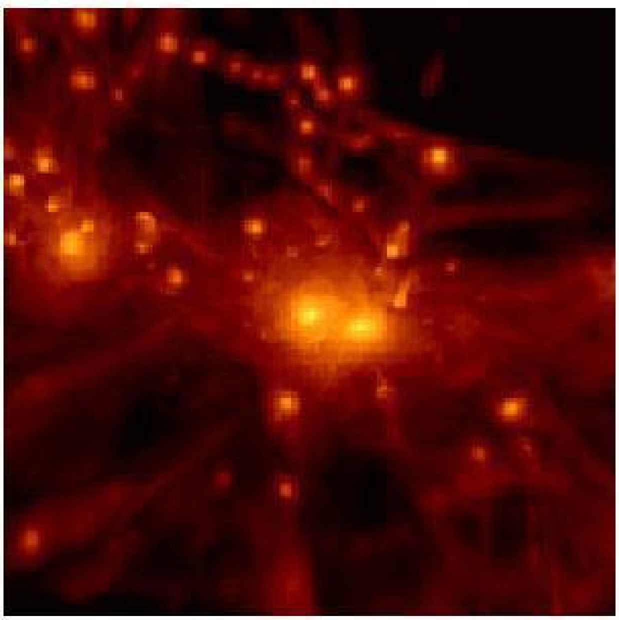
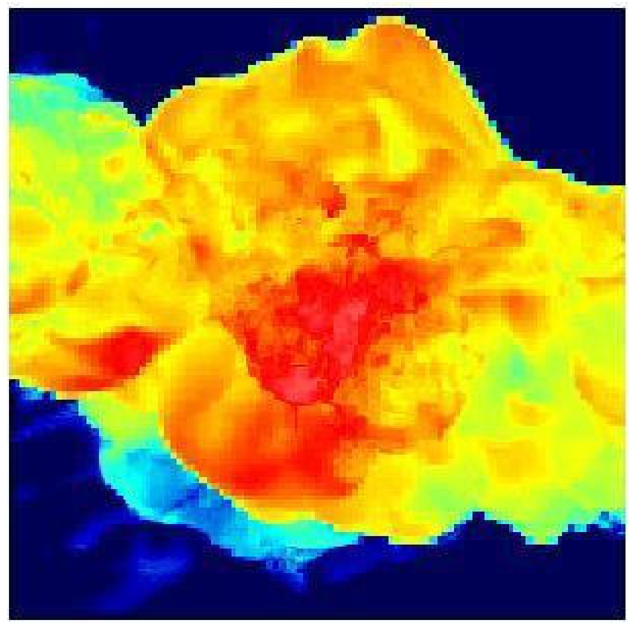
High- resolution simulations of galaxy clusters





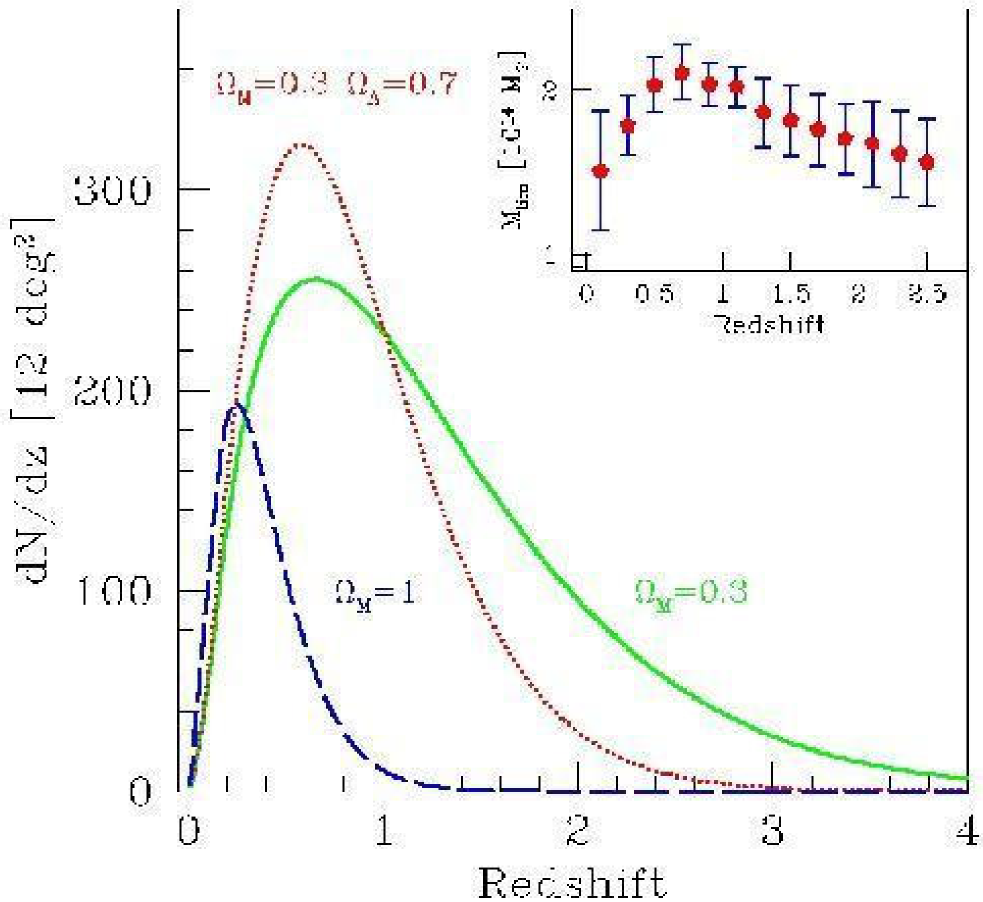
Andrey Kravtsov

Department of Astronomy & Astrophysics

Center for Cosmological Physics

The University of Chicago

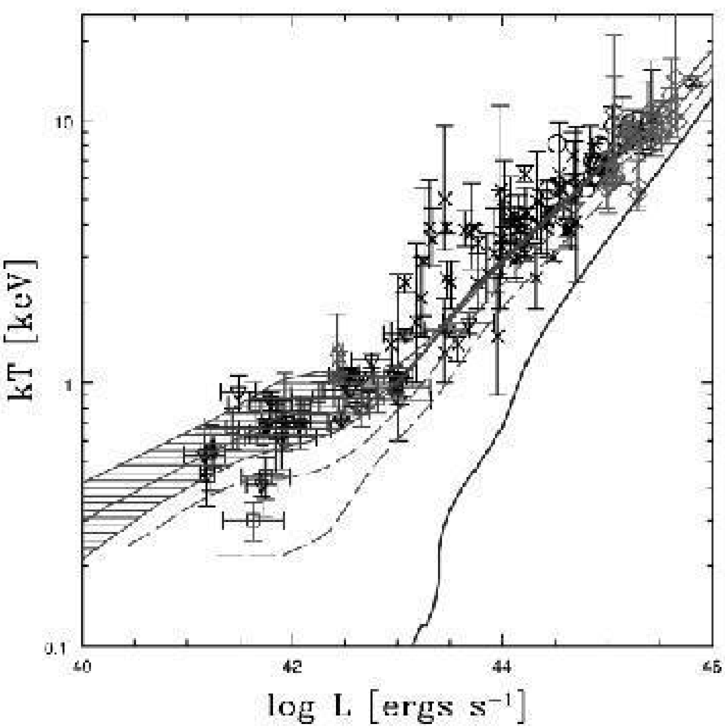
Cluster abundances are very sensitive to cosmological parameters



Mohr 2001

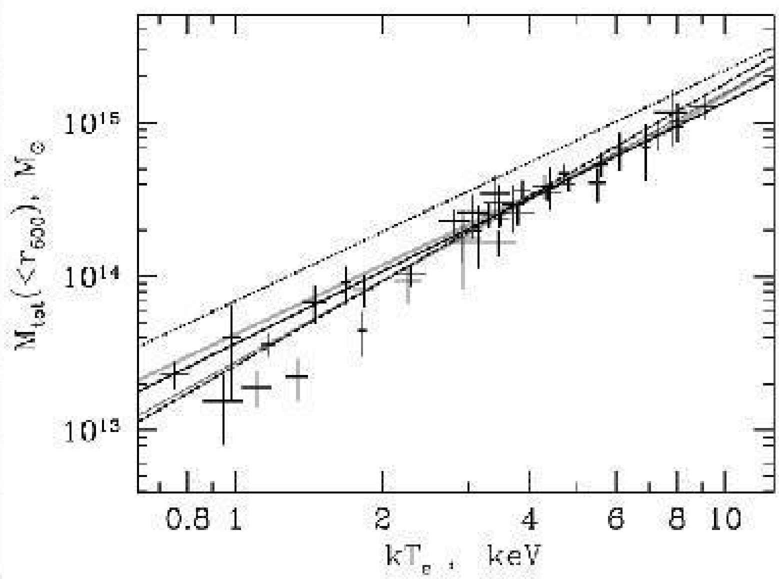
Global scaling relations

Lx - T relation



Babul et al. 2002

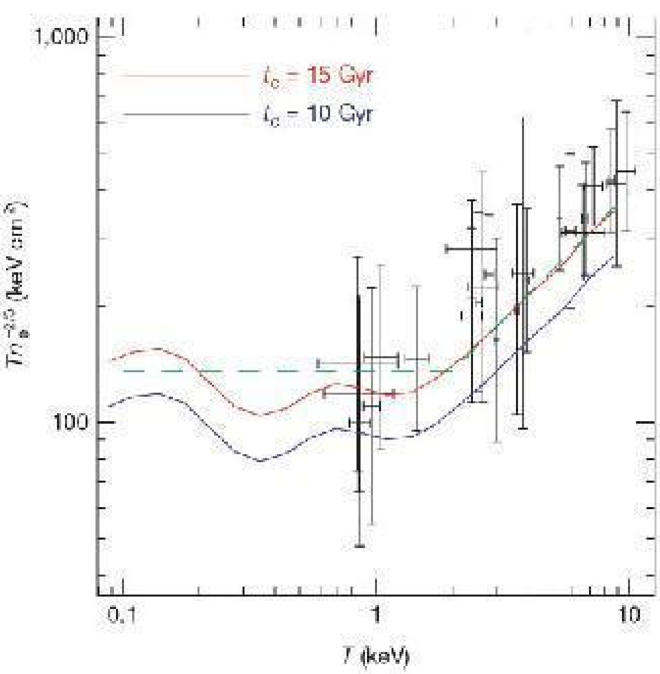
M - T relation



Finoguenov et al. 2000

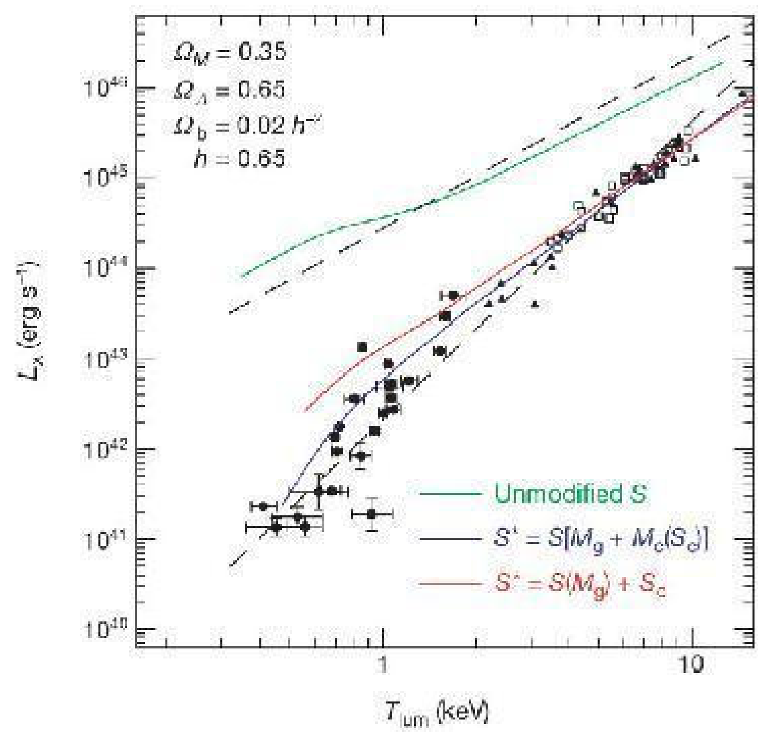
effects of cooling

gas entropy



gas temperature [keV]

X- ray luminosity [ergs/s]

