Cluster Assembly and Non-Equilibrium in the Outer ICM

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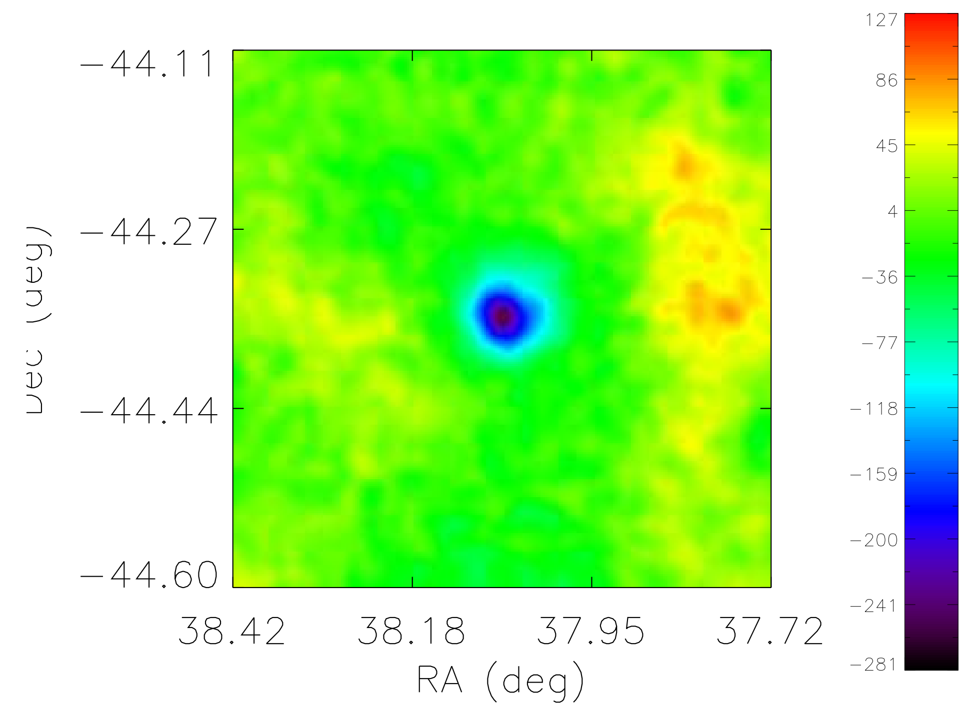
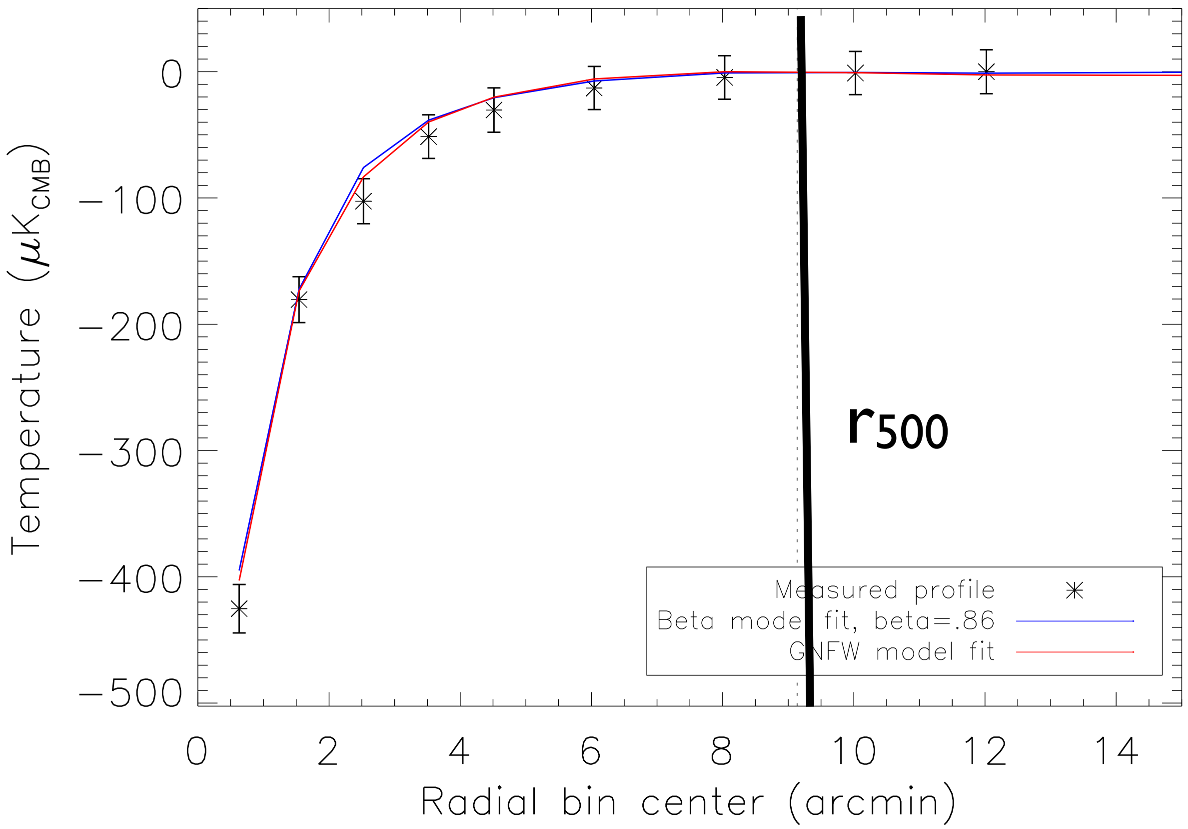
SZ Observations of outer ICM

