Evolution (or not) of Cool Cores

G M Voit — Michigan State U

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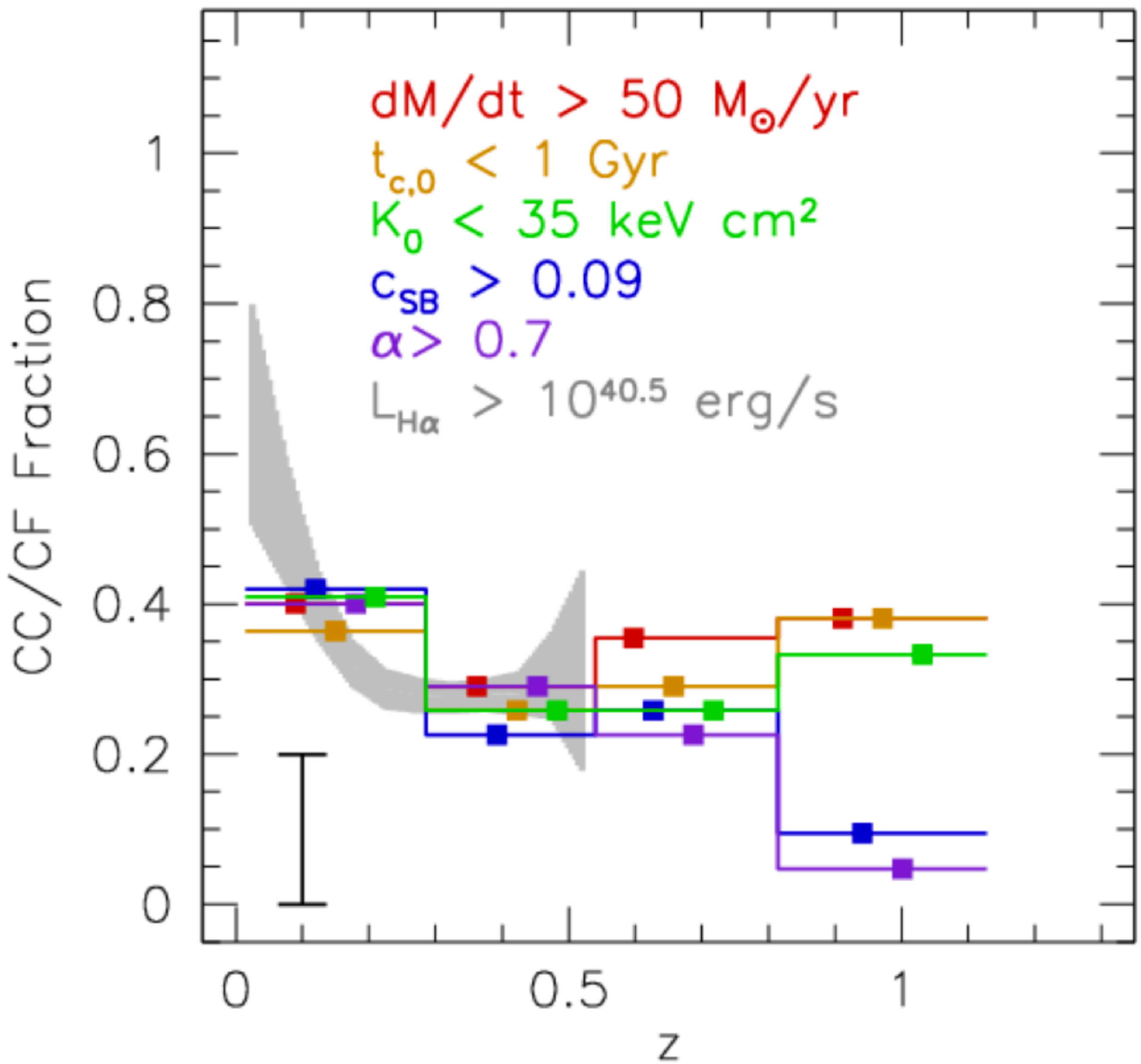
1

Cool-Core Evolution: Observations

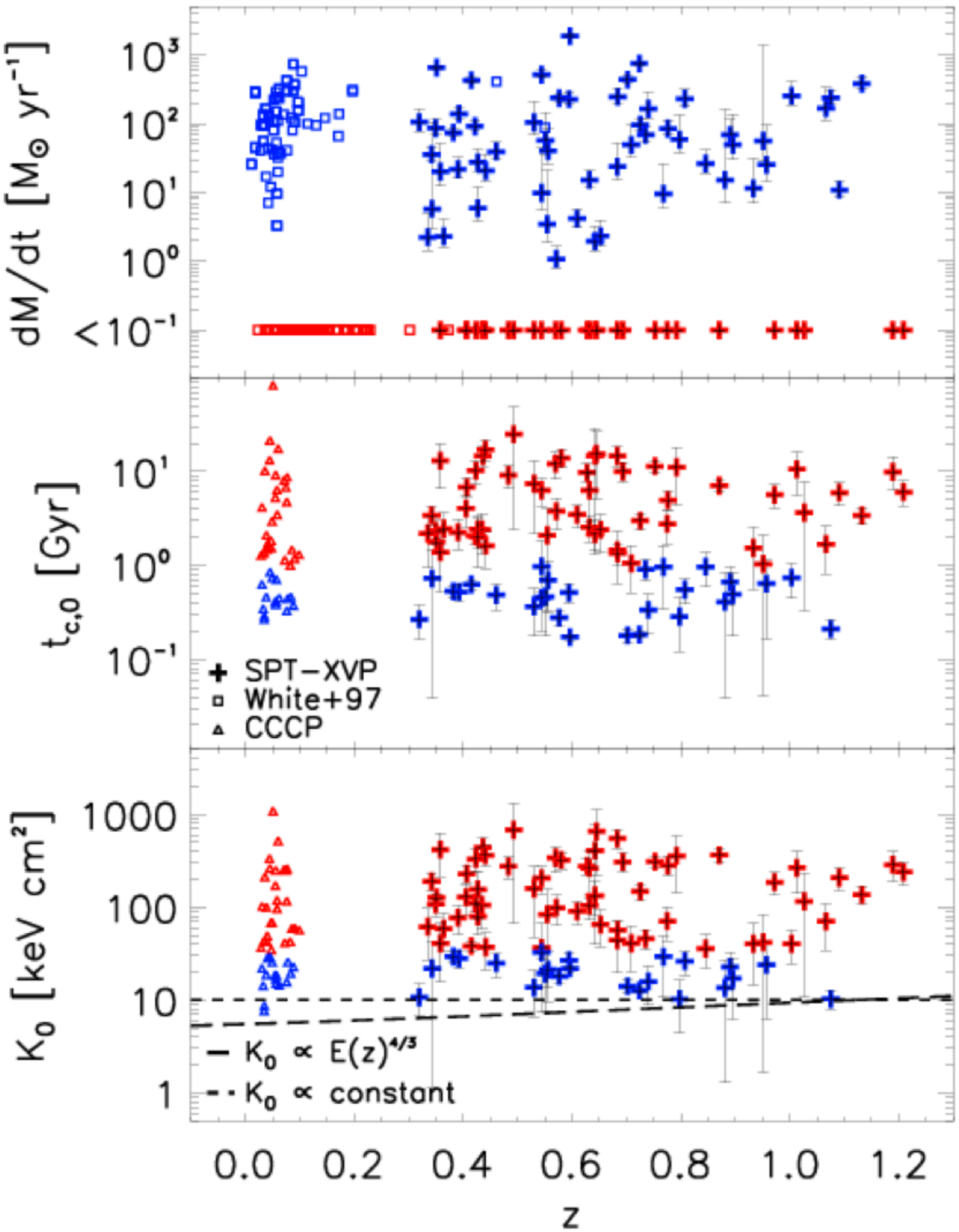
McDonald+13



Evolution of cool cores in SPT clusters depends on how one defines a cool core.

Evolution (or not) of Cool Cores

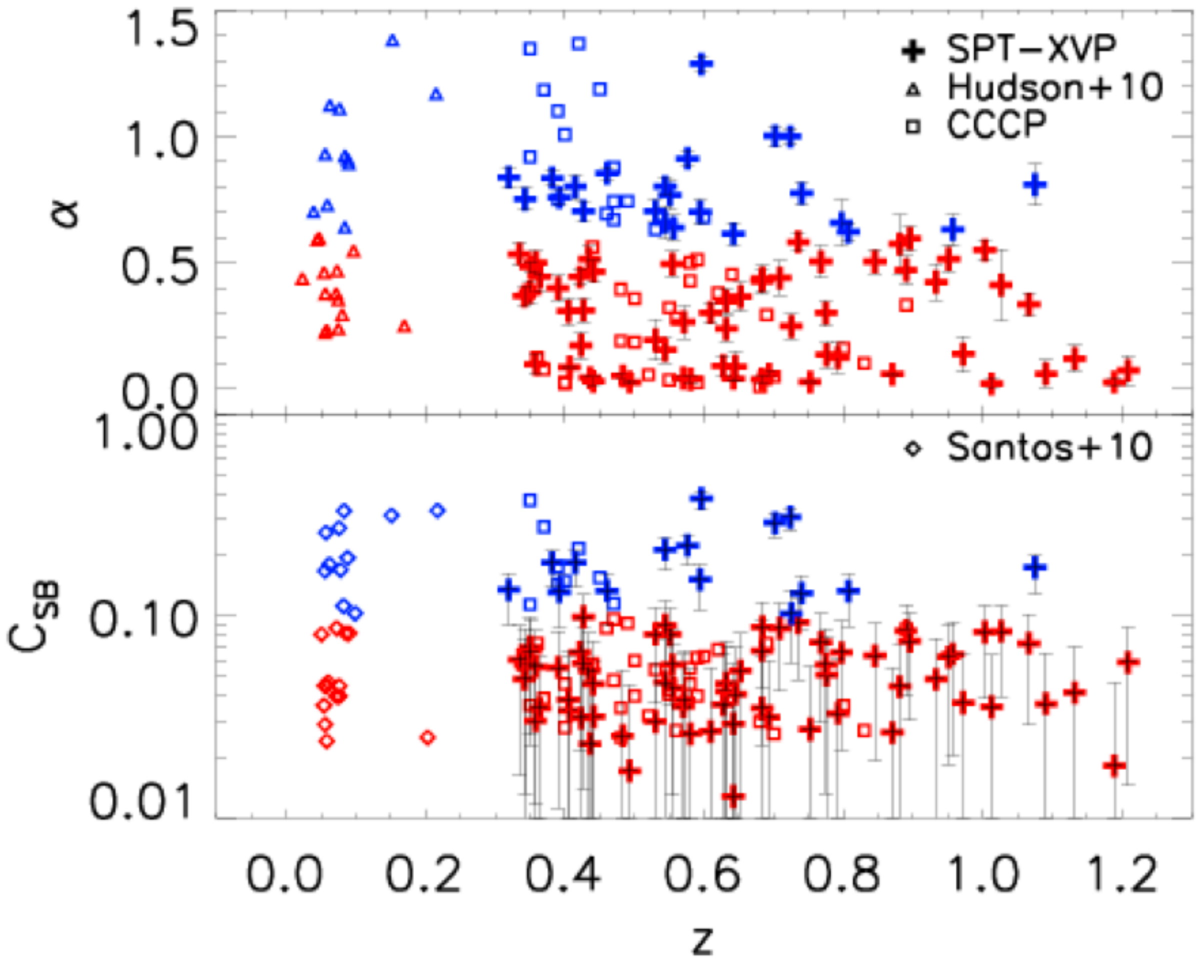
McDonald+13



Evolution of cool cores in SPT clusters depends on how one defines a cool core.

Definitions based on the central cooling time or central entropy show little evolution.

McDonald+13



Evolution of cool cores in SPT clusters depends on how one defines a cool core.

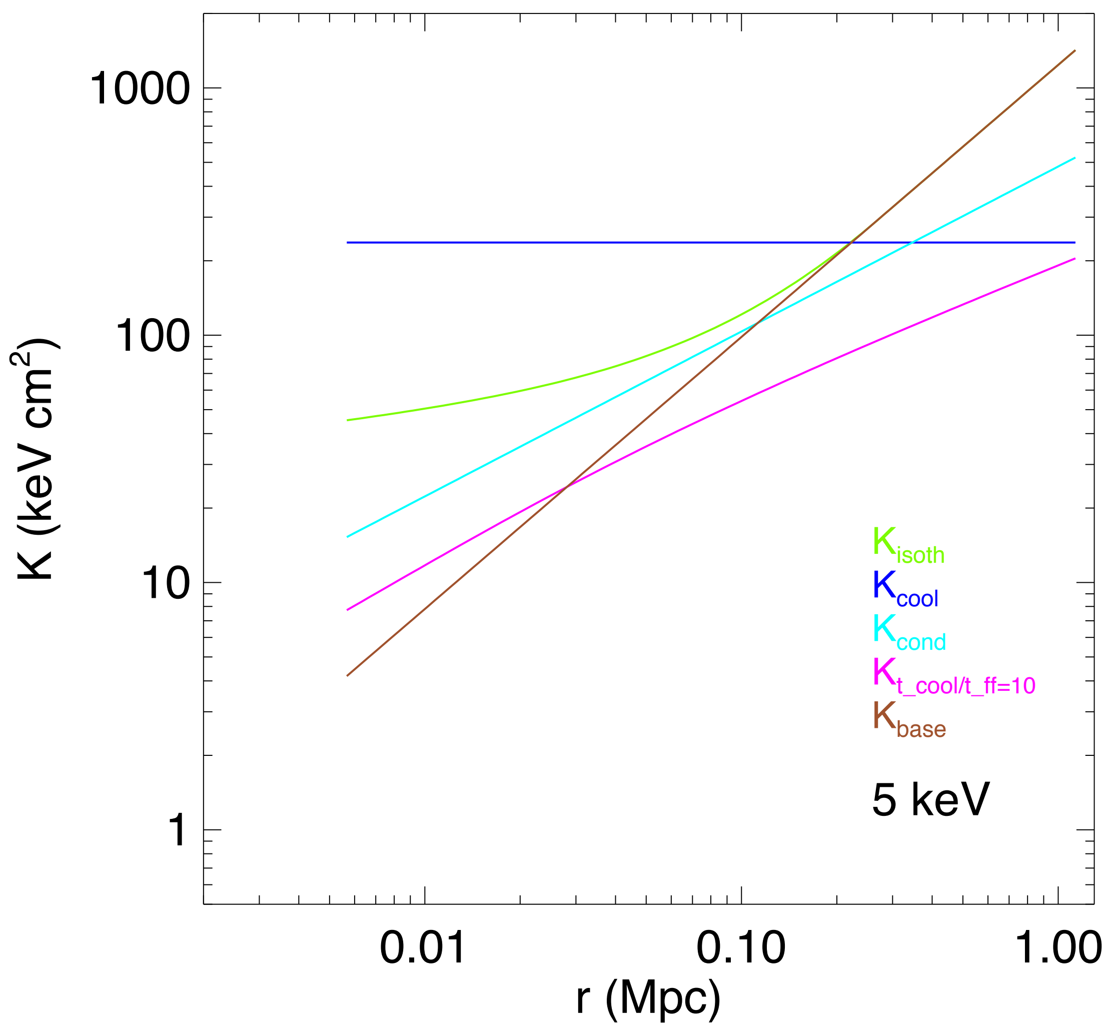
Definitions based on the central cooling time or central entropy show little evolution.

Definitions based on the "cuspiness" of the central density or surface-brightness profile ***do*** show evolution.

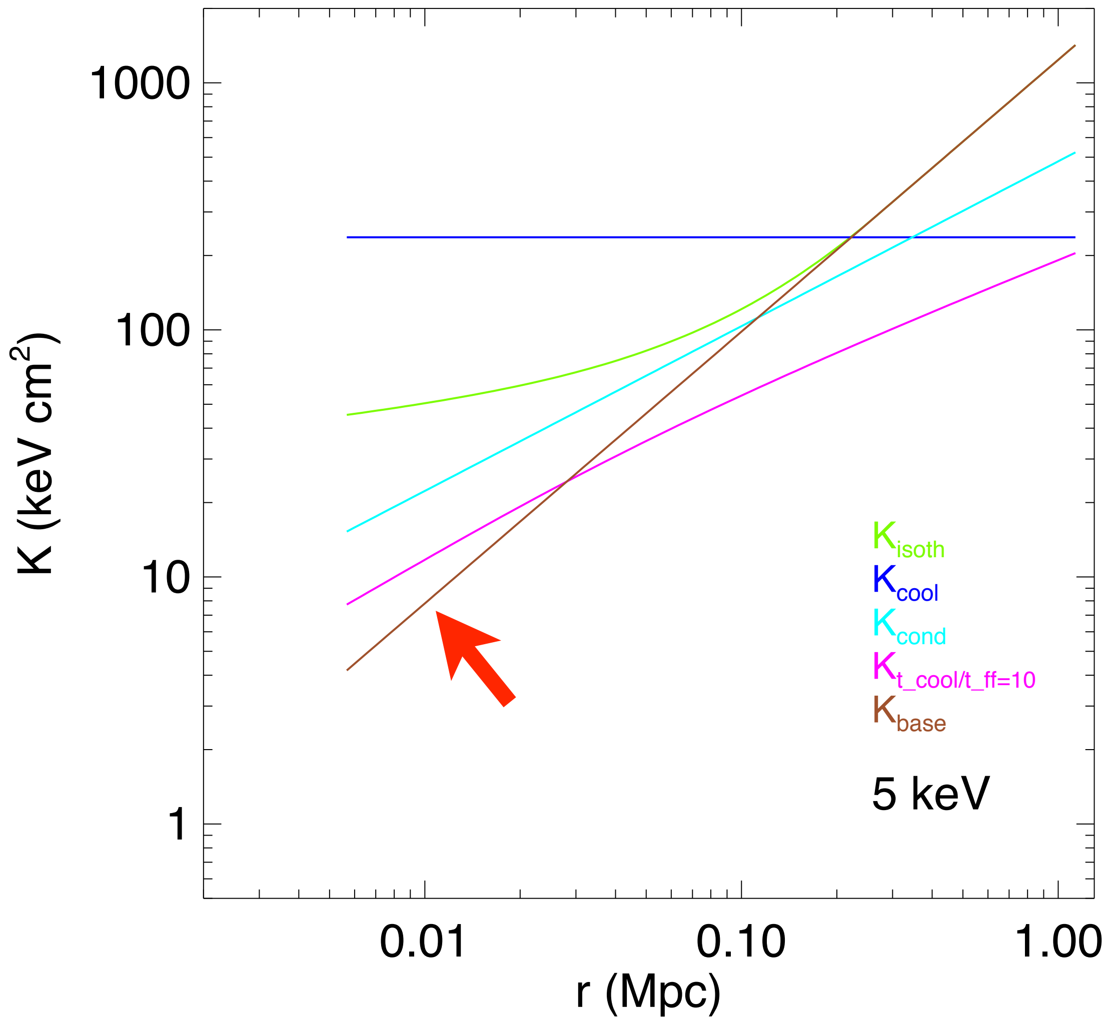
$$\alpha \equiv \left. \frac{d\log \rho_g}{d\log r} \right|_{r=0.04\mathrm{R}_{500}} \qquad c_{SB} \equiv \frac{F_{0.5-5.0\mathrm{keV}}(r < 40\ \mathrm{kpc})}{F_{0.5-5.0\mathrm{keV}}(r < 400\ \mathrm{kpc})}$$

2

Critical Lines in the K(r) Plane: A Framework



Critical lines in the entropy-radius plane (Voit & Bryan, in prep).



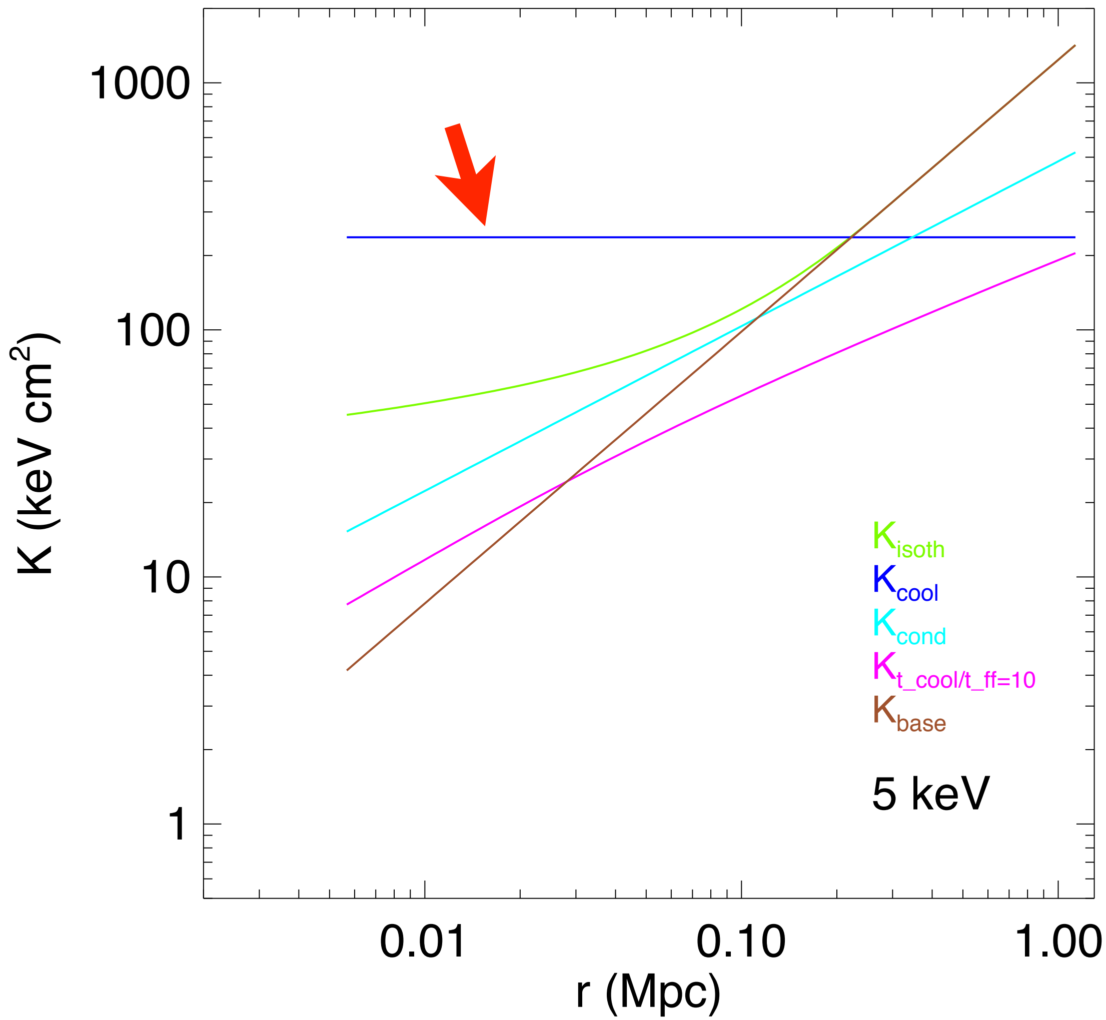
The ***brown*** line is the power-law baseline entropy profile from Voit, Kay & Bryan (2005).

This particular version is the Pratt et al. (2010) conversion of the baseline profile to r_{500} scaling:

$$K_{\mathrm{base}} = 1.46\, K_{500}\, (r/r_{500})^{1.1}$$

A generic $\Omega_M = 0.3$, $f_b = 0.155$ cosmology gives this normalization factor for a 5 keV cluster:

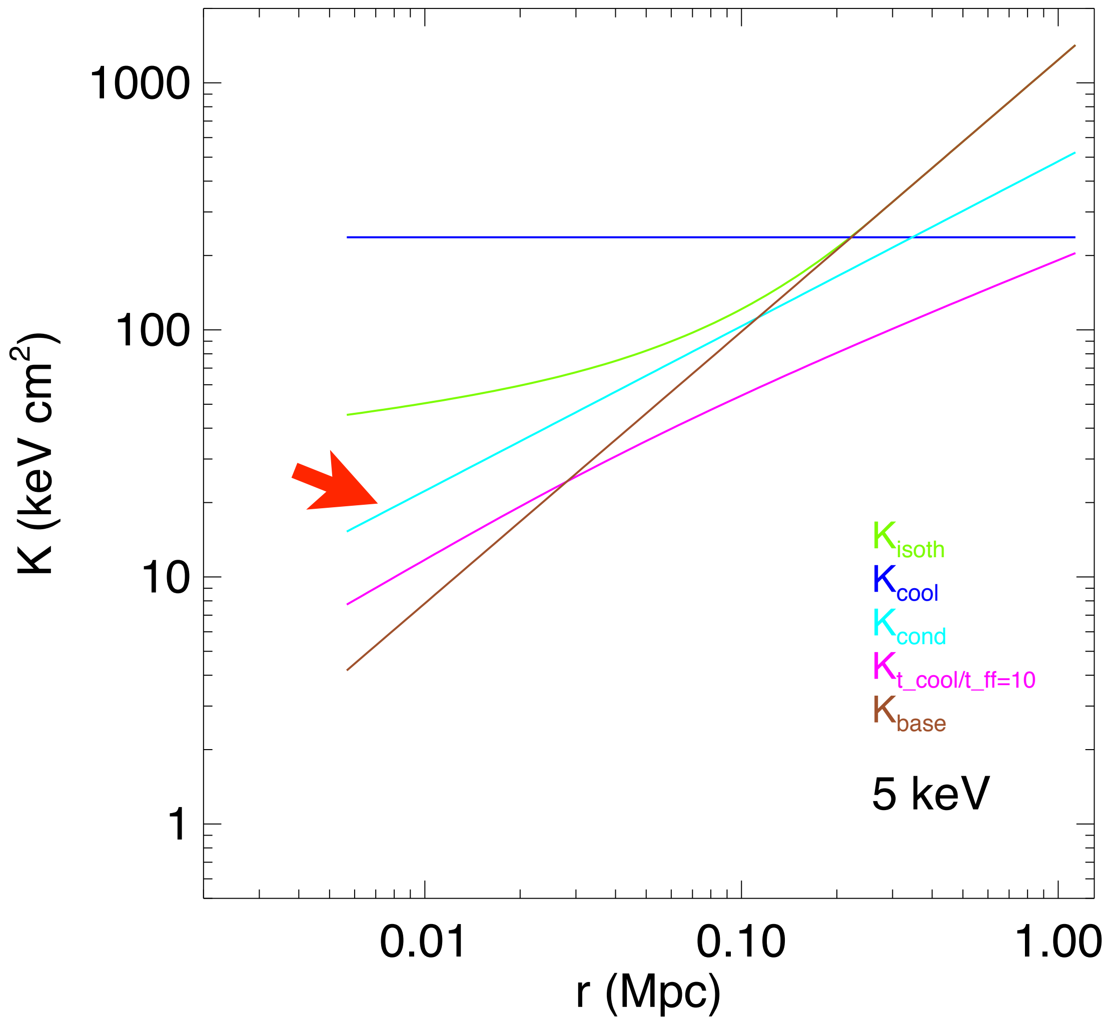
$$K_{500} = 1255 \text{ keV cm}^2$$



The ***blue*** line is the cooling threshold at which gas at the halo's characteristic temperature would have a cooling time of 14 Gyr.

Voit & Bryan (2001) pointed out that radiative cooling and the resulting feedback inevitably modify the entropy of gas below this line.

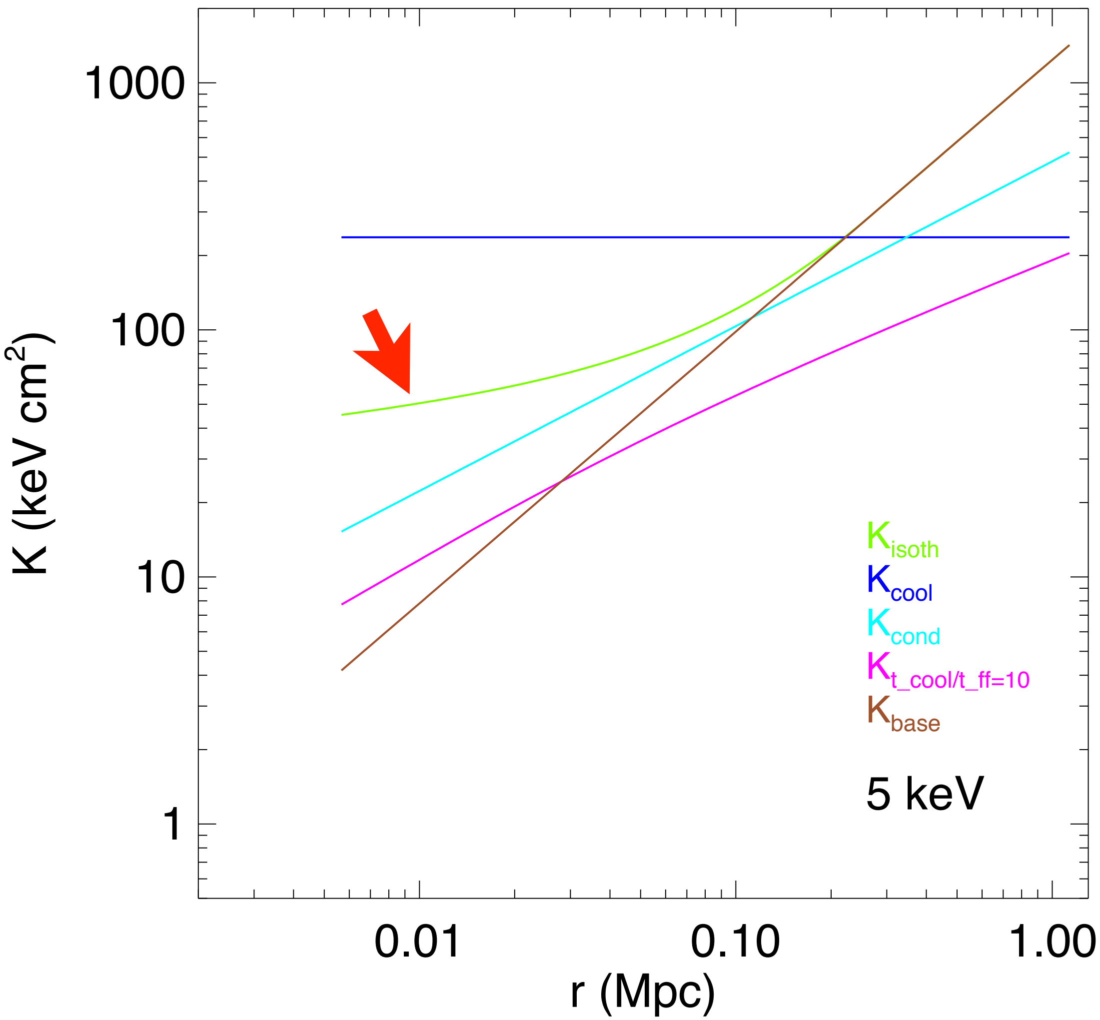
This particular line is based on equation (75) from the Voit (2005) review article.



The ***cyan*** line is the critical entropy profile at which conductive heat transport into the core would balance radiative cooling for a Spitzer suppression factor of 1/3.

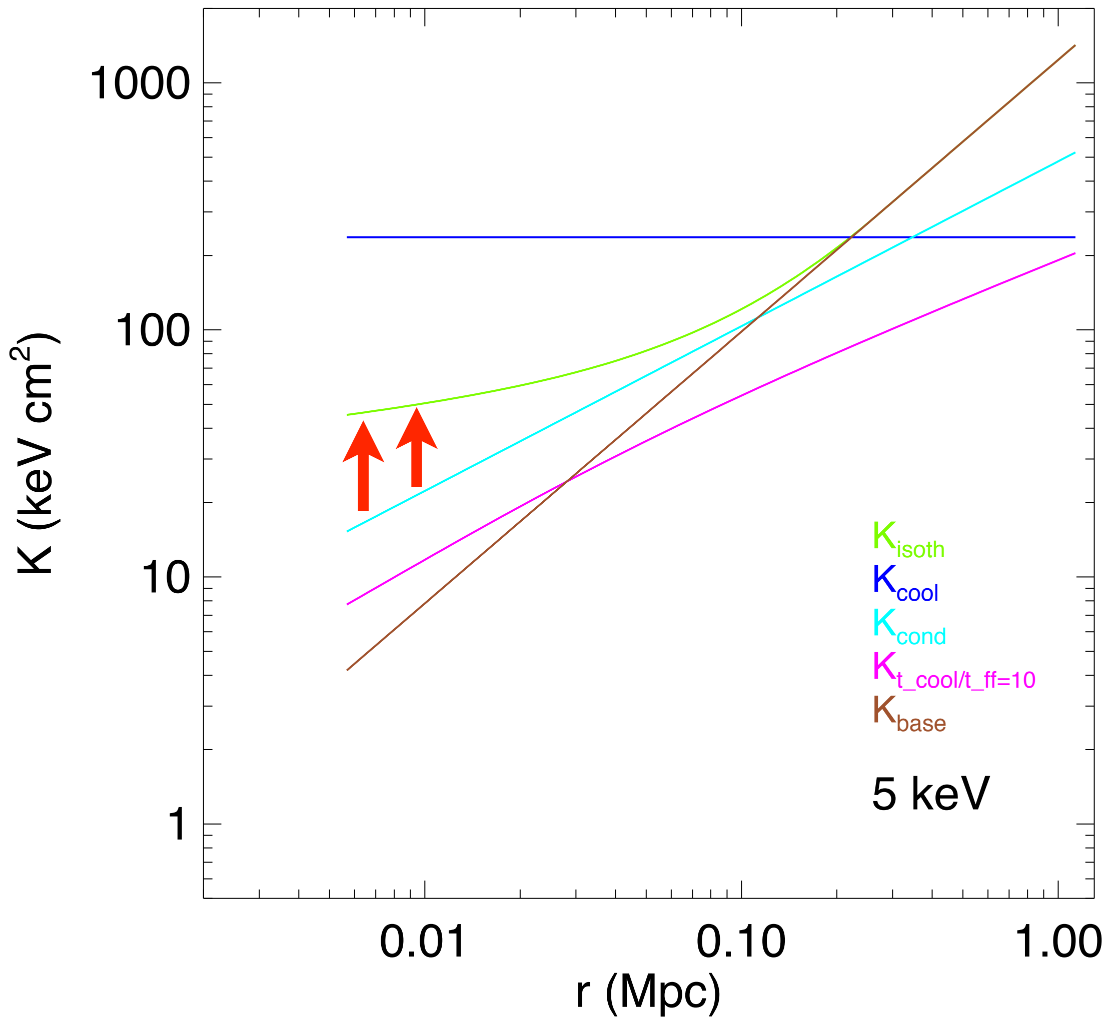
Donahue et al. (2005) suggested that conduction might produce bimodality in cluster cores.

This particular line is based on equation (21) from the calculation in Voit (2011).



The ***green*** line is the entropy profile corresponding to a cluster with an isothermal core at the peak temperature of the baseline cluster.

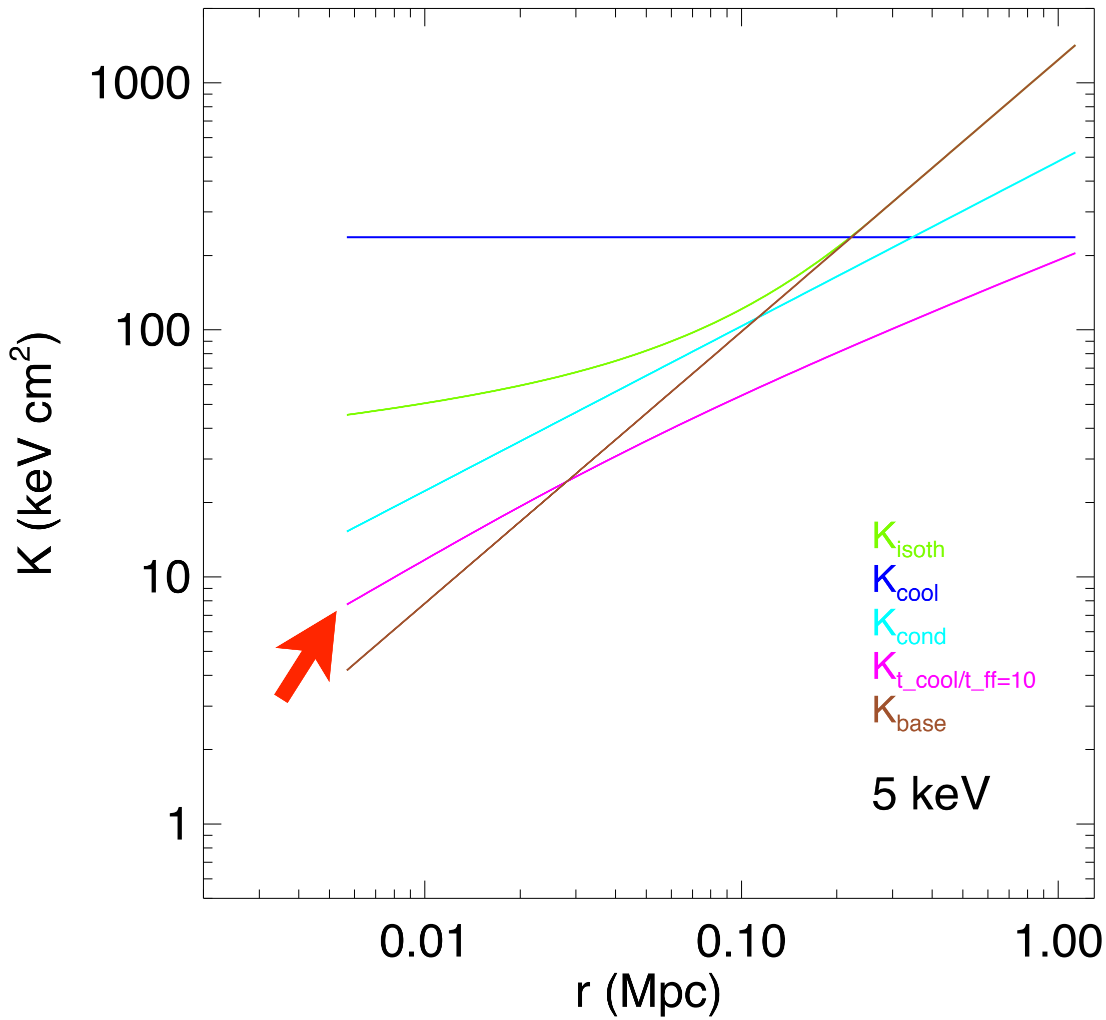
It is calculated simply by taking the temperature profile from the baseline model and finding the hydrostatic model for which the temperature remains constant at radii smaller than the peak radius of the baseline temperature profile.



The ***green*** line is significant for clusters in which conduction is more efficient than radiative cooling, because conduction will drive their entropy profiles from the ***cyan*** line toward the ***green*** line.

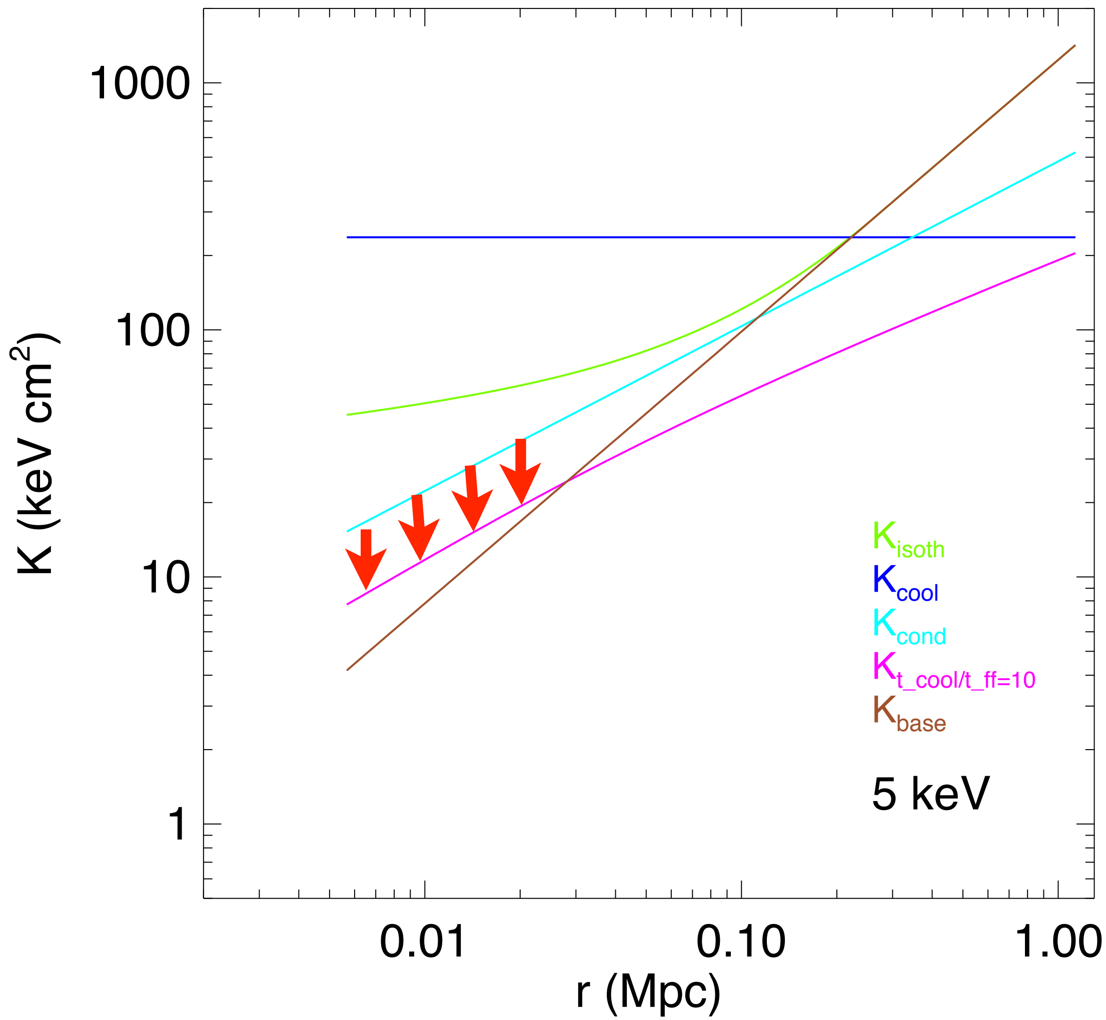
The gravitational potential in this model is an NFW dark-matter potential with $c_{500} = 3$ plus a singular isothermal BCG potential with a 300 km/s velocity dispersion.

Notice that the core entropy corresponding to the ***green*** line is $K_0 \sim 40$ keV cm^2.



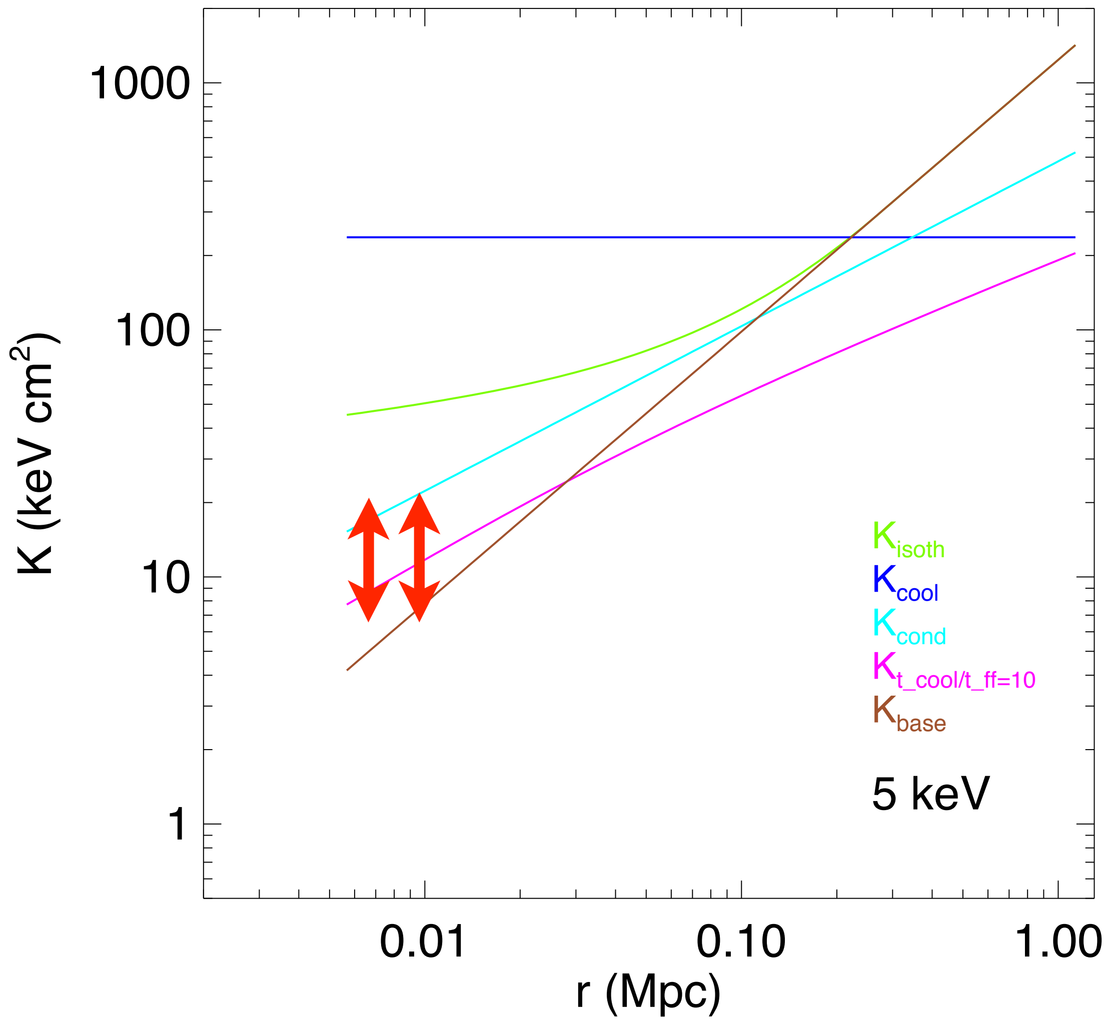
The *magenta* line is the entropy locus at which the cooling time equals 10 times the freefall time in the combined NFW+BCG potential.

It is the locus at which thermal instability is expected to produce multiphase gas when radiative cooling and feedback heating are in global balance (see McCourt et al. 2012, Sharma et al. 2012, Gaspari et al. 2012, Li & Bryan 2014).



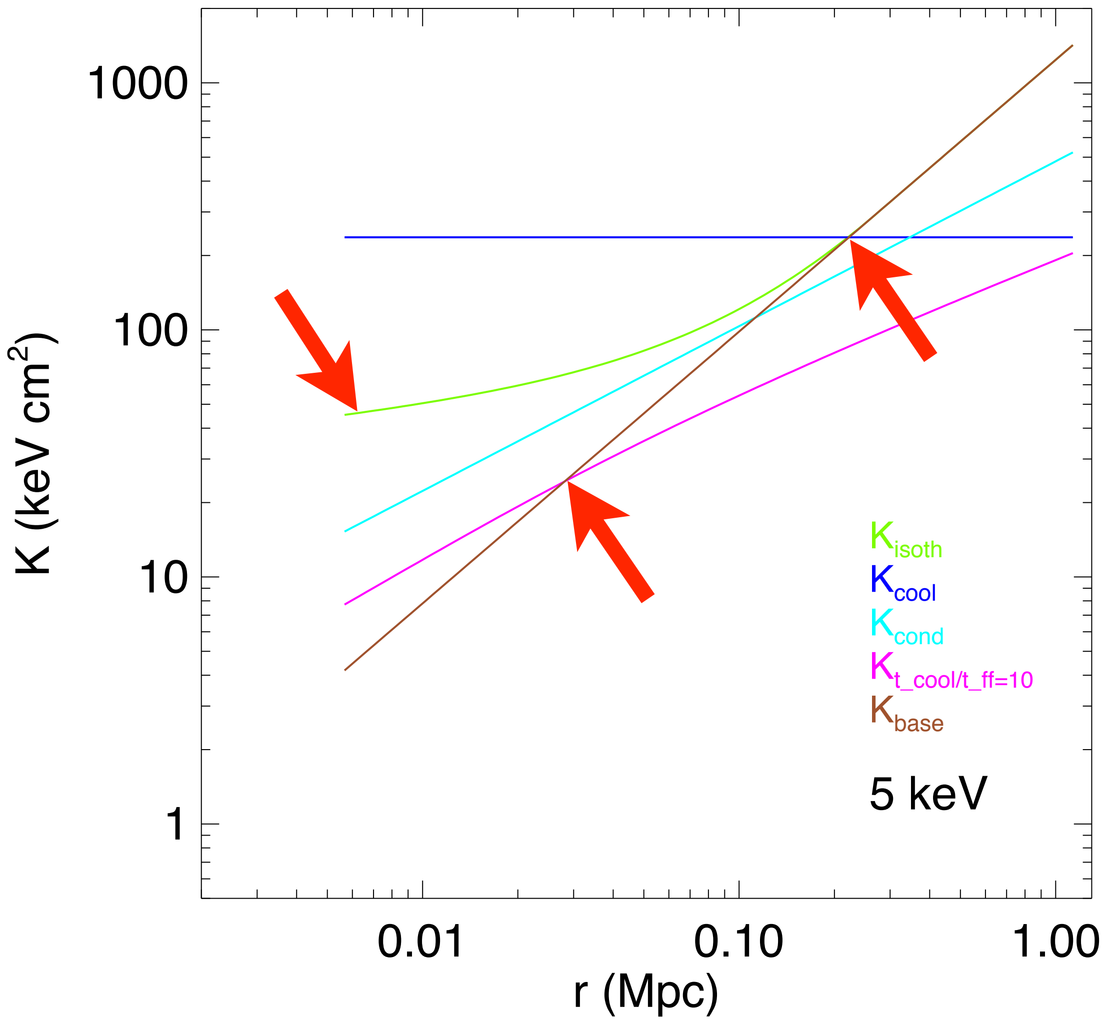
Voit (2011) argued that AGN feedback is not necessary for clusters above the ***cyan*** line but that it should rapidly increase as clusters fall below the line.

Clusters below the ***cyan*** line are therefore expected to approach the ***magenta*** line, at which point the development of a multiphase core should fuel strong AGN feedback.



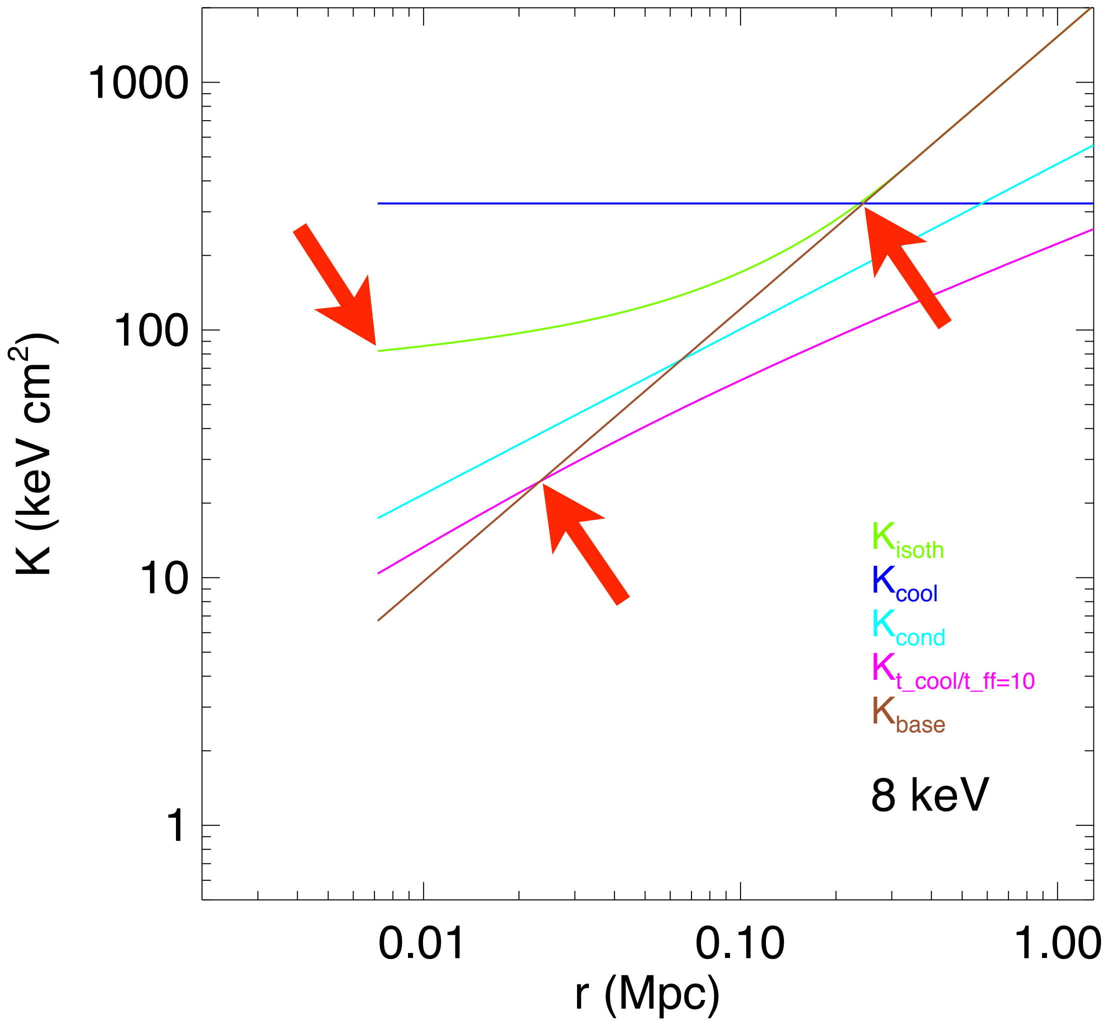
Voit & Donahue (2005) showed that bursts of AGN feedback at the ~10^{45} erg/s level could buffet the core entropy distribution, producing excursions of ~20 keV cm^2 at radii ~ 10 kpc, but that much larger outbursts would be needed to destroy the cool core.

(See also Gaspari et al. 2014.)



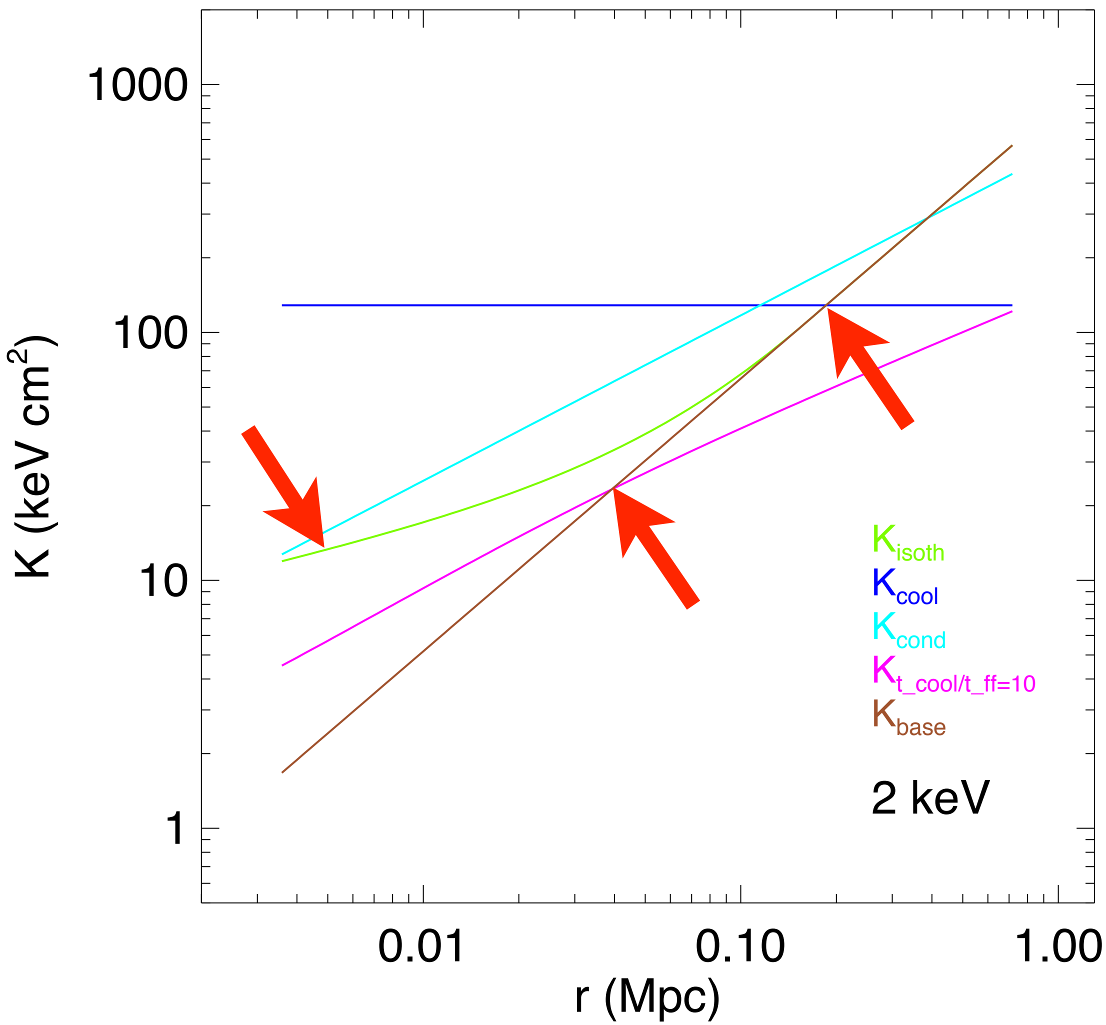
Notice that there are three entropy scales with the potential to break the self-similarity of the baseline profile for a 5 keV halo at $z = 0$:

- the ***cooling threshold***
  ($K \sim 250$ keV cm^2, $r \sim 200$ kpc)
- the ***isothermal core scale***
  ($K \sim 40$ keV cm^2)
- the ***precipitation threshold***
  ($K \sim 25$ keV cm^2, $r \sim 30$ kpc)



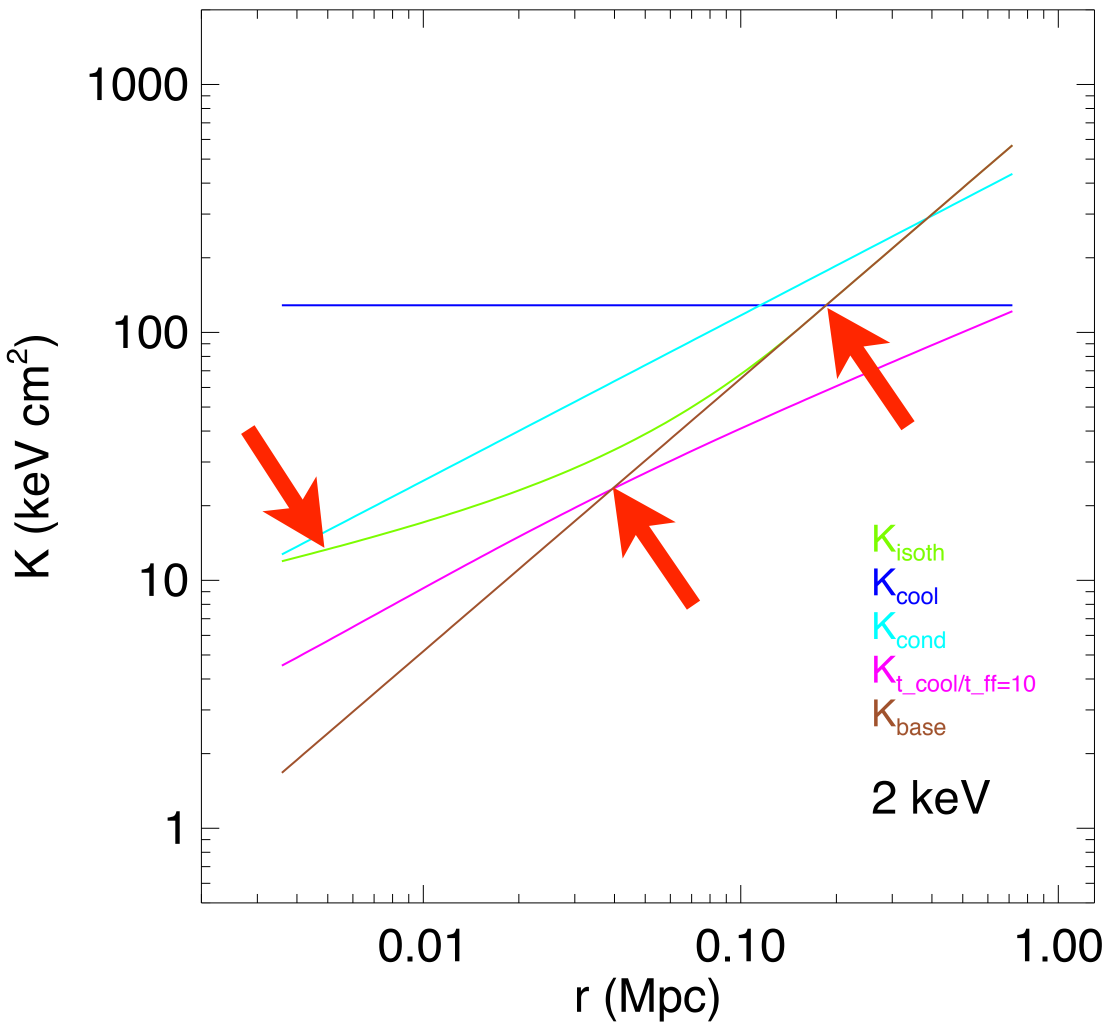
The corresponding scales for an 8 keV halo at $z = 0$ are slightly different but not very different:

- ***cooling threshold***
  ($K \sim 220$ keV cm^2, $r \sim 220$ kpc)
- ***isothermal core scale***
  ($K \sim 80$ keV cm^2)
- ***precipitation threshold***
  ($K \sim 22$ keV cm^2, $r \sim 20$ kpc)



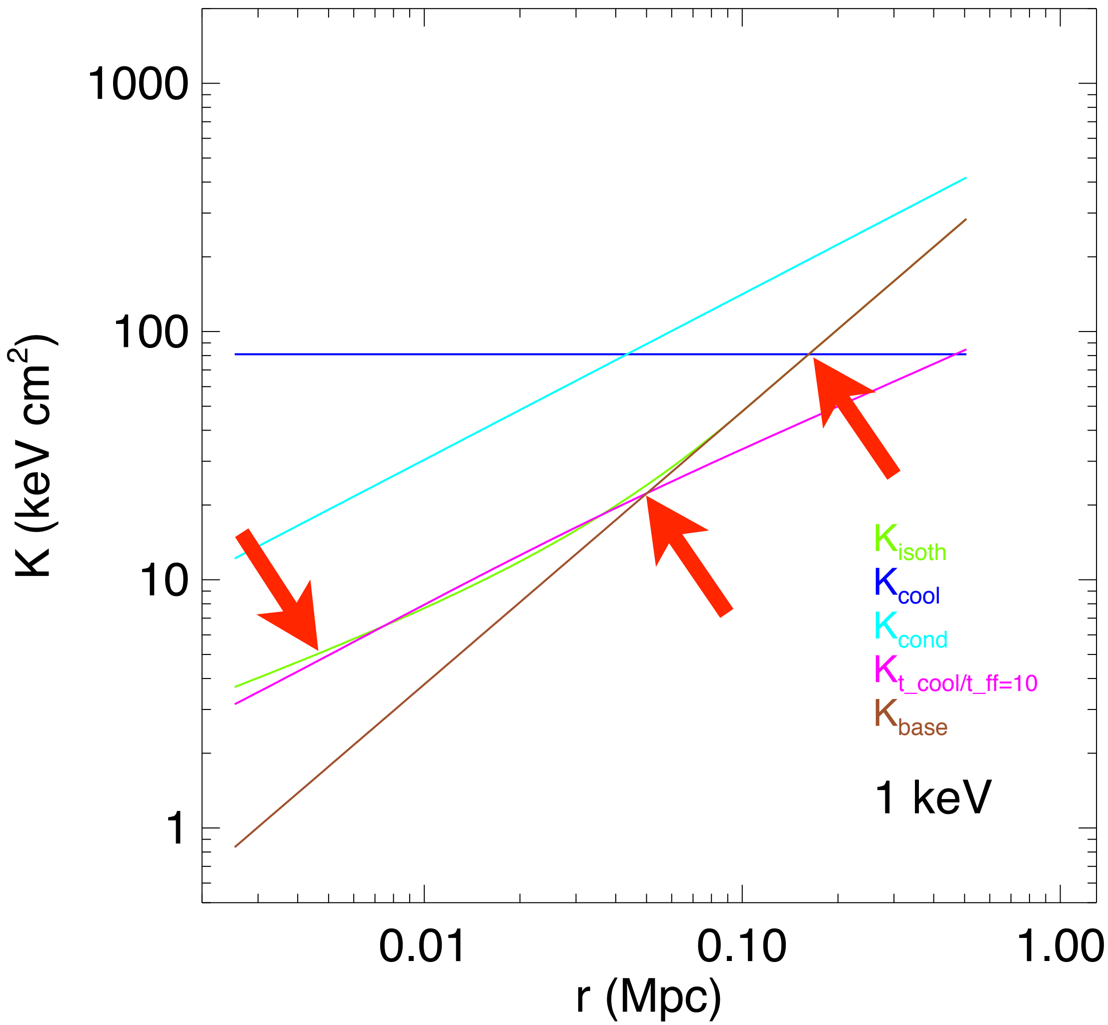
The situation in a 2 keV halo at $z = 0$ is qualitatively different because the isothermal core scale is below the locus of conductive balance:

- ***cooling threshold***
  ($K \sim 130$ keV cm^2, $r \sim 180$ kpc)
- ***isothermal core scale***
  ($K \sim 10$ keV cm^2)
- ***precipitation threshold***
  ($K \sim 20$ keV cm^2, $r \sim 40$ kpc)



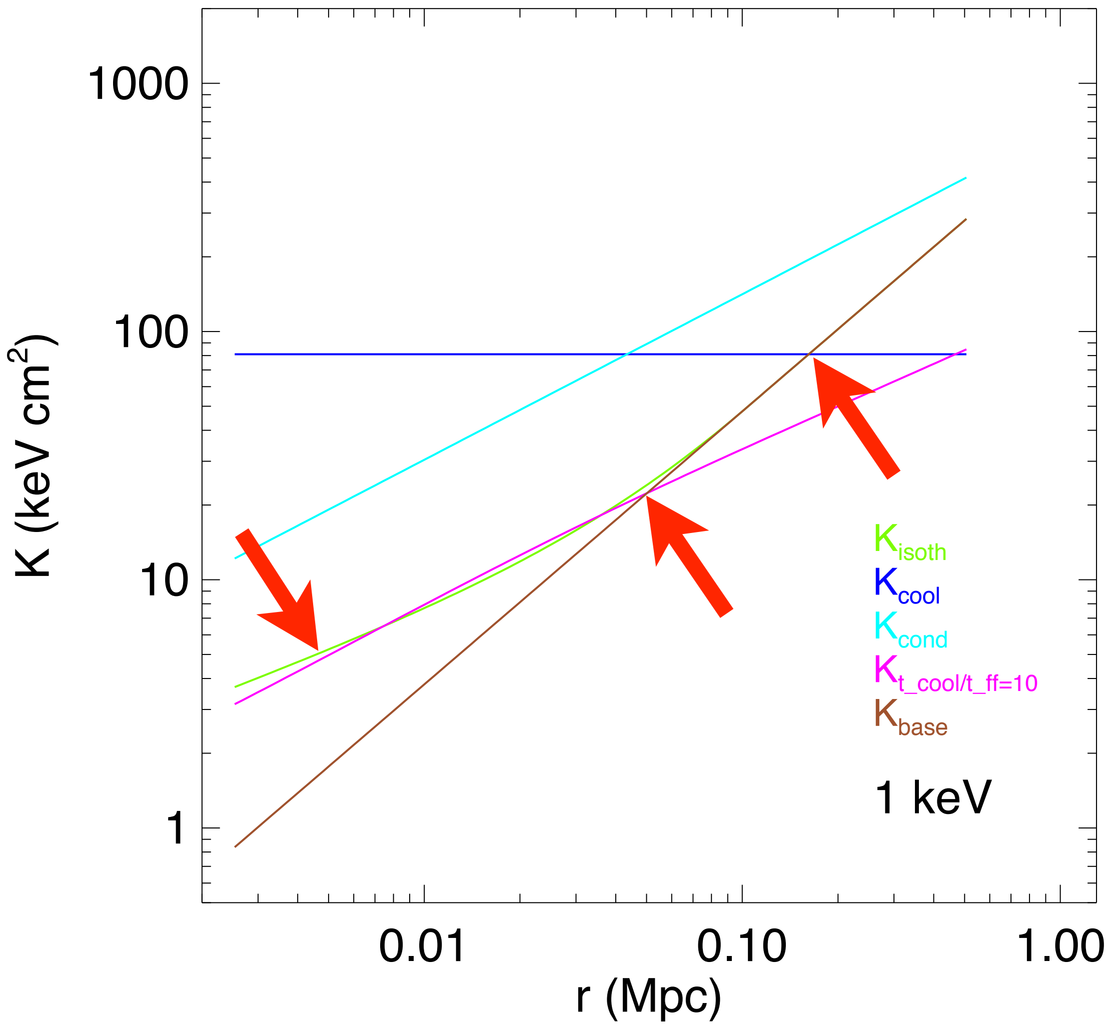
Conduction in such a lower-mass halo is therefore too inefficient to produce a bimodal core entropy distribution.

Furthermore, the transition to a precipitation-regulated profile occurs at a larger radius, which suppresses the core density to a greater degree, relative to the self-similar baseline.



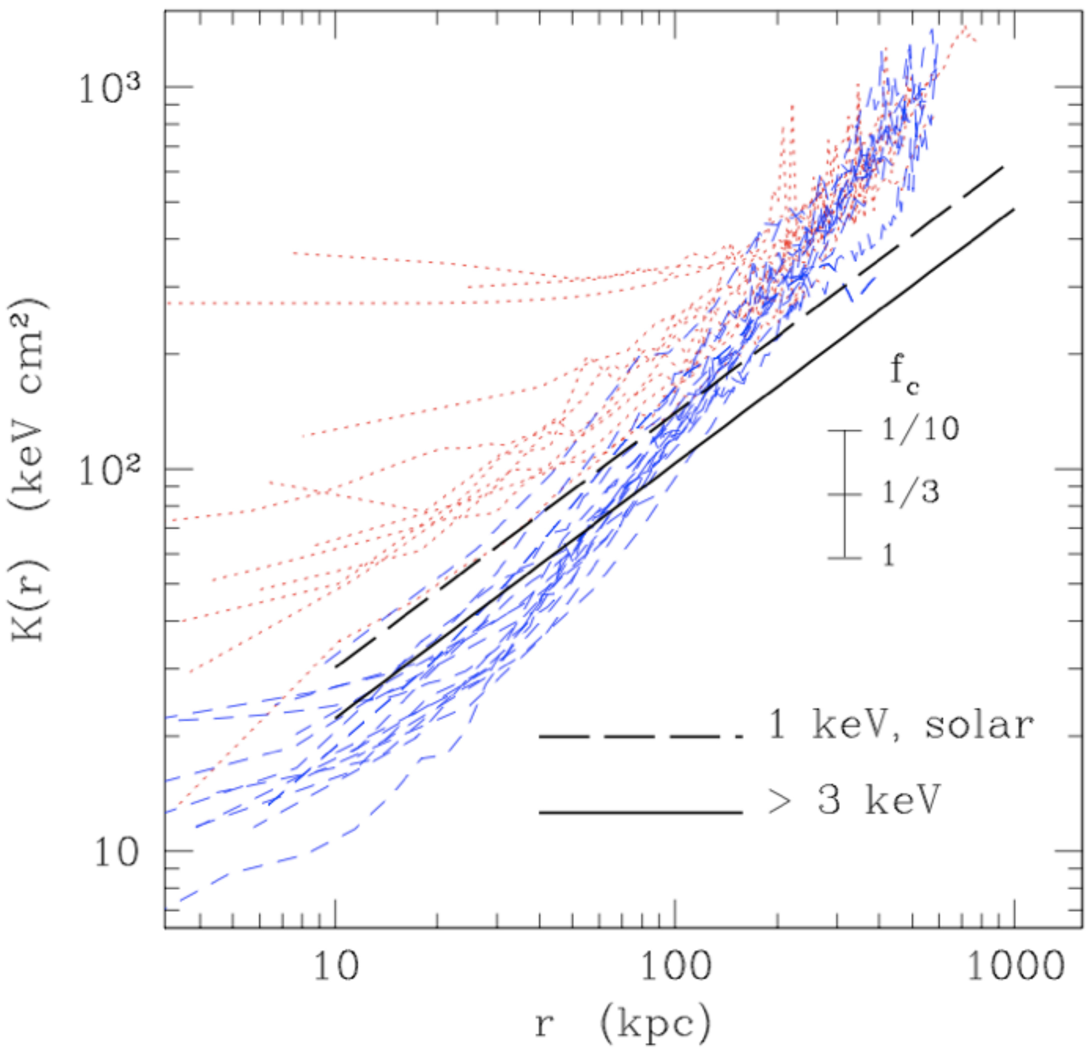
These effects are even more extreme in a 1 keV halo at $z = 0$:

- ***cooling threshold***
  ($K \sim 81$ keV cm^2, $r \sim 150$ kpc)
- ***isothermal core scale***
  ($K \sim 4$ keV cm^2)
- ***precipitation threshold***
  ($K \sim 20$ keV cm^2, $r \sim 50$ kpc)

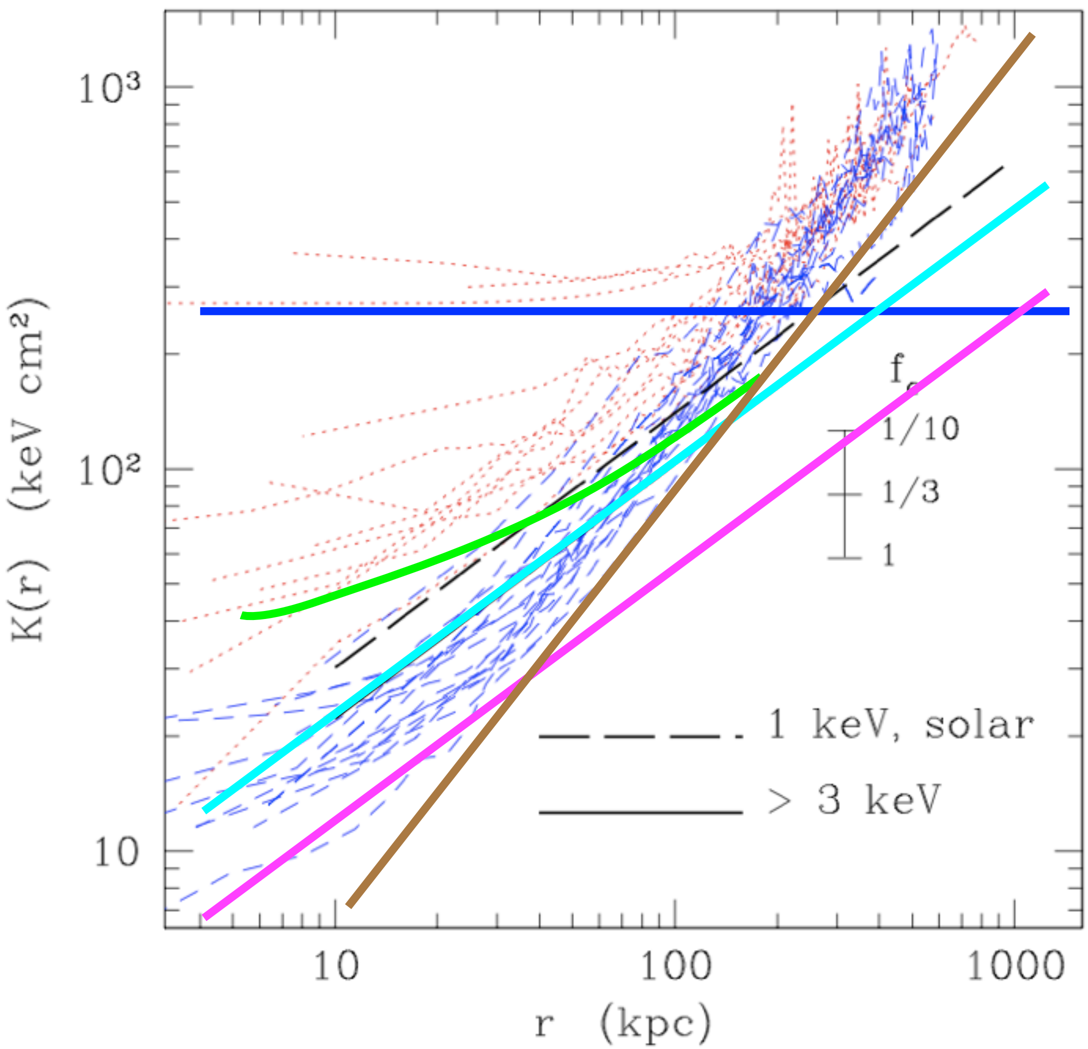


The isothermal core and precipitation-regulated profiles are now indistinguishable, meaning that feedback driven by condensation should prevent positive temperature gradients from developing in halos of this mass scale.

However, a cool central corona resulting from a discontinuous entropy distribution is still possible.



This figure from Voit (2011) shows a plot of ***ACCEPT*** entropy profiles for a set of clusters with star-forming central galaxies (***blue***) and a set of clusters showing no evidence for star formation or multiphase gas (***red***).



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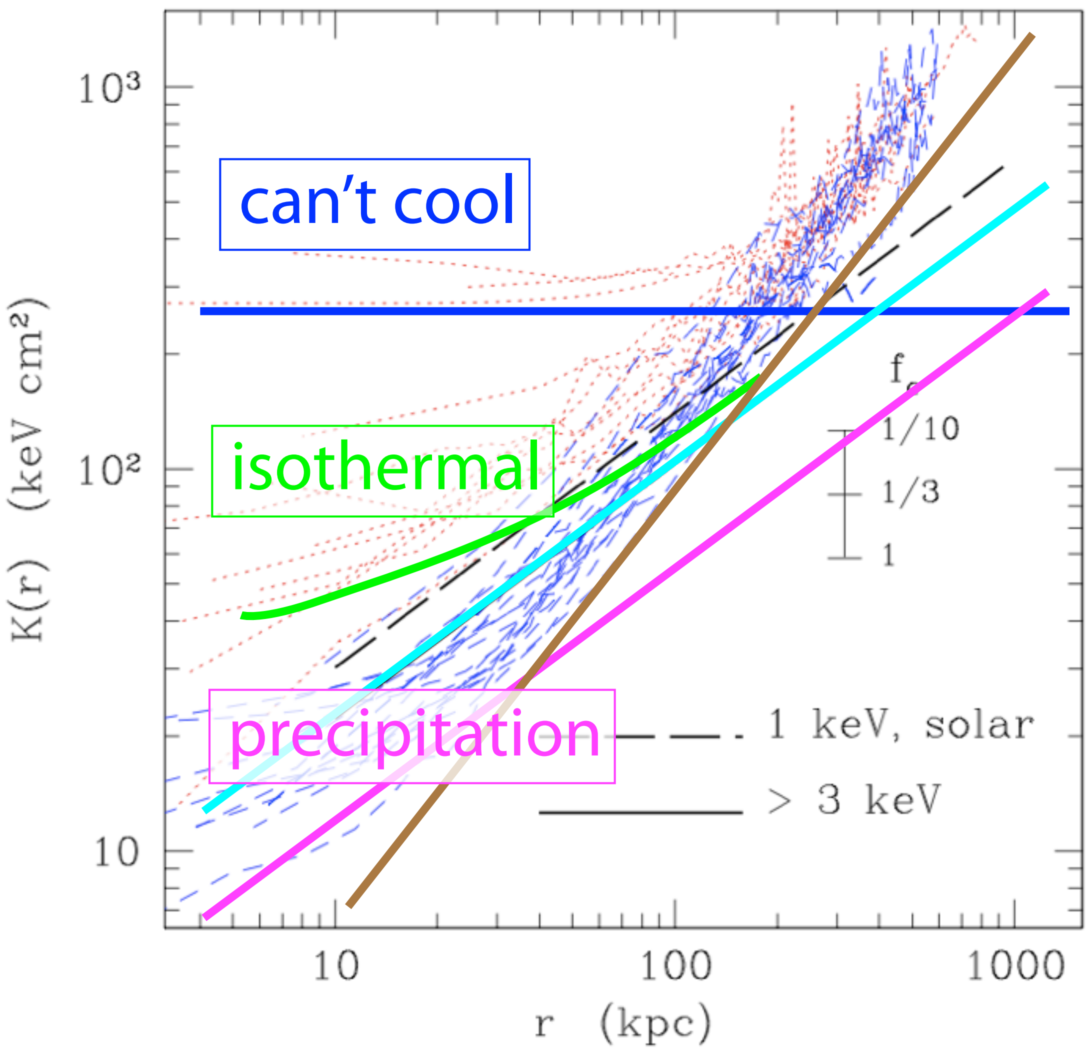
Overlaying the critical lines for a 5 keV halo suggests that the profiles show "***trifurcation***."



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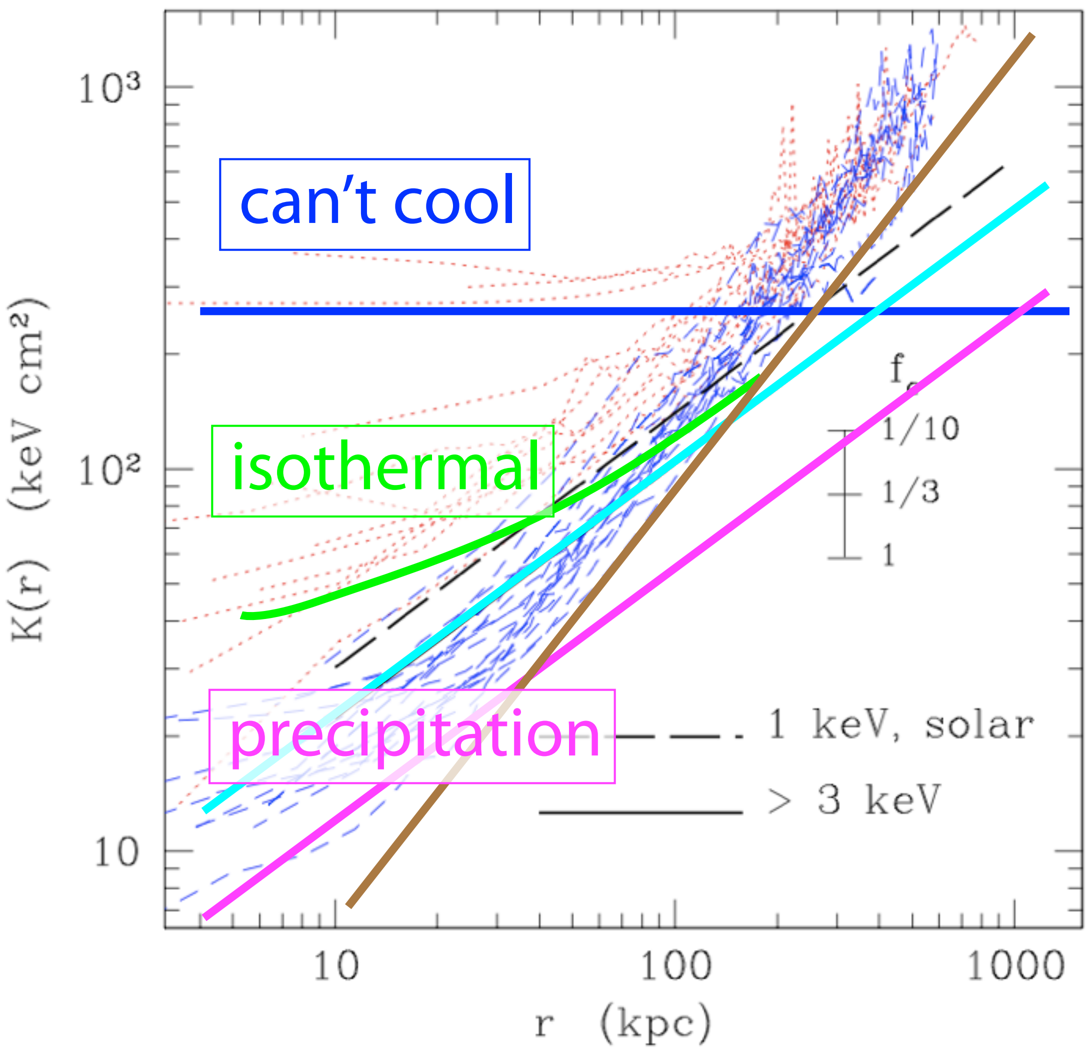
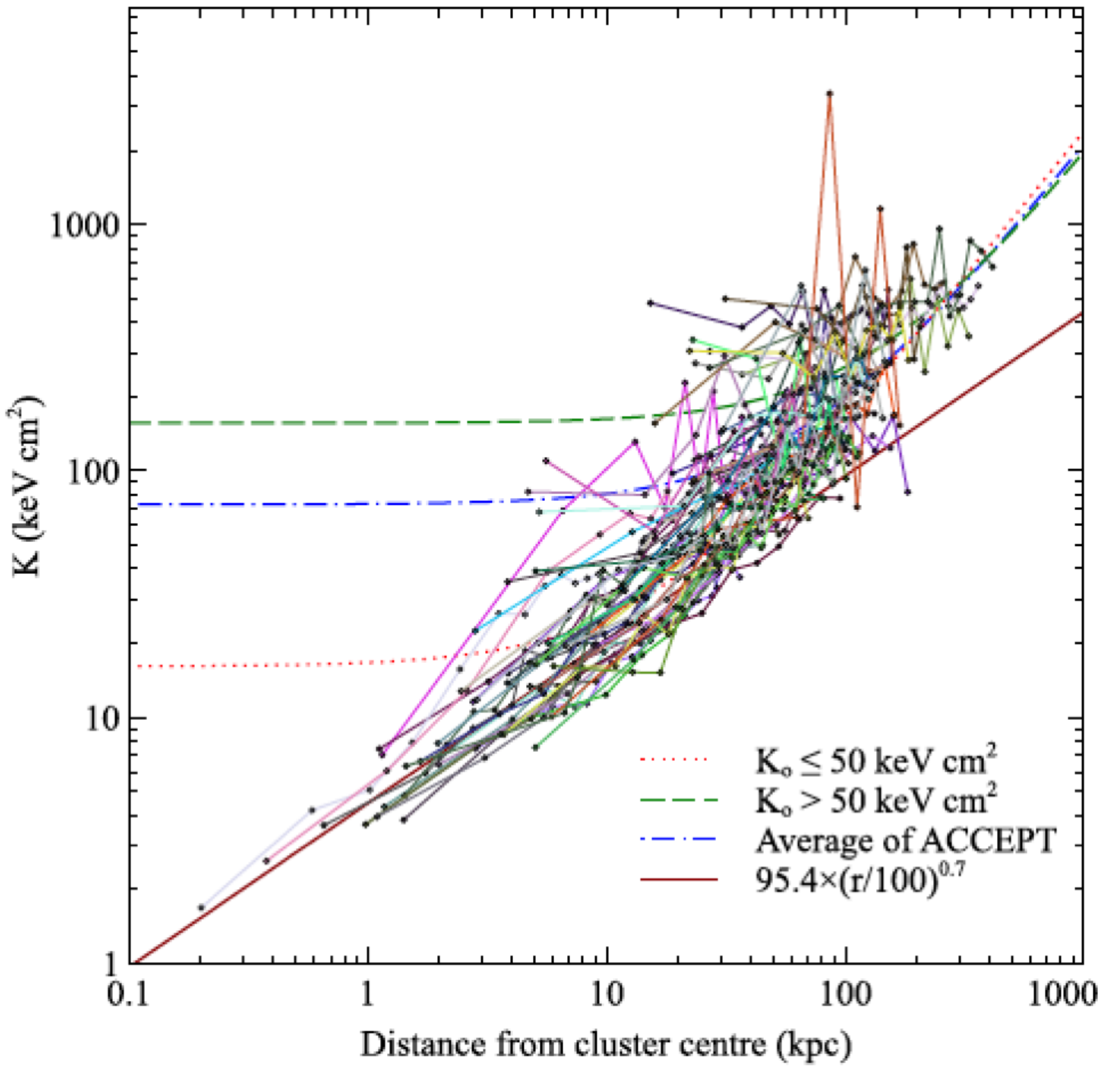


The precipitating state will persist until a large burst of feedback (or a merger event) boosts the core entropy above the locus of "conductive" balance.

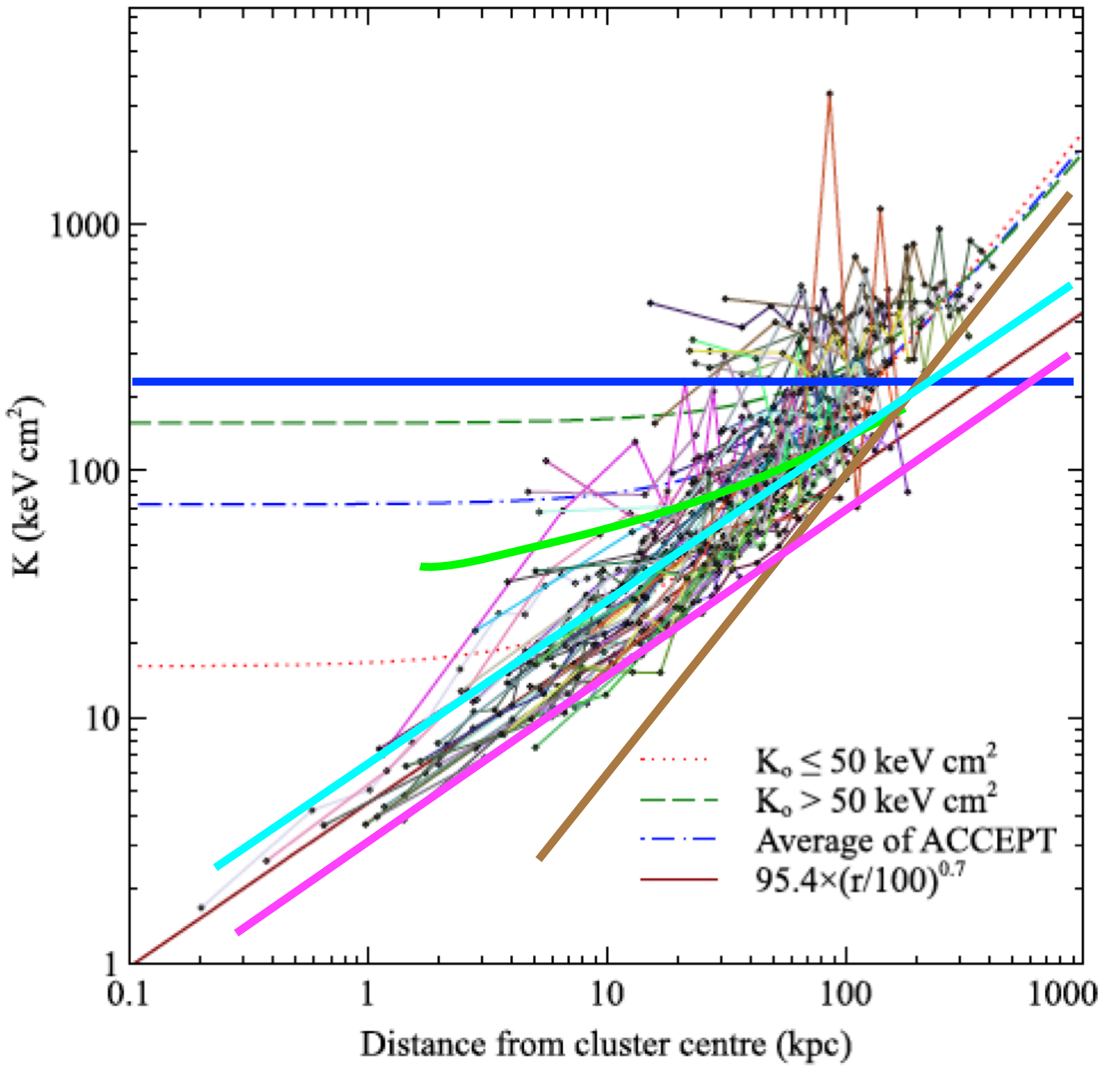
If that happens, then heat transport can potentially evaporate the multiphase medium and create an isothermal core.

An isothermal core is more susceptible to merger heating than a precipitating one, and can be pushed more easily above the cooling threshold.



Panagoulia, Fabian, & Sanders (2014) provide additional support for this picture (even though they paint a misleading picture of ***ACCEPT***).

Their work independently shows that the entropy profiles of clusters follow a two power-law model, with an outer power-law slope ~1 and an inner power-law slope ~0.7.



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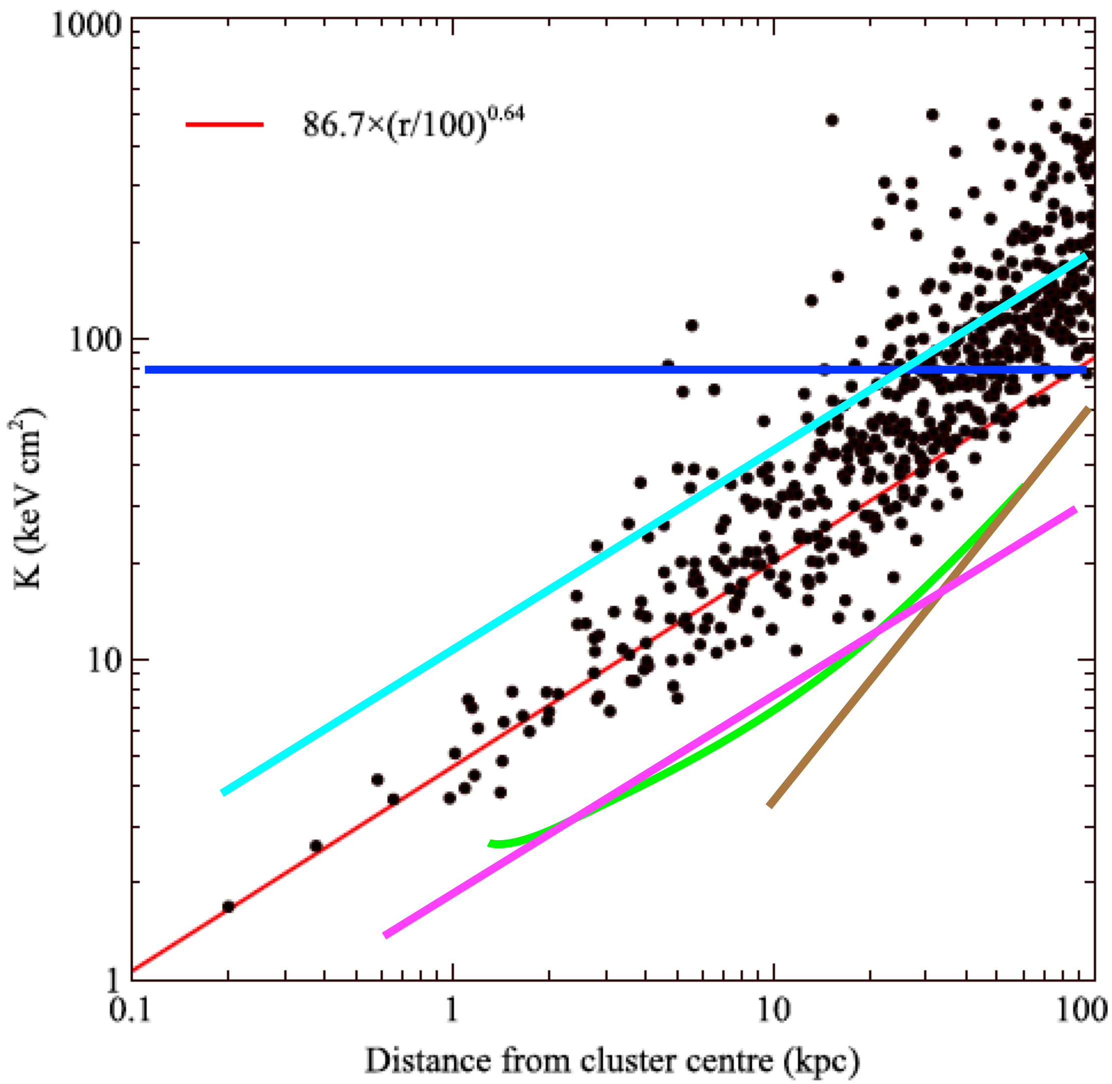
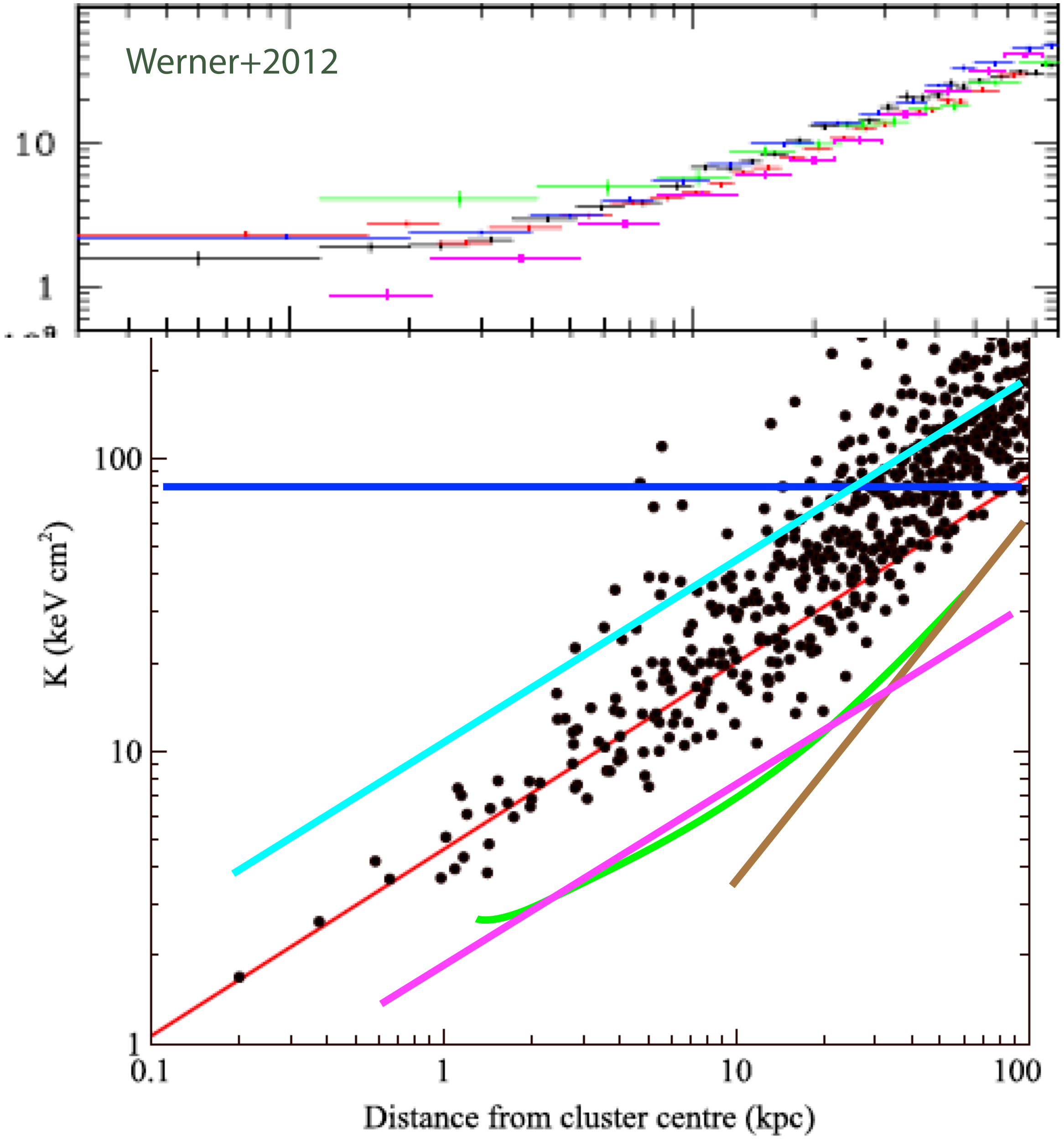
Overlaying the critical lines shows that low-entropy cluster cores are pinned between the locus of "conductive" balance and the precipitation threshold.



Panagoulia et al. also analyze a subsample of elliptical galaxy halos with *kT* < 1.2 keV, represented in this figure, along with the critical lines for a 1 keV halo at *z* = 0.

The framework still looks pretty good, although the points are farther above the precipitation threshold than one might expect.

A more precise treatment of the stellar potential well might be necessary here, because it dominates the central ~30 kpc in these objects.



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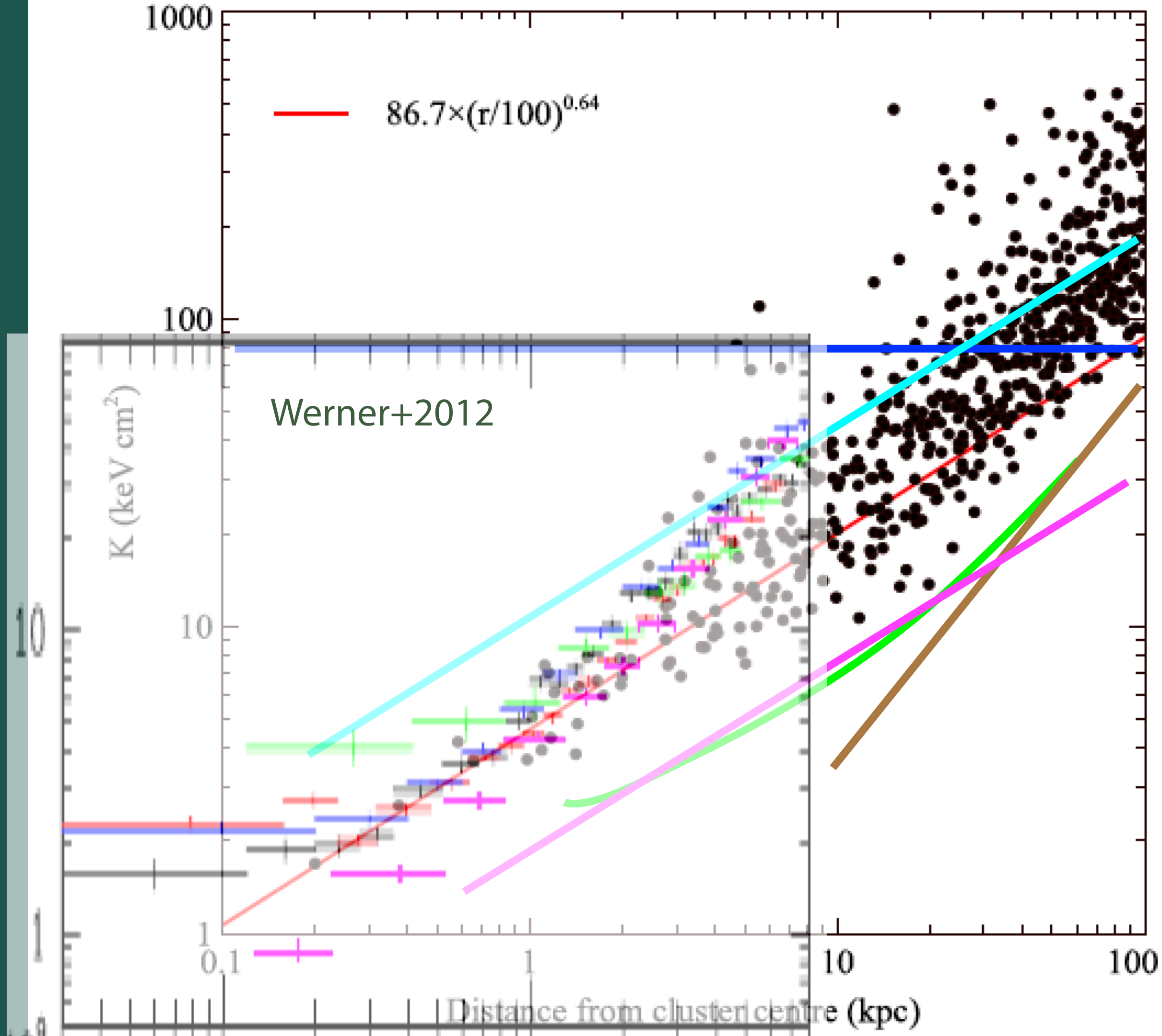

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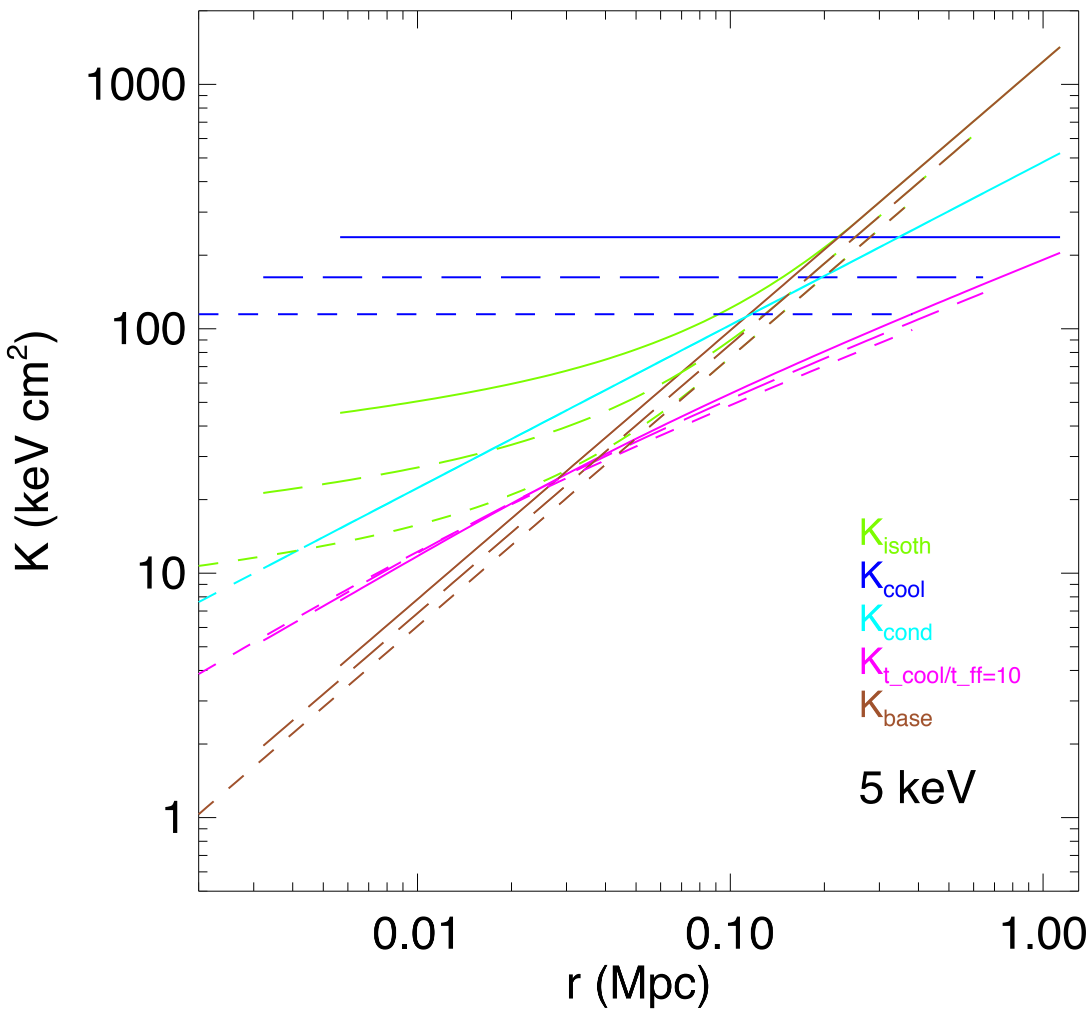
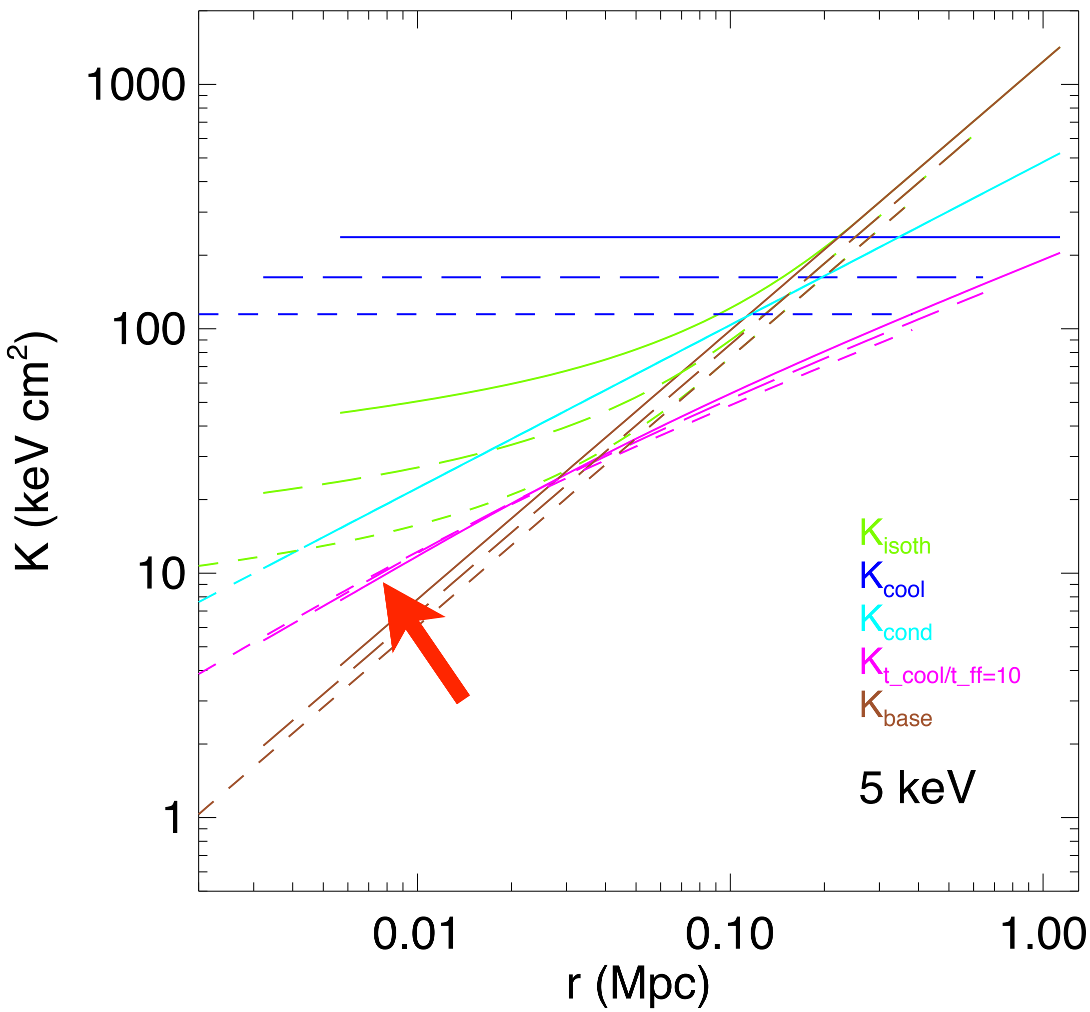


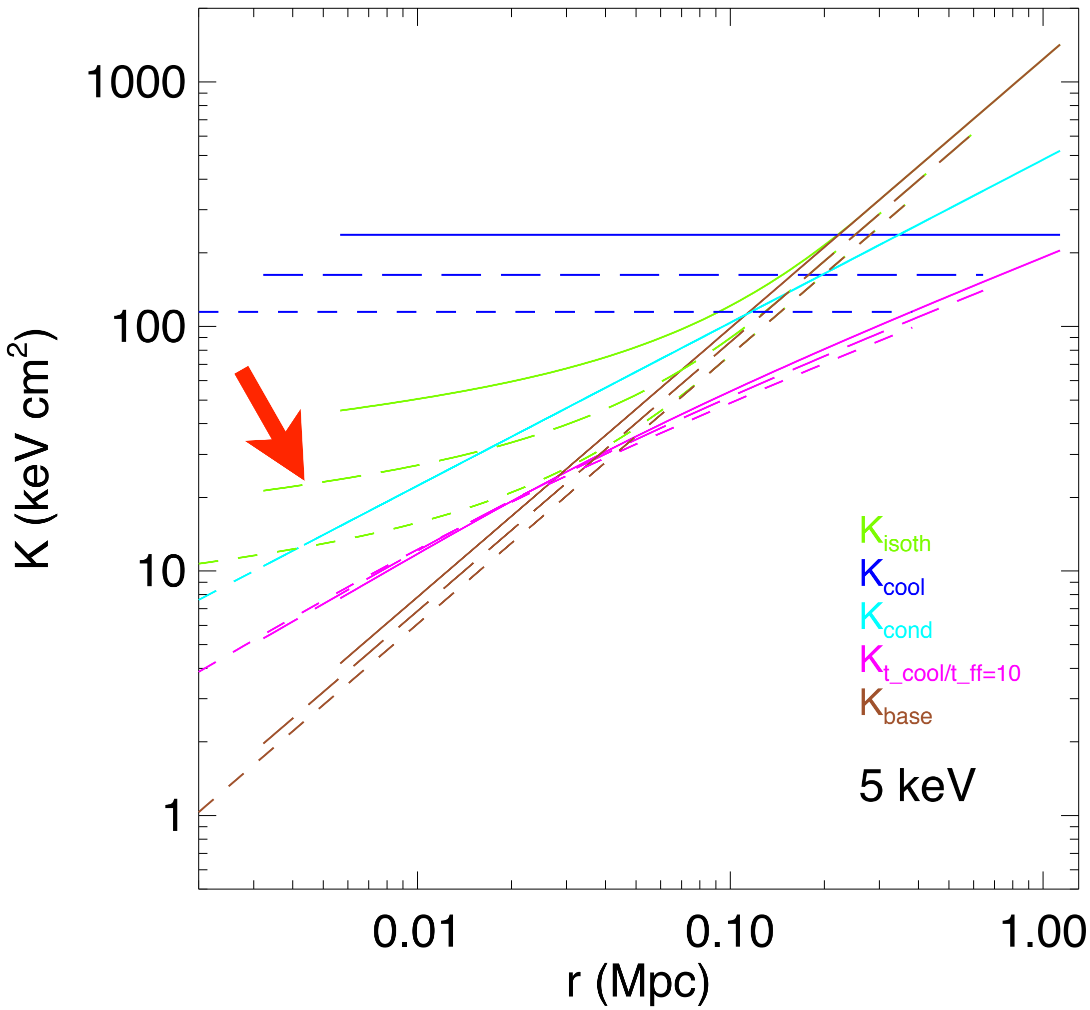
Consider how ICM evolution changes the critical lines for a 5 keV halo.

- $z = 0$, solid lines
- $z = 1$, long-dashed lines
- $z = 2$, short-dashed lines

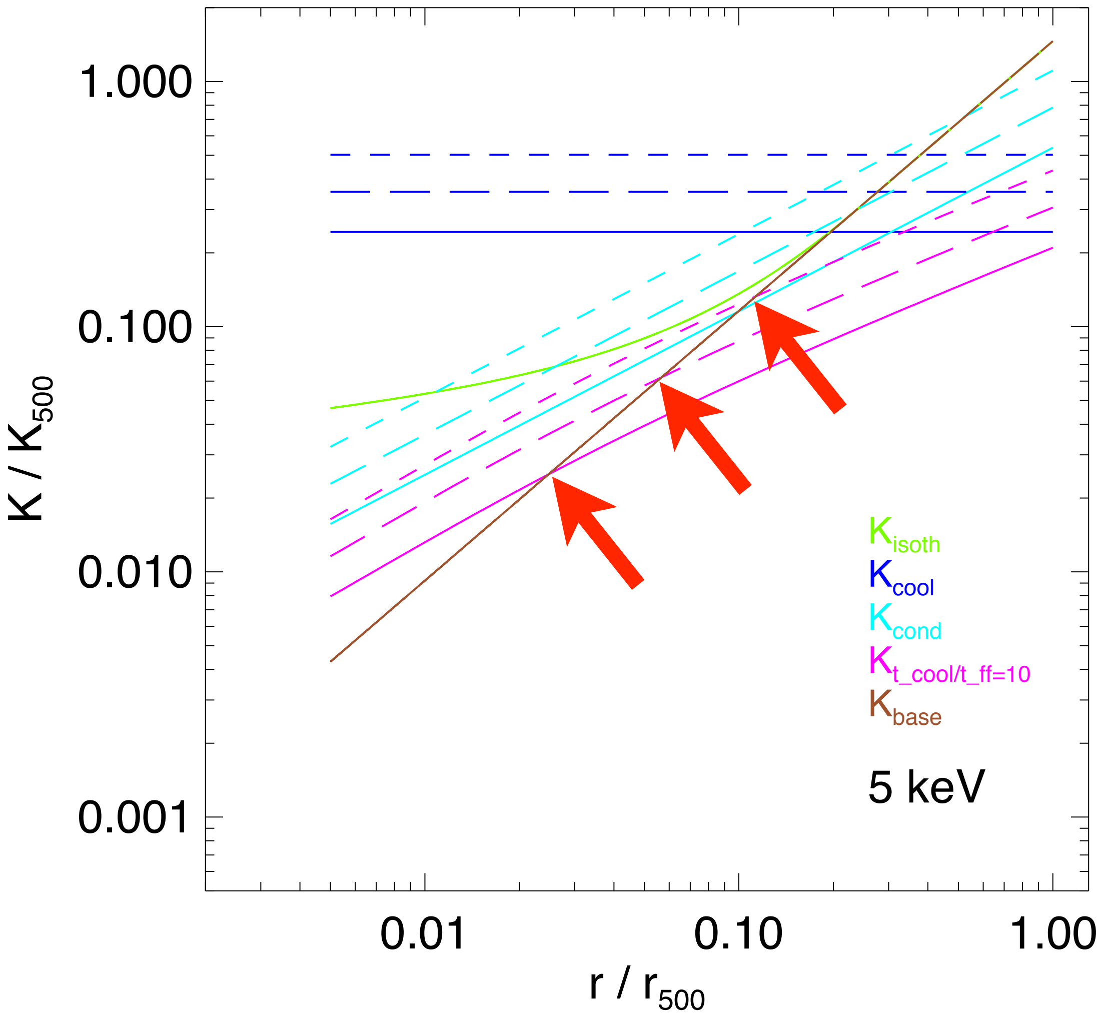


The precipitation threshold changes very little with redshift, remaining near 10 keV cm^2 at ~ 10 kpc.

This is consistent with the K_0 findings for SPT clusters by McDonald et al. (2014).



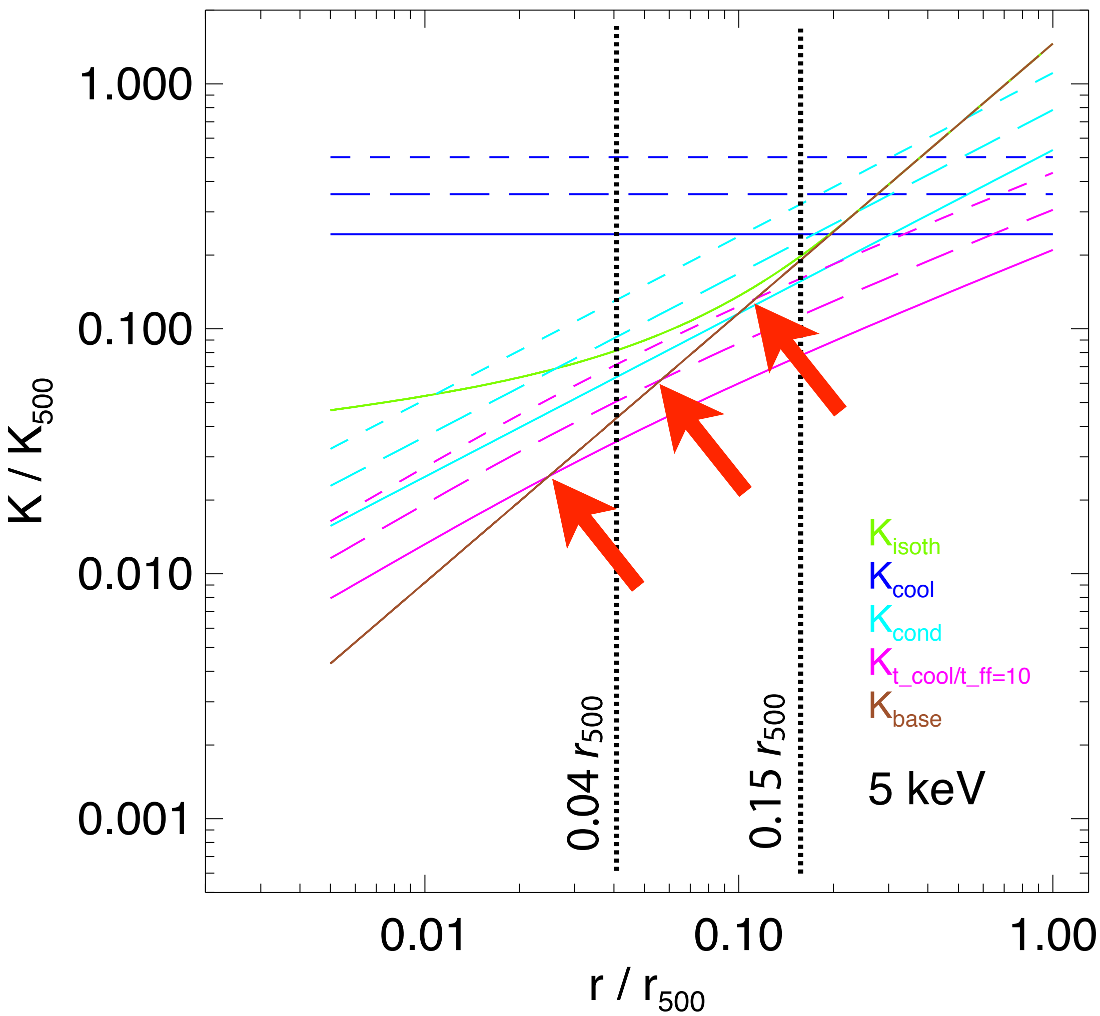
Isothermal core profiles at higher redshift are closer to the precipitation threshold, implying that bimodality produced by heat transport into the core should be less pronounced.



It's illustrative to look at the same set of critical lines in a ***scaled*** entropy-radius diagram.

Similarity breaking through precipitation-driven feedback should occur at substantially larger radii in high-redshift clusters.

The surface-brightness profiles of high-redshift cool-core clusters should therefore be significantly less cuspy than at lower redshift.



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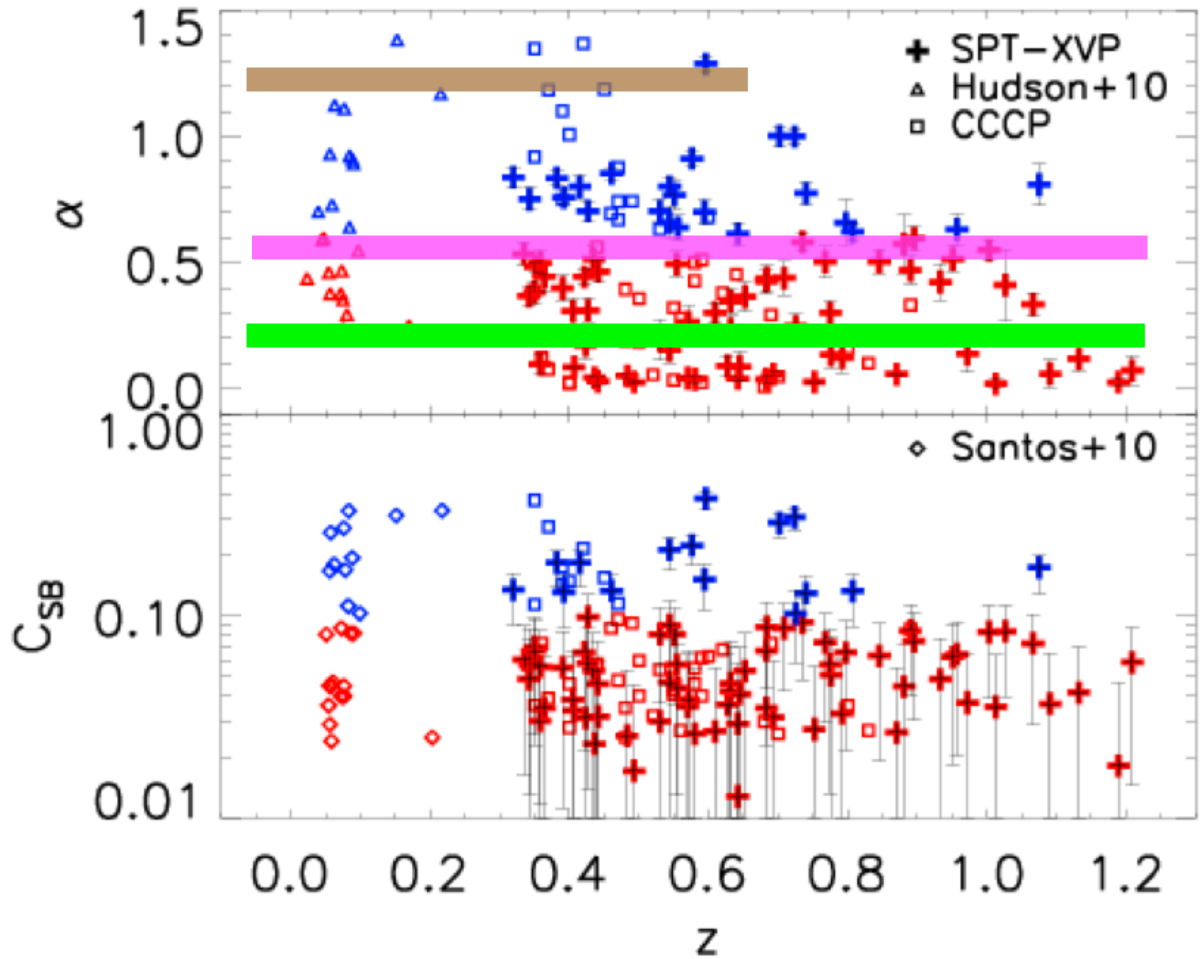
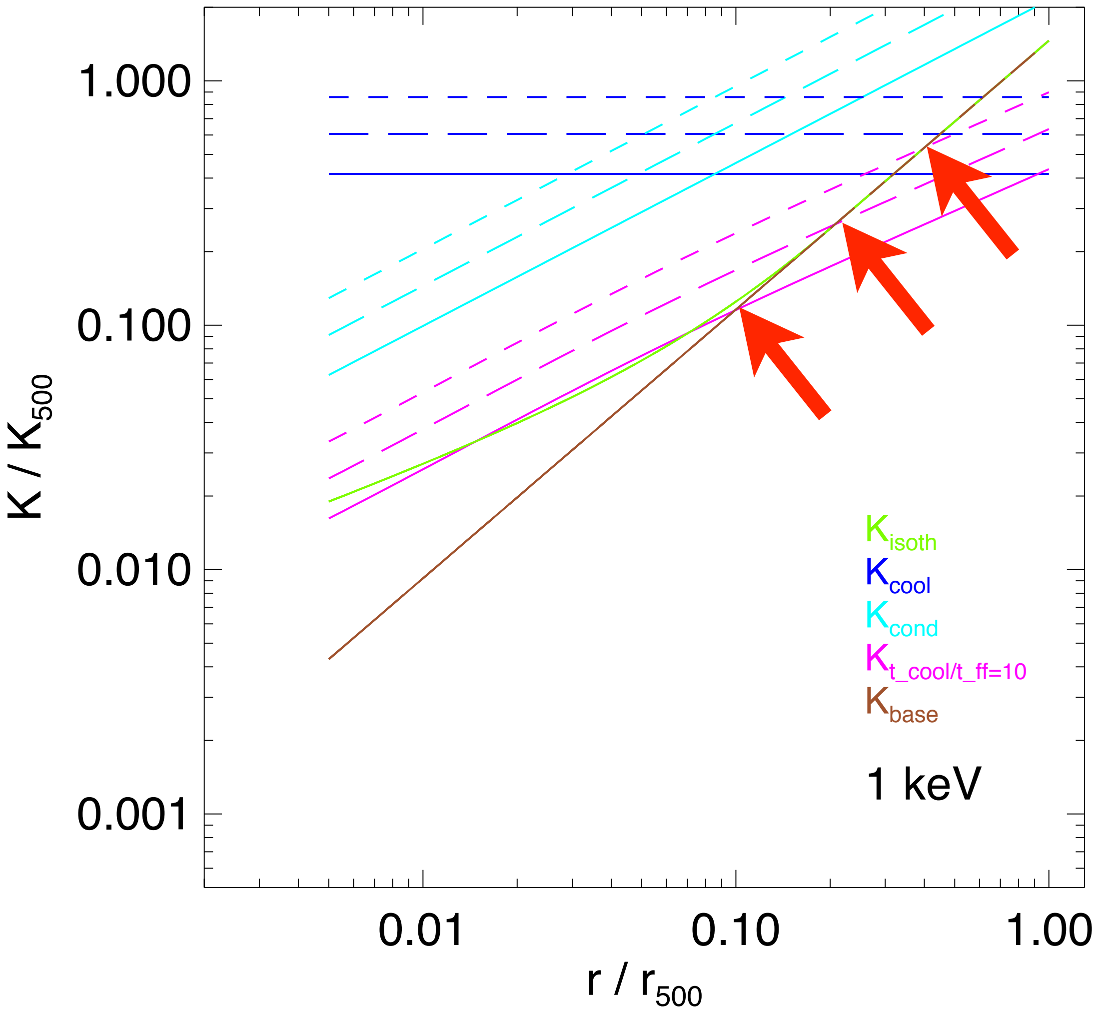


$$\alpha \equiv \left.\frac{d\log\rho_g}{d\log r}\right|_{r=0.04\mathrm{R}_{500}}$$

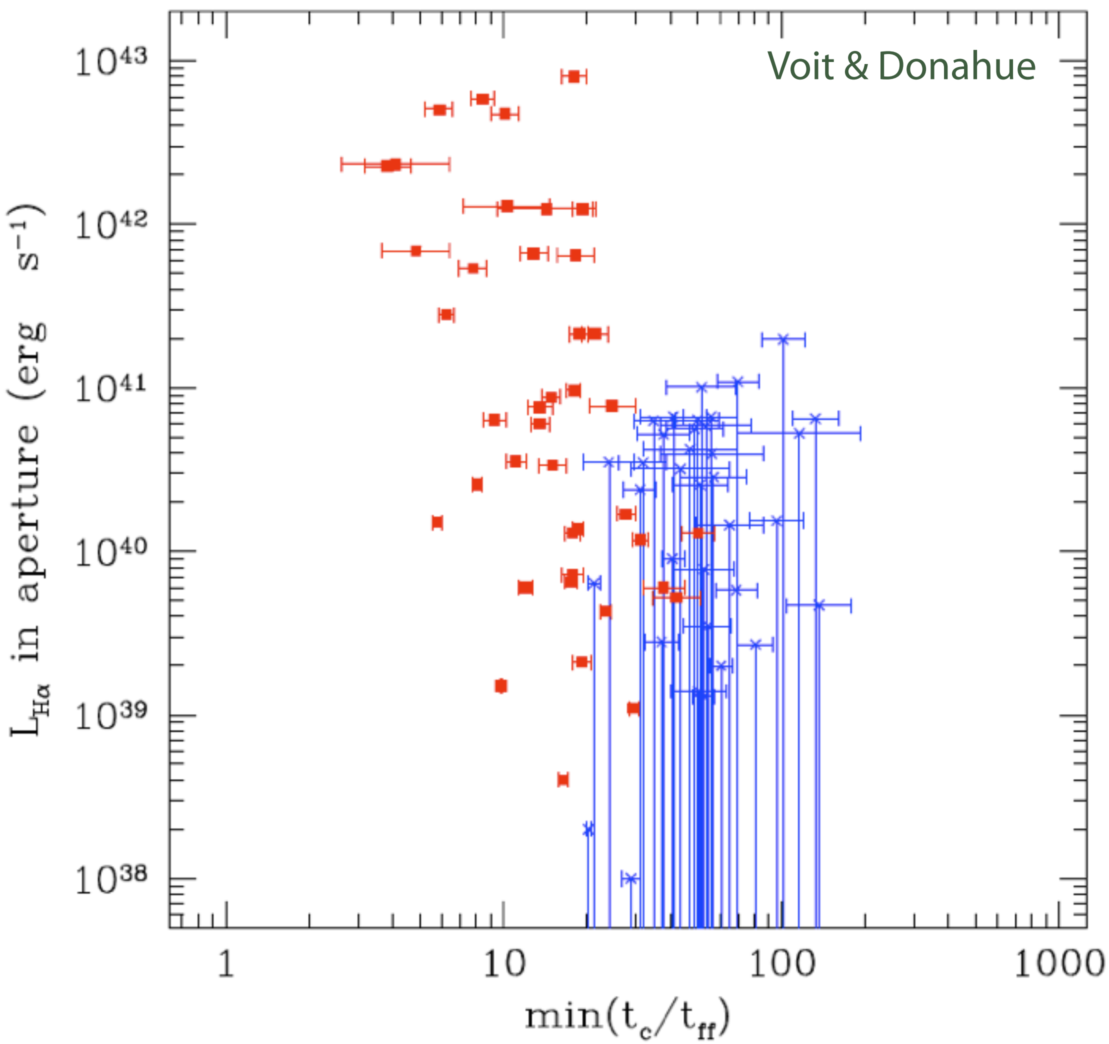
Precipitation-driven feedback should limit cuspiness at ~0.04 r_{500} in SPT clusters more distant than $z \sim 0.6$.



In group-scale halos, the precipitation threshold should break self-similarity at a substantial fraction of r_{500}, with implications for the SZ contribution to the CMB power spectrum.

3

Toward Understanding t_c/t_{ff}: Simulations



Feedback response appears to be a strong function of t_c/t_{ff}.

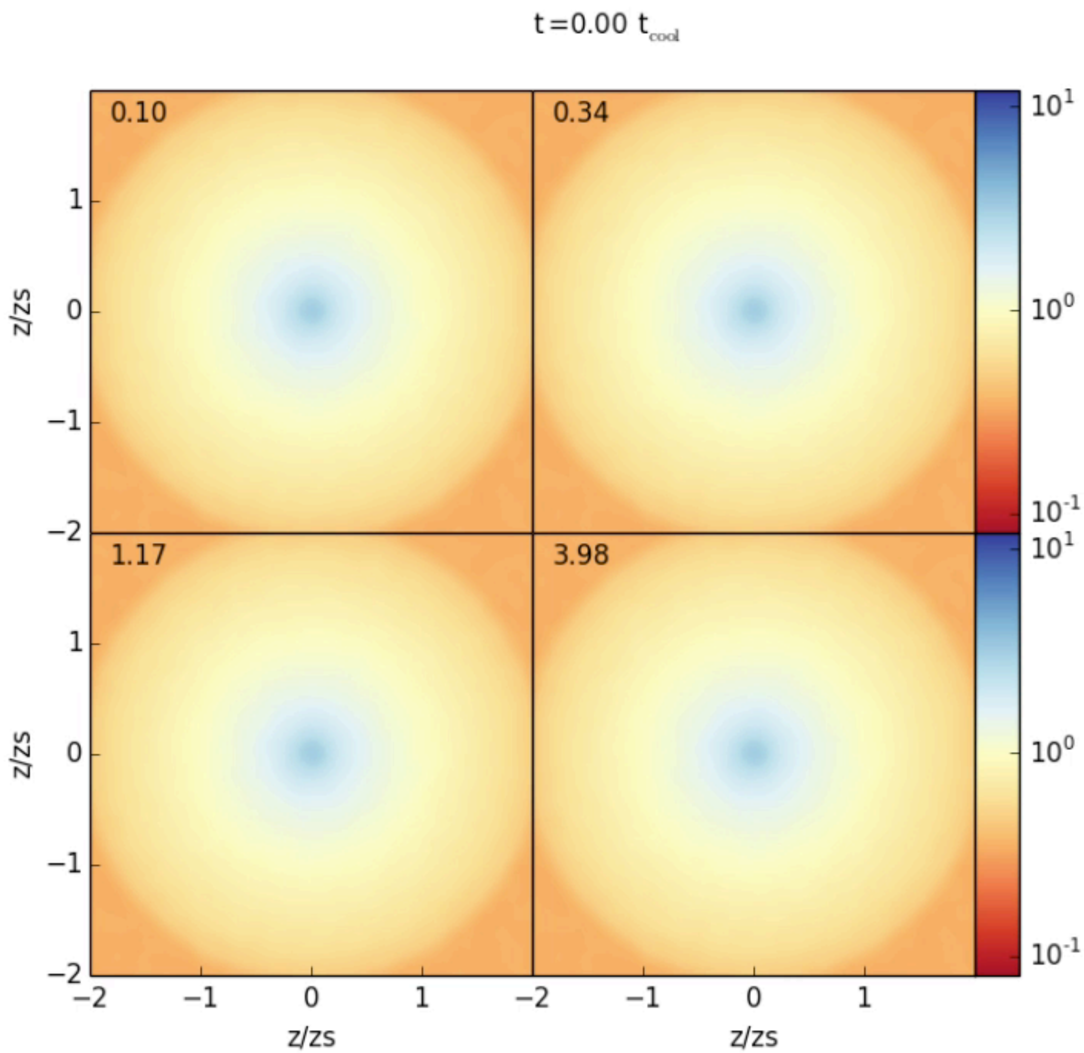
Precipitation-driven feedback prevents cluster cores from dropping much below $t_c/t_{ff} \sim 10$.

Cosmological cluster simulations require a sub-grid treatment of precipitation threshold.

ENZO

Greg Meece
(grad student)

Colors represent density.

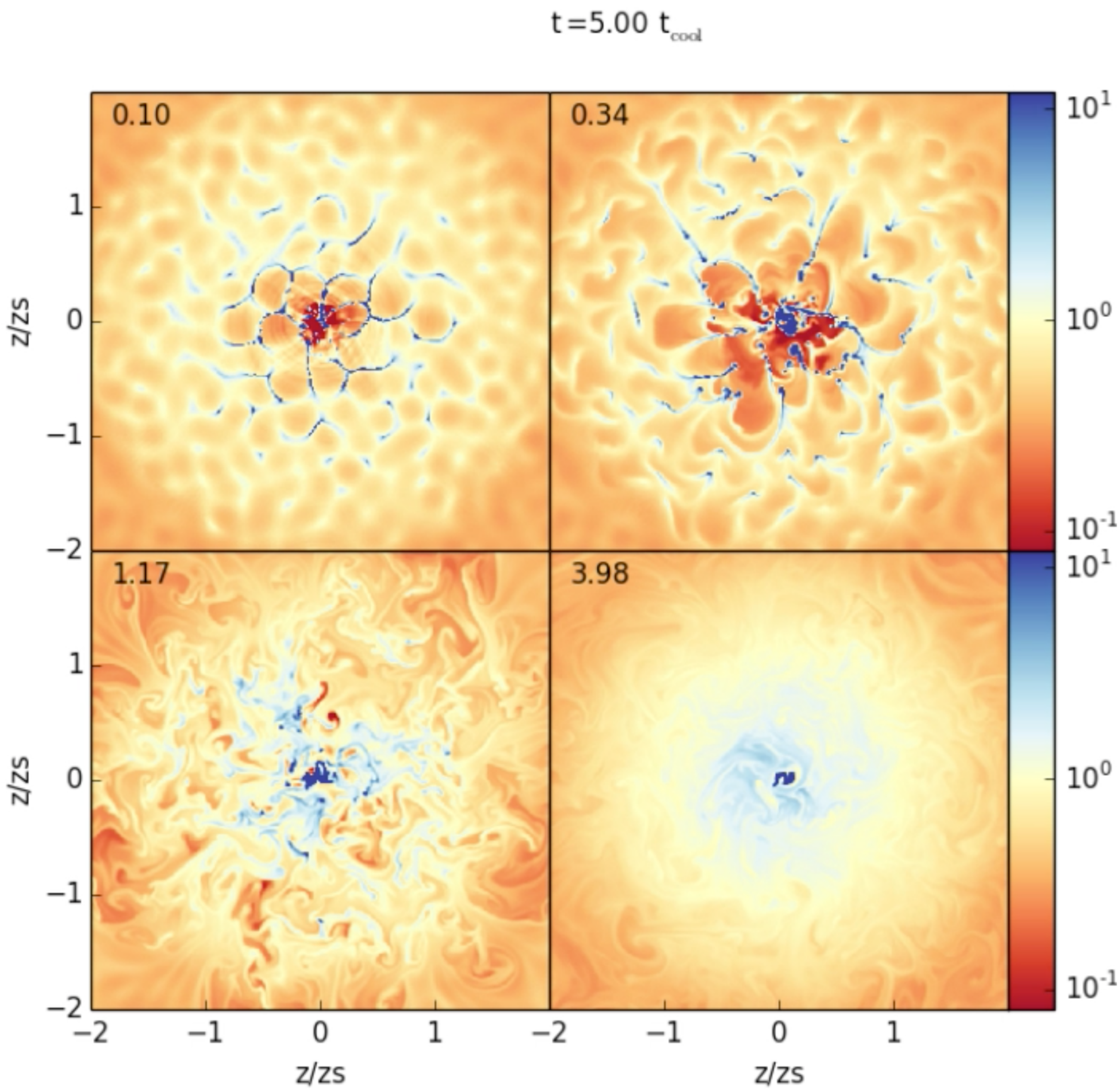


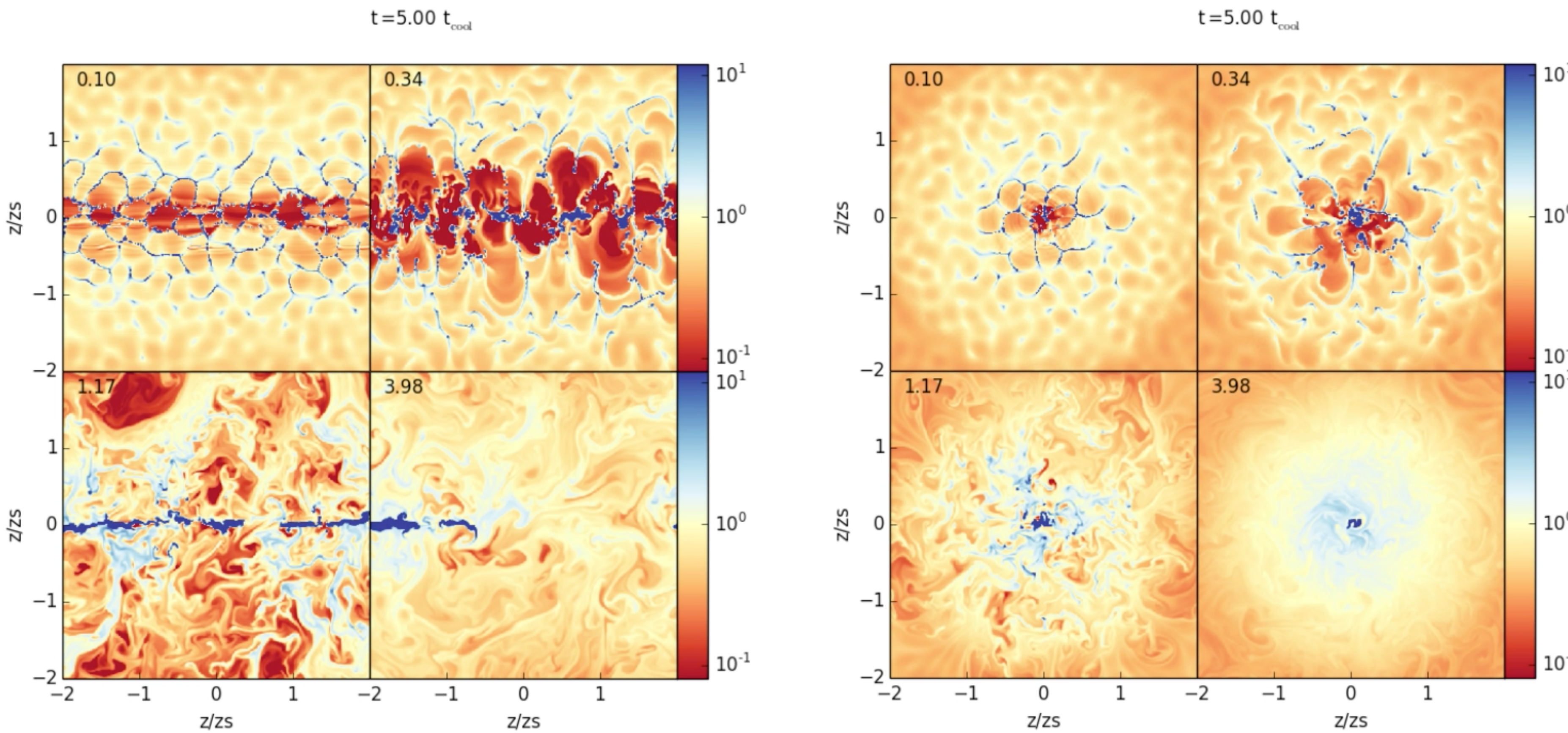
Testing:

- t_c/t_{ff}
- lumpiness
- geometry
- feedback mechanism

Heating balances cooling within each equipotential layer (as in McCourt+12).

Initial condition is uniform value of t_c/t_{ff}.


t =5.00 t_cool
0.10
0.34
1.17
3.98
z/zs
z/zs
z/zs
z/zs
1
0
−1
−2
−2
−1
0
1
10^{1}
10^{0}
10^{-1}



So far, convergence of the potential seems not to make a big difference.

Feedback-driven advection/entrainment of cold clouds may be necessary to make extended filament systems with $t_c/t_{ff} > 1$.

Suggested Questions

- Which cool-core definition is best for measuring evolution?
- How do clusters switch between precipitating, isothermal, and "uncool" states?
- What phenomena can trigger precipitation?
- What's so special about $t_c/t_{ff} = 10$?
- What's the right parameter set for sub-grid modeling of precipitating cores?

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