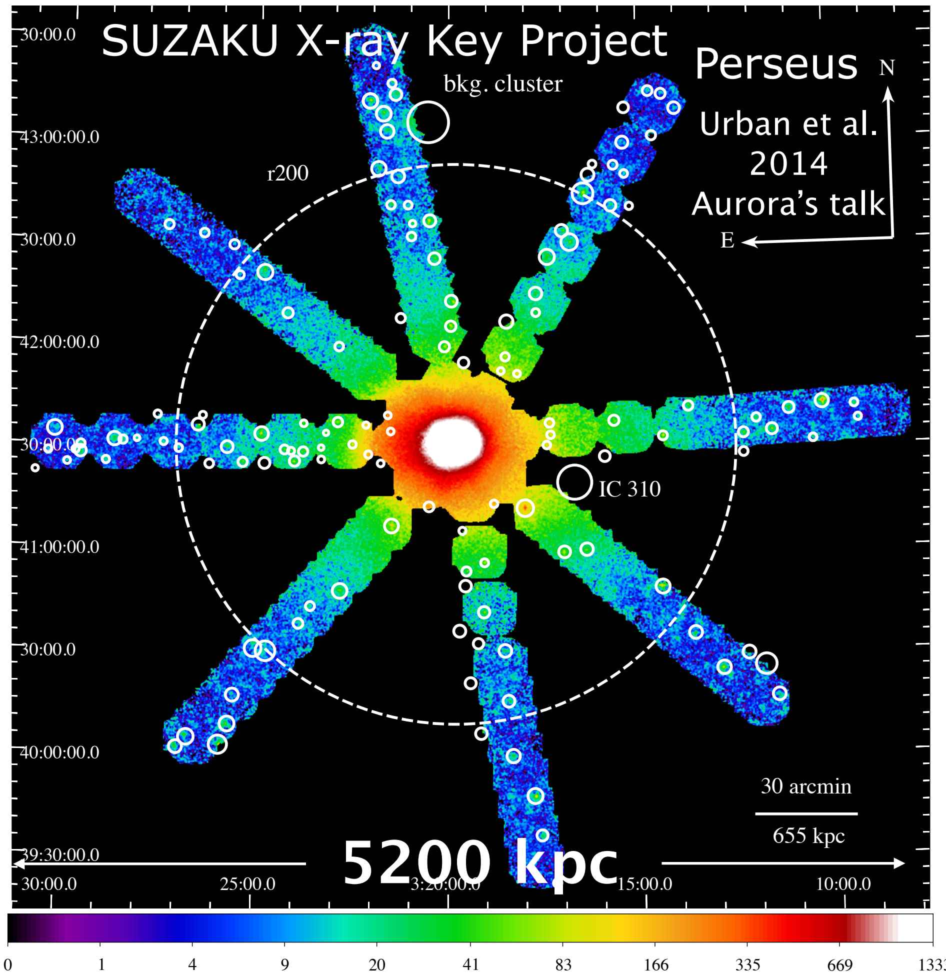
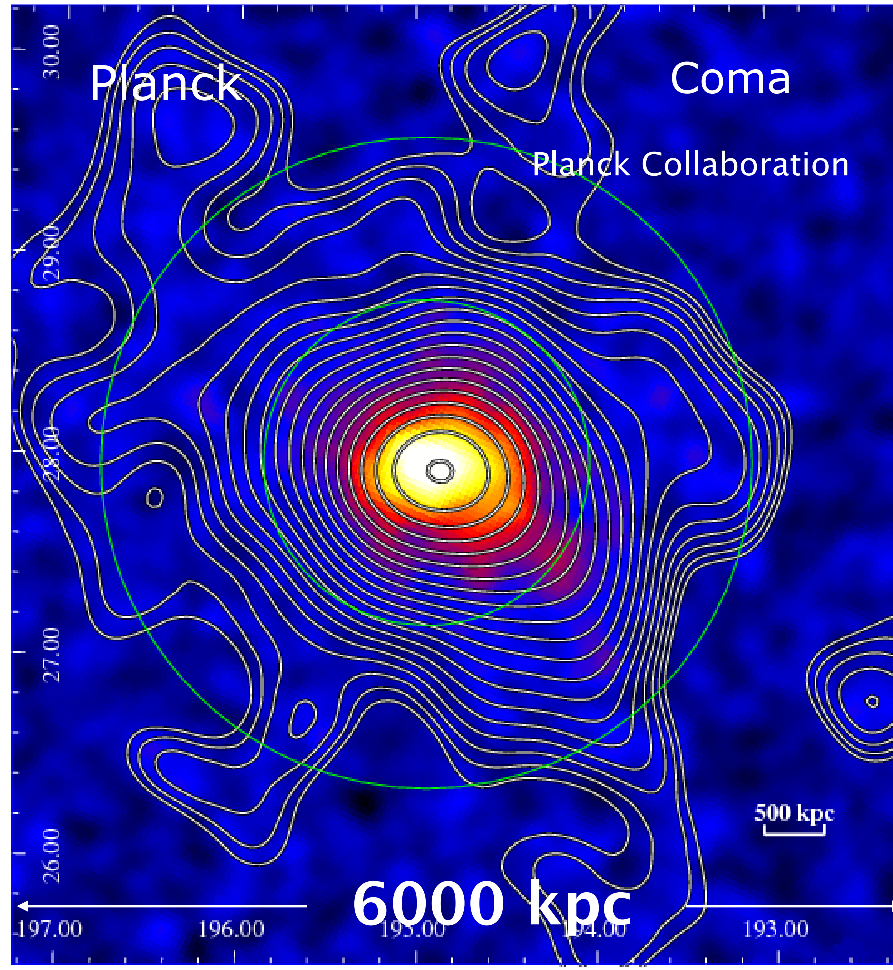
**Yale University**


*ICM theory & computation workshop*

*Copenhagen, August 14 2014*

# X-ray+SZ measurements of cluster outskirts

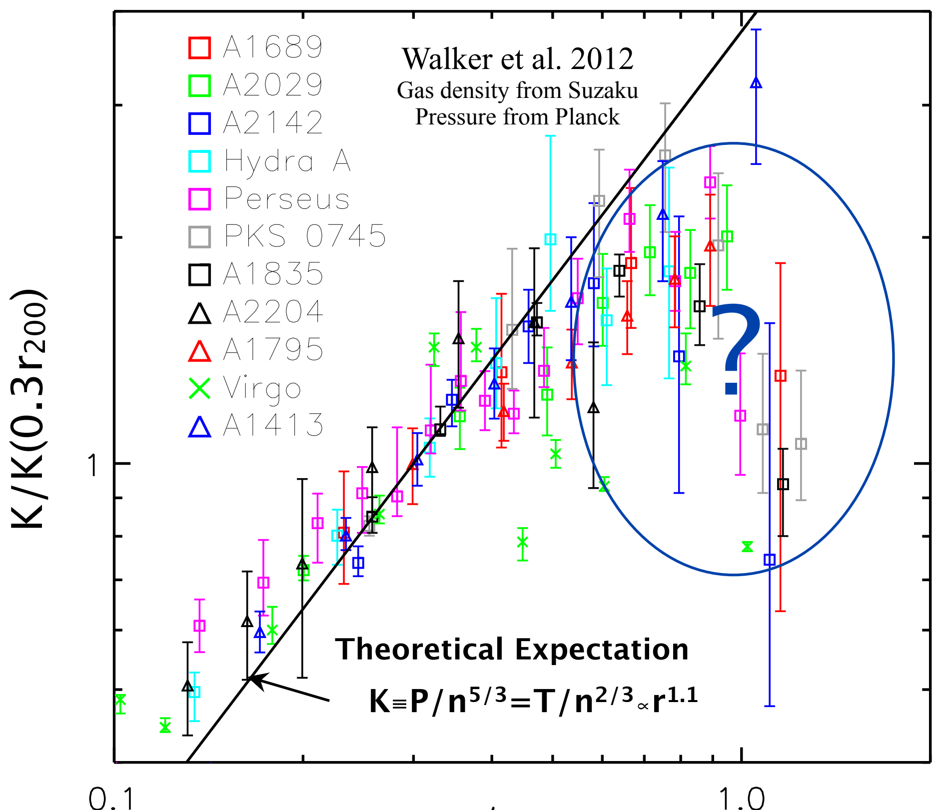



*Recent X-ray and microwave observations have detected the hot gas in the outskirts of galaxy clusters*