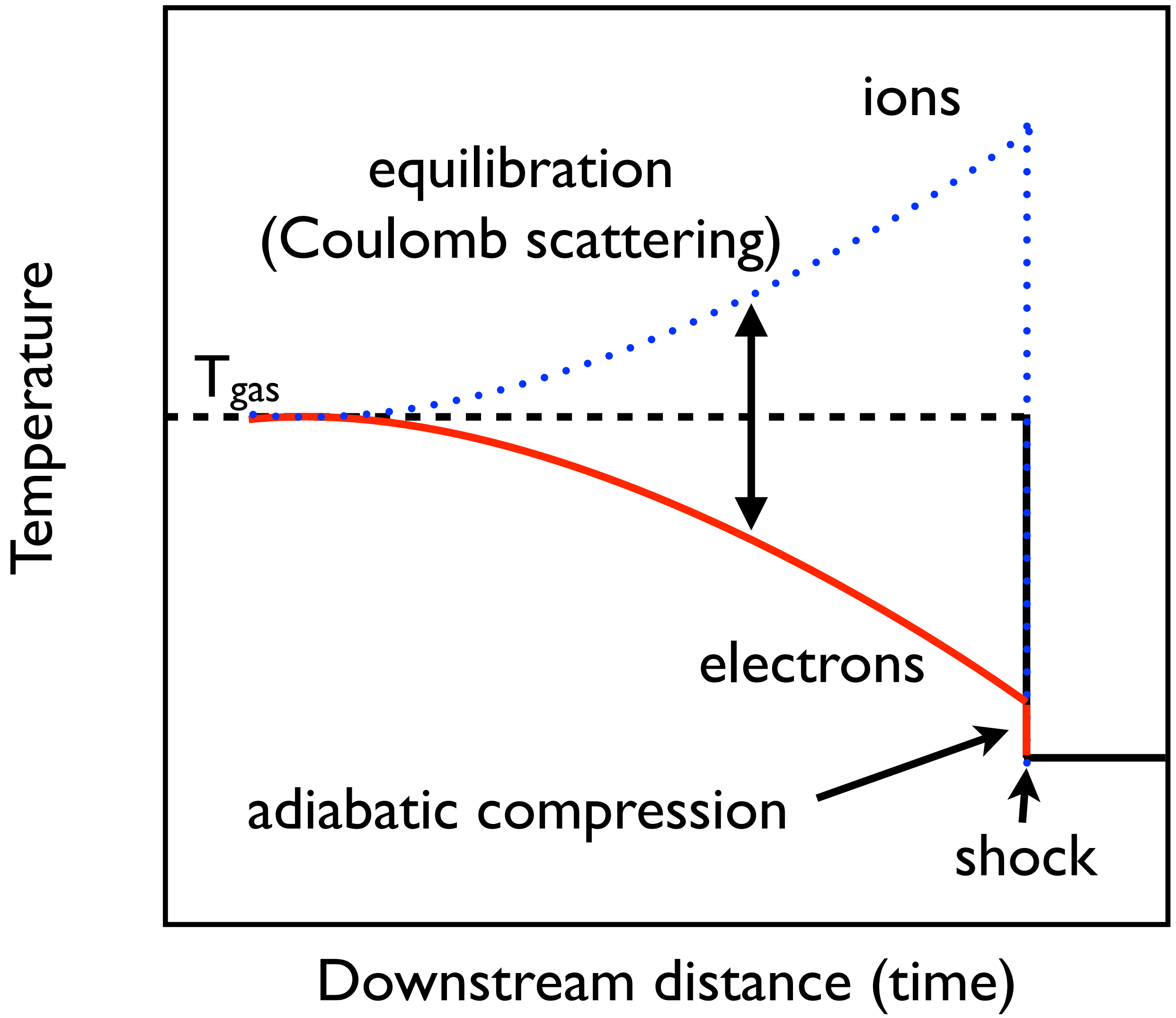




RXCJ0232.2-4420, Plagge et al (arXiv:0911.2444)

- SZ experiments measuring electron pressure in outskirts directly and indirectly through projection
- Less sensitive to complex baryon physics operating in cluster cores.
- Electron pressure may deviate from equilibrium in two ways: turbulence/bulk motion (incomplete kinetic dissipation) and incomplete thermal equilibration

Electron Equilibration: Physical Picture



Heavy ions carry bulk of kinetic energy (~m_i/m_e) through shock due to weak coupling between species (long mfp)

Two major uncertainties:

- amount of electron heating at the shock (min adiabatic compression)
- rate of temperature equilibration downstream from the shock front (min due to Coulomb collisions)

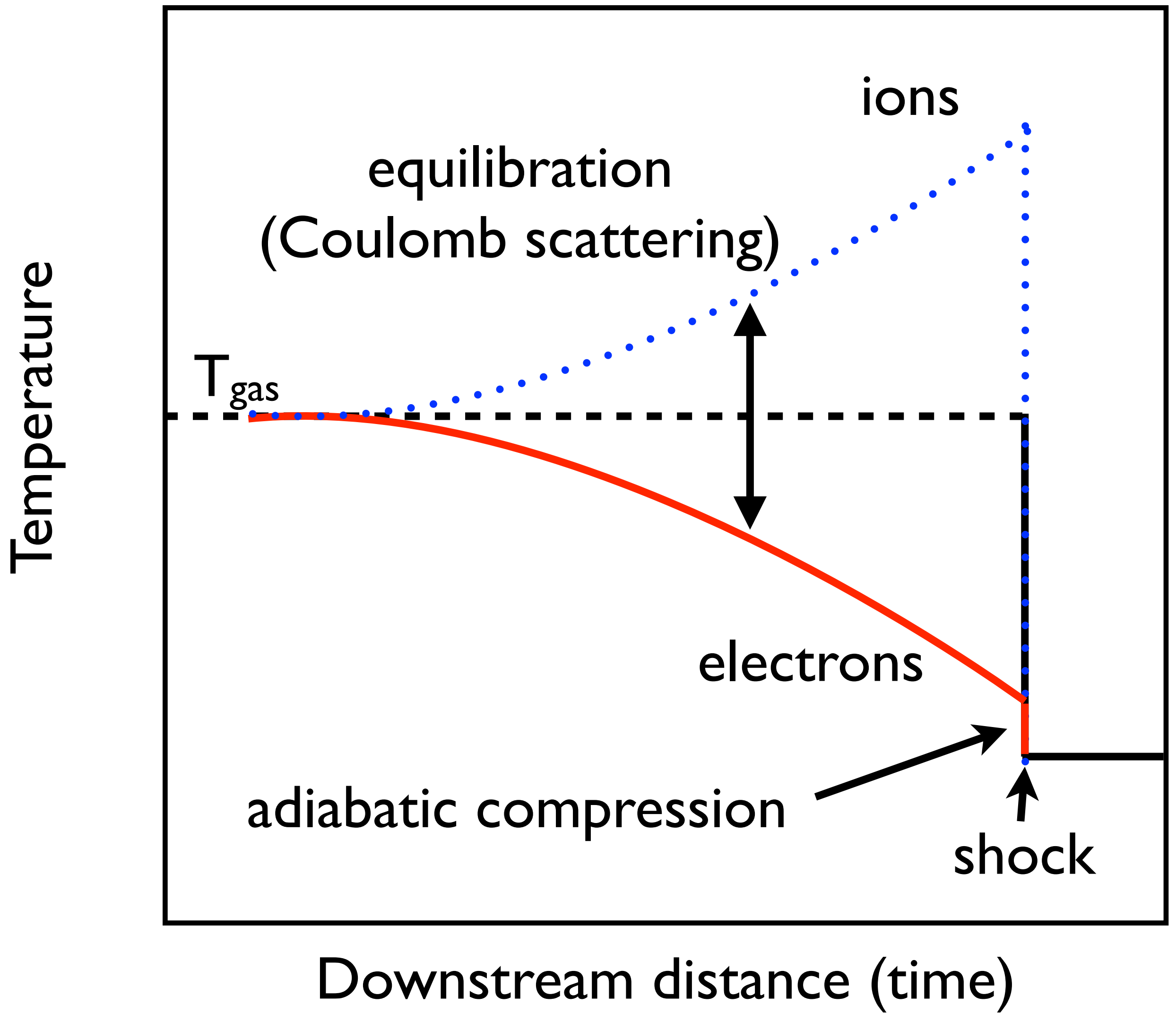
Simulations implicitly assume instant equilibration and may overestimate electron temperature

