# Simulating the Universe: Giant Light Cones & Cool Cores in Galaxy Clusters


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*October 13, 2006*

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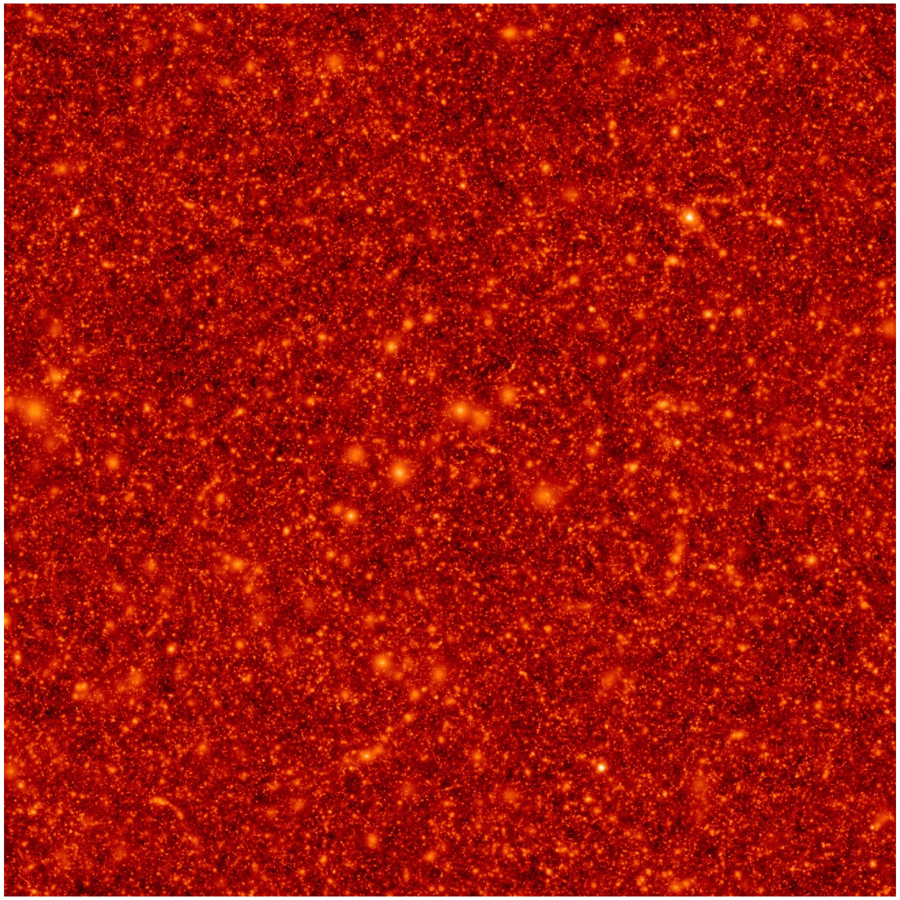
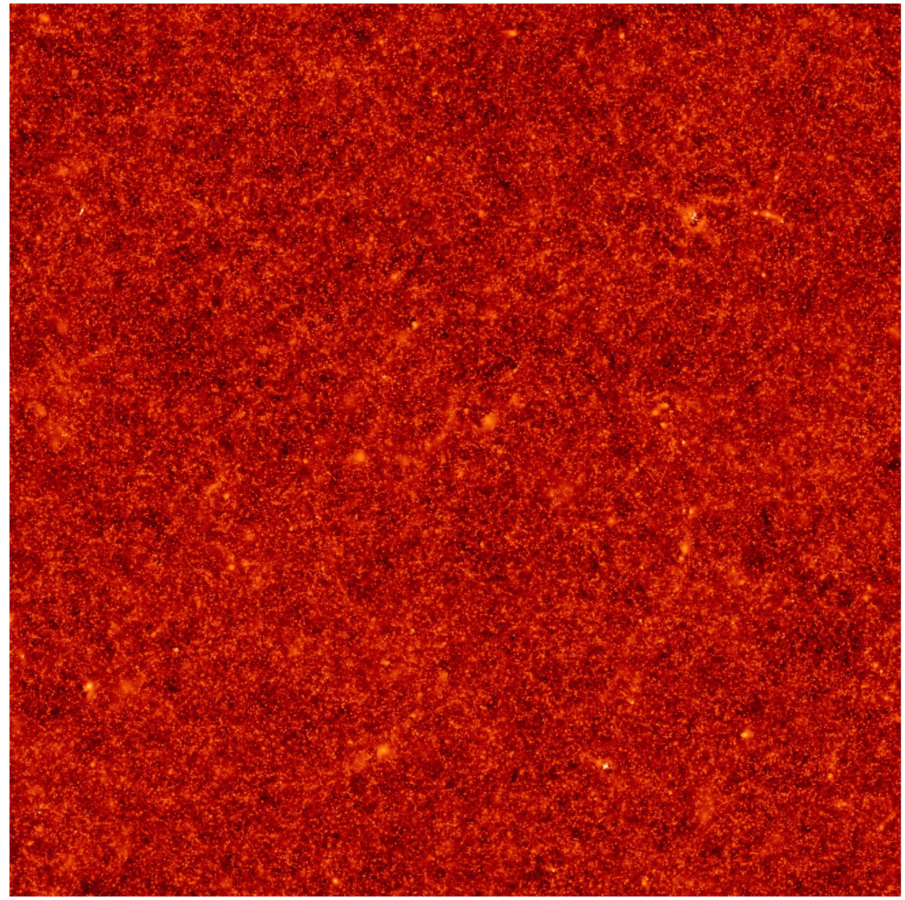
- Patrick Motl, LSU
- Michael Norman, University of California - San Diego
- Brian O’Shea, Los Alamos National Laboratory

