# Challenges of Using Galaxy Clusters with Cool Cores for Precision Cosmology

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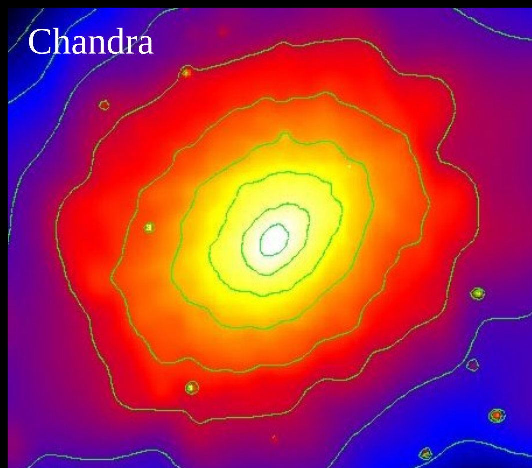
(adapted from A. Fabian)

# **Cooling Core *vs* Non-Cooling Core Clusters**

Abell 478

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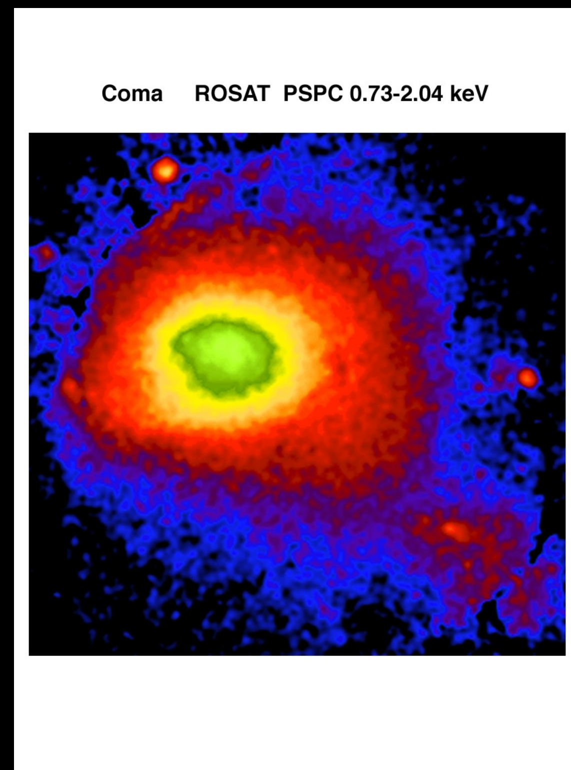
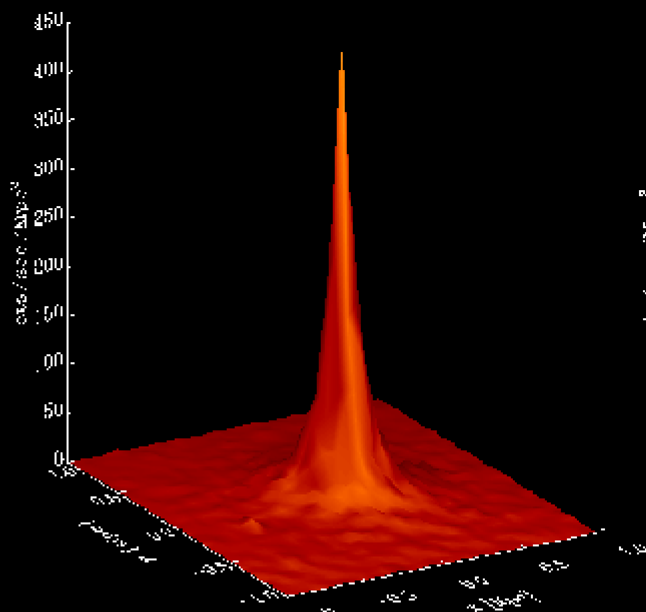
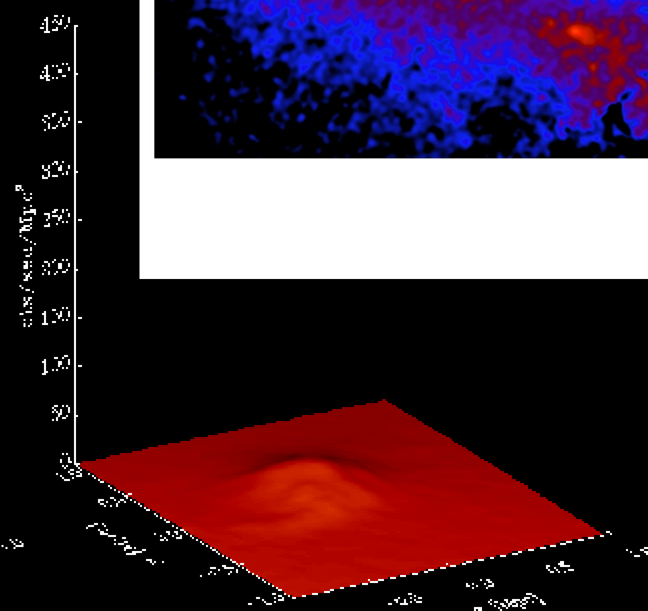


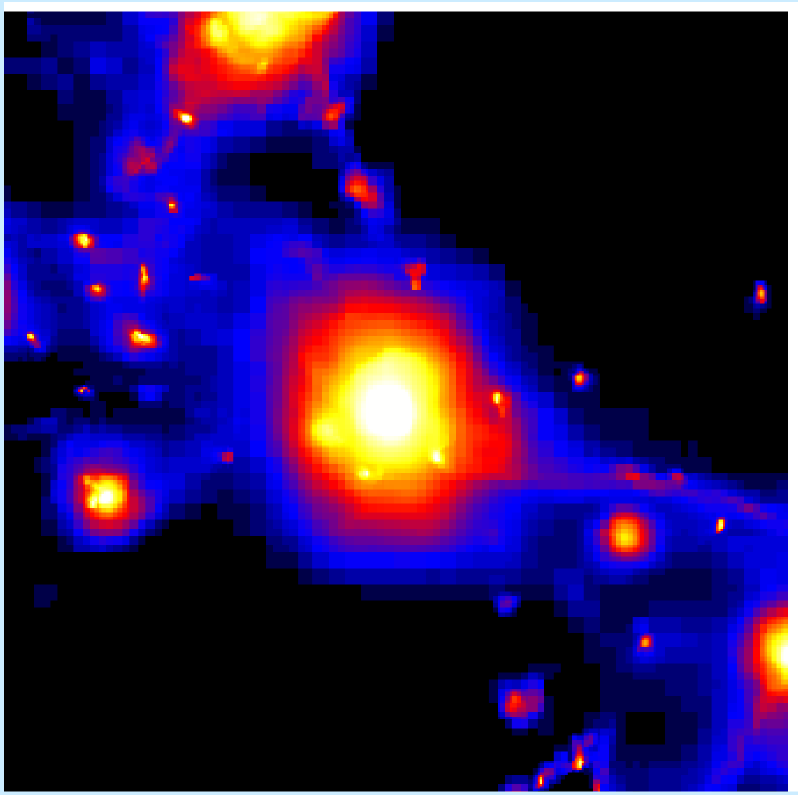


# Simple Cooling Flow Model

- Assumes an isolated, spherical cluster in quasi-hydrostatic equilibrium.
- Central gas thermally cools from $T_{virial}$ at constant pressure driving a subsonic accretion flow onto the central galaxy.
- Expect mass accretion rates of hundreds of solar masses per year.