# *Suzaku+Planck measurements of cluster outskirts*

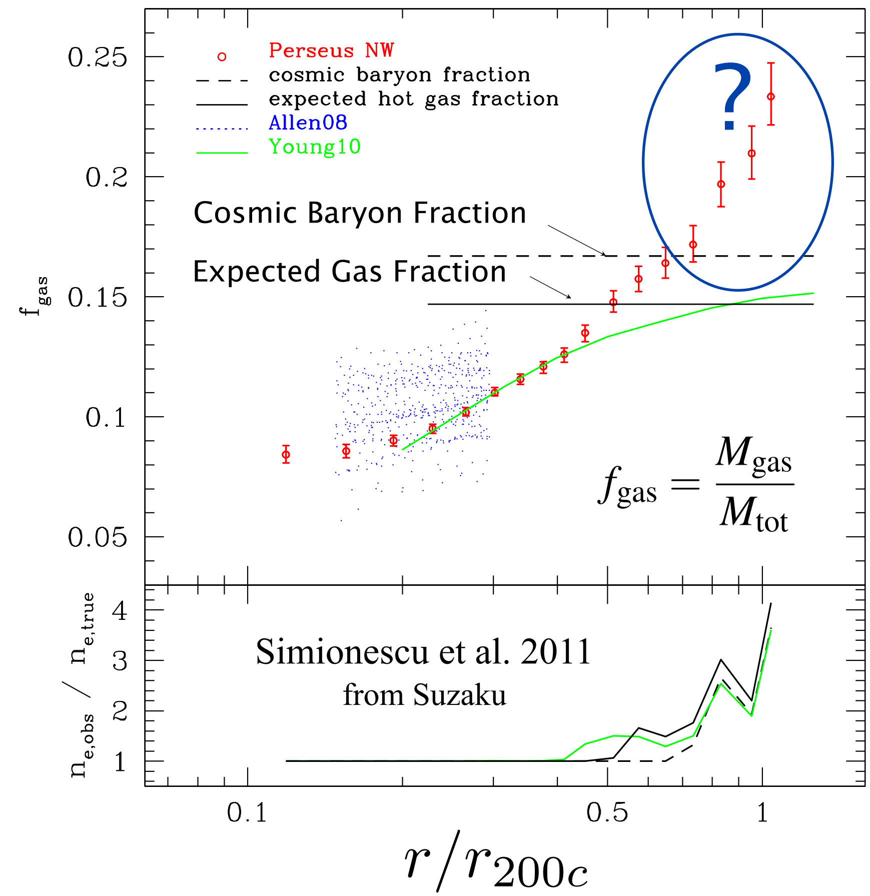
Entropy profiles of 11 nearby relaxed clusters




$s = \log K$
specific entropy

$P = K\rho^{5/3}$
for monoatomic gas

Gas fraction profile in Perseus cluster

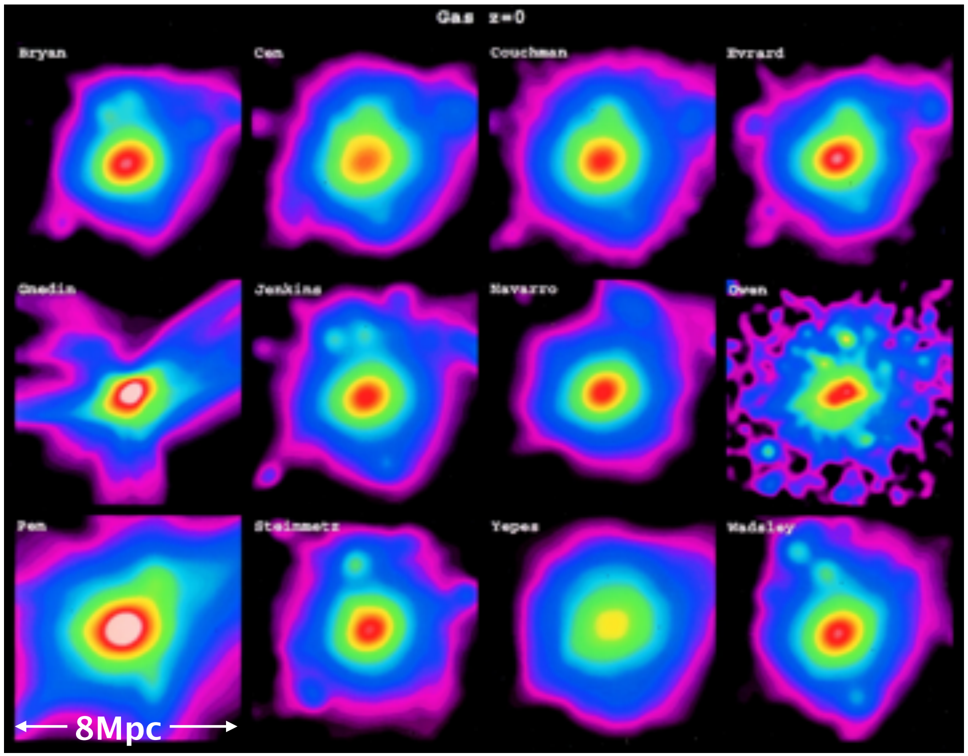


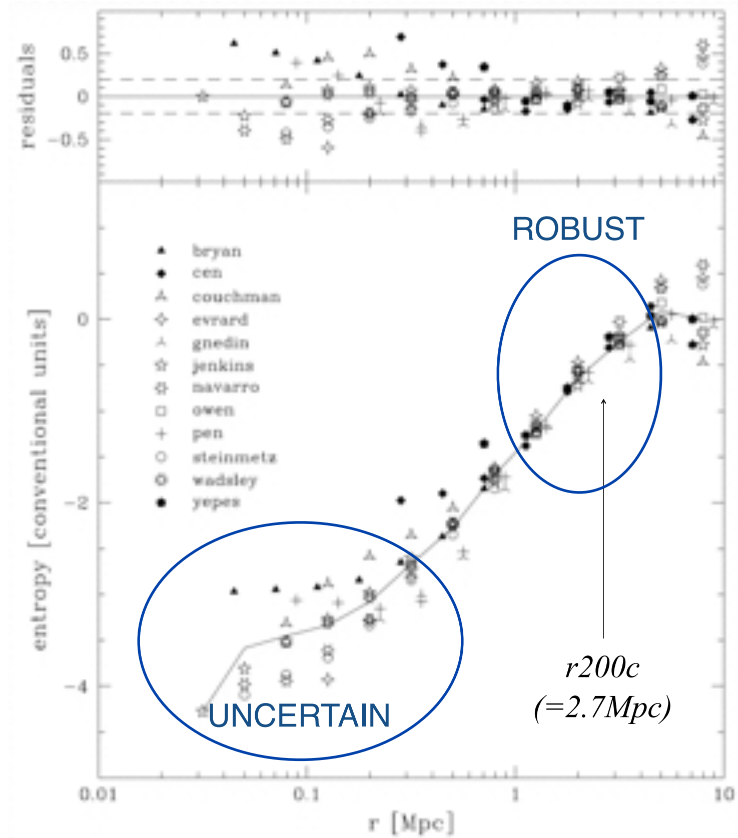

***PUZZLES:*** Observed entropy and gas fraction profiles are strongly inconsistent with theoretical expectations

# Theoretical Prediction of the ICM Entropy Profile

Santa Barbara Cluster Comparison Project (Frenk et al. 1999)

Non-radiative simulations with $M_{200c}=10^{15}$Msun and Tx=5keV



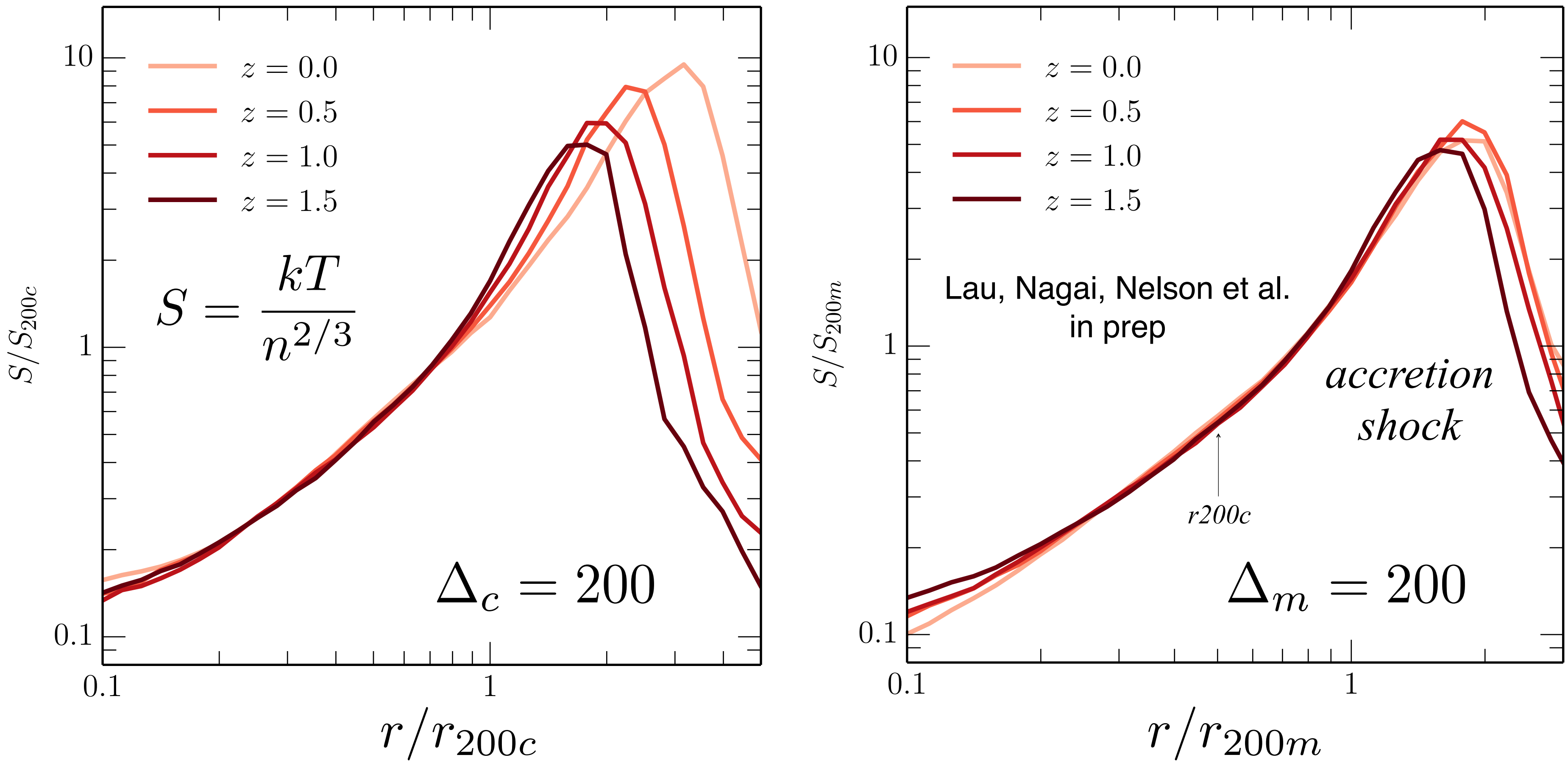




ROBUST PREDICTION: Gas entropy profile increases monotonically at large radii.