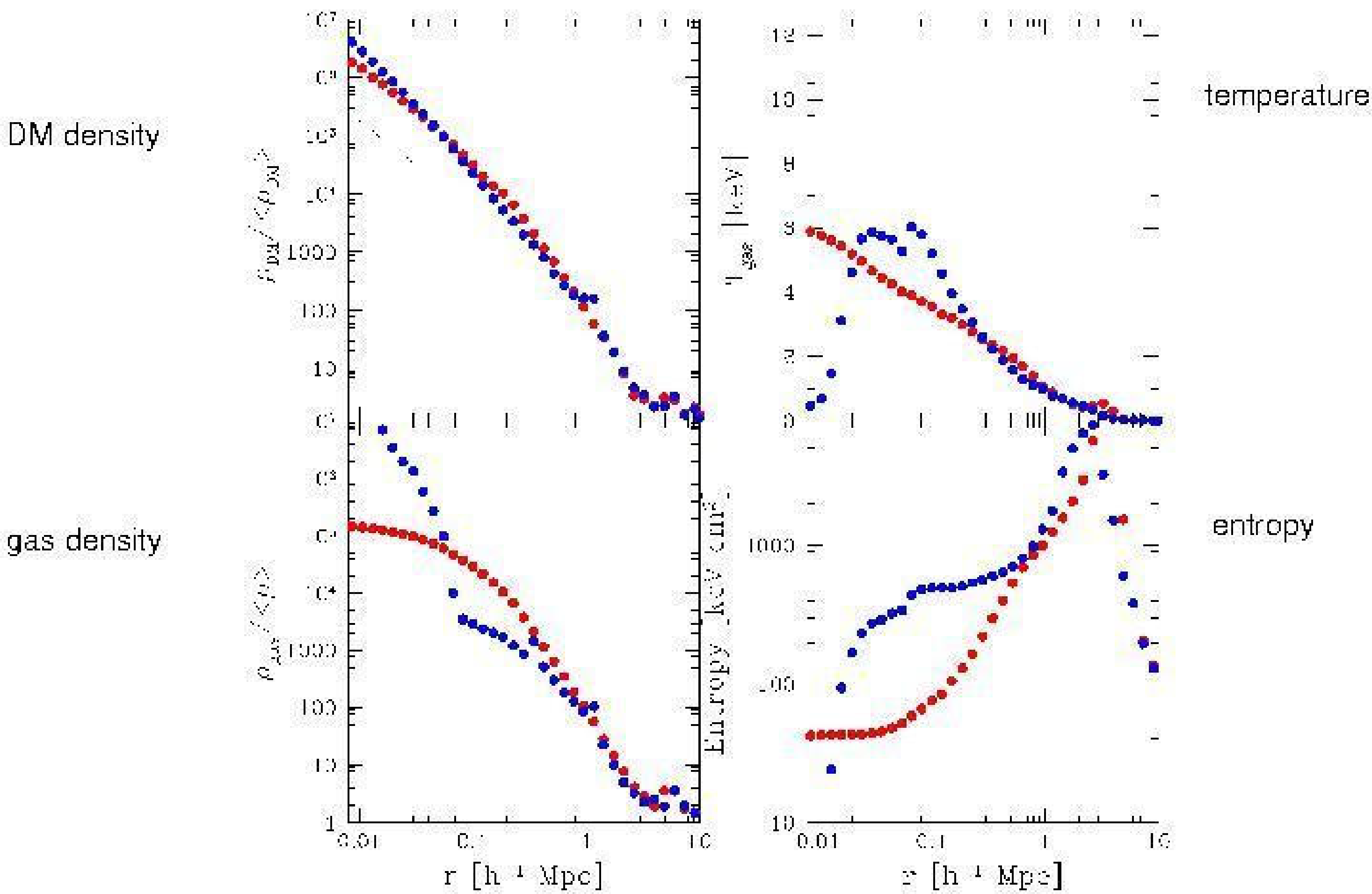


gas temperature [keV]

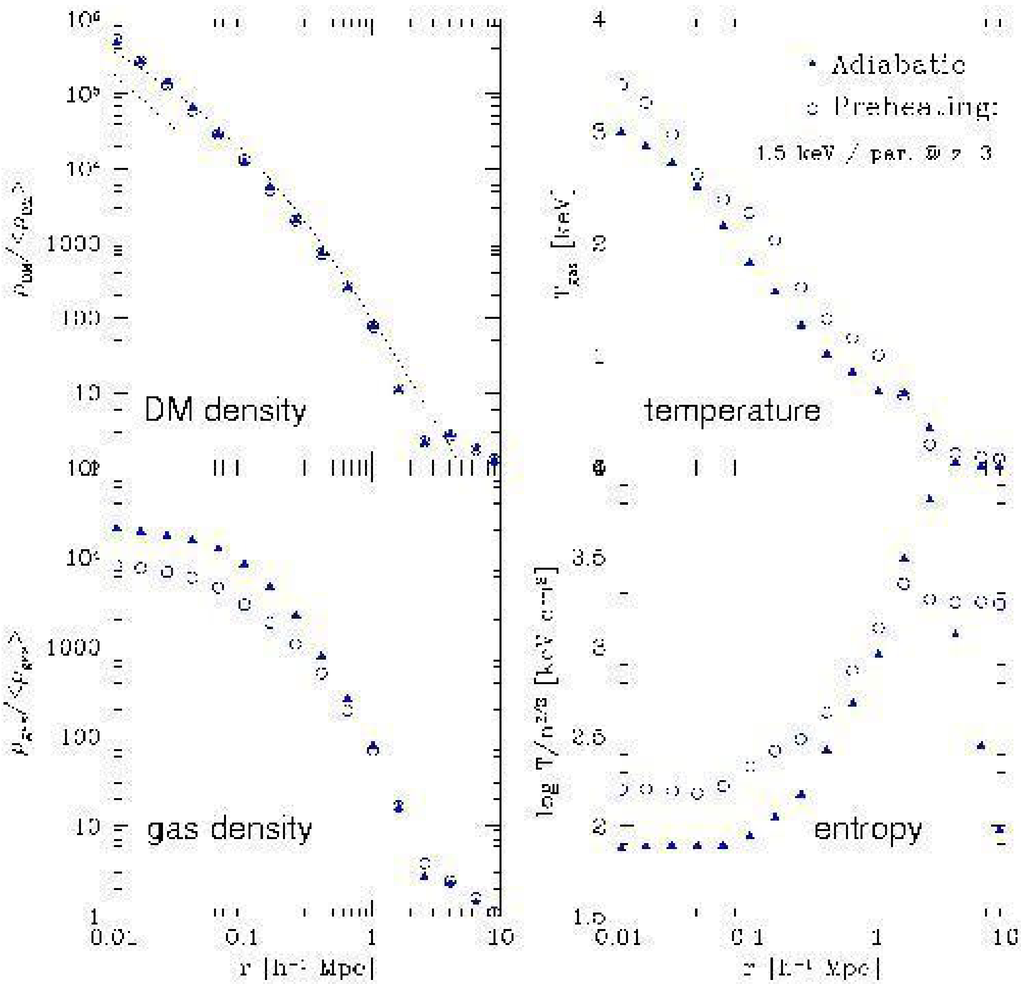
Voigt & Bryan 2001, Nature

effects of cooling in simulated clusters

ART simulation of a medium mass (2×10^{14} Msun) cluster



Virgo cluster: profiles



Adiabatic:

$L_X = 8 \times 10^{43}$ ergs/s

$T_X = 1.5$ keV

Preheating:

$L_X = 1.3 \times 10^{43}$ ergs/s

$T_X = 1.72$ keV

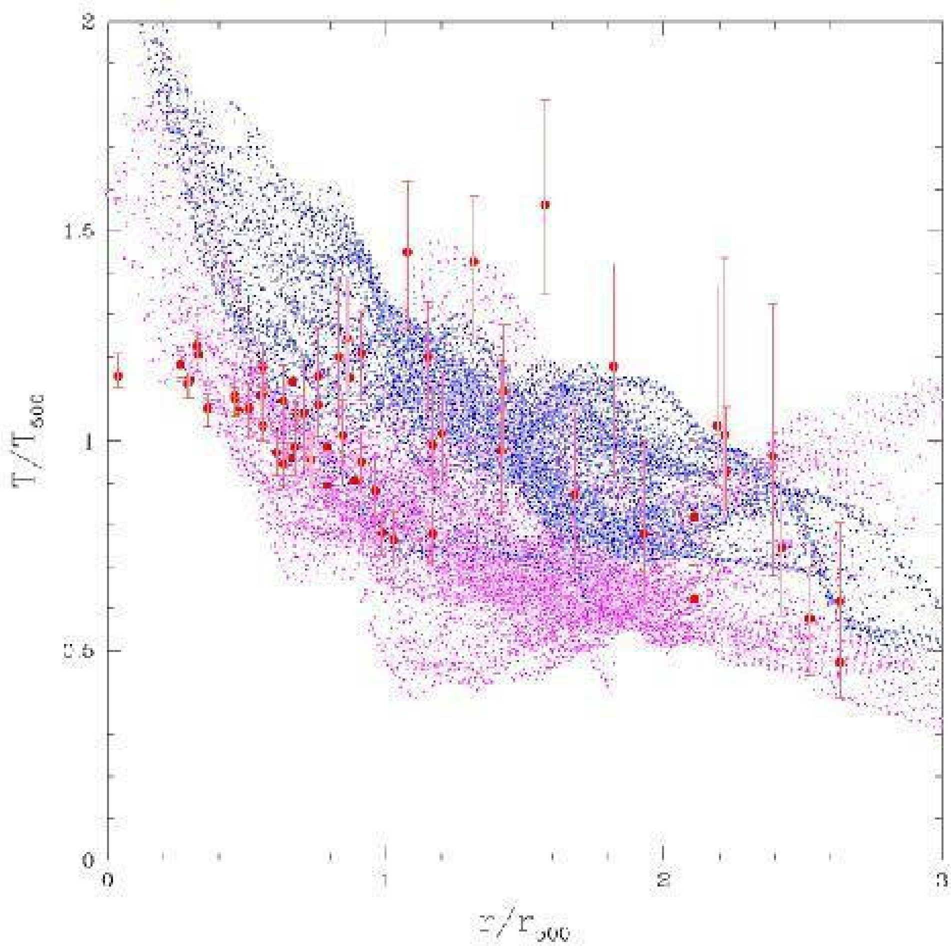
Observed:

$L_X = 1- 1.3 \times 10^{43}$

$T_X = 1.5- 1.7$ keV

Virgo cluster: projected temperature profiles simulations vs observations

gas temperature
in units of T500



radius in units
of R500

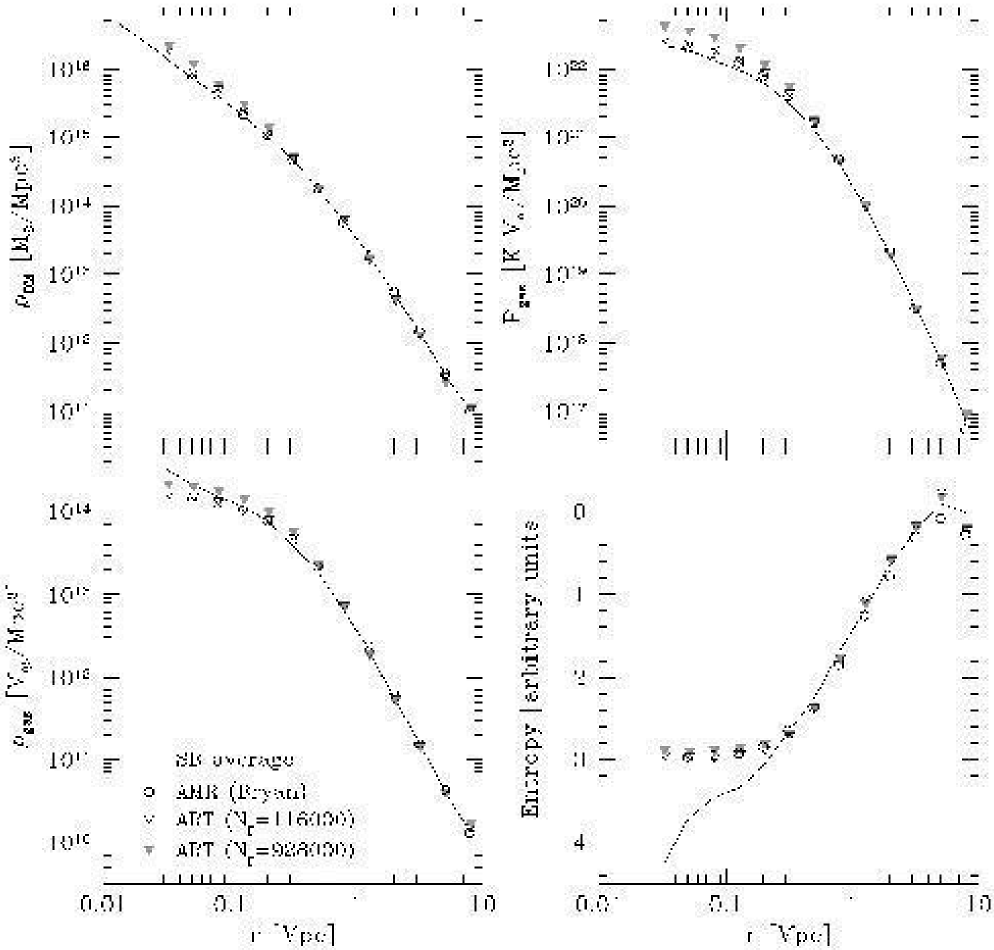
Convergence among simulations?