# Sunyaev-Zeldovich Effect Light Cone 10º x 10º

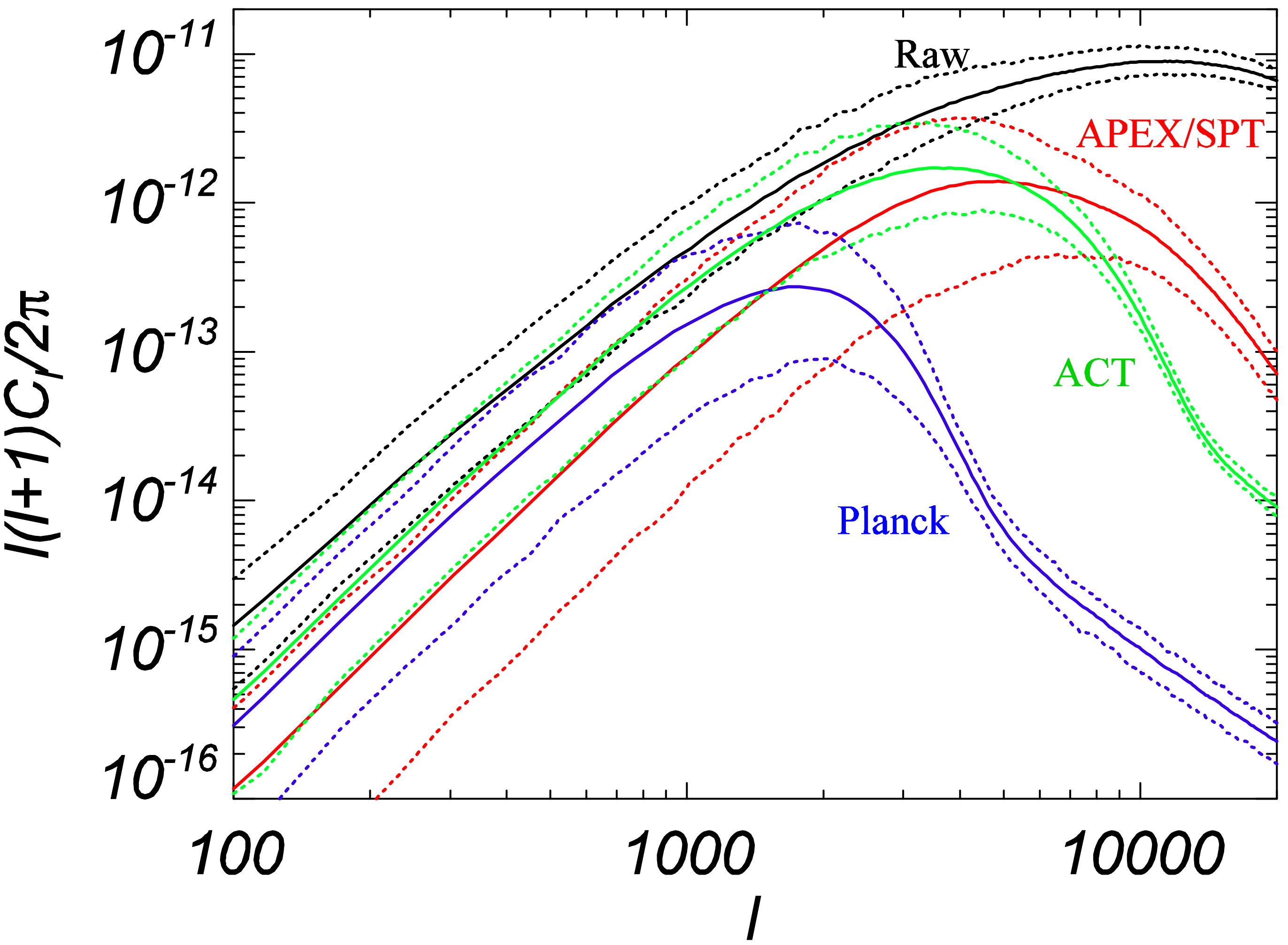




Enzo simulation with $(500\ h^{-1}\ Mpc)^3$ volume, 4 levels of refinement, $0<z<3$, adiabatic physics, 10" resolution.

Same as left image but clusters with $M>5x10^{13}$ solar masses have been removed.

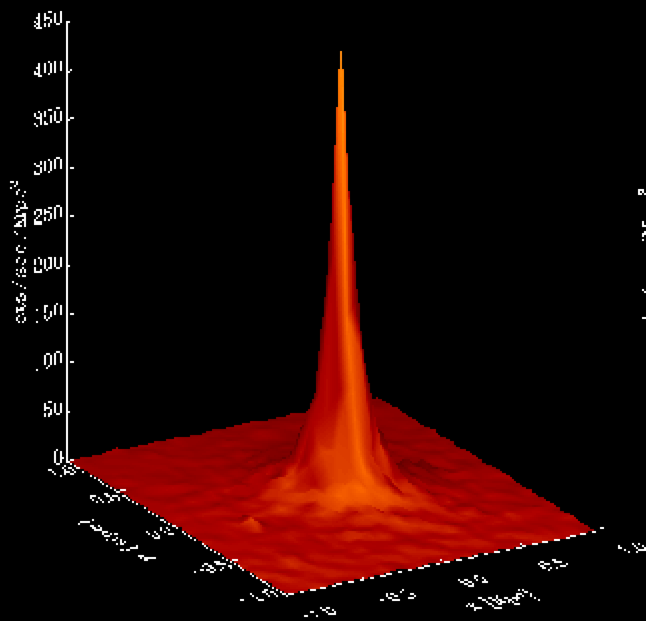
**=>Fully half of the SZE flux comes from very low mass halos and filamentary structures made up of gas in the Warm Hot Ionized Medium (WHIM) phase.**



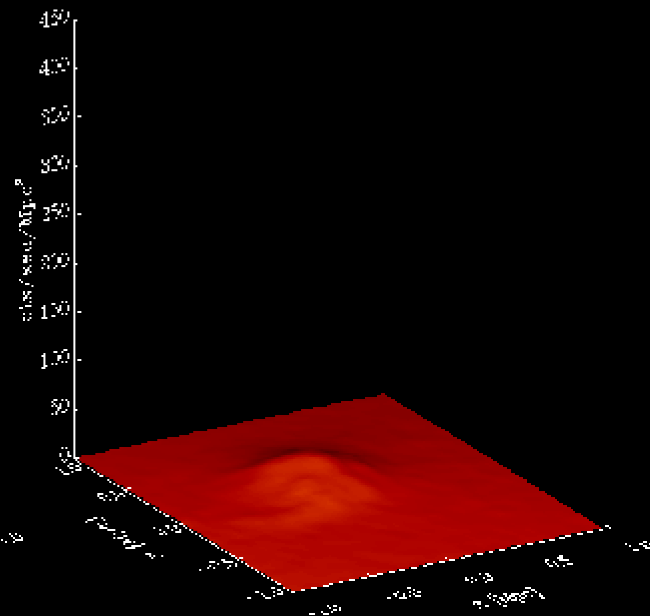

Power spectra of the Light Cone images including instrumental response for 4 upcoming experments.

