Evolution of Cluster Scaling Relations

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Cluster simulations: introduction

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

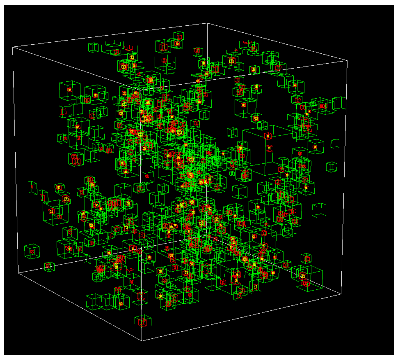
Density perturbations: $\Gamma = 0.21$, $\sigma_8 = 0.91$

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

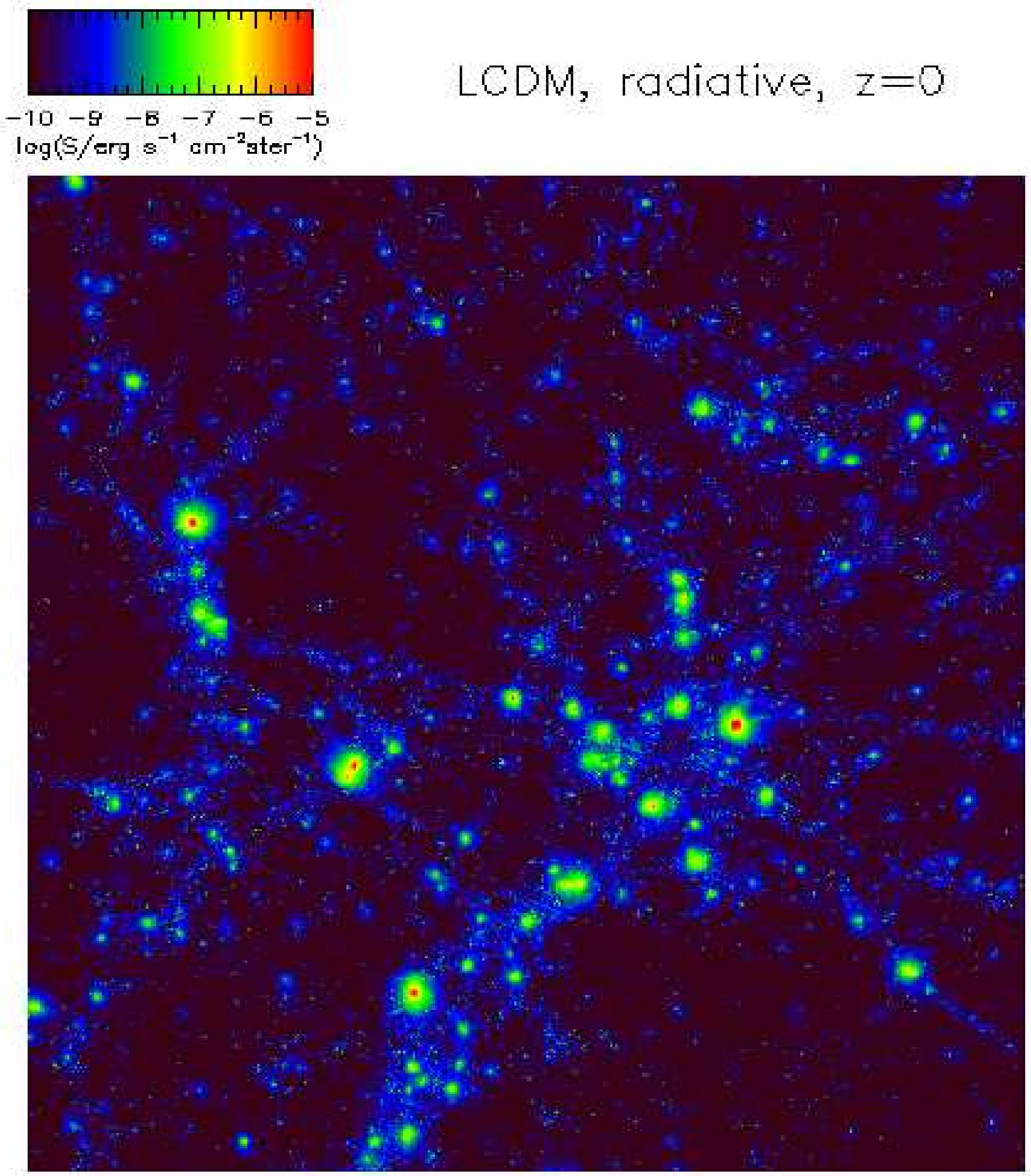
Particle number: 160^3 each of gas and dark-matter

