Energy Balance in Clusters of Galaxies

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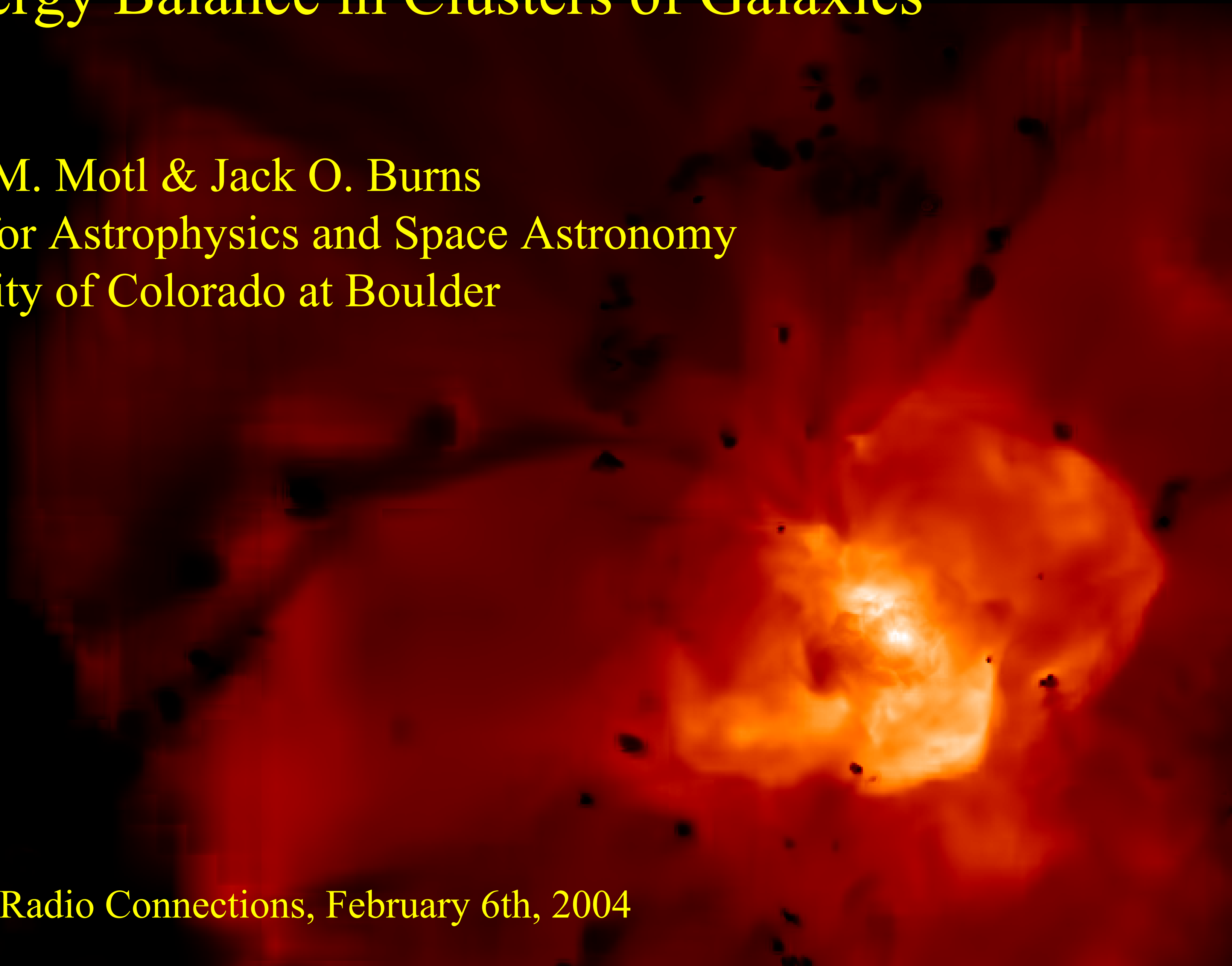

X-ray and Radio Connections, February 6th, 2004

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LCA

Laboratory for Computational Astrophysics
University of California, San Diego

For development and support of the numerical code, *enzo*.
The code is currently available to “friendly users”.
Information available at http://cosmo.ucsd.edu/enzo

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For a grant of time on NCSA supercomputing facilities and valuable support.

Statement of the Problem:

Need a predictive, numerical model for clusters of galaxies.

This means simulating clusters in a cosmological setting but also need input physics for radiative cooling, star formation, feedback from supernova and active galactic nuclei, thermal conduction - everything that can significantly impact energy balance in the gas.

Energy Balance in Clusters of Galaxies

Look at the big things, rich clusters of galaxies but keep in mind that scales will change for poor clusters down to groups

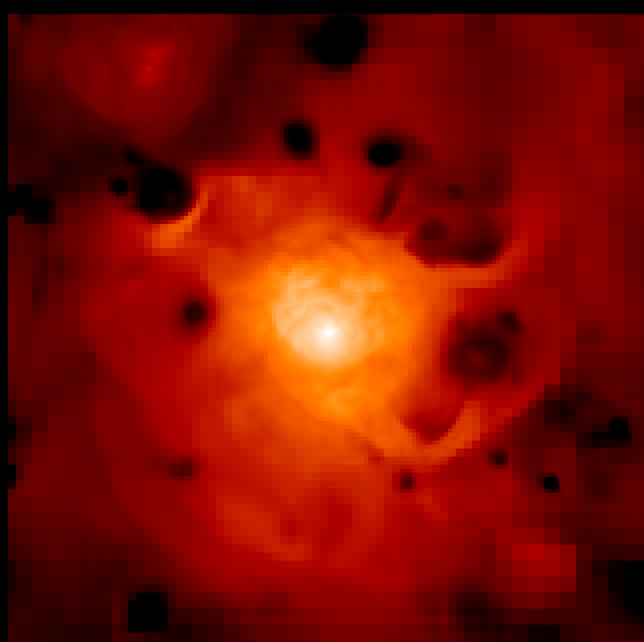
Measure energy relative to the gravitational potential energy of the cluster, $|W| \sim 10^{65}$ ergs

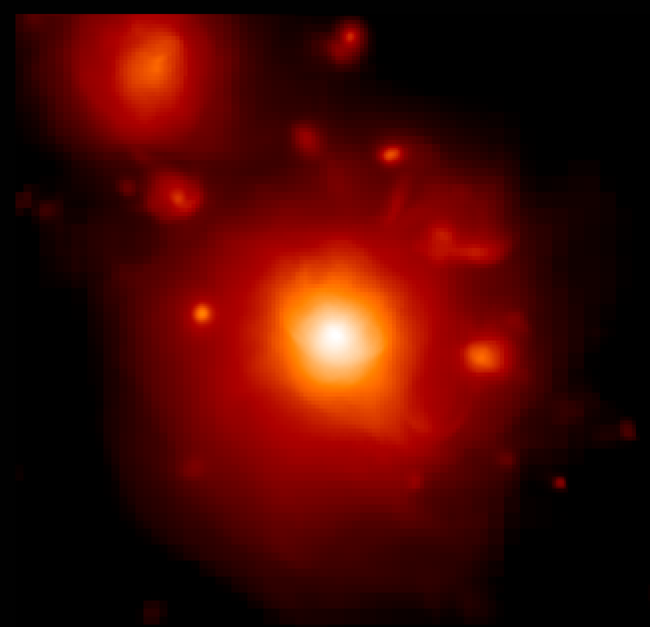
Measure time in units of the cluster dynamical time, $t_{dyn} \sim 1$ Gyr