*also Voit et al. 2003; Mark Voit's talk*

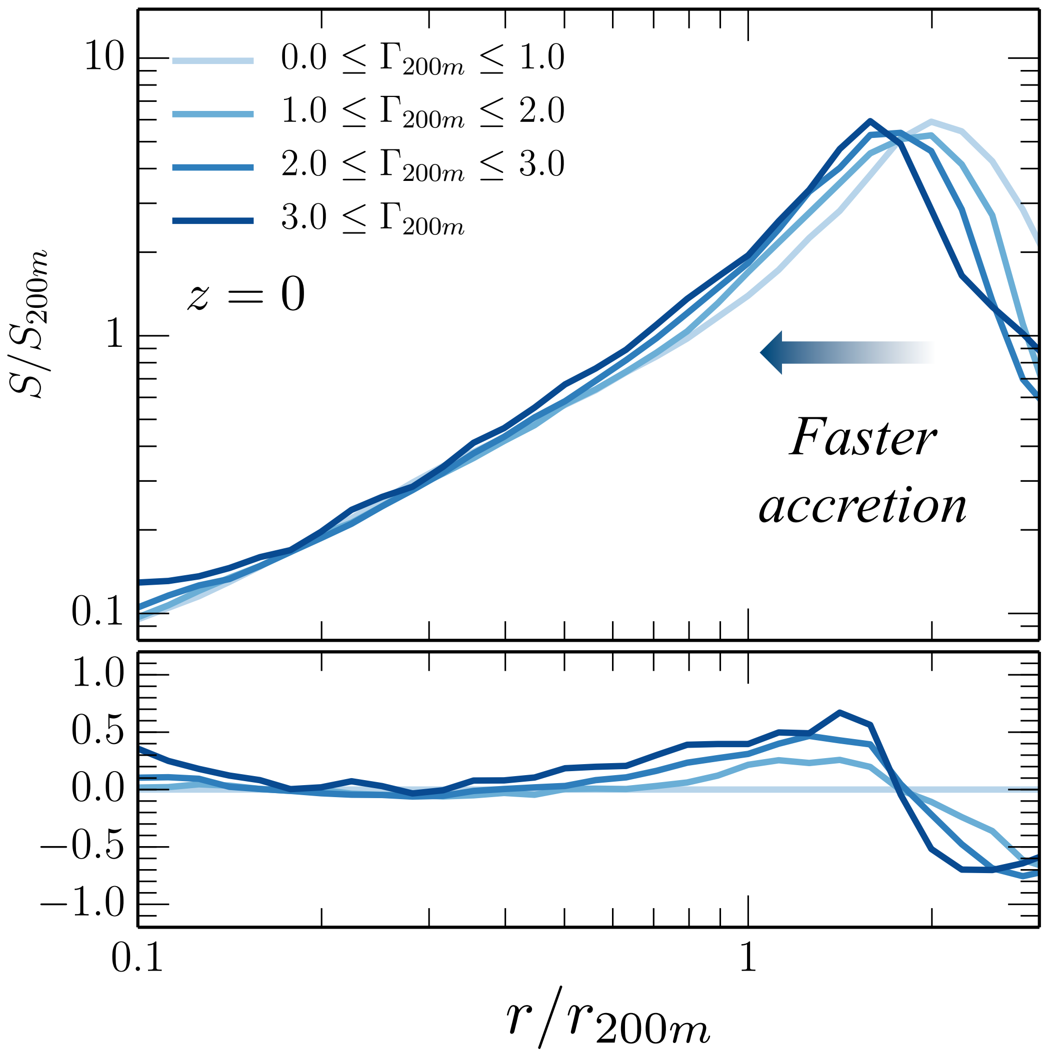
# “Universal” Entropy Profile?

**Omega500 Cluster Simulation Project (Nelson et al. 2014)**
Mean Entropy Profiles of 65 simulated clusters at z=0 and their progenitors




- Gas entropy profile is more *universal* when halos are defined with respect to the *mean* density than the *critical* density.
- Alignment of accretion shocks at r=1.4$R_{200m}$

# Mass Accretion breaks Universality



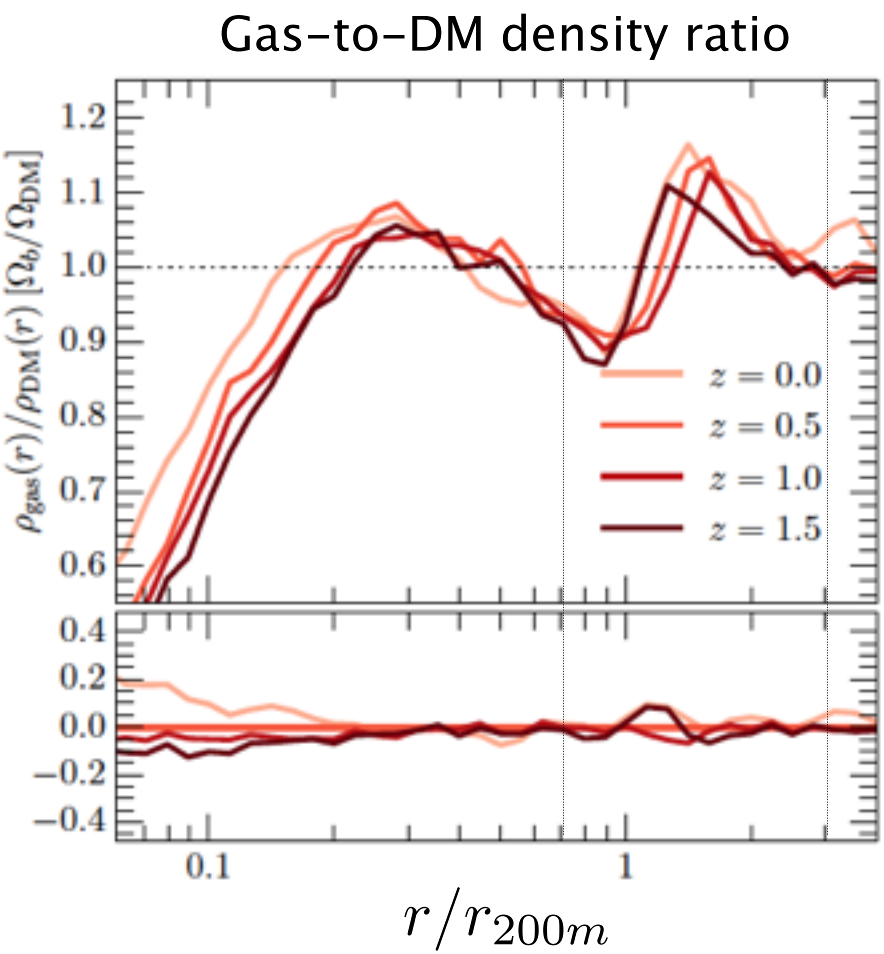

**Mass Accretion Rate**

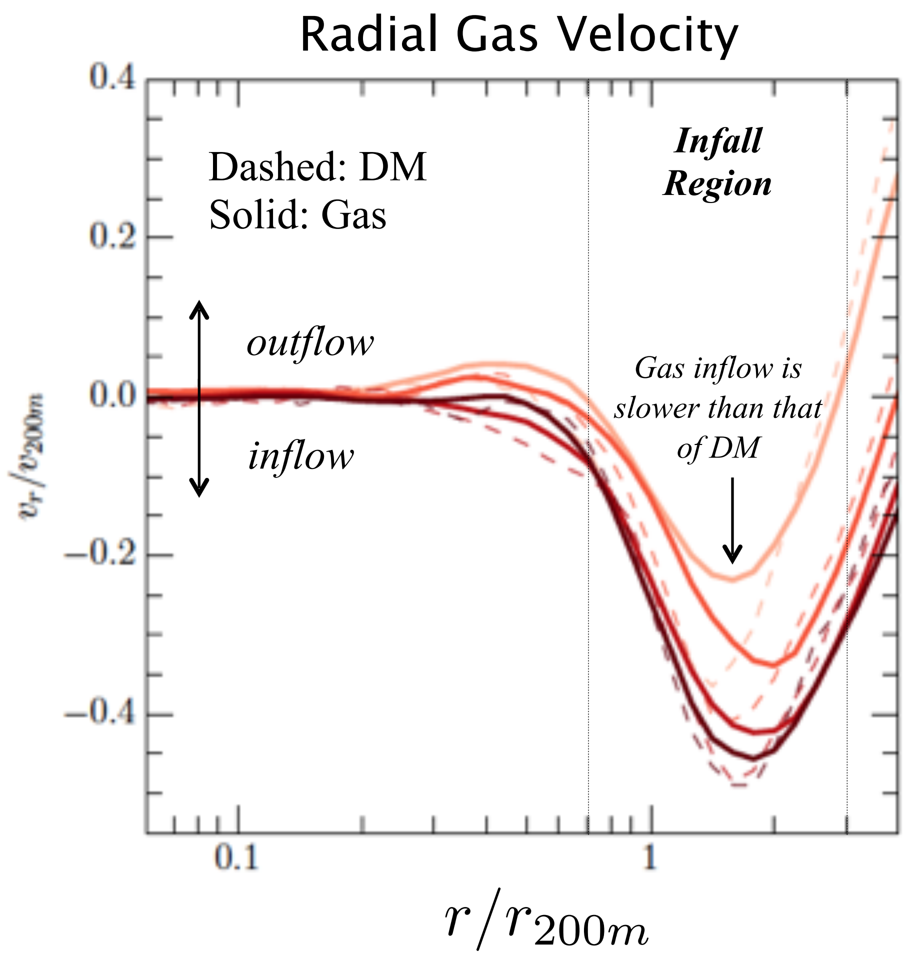
$$\Gamma_{200m} \equiv \frac{\Delta \log_{10} M_{200m}}{\Delta \log_{10} a}$$

between z=0 and 0.5
(Diemer & Kravtsov 2014)