DM density

temperature

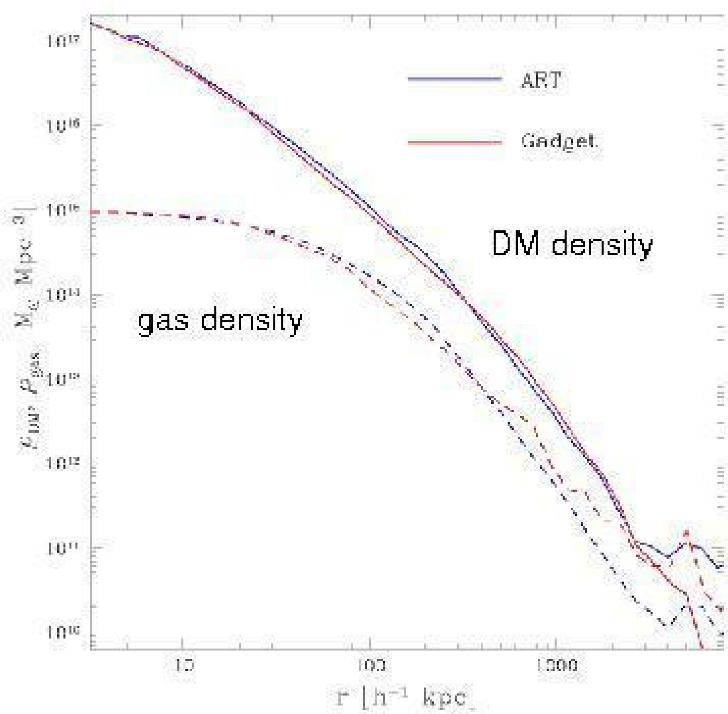
gas density

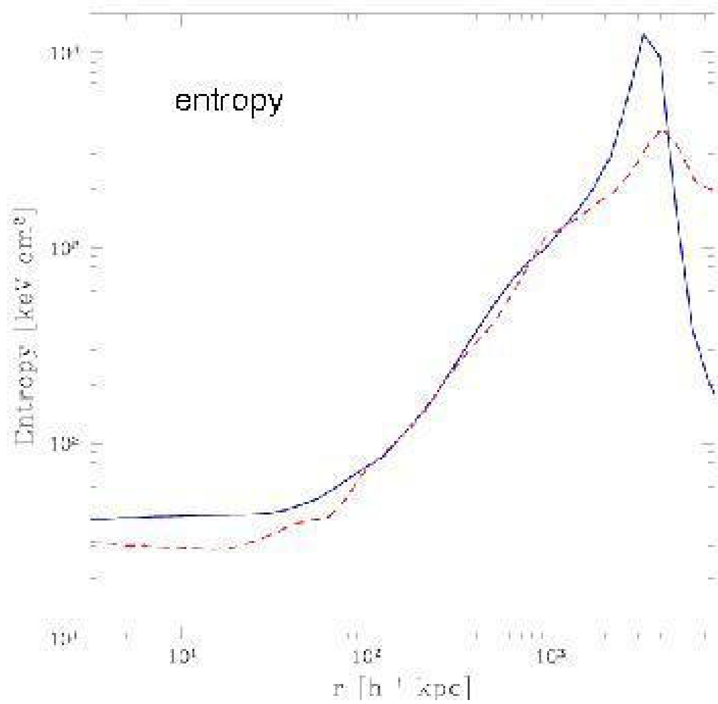
entropy



Kravtsov, Klypin & Hoffman 2002, ApJ 571, 563

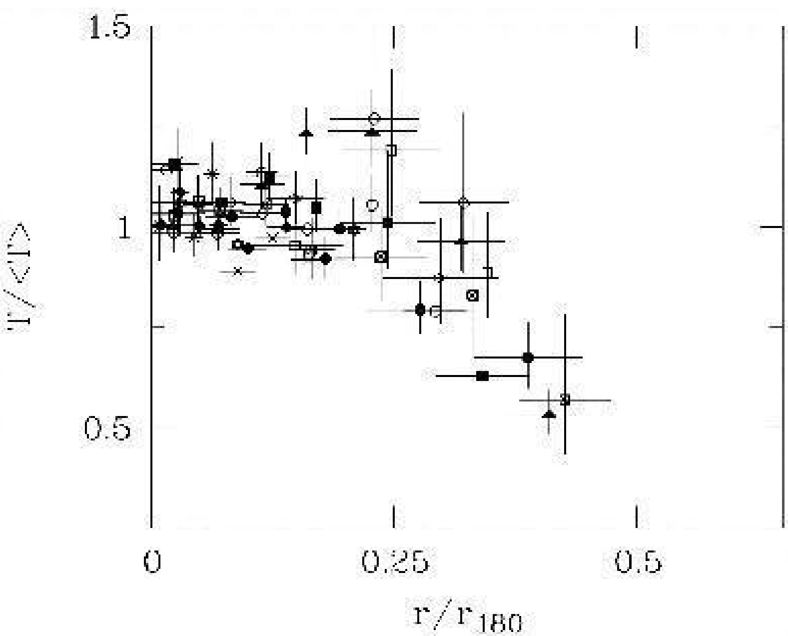
ART vs SPH with improved treatment of entropy (Springel & Hernquist 2002)

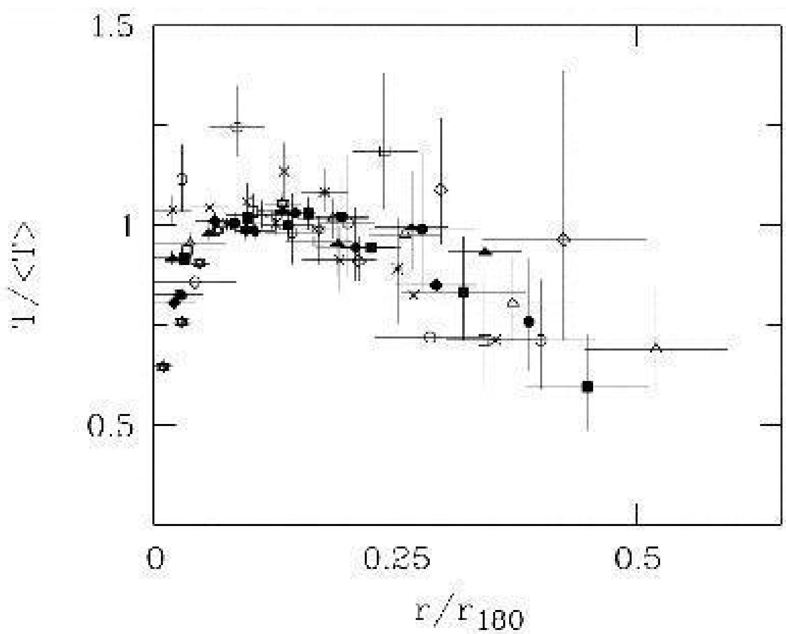




Cluster temperature profiles

Projected Temperature in units of the mean emission- weighted temperature vs. projected radius in units of the virial radius