# Cooling Core *vs* Non-Cooling Core Clusters

Abell 478

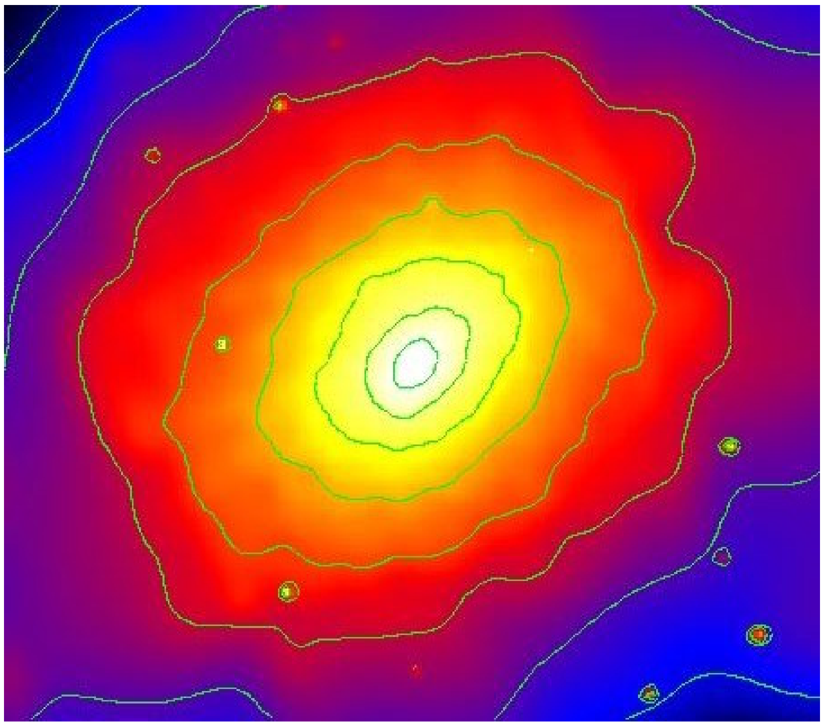


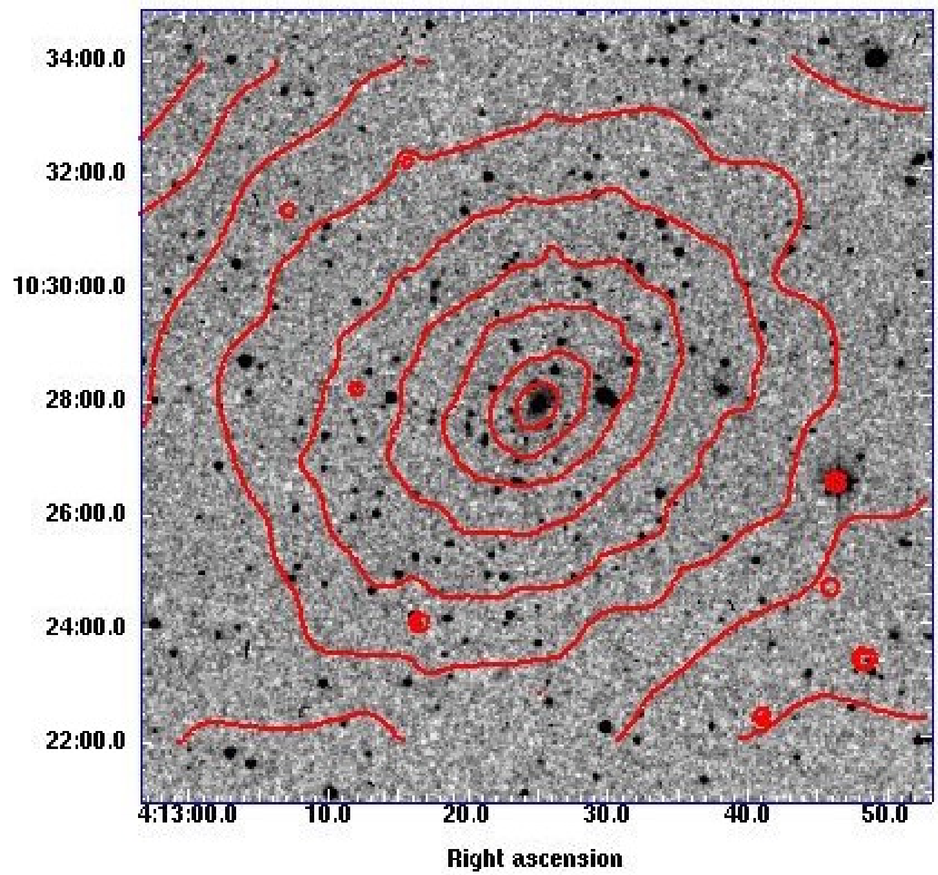
Coma



(slide courtesy of A. Fabian)

# ABELL 478





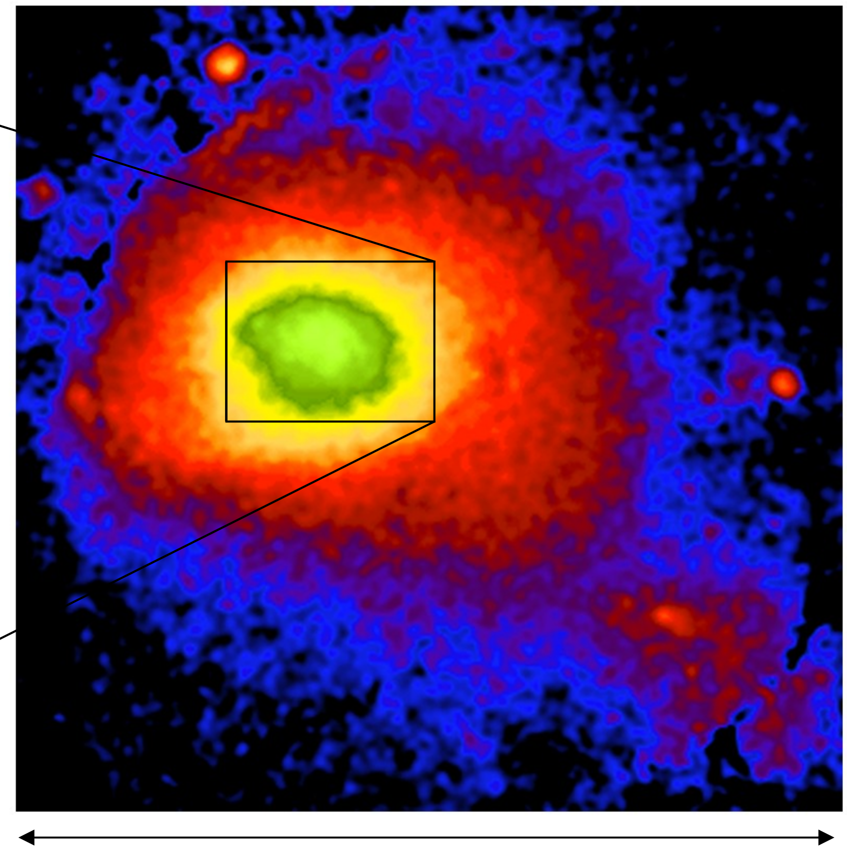

*Chandra* observations of a cool core cluster

# THE COMA CLUSTER

DSS Image of Coma Core

22’

Coma ROSAT PSPC 0.73-2.04 keV



~ 3 Mpc

Burns *et al*. 1994, ApJ, **427,** L87

# Simple Cooling Flow Model

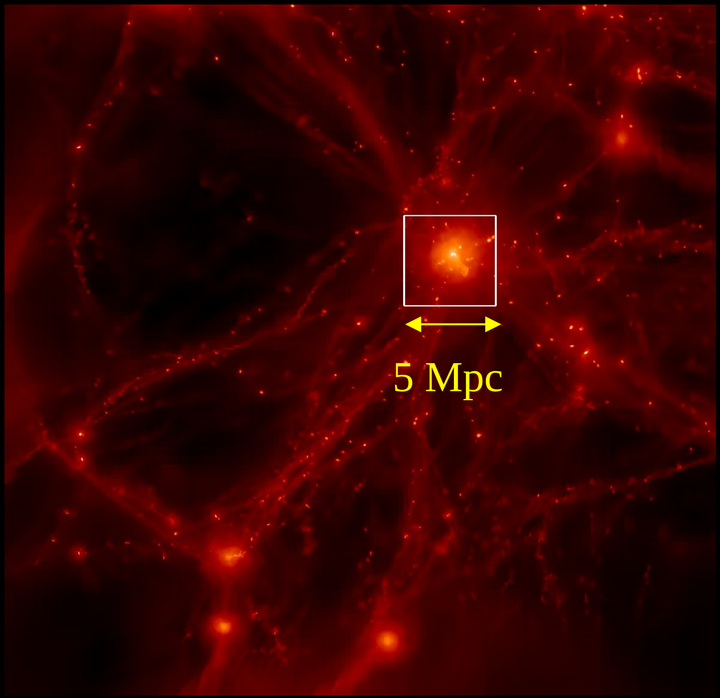
- Assumes an isolated, spherical cluster in quasi-hydrostatic equilibrium.
- Central gas thermally cools from $T_{virial}$ at constant pressure driving a subsonic accretion flow onto the central galaxy.
- Expect mass accretion rates of hundreds of solar masses per year.