- Accretion rate changes location of accretion shock
- Accretion shock penetrates deeper for faster accreting clusters because of their higher momentum flux

# How well does gas trace DM?

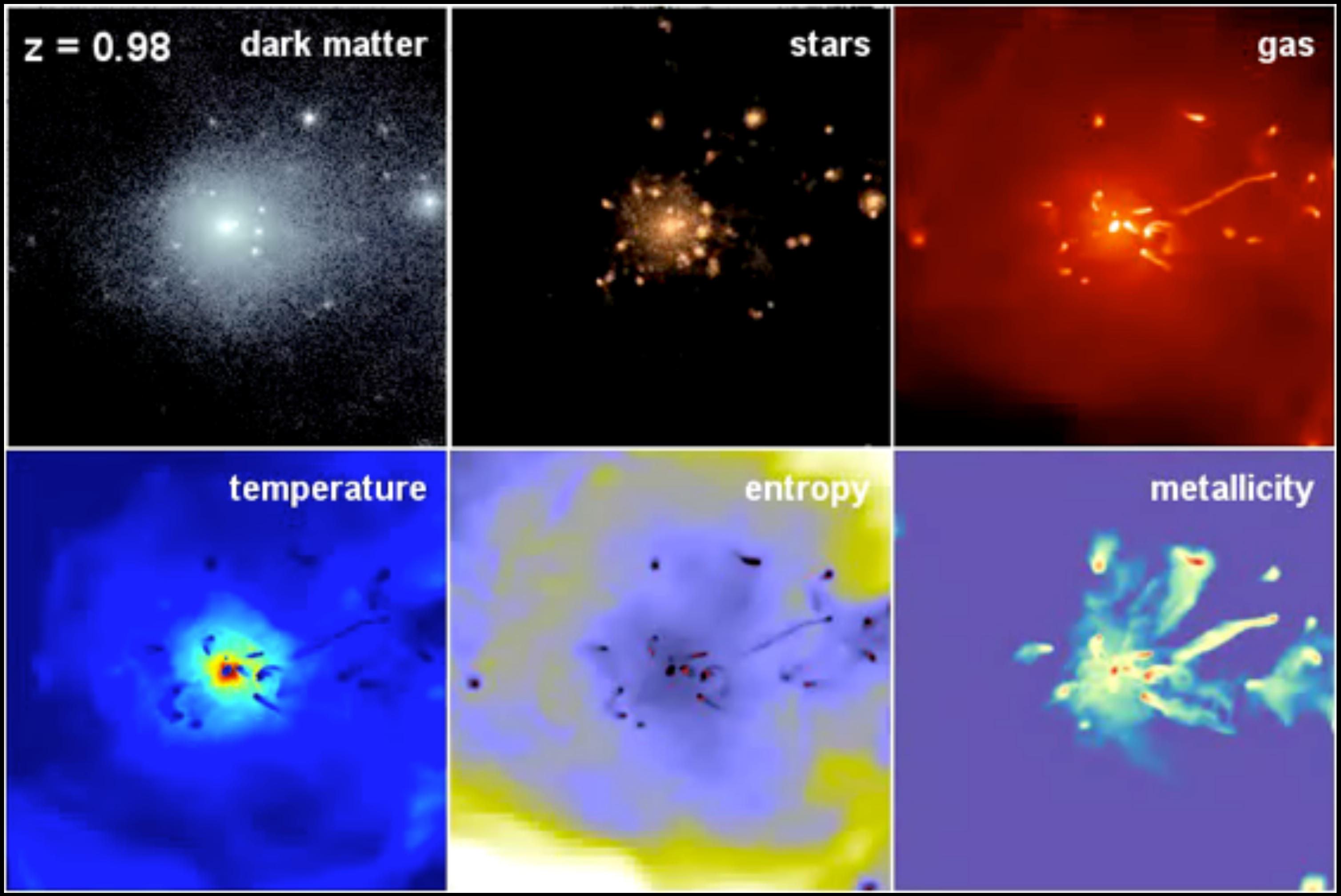



- Gas density does NOT trace DM density perfectly
- Gas lags behind DM near the location of accretion shocks

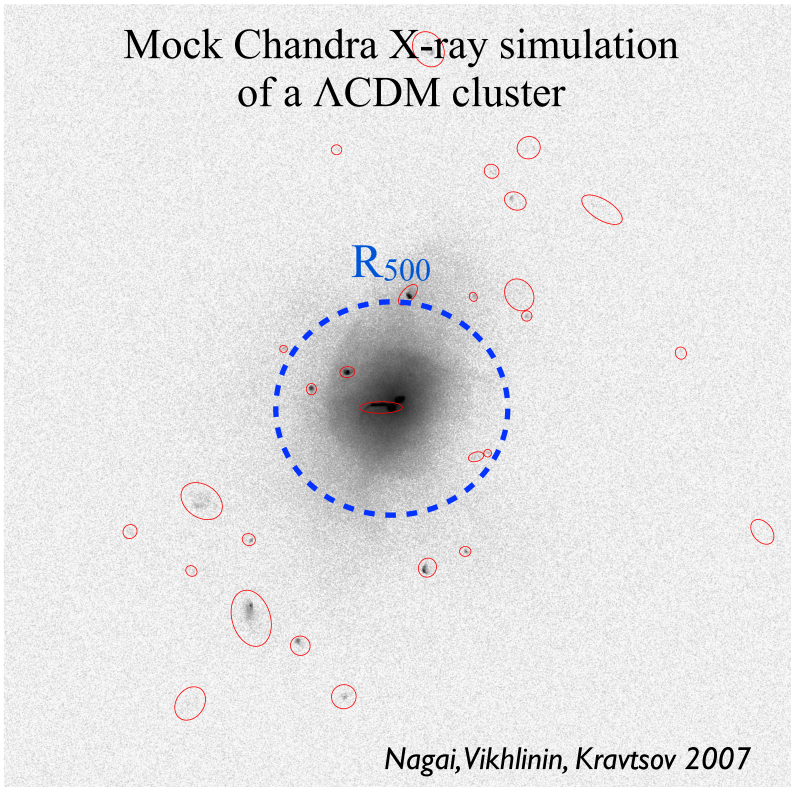
# *Cosmological Simulations of Galaxy Cluster Formation*

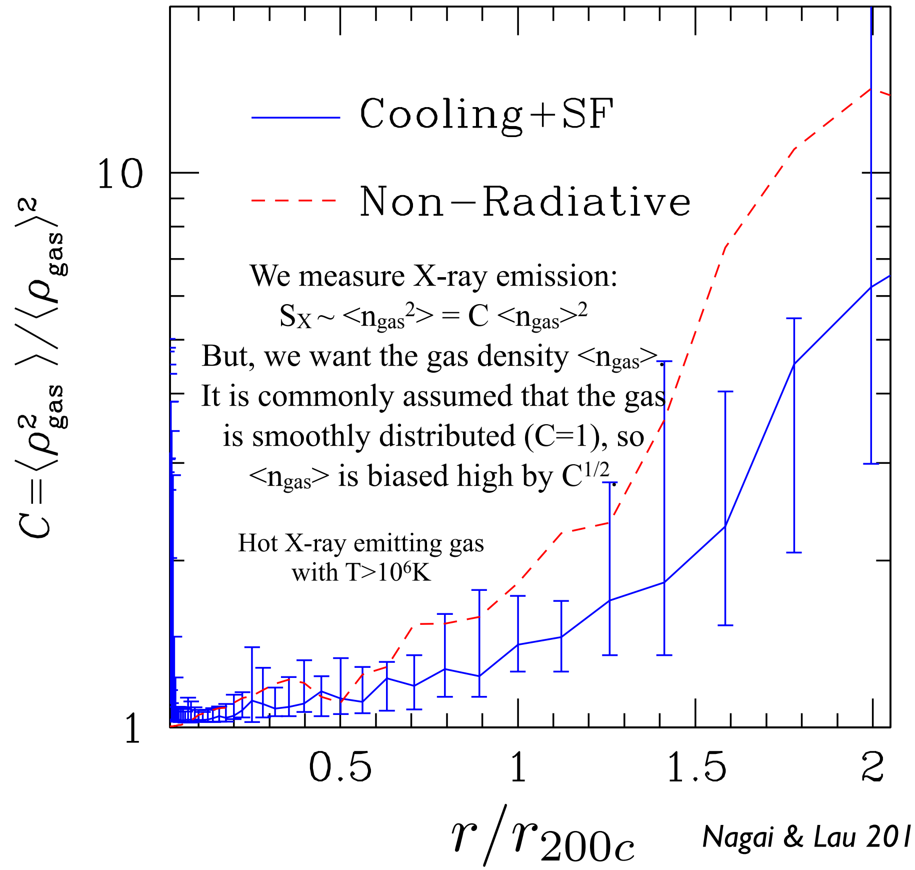
**N-body+Gasdynamics with Adaptive Refinement Tree (ART) code**
**Box size ~ 80/h Mpc; Region shown ~ 2/h Mpc; Spatial resolution ~ a few kpc**