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

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



X-ray surface brightness map, radiative simulation



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

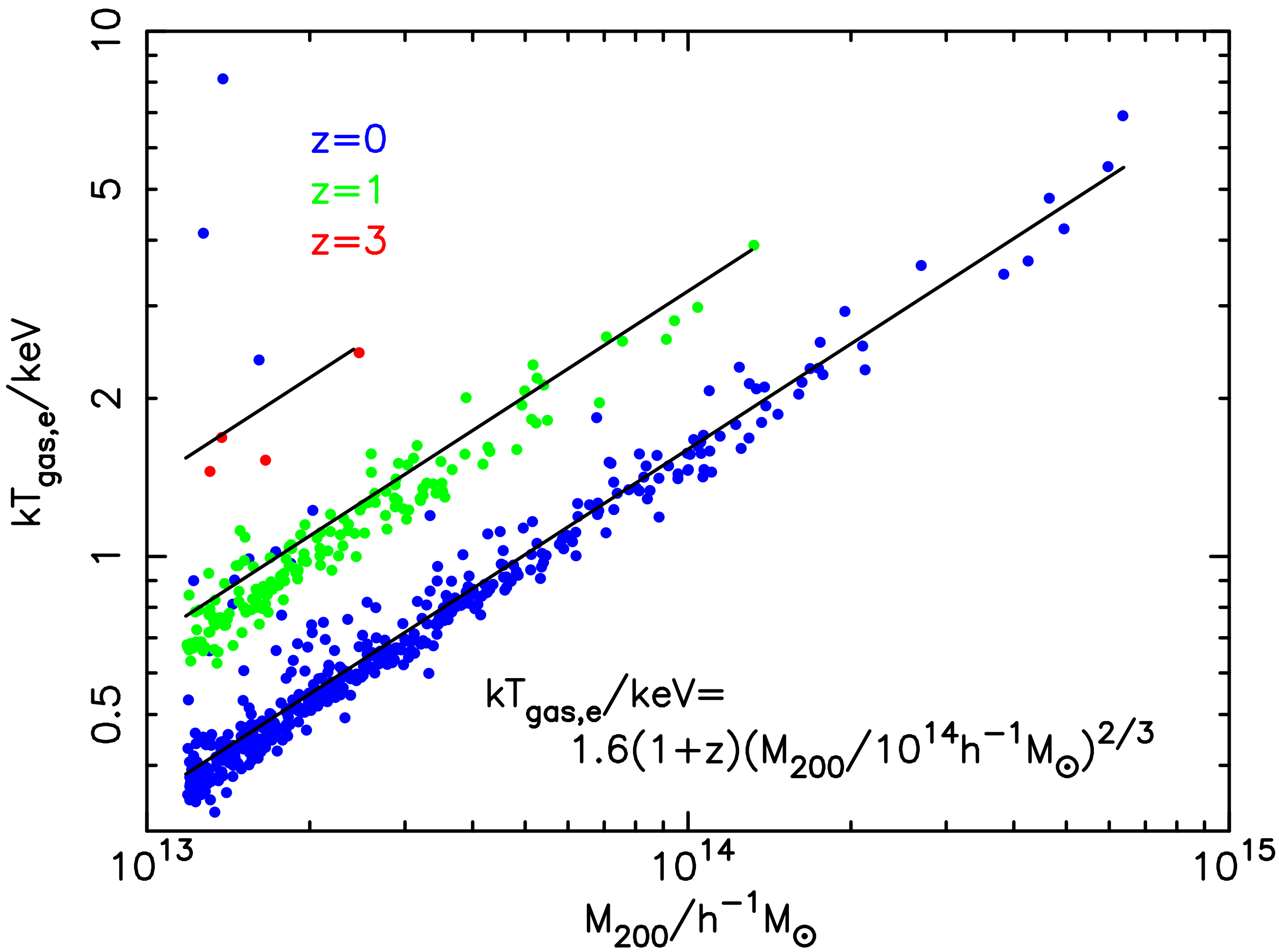
Theoretical T-M relation

Assuming self-similar clusters, then

$$T \propto \frac{M}{R} \propto M^{\frac{2}{3}} \rho^{\frac{1}{3}} \propto M_{200}^{\frac{2}{3}} (1 + z)$$