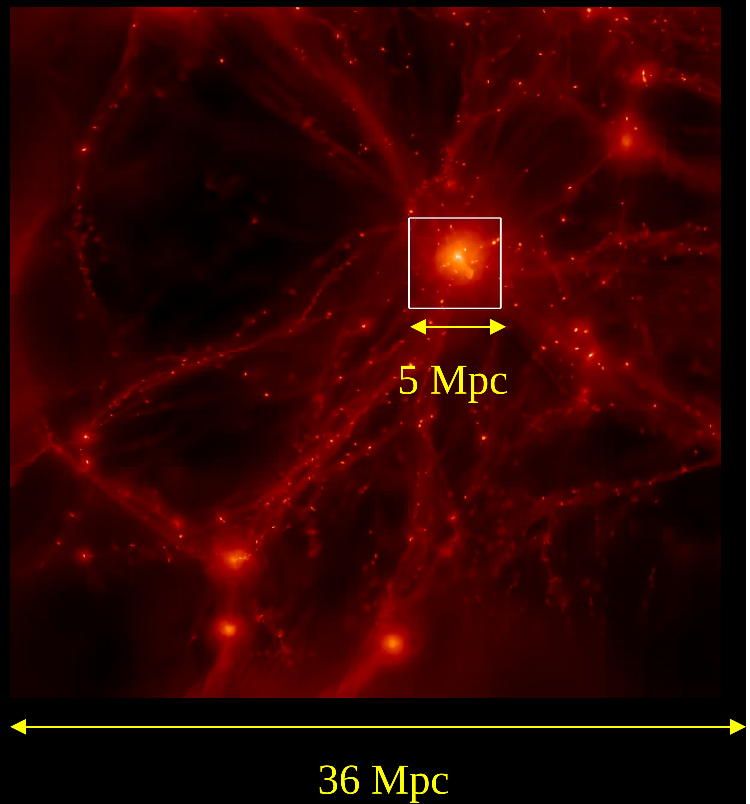
# Why “Cooling Flows” Don’t Work

- End-products of presumed 100 $M_{\odot}$ /yr infall are not seen:
  - Star-formation <1000 times of expected rate
  - Little or no HI
  - Molecules like CO not detected in abundance or over extended volume
- Central temperatures observed to be not less than ~0.3•$T_{virial}$.
- Simple model does not account for on-going accretion/mergers from supercluster environment, producing turbulent, shock-filled ICM => such clusters may be far from dynamical equilibrium.
- Does not explain why only 49% of clusters from the HIFLUGCS sample (Chen et al. 2006) have cool cores.



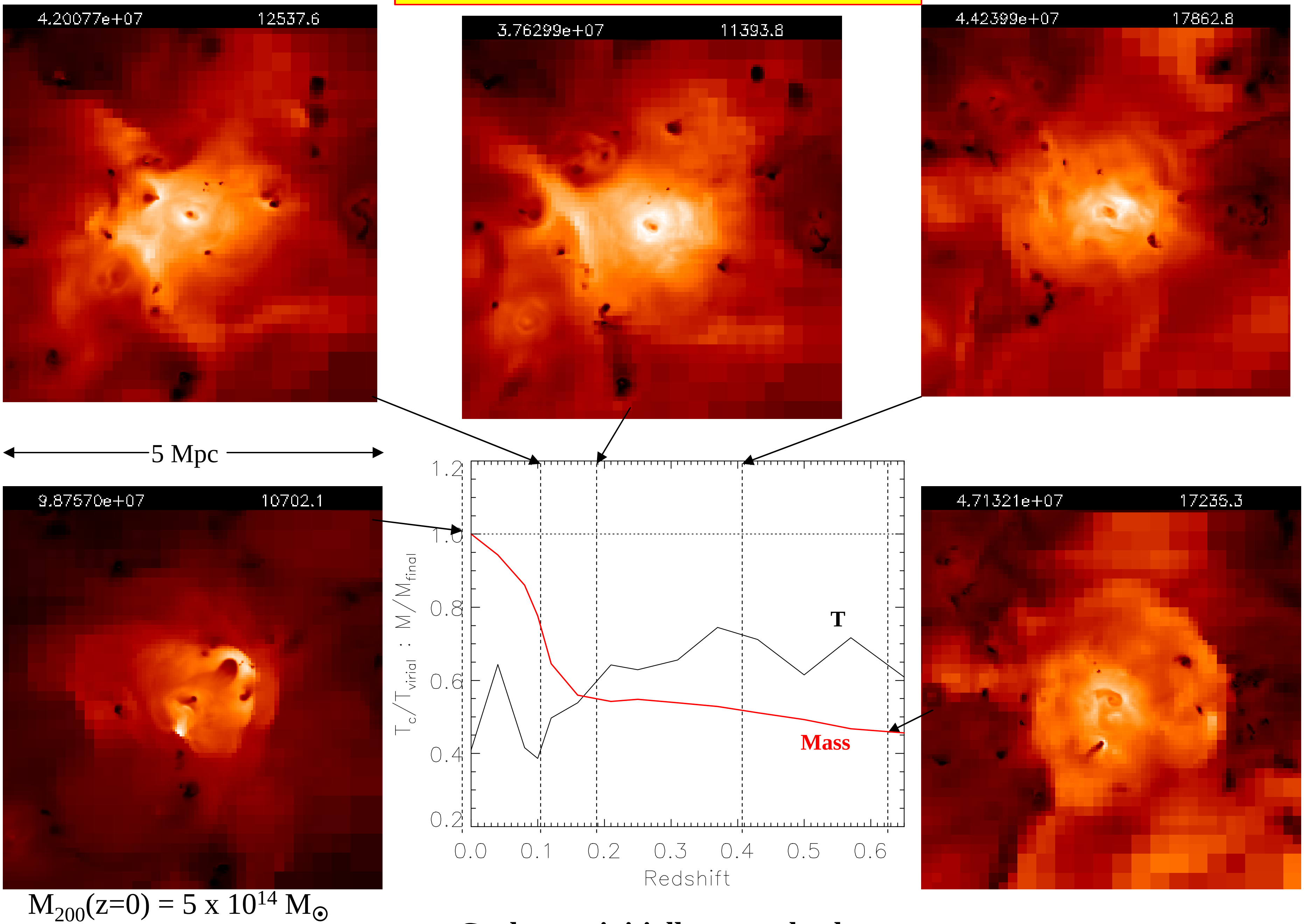
# Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

Enzo (e.g., O'Shea et al. 2006, http://cosmos.ucsd.edu/enzo)



