Entropy Excess without Preheating

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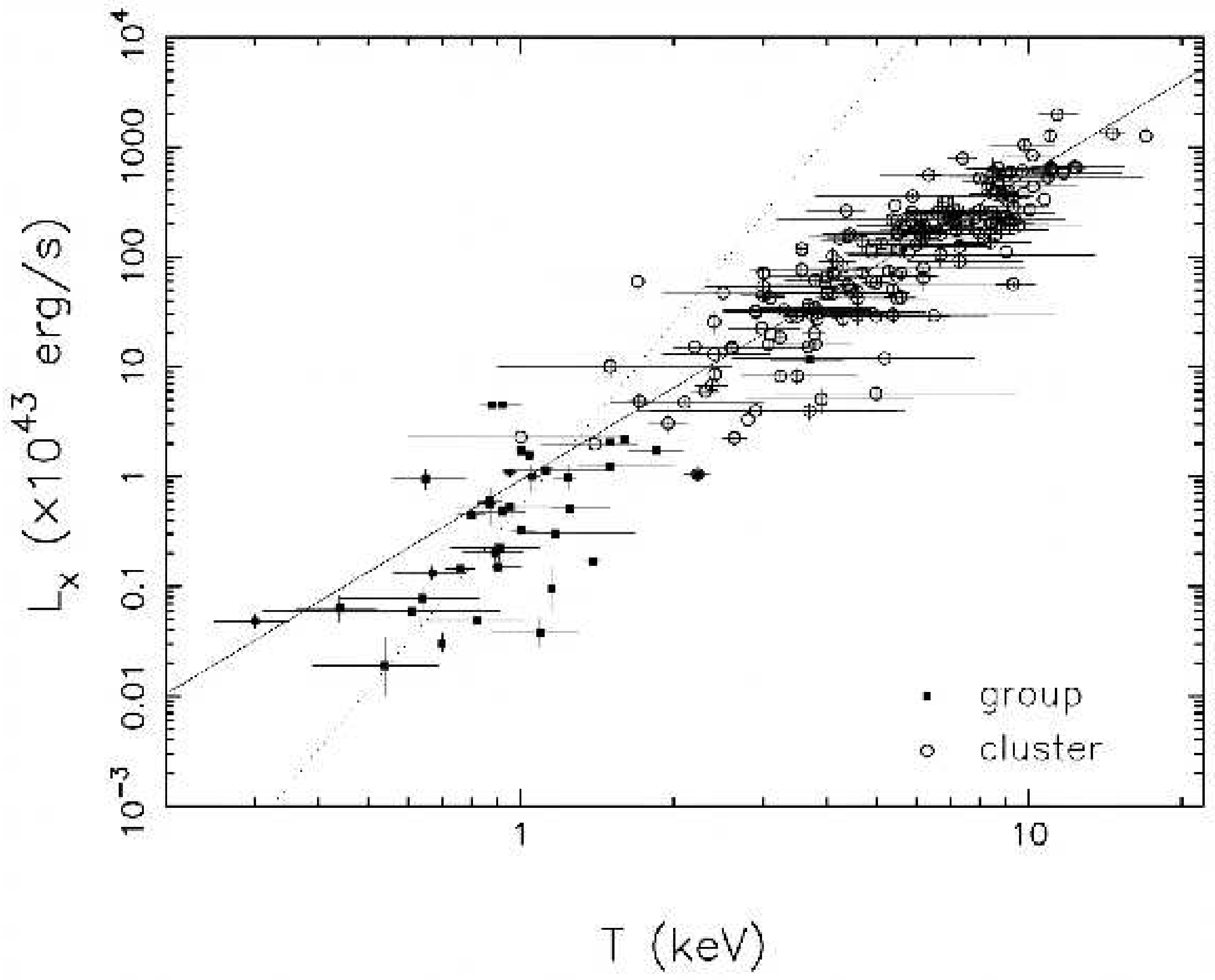
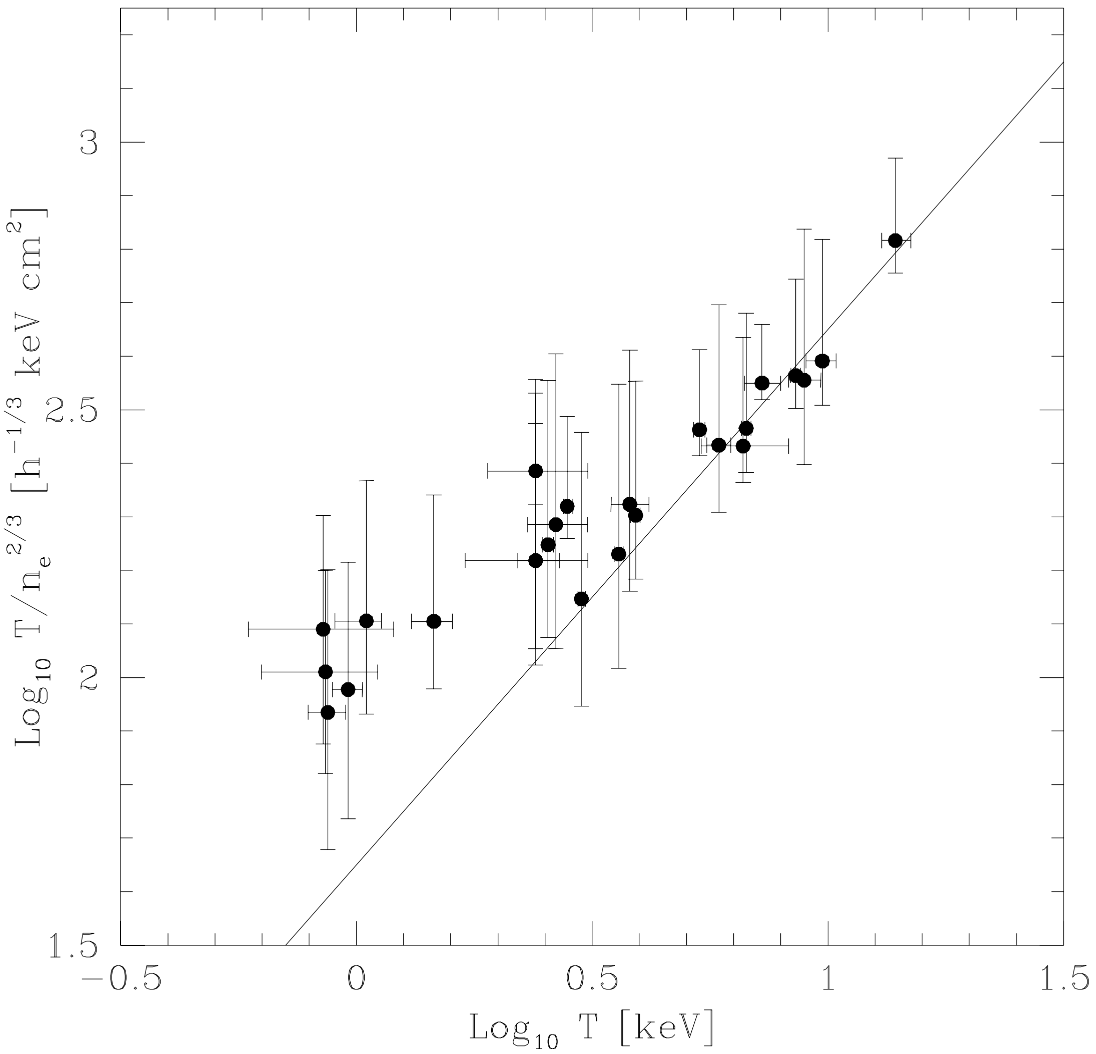
Observed $L_{\rm bol}$-$T_{\rm ew}$ relation



