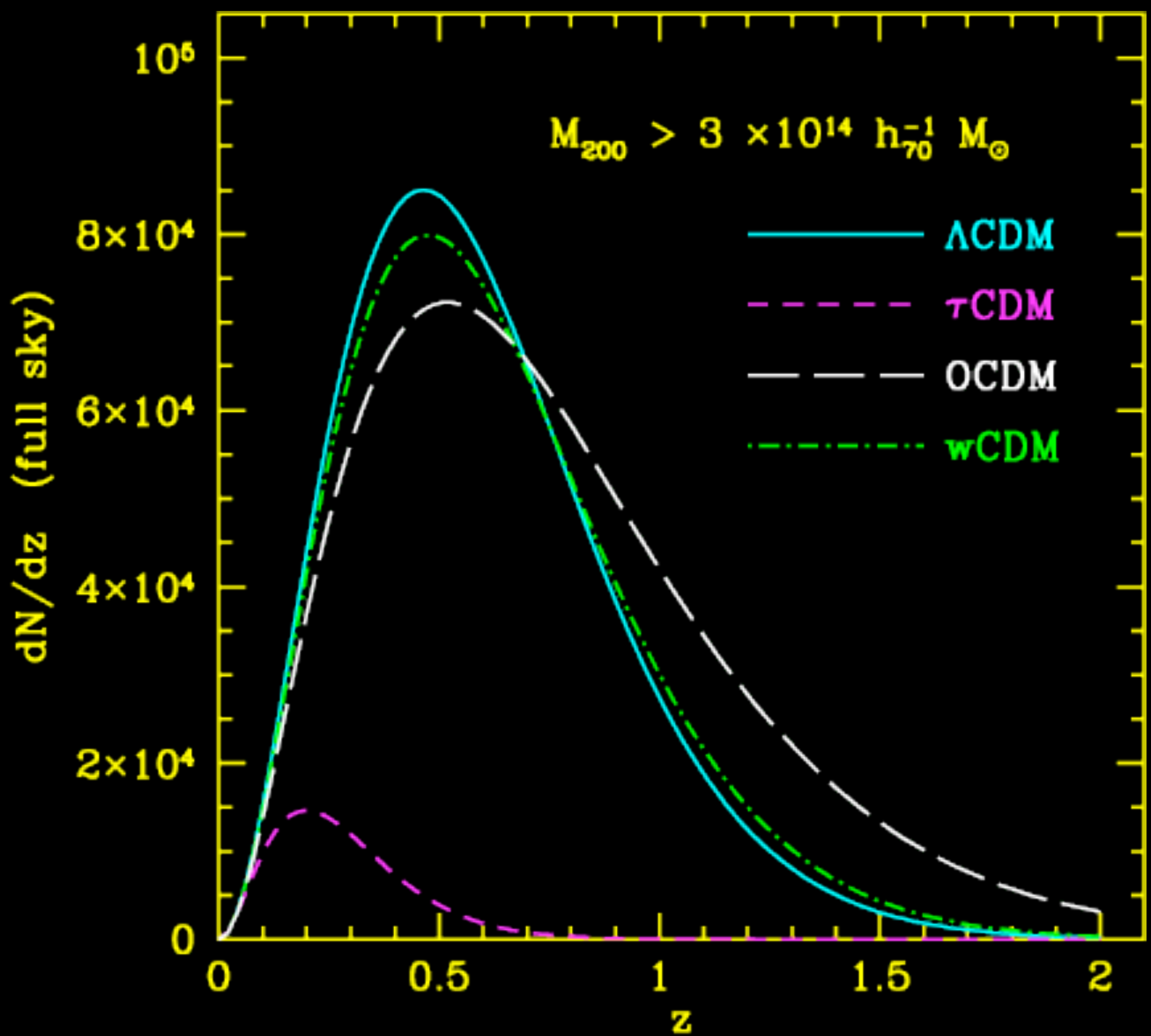
Mysteries of Cluster Cores

The Plan

- Cluster Cosmology & the Baryon Fraction
- Three Related Mysteries
- *Chandra* Core Entropy Survey

Cluster Cosmology &
the Baryon Fraction

Cluster Counts and Cosmology



A large cluster survey has the potential to discriminate between models of dark energy or modified gravity

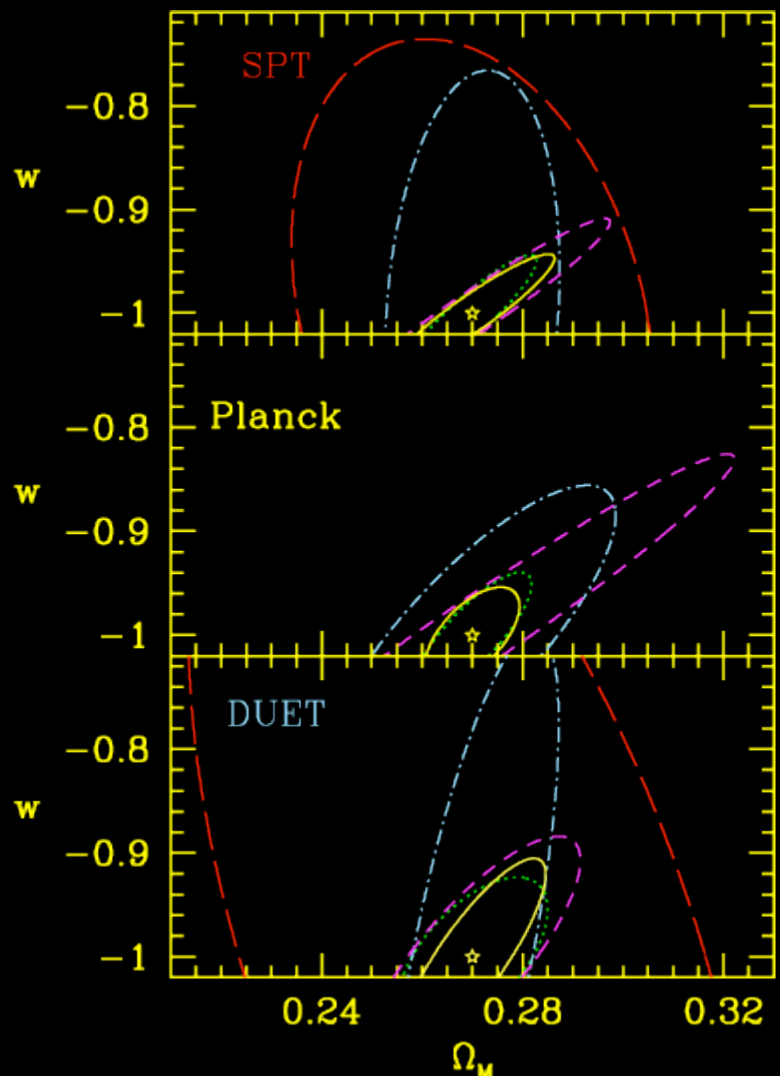
(wCDM: w = -0.8)

Complementary Cluster Information

- Cluster abundance at $z \sim 0$
- Evolution of cluster abundance
- Shape of cluster mass function
- Clustering of clusters

Opportunity for cross checks inspires guarded optimism

Self-Calibration of Large Surveys



Large cluster surveys (> 10,000 clusters) will allow us to treat the mass-proxy parameters as free parameters:

$$M = T_X^{3/2}\, H^{-1}(z)\; f(T,z;a,b,c,\ldots)$$

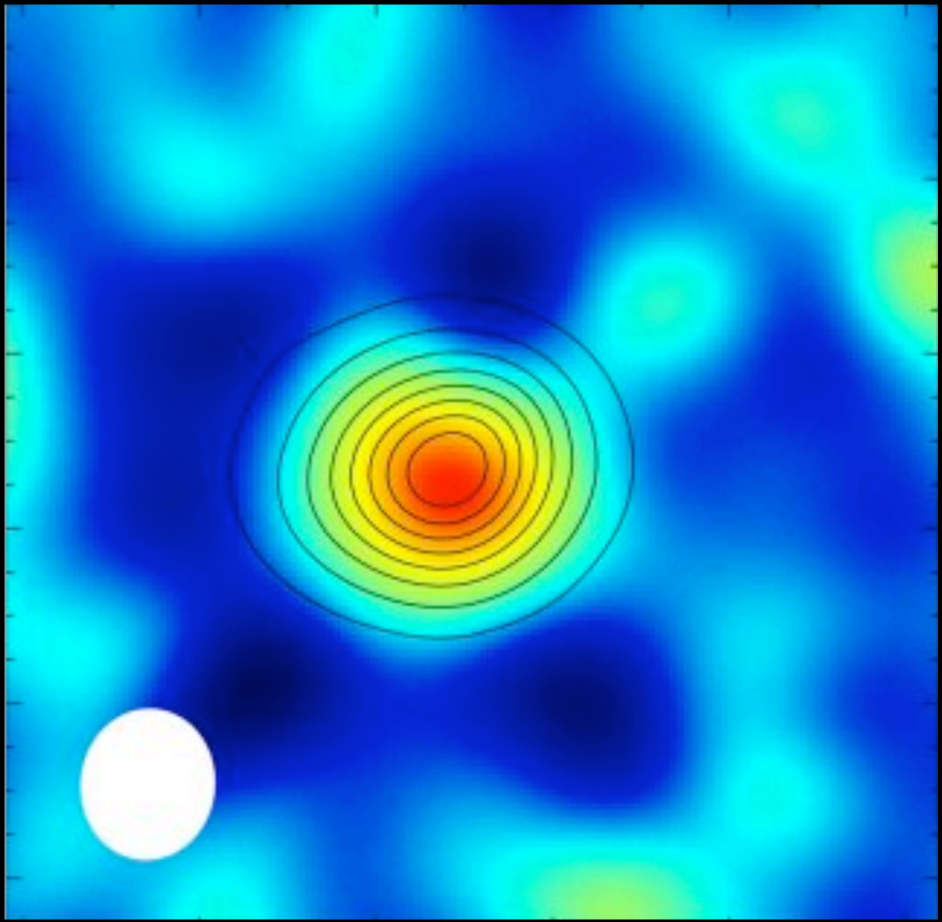
… but parametric forms of the relations must be correct for self-calibration to be accurate

(Majumdar & Mohr 2003, Hu 2003)

Number of Galaxies (N_{gals})

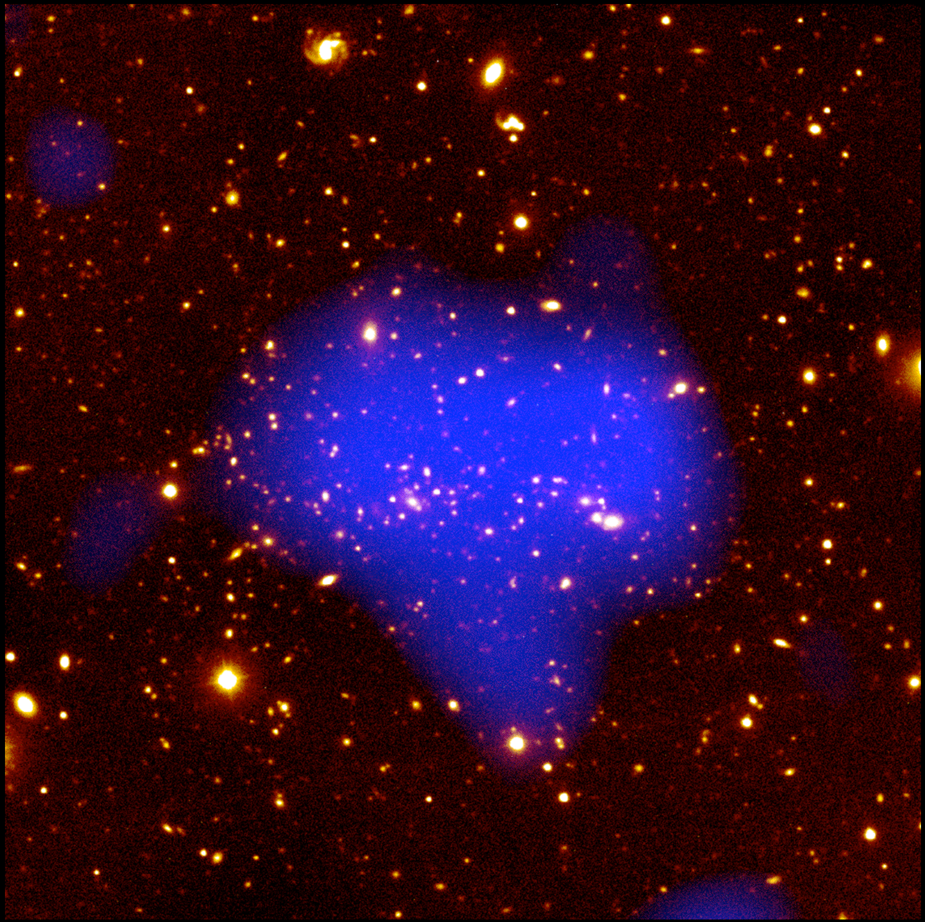
- Count number of galaxies above luminosity limit
- Correct for galaxy evolution
- Expect $M \propto N_{gals}$ (but maybe not)
- Projection effects problematic

Integrated CMB Distortion (Y)



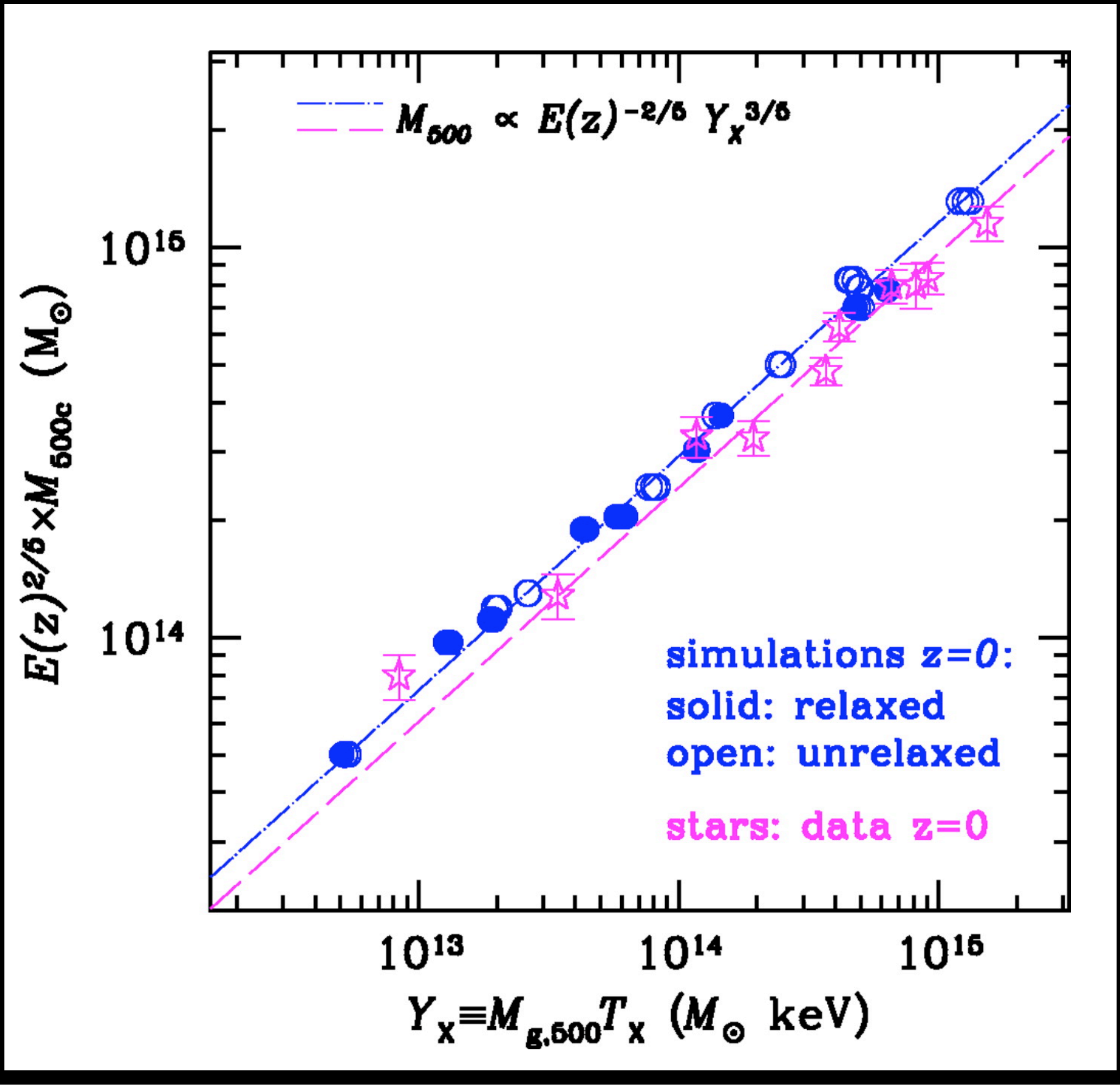
- Measure CMB distortion
- Expect $M \propto Y^{3/5}$ because $Y \propto M_{gas}T$
- Subject to uncertainties in structure of the intracluster medium