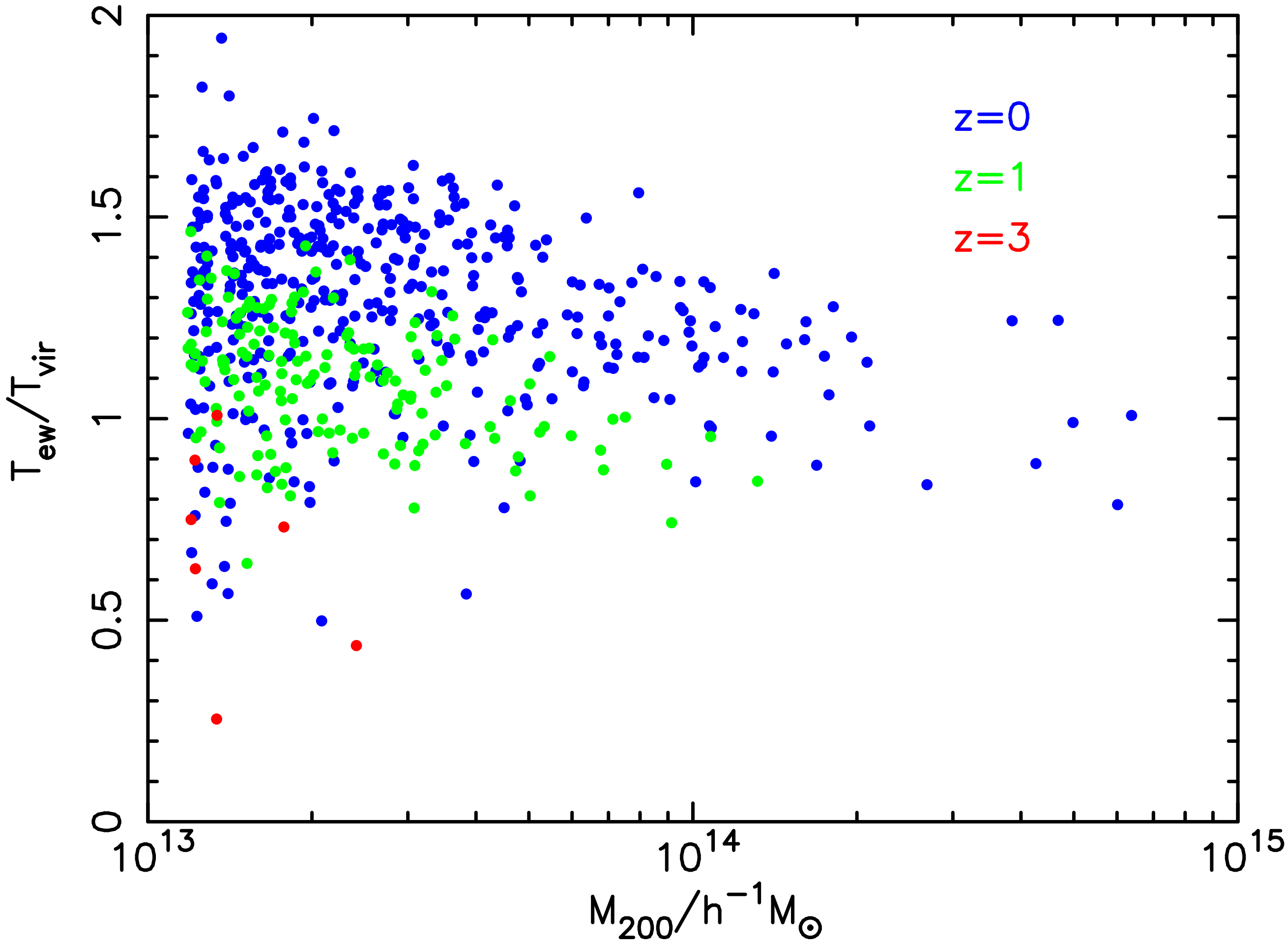
where M_{200} is measured within a fixed overdensity relative to the critical density.

We can test this with the non-radiative simulation:



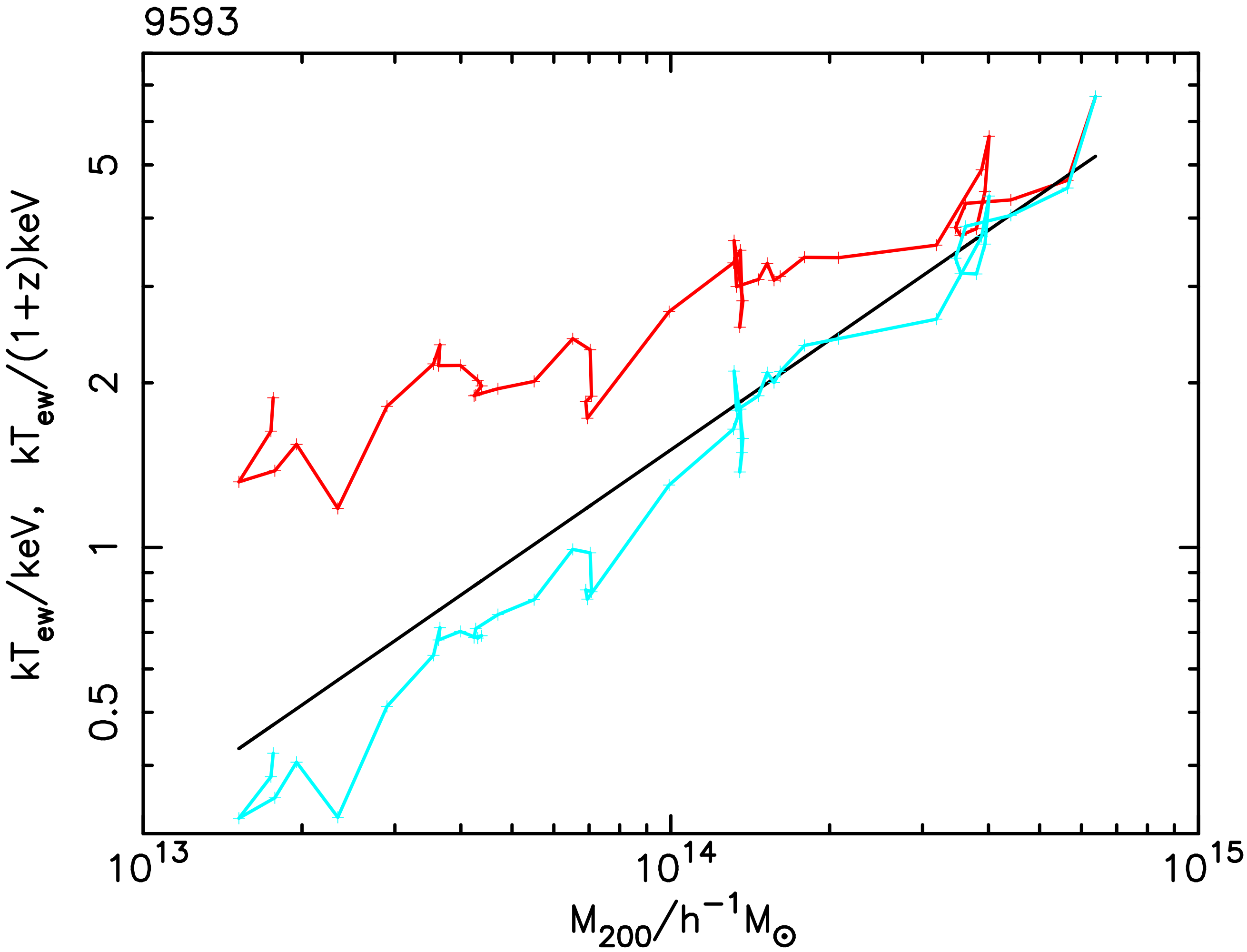
Emission-weighted vs virial temperature

For the radiative run, the self-similar scaling between the emission-weighted and the virial temperature breaks down:



Note: the mass-dependence of the temperatures
the wide spread in temperatures at a given mass
the most massive clusters to $z = 1$ have $T_{\rm ew} \approx T_{\rm vir}$

$T_{\rm ew}$-M evolution for largest cluster



The red line shows the evolution of the emission-weighted temperature versus mass for the largest cluster in the radiative simulation.

The cyan line shows the redshift-corrected temperature which should follow the solid line for self-similar scaling.

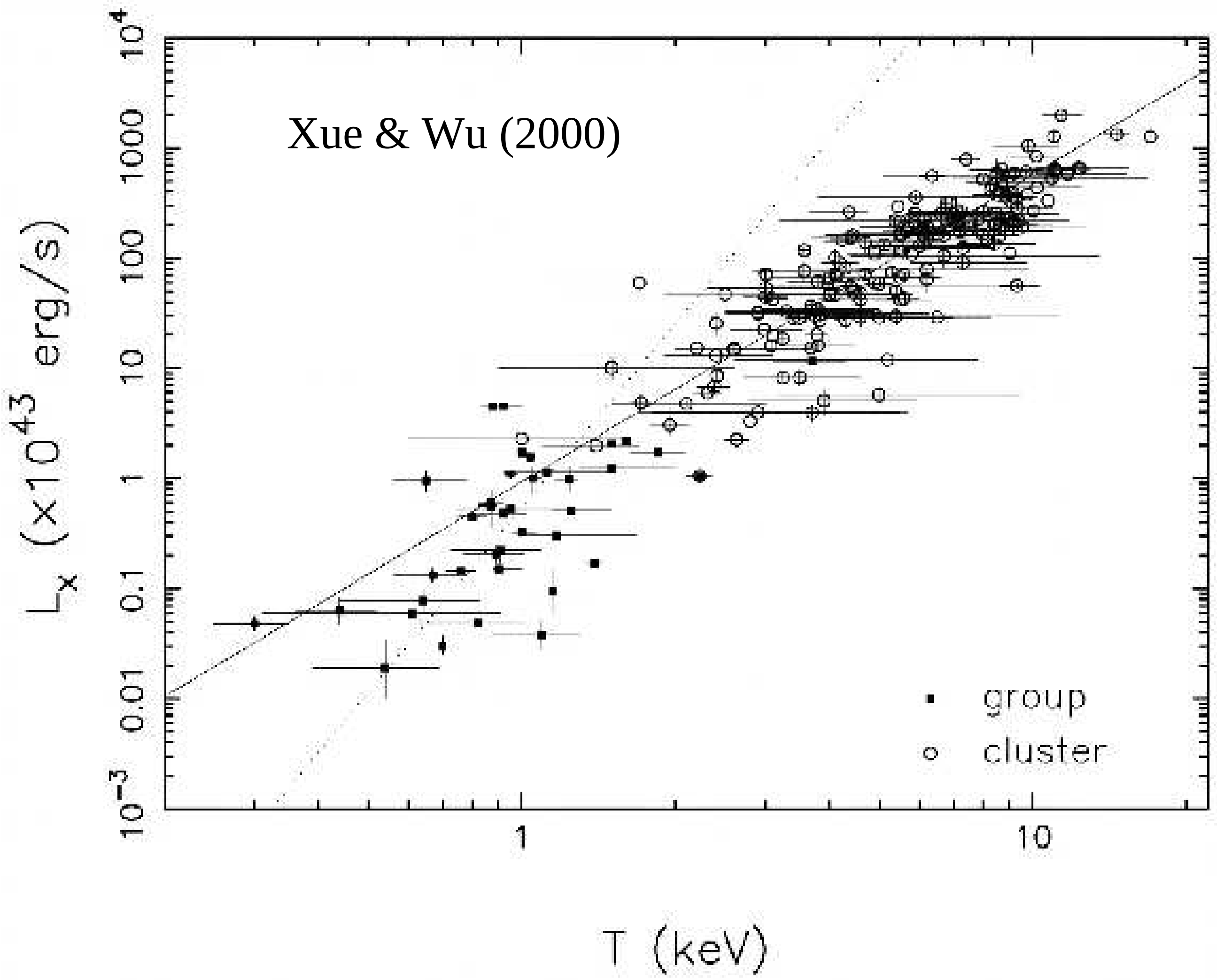
The other massive clusters have similar trajectories.