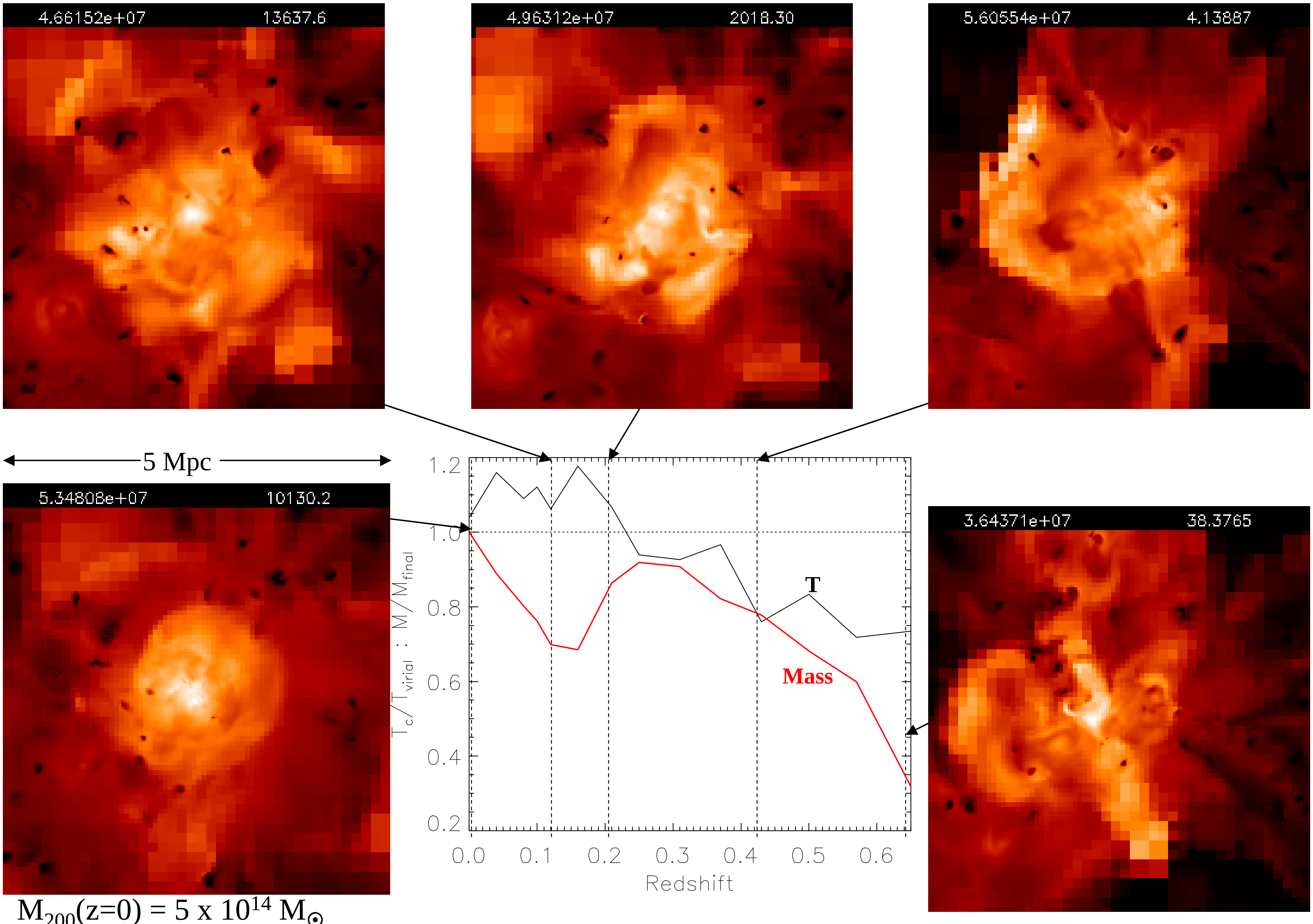

- $\Lambda$CDM Cosmology with $O_m = 0.3$, $O_b = 0.026$, $O_\Lambda = 0.7$, $h = 0.7$, and $s_8 = 0.9$.
- Hydro + N-body code uses AMR to achieve high resolution (2.0 to 15.6 $h^{-1}$ kpc) in dense regions.
- Simulation volume is 256 $h^{-1}$ Mpc on a side, use 7 to 9 levels of refinement with cluster subvolumes => 1500 clusters with $>10^{14}\,M_\odot$ for $z < 1$.
- Mass resolution is $10^{10}\,h^{-1}\,M_\odot$ (Dark Matter).
- Baryon physics includes thermal cooling, star formation, supernova (Type II) feedback, and AGN heating (in progress).