Total gas pressure downstream from shock given by standard jump conditions

$$T_{\mathrm{gas}} = \frac{n_e T_e + n_i T_i}{n_e + n_i}$$

Rudd & Nagai (2009), Fox & Loeb (1997), see also Bykov et al (2008)

Numerical Scheme



Separately track electron internal energy which is advected with the fluid (not subject to shocks) with source terms:

$$\frac{dT_e}{dt} = \frac{T_i - T_e}{t_{ei}} - (\gamma - 1)\, T_e\, (\nabla \cdot \mathbf{v})$$

Relaxation term coupling to ions

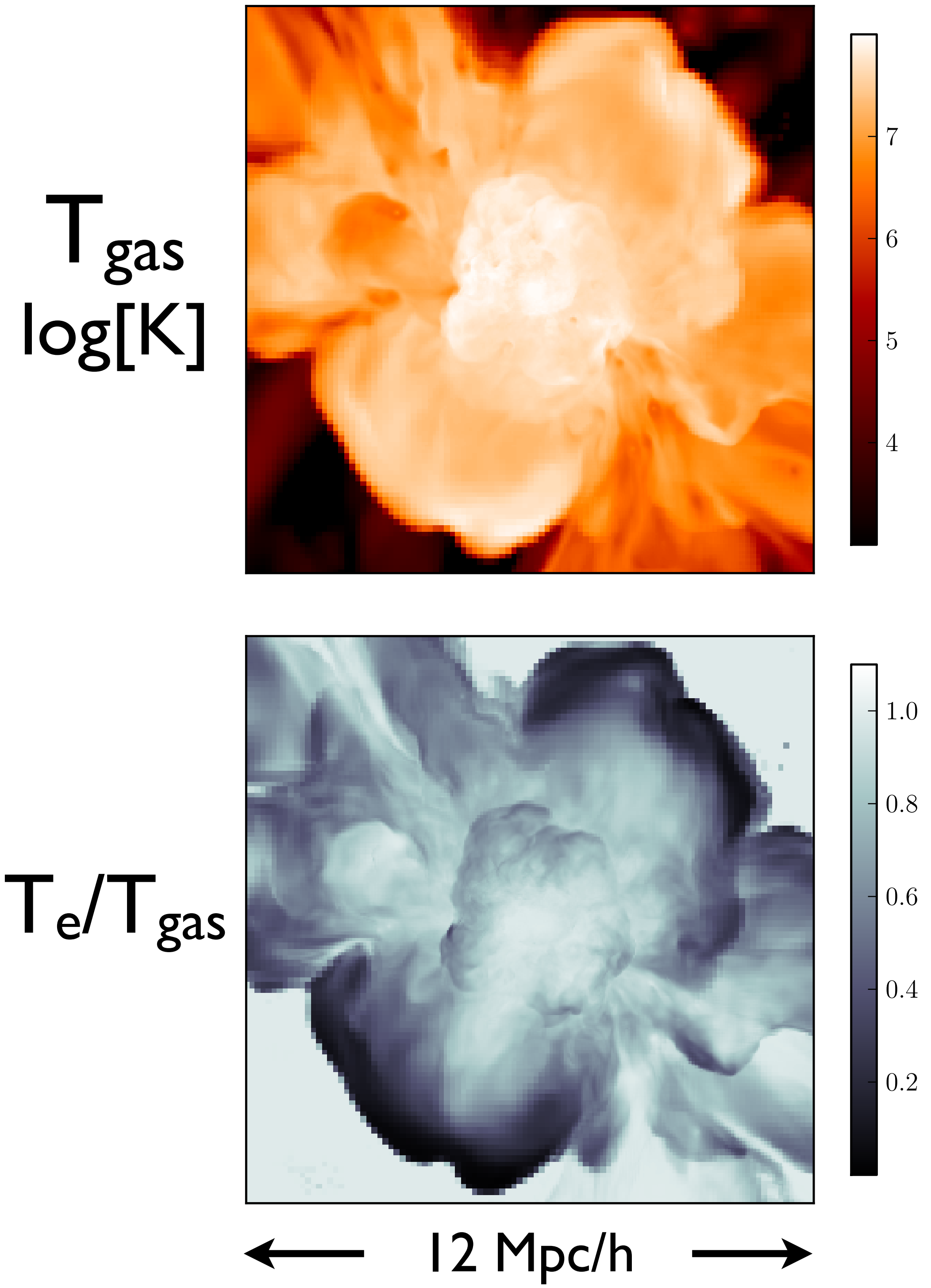
adiabatic heating/cooling

Coulomb equilibration timescale:

$$\begin{aligned} t_{ei} &\sim T^{3/2}/n_e \sim K^{3/2} \\ &\approx 6.3 \times 10^8 \text{ yr } \left(T_e/10^8 \text{K}\right)^{3/2} \left(n_i/10^{-5} \text{ cm}^{-3}\right)^{-1} \end{aligned}$$

Simple model allows us to probe max/min effect in single simulation, unable to model shock-dependent heating