Theoretical L-T relation

Assuming isothermal, self-similar clusters, radiating via bremsstrahlung ($kT \gtrsim$keV) then

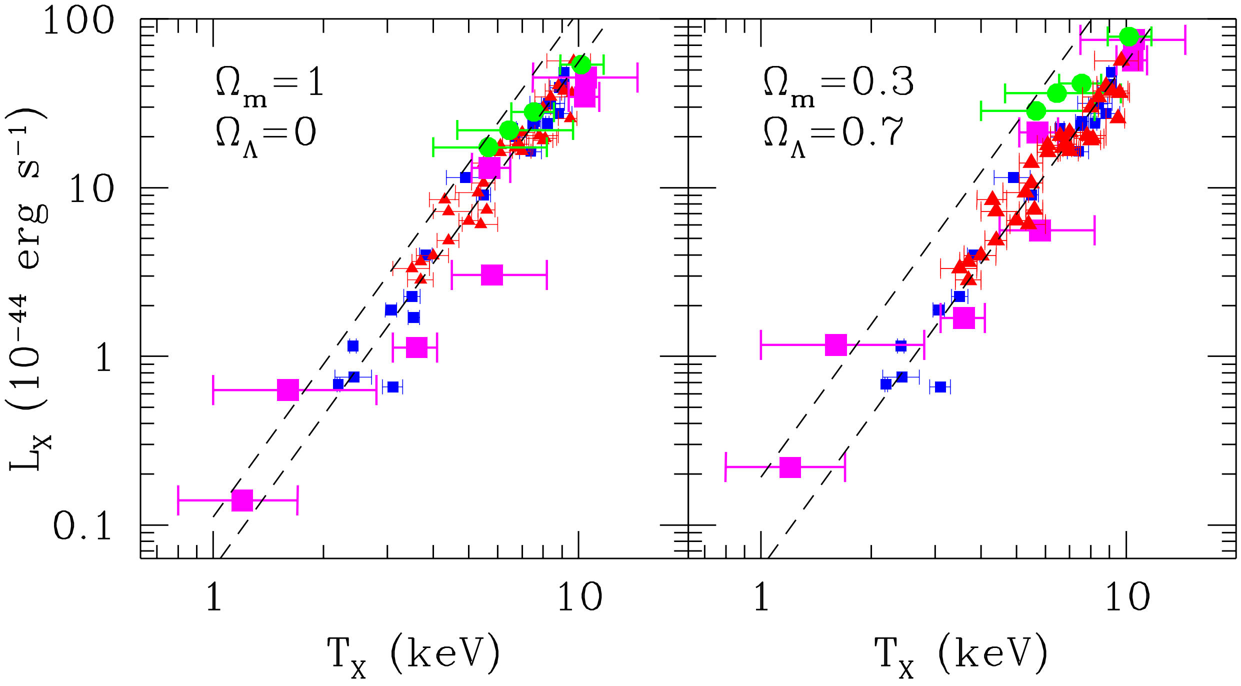
$$L \propto \int \rho^2 T^{\frac{1}{2}} \mathrm{d}V \propto M \rho T^{\frac{1}{2}} \propto (1+z)^{\frac{3}{2}} T^2.$$

The observed L-T relation is steeper than this self-similar prediction because the luminosity is dominated by the core emission that is strongly affected by heating and cooling.