# Evolution of a Cool Core Galaxy Cluster



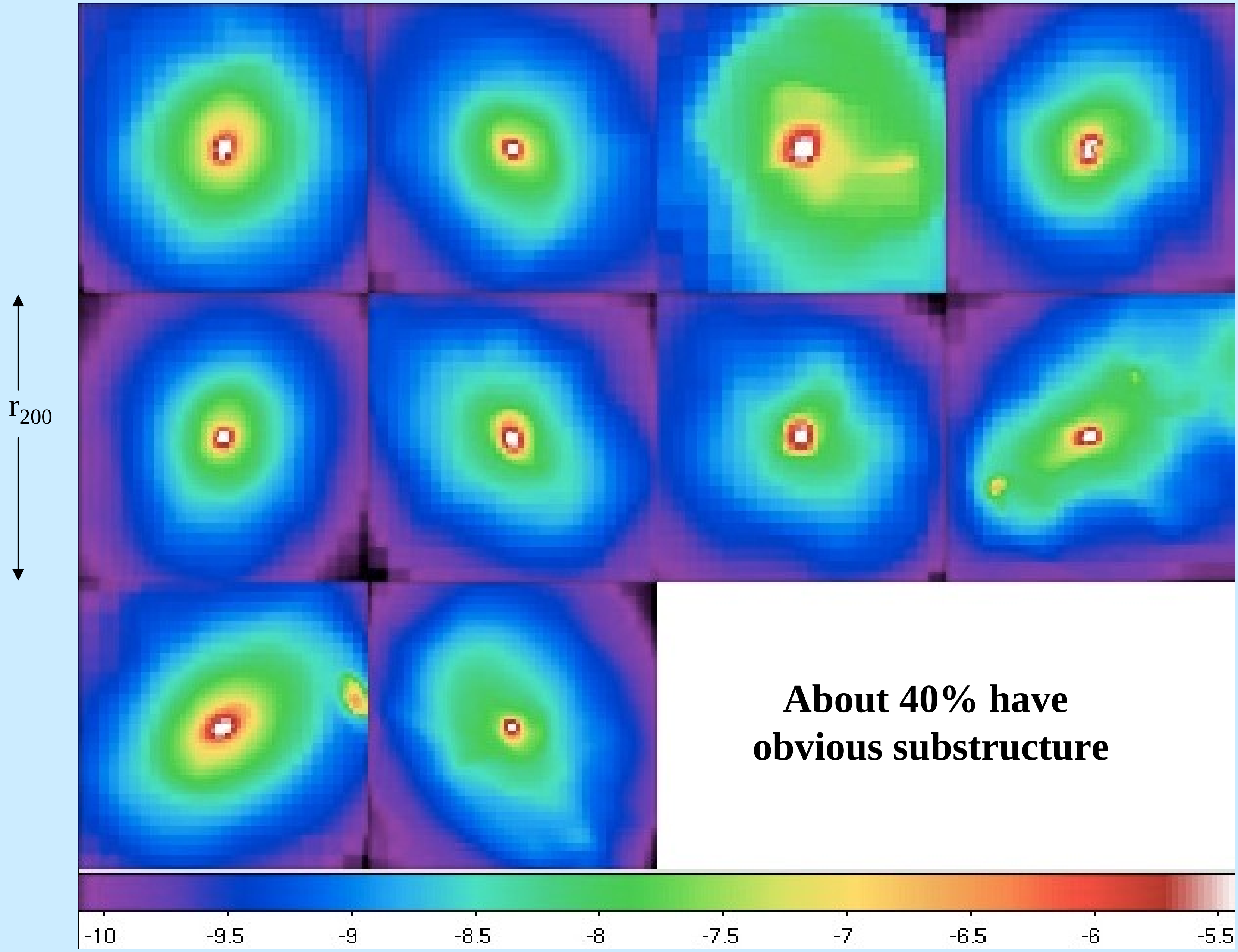

**Cool cores initially grow slowly**

# Evolution of a Non-Cool Core Galaxy Cluster



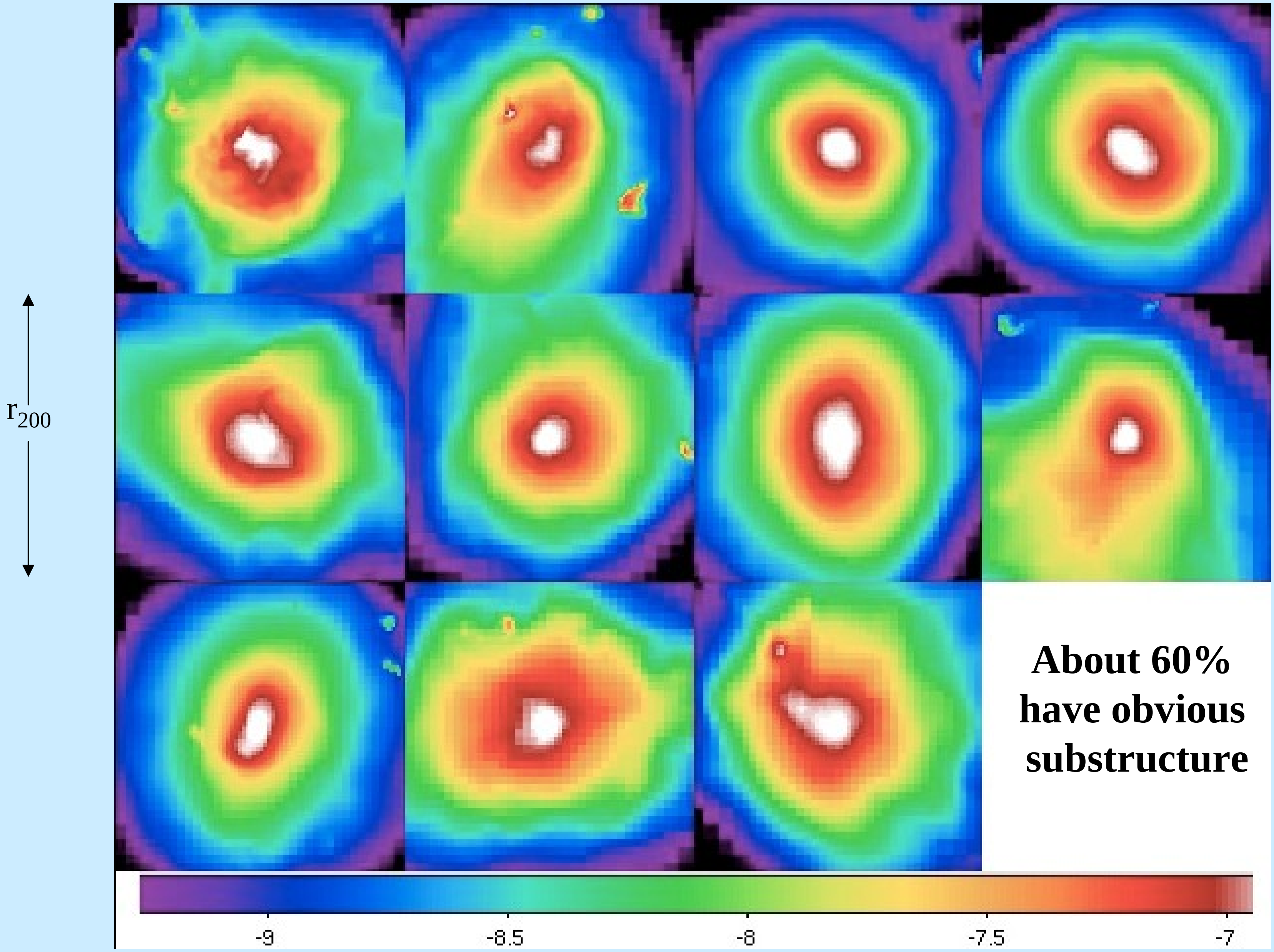

**Non-cool cores suffer major mergers**

# Synthetic X-ray Images for Numerical Cool Core Clusters



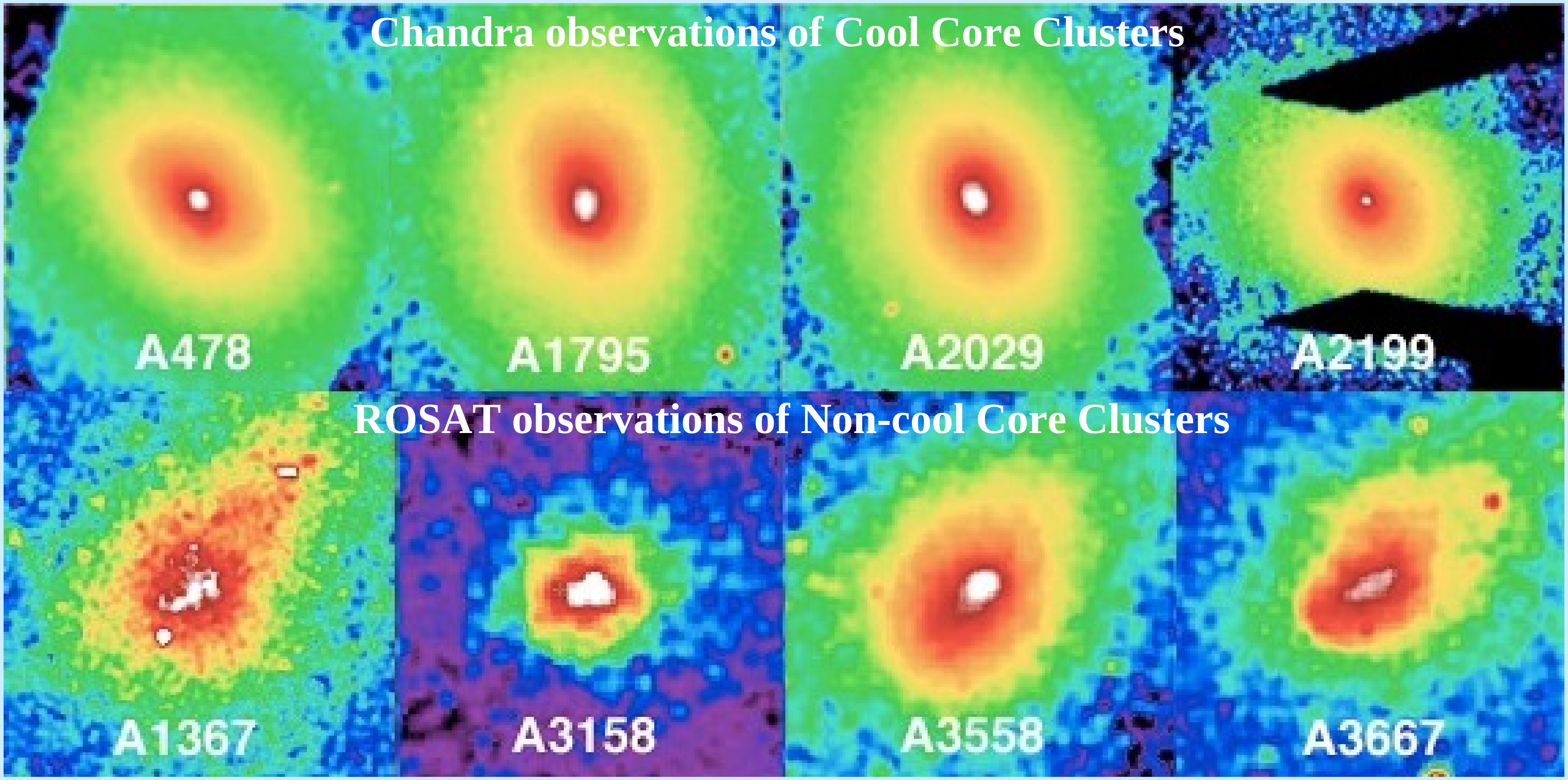