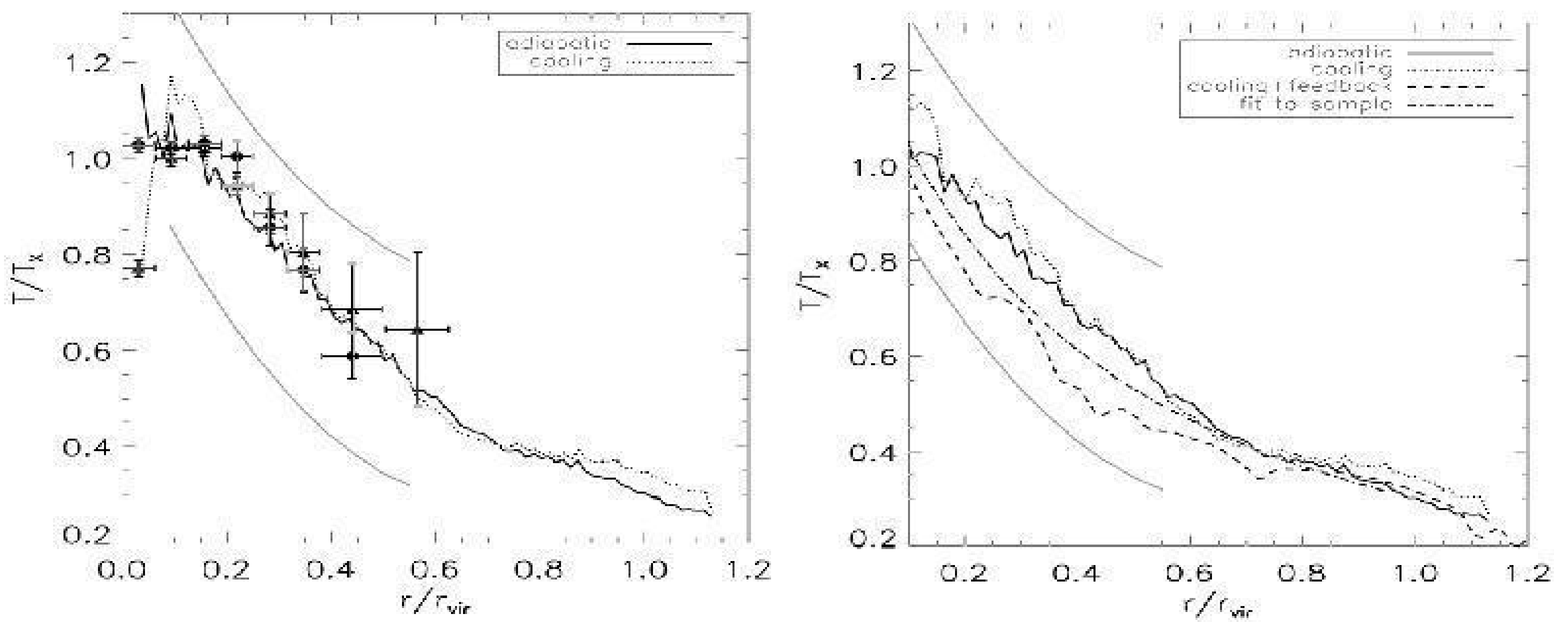




De Grandi & Molendi 2001
Markevitch 1998

Cluster temperature profiles: simulations vs observations

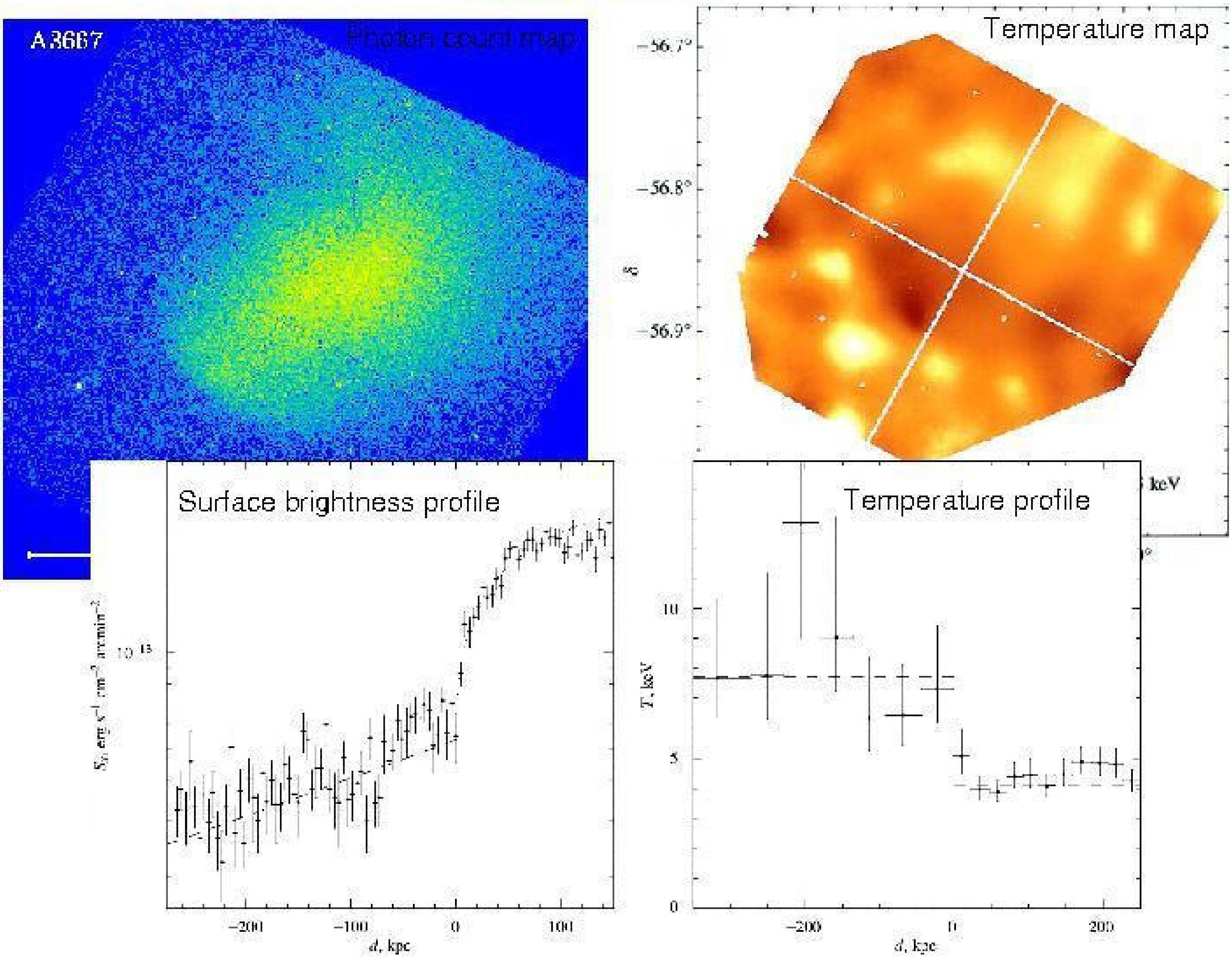
Projected Temperature in units of the mean emission- weighted temperature vs. projected radius in units of the virial radius



Loken et al. 2002

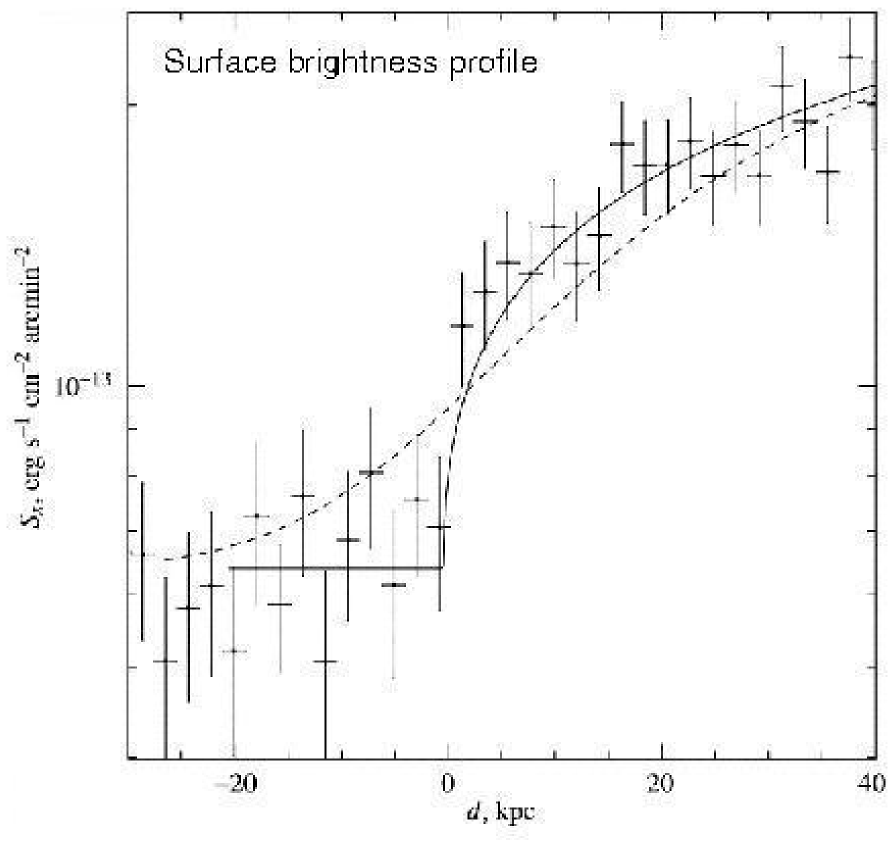
Cold Fronts

Vikhlinin et al. 2001



Cold Fronts

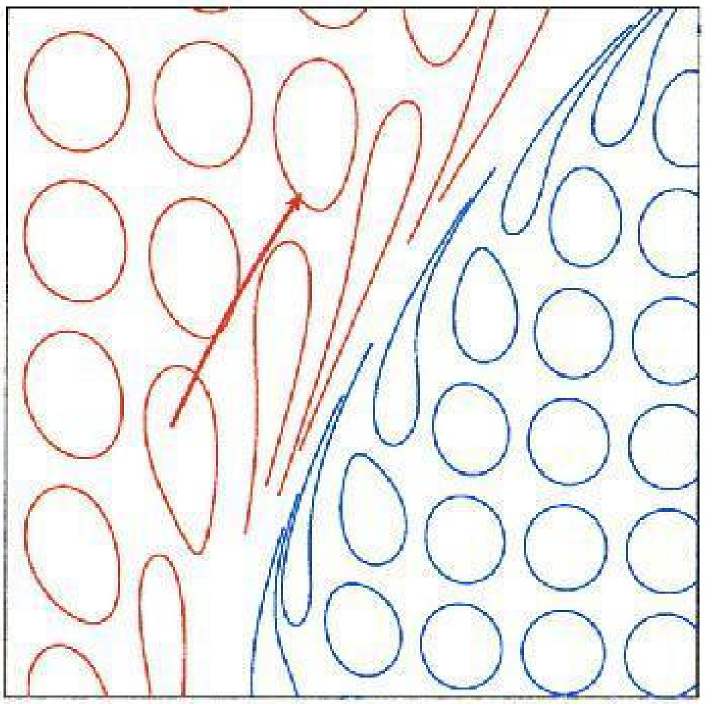
Vikhlinin et al. 2001

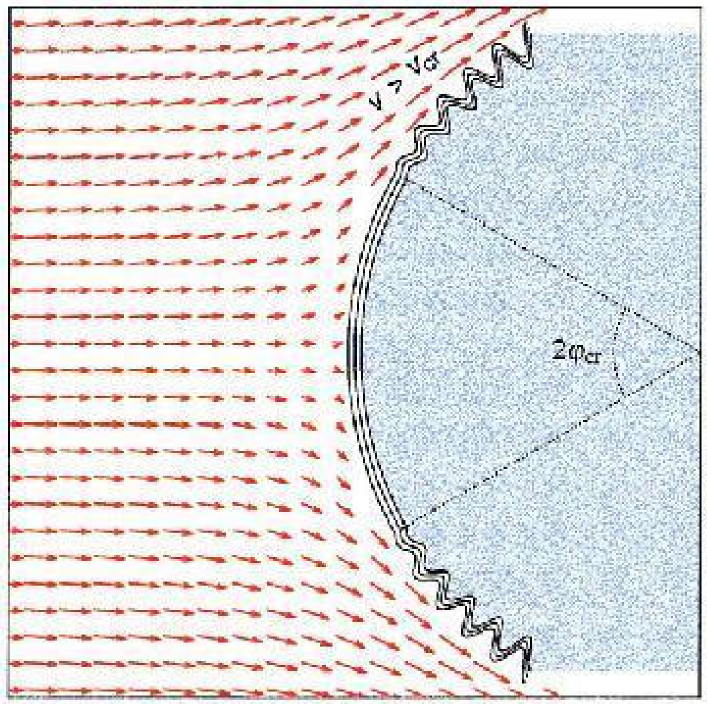


sharpness of the front implies that the mean free of electrons across the front is << the Coulomb mean free path

Cold Fronts: why so thin?

Vikhlinin et al. 2001





In this model the sharpness and stability of the front imply magnetic fields of ~7- 20 μG roughly parallel to the front

"Sloshing" of gas in the cores of relaxed clusters

sharp features in the central ~100 kpc indicate gas motions of ~ 200- 500 km/s observed in ~2/3 of the classic 'relaxed' clusters!

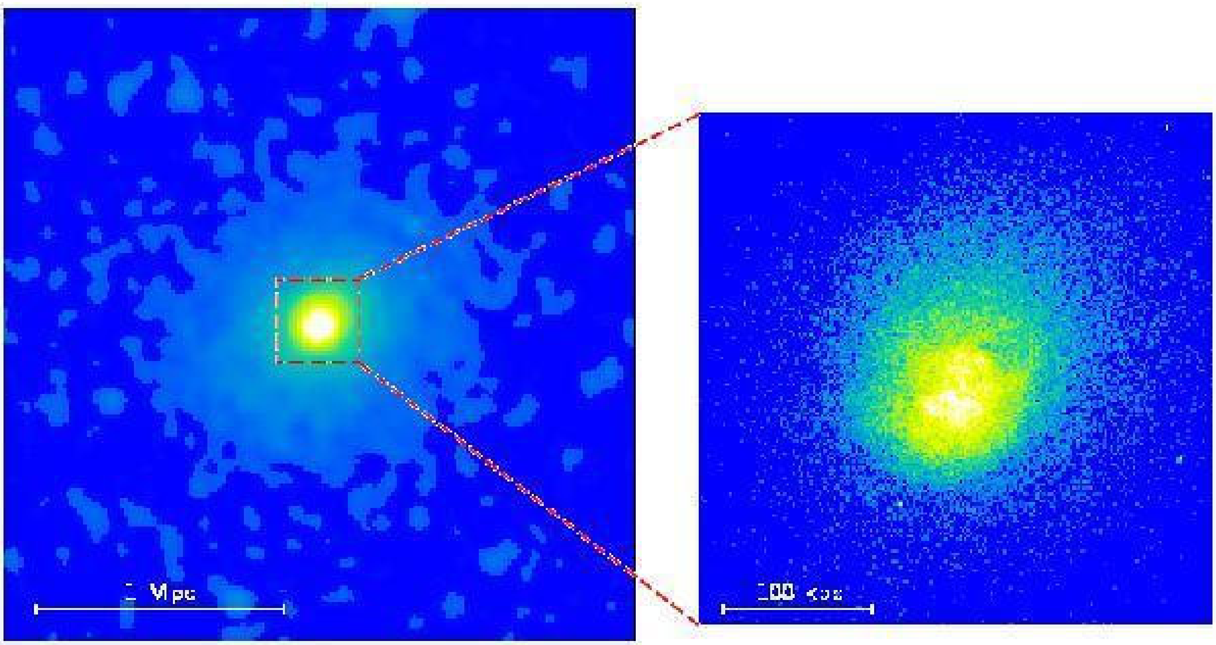
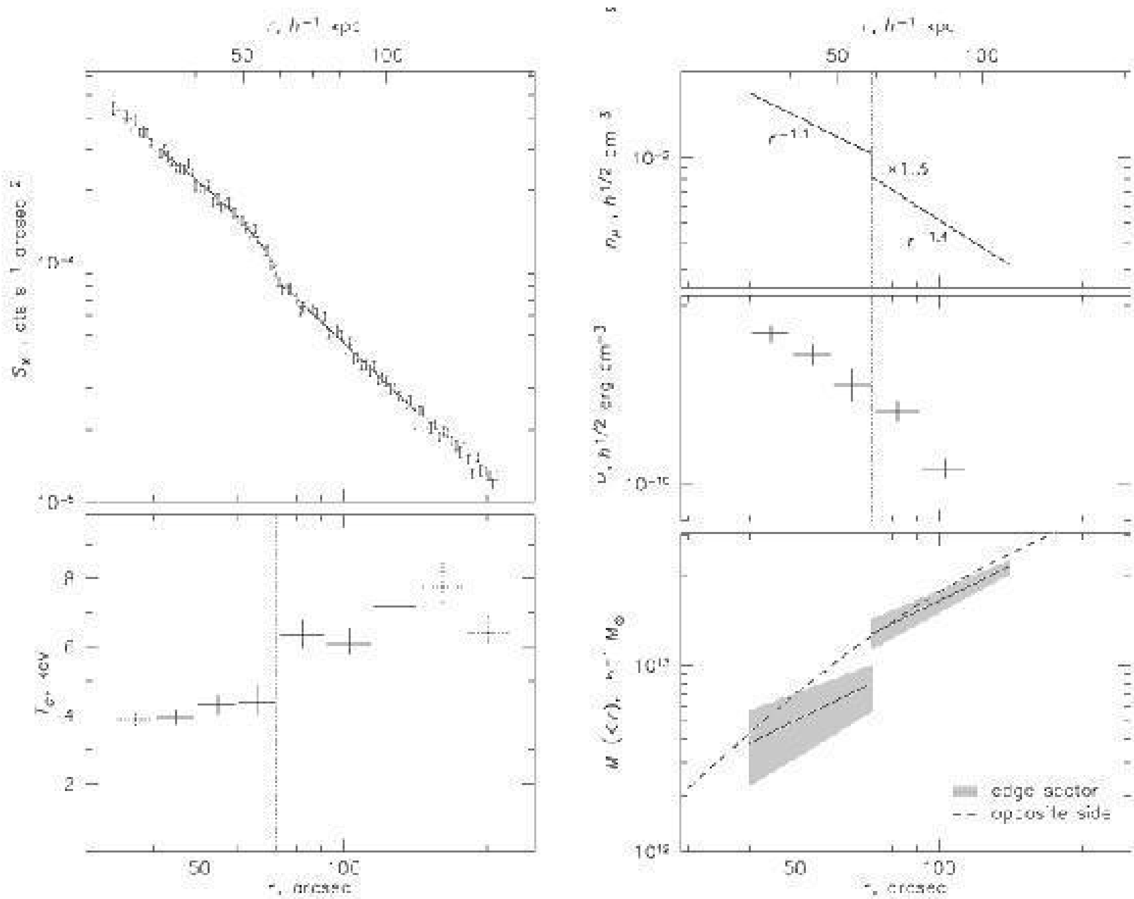