**Modern cosmological hydro simulations include the effects of baryons (i.e., gas cooling, star formation, heating by SNe/AGN, metal enrichment and transport). But, also remember limitations - e.g., a single fluid approximation!**

# *Cluster outskirts are very "clumpy"*




Hydrodynamical simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}=0.7r_{200}$) arise from infalling groups from filaments

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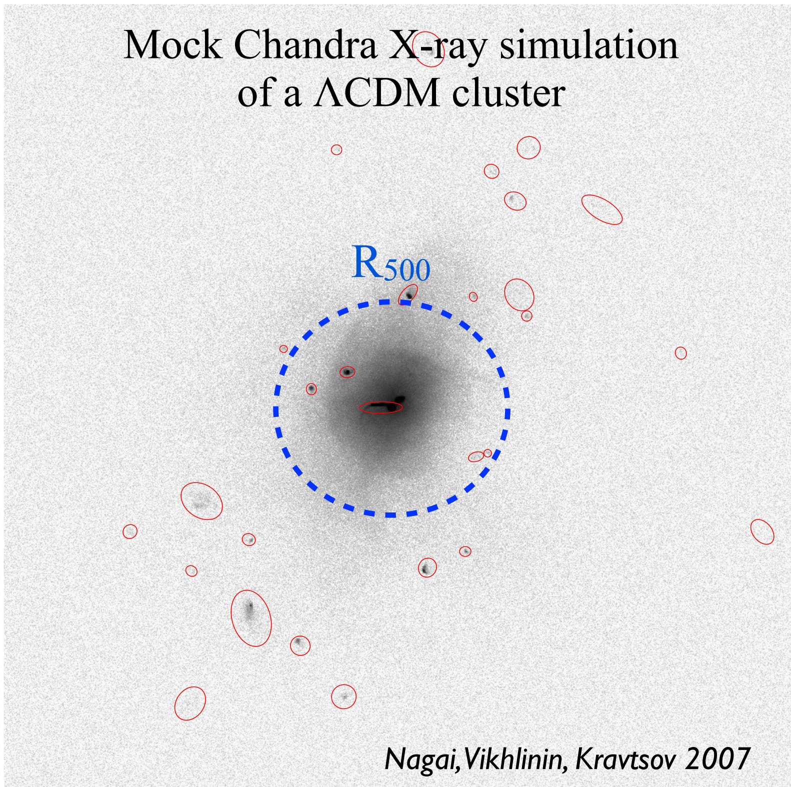


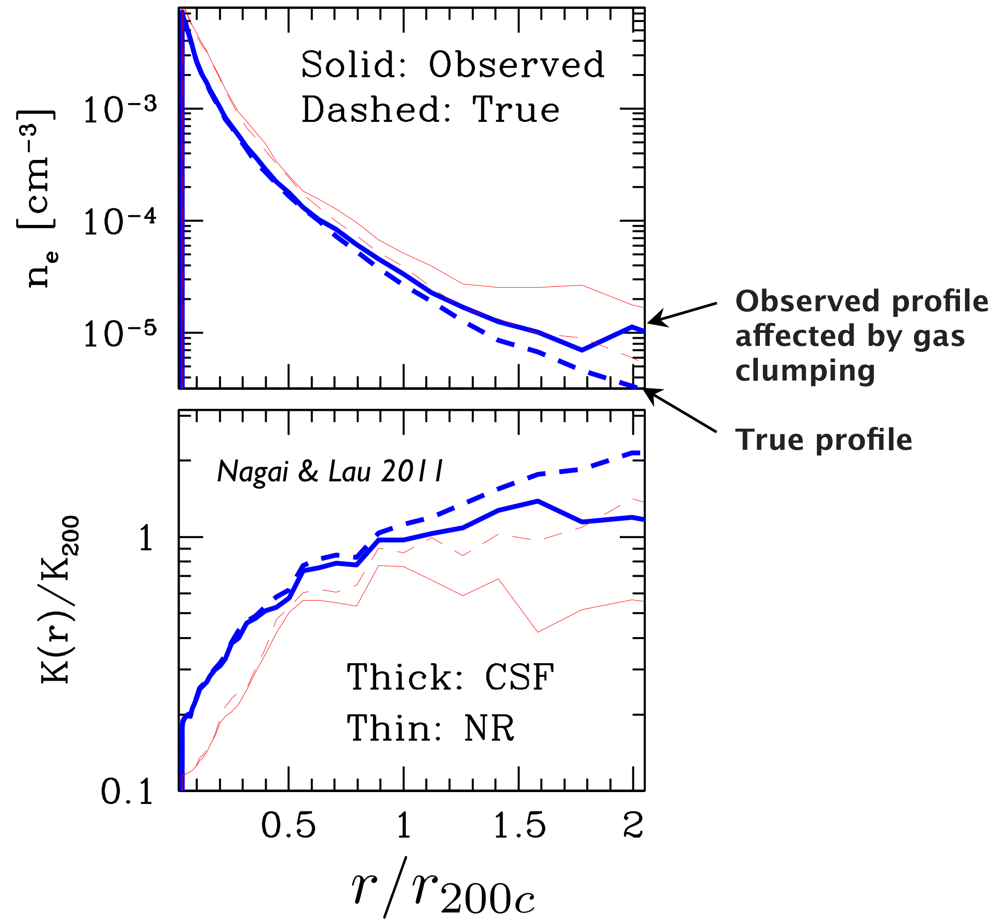


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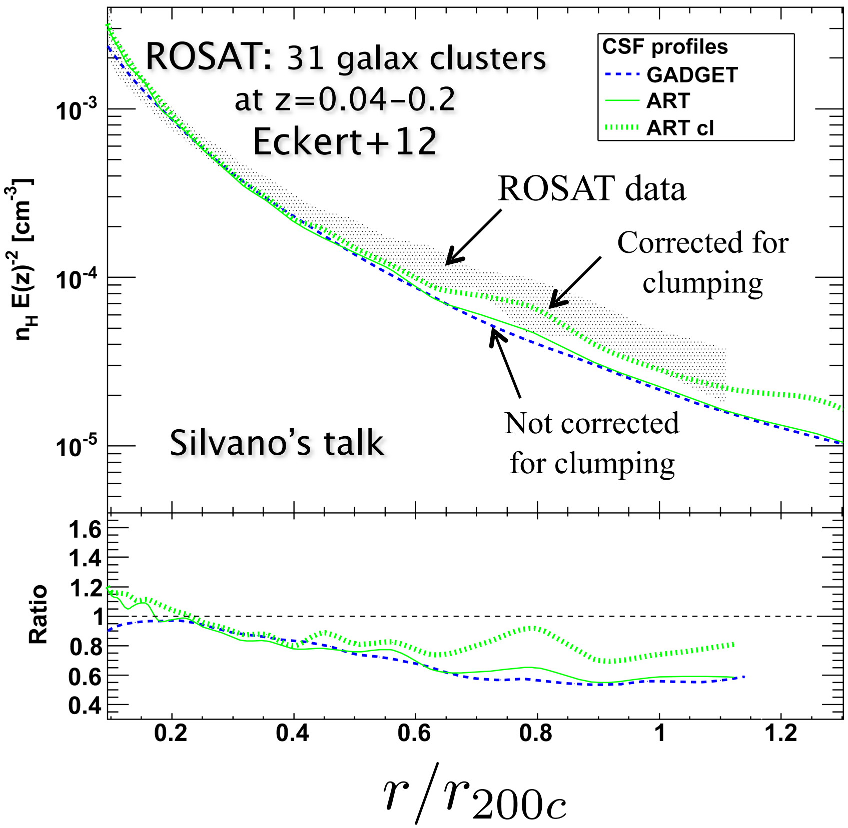
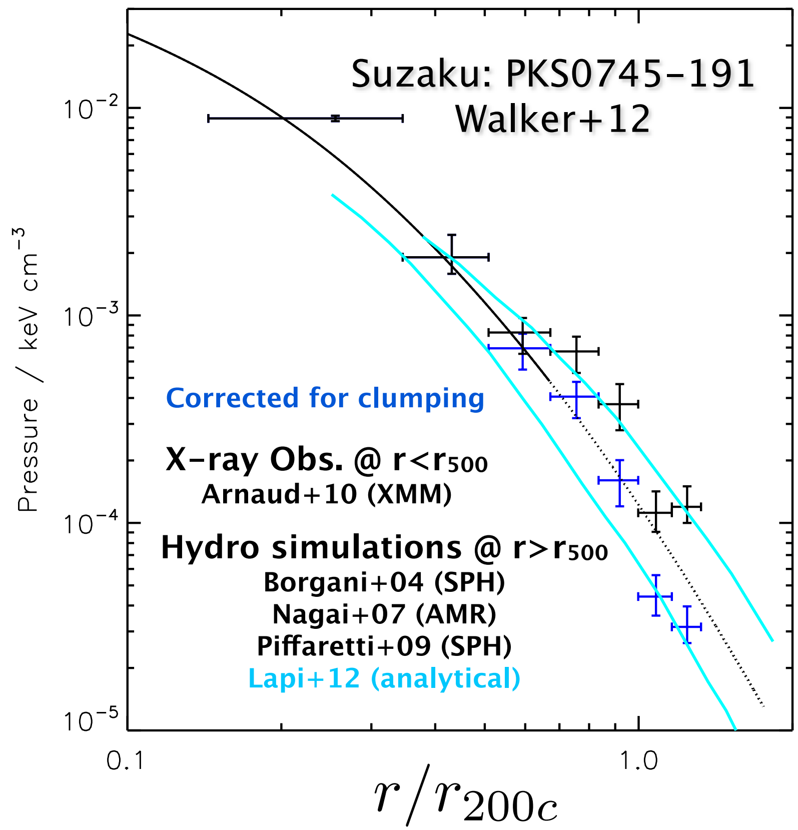
# SZ+X-ray Observations of Pressure Profiles in Cluster Outskirts