Major Mergers

For merger of two, equal mass clusters free-falling into one another expect the cluster to thermalize the kinetic energy of the impact, up to ~ 0.1 |W|

emission-weighted temperature





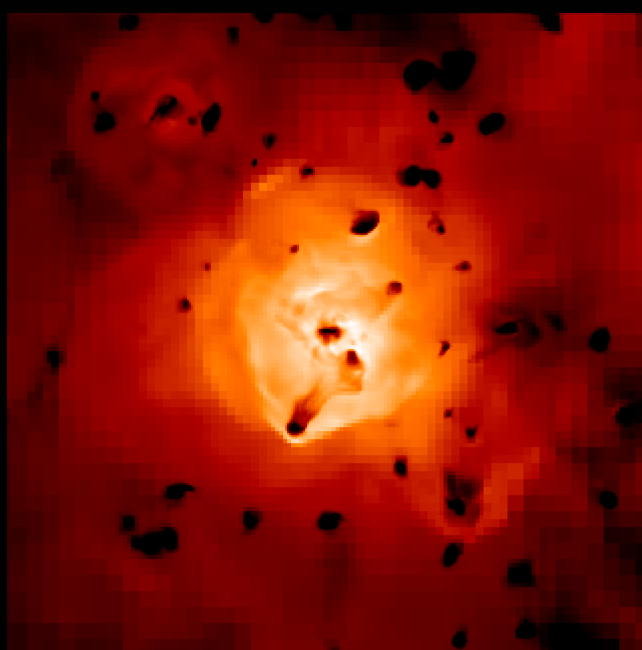
X-ray surface brightness

Radiative Cooling

For $L_X \sim 10^{45}$ erg s^{-1}, over t_{dyn}, loose $\sim 10^{-3}$ $|W|$

Not a global loss, however, effective on the scale of the core only

emission-weighted temperature



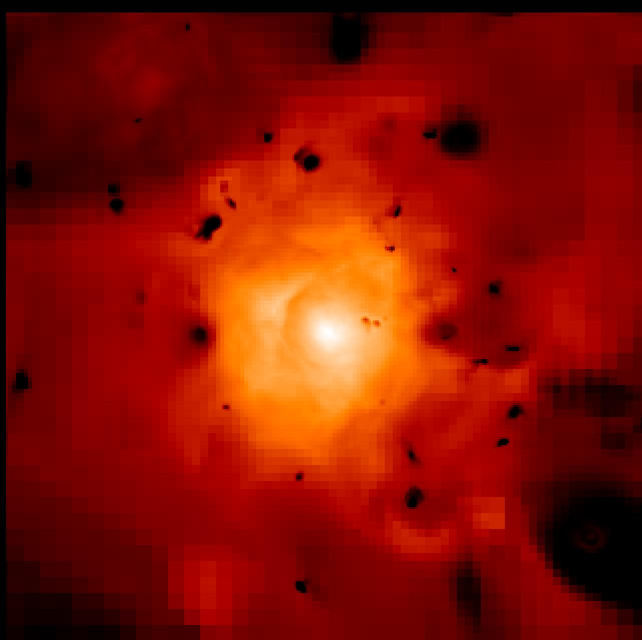
X-ray surface brightness

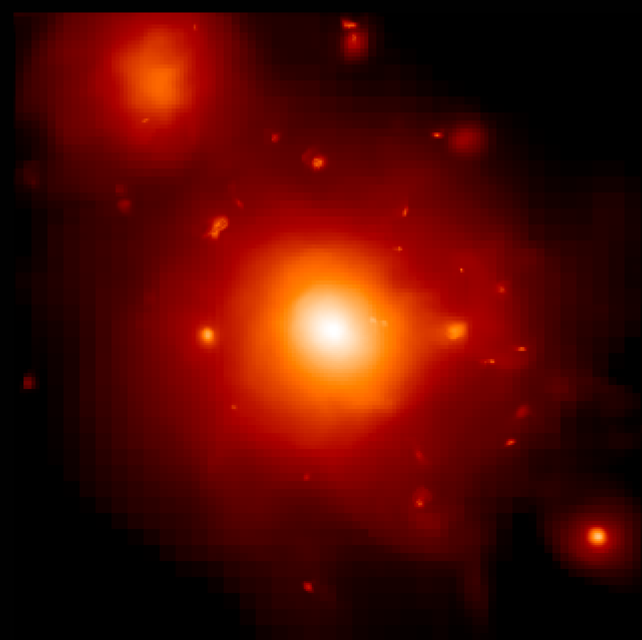
Star Formation and Supernova Feedback

In runs with star formation and supernova feedback, we find a realistic fraction of baryons in stars for thermal feedback of ~ 0.5 keV per particle in the clusters

Assume the star formation rate to be uniform in time and supernova feedback provides ~ 10^{-4} |W| of energy over t_{dyn}

emission-weighted temperature





X-ray surface brightness

Thermal Conduction

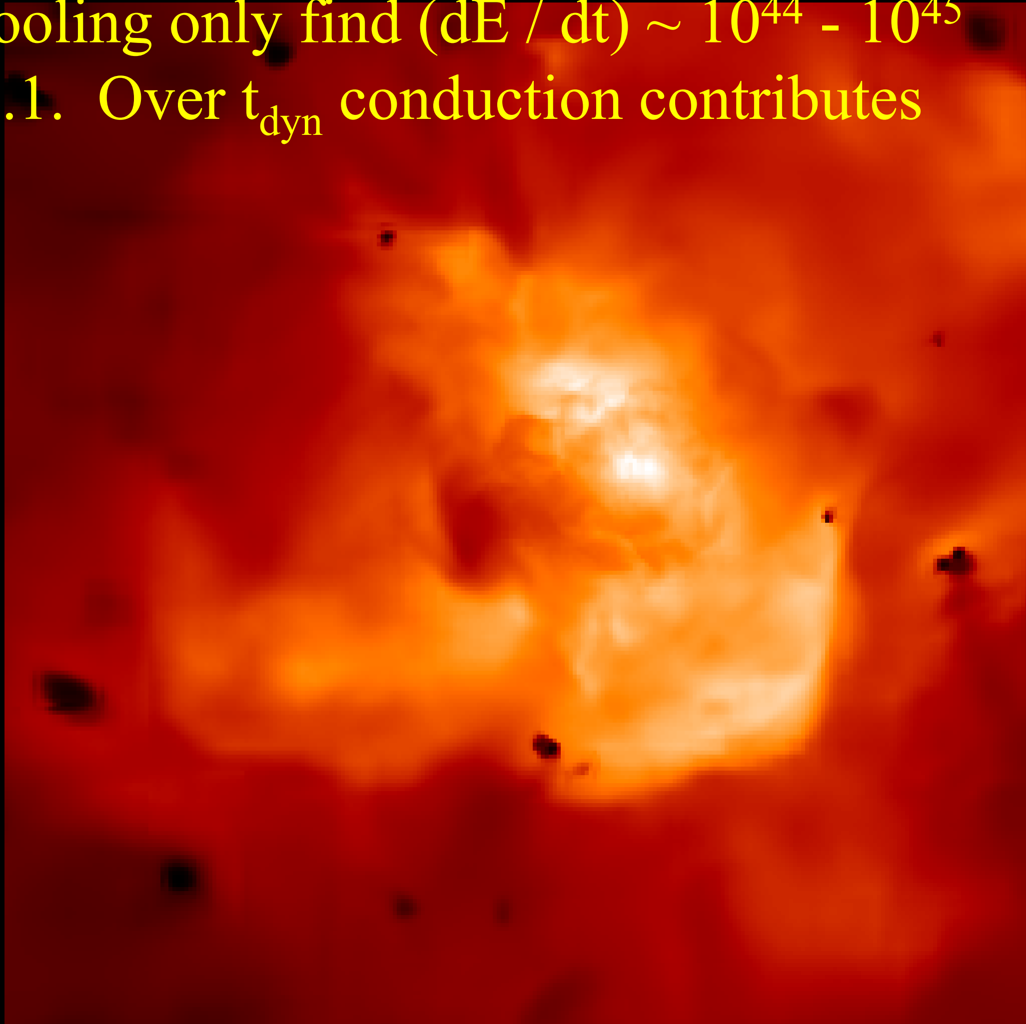
$$(dE / dt)_{conduction} = - 4 \pi r^2 \kappa_{eff} (dT / dr) \text{ erg s}^{-1}$$