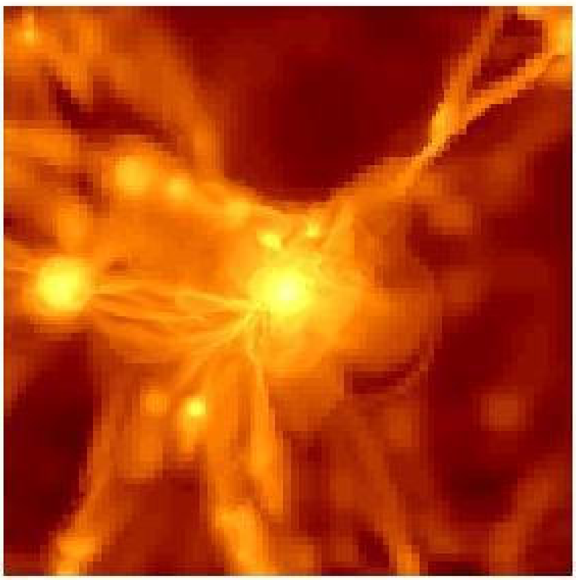
Figure 1. *Left:* *ROSAT* PSPC image of the relaxed cluster 2A0335+096 (z=0.03, T=3 keV). *Right:* *Chandra* image reveals complex and dynamic structure of its core.

Markevitch et al. 2002, astro- ph/0208208 *important implications for mass modeling in cluster cores!*



Markevitch et al. 2002, astro- ph/0208208

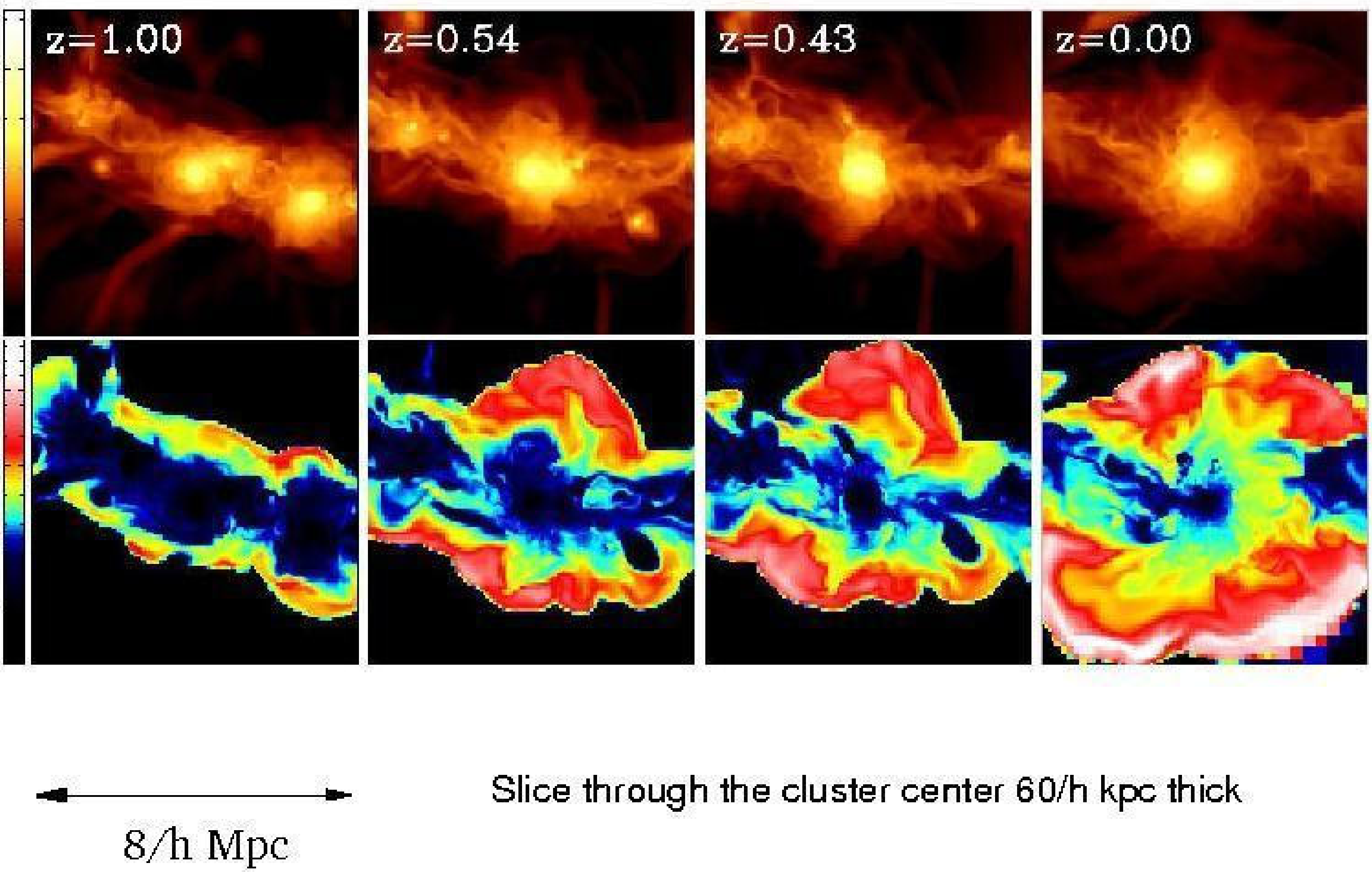
THE ADAPTIVE REFINEMENT TREE (ART) CODE



- Starting from a uniform grid, the code adaptively increases the spatial resolution locally.
- Fast N- body + eulerian Godunov shock capturing hydro solver.
- The code *refines (and derefines) mesh cells individually and* uses a fully- threaded oct tree data structure (hence, the ART name) to support the resulting refinement mesh hierarchy.
- This allows us to construct flexible refinements that can be easily modified, which makes the algorithm truly adaptive. The meshes can effectively match the complex geometry of filaments, sheets, and clumps in a cosmological simulation.