# 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 ~ $0.3 \bullet T_{virial}$
- Simple model does not account for on-going accretion/mergers from supercluster environment, producing turbulent, shock-filled ICM (i.e., stormy weather) => such clusters may be far from dynamical equilibrium

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

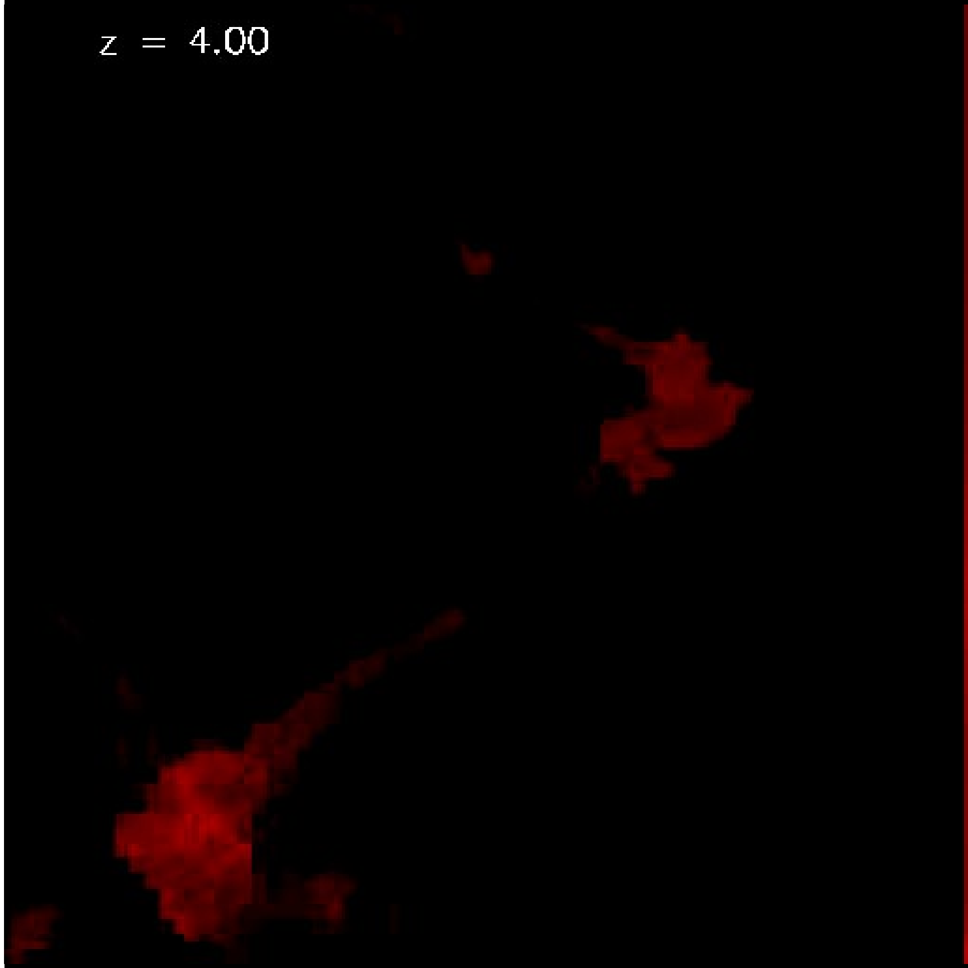
Enzo (e.g., O'Shea et al. 2006, http://cosmos.ucsd.edu/enzo)

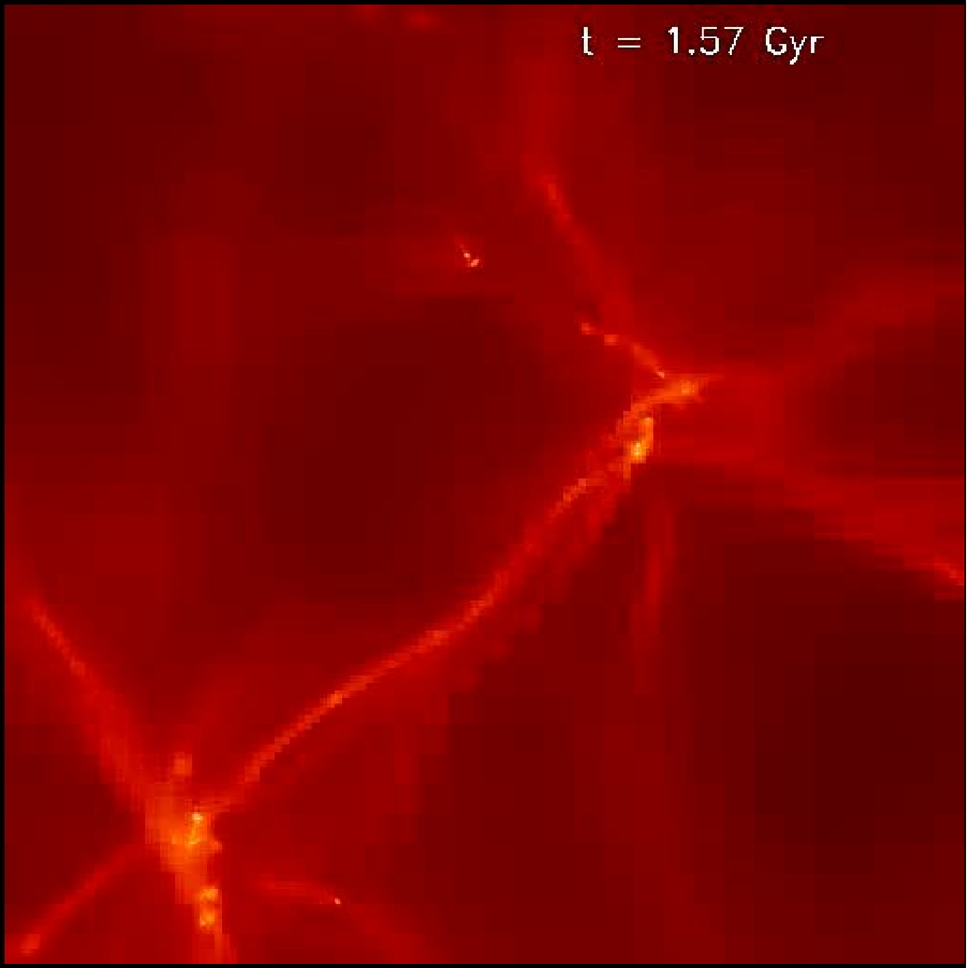



36 Mpc

- ΛCDM 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.
- 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).