$$\kappa_{eff} = f \kappa_{Spitzer} \quad \text{where } f \sim 0.3 \text{ (Narayan \& Medvedev 2001)}$$

For our simulated clusters with cooling only find $(dE / dt) \sim 10^{44} - 10^{45}$ erg s^{-1} in the core region for $f = 0.1$. Over t_{dyn} conduction contributes $\sim 10^{-4} - 10^{-3} |W|$

<u>caveats</u>:

- magnetic fields
- preserve cold fronts and small scale temperature structure
- if κ_{eff} is too high, heat the surrounding intracluster medium (Loeb 2003)

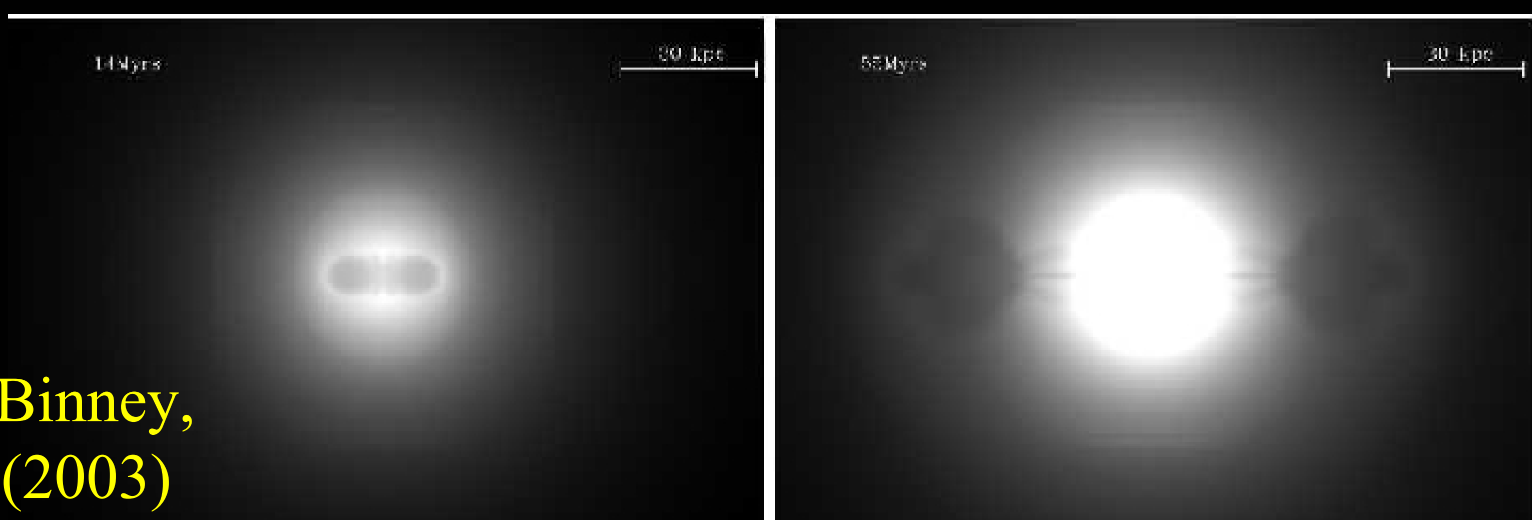


Feedback from Active Galactic Nuclei

From published observations of "bubble" clusters estimate the mechanical work to be ~ 10^{58} - 10^{59} ergs

For a cycle time of ~ 0.1 Gyr, roughly expect that AGN can contribute energy at the level of 10^{-6} - 10^{-5} $|W|$ over t_{dyn}

Most effective in the cluster core. Consistent with balancing cooling in cluster cores (Ruszkowski & Begelman 2002)



From Omma, Binney, Bryan & Slyz (2003)

Scorecard

Structure formation, up to ~ 0.1 |W|

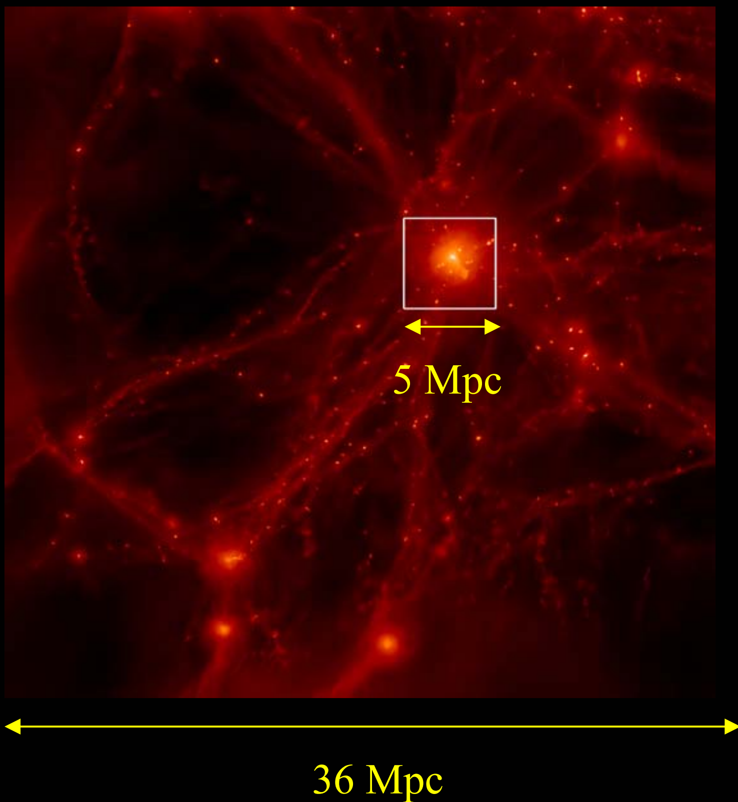
Radiative Cooling (loss of) ~ 10^{-3} |W|