X-ray Properties (L_X, T_X)



- Measure L_X (from $>10^2$ photons) and T_X (from 10^4 photons)
- Expect $M \propto T^{2/3}$
- Calibrate $M(L_X)$ relation
- Also subject to uncertainties in ICM structure

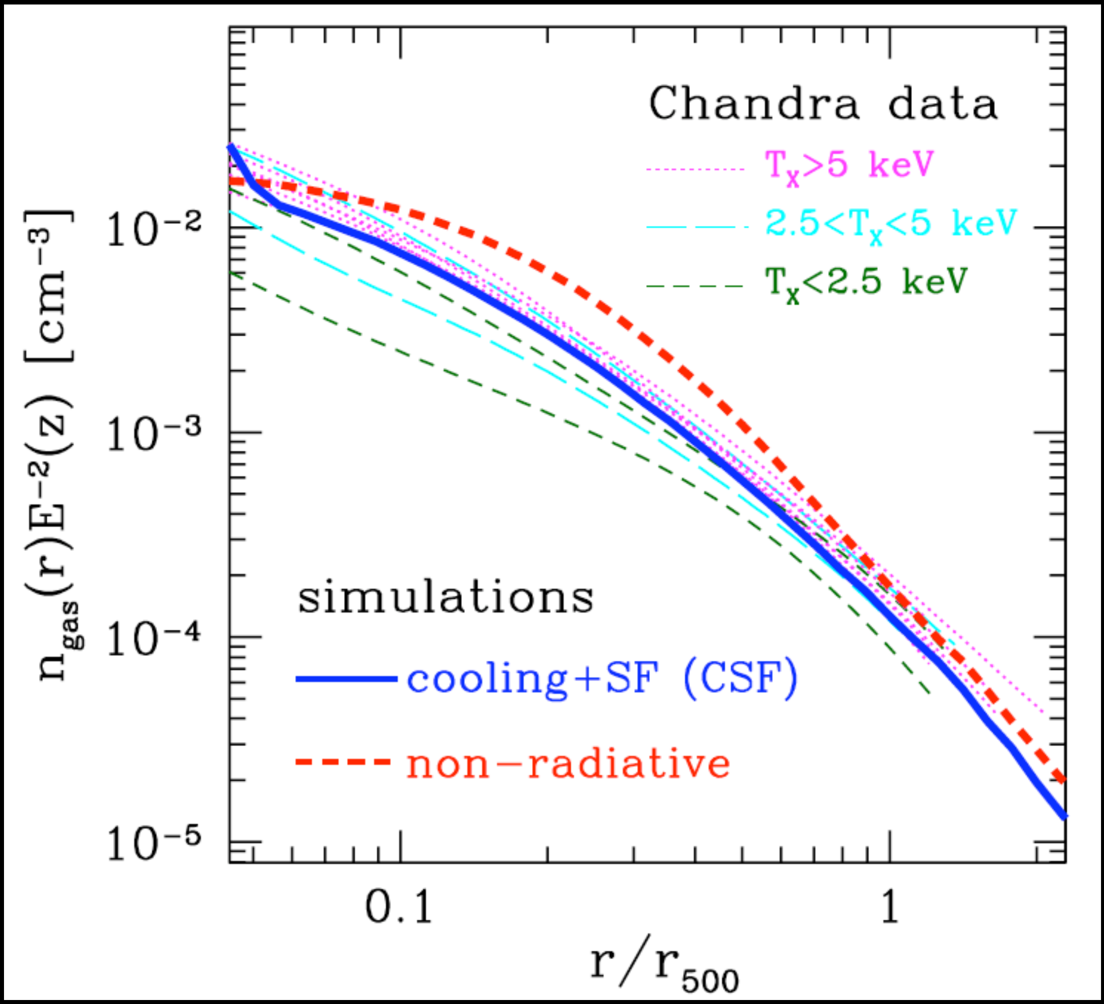
M-Y_X Scaling Relation



Simulations suggest that product of gas mass and X-ray temperature may be a low-scatter mass proxy

(Kravtsov et al. 2006)

Baryon Accounting Problem

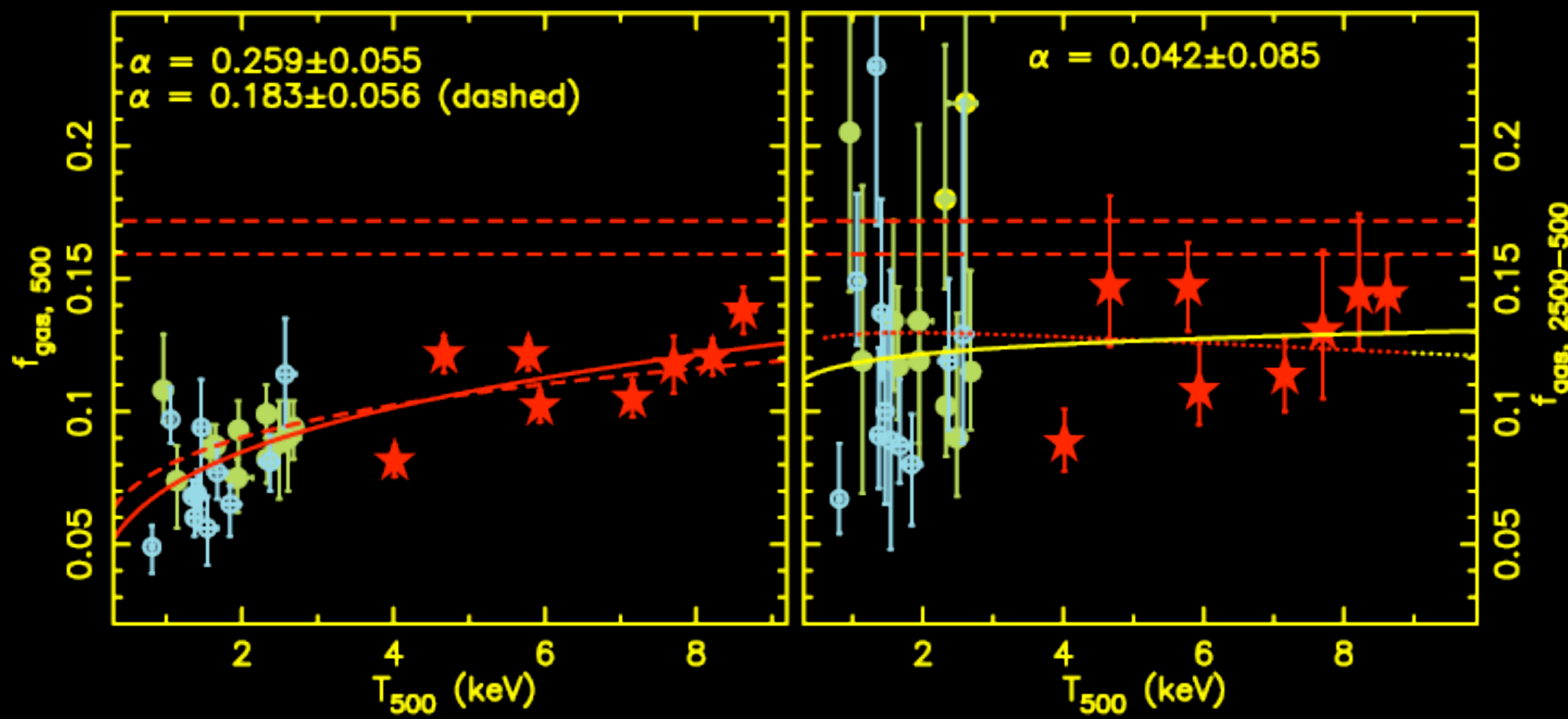


Simulations that agree with X-ray data have very large fraction of condensed baryons (~40%)

Condensed baryon fraction appears inconsistent with observed starlight

Nagai et al. (2007)

Dependence of f_{gas} on T



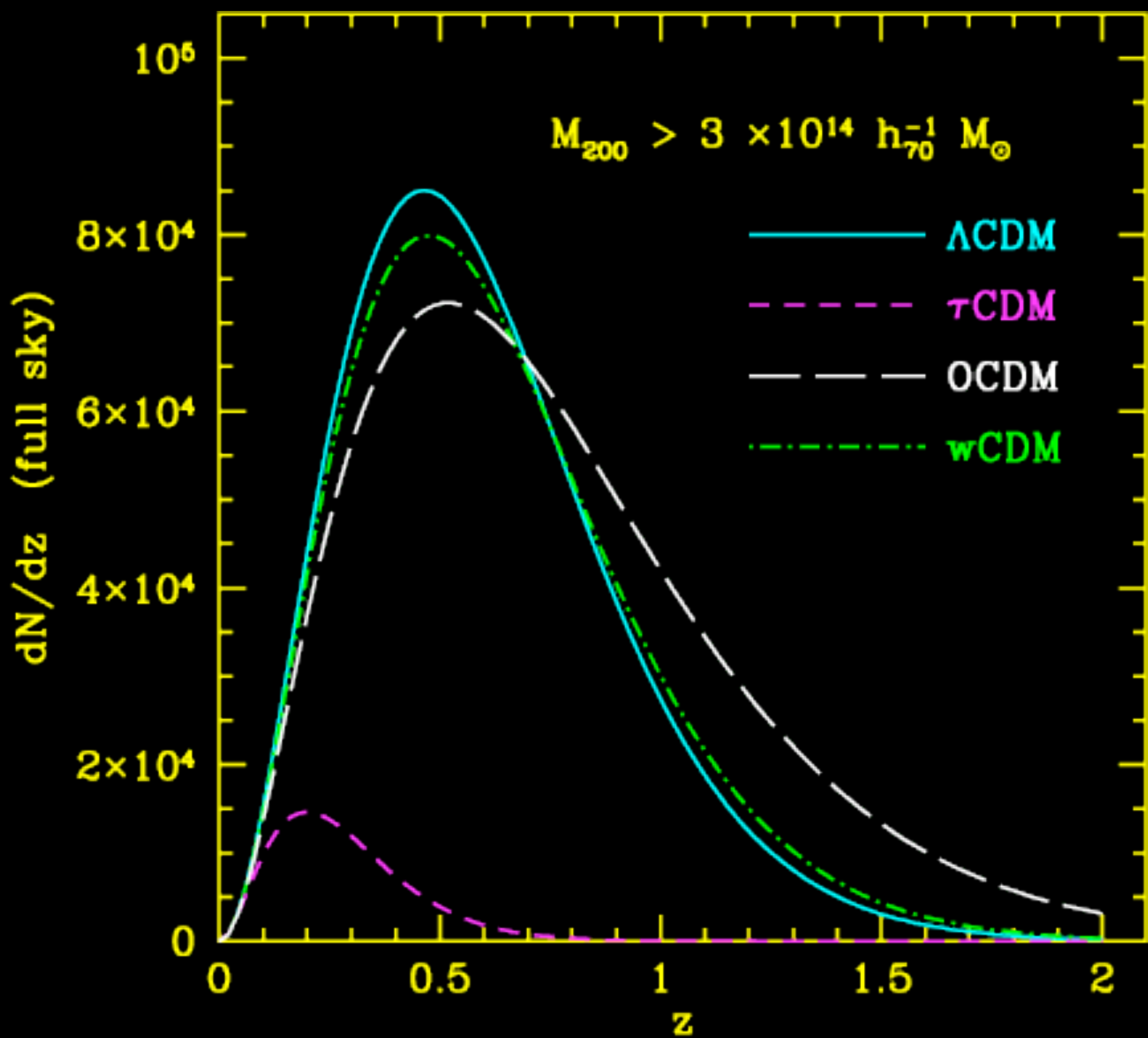
Gas fraction in groups is similar to that in clusters outside of r_{2500}

Sun et al. (2008)

Cluster Mass & Baryon Fraction

- If $T_{gas} \sim T_{DM}$ then
  - Observed baryons $\sim 0.7 f_b$
  - $\sigma_8 \sim 0.9$
- If $T_{gas} \sim 1.5\, T_{DM}$ then
  - Observed baryons $\sim 1.0 f_b$
  - $\sigma_8 \sim 0.7$

Cluster Counts and Cosmology



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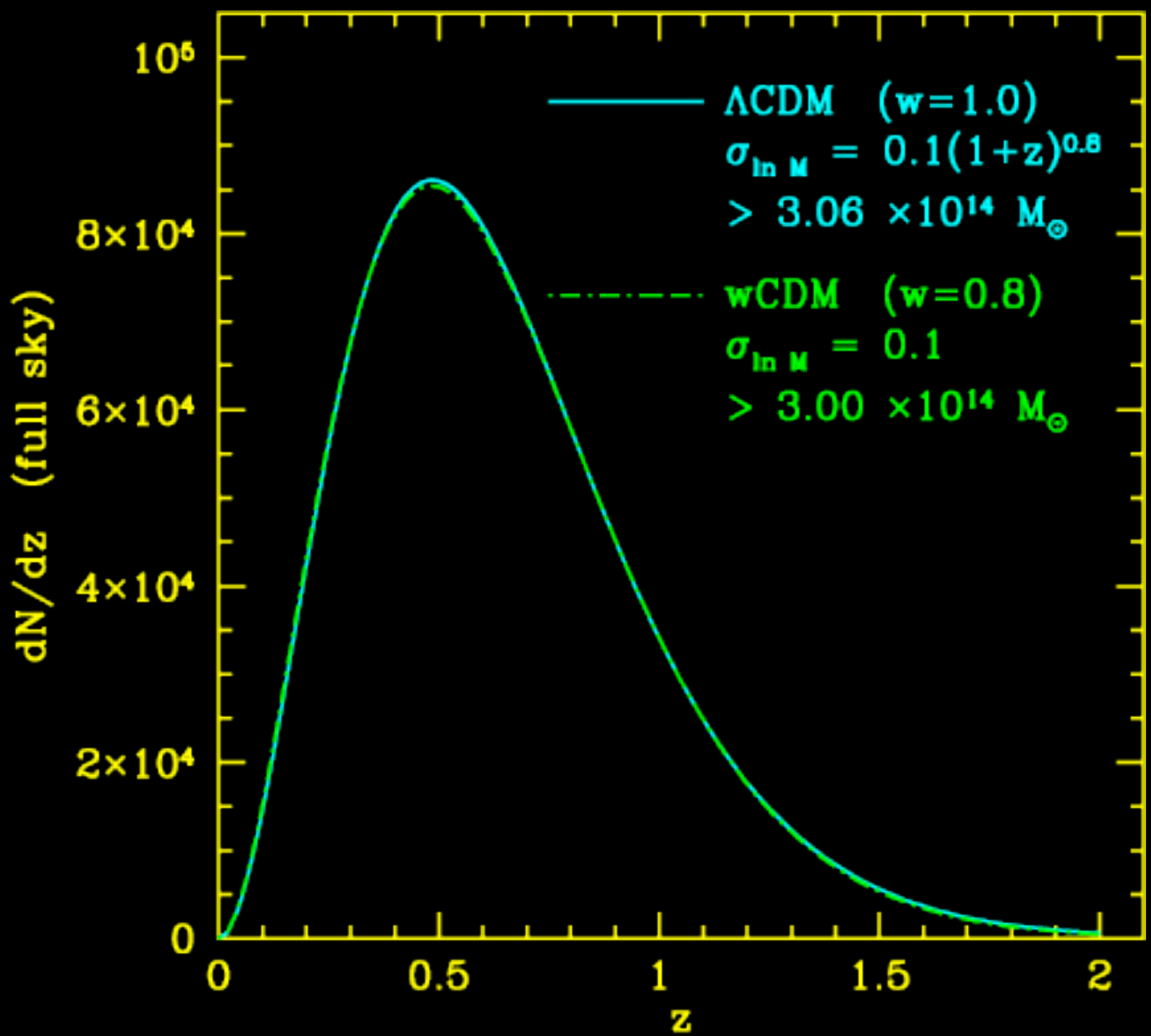
Cluster Counts and Cosmology



Evolution of scatter in mass-observable relation can mimic effects of varying dark energy

Precision cluster cosmology will require an understanding of scatter

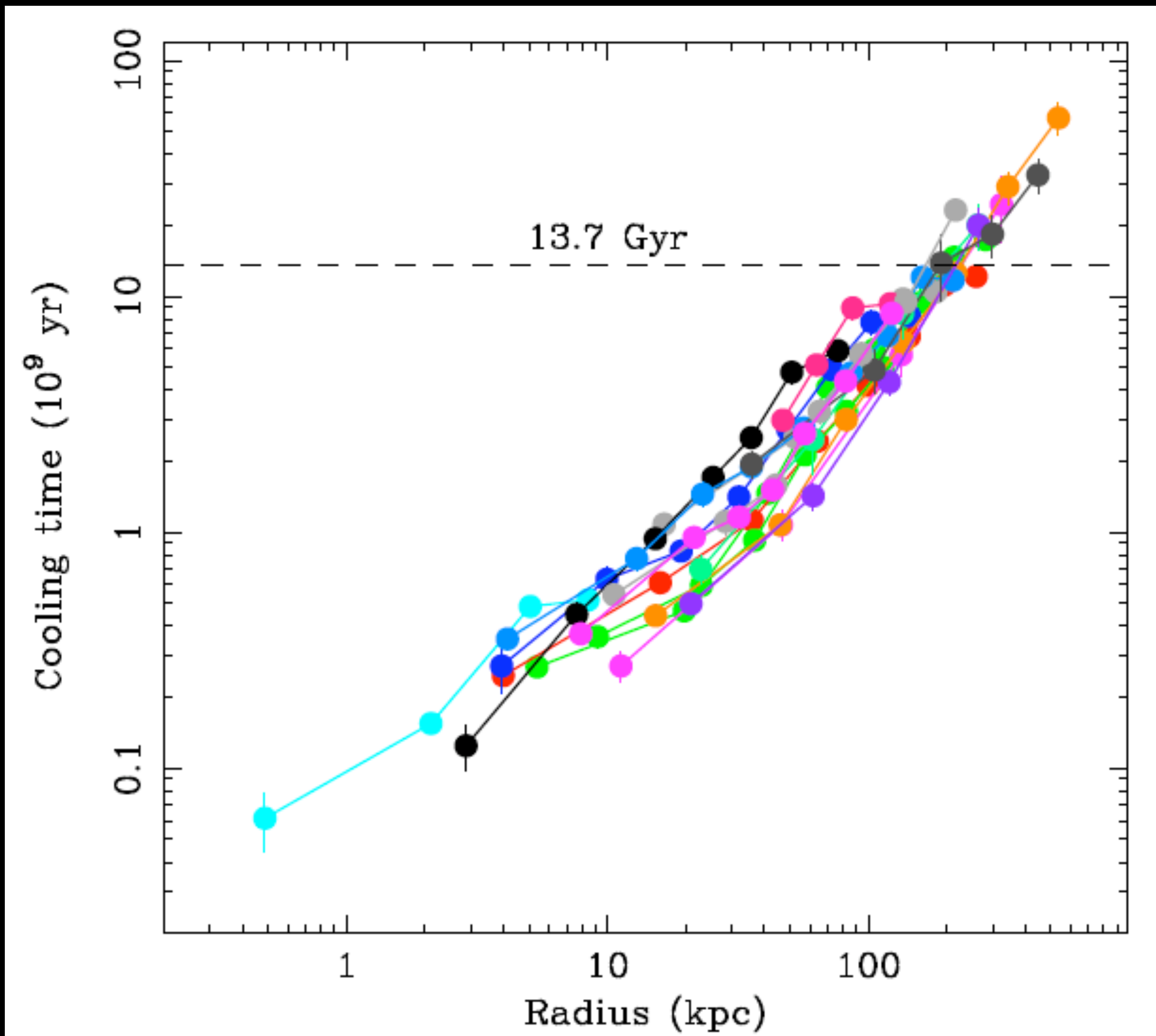
Three Related Mysteries

Three Related Mysteries

- Cooling Flow Problem
- Large Blue Galaxy Problem
- Cluster Entropy Problem

The Cooling Flow Problem

Central Cooling Time



In many clusters, gas near the center can radiate its thermal energy in << 10^{10} yr

If not reheated, it would cool, condense, and flow inward

Peterson & Fabian (2005)

Mass-Sink Cooling-Flow Problem

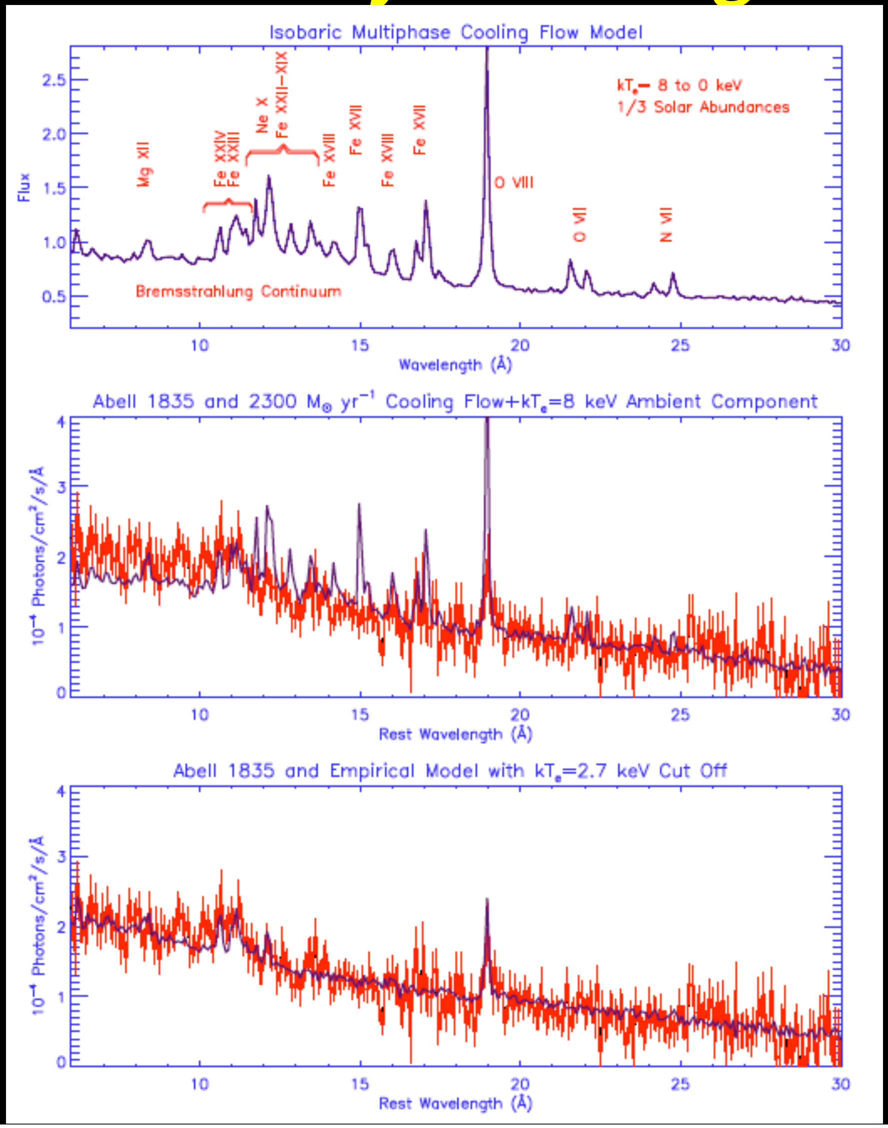
$t_{cool} \sim 10^{10}$ yr @ ~ 100 kpc

$M_{gas}(< 100 \text{ kpc}) \sim 10^{12}\ M_{Sun}$

$\Rightarrow$ $dM/dt \sim 10^{2}\ M_{Sun}\ yr^{-1}$

… but observed star-formation rate is generally <10% of implied cooling rate and there is no evidence for $10^{12}\ M_{Sun}$ of cooled gas

Soft X-ray Cooling-Flow Problem

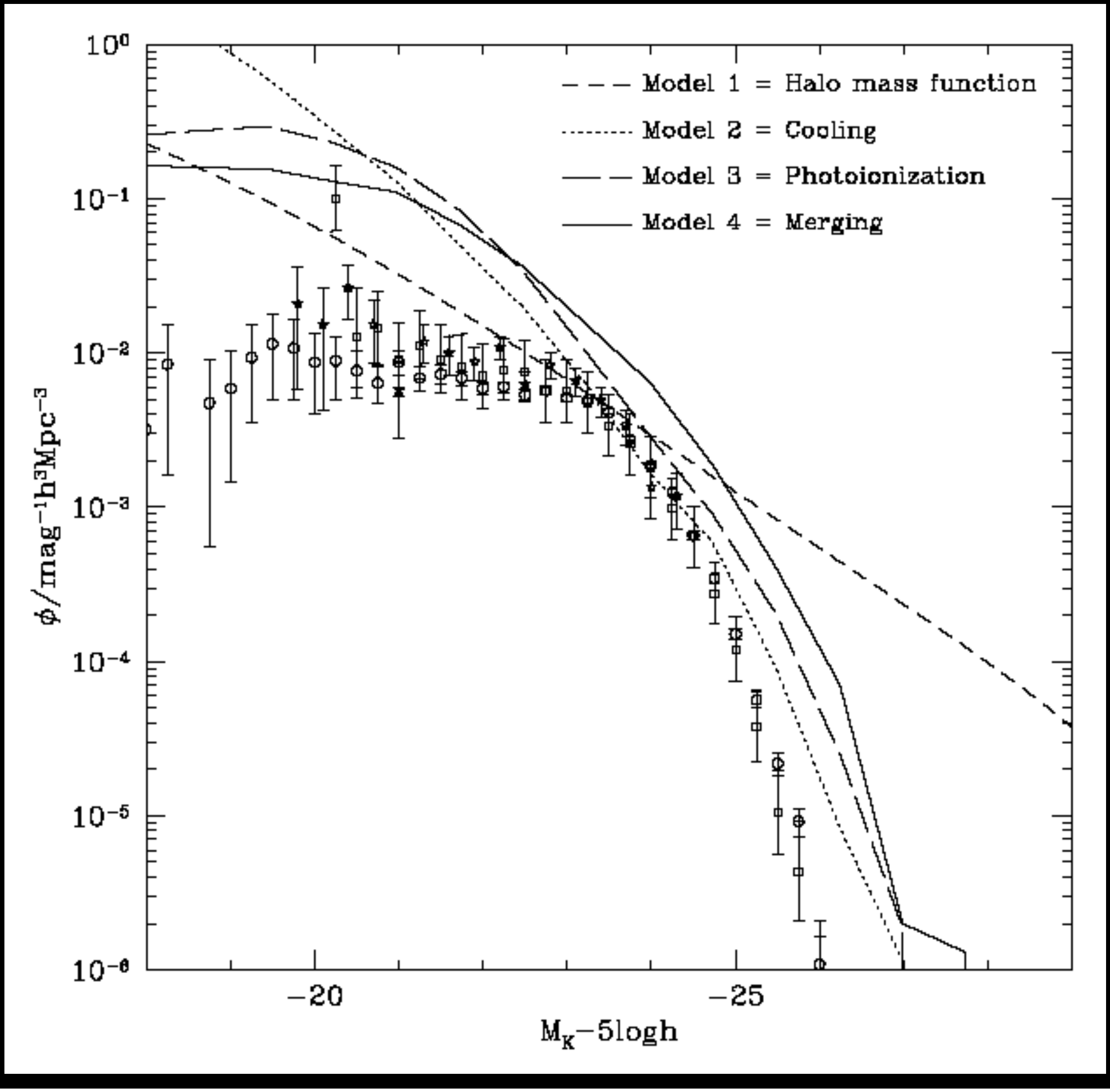


X-ray spectra show little evidence for gas cooling below 1/3 of mean cluster temperature

Peterson & Fabian (2005)

The Large Blue Galaxy Problem

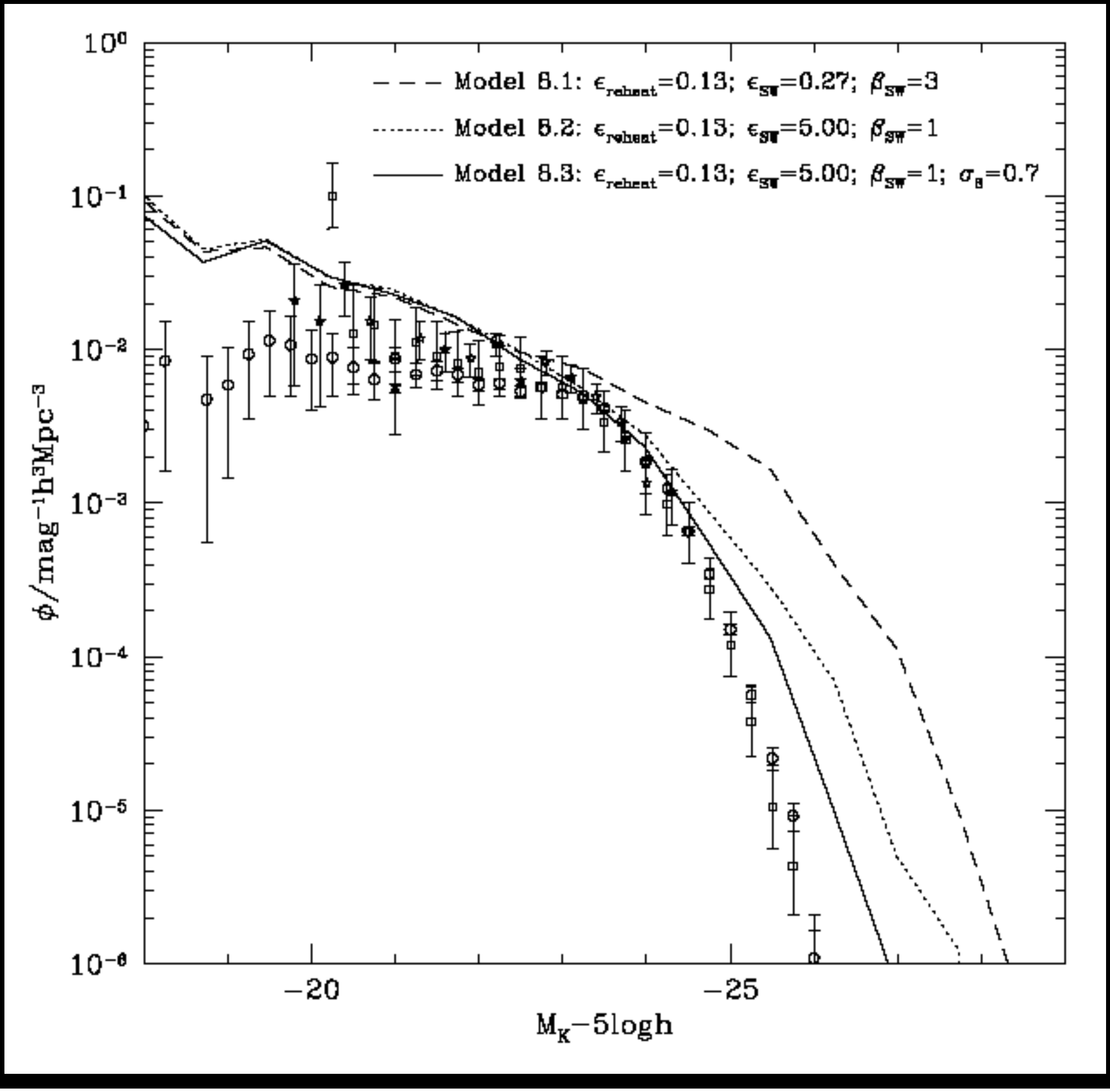
Semi-Analytic Luminosity Function



Bright end of the galaxy luminosity function cuts off much more sharply than the halo mass function

Benson et al. (2003)

Semi-Analytic Luminosity Function

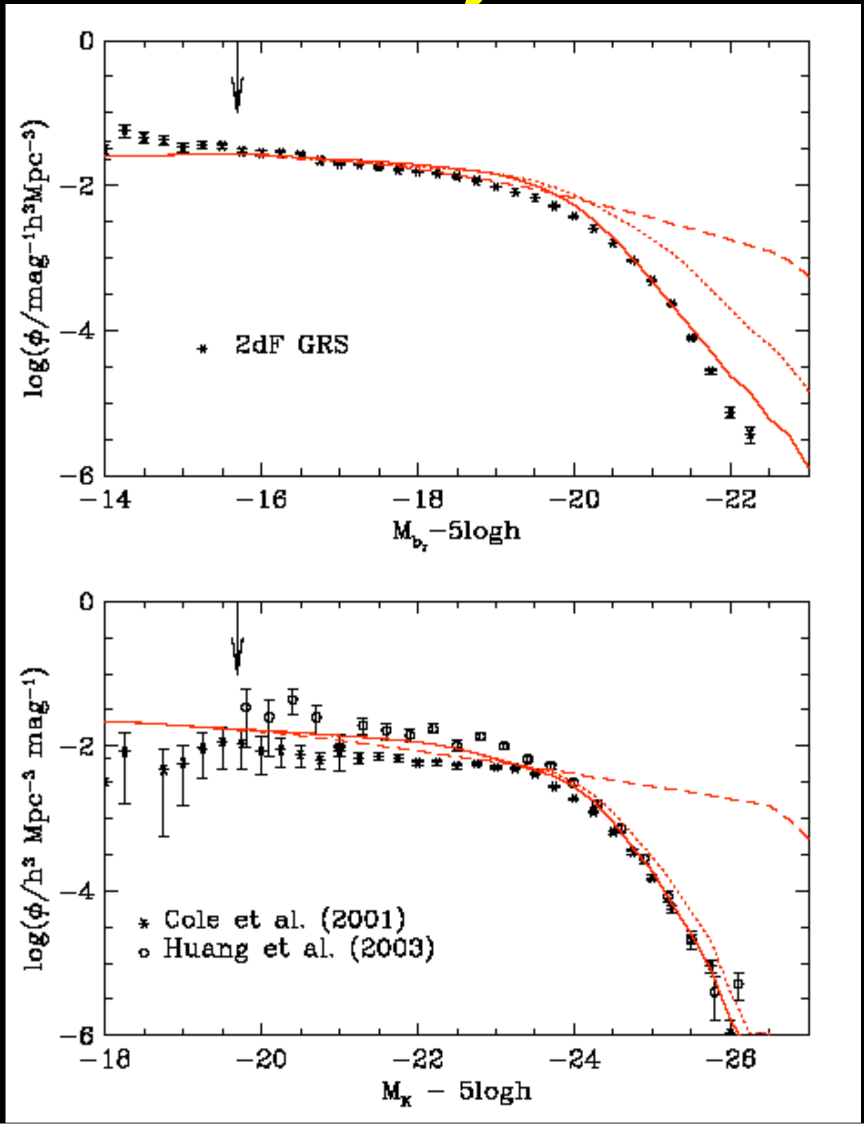


Even models with extreme SN-driven winds cannot reproduce the luminosity function

SN feedback at late times implies blue color

Benson et al. (2003)

Semi-Analytics with Black Holes



Implementation of AGN feedback in semi-analytic models can reproduce high-L cutoff and red colors

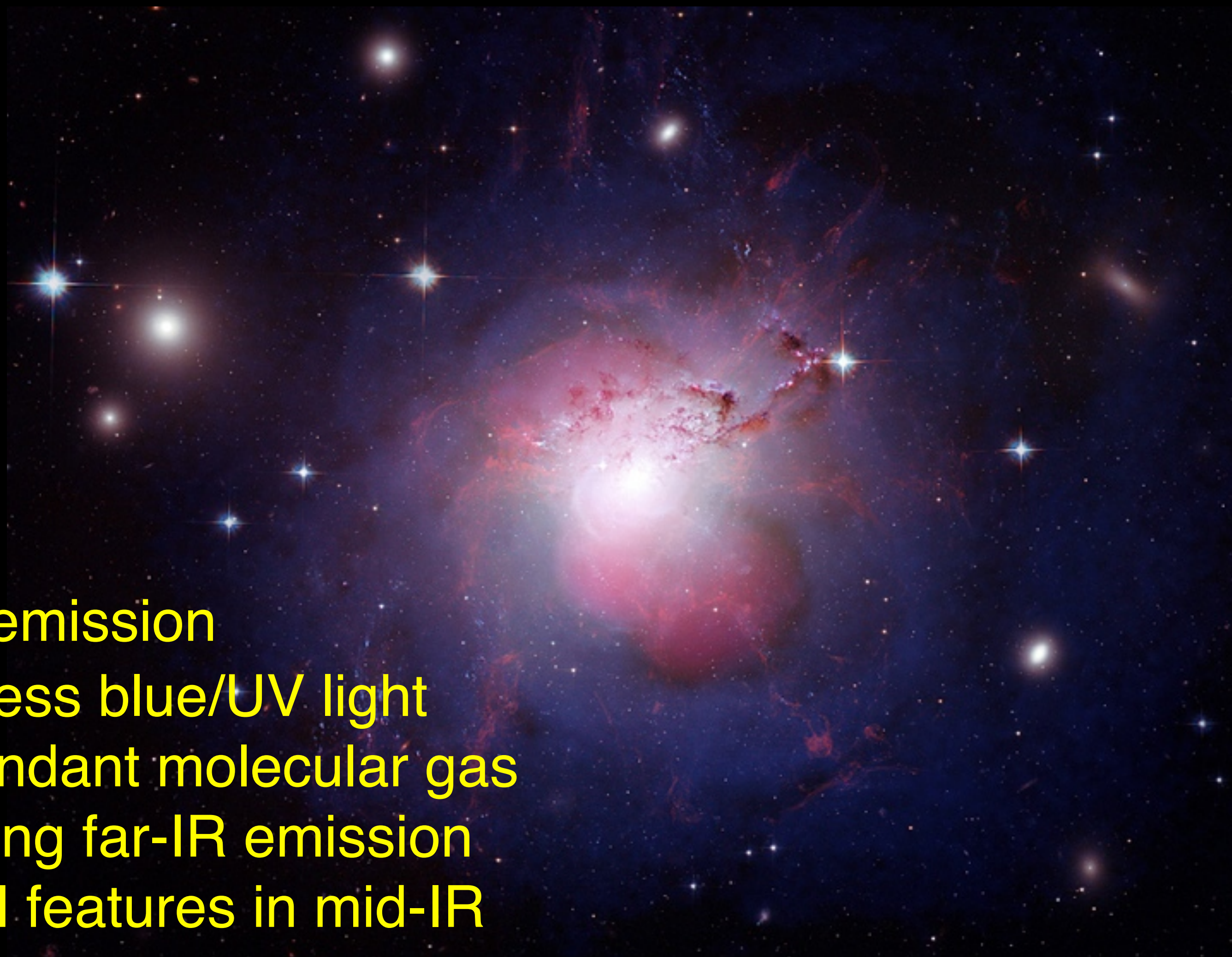
Croton et al. (2006)

Bower et al. (2006)

Star Formation in Large Galaxies

NGC 1275: Perseus Cluster

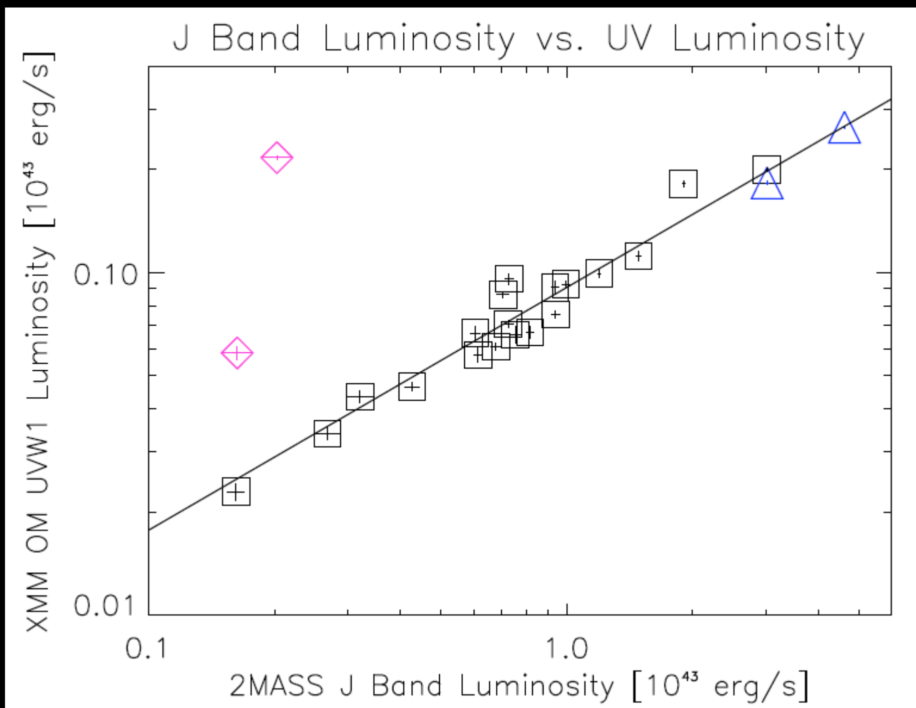
Star Formation in Large Galaxies



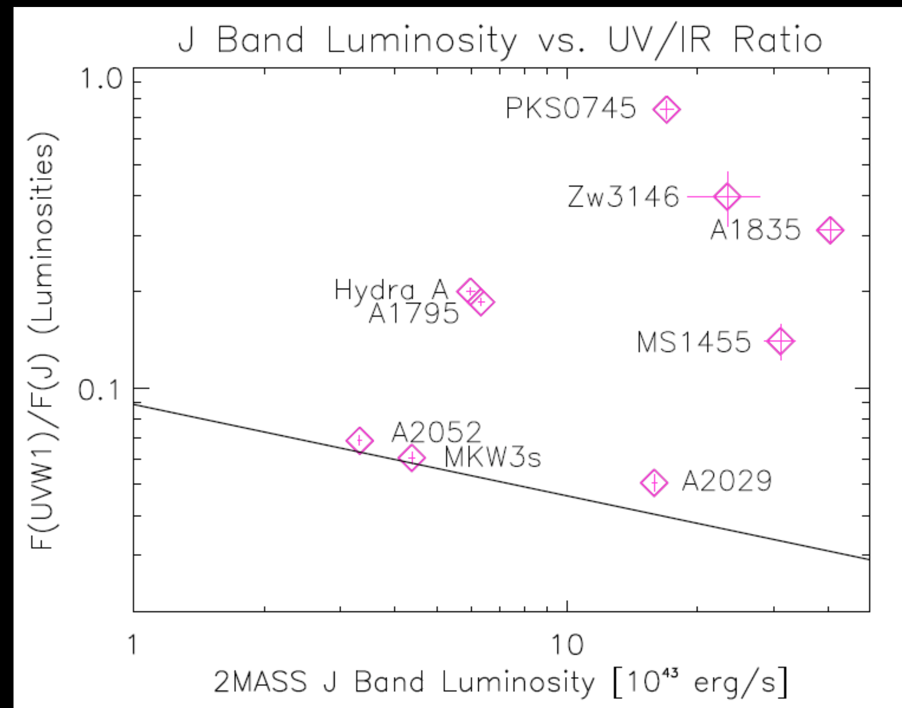
- Hα emission
- Excess blue/UV light
- Abundant molecular gas
- Strong far-IR emission
- PAH features in mid-IR

NGC 1275: Perseus Cluster

Star Formation in Large Galaxies



Passively Evolving Galaxies

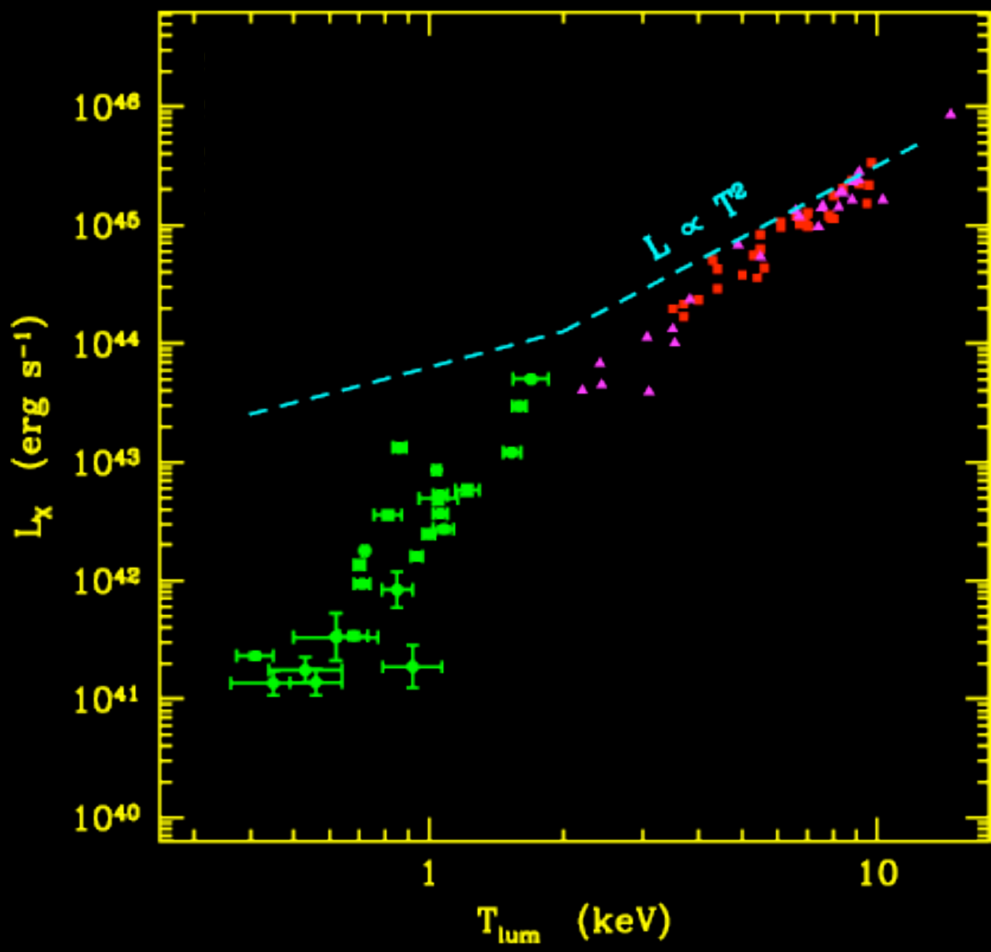


"Cooling Flow" Galaxies

Hicks & Mushotsky (2005)

The Cluster Entropy Problem

Luminosity-Temperature Relation

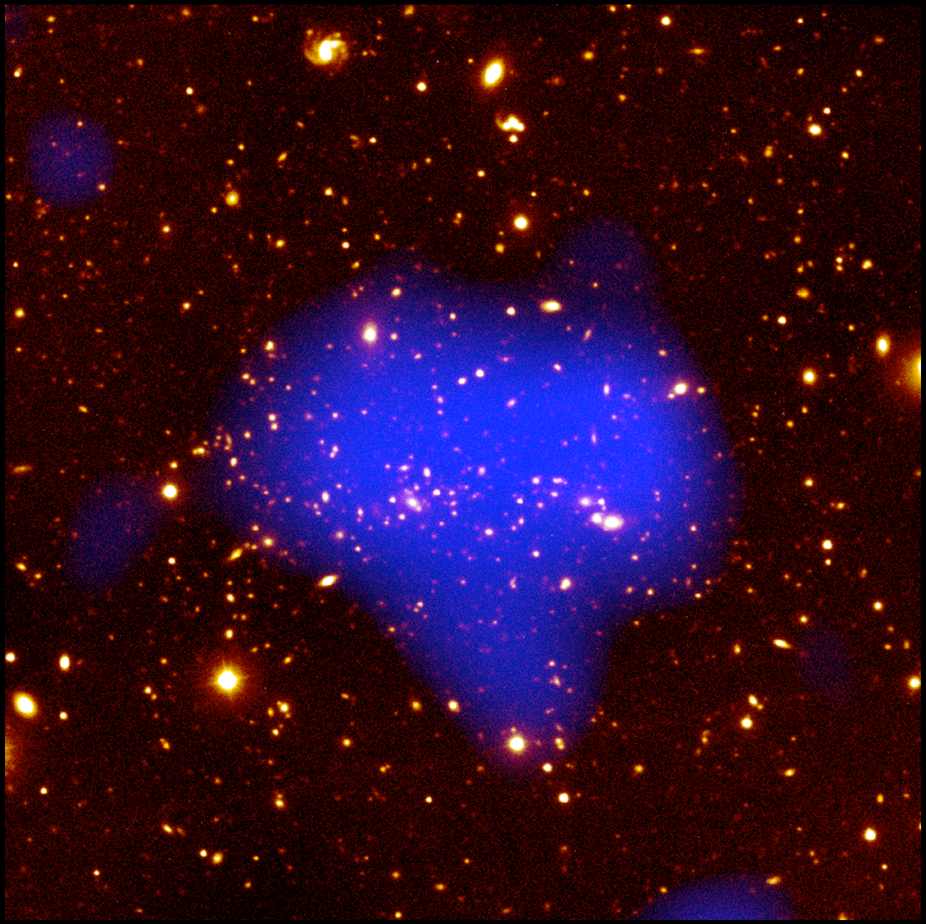


Gravitational structure formation leads us to expect $L \propto T^2$

Observations disagree, but why?

Preheating by supernovae & AGNs?

Energetics of the ICM



MS 1054-0321 / Donahue et al. (1998)

kT $\approx$ 10 keV

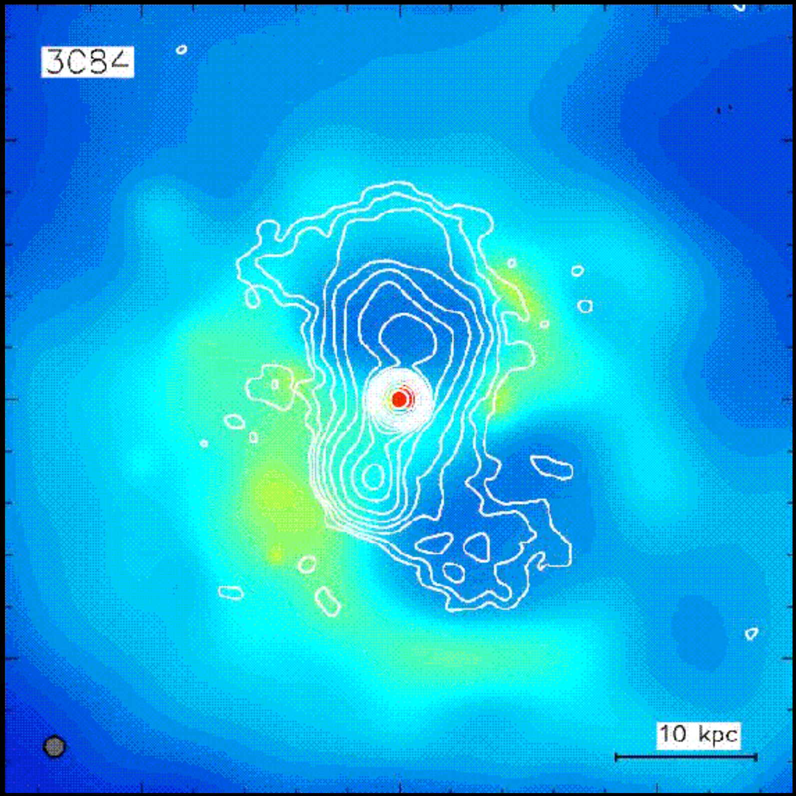
Fe/H $\approx$ 0.3 solar

z = 0.83

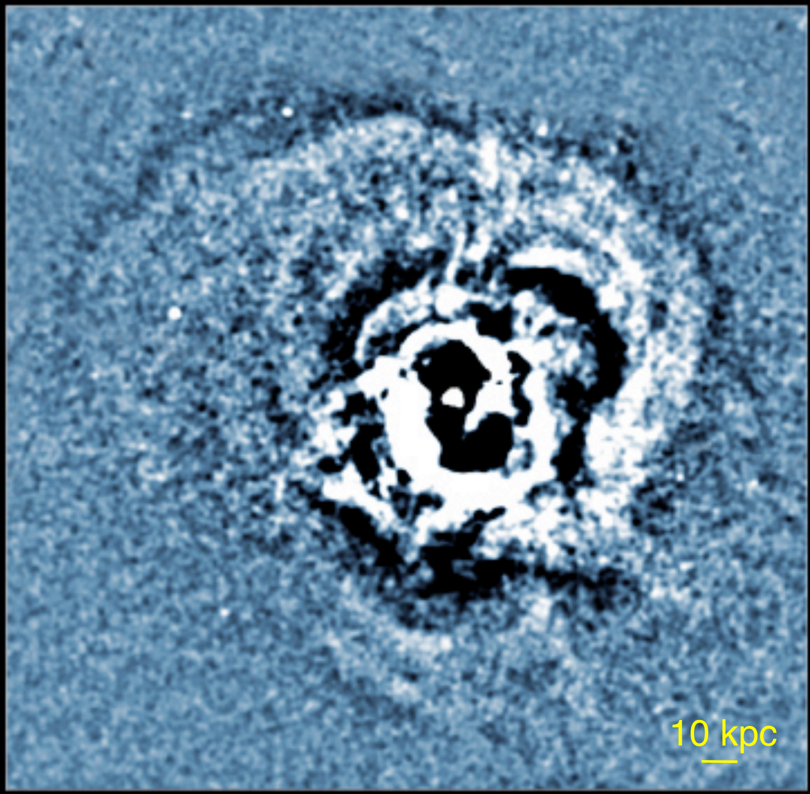
$E_{SN} \approx$ 1 keV/particle

$E_{AGN} \approx$? keV/particle

AGN Feedback

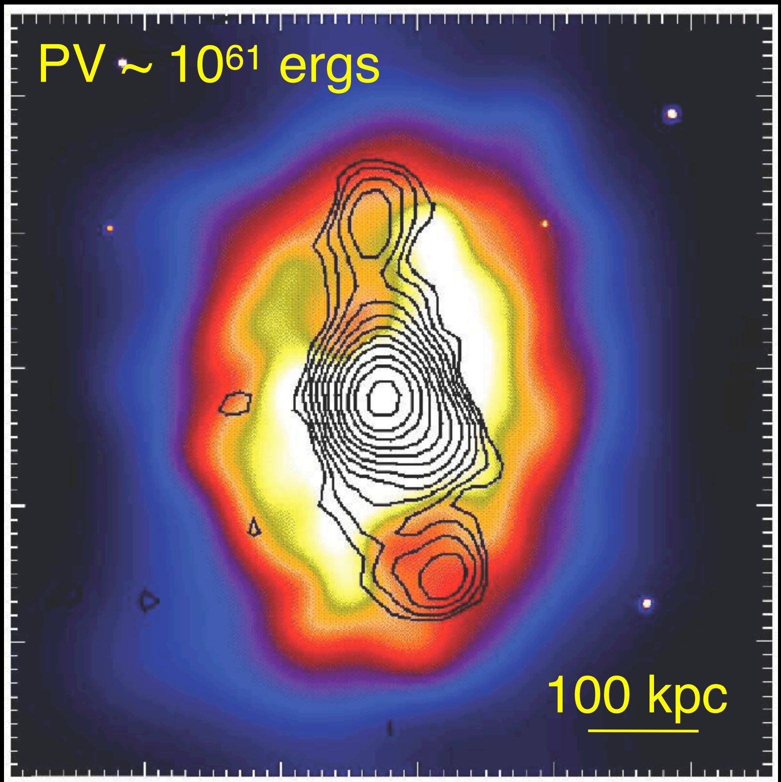


Perseus Cluster & 3C 84

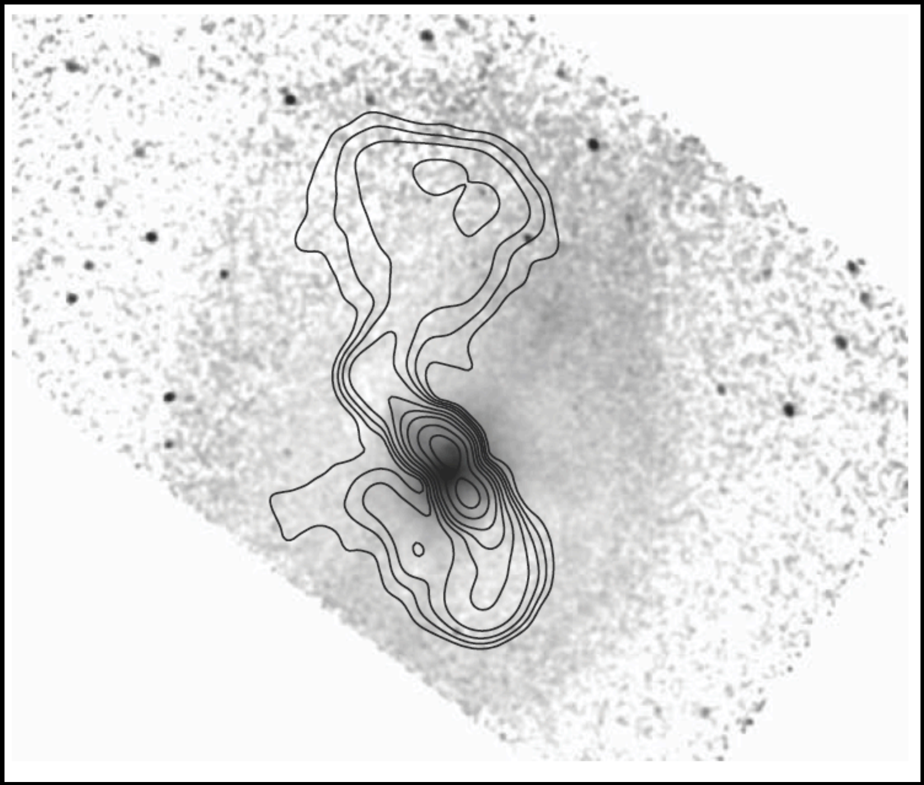


Sound Waves in Perseus

Dramatic Heating Events



MS0735 (McNamara et al.)



Hydra A (Nulsen et al.)

Why entropy?

Entropy: A Review

Definition of S: $\Delta S = \Delta(\text{heat}) / T$

Equation of state: $P = K\rho^{5/3}$

Relationship to S: $S = N \ln K^{3/2} + \text{const.}$

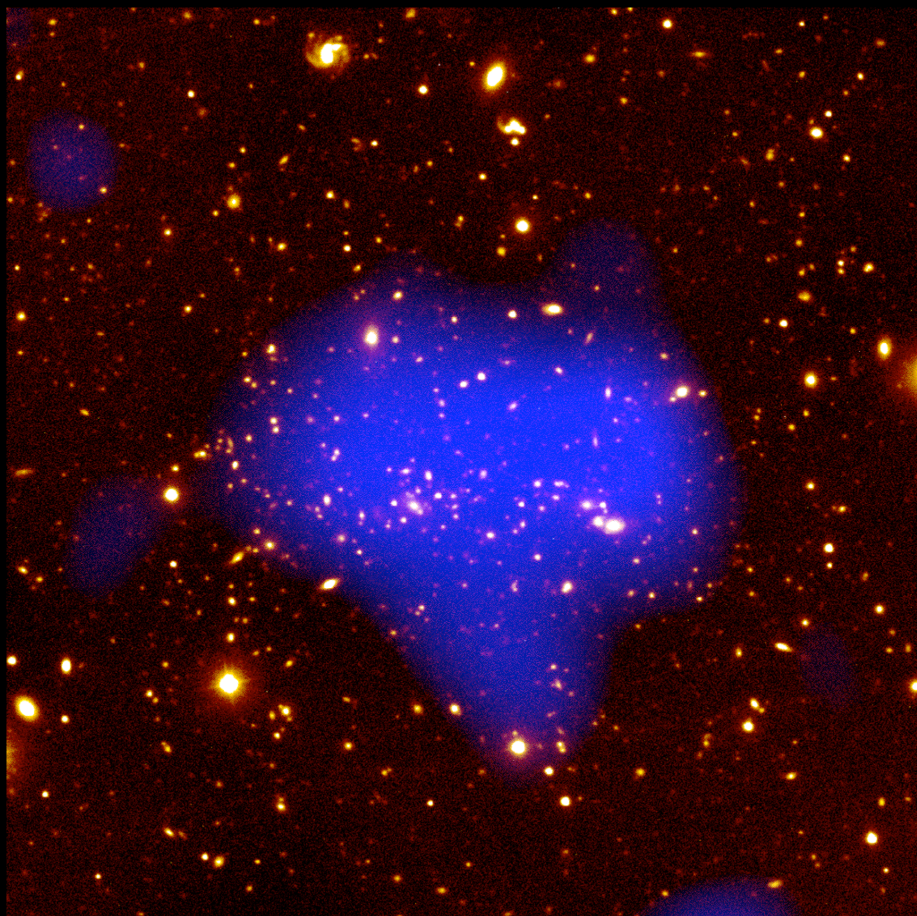
Convective Stability: $dS/dr \geq 0$

Useful Observable: $Tn_e^{-2/3} \propto K$

Only heat loss can reduce $Tn_e^{-2/3}$

Only heat input can raise $Tn_e^{-2/3}$

Fundamentals of Cluster Structure

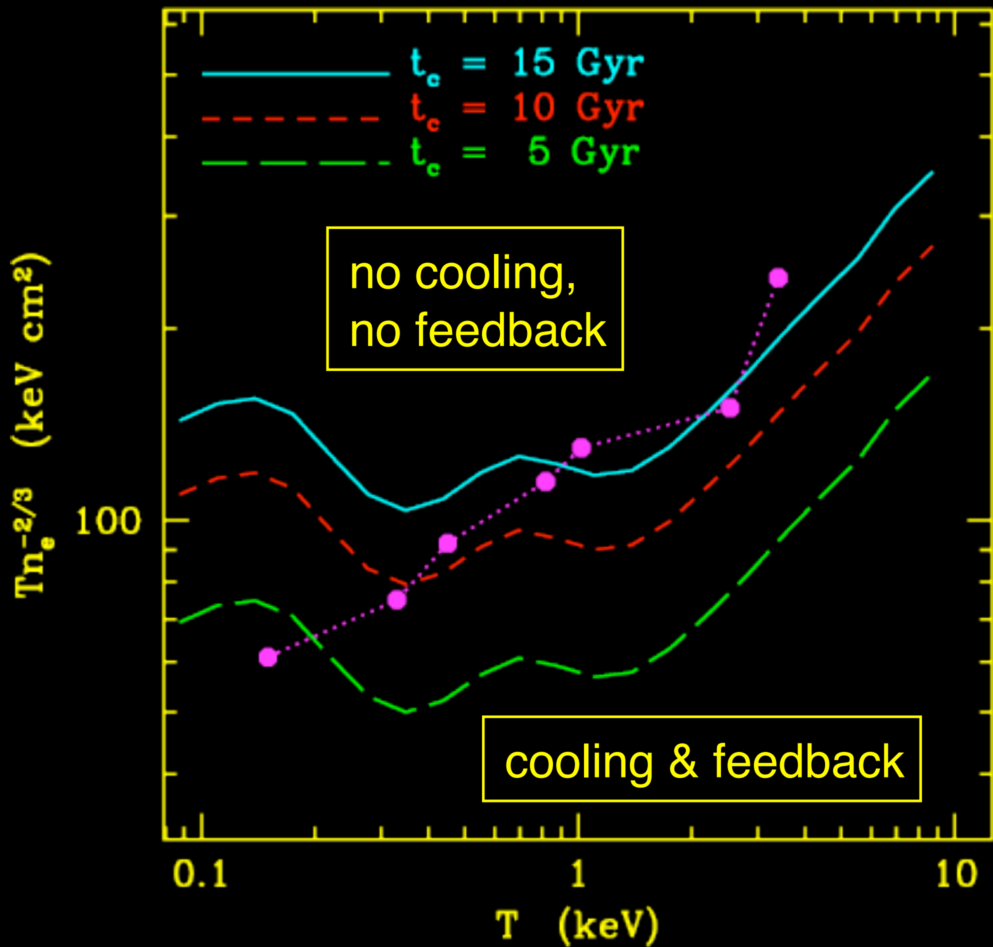


MS 1054-0321 / Donahue et al. (1998)

Properties of relaxed cluster determined by:

- shape of halo
- entropy distribution of intracluster gas

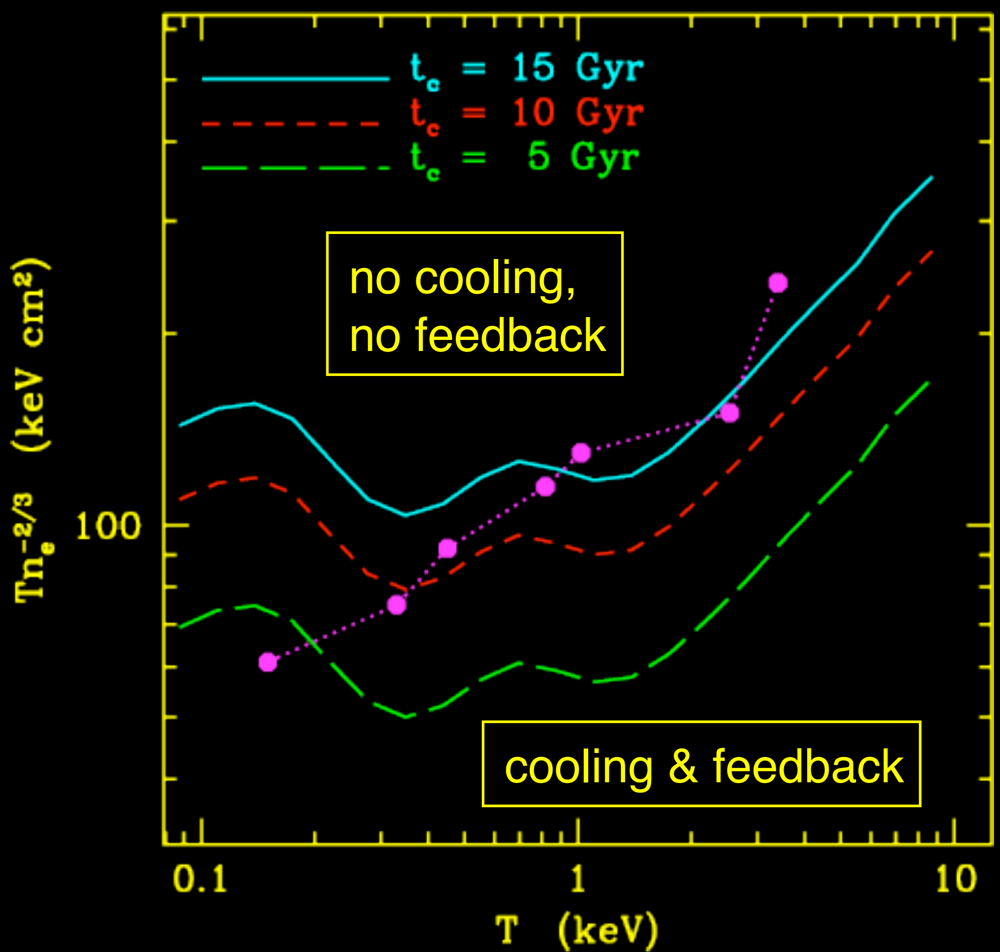
Entropy History of a Gas Blob



Gas that remains above threshold does not cool and condense.

Gas that falls below threshold is subject to cooling and feedback.

Entropy History of a Gas Blob

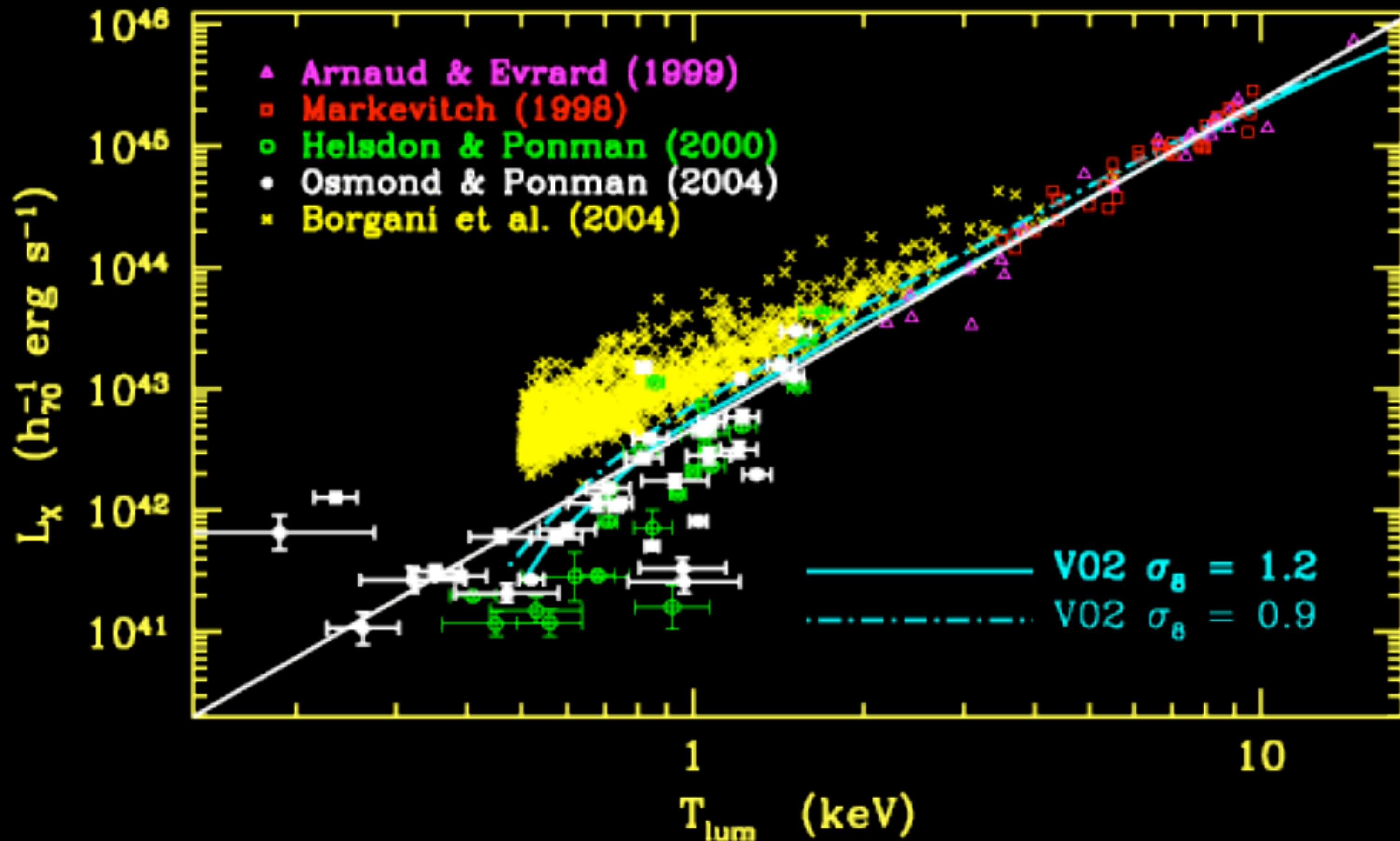


Cooling & feedback have greater impact on groups.

L-*T* relation insensitive to feedback.

Need to know condensed baryon fraction

L-T Relation with Cooling & Feedback



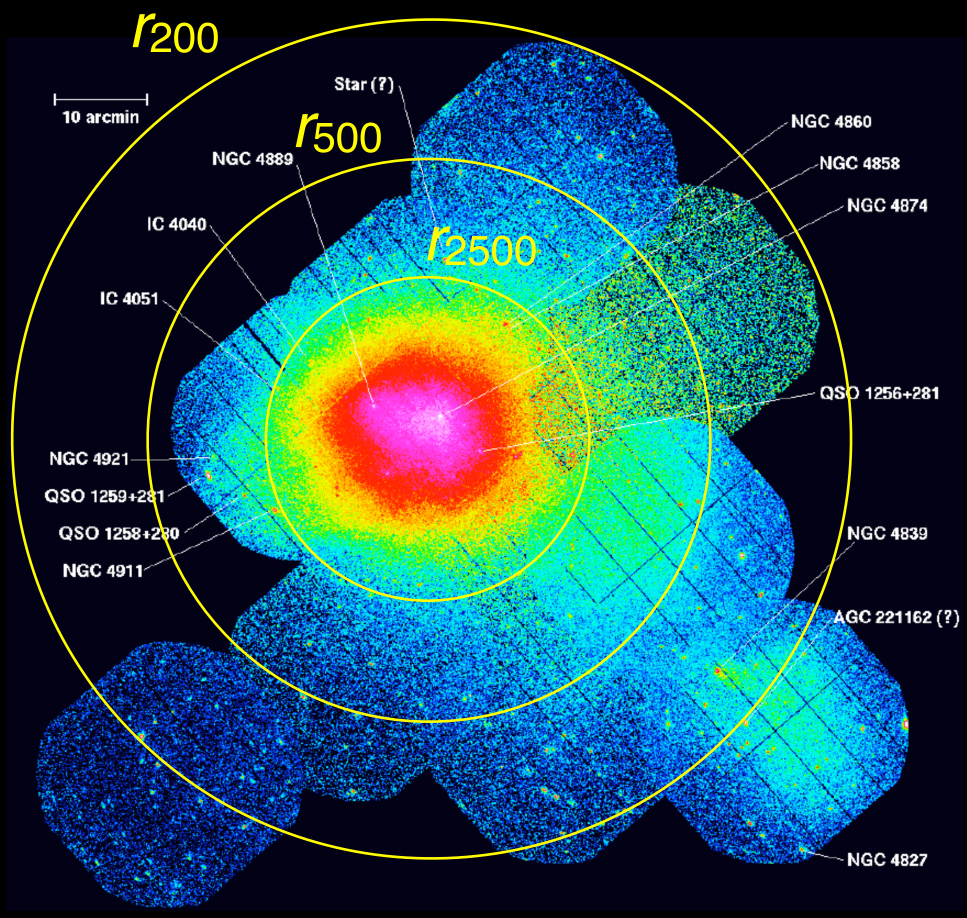
Simulations (yellow) that include cooling and supernova feedback in better agreement with data at $T > 2$ keV

Status of Mysteries

- Cooling Flow Problem
  - Quasi-steady heat source needed
- Large Blue Galaxy Problem
  - SN feedback insufficient
  - AGN feedback a potential solution
- Cluster Entropy Problem
  - Condensed baryon fraction uncertain
  - AGN heating poorly understood

Chandra Core Entropy Survey

Defining Mass & Radius

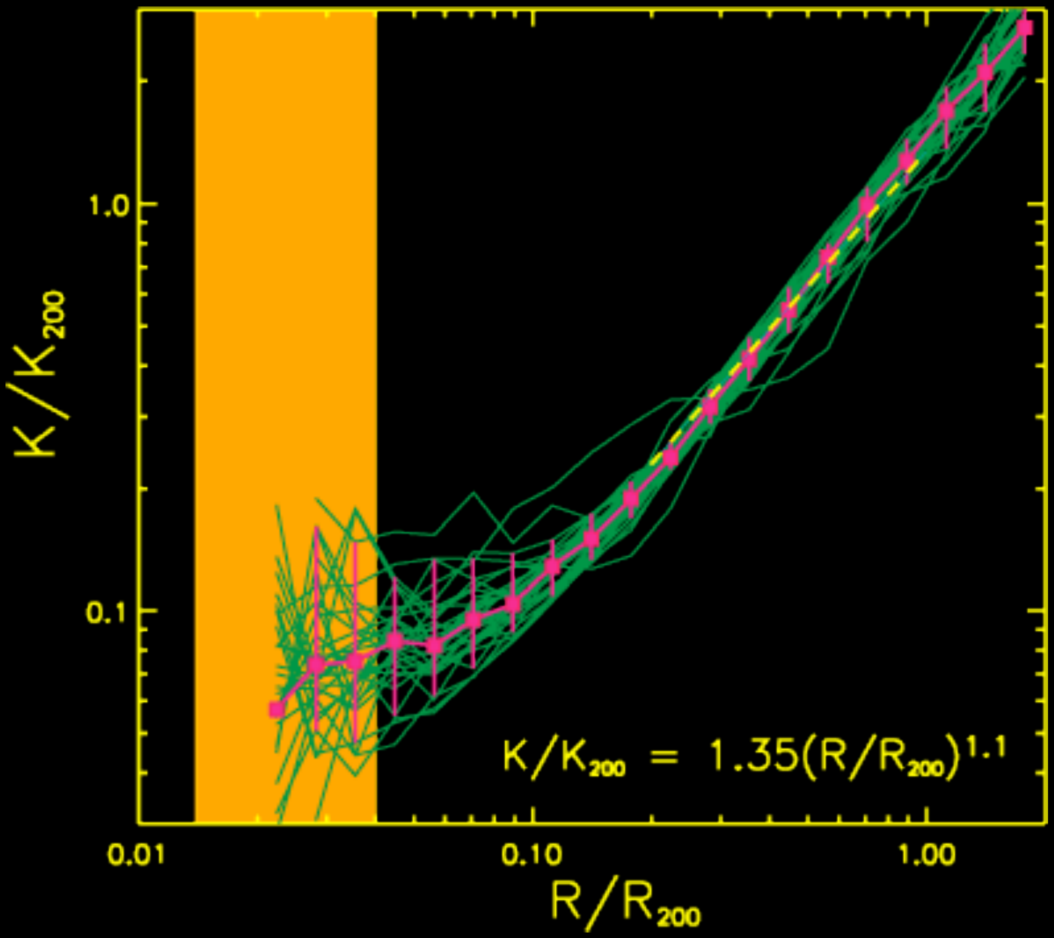


Cluster masses and radii are defined with respect to critical or background density

$$M_\Delta = \frac{4\pi}{3}\, r_\Delta{}^3 \;\; \Delta\, \rho_{cr}$$

Cluster core is innermost ~10%

Clusters without Feedback



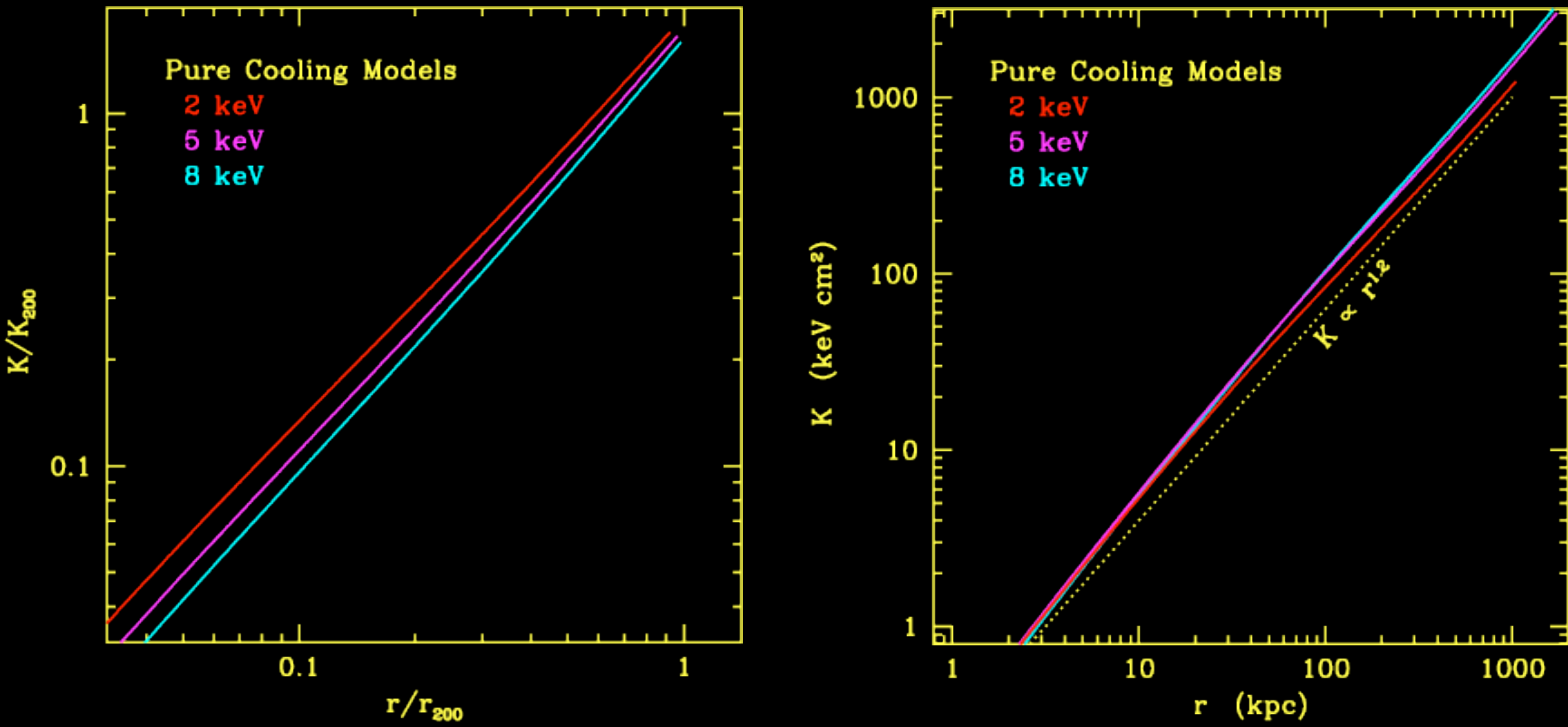
Self-similar entropy profiles in absence of galaxy formation scale with

$$K_{200} = \frac{T_{200}}{(200\ f_b\ \rho_{cr})^{2/3}}$$

Also, $K(r) \sim r^{1.2}$

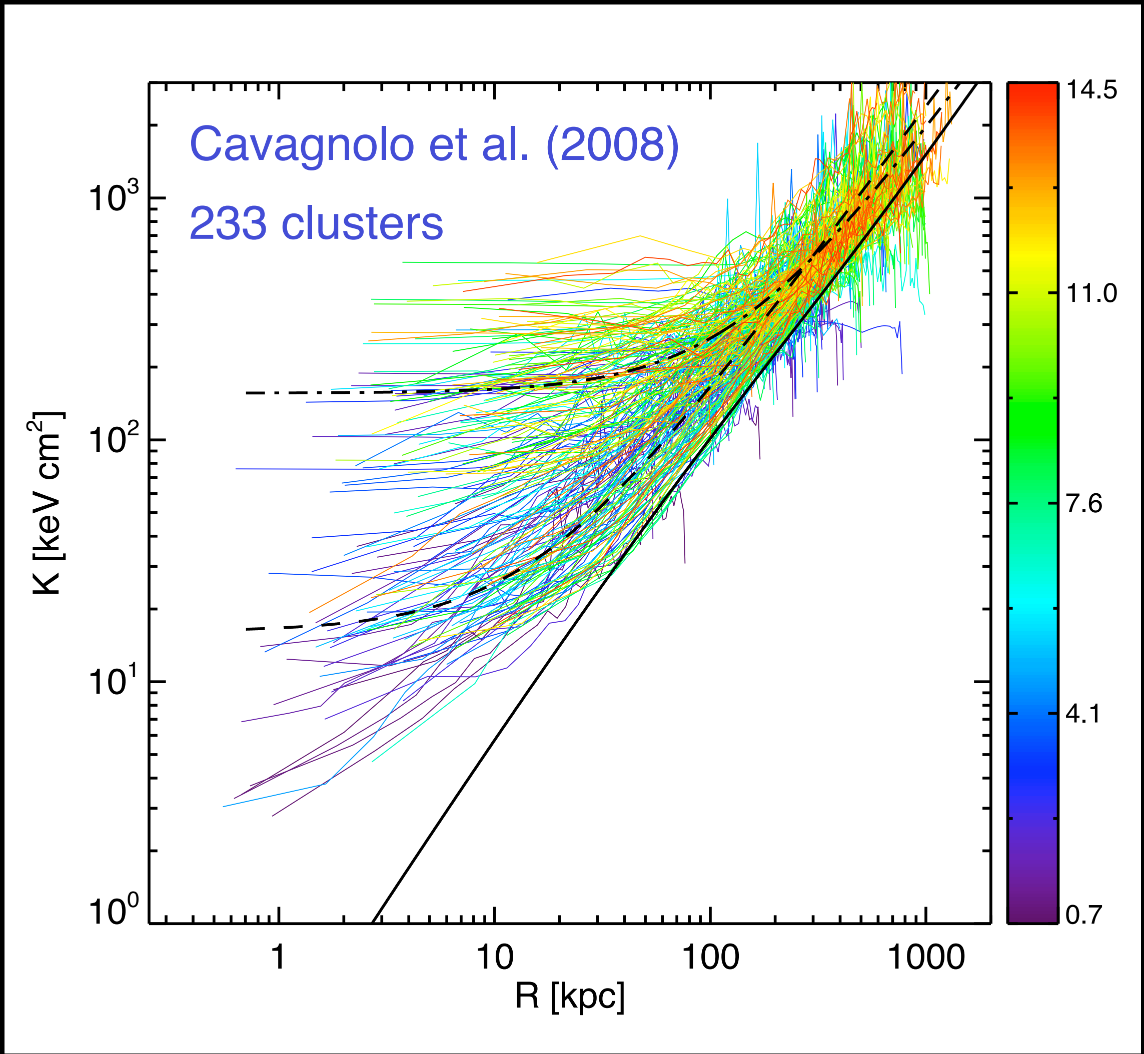
Voit, Kay, & Bryan (2005)

Pure Cooling Model



Allow baseline profile to cool for a Hubble time in an NFW potential, and remove gas at $r = 0$ when $K = 0$.

Chandra Entropy Profiles



Pure cooling model is lower limit to observed profiles

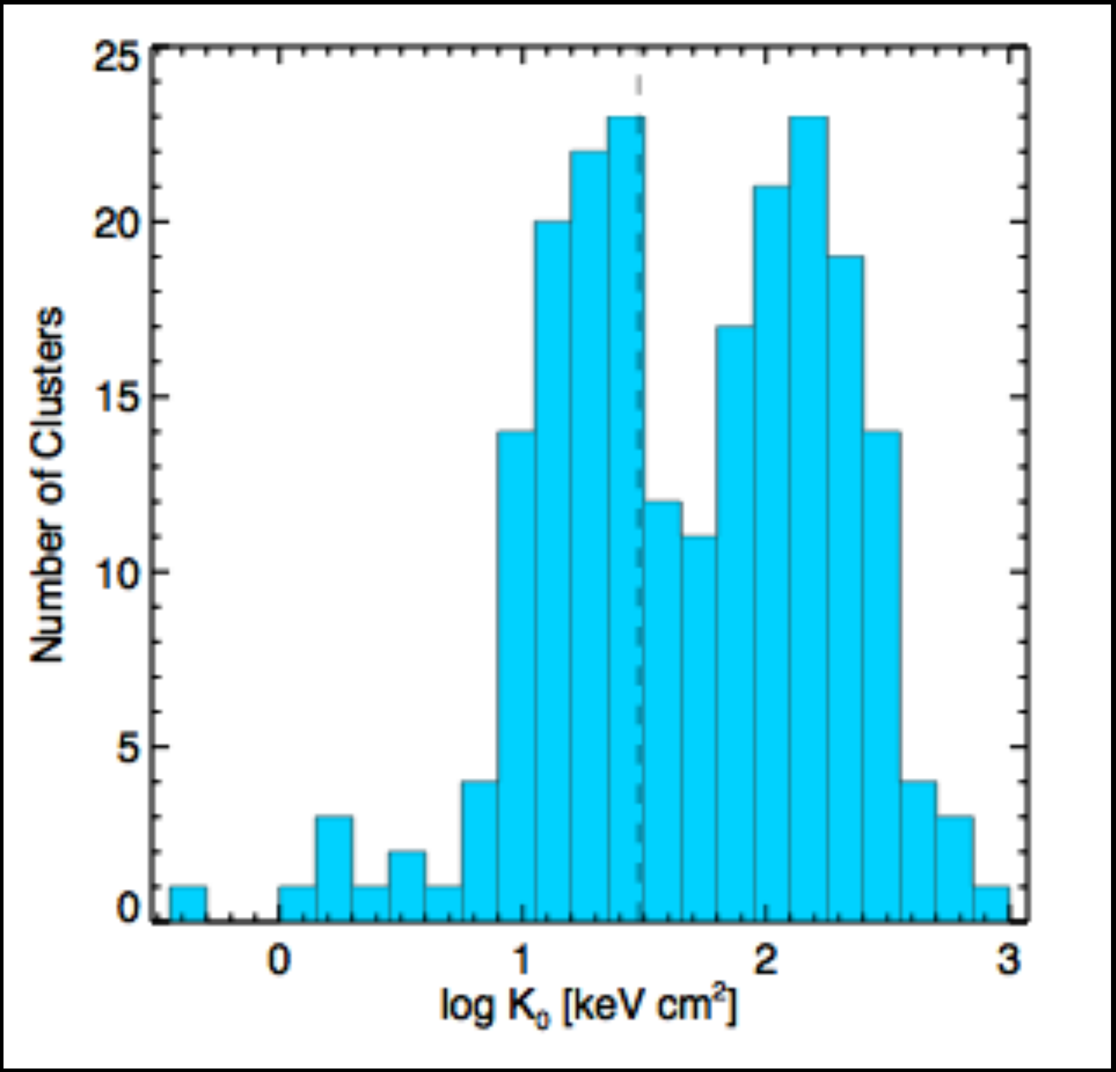
Most profiles are well fit with:

$$K(r) = K_0 + \left(\frac{r}{100\ \mathrm{kpc}}\right)^{\alpha}$$

$K_{100} \sim 150$ keV cm^2

$\alpha \sim 1.2$

Distribution of Core Entropy

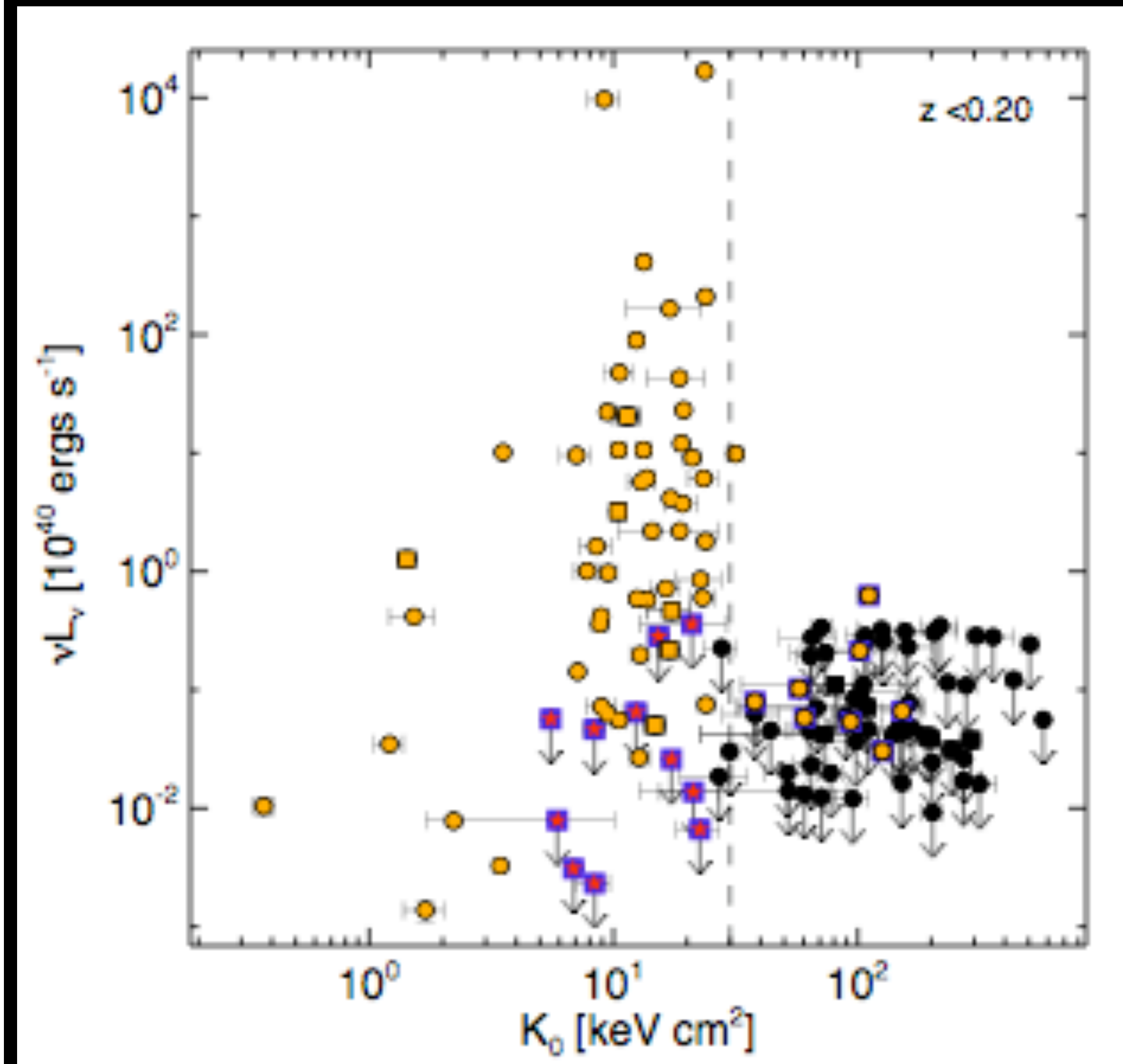


Distribution of K_0 is bimodal with deficit at K_0 ~ 30-50 keV cm^2 corresponding to a cooling time ~ 1 Gyr

Cavagnolo et al. (2008)
See also Hudson & Reiprich

How is core entropy related to feedback signatures?

K_0 and Radio Power



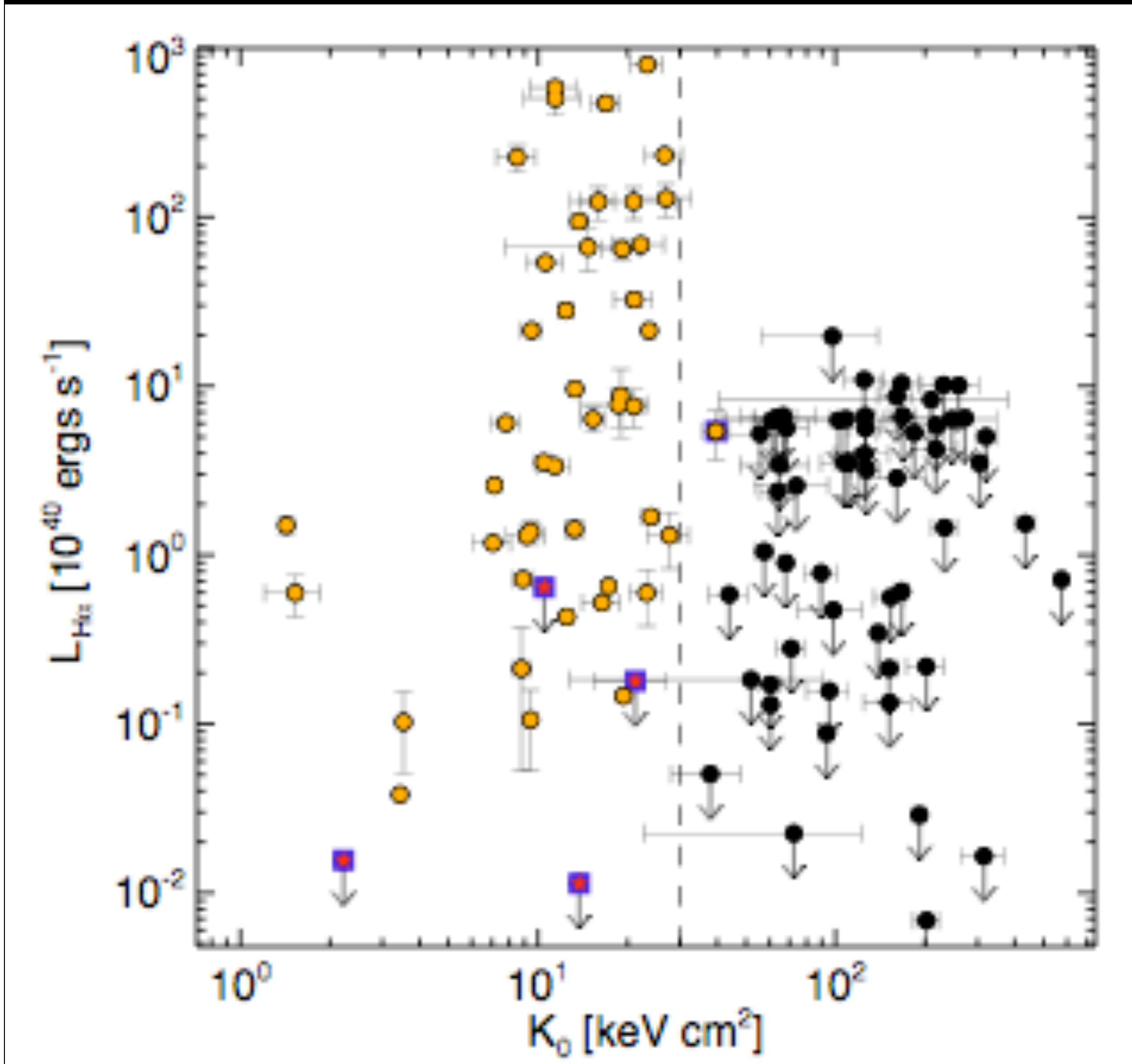
Central galaxy of a $z < 0.2$ cluster can be a strong radio source only if

$K_0 < 30$ keV cm^2

Radio data from NVSS+SUMMS within 20” of X-ray peak

Cavagnolo et al. (2008)

K_0 and Hα Emission



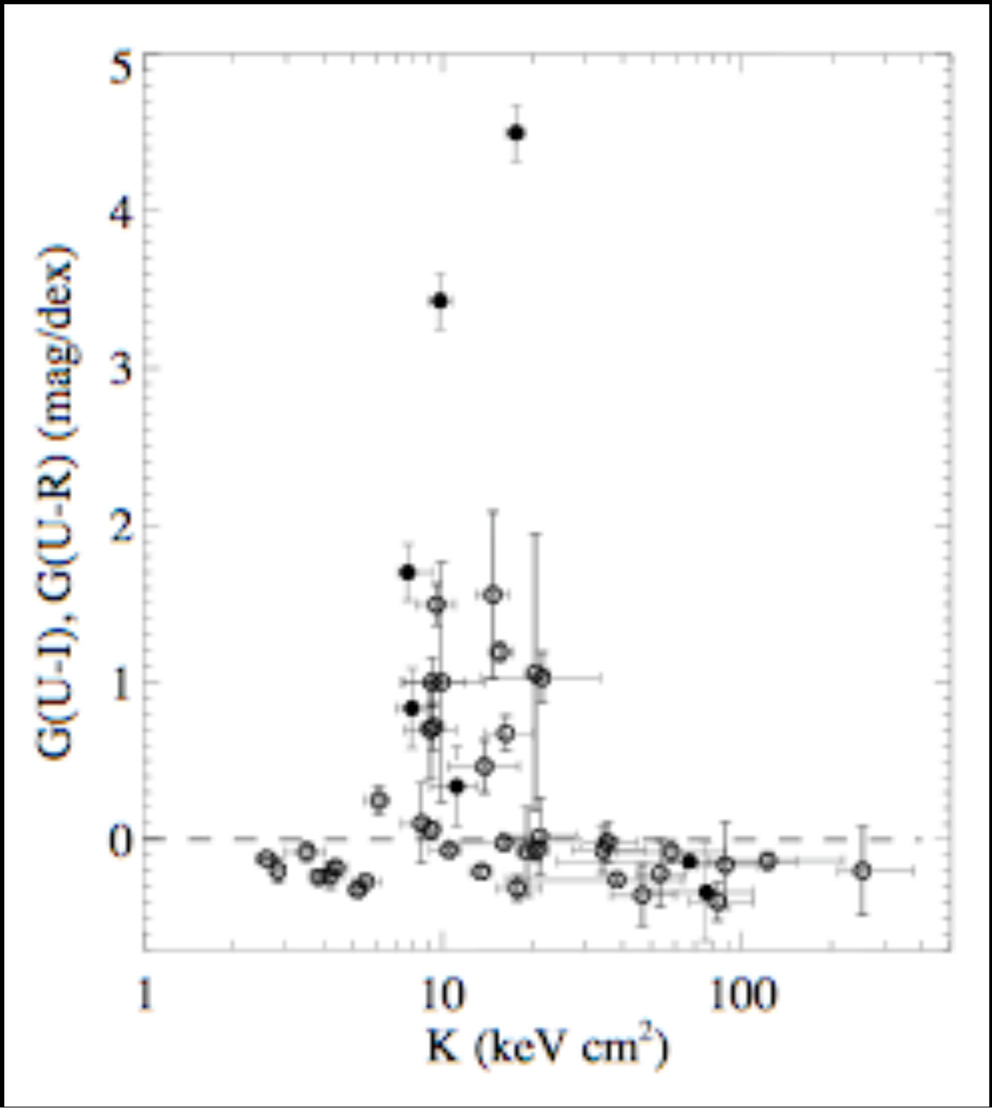
Central galaxy can have emission-line nebulosity only if

$K_0 < 30$ keV cm^2

Hα data from many diverse sources

Cavagnolo et al. (2008)

K_0 and Central Blue Gradient



Central galaxy can have blue gradient indicating star formation only if

$$K_0 < 30 \text{ keV cm}^2$$

Rafferty et al. (2008)

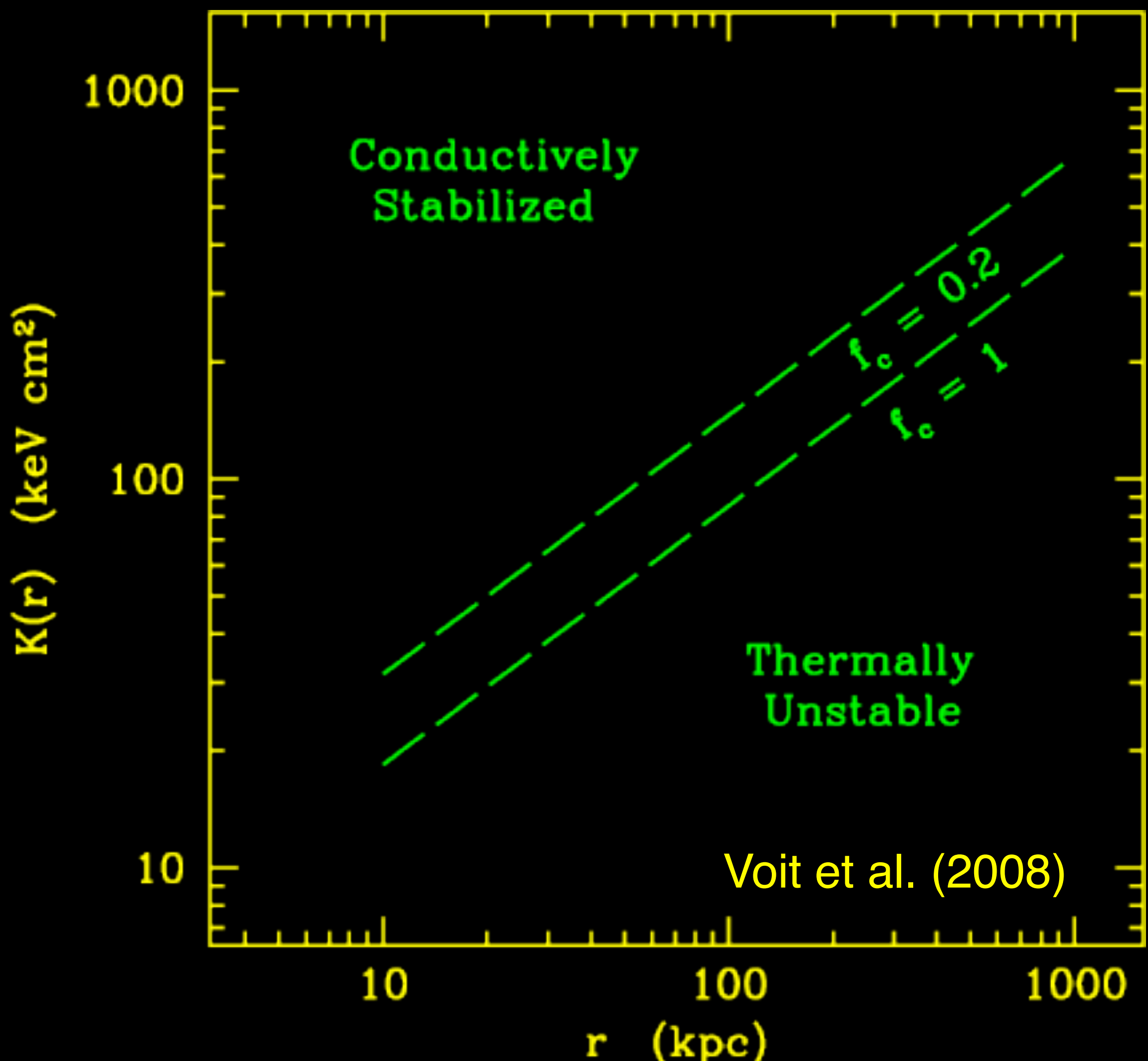
Why is there such a sharp transition in core properties?

Conduction vs. Cooling

$$\lambda_F = \sqrt{\frac{\kappa T}{n_e^2 \Lambda}} \approx 4 \text{ kpc } (K / 10 \text{ keV cm}^2)^{3/2} \ f_c^{1/2}$$

- Field length depends uniquely on *K* for free-free cooling
- Donahue et al. (2005) suggested that this conduction threshold could produce a bifurcation in cluster properties
- See also Guo et al. (2008)