# Formation of Cool Core Clusters




**Emission-Weighted Temperature**

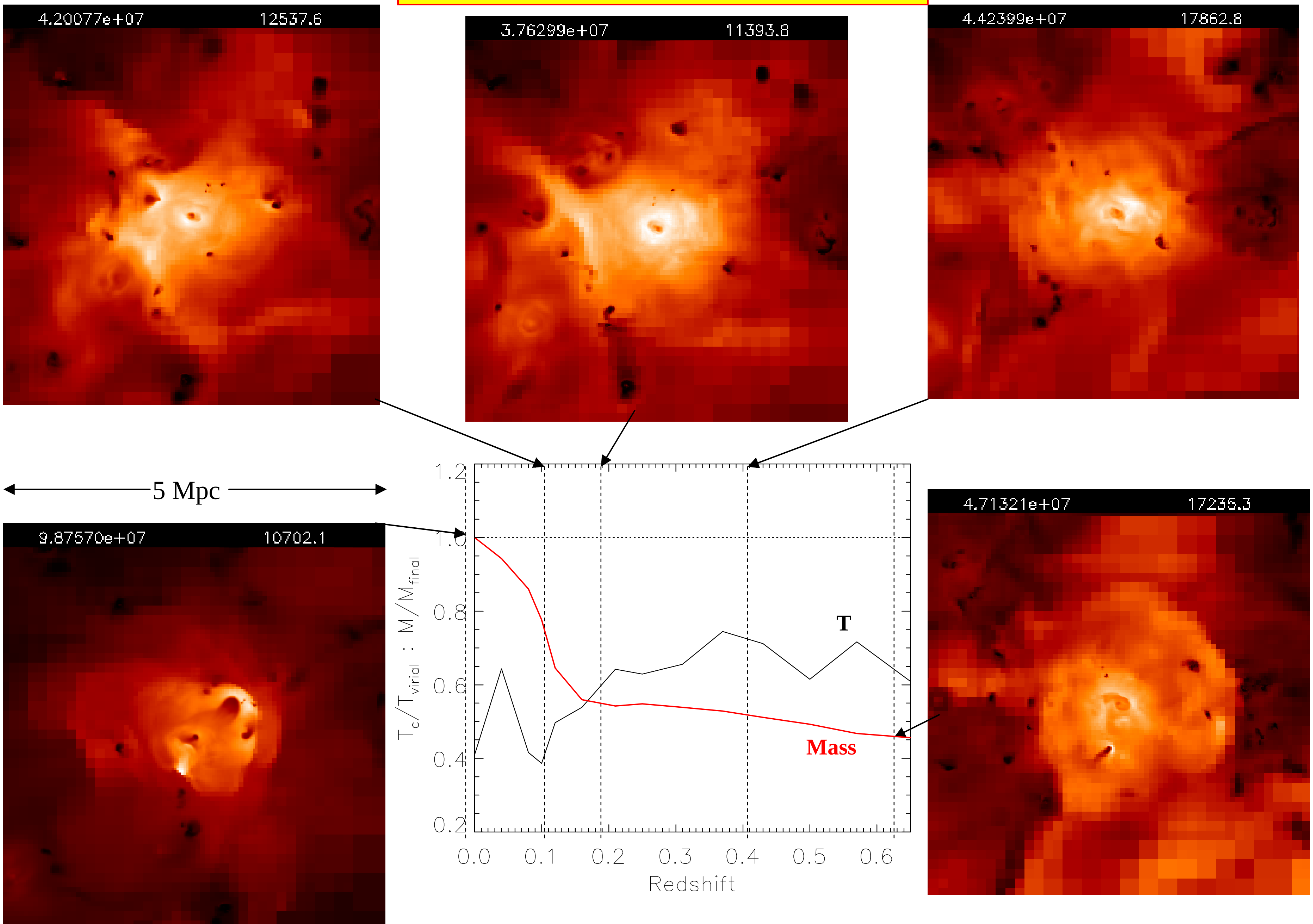
**Projected Density**

# Statistics of Cool Core Clusters

- White et al. (1997) sample of clusters from *Einstein* found cool cores in ≈60% of their 207 cluster sample.
- Peres et al. (1998) found over 70% of their sample of clusters observed with *ROSAT* to have cool cores.
- Chen et al. (2006) identify 49% of their HIFLUGCS sample, based on *ROSAT* and *ASCA* data, as having cool cores.

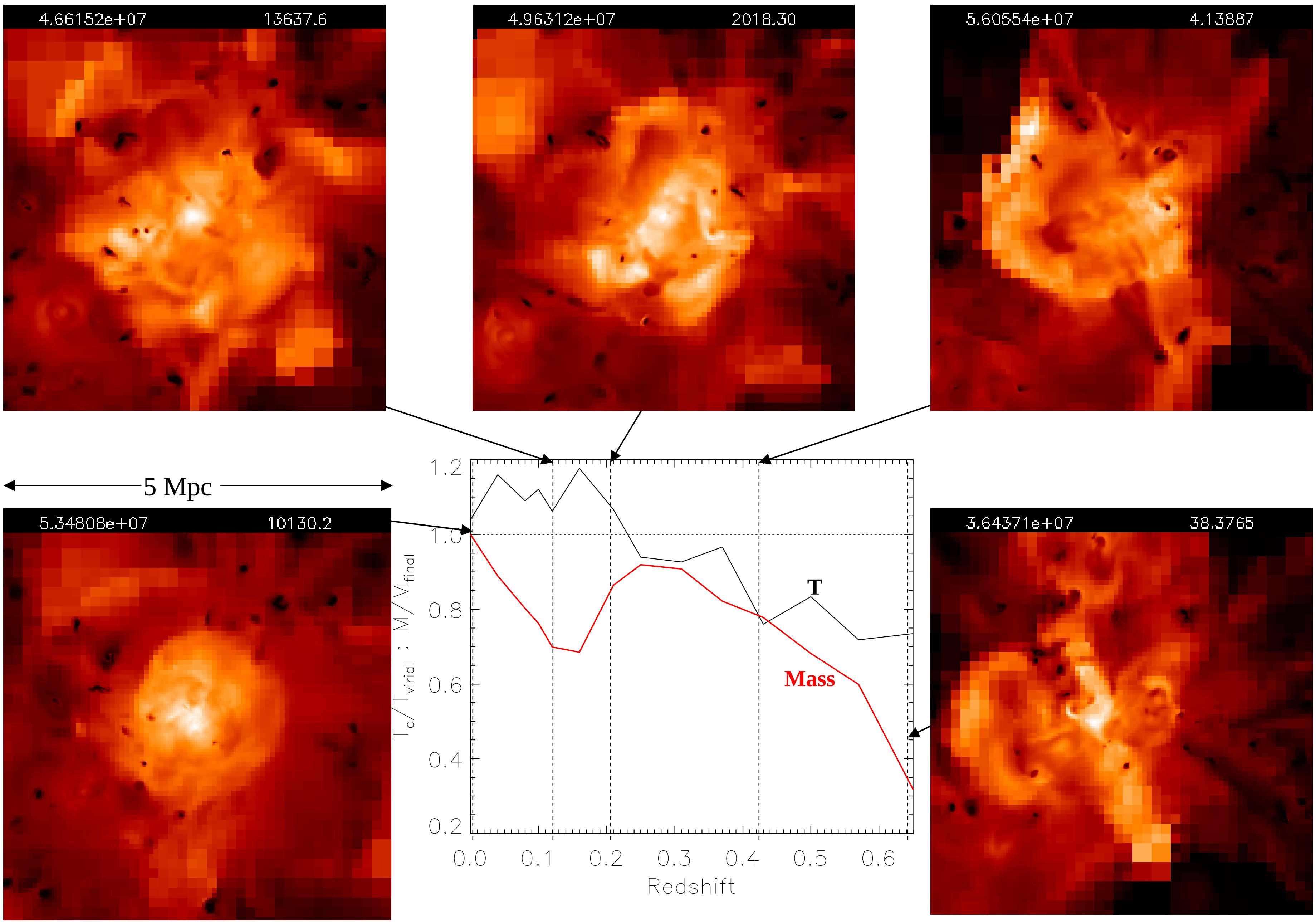
Why do only about half of clusters in flux-limited samples have cool cores?