Cosmological Simulations



Rudd & Nagai (2009)

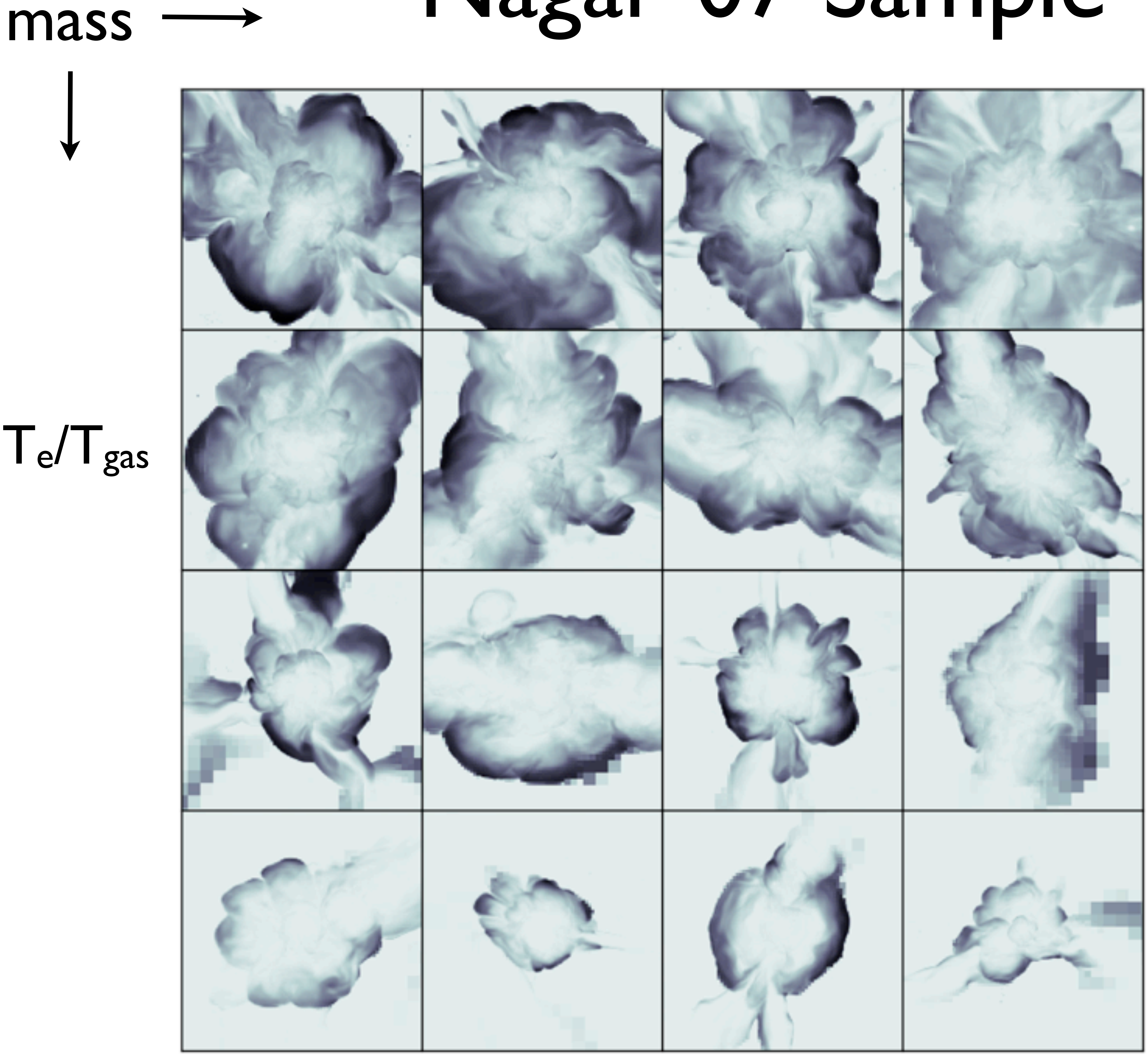
Modified the distributed Adaptive Refinement Tree (ART) code to simulate several samples of galaxy clusters using this scheme (without cooling and feedback physics)

16 galaxy clusters and groups from
Nagai et al (2007)
$M_{500} = 0.31\text{-}7.3\times10^{14}\ h^{-1}\ M_\odot$

Hydro resimulation of Bolshoi N-body simulation (Klypin et al 2010)
250 h^{-1} Mpc 1024^3 particles
~130 clusters $M_{500} > 10^{14}\ h^{-1}\ M_\odot$

High resolution (~few kpc) in cluster core, degrading to several ~10s kpc in outskirts