Observed L-T evolution

There is also little observational evidence for redshift evolution of L-T, as is shown by this plot from Borgani et al. (2001):



Small symbols are nearby clusters:

triangles—Markevitch (1998)

squares—Arnaud & Evrard (1999)

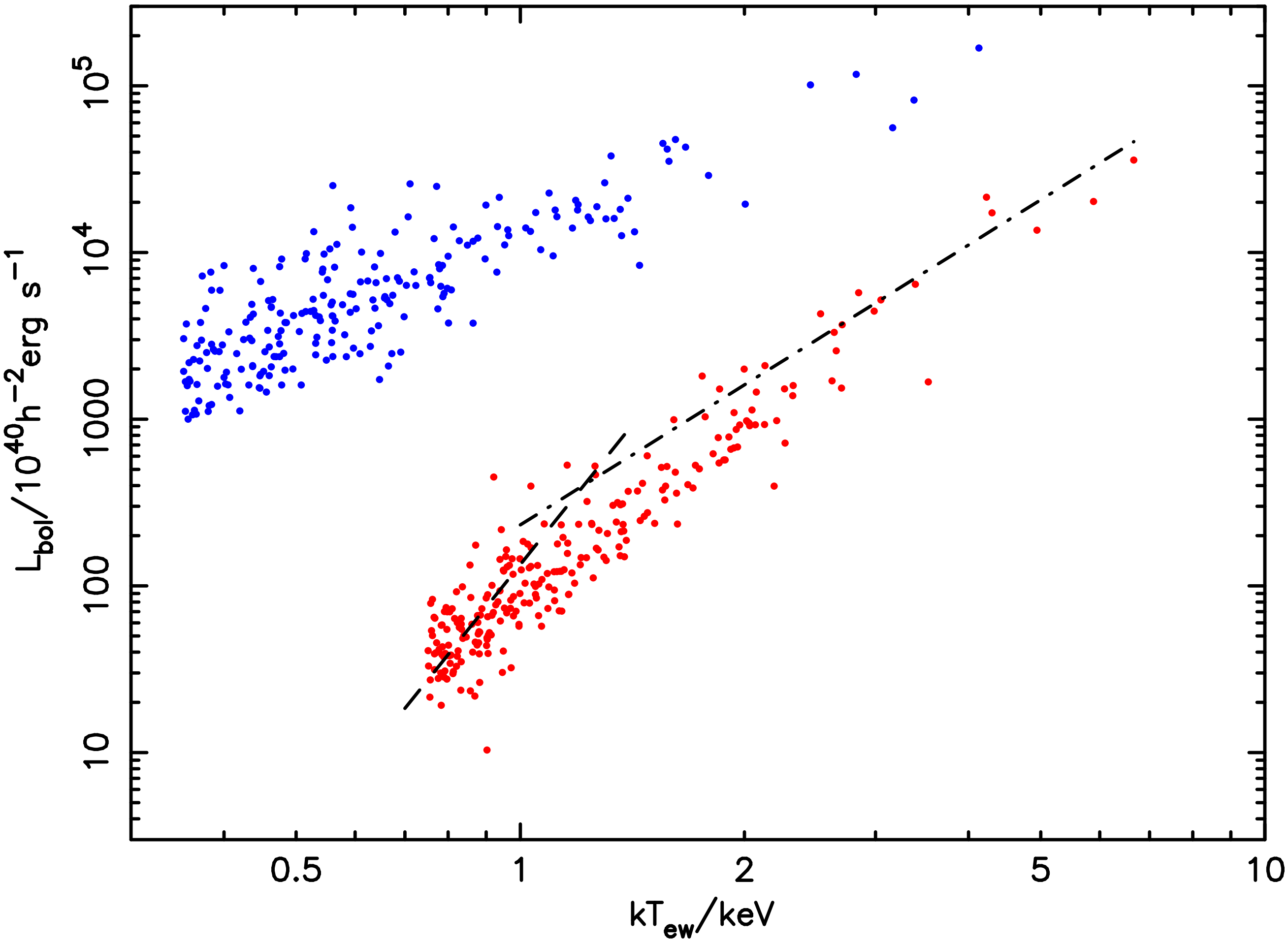
Large symbols are more distant clusters:

circles—$0.5 < z < 0.8$, Della Ceca et al. (2000)

squares—$0.57 < z < 1.27$, Borgani et al. (2001)

Given this lack of correspondence with the theoretical prediction, we will predict the evolution of L-T empirically from the simulations.