# Evolution of a Cool Core Galaxy Cluster

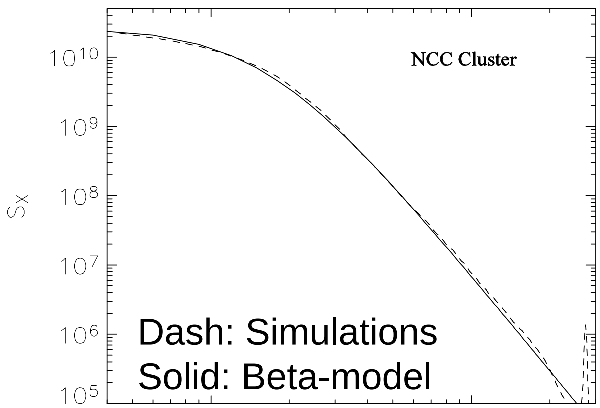


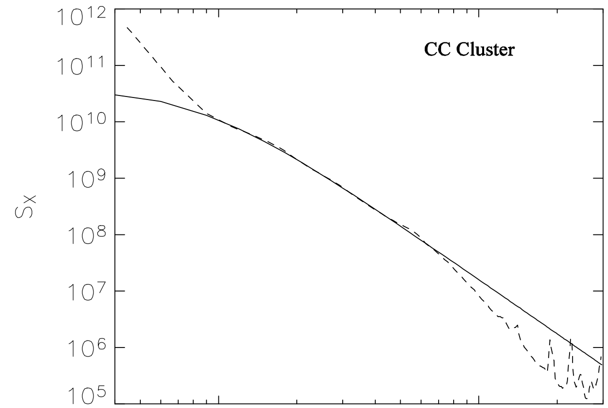

**Cool cores initially grow slowly**

# Evolution of a Non-Cool Core Galaxy Cluster



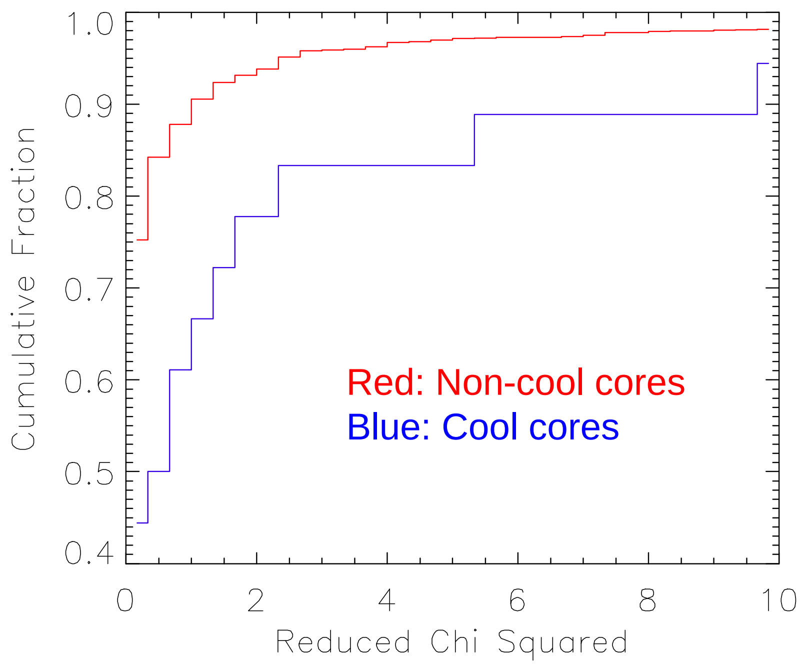

**Non-cool cores suffer early major mergers**

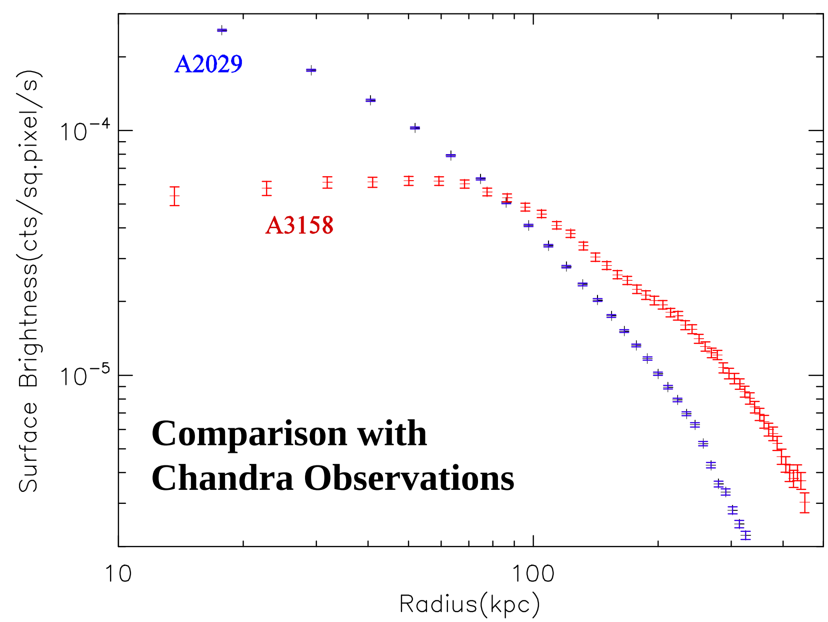


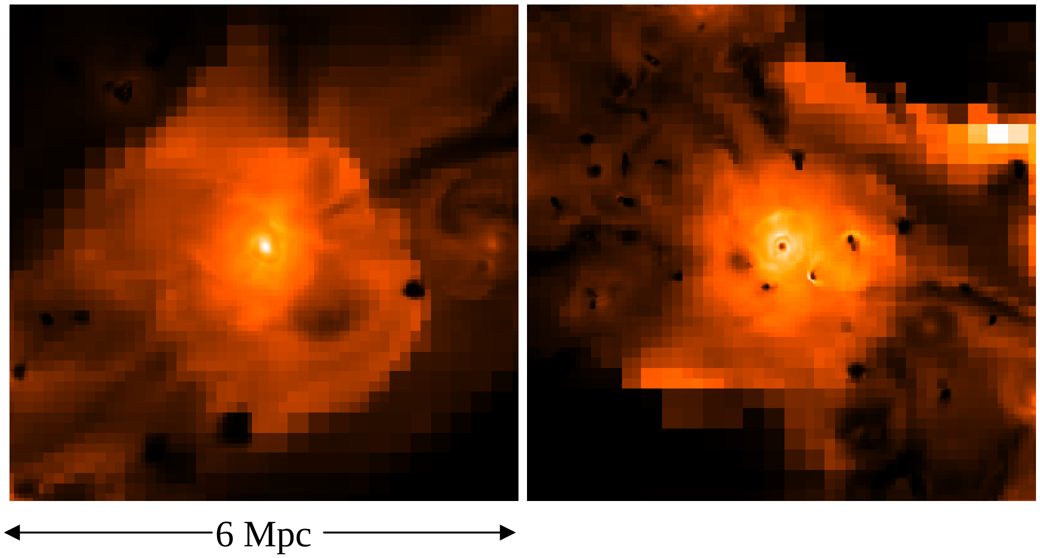

# X-ray Surface Brightness Profiles

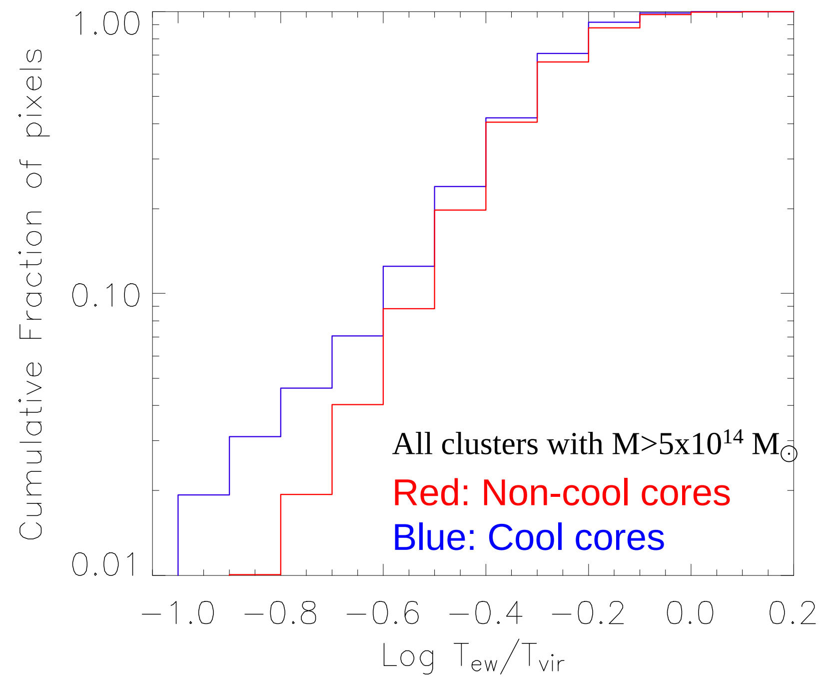
- Non-cool core clusters are fit very well to beta-models, $S_x=S_0[1+(r/r_c)^2]^{1/2-3\beta}$.
- Cool core clusters are fit poorly by beta models between $r_{500}$ and $r_{200}$ .
- Mass in CC clusters over-estimated by 3-5x.