Supernova Feedback ~ 10^{-4} |W|

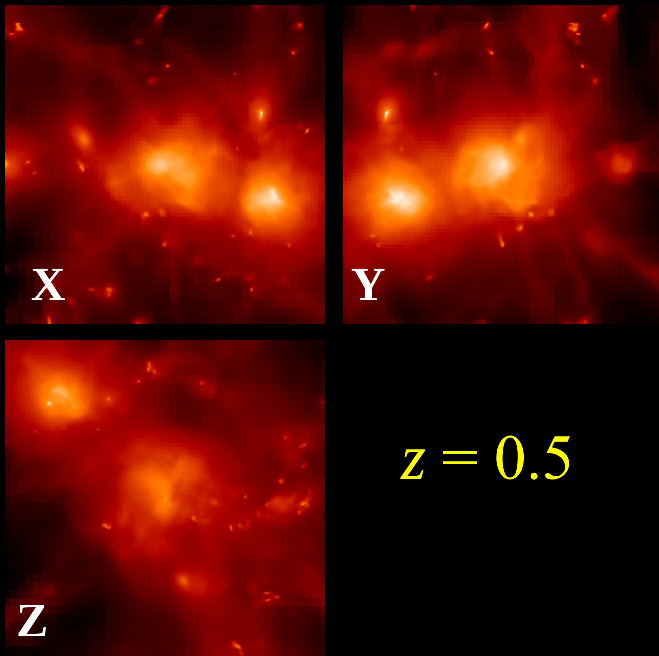
Thermal Conduction ~ 10^{-4} - 10^{-3} |W|

Active Galactic Nuclei Feedback ~ 10^{-6} - 10^{-5} |W|

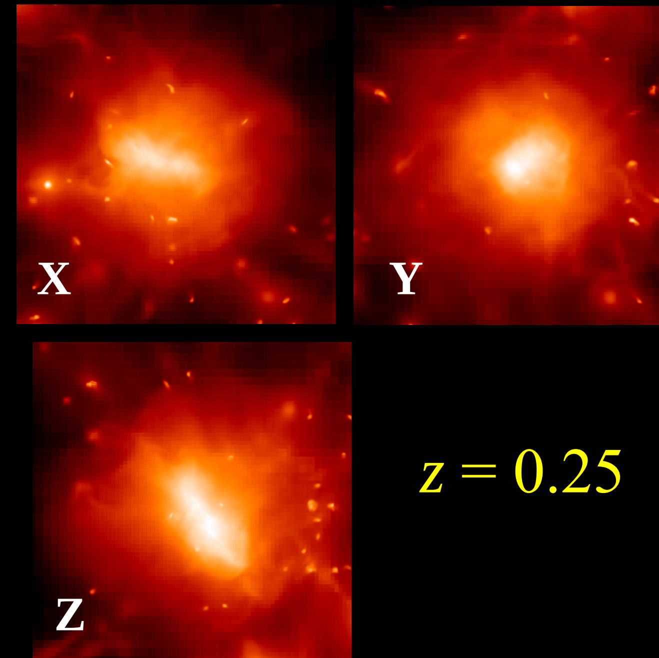
Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution



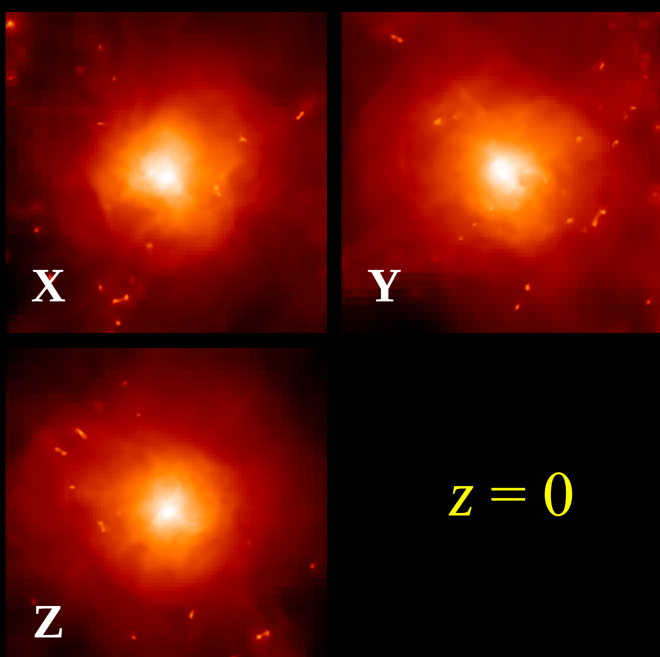
- ΛCDM Cosmology with $\Omega_m = 0.3$, $\Omega_b = 0.026$, $\Omega_\Lambda = 0.7$, and $\sigma_8 = 0.928$
- Hydro + N-body code uses AMR to achieve high resolution (to 1 kpc) in dense regions
- Simulation volume is 256 Mpc on a side, use 7 to 11 levels of refinement within cluster subvolumes
- Current generation of simulations includes both radiative cooling and star formation with supernova feedback using the Cen & Ostriker (1992) model
- Archive of numerical clusters with analysis tools available through the Simulated Cluster Archive http://sca.ncsa.uiuc.edu



