Beyond the Cool Core: The Formation of Cool Core Galaxy Clusters

Jack Burns, Eric Hallman, & Brennan Gantner
University of Colorado, Boulder

Patrick Motl
Louisiana State University

Michael Norman
University of California, San Diego

Heating vs. Cooling in Galaxies & Clusters of Galaxies
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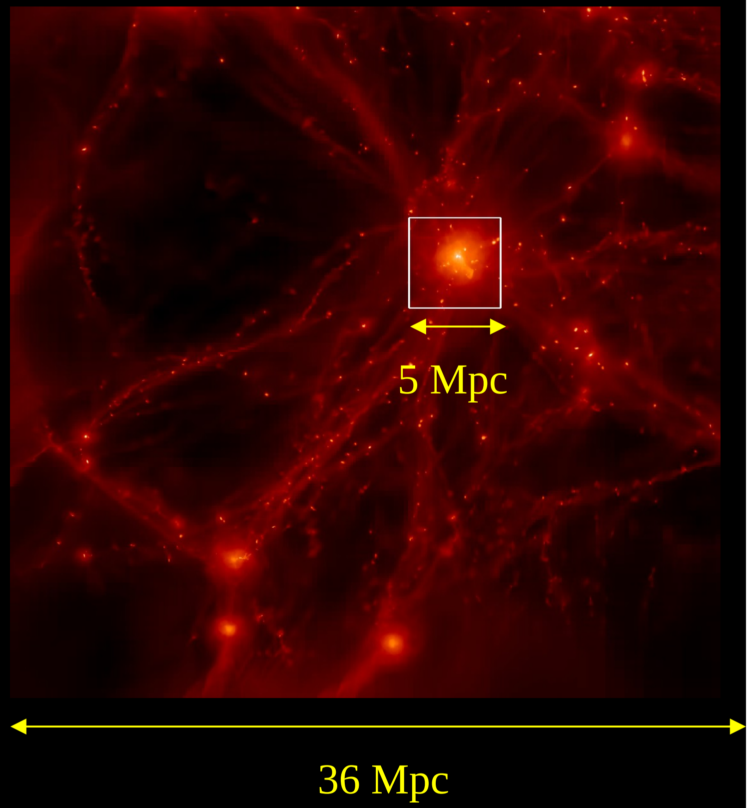
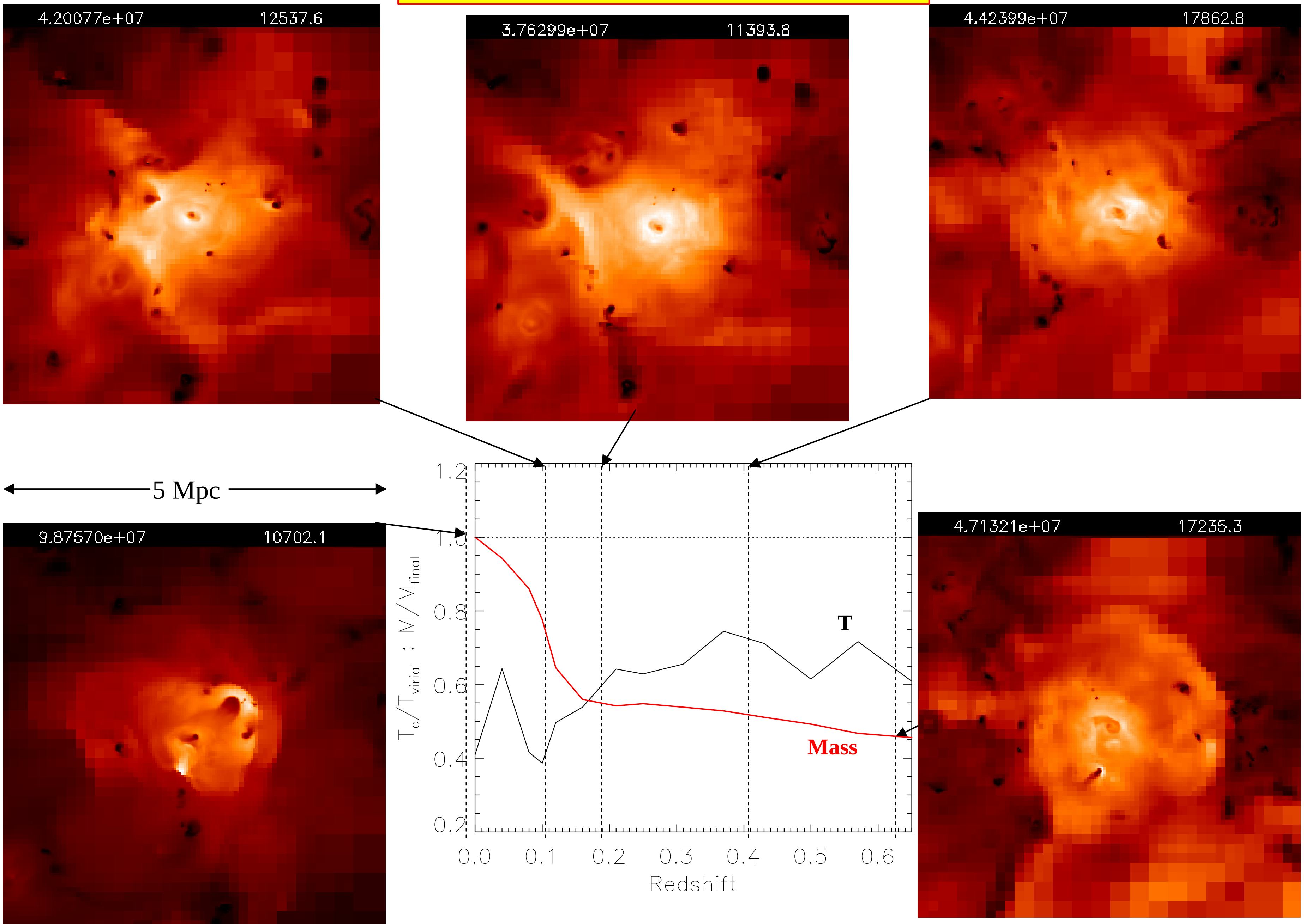
Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

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



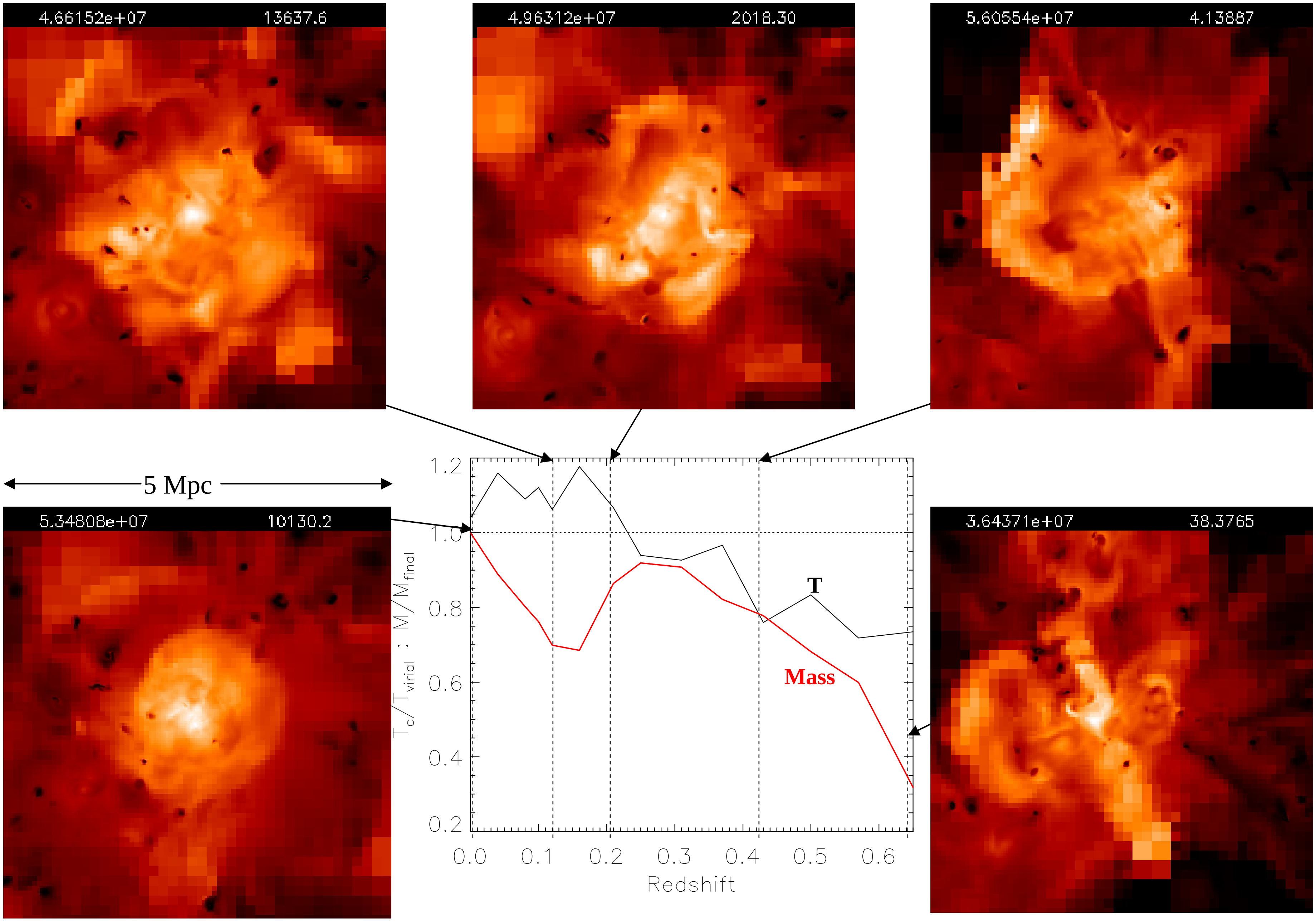
- ΛCDM Cosmology with $O_m = 0.3$, $O_b = 0.026$, $O_\Lambda = 0.7$, $h = 0.7$, and $s_8 = 0.9$.
- Hydro + N-body code uses AMR to achieve high resolution (2.0 to 15.6 h^{-1} kpc) in dense regions.
- Simulation volume is 256 h^{-1} Mpc on a side, use 7 to 9 levels of refinement with cluster subvolumes.
- 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).

Evolution of a Cool Core Galaxy Cluster

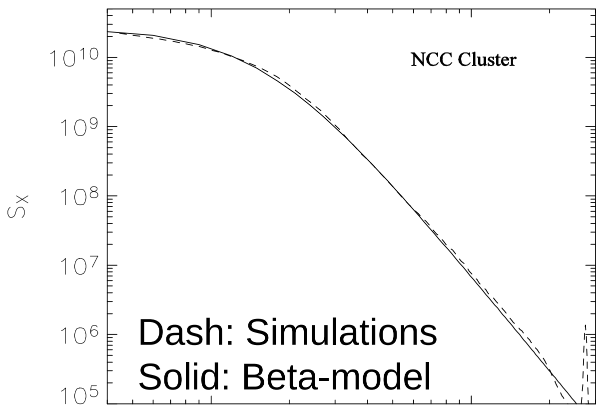


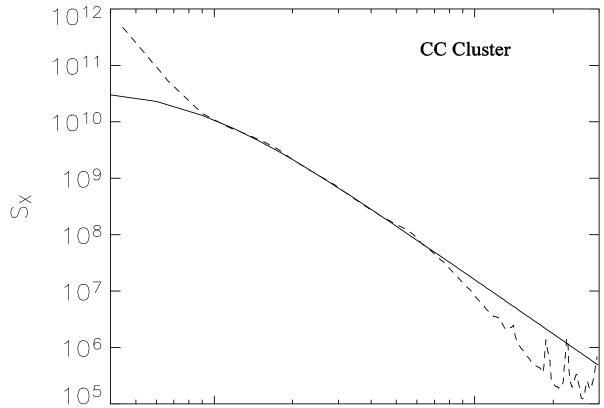
Cool cores initially grow slowly

Evolution of a Non-Cool Core Galaxy Cluster



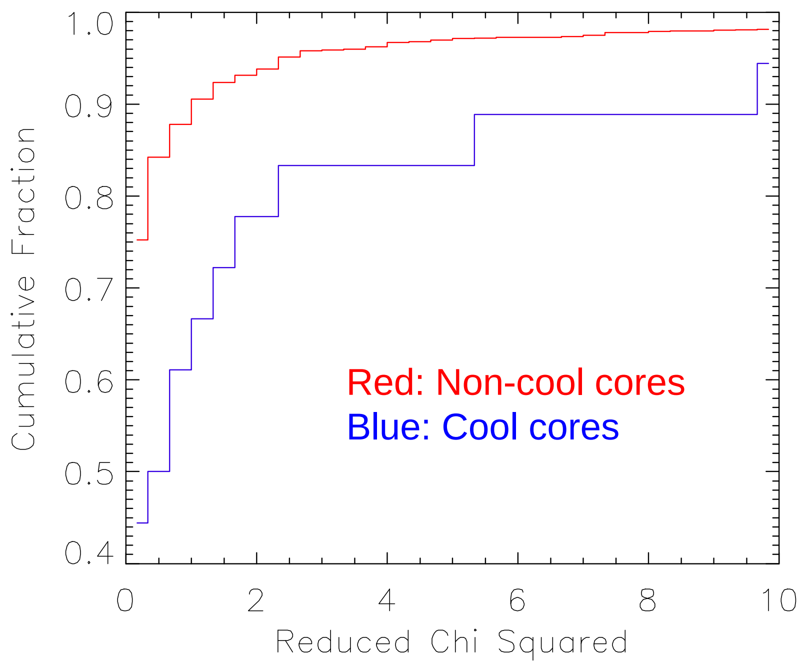
Non-cool cores suffer early major mergers

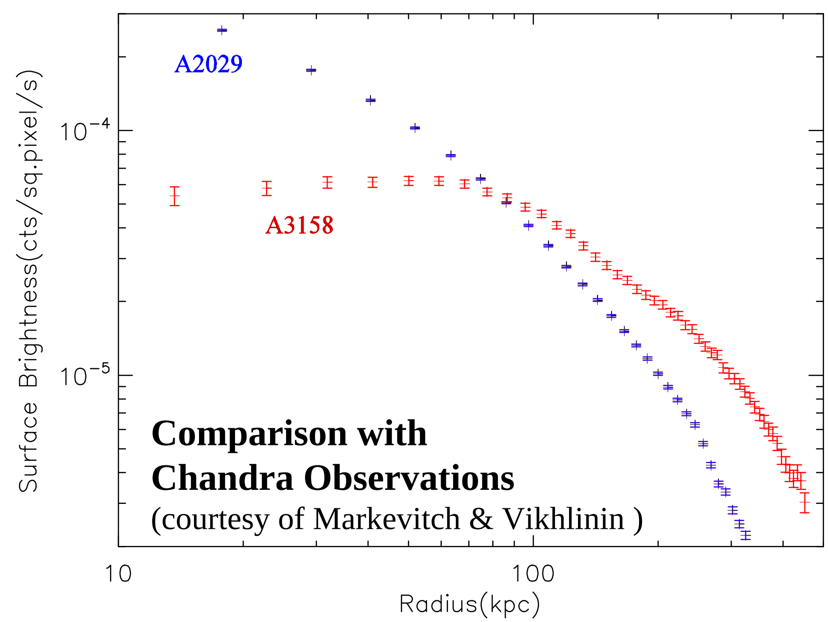




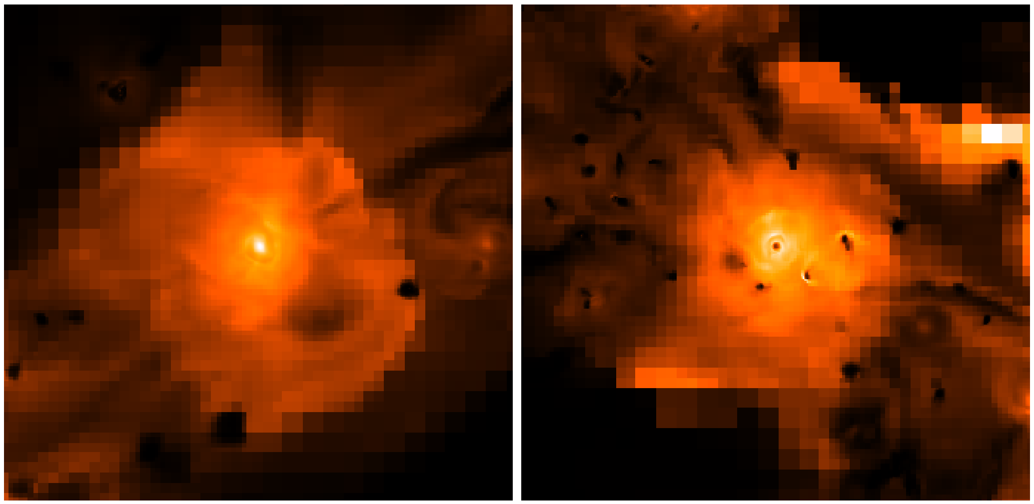
X-ray Surface Brightness Profiles

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

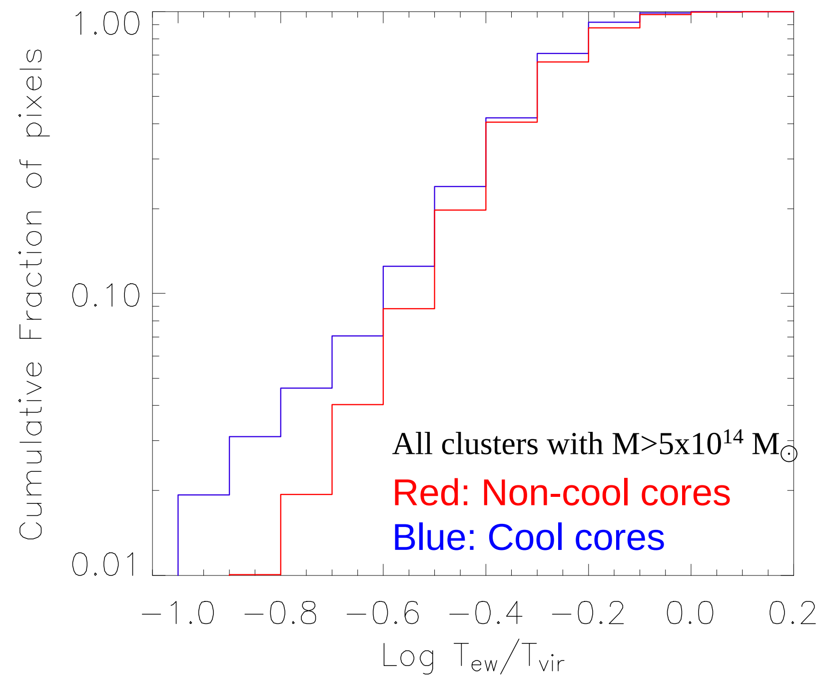




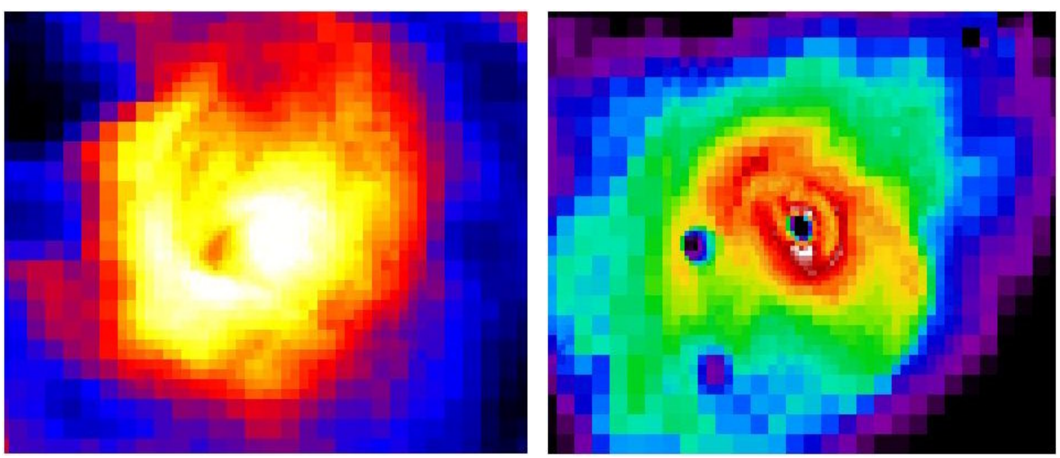
Emission-Weighted Temperature



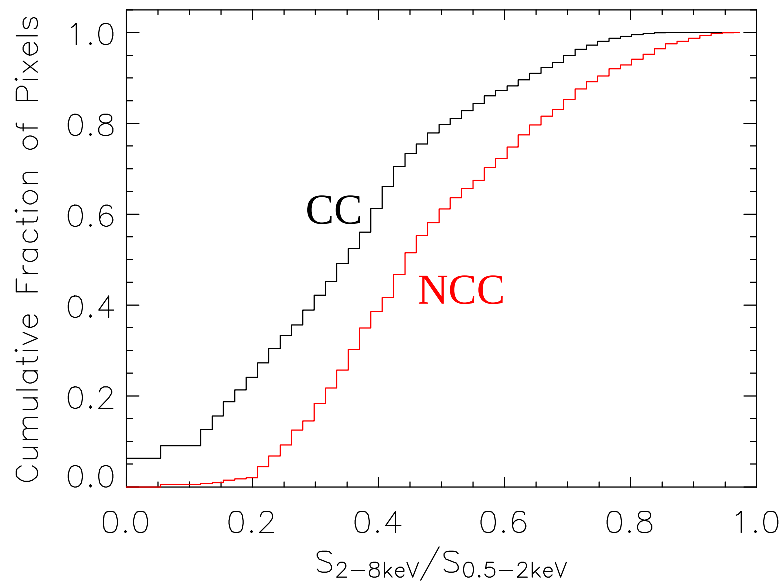
6 Mpc



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



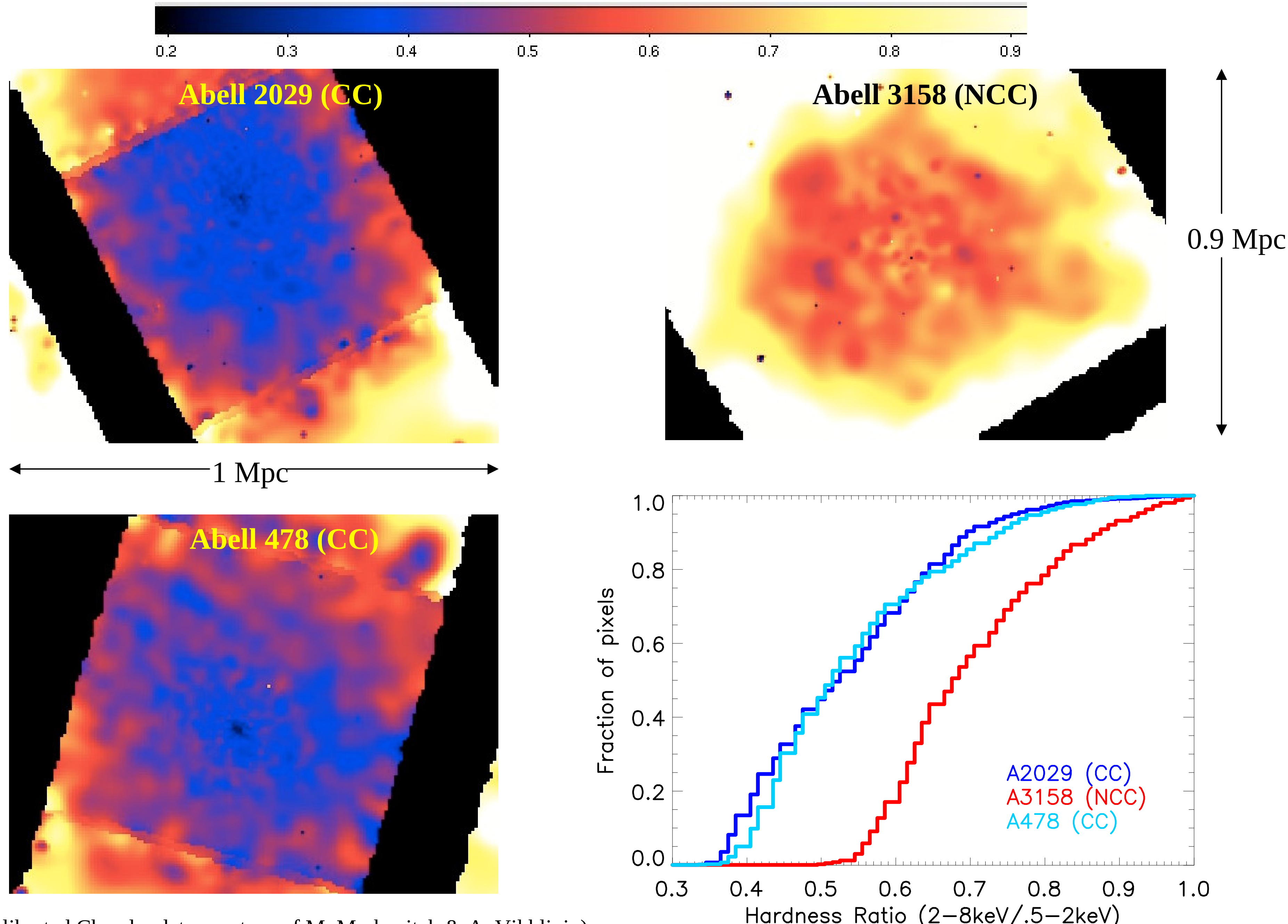
3 Mpc



Non-cool Core **Cool Core**

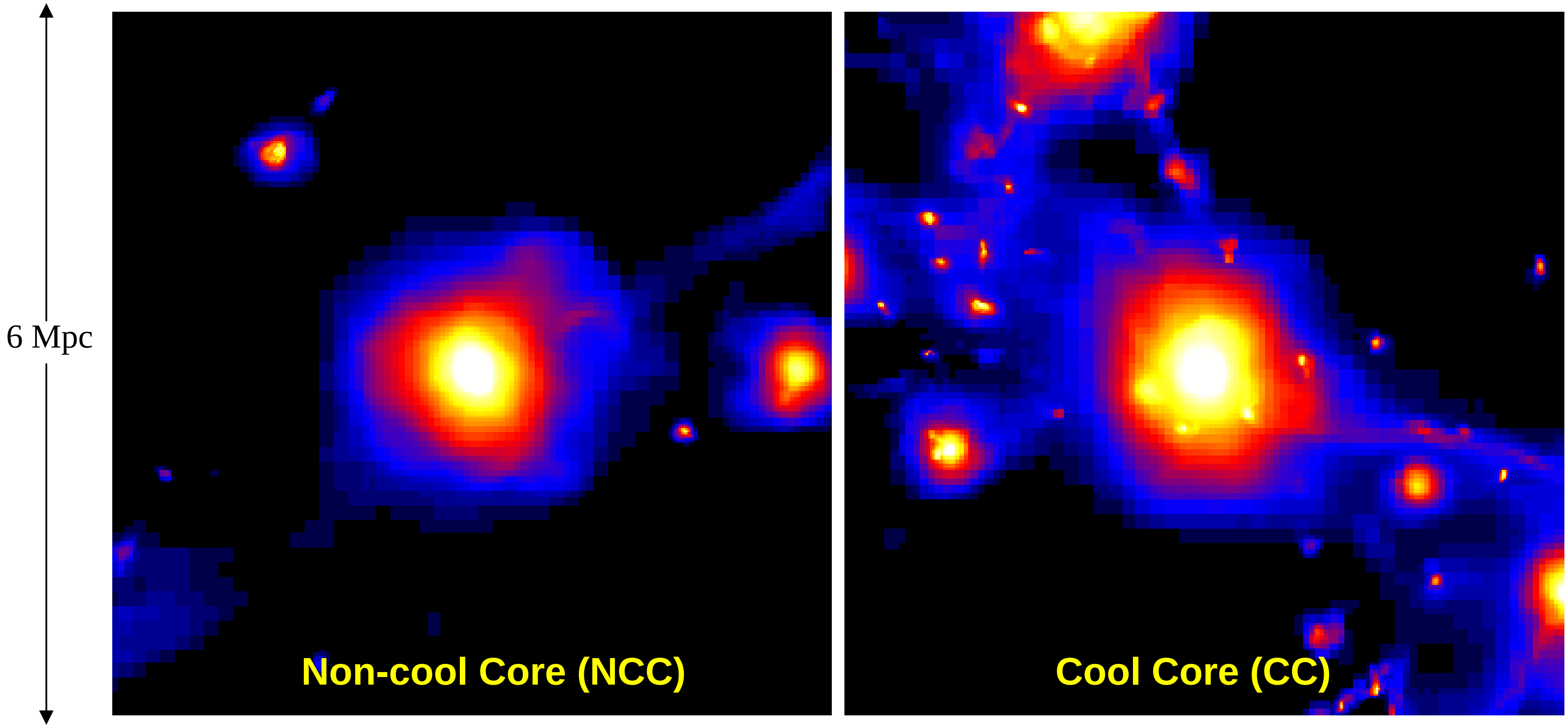
=>Simulations predict more cold gas outside the cores in cool core clusters than in non-cool core clusters.

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



(calibrated Chandra data courtesy of M. Markevitch & A. Vikhlinin)

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.