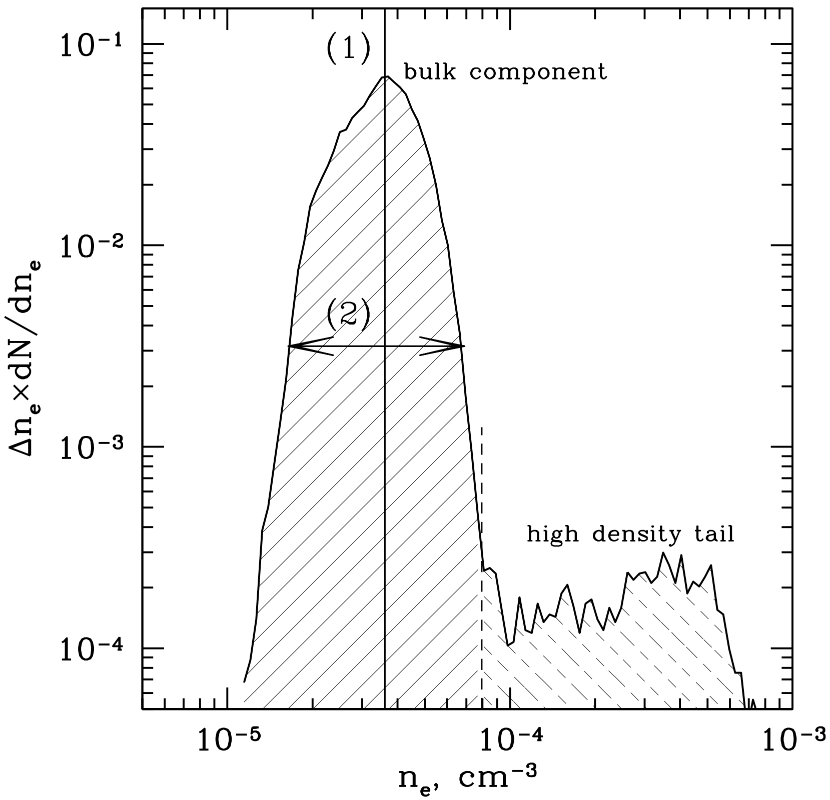


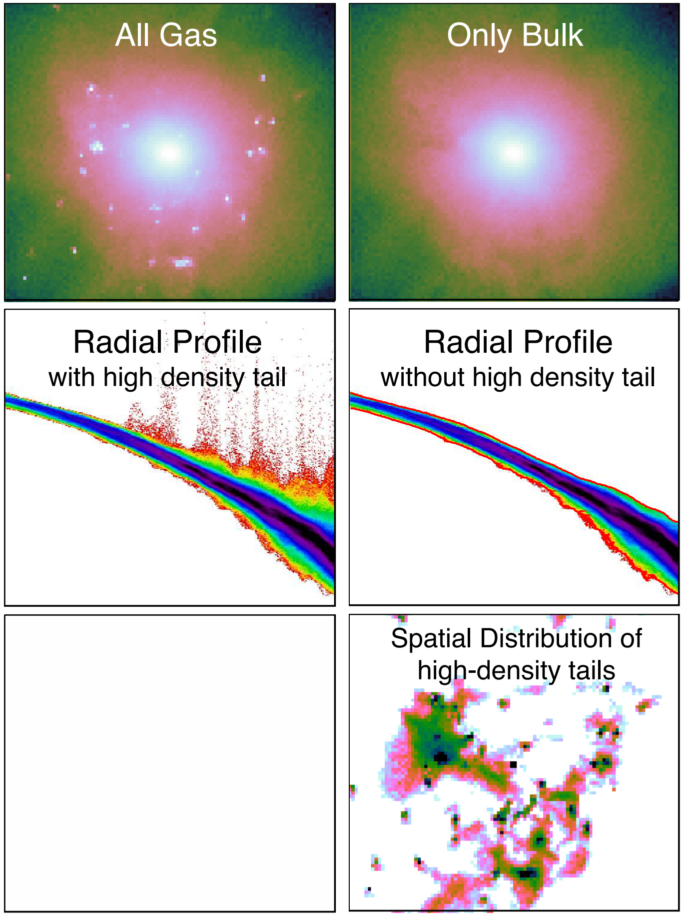




SZ and X-ray observations provide complementary views of cluster outskirts;
i.e., SZ signal is less sensitive to gas clumping, but affected by non-thermal pressure, while both SZ and X-ray signals are susceptible to non-thermal pressure or non-equilibrium electrons.

*also Eckert et al. 2013a,b; Khedekhar+13*

# Gas "Clumpiness" vs. "Inhomogeneities"

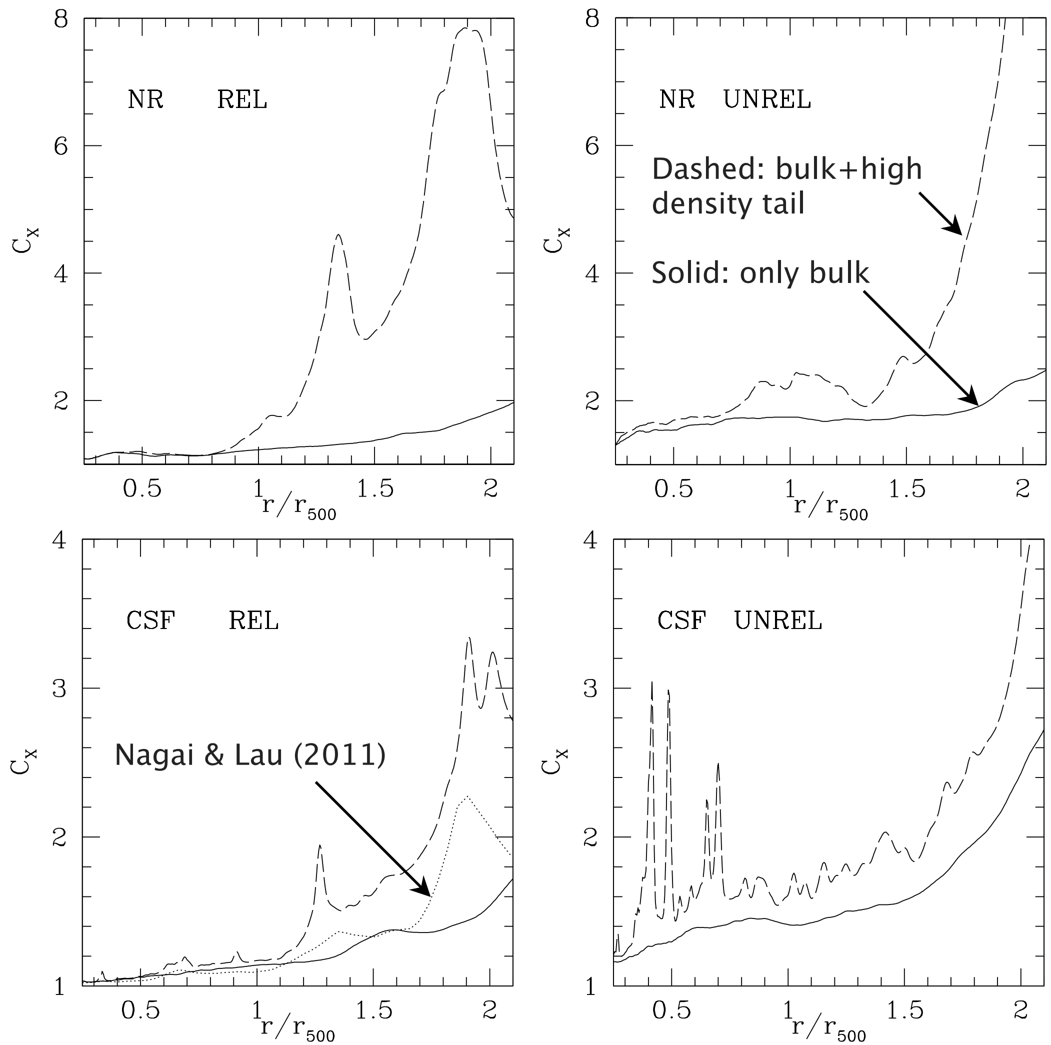



Gas "inhomogeneities" consist of (1) bulk component + (2) high density tail.
Power spectrum analysis is a method of choice for the bulk component!