$z = 0.5$



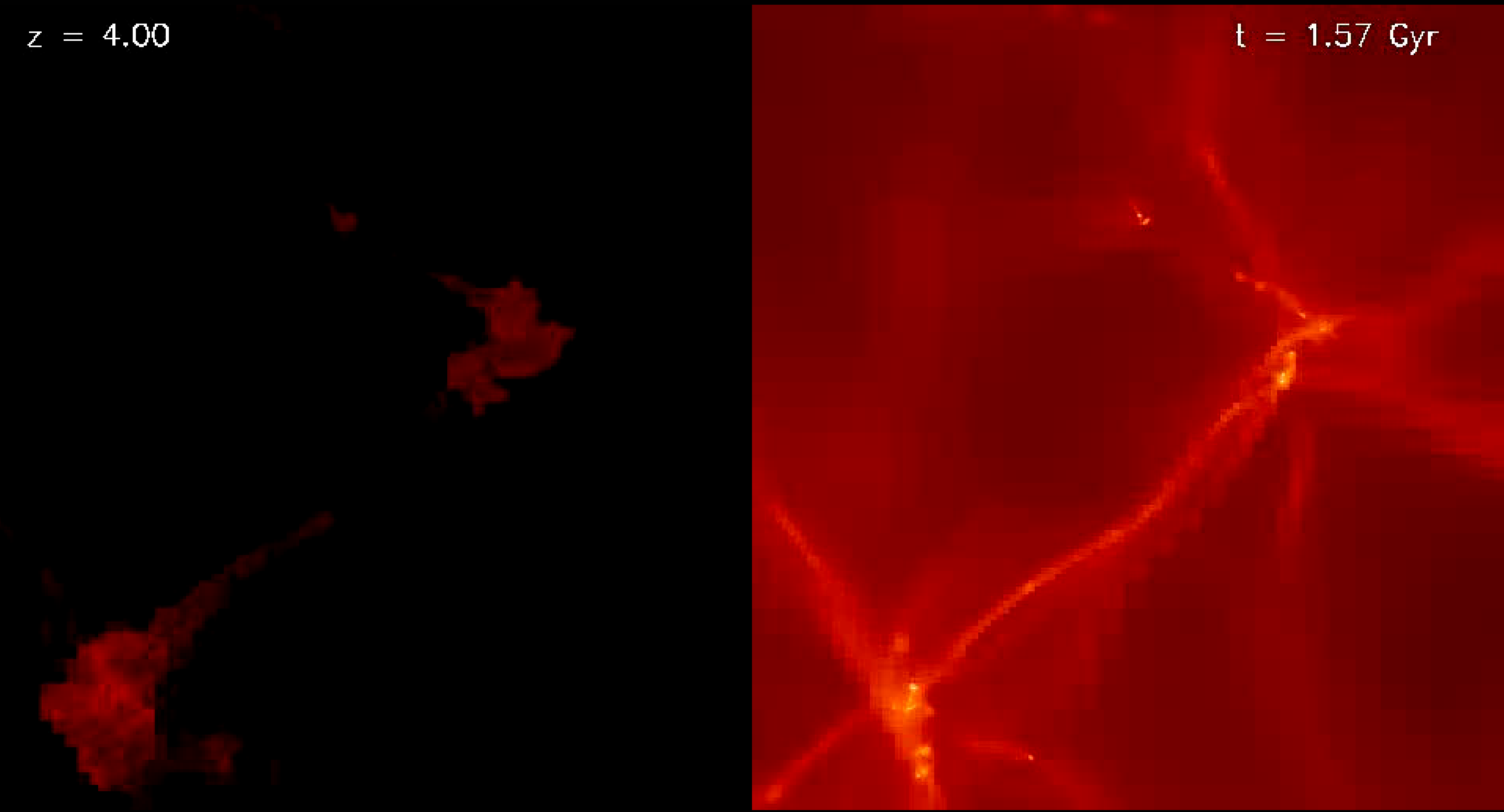
$z = 0.25$

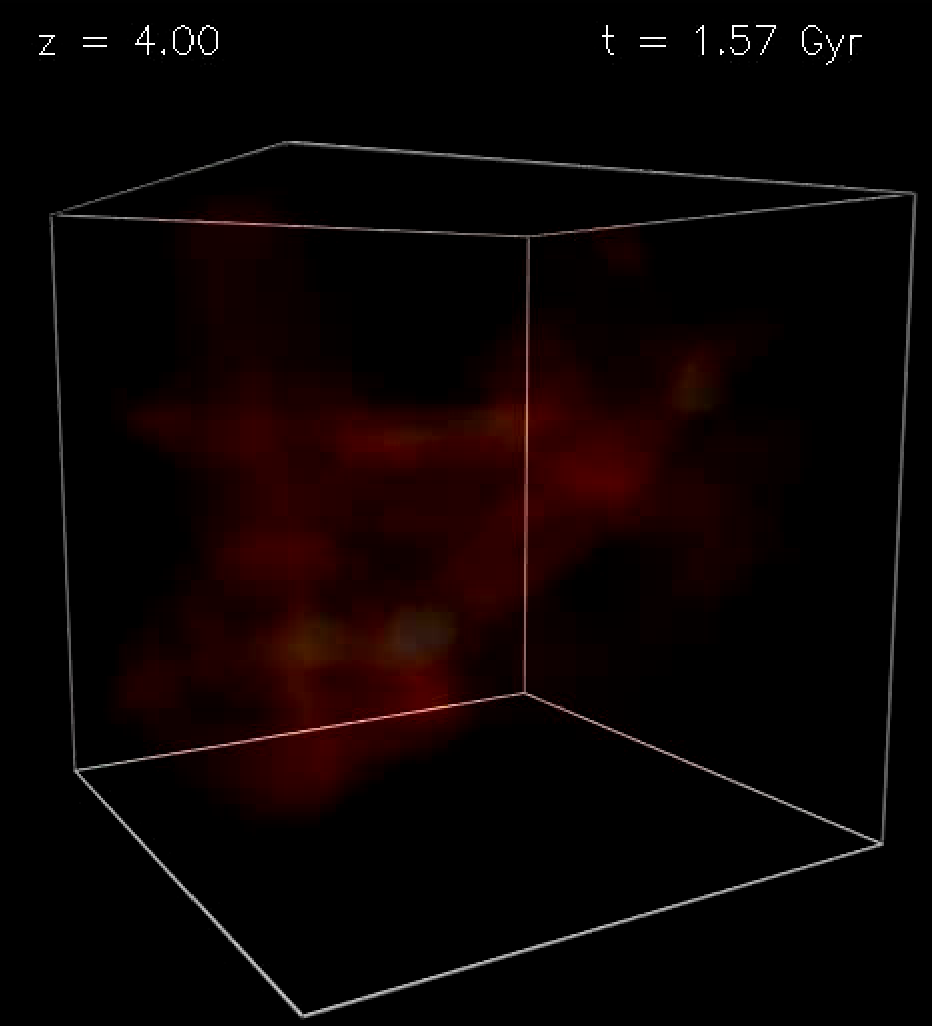


$z = 0$

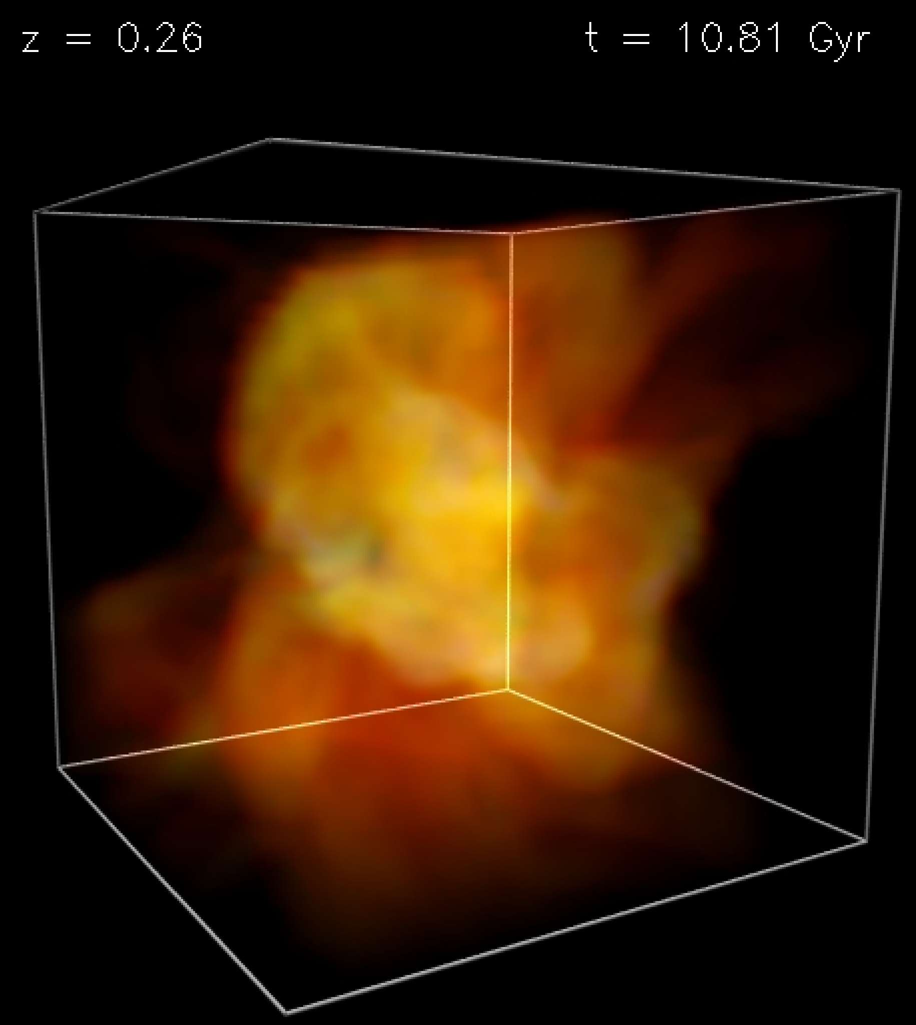
Simulation Information

- 10 levels of refinement (2 kpc)
- Radiative cooling
- Star formation and feedback
- $R_{200} = 2.6$ Mpc
- $M_{200} = 2.1 \times 10^{15}\ M_{solar}$
- $M_{dm} = 2.0 \times 10^{15}\ M_{solar}$
- $M_{gas} = 1.0 \times 10^{14}\ M_{solar}$
- $M_{stars} = 2.0 \times 10^{13}\ M_{solar}$


z = 4.00
t = 1.57 Gyr


z = 4.00
t = 1.57 Gyr

A Note of Caution, clusters are not very spherical!