**About 40% have obvious substructure**

# Synthetic X-ray Images for Numerical Non-cool Core Clusters



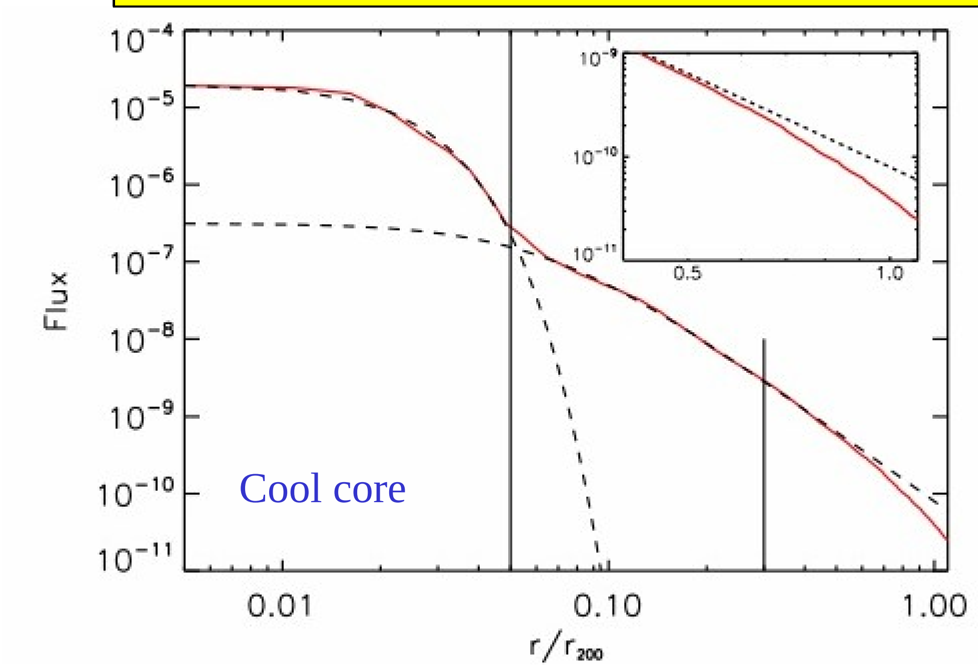

**About 60% have obvious substructure**

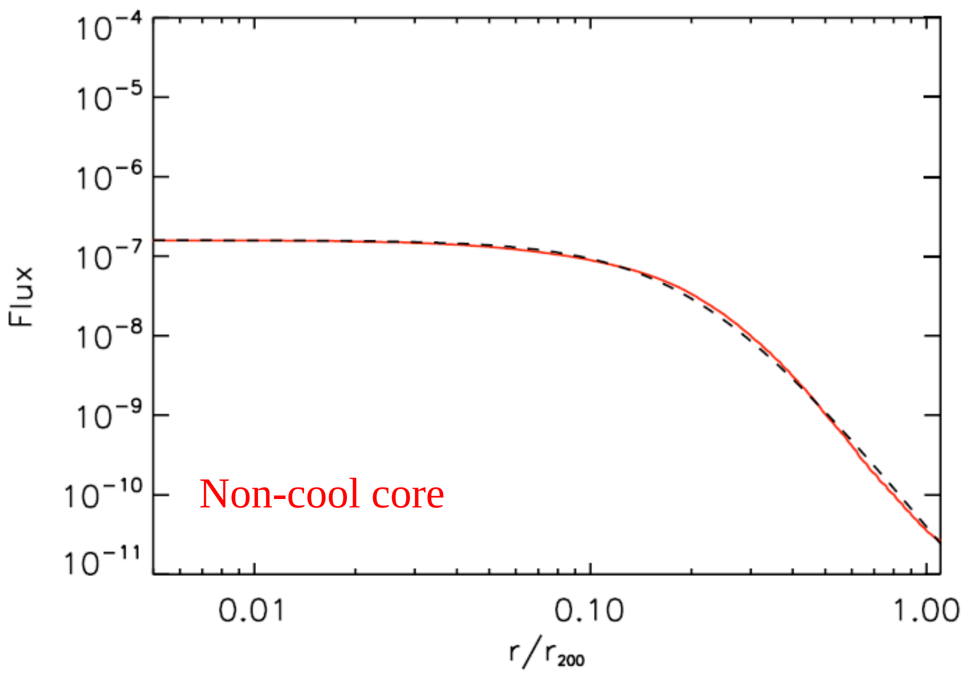
# X-ray Images of Abell Clusters



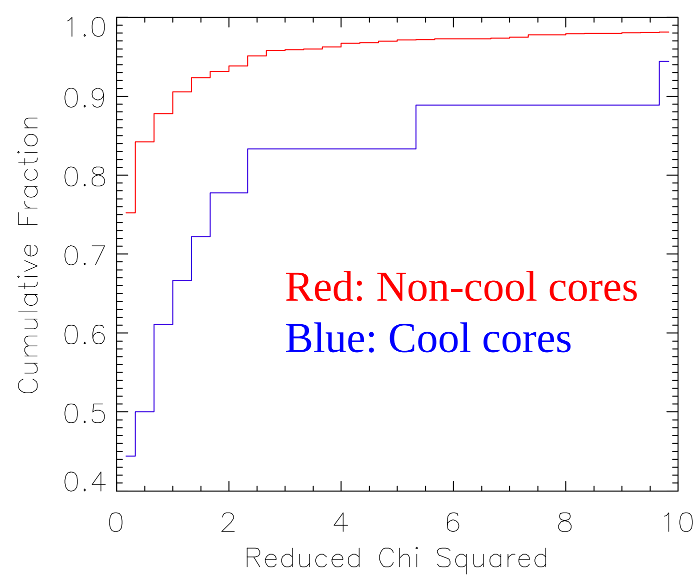

$\longleftarrow 0.5r_{200} \longrightarrow$