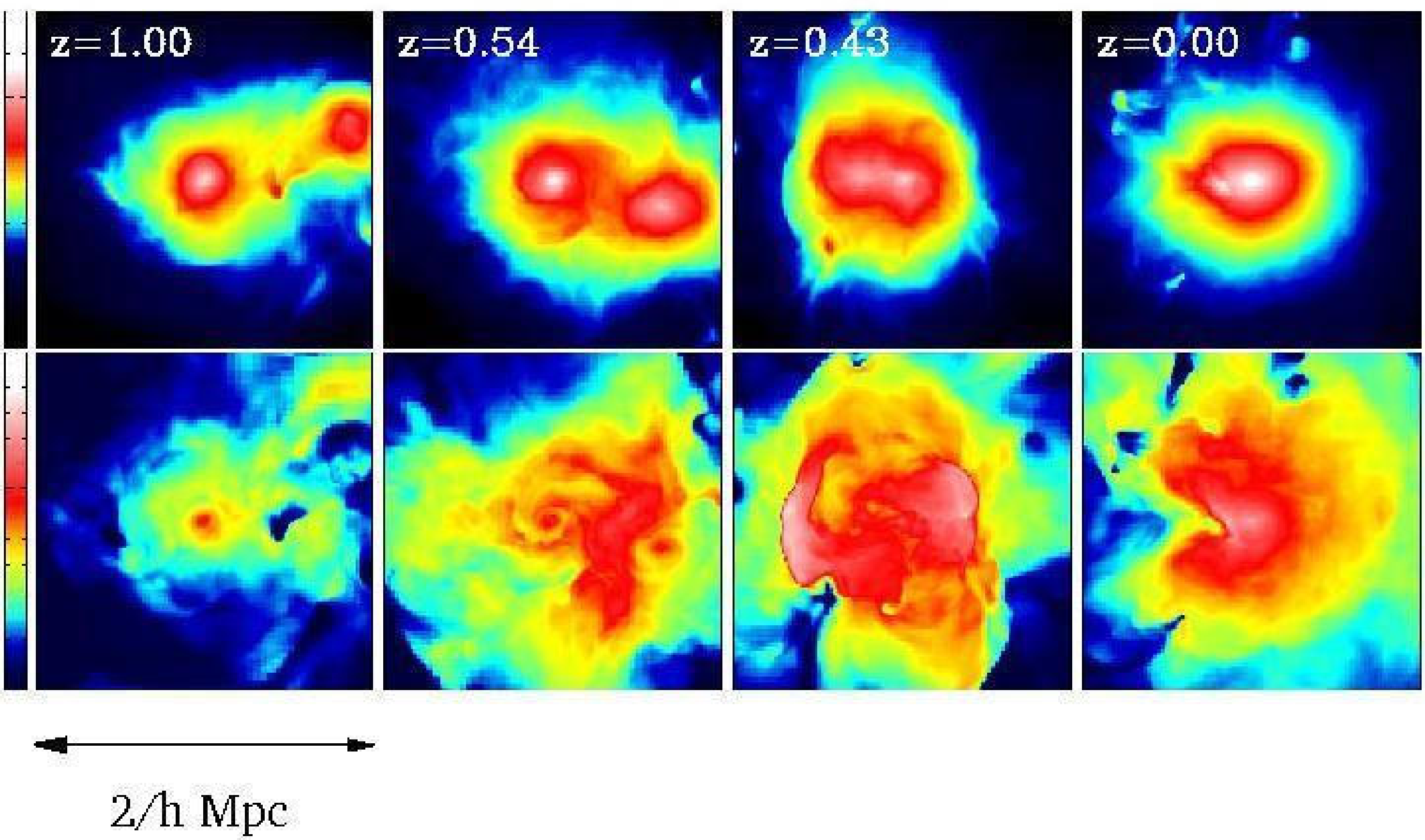
Kravtsov 1999

Cluster evolution:
density and entropy slices



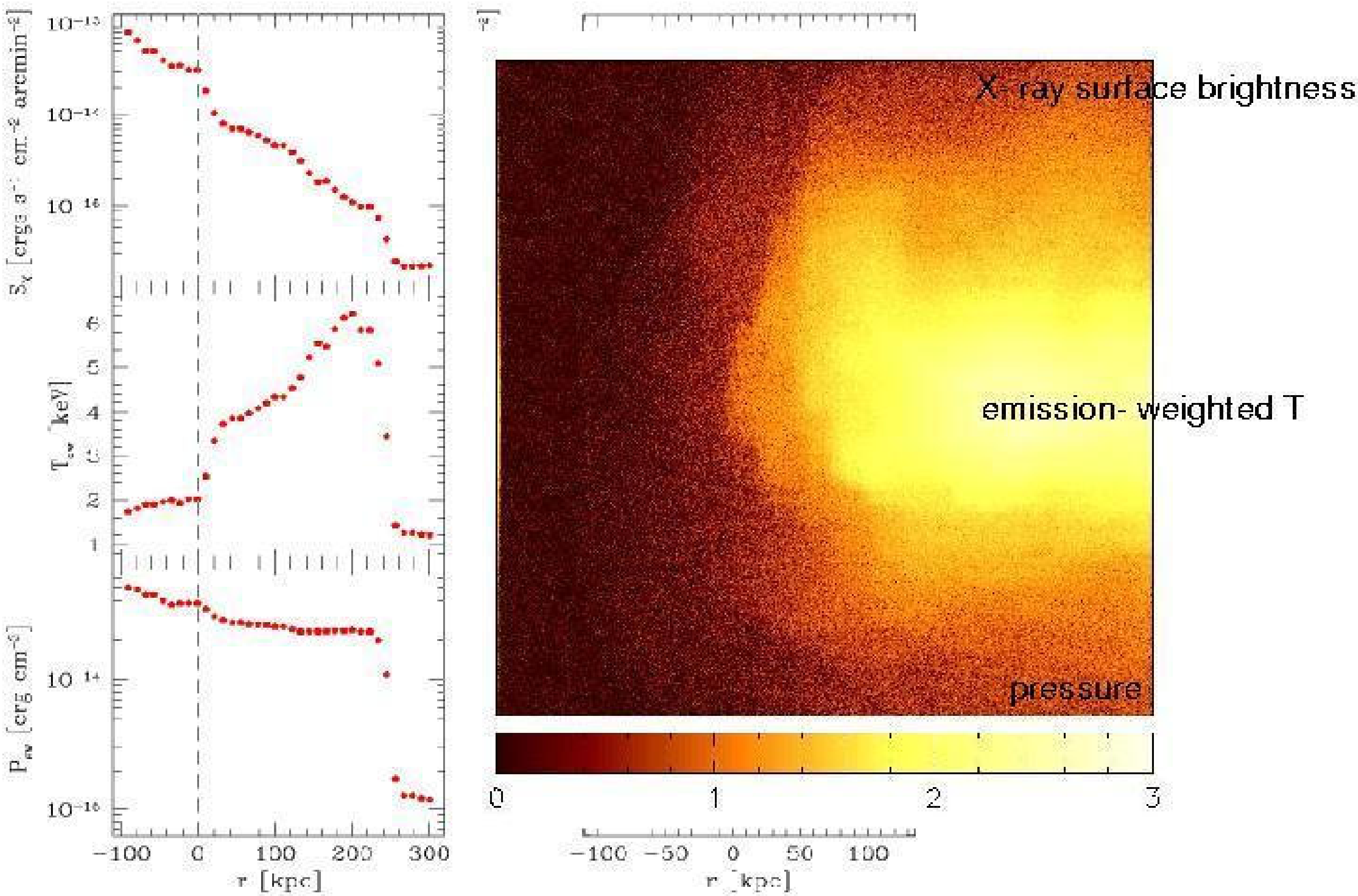
Slice through the cluster center 60/h kpc thick

Cluster evolution:
X- ray surface brightness and emission- weighted T



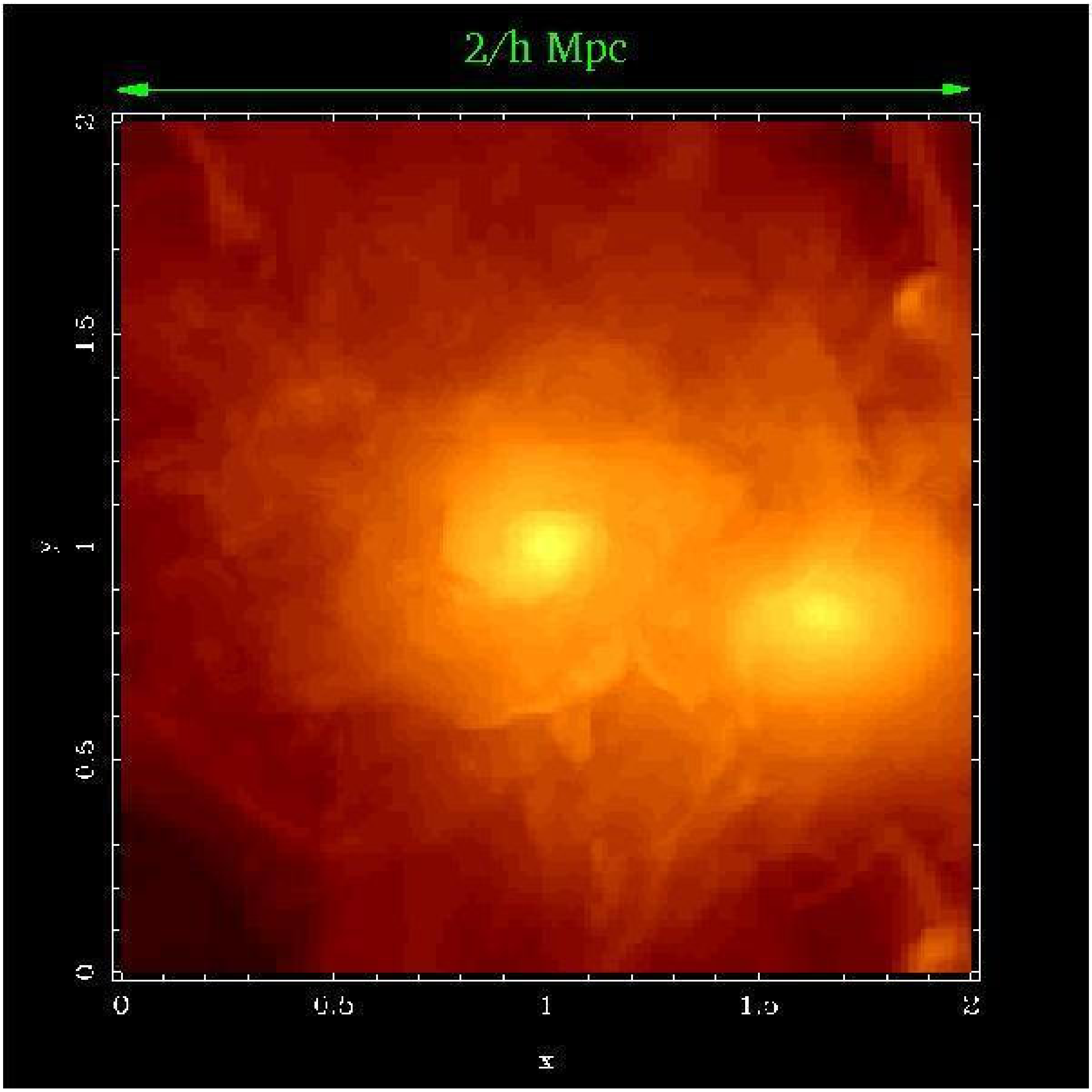
Cold Fronts in LCDM clusters: profiles

Nagai & Kravtsov 2002, astro- ph/0206469

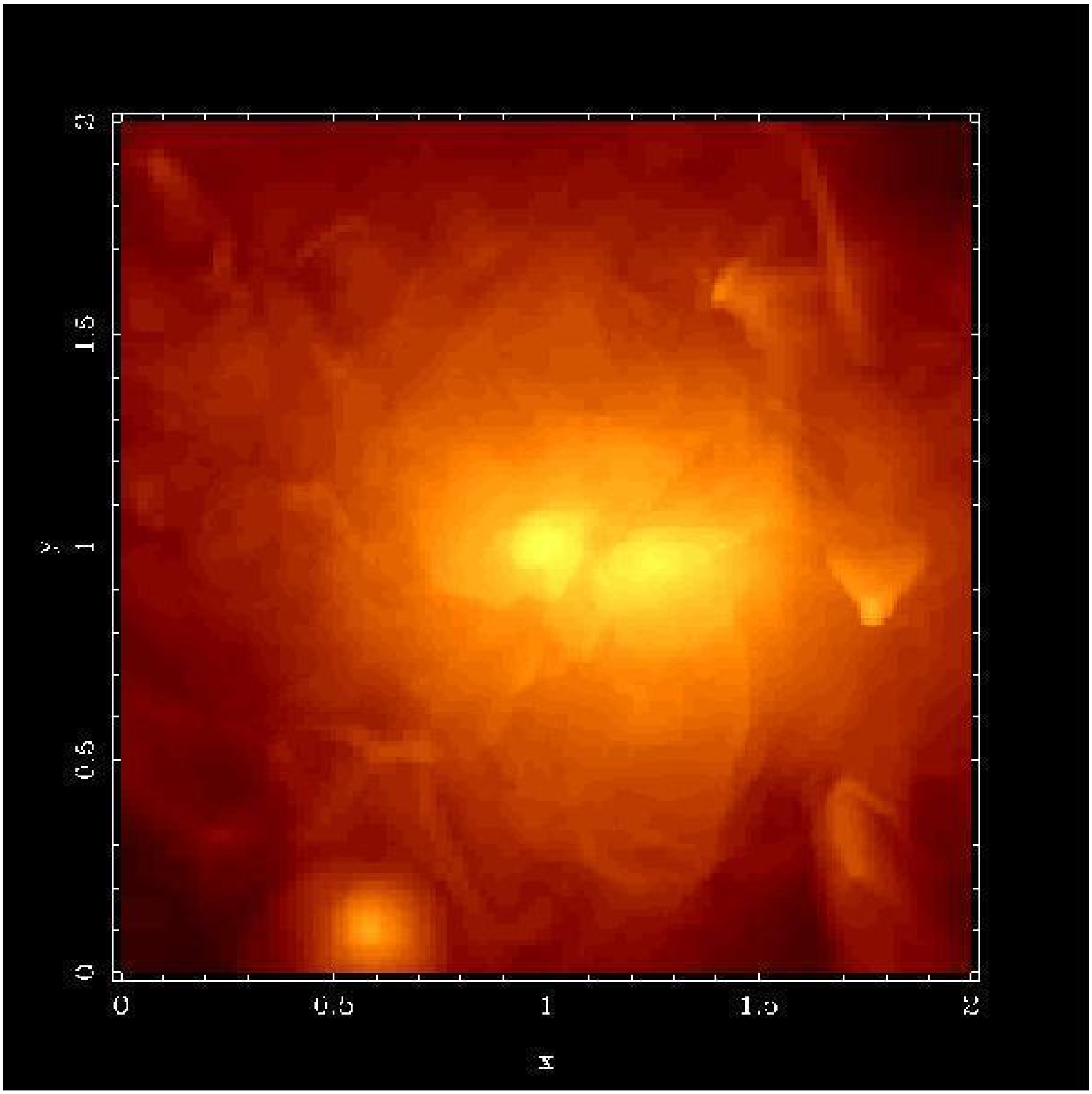


distance from the cold front (indicated by the vertical dashed line)