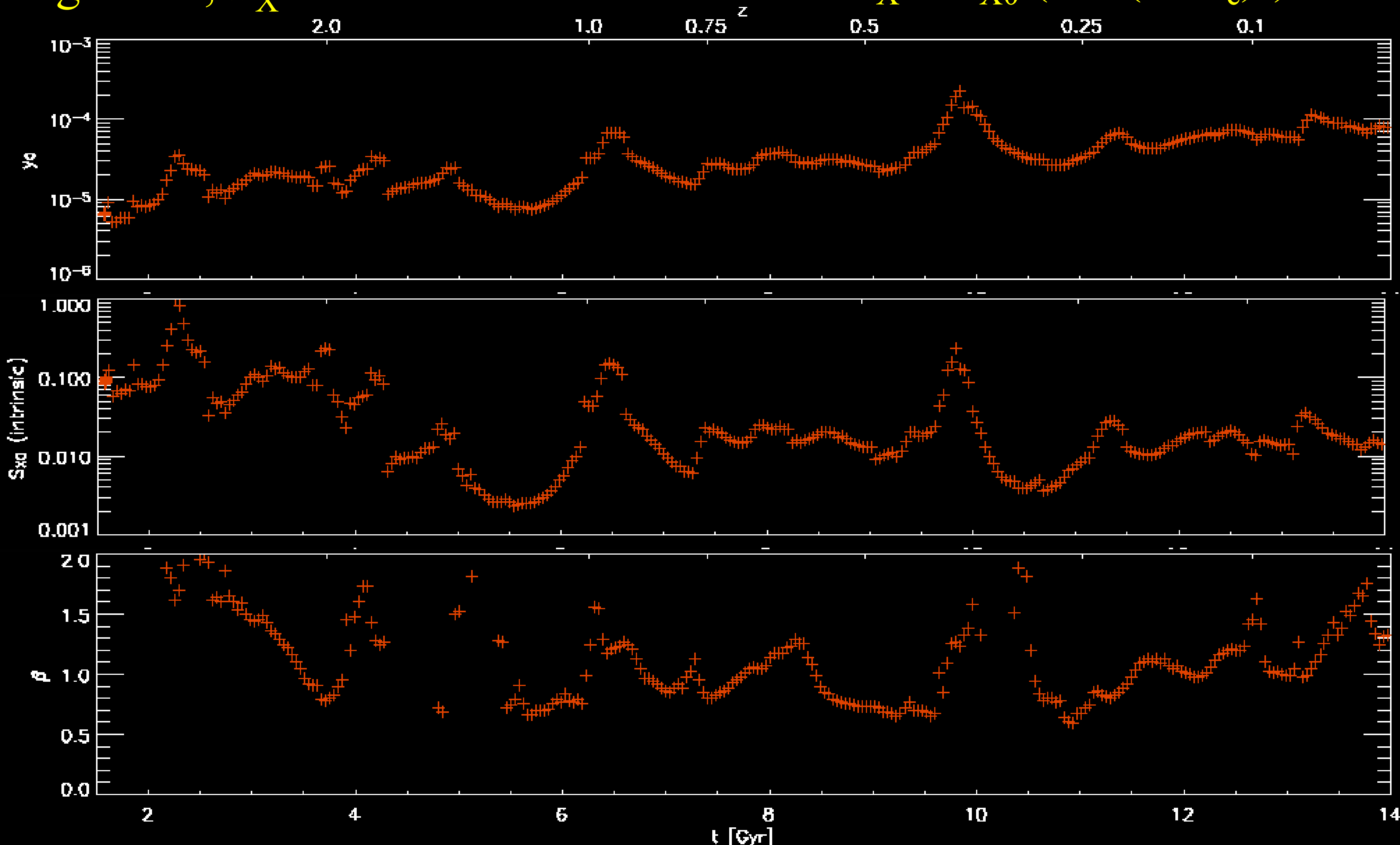


Clusters are dynamical...

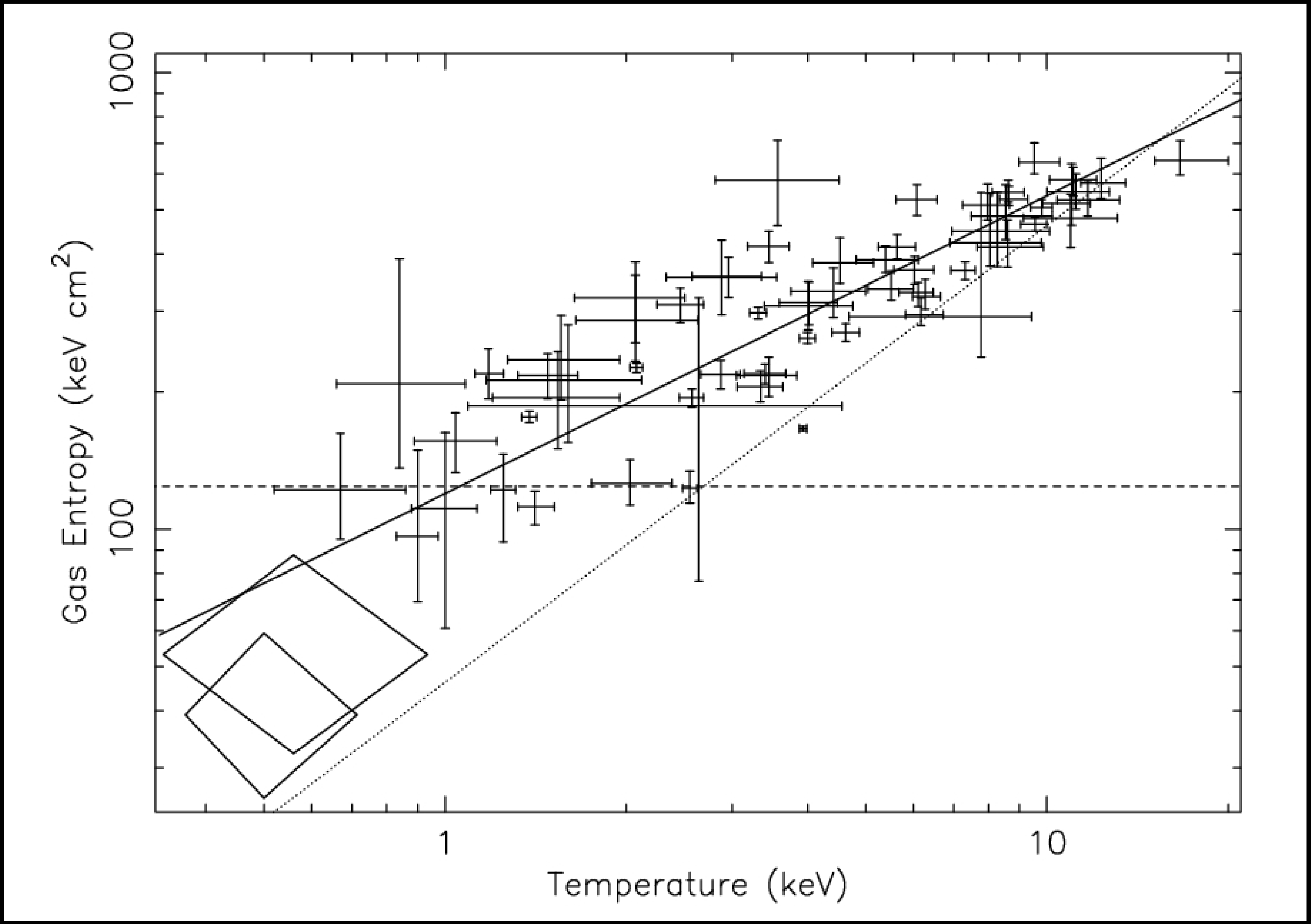
Simultaneous β model fit of Compton parameter, y, and X-ray surface brightness, S_X