The Figure shows the observed $L_{\rm bol}$-$T_{\rm ew}$ relation for clusters from Xue & Wu (2000).

The best-fit relations for groups (dotted line) $L_{\rm bol} \propto T_{\rm ew}^{5.6}$
and clusters (solid line) $L_{\rm bol} \propto T_{\rm ew}^{2.8}$
are both much steeper than the theoretical relation $L_{\rm bol} \propto T_{\rm ew}^{2}$.

Observed entropy "floor"



The Figure shows the observed entropy at $0.1\,R_{200}$ from Ponman, Cannon & Navarro (1999).

At low temperatures the entropy rises above the expected relation $S \propto T$ and seems to tend to a constant floor value.

Note, however, that the entropy of any individual cluster does not tend to a constant within $0.1\,R_{200}$ but decreases with radius.

Cluster simulations: introduction

Peter Thomas, with
Orrarujee Muanwong, Scott Kay, Frazer Pearce, Hugh Couchman

Cosmological parameters: $\Omega_0 = 0.35$, $\lambda_0 = 0.65$, $\Omega_{b0} = 0.038$

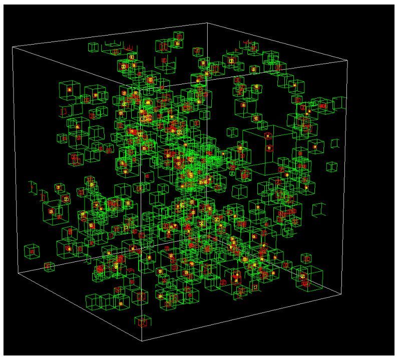
Density perturbations: $\Gamma = 0.21$, $\sigma_8 = 0.91$