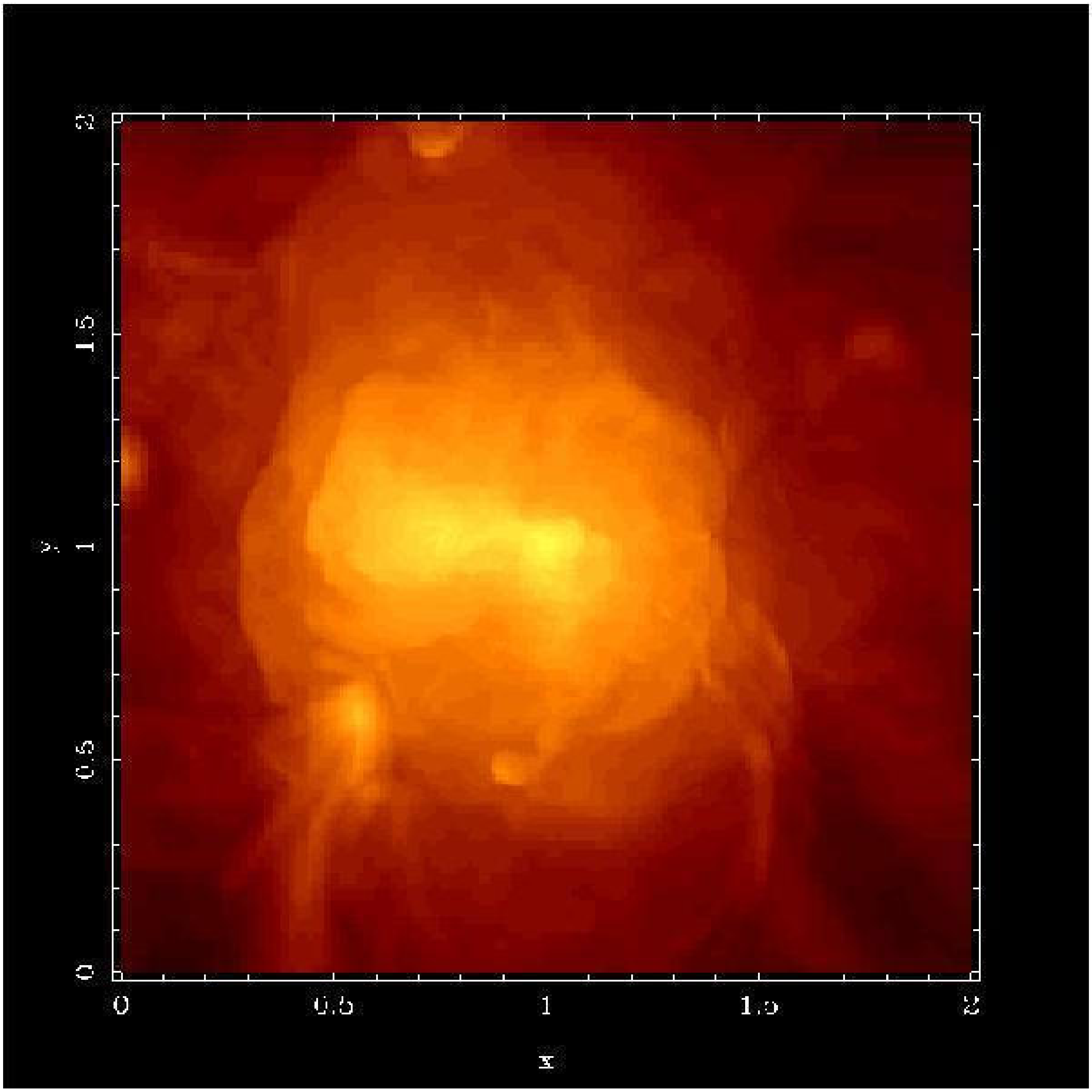
Z=0.54



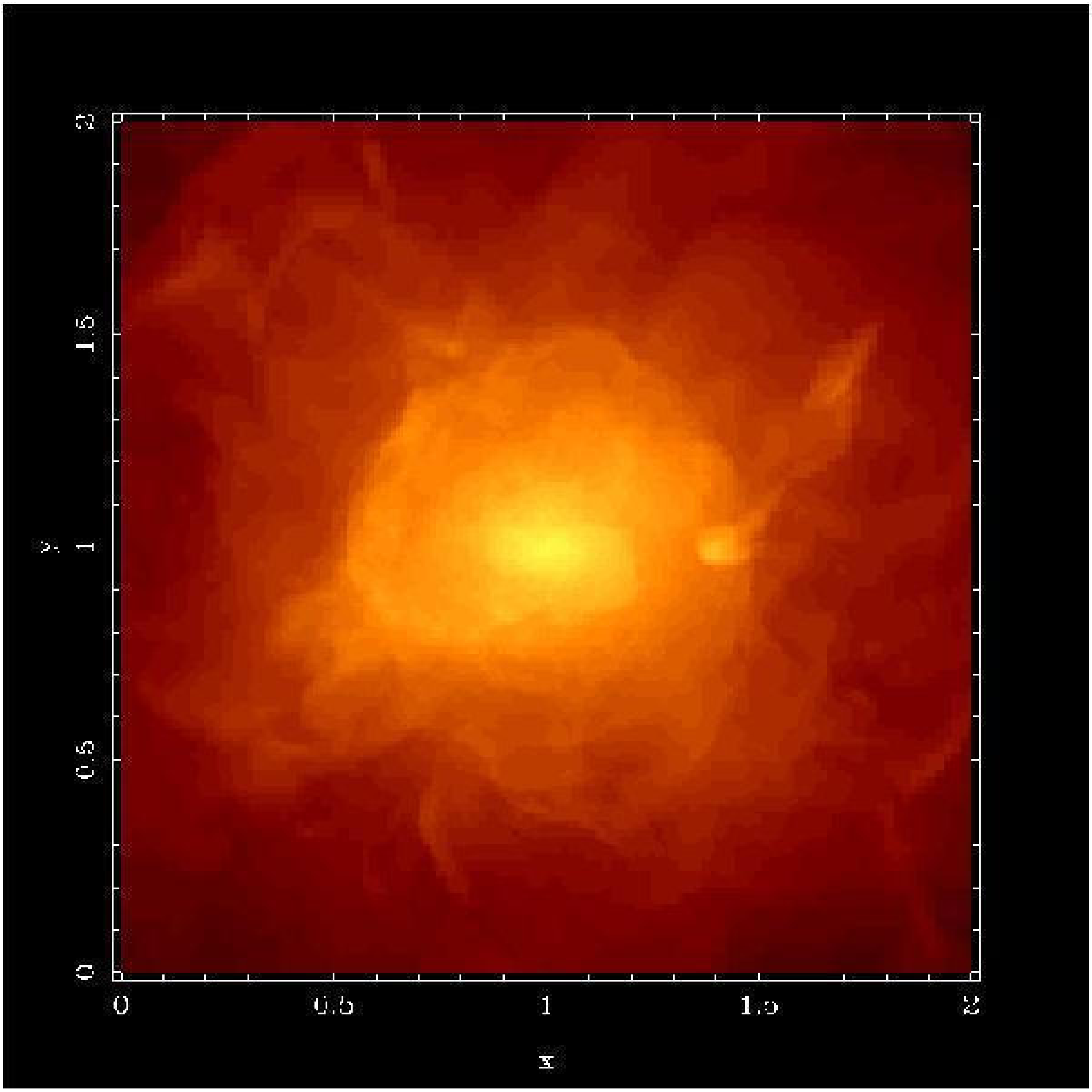
Z=0.50



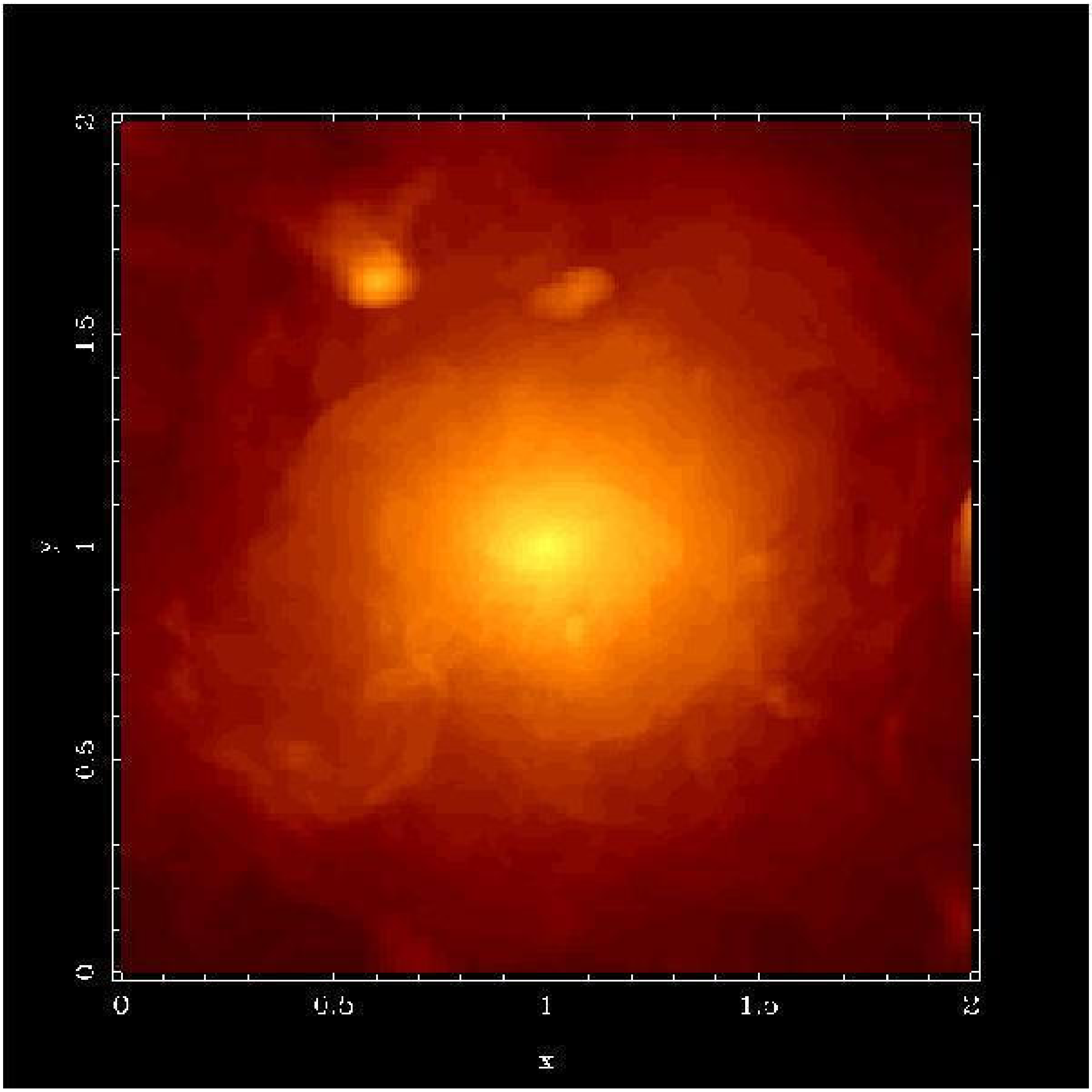
Z=0.43



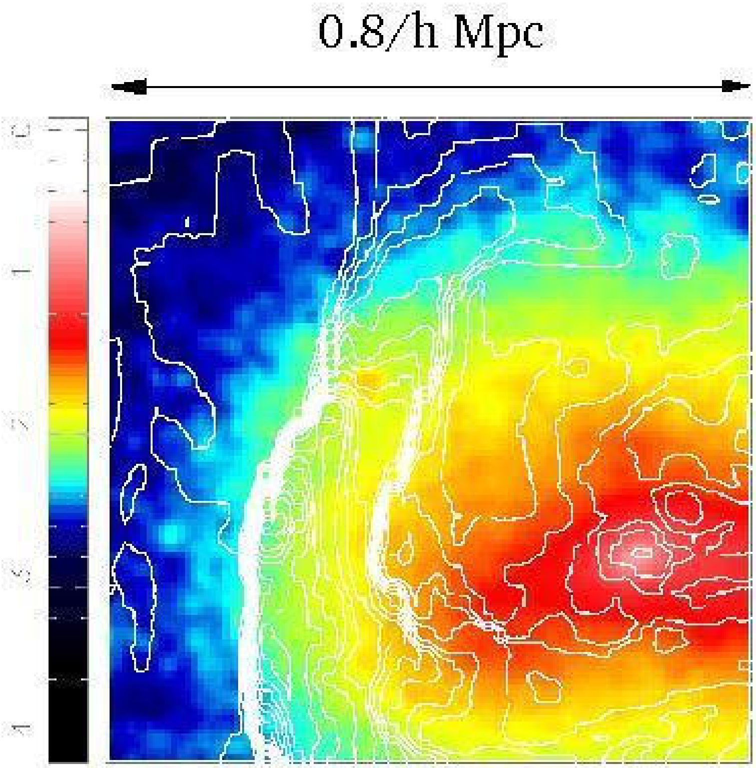
Z=0.33



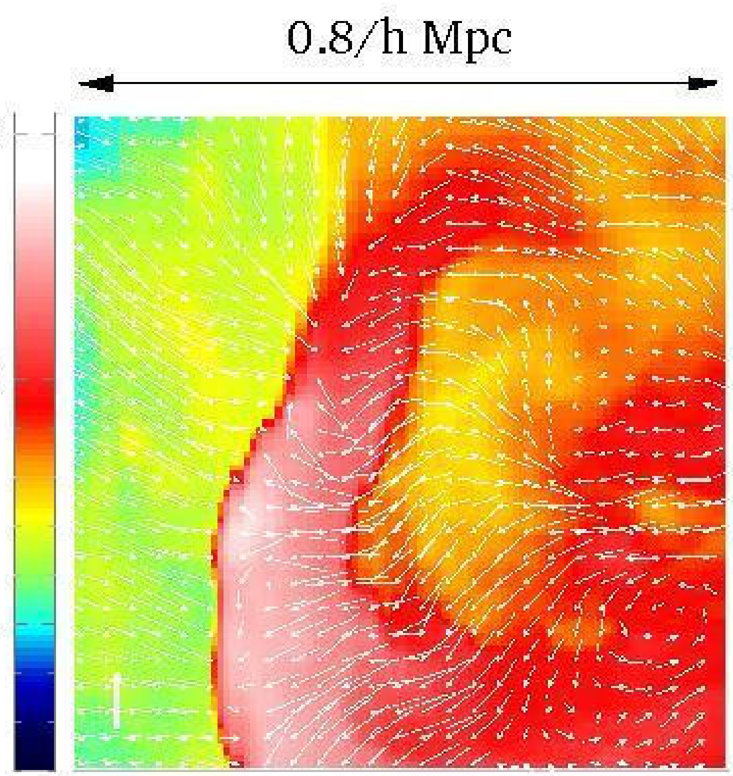
Z=0.25



Cold front in simulation: structure and dynamics



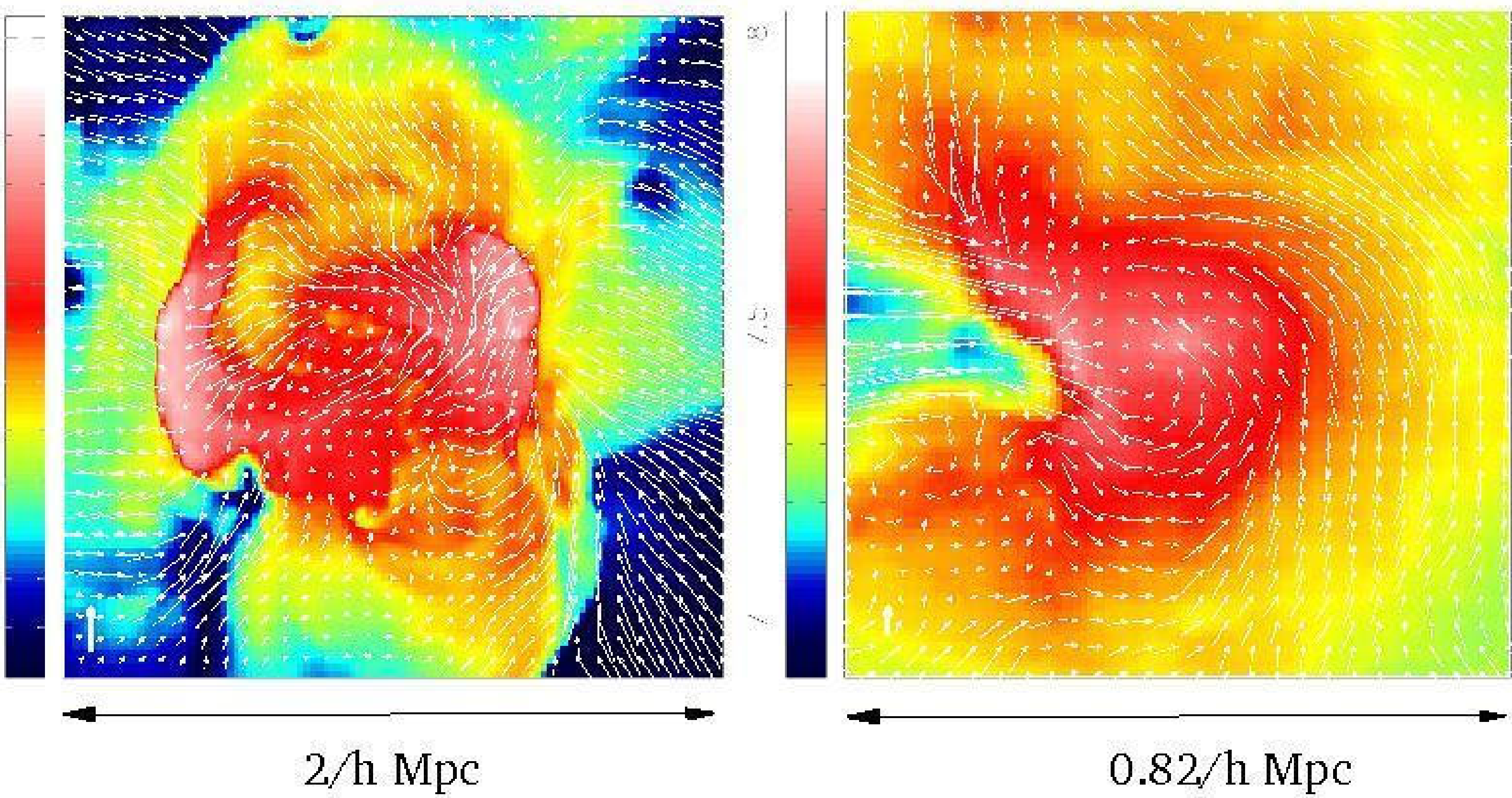
T- contours on the color map of projected DM density



Velocity field in a thin slice centered on the fron overlayed on the color map of emission weighted temperature (vertical vel. vector in the lower left corner corresponds to 1000 km/s

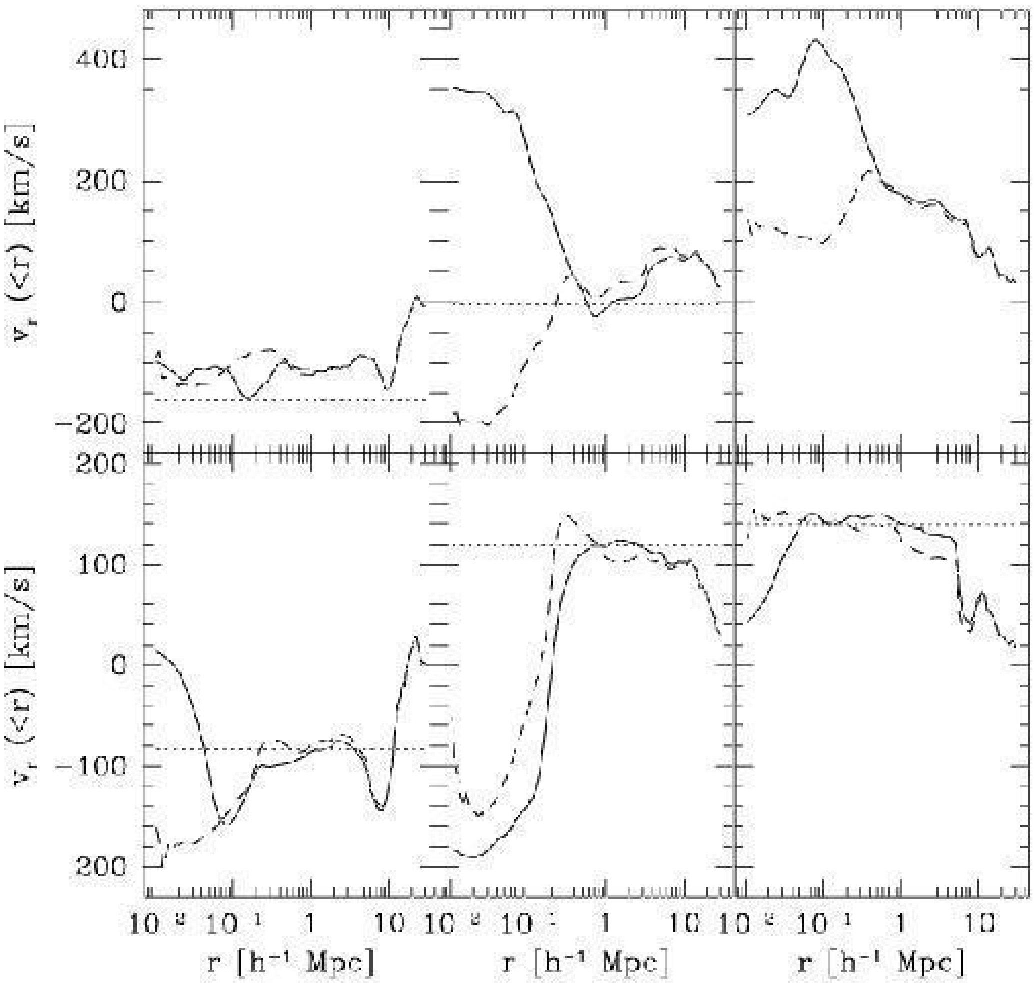
Nagai & Kravtsov 2002, astro- ph/0206469

Internal gas motions in simulated clusters



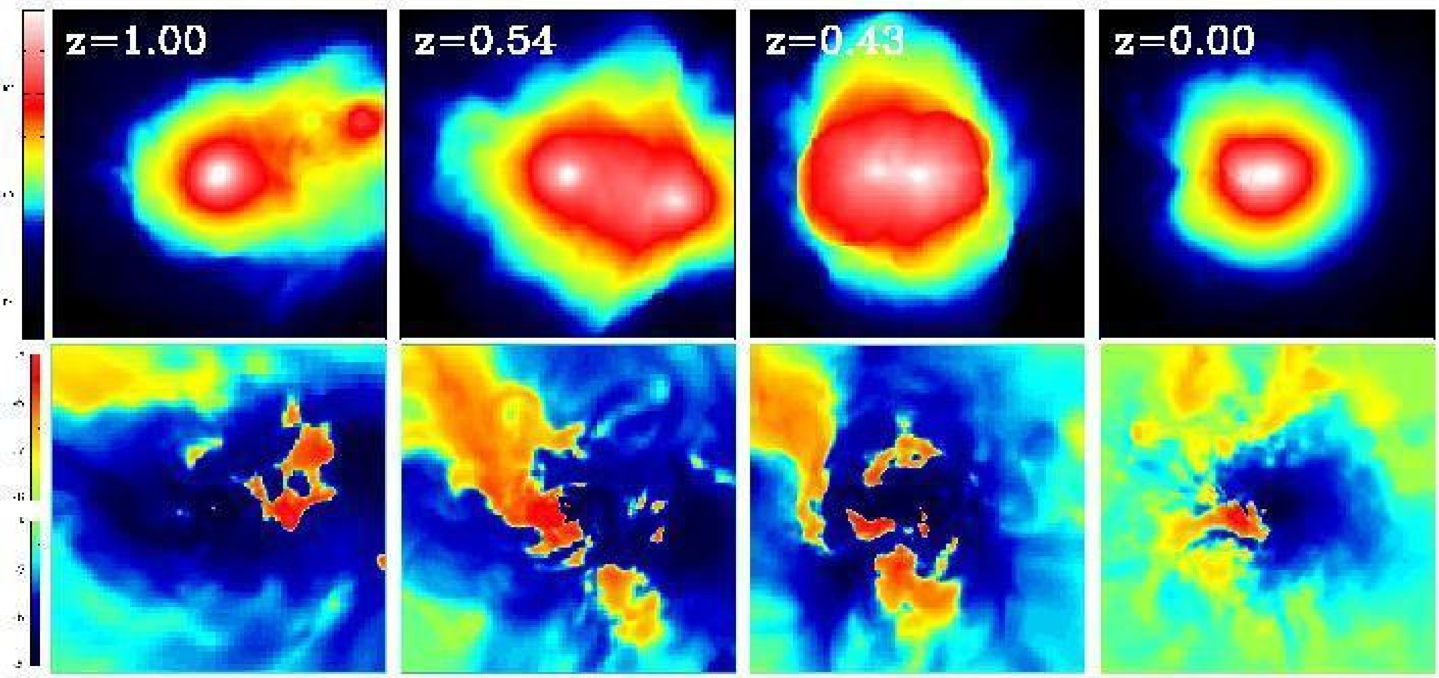
Nagai, Kravtsov & Kosowsky 2002, astro- ph/0208308

Internal gas motions in simulated clusters



Nagai, Kravtsov & Kosowsky 2002, astro- ph/0208308

Thermal and kinetic SZ maps



Internal gas motions may introduce errors in peculiar velocity measurements via SZ (of order of pec. velocity itself)

Nagai, Kravtsov & Kosowsky 2002, astro- ph/0208308

Future Prospects

- After a decade of simulations we still do not understand which processes determine properties of the intracluster medium

- We are at a stage where quality of the data exceeds quality of cosmological simulations.

- This is a challenge to theoreticians, but also a great opportunity. Detailed high- resolution observations will help us understand which processes are important in shaping properties of the intracluster medium.

The progress will come from synergy of models and observations

- At the same time, advances in computer hardware and algorithms should allow for more sophisticated modeling and higher resolution

I illustrated work in this direction with a couple of examples