*Zhuravleva et al. 2013; see also Roncarelli+13, Vazza+13*

# Gas Clumping Factors




Gas clumping factors @ $R_{200c}$=1.5$R_{500c}$

(1) All gas (bulk+high density tail)

$C_X$ = 3-4 (NR Relaxed)
$C_X$ = 2.5 (NR Unrelaxed)
$C_X$ = 1.6 (CSF Relaxed)
$C_X$ = 2.0 (CSF Unrelaxed)

(2) Only bulk component

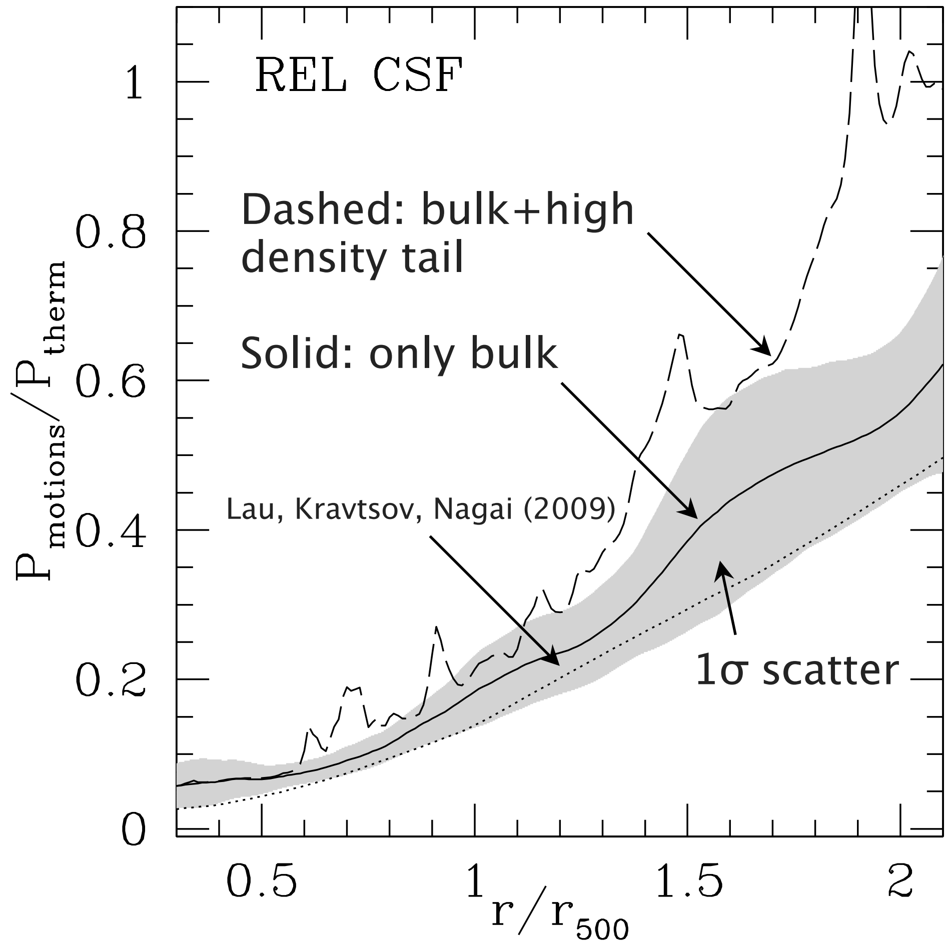
$C_X$ = 1.5 (NR Relaxed)
$C_X$ = 1.8 (NR Unrelaxed)
$C_X$ = 1.4 (CSF Relaxed)
$C_X$ = 1.3 (CSF Unrelaxed)

Gas clumping factors depend on

(1) input gas physics (CSF<NR)
(2) details of clump excision
(3) dynamical state (but only weakly)

*Zhuravleva et al. 2013*

# Impact of ICM inhomogeneities on Non-thermal Pressure Support

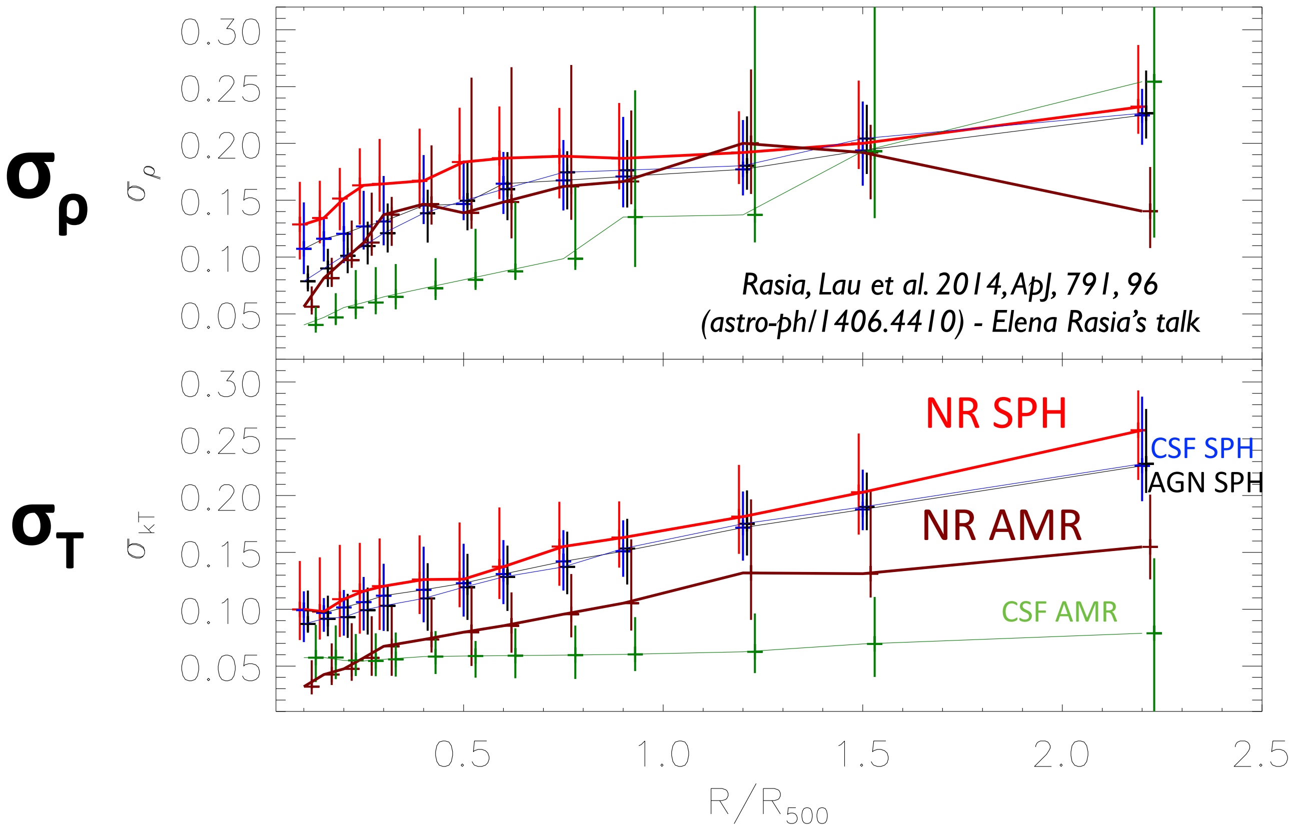



Fast moving, high-density clumps occupy small mass and volume fraction in clusters, but contribute significantly to the non-thermal pressure support in cluster outskirts.

*Zhuravleva et al. 2013; also Kaylea Nelson's talk yesterday*

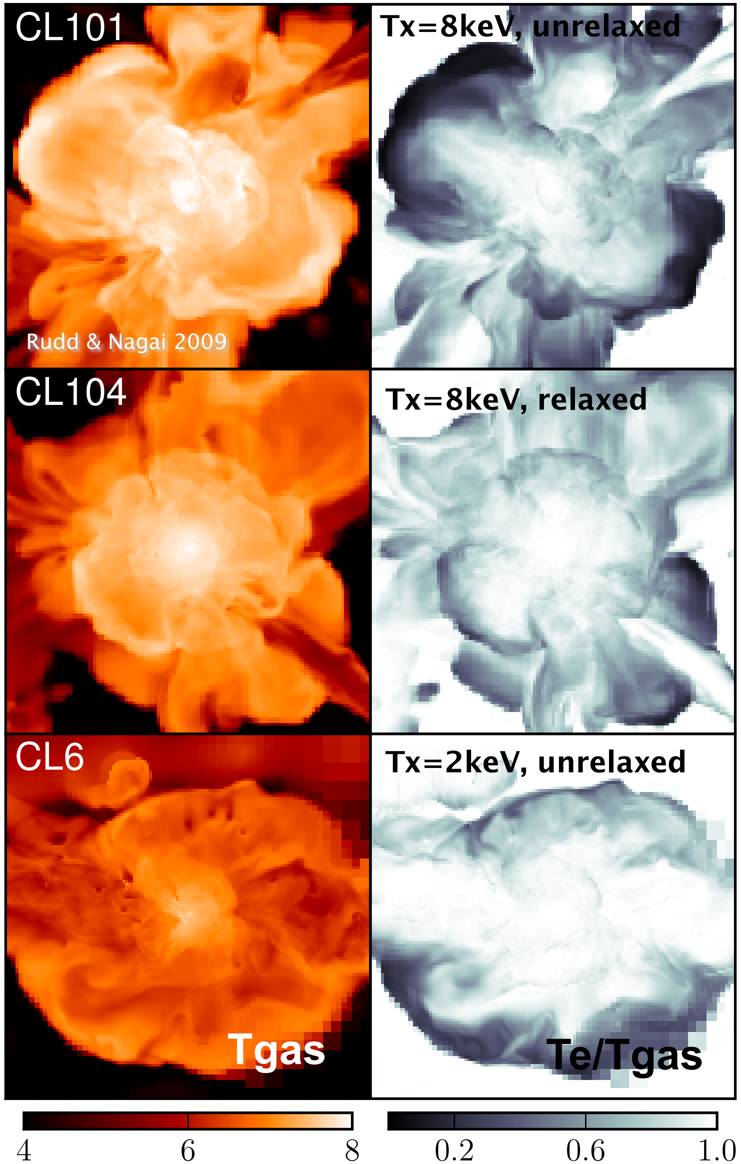
# Temperature "Inhomogeneities"
## SPH vs. AMR simulations

Dispersions in logarithmic gas density and temperature
after excluding high-density gas inhomogeneities