Box-size: $100\,h^{-1}$Mpc, $h = 0.71$

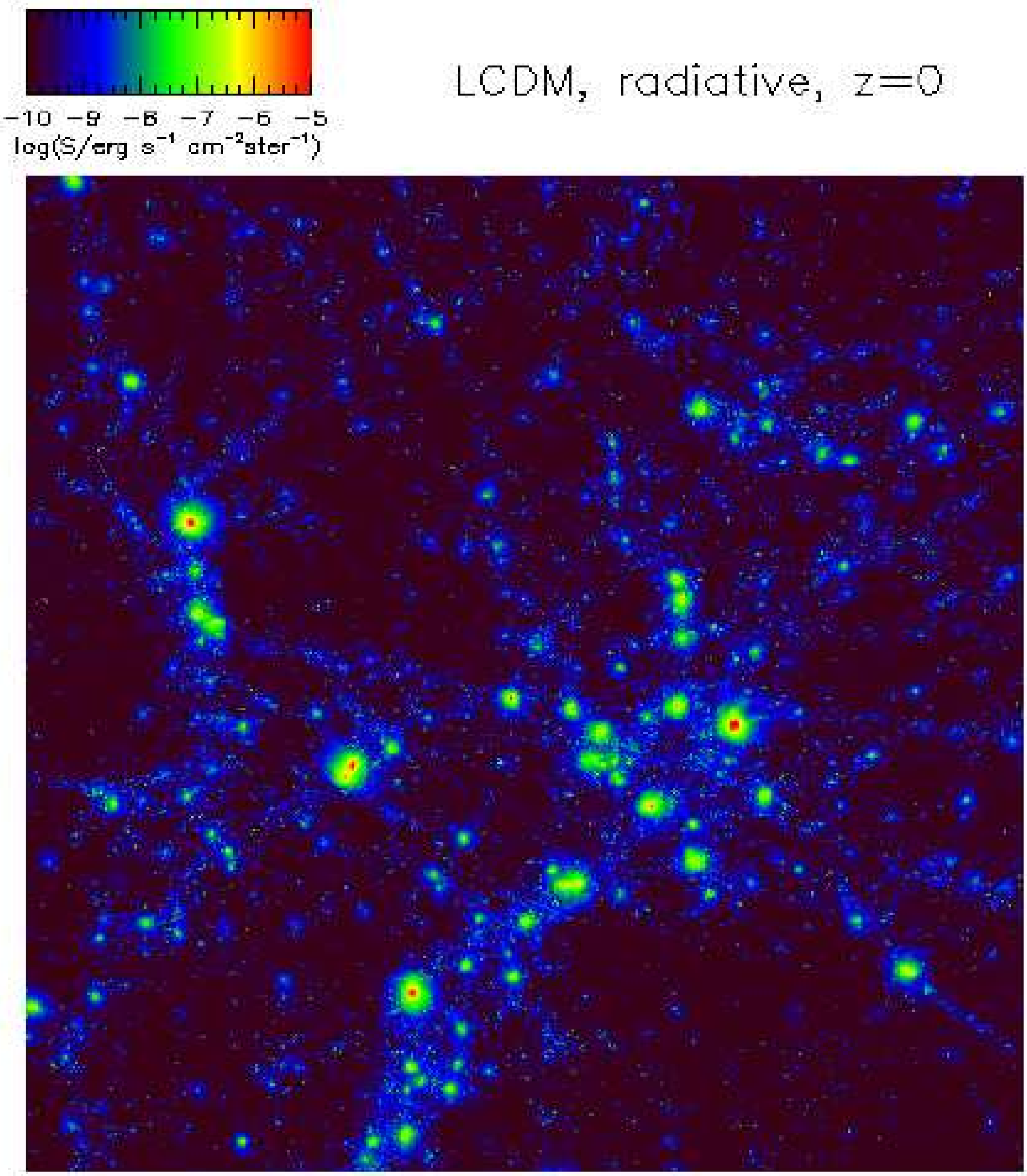
Particle number: 160^3 each of gas and dark-matter