Nagai '07 Sample



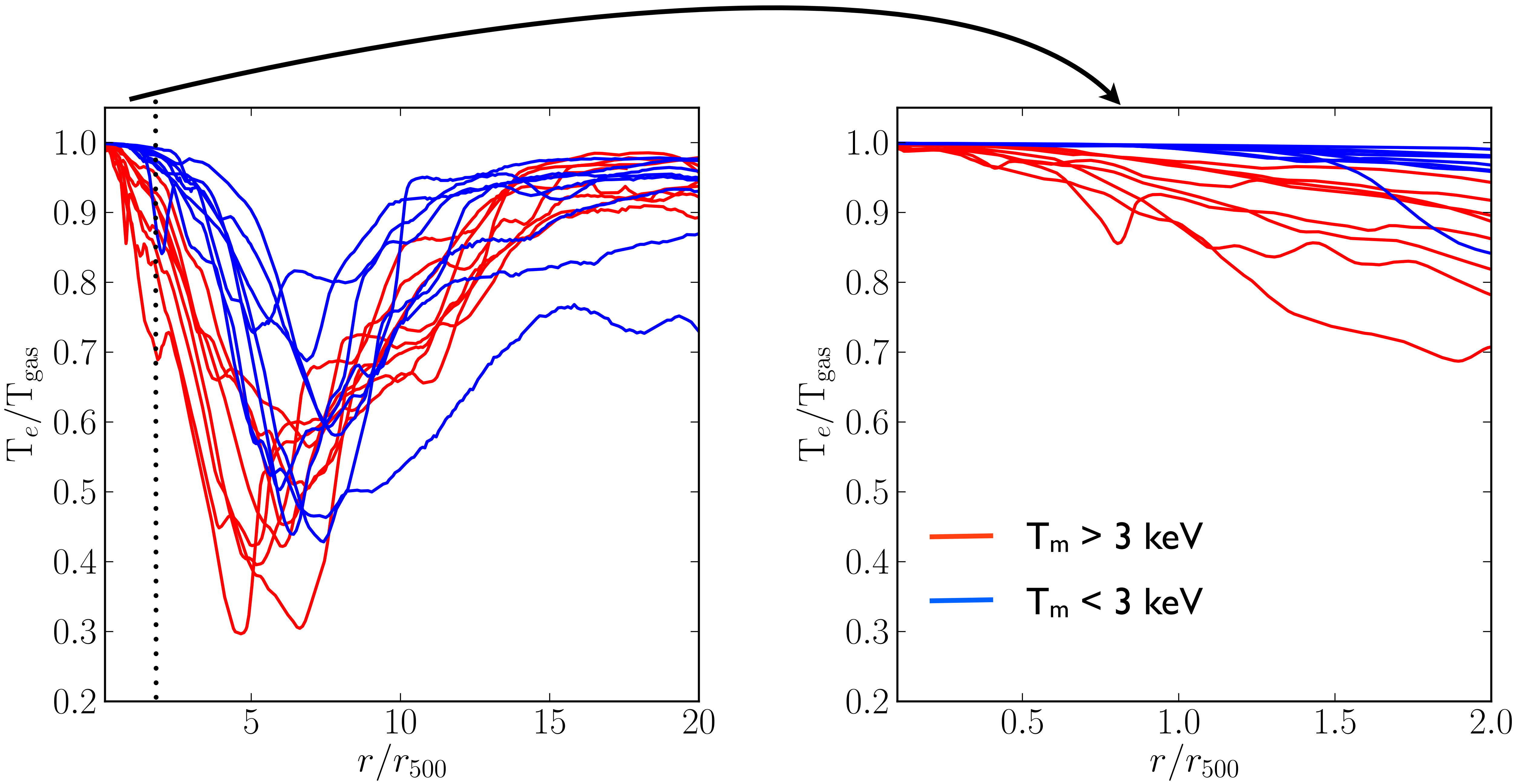
← 12 Mpc/h →

Range of temperatures and shock morphologies leads to qualitatively different distribution of "cold" electrons

Expected mass trend broadly reproduced with some scatter due to formation history

Only self-consistent simulations can model the full distribution of accretion histories

Radial Temperature Profile



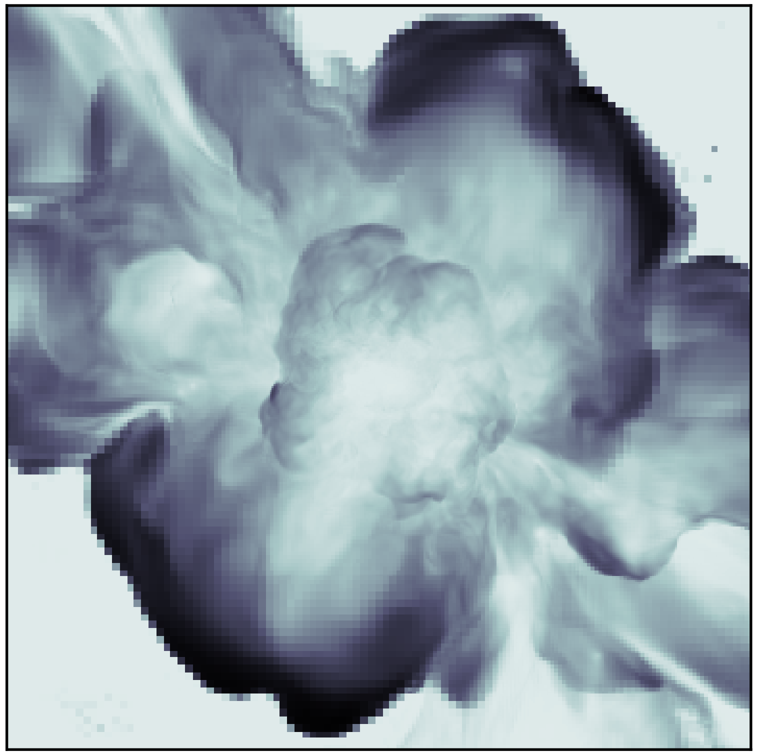
Spherically averaged electron temperature profiles reach minimum relative to mean gas temperature near shock radius.

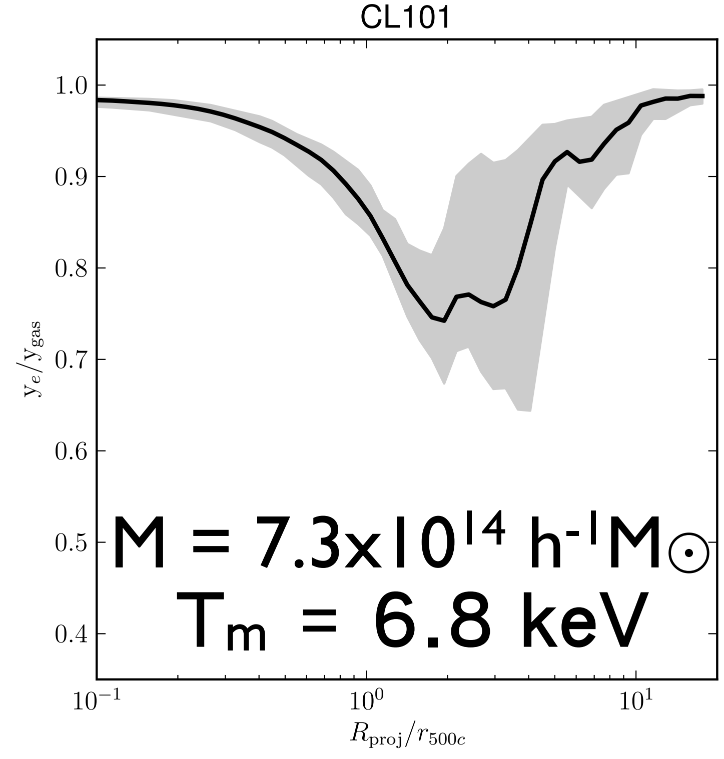
Rudd & Nagai (2009); see also Fox & Loeb (1997)

Relaxation State/Cluster Assembly

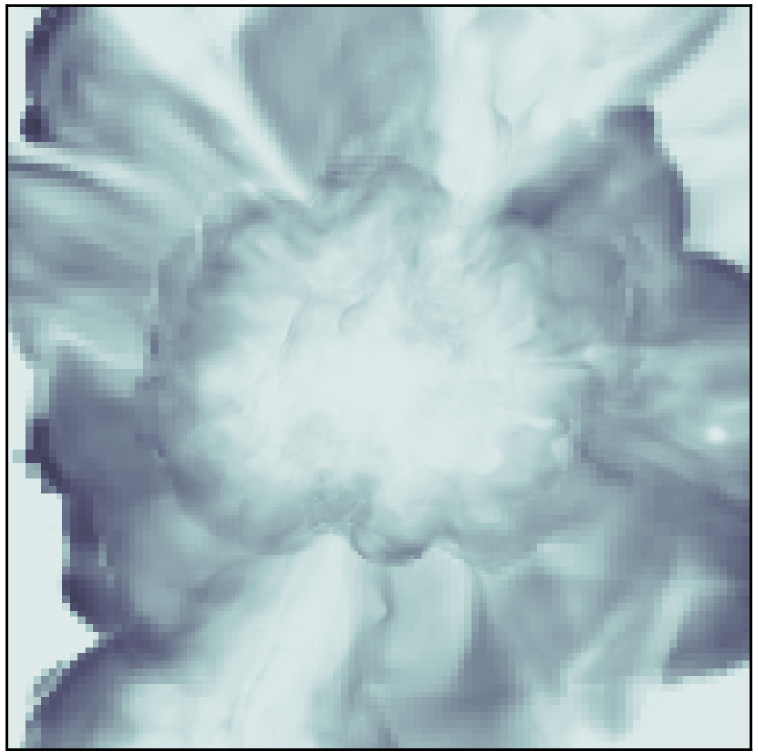
T_e/T_{gas}

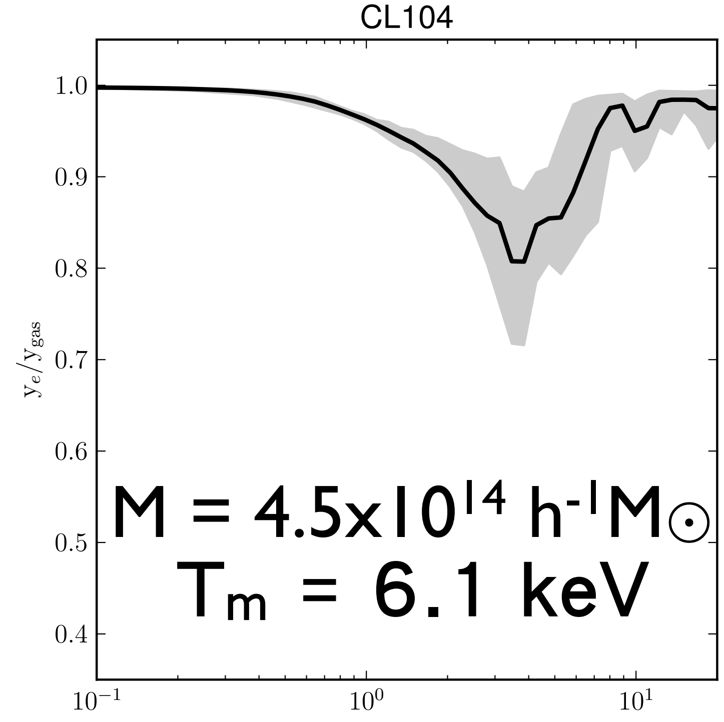
y_e/y_{gas} $y(R_{\rm proj}) \sim \int T_e n_e d\ell$





M = 7.3x10^{14} $h^{-1}M_\odot$
T_m = 6.8 keV





M = 4.5x10^{14} $h^{-1}M_\odot$
T_m = 6.1 keV

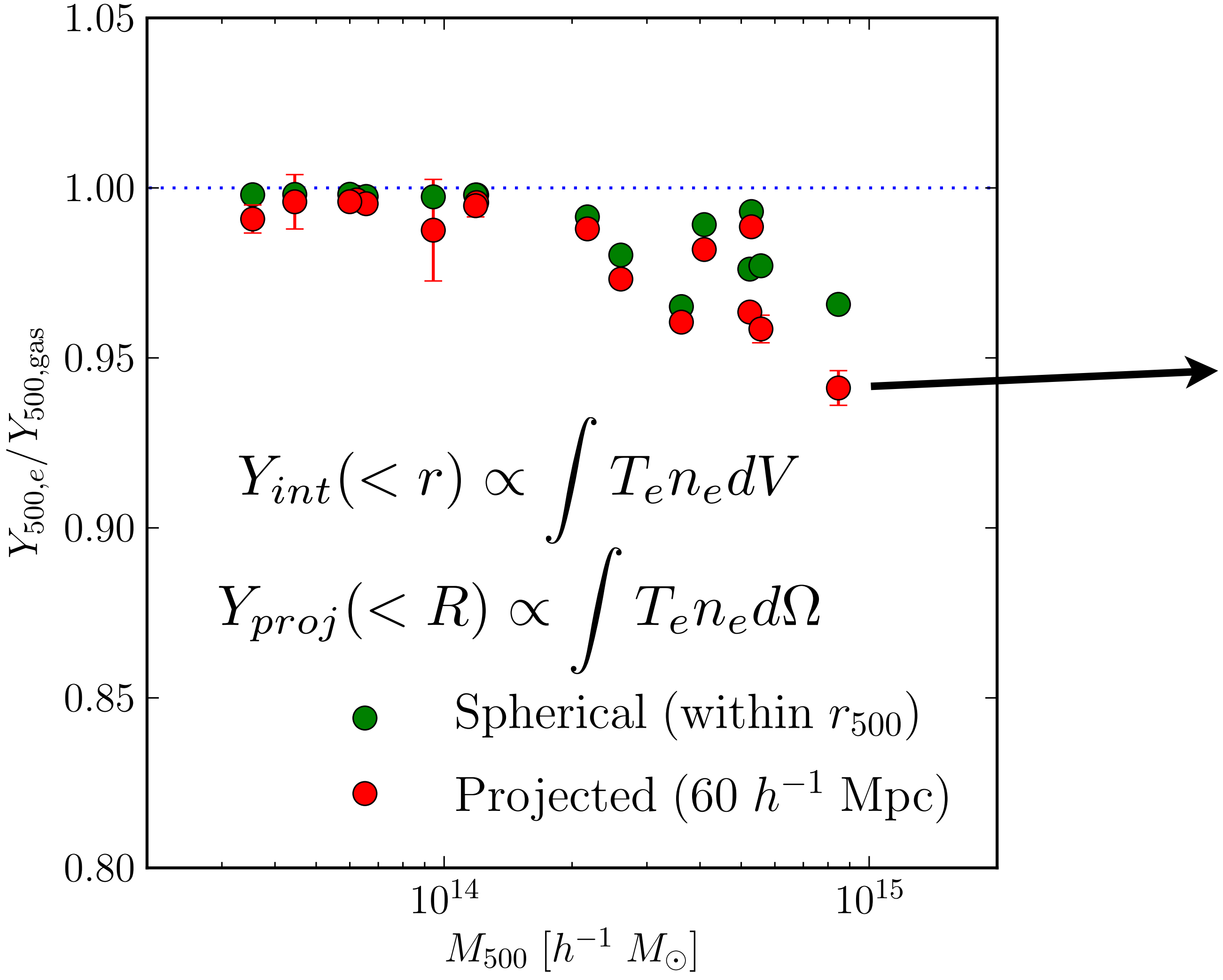
$R_{\rm proj}/r_{500}$

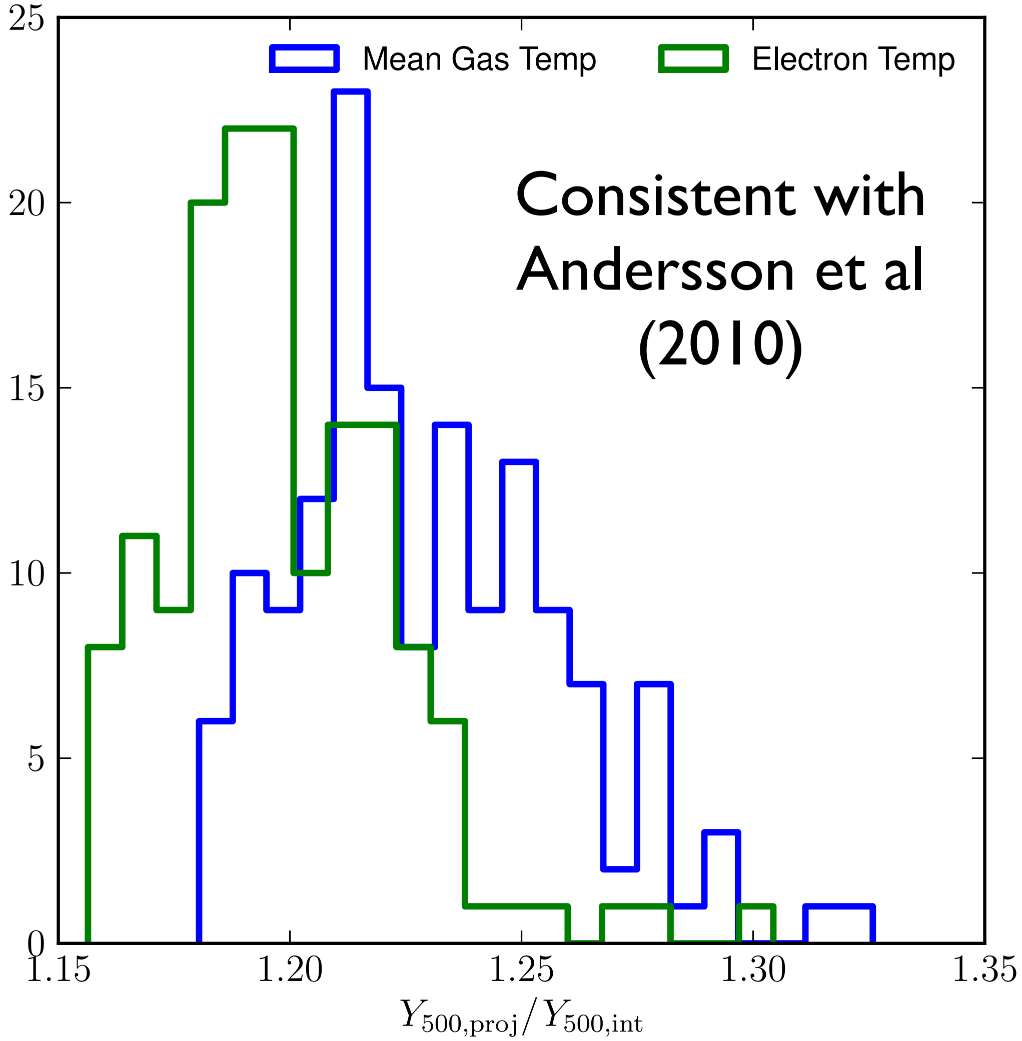
Two of the most massive clusters in our sample have similar mean gas temperatures (~6 keV) but dramatically different distribution of non-equilibrium electrons

Understanding effect of cluster assembly history is critical to predicting the SZ signal from cluster populations

Effect on SZ Flux

Average of 150 sightlines/cluster





Consistent with Andersson et al (2010)

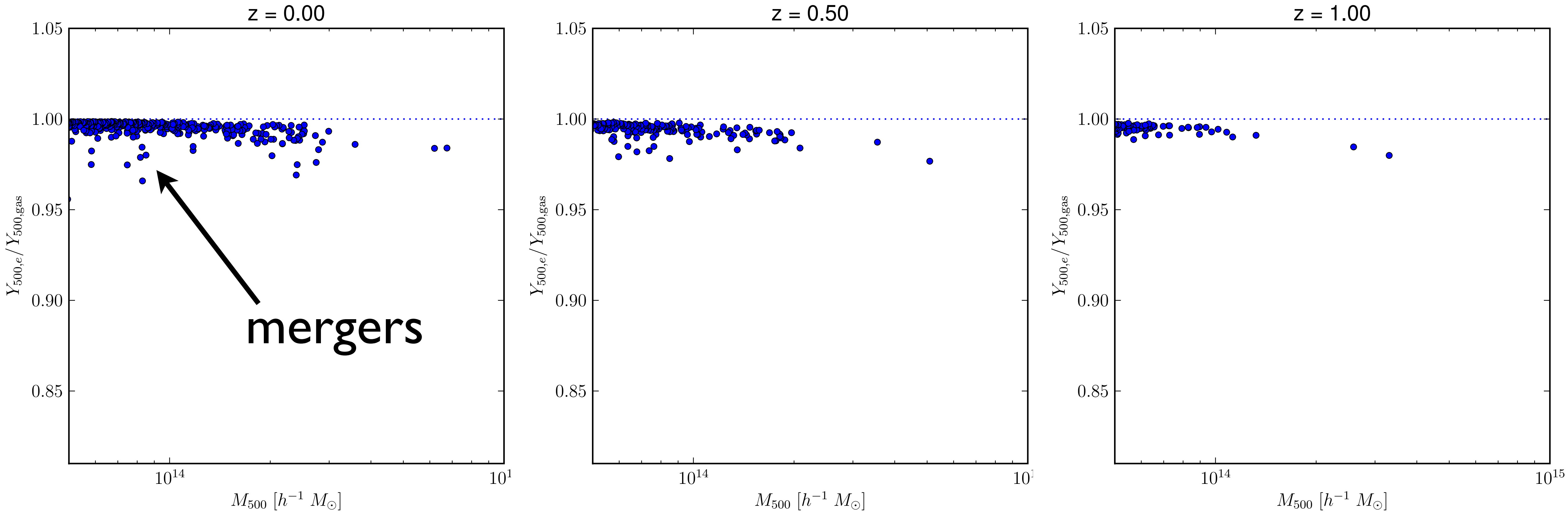
Y_{proj}/Y_{int}

Effect is strongest for more massive clusters (up to ~6% in the projected SZ flux). Lower electron temperature in outer regions leads to lower flux when computed in projection.

Redshift Evolution

Integrated (within r_{500})

Y_e/Y_{gas}



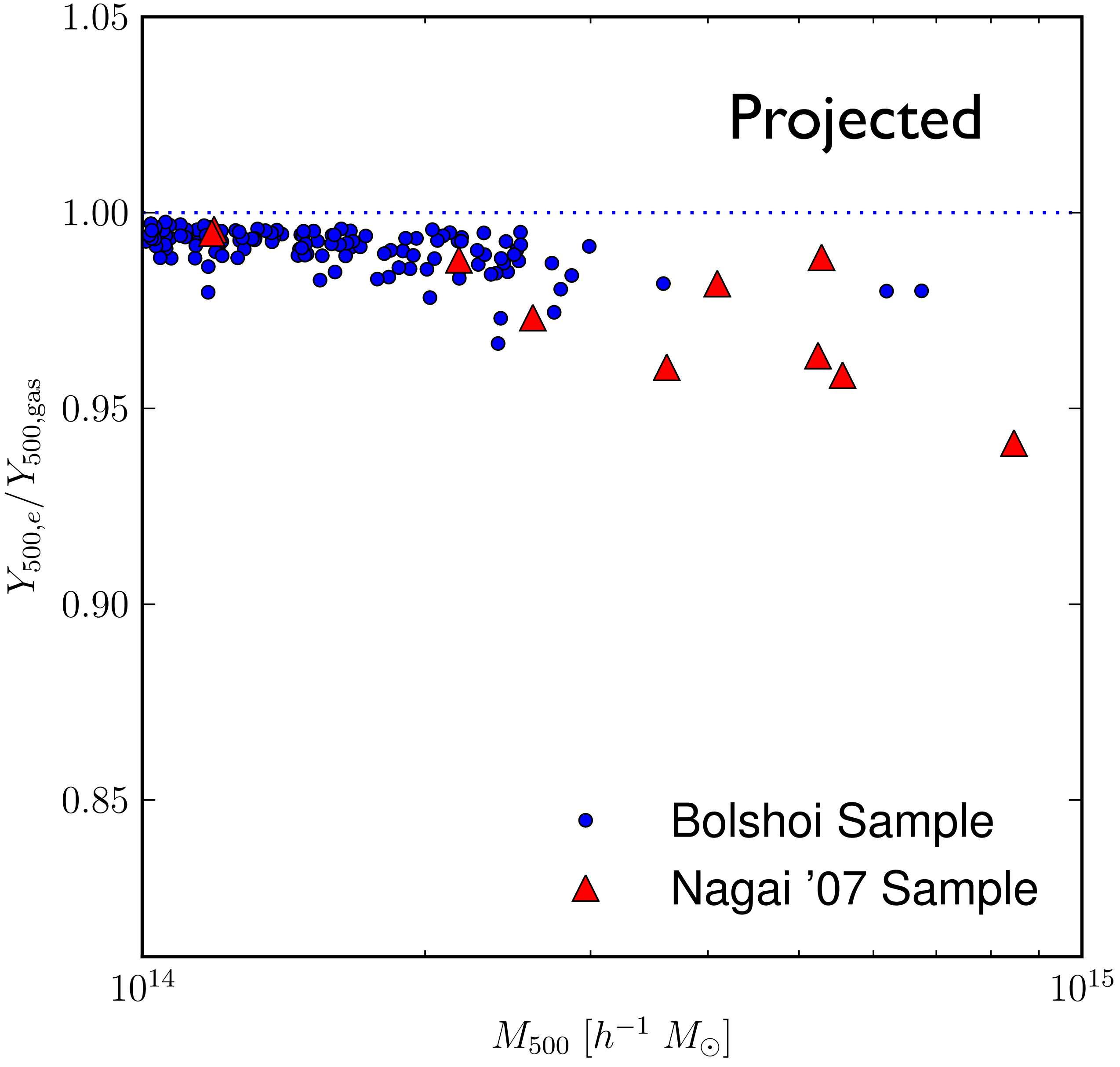
mergers

M_{500}

Mass scale moves to lower mass with redshift (combination of evolution in age-mass relation and entropy-mass relations)

Wednesday, August 25, 2010

Summary



Rudd, Shaw & Nagai (2010, in prep)

- Electron temperatures may be suppressed by up to 60% in the outskirts of massive clusters if equilibration proceeds through Coulomb collisions.
- Effect stronger in hotter and more massive clusters; projected SZ flux suppressed by ~6% at 8×10^{14} $M_\odot$ at z = 0
- Effect grows to lower mass with increasing redshift due partly to evolution of mass-entropy relation
- Unfortunately unlikely to be directly constrained by observations in the near future