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

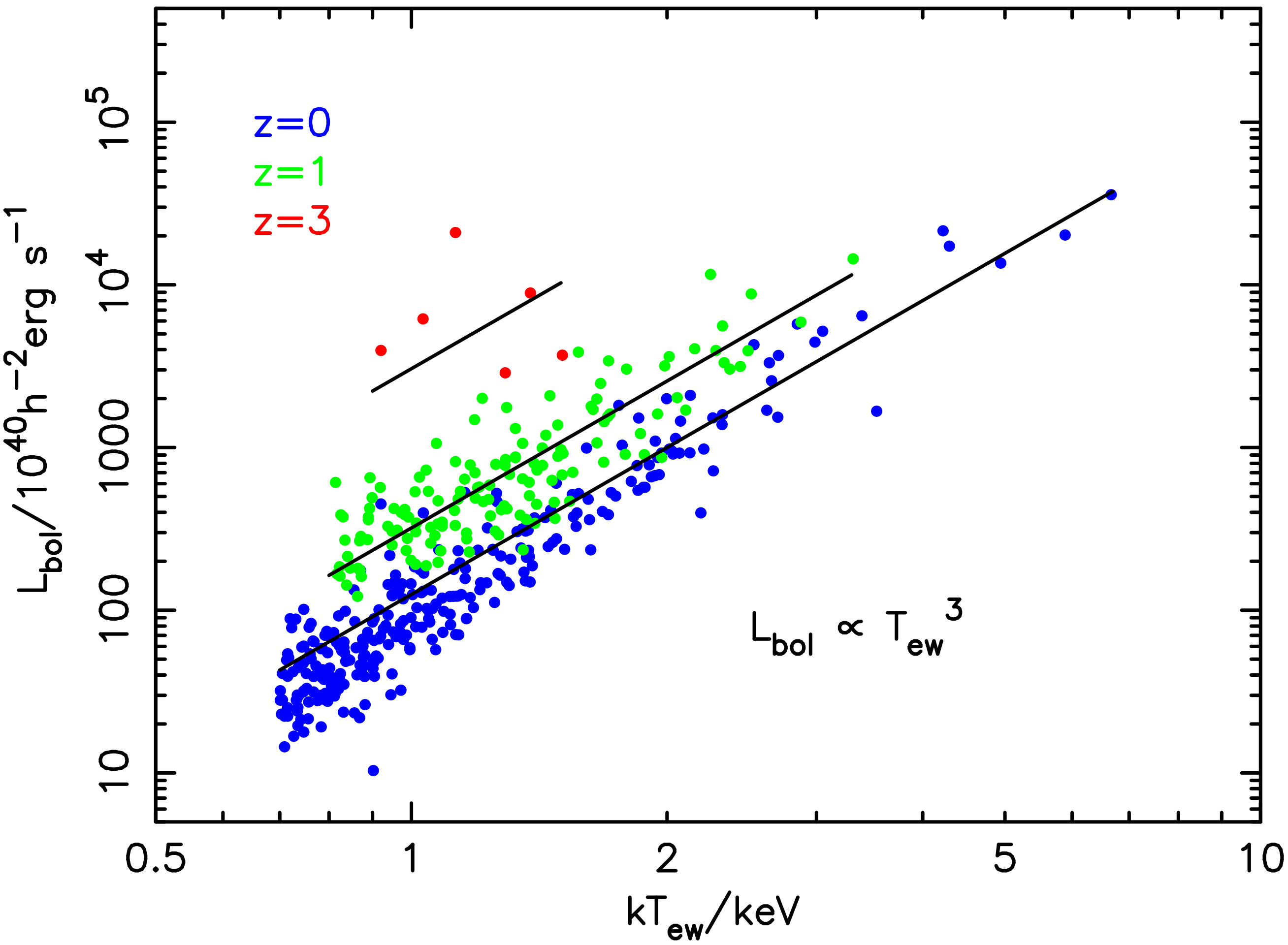


The Figure shows the simulated $L_{\rm bol}$-$T_{\rm ew}$ relation for clusters from both the non-radiative and radiative simulations.