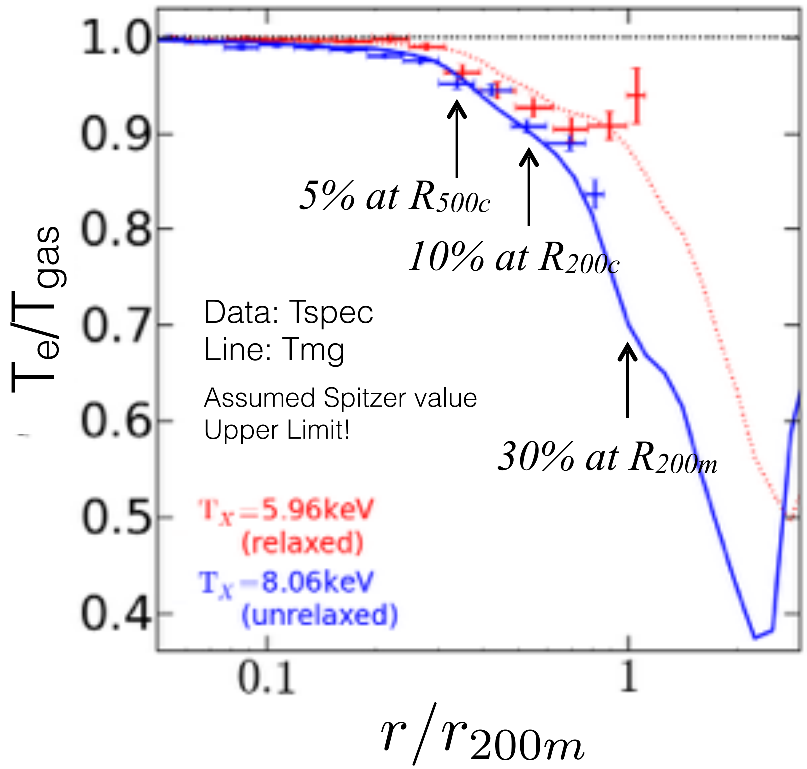



AMR have similar dispersion in gas density but significantly lower temperature than SPH runs.
This is the origin of the differences in the predicted HSE mass bias:
30% (SPH: Rasia+12) & 10-15% (AMR: Nagai+07)

# Electron-Proton Equilibration in Cluster Outskirts



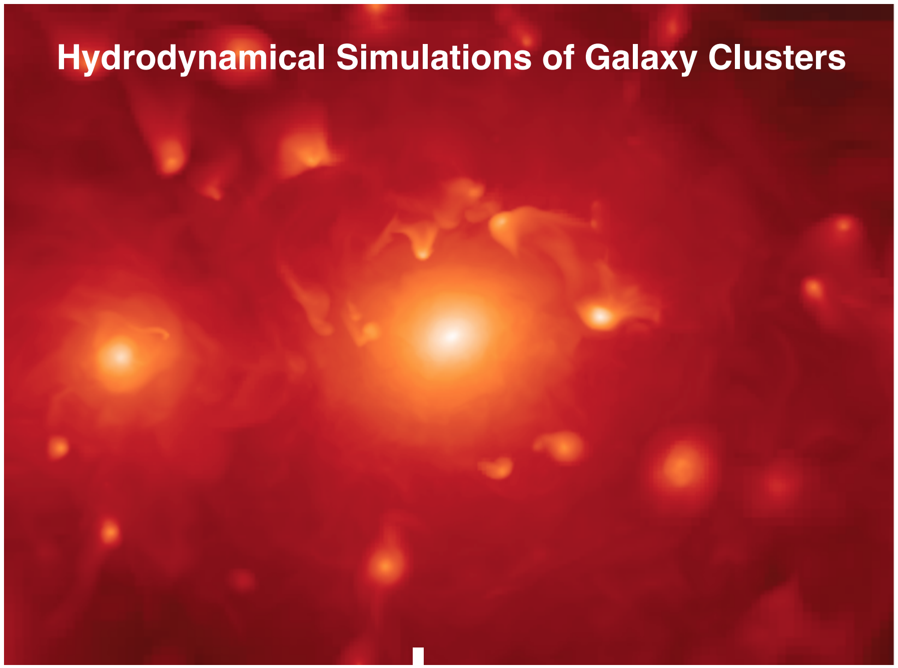

**In the outskirts of galaxy clusters, the collision rate of electrons and protons becomes longer than the age of the universe.**

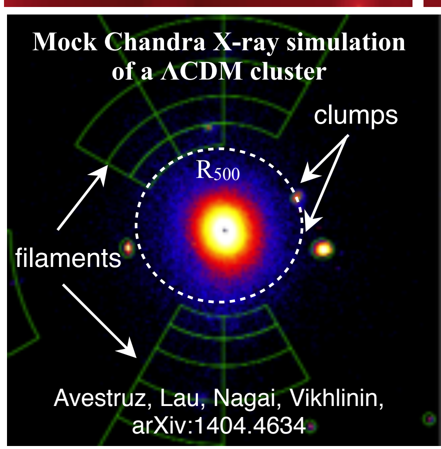


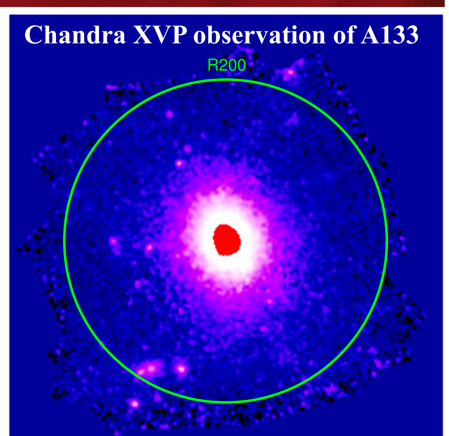

Avestruz, Nagai, Lau, Nelson, in prep

Spitzer 1962, Takizawa 1999, Chuzhoy & Loeb 2004, Rudd & Nagai 2009, Akahori & Yoshikawa 2010

# *PREDICTIONS: Hydrodynamical Simulations of Galaxy Cluster Outskirts*




(1) ICM inhomogeneities in *both* gas density and temperature

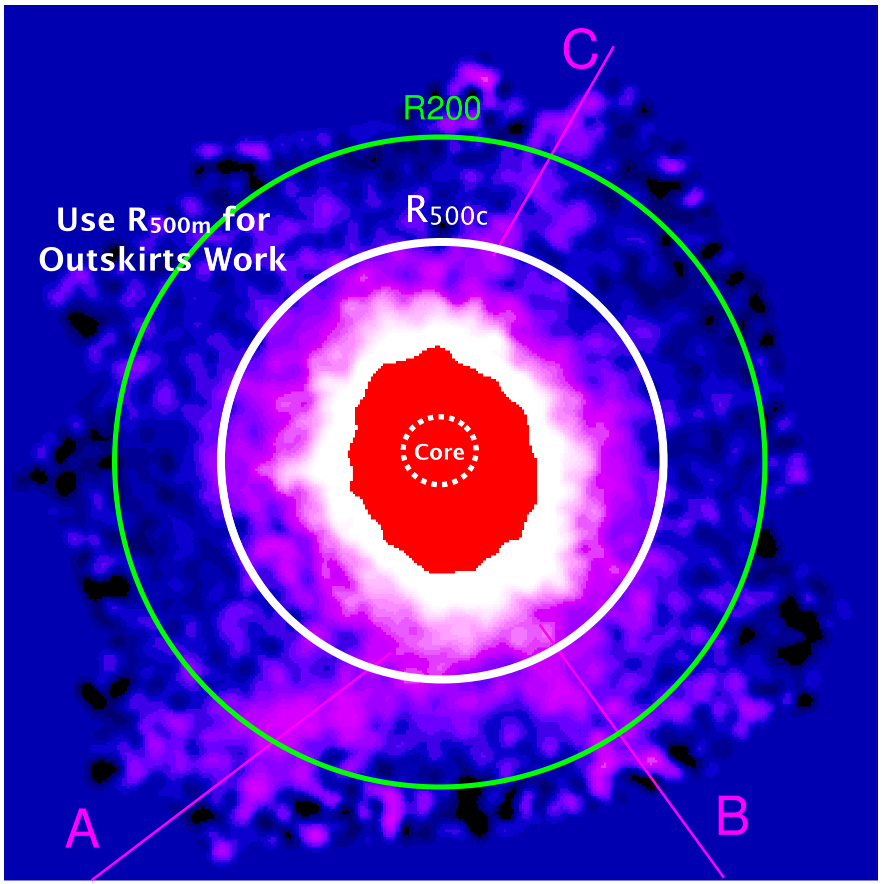
- ❖ the former important at $r > r_{500c}$
- ❖ the latter important even in $r < r_{2500c}$

(2) Gas motions - become increasingly important at large radii ($r >> r_{2500c}$)

(3) Non-equilibrium electron - could be important at $r > r_{200c}$ of high-Tx, unrelaxed clusters, but the exact prediction depends on uncertain plasma physics

(4) Observational bias (metallicity & multiphase temperature structure) - is a concern at $r > r_{500c}$ (Avestruz+14)

# Galaxy Clusters Outskirts: New Frontier and Crossroads of Cosmology & Astrophysics




## ✦ Cluster Core ($r<0.1R_{500c}$)

Heating, Cooling, & Plasma physics

1. AGN feedback (Mechanical/CR heating)
2. Dynamical Heating, Gas sloshing
3. Thermal Conduction, Magnetic Field, He sedimentation

## ✦ Cluster outskirts ($r>R_{500c}$)

Gas Accretion & Non-equilibrium phenomena

1. Gas inhomogeneities
2. Gas motions
3. Non-equilibrium electrons

## ✦ Intermediate Region ($r\sim R_{500c}$)

Sweat Spot for Cluster Cosmology, but the physics of cluster outskirts affects this region.