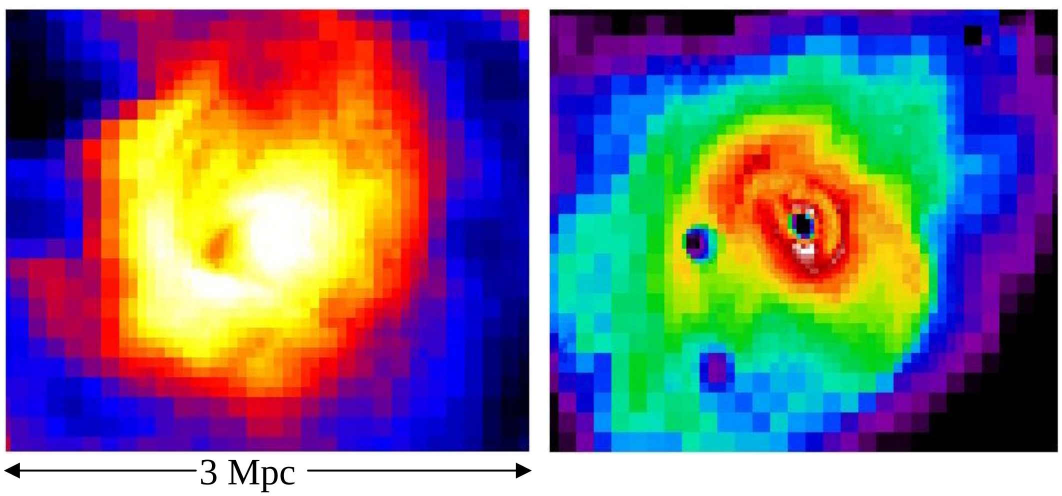



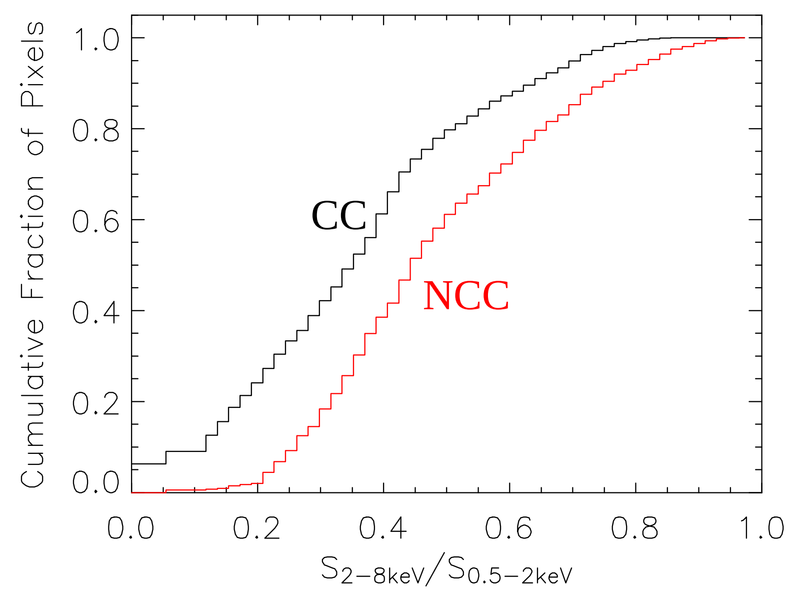
**Emission-Weighted Temperature**




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

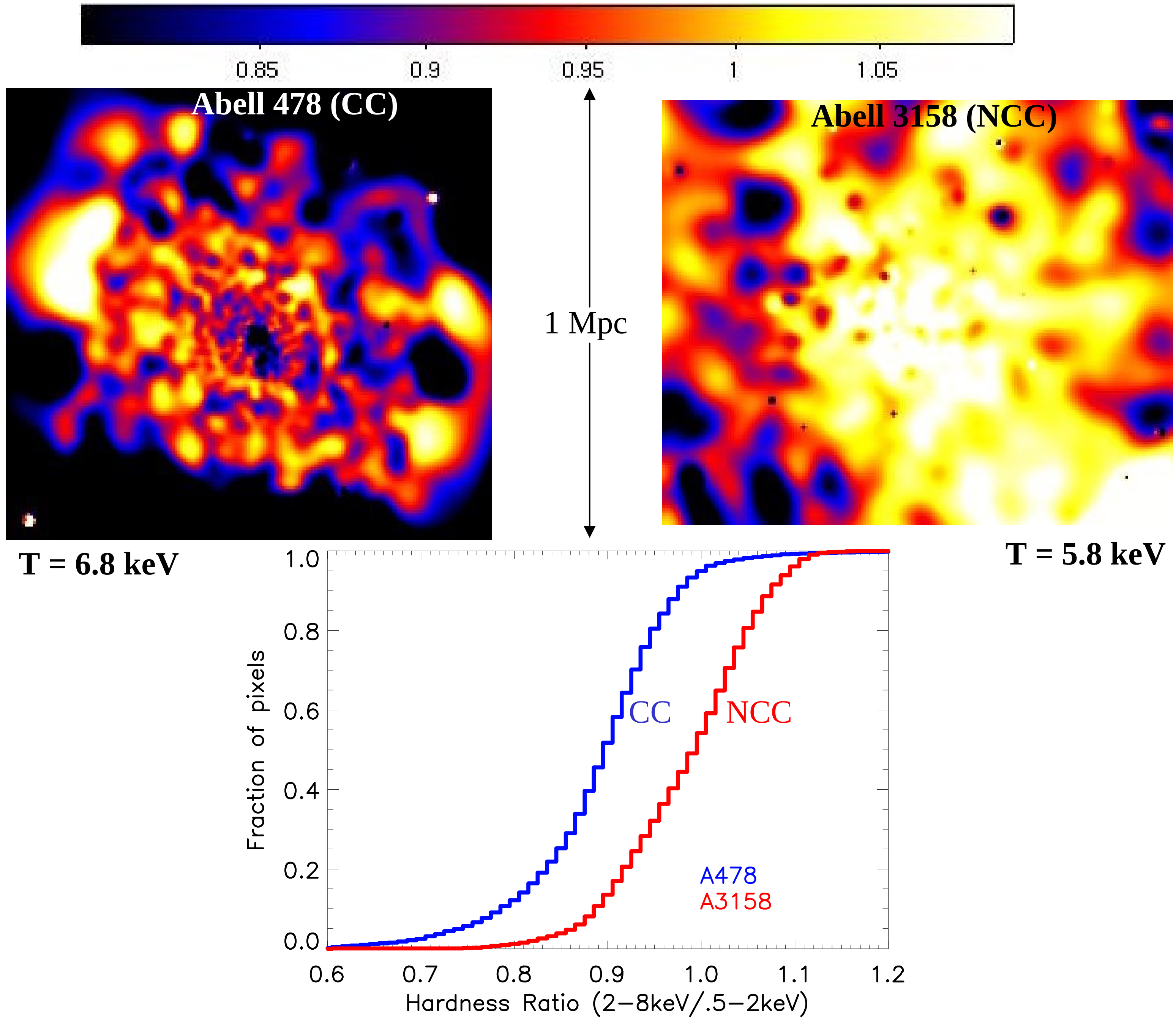


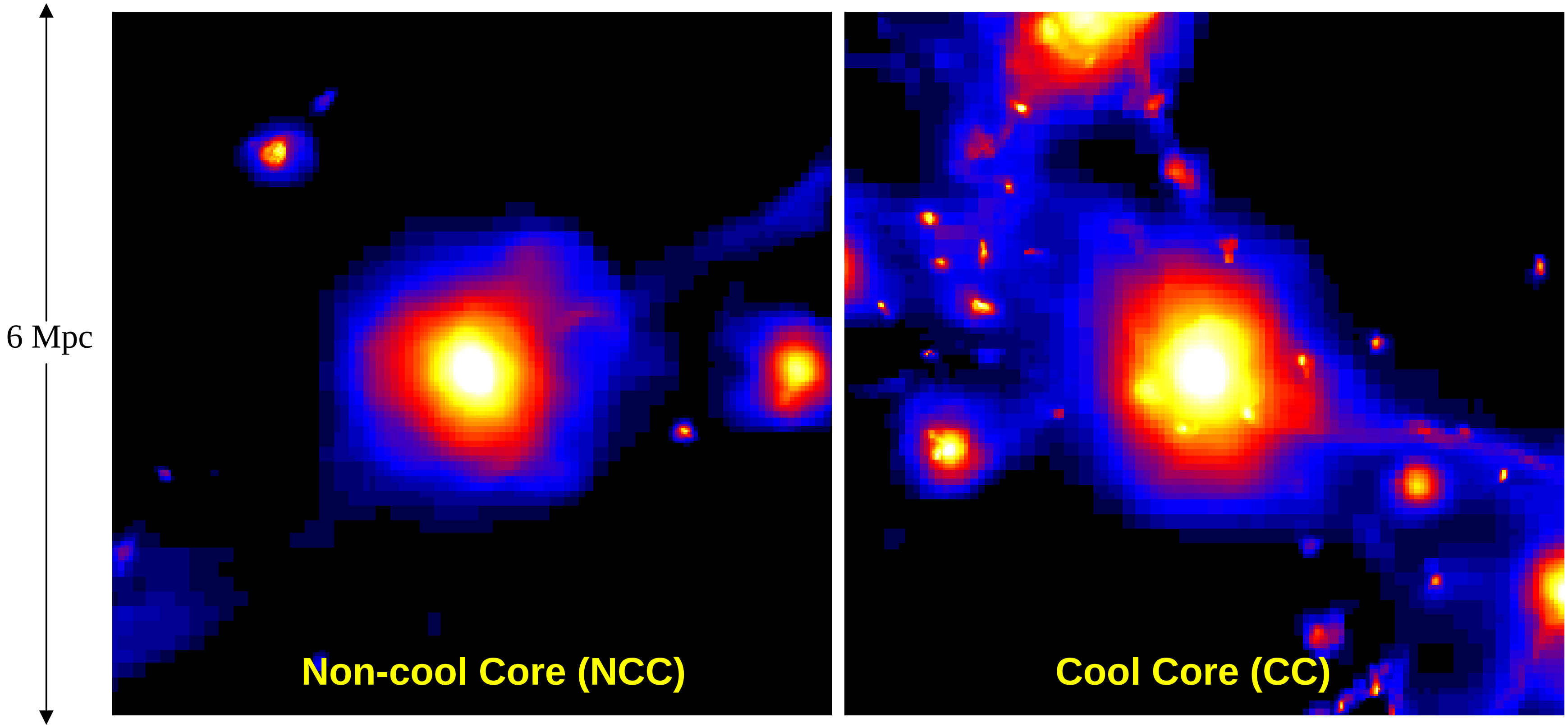

**Non-cool Core** **Cool Core**

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

# Hardness Ratio (2-8 kev/0.5-2 keV) Comparisons with Chandra Observations



# Different Supercluster Environments for CC and NCC Clusters




**Synthetic X-ray Emission**

- Numerical CC clusters lie within denser, more crowded supercluster environment than NCC clusters.
- Agrees with Loken et al. (1999) who find that CC Abell clusters are surrounded by a higher density of other Abell clusters than NCC clusters.

# 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 40% more cool gas beyond the cores than do NCC clusters.
- CC clusters generally lie within higher density supercluster environments in comparison to NCC clusters.