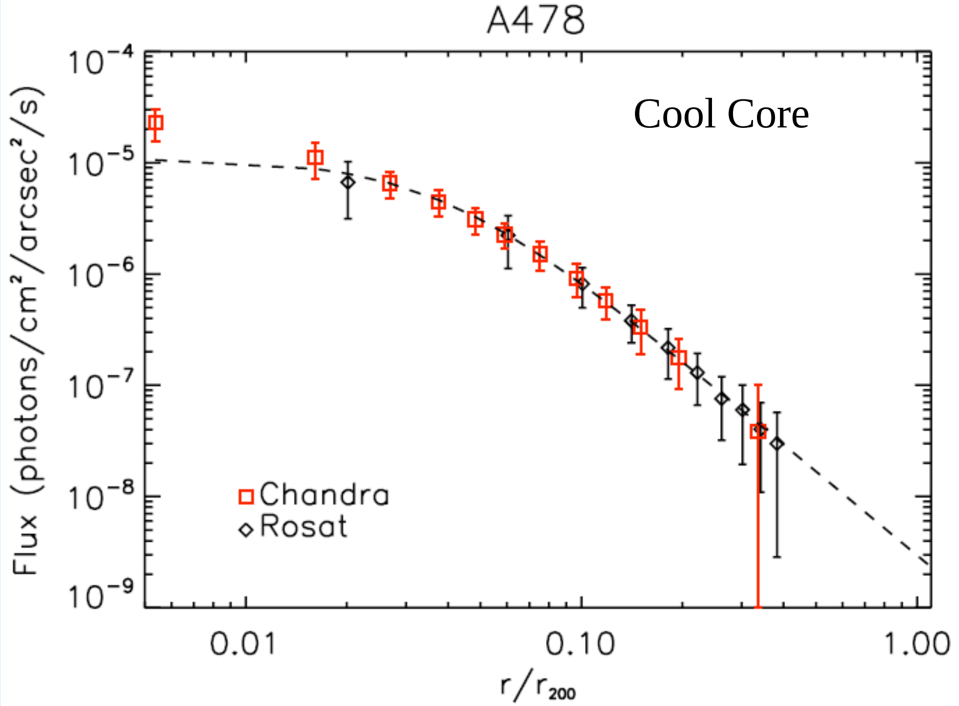
# Synthetic X-ray Surface Brightness Profiles for Numerical Clusters

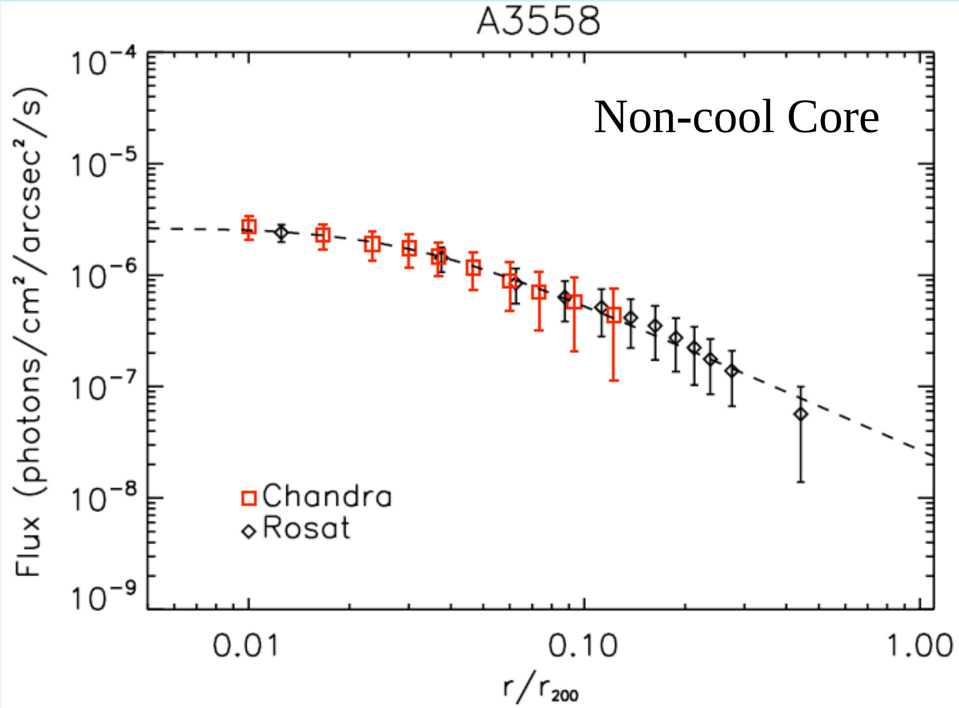



- Cool core clusters are fit poorly by beta models ($S_x = S_0[1+(r/r_c)^2]^{1/2-3ß}$) between $r_{500}$ and $r_{200}$ .
- Non-cool core clusters are fit very well to beta-models.
- Mass in CC clusters over-estimated by 3-5x.