$$y = y_0 \left(1 + (\theta / \theta_c)^2\right)^{1/2 - 3\beta/2}$$

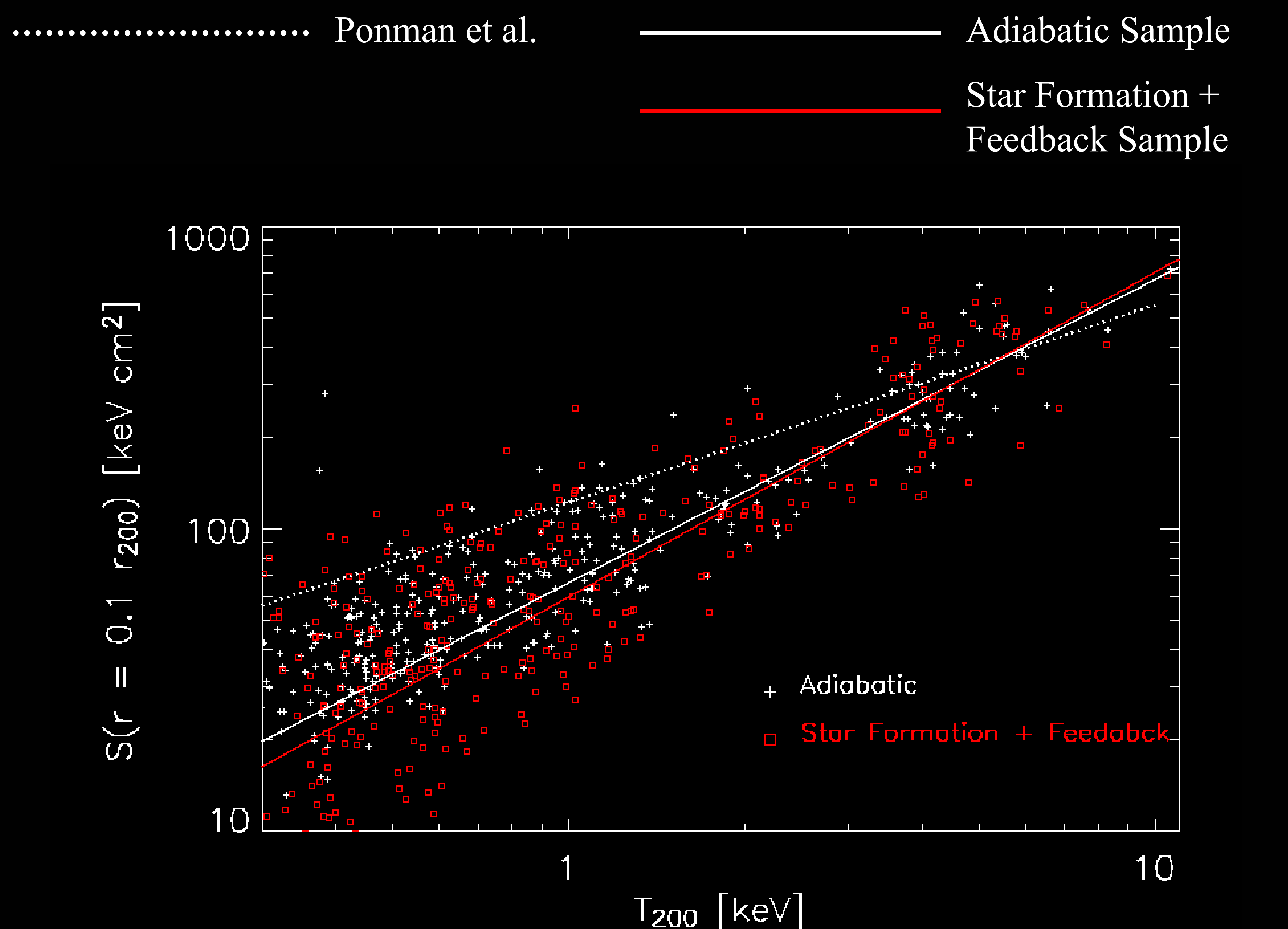
$$S_X = S_{X0} \left(1 + (\theta / \theta_c)^2\right)^{1/2 - 3\beta}$$