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

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

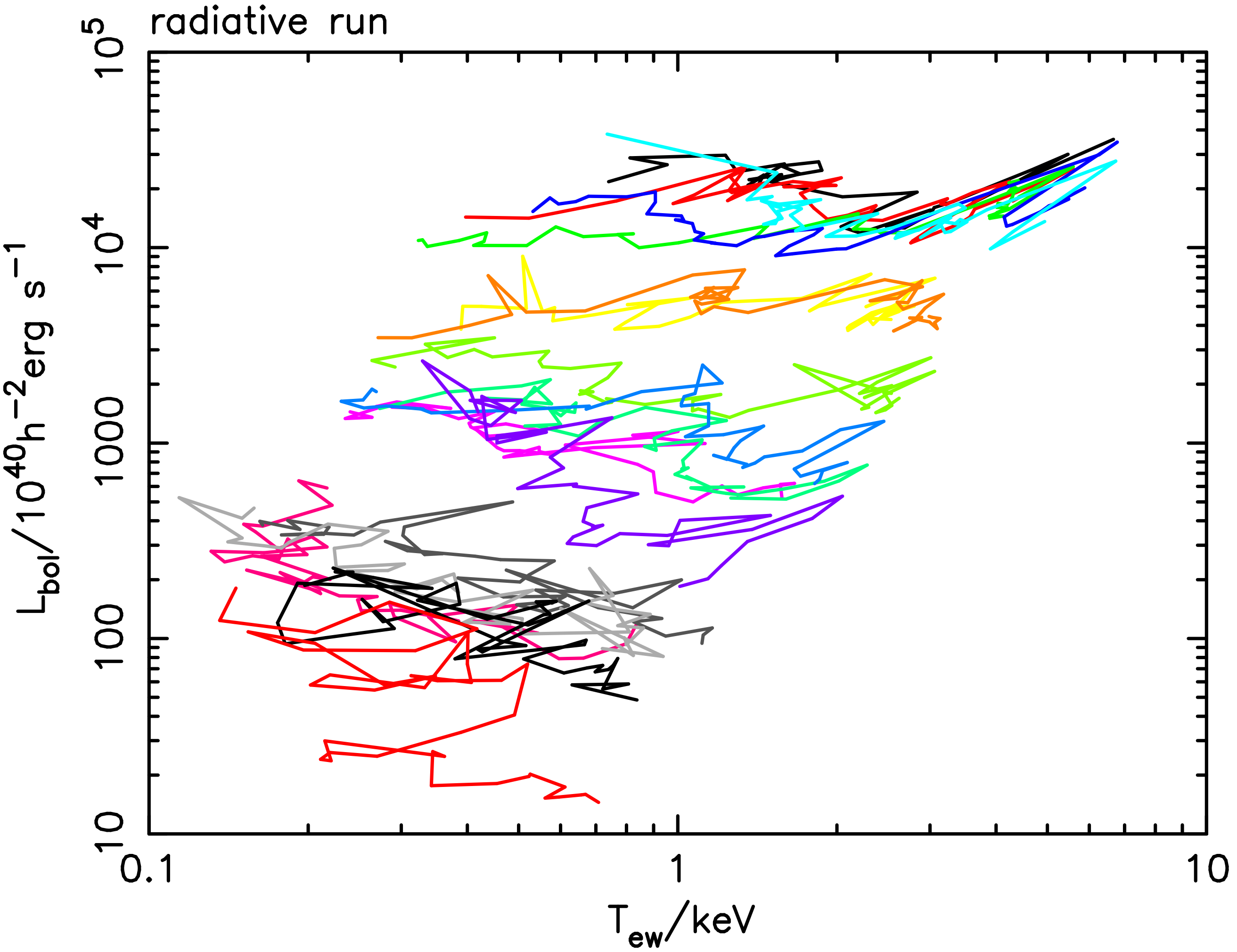
Simulated $L_{\rm bol}$-$T_{\rm ew}$ evolution (1)



The simulated $L_{\rm bol}$-$T_{\rm ew}$ evolution in the radiative simulation is greater than is seen in the observations.

The slope of the $L_{\rm bol}$-$T_{\rm ew}$ is constant, $L_{\rm bol} \propto T_{\rm ew}^3$, but there is no simple scaling with redshift.

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



This figure shows the trajectory of sample clusters from the radiative simulation in the $L_{\rm bol}$-$T_{\rm ew}$ plane.

The largest clusters maintain a roughly constant luminosity as they increase by a factor of 10 in temperature.

Merger simulations: introduction

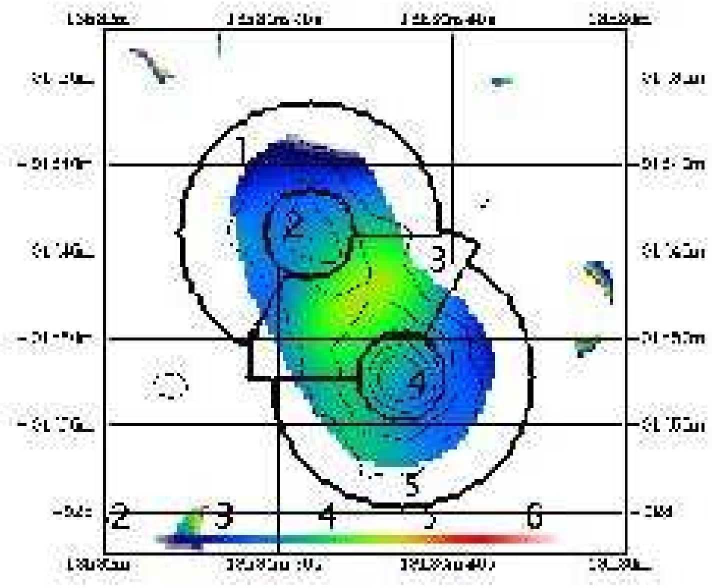
Ben Ritchie and Peter Thomas

Isolated simulations of two merging, relaxed clusters

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

Up to 32^3 each of gas and dark-matter per cluster

Varying impact parameters, mass ratios and speeds



A1790—Donnelly et al. (2001)