Radiative cooling: Sutherland & Dopita, $Z = 0.3\,(t/t_0)\,Z_\odot$

Numerical technique: Hydra—adaptive P^{3}M+SPH

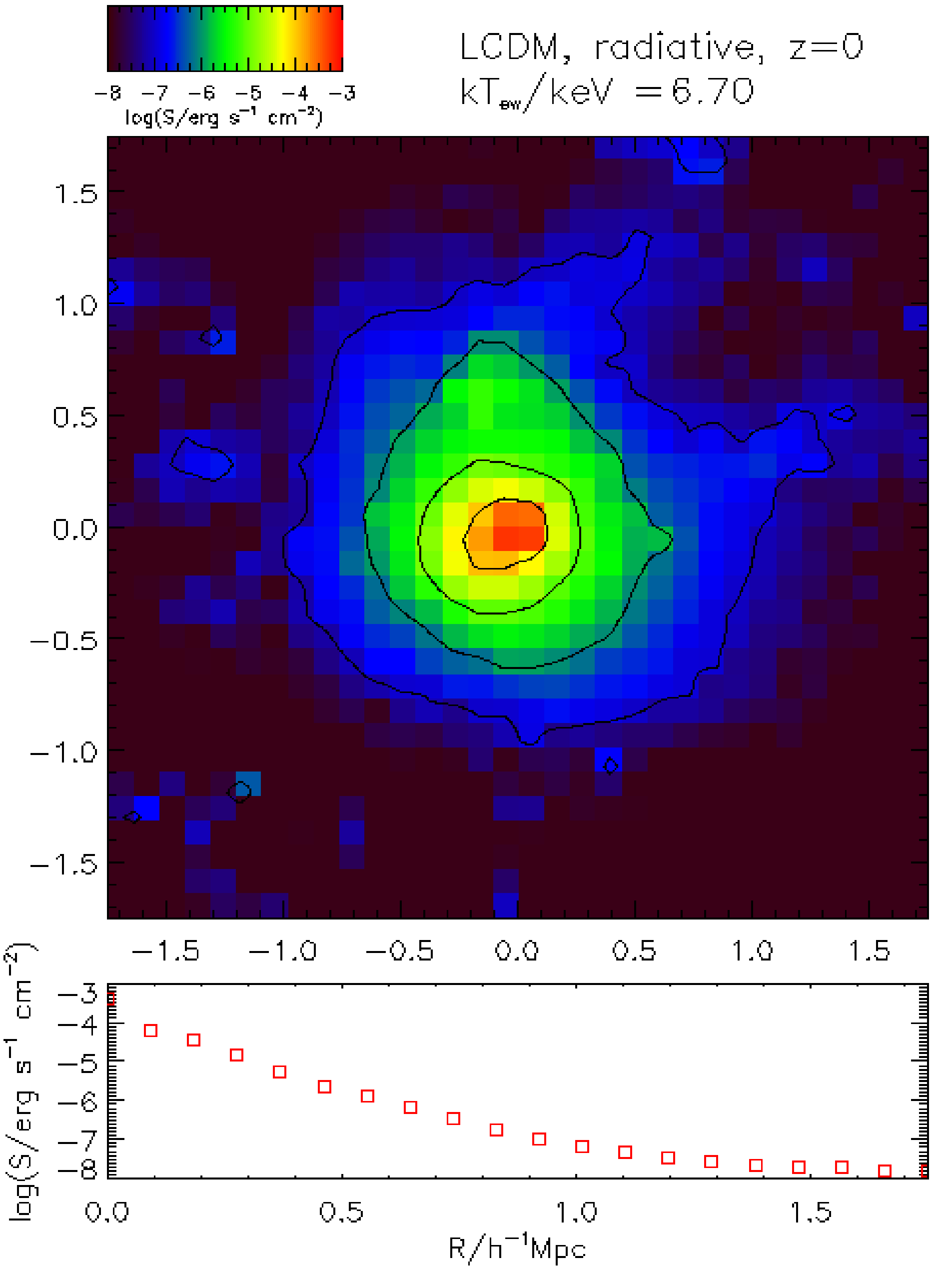


X-ray surface brightness map, radiative simulation



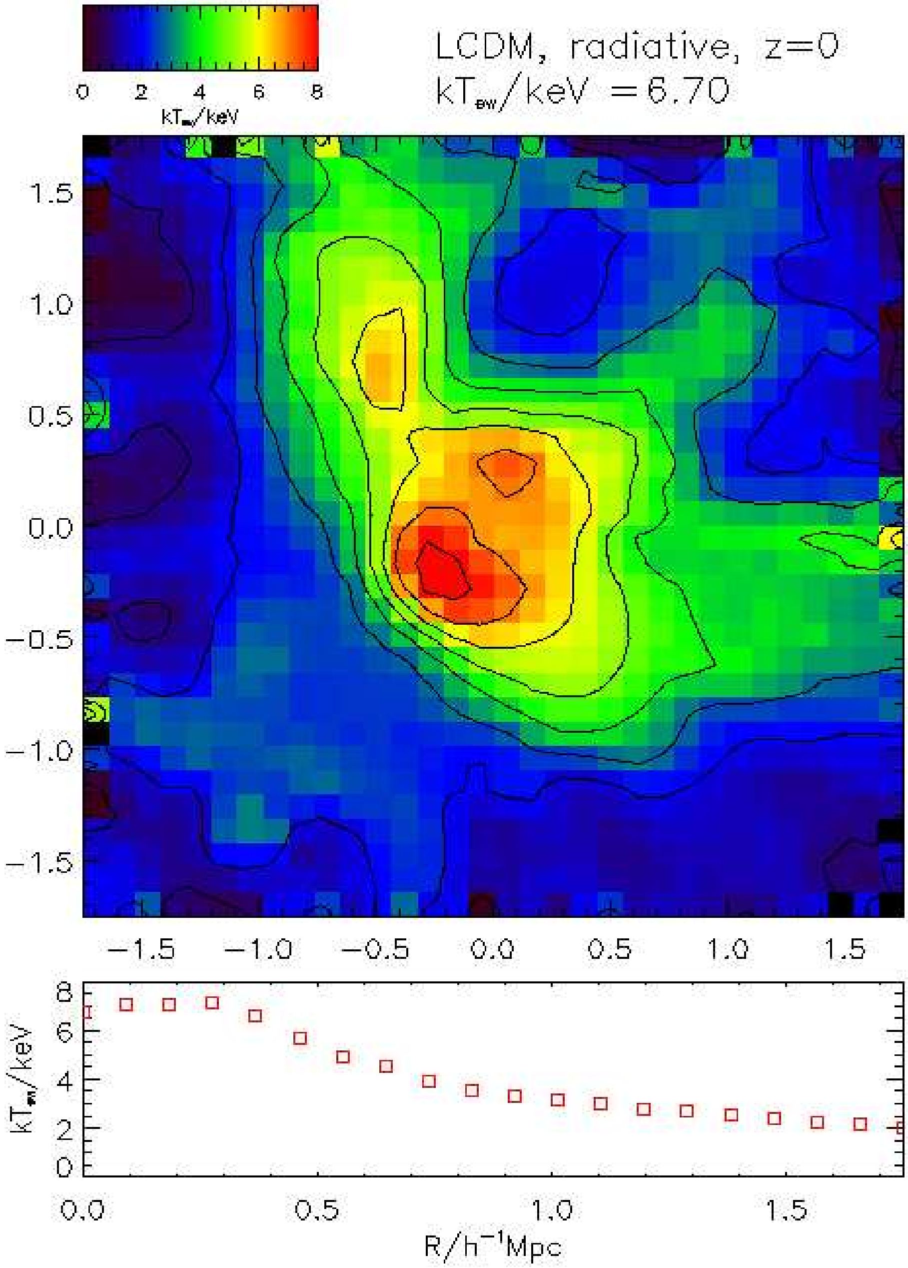
The X-ray surface brightness in a region $50\,h^{-1}$Mpc on a side.