An Additional Argument for AGN feedback



Ponman, Sanderson & Finoguenov (2003); entropy = S = T / $n_e^{2/3}$

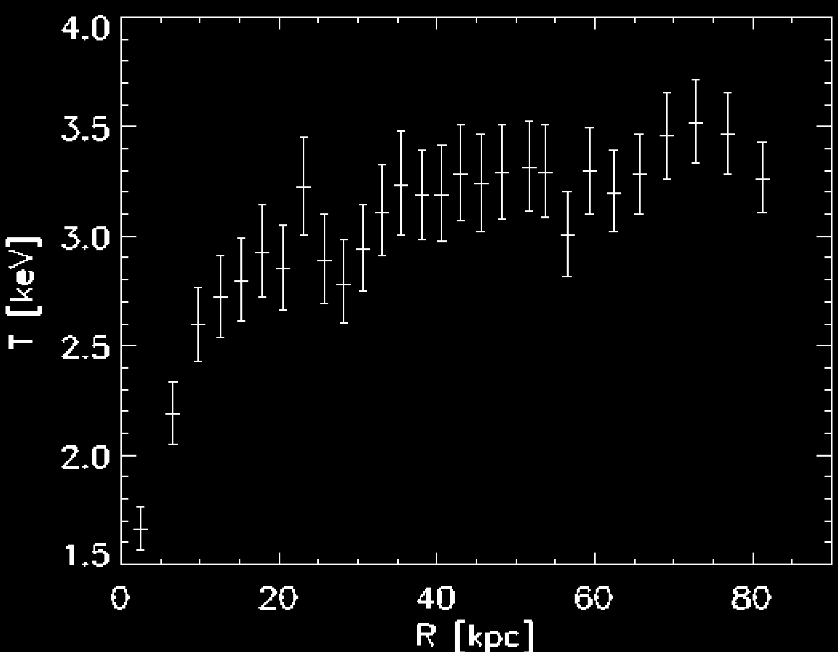


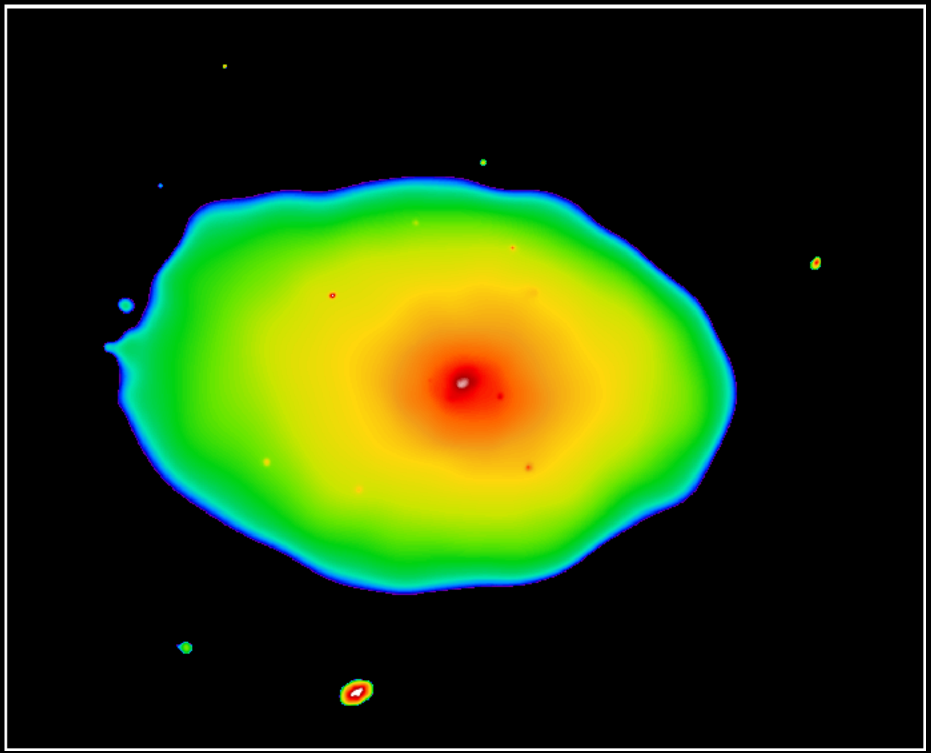
Ponman et al.
Adiabatic Sample
Star Formation +
Feedback Sample
1000
100
10
1
10
S(r = 0.1 r200) [keV cm2]
T200 [keV]
Adiabatic
Star Formation + Feedabck

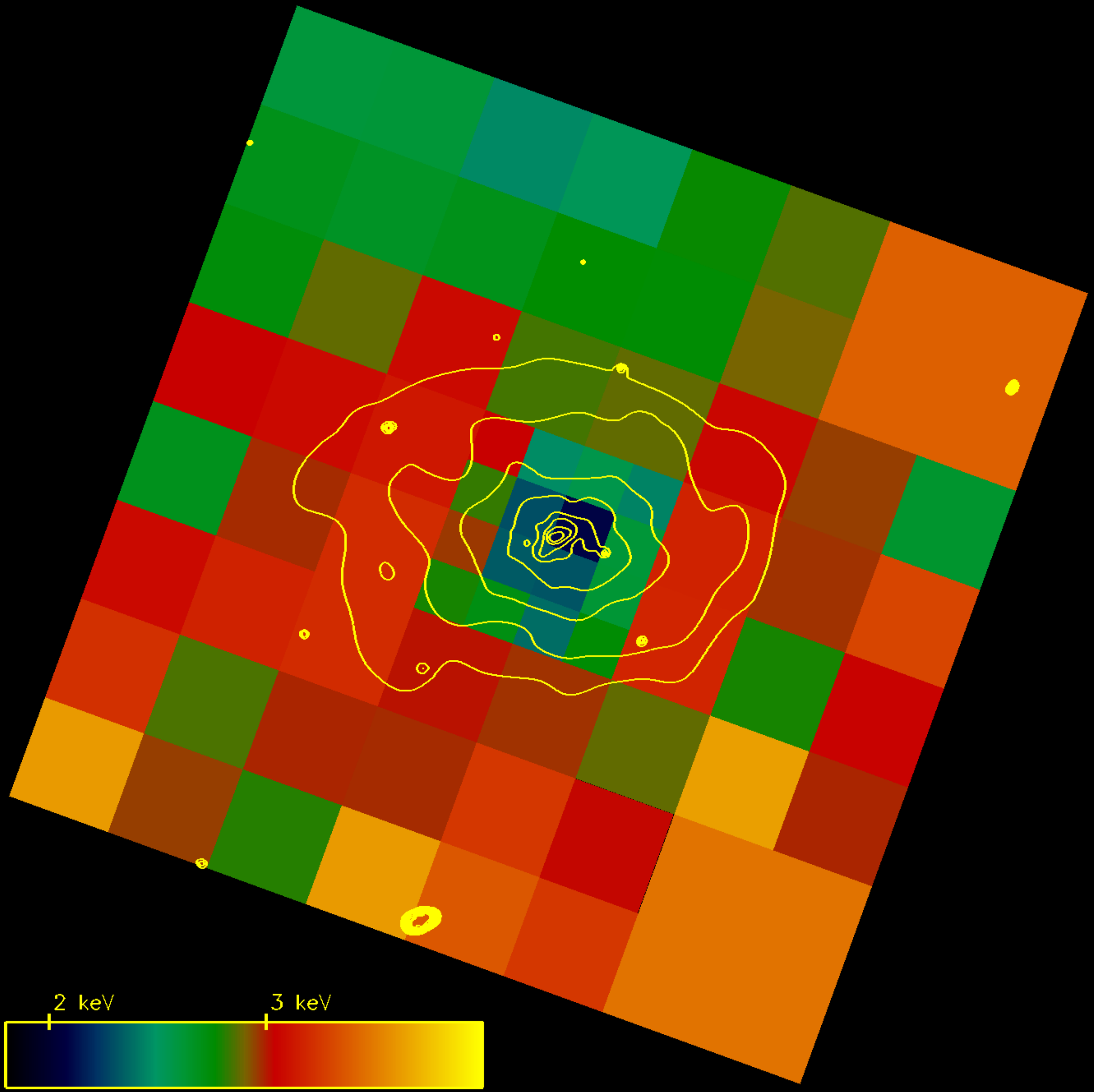
Constraints from testbed clusters

- Dynamically relaxed systems, no recent mergers to reset the clock
- No sign of AGN outbursts
- Yet, has canonical thermal properties in the cluster core

Chandra ACIS-I observation of the poor cluster of galaxies, AWM7






2 keV
3 keV

Conclusions

- Energy balance in clusters requires the interplay of several coupled mechanisms
- Thermal conduction comparable in magnitude to radiative cooling
- AGN feedback is likely important in cluster cores
- Clusters are inherently dynamic, geometrically complex systems
- Major mergers can significantly boost observational signatures (e.g., factor of ~ 10 in the thermal Sunyaev-Zeldovich effect) for short periods (<~ 1 Gyr)
- Need to observe clusters without X-ray bubbles where astrophysical mechanisms can be isolated