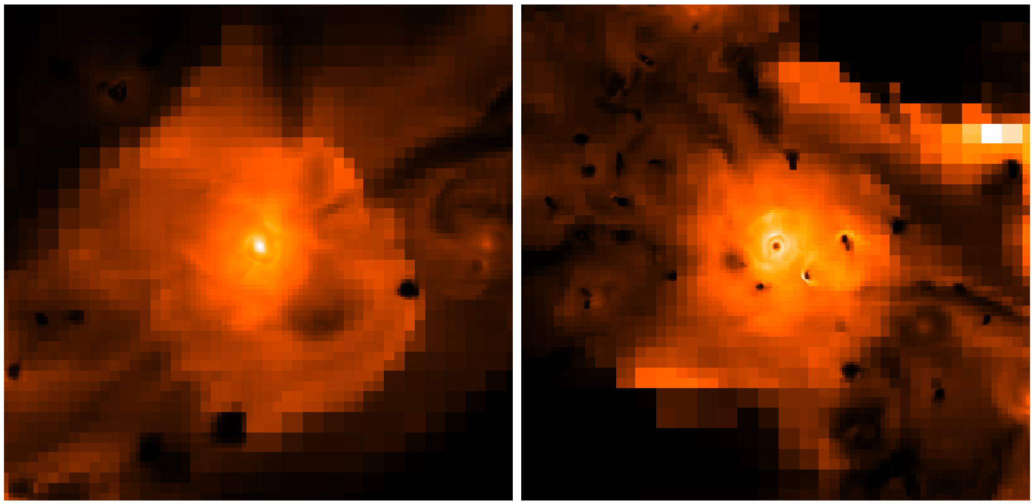



# Beta-model fits To Abell Clusters

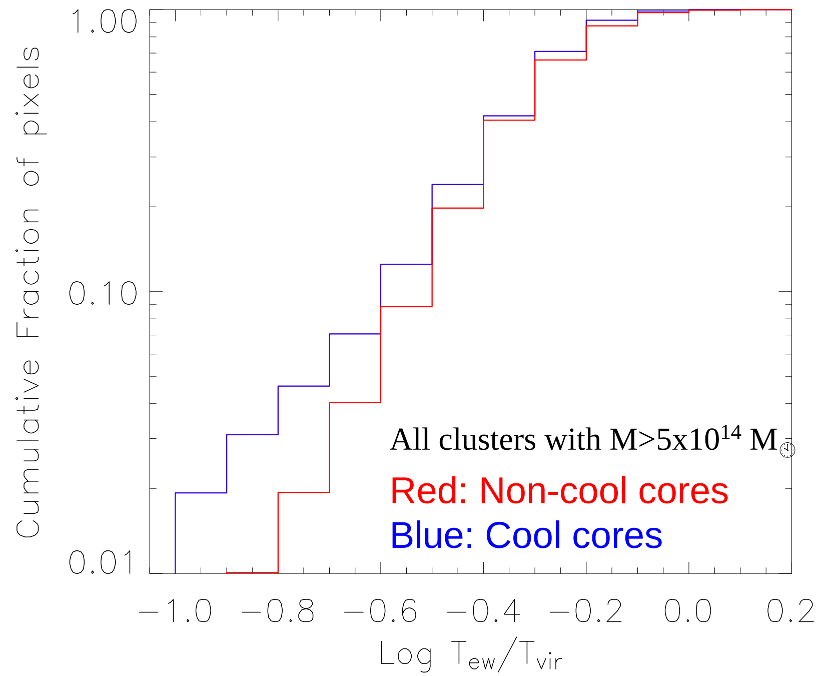
Observations currently do not extend far enough from the cluster core to see deviations from simple Beta model in outer part of CC cluster!

## Emission-Weighted Temperature

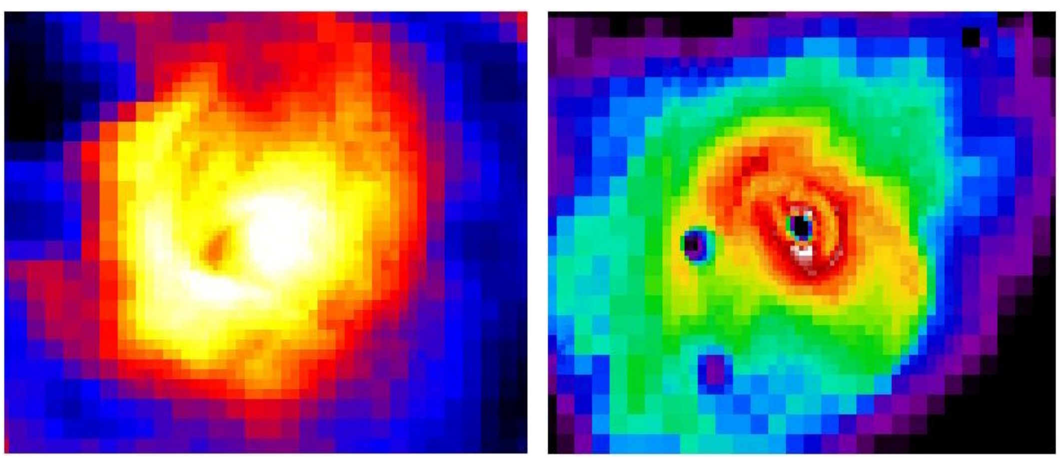


6 Mpc

$M_{200} = 2 \times 10^{14}\ M_\odot$



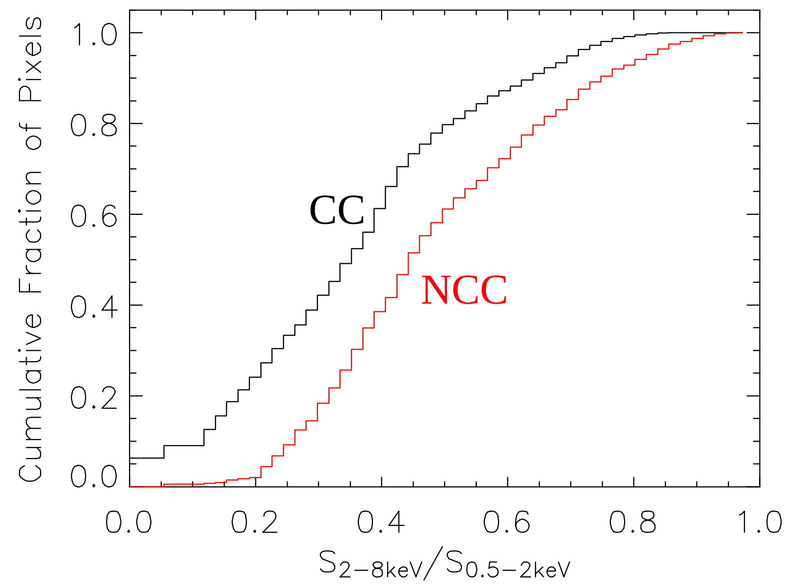

## Hardness Ratios (2-8 keV/0.5-2 keV)



3 Mpc

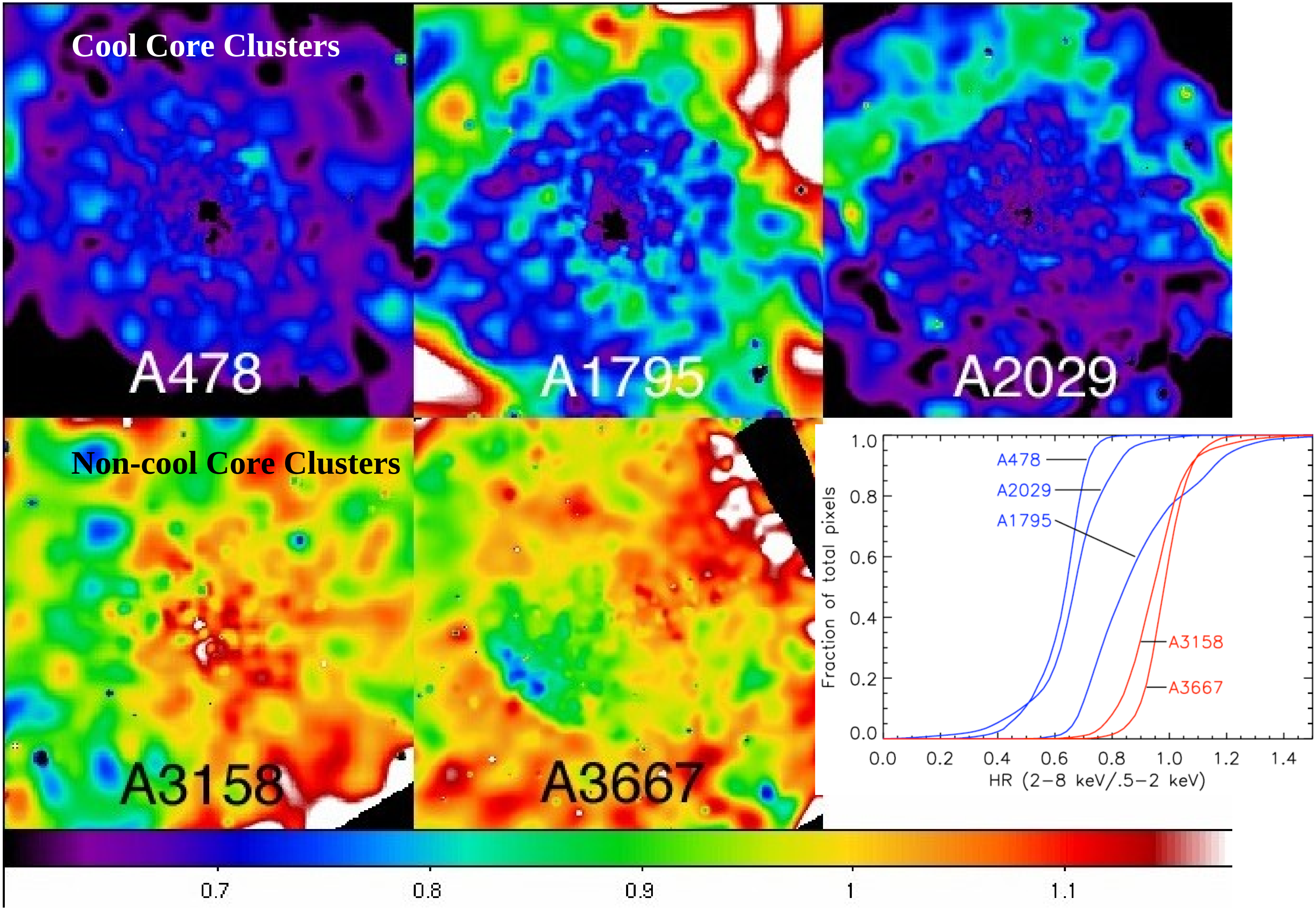
$M_{200} = 5 \times 10^{14}\ M_\odot$

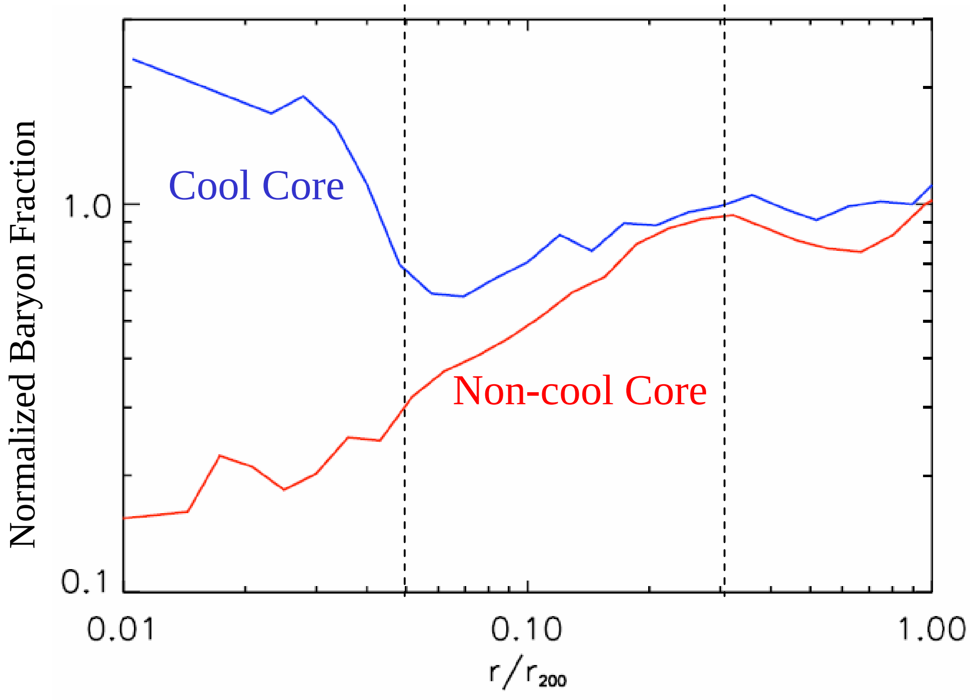
**Non-cool Core** **Cool Core**

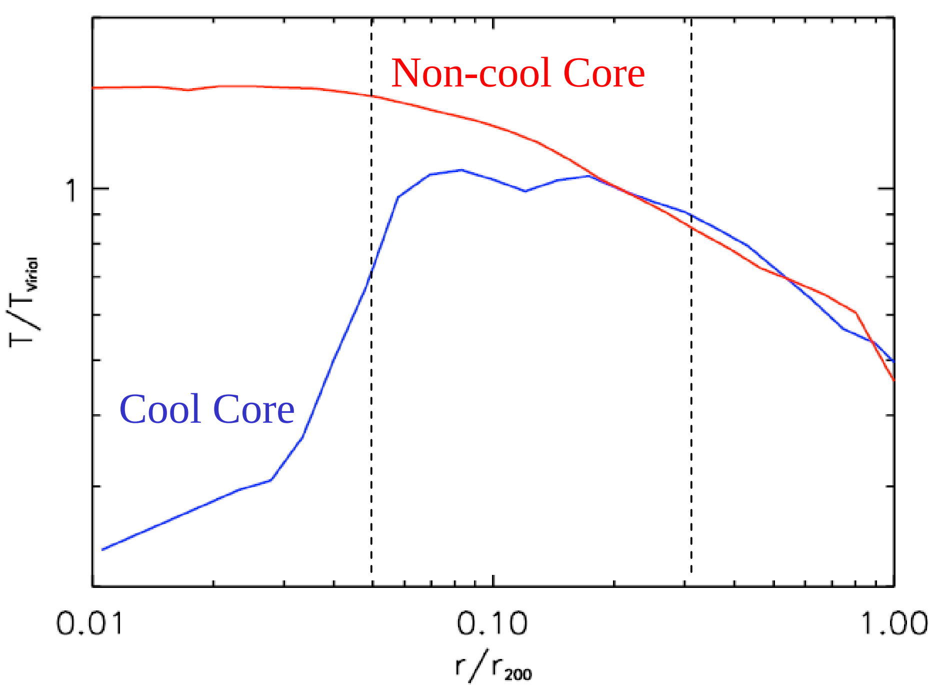



*=>Simulations predict more cold gas* ***outside the cores*** *in cool core clusters than in non-cool core clusters.*

# Hardness Ratios (2-8 keV/0.5-2 keV) for Abell Clusters from Chandra






# Comparison of Simulated CC & NCC Clusters

- NCC baryon properties approximate that of adiabatic gas.
- In contrast, CC cluster gas show strong non-adiabatic transition in thermodynamic properties where X-ray observations are typically made.

# Conclusions

- Cool core clusters are complicated, generally non-equilibrium systems where nongravitational physics is important.
- Our simulations suggest that *Non-cool core* (NCC) clusters suffer early major mergers when embryonic cool cores are destroyed. *Cool core* (CC) clusters grow more slowly without early major mergers.
- X-ray surface brightness profiles for NCC clusters are well fit by single ß-models whereas the outer emission for CC clusters is biased low compared to ß-models (resulting in masses and densities too high by factors of 3-5).
- CC clusters have roughly 40% more cool gas beyond the cores than do NCC clusters.
- These X-ray properties are produced by non-adiabatic transition region between cool core and outer cluster.