Largest cluster: X-ray surface brightness



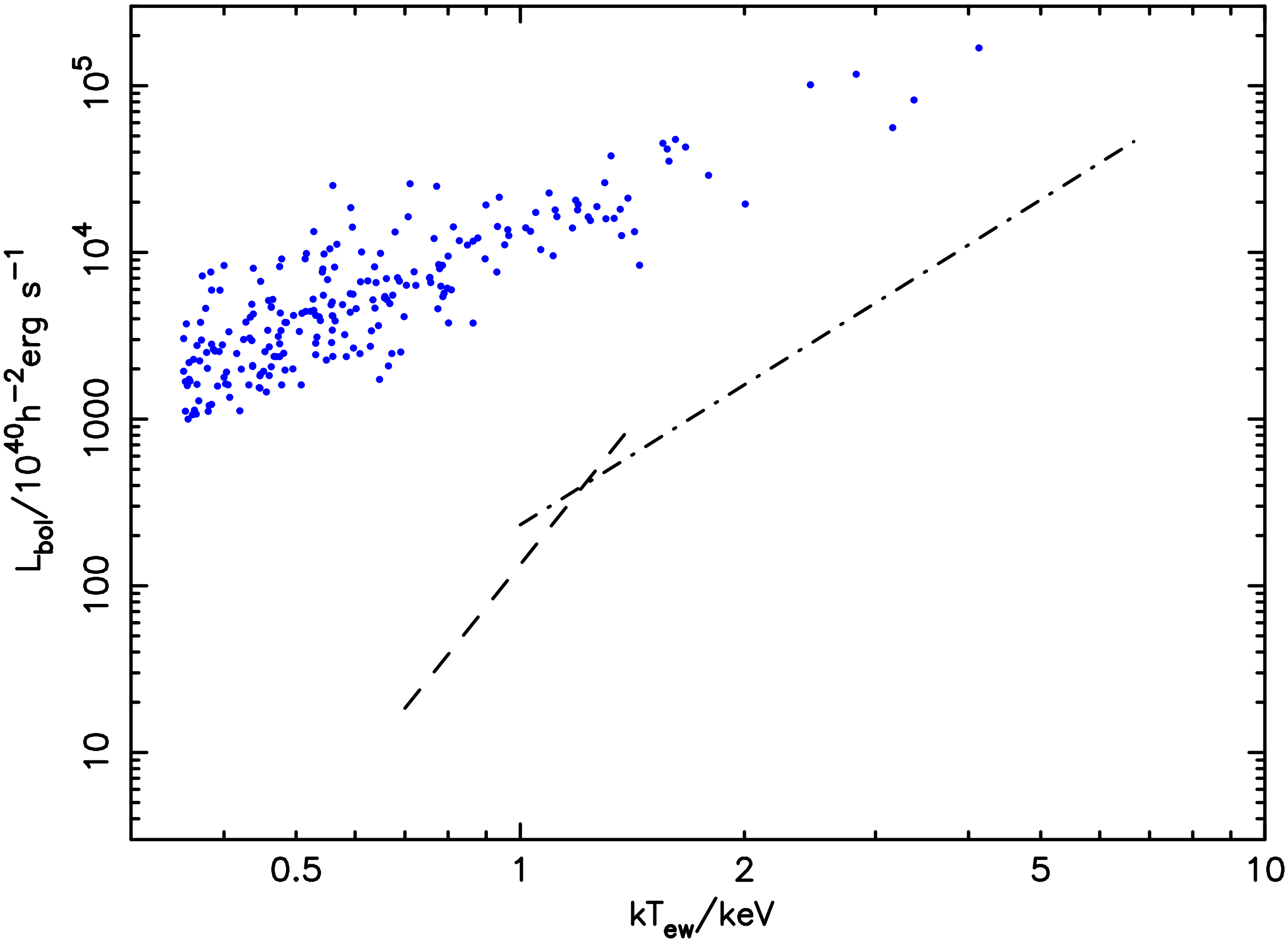
The X-ray surface brightness of the largest cluster, from the radiative simulation.

Largest cluster: emission-weighted temperature



The emission-weighted temperature of the largest cluster, from the radiative simulation.

Simulated $L_{\rm bol}$-$T_{\rm ew}$ relation (1)



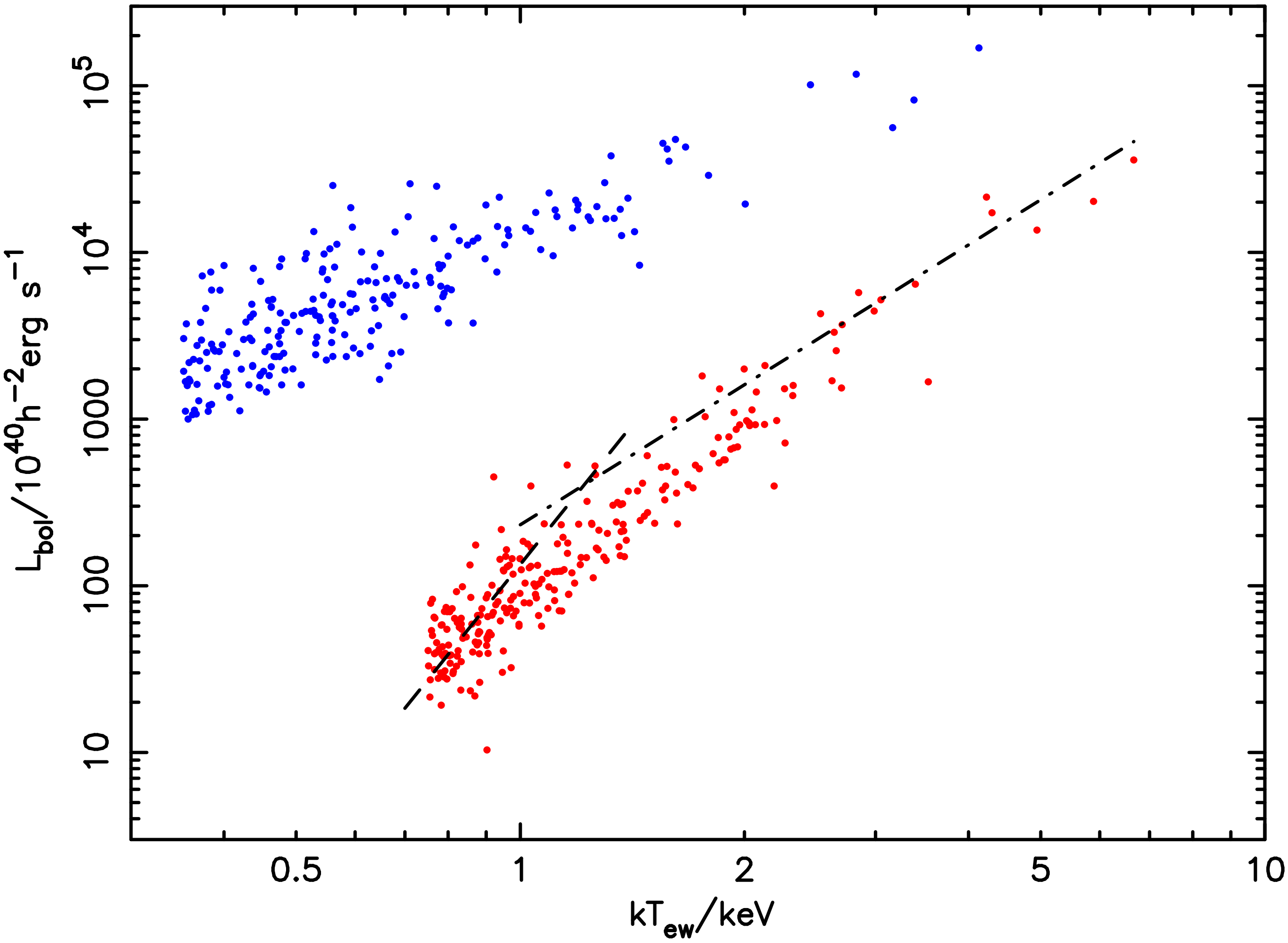
The Figure shows the simulated $L_{\rm bol}$-$T_{\rm ew}$ relation for clusters from the non-radiative simulation.

The dotted and dashed lines show the observed relation from Xue & Wu (2000).

The simulated clusters lie close to the theoretical relation $L_{\rm bol} \propto T_{\rm ew}^2$ but are highly over-luminous.

The emission is dominated by core gas that has a short cooling time and would not be present in real systems.

Simulated $L_{\rm bol}$-$T_{\rm ew}$ relation (2)

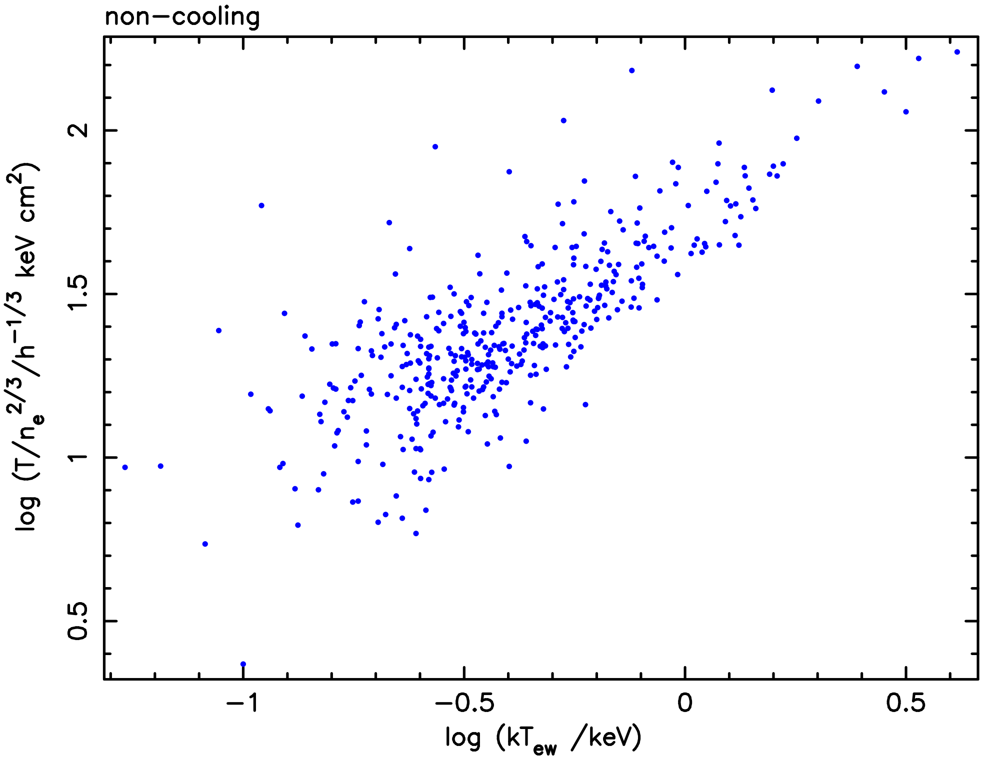


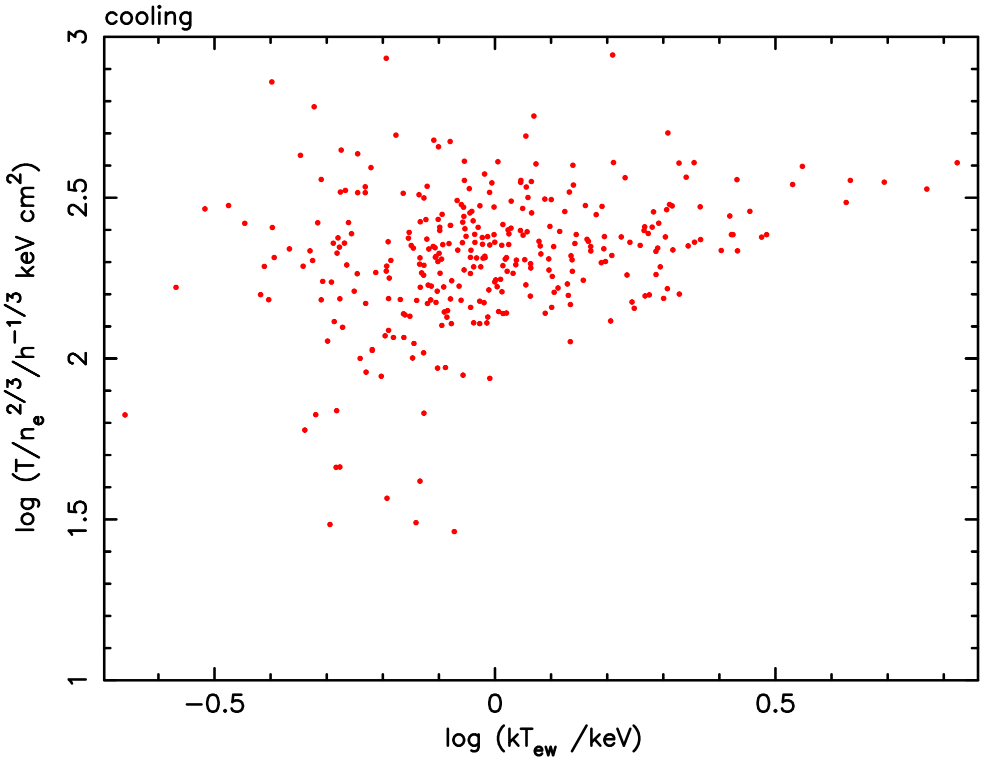
The Figure shows the simulated $L_{\rm bol}$-$T_{\rm ew}$ relation for clusters from both the non-radiative and radiative simulations.

The dotted and dashed lines show the observed relation from Xue & Wu (2000).

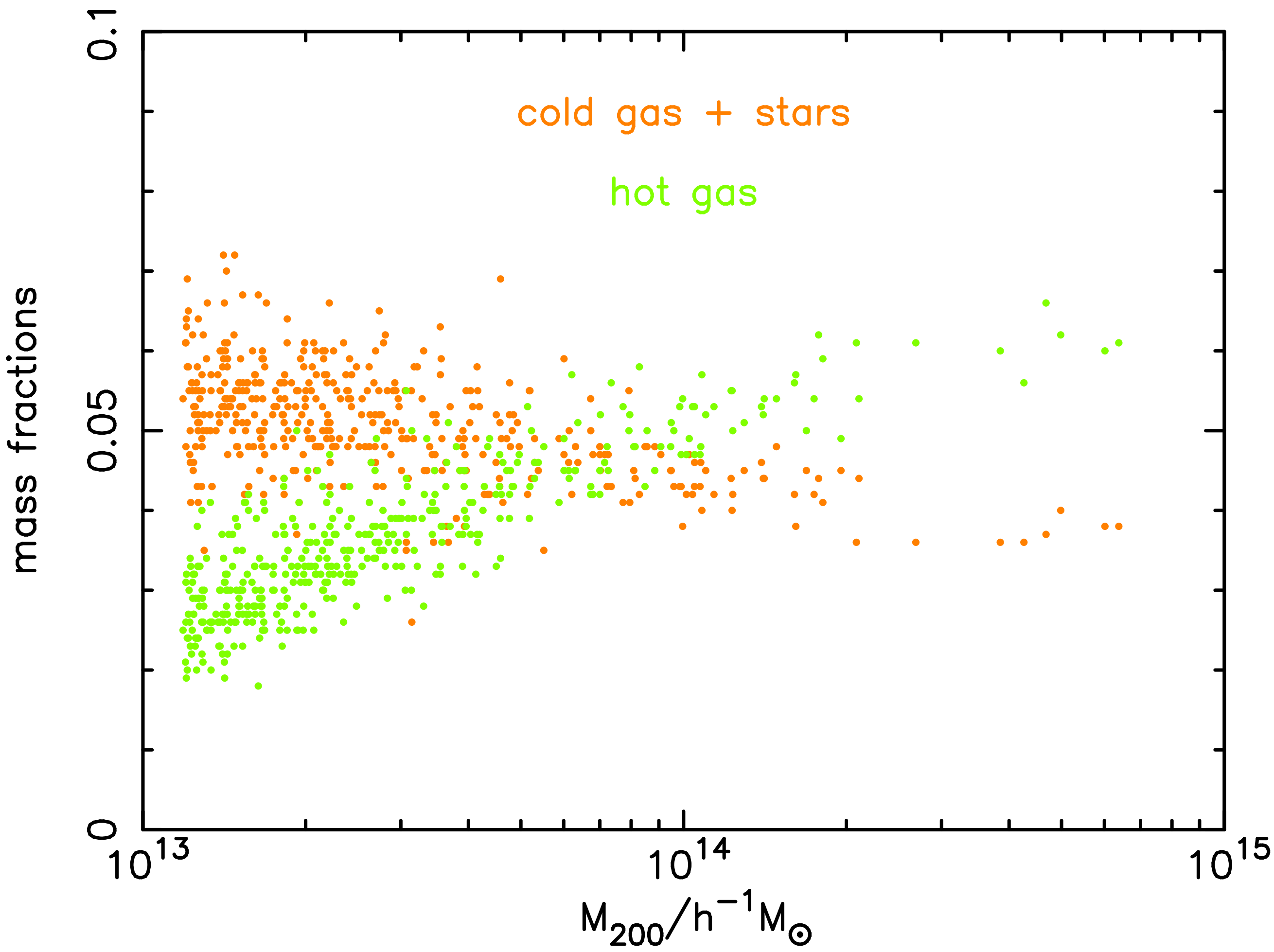
Cooling raises the temperature and
lowers the X-ray luminosity,
bringing the simulations into agreement with observations.

Simulated entropy "floor"





Mass fractions of gas, radiative simulation



The Figure shows the mass fractions of cold gas (and stars) and hot gas within R_{200} for each cluster.
The mean gas fraction within the simulation is 0.12.

Although the cold gas fractions cannot be ruled out by observation, they are rather large—however, we have neglected feedback of energy associated with metal enrichment of the intracluster medium.

Conclusions

Cooling raises the temperature and
lowers the X-ray luminosity of clusters,
reproducing the observed L_X-T_X relation.

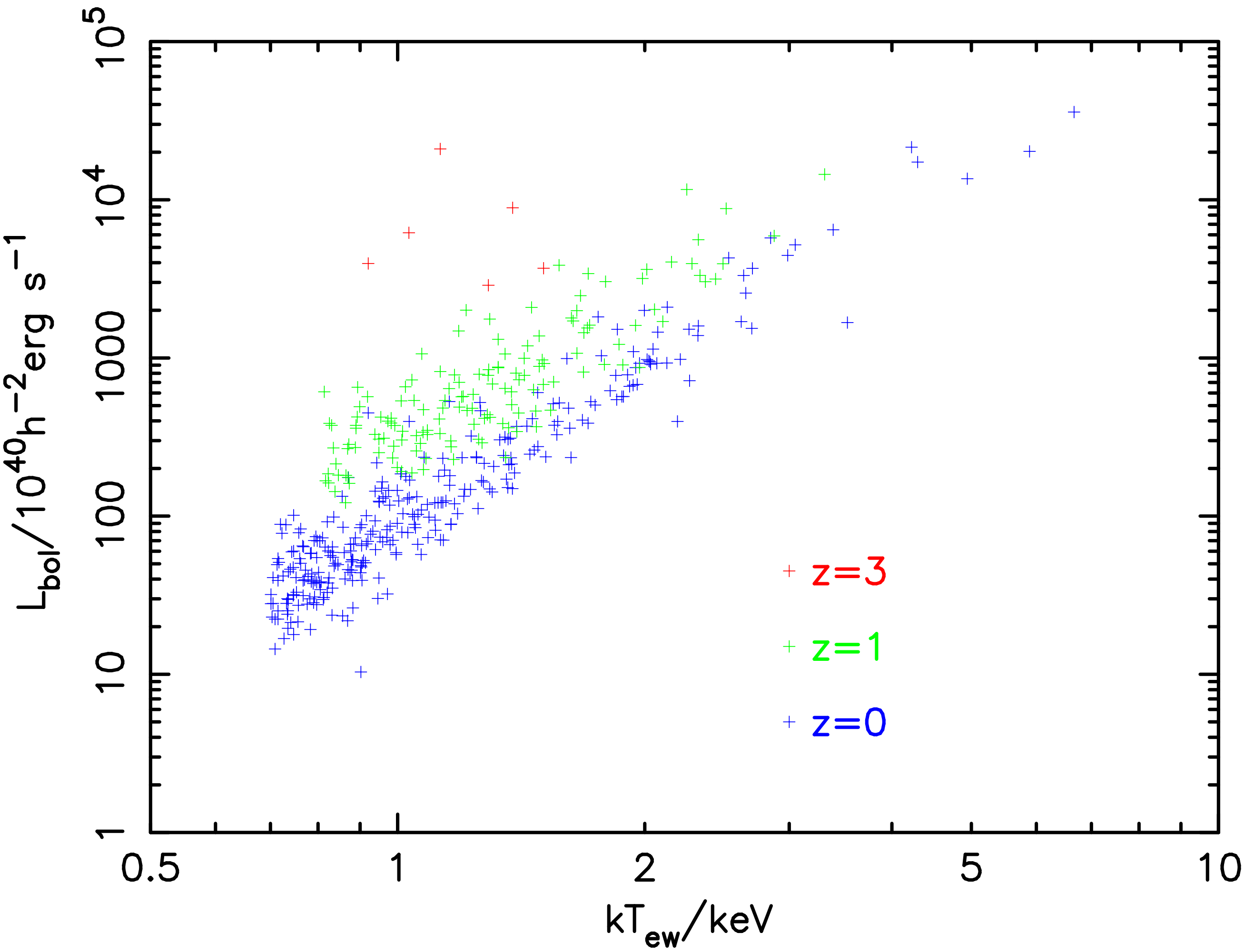
Cooling selectively raises the entropy of low-mass clusters
leading to the appearance of an entropy floor, and
reproducing the observed $S(0.1\,R_{200})$-T_X relation.

There is no heating in our simulations except that provided by shocks.

The clusters in our simulations have a large cooled gas fraction. However, we have neglected the heating associated with metal-enrichment of the intracluster medium.

There is no compelling evidence for excessive amounts of preheating of the intracluster medium.

Evolution of $L_{\rm bol}$-$T_{\rm ew}$, radiative simulation



The evolution of the $L_{\rm bol}$-$T_{\rm ew}$ relation is roughly given by

$$L_{\rm bol} = 8 \times 10^{41}\,(1+z)^{2.2}\left(\frac{kT_{\rm ew}}{\rm keV}\right)^3\,h^{-2}{\rm erg\,s^{-1}}$$

Note that the most massive clusters change only slightly in luminosity but greatly increase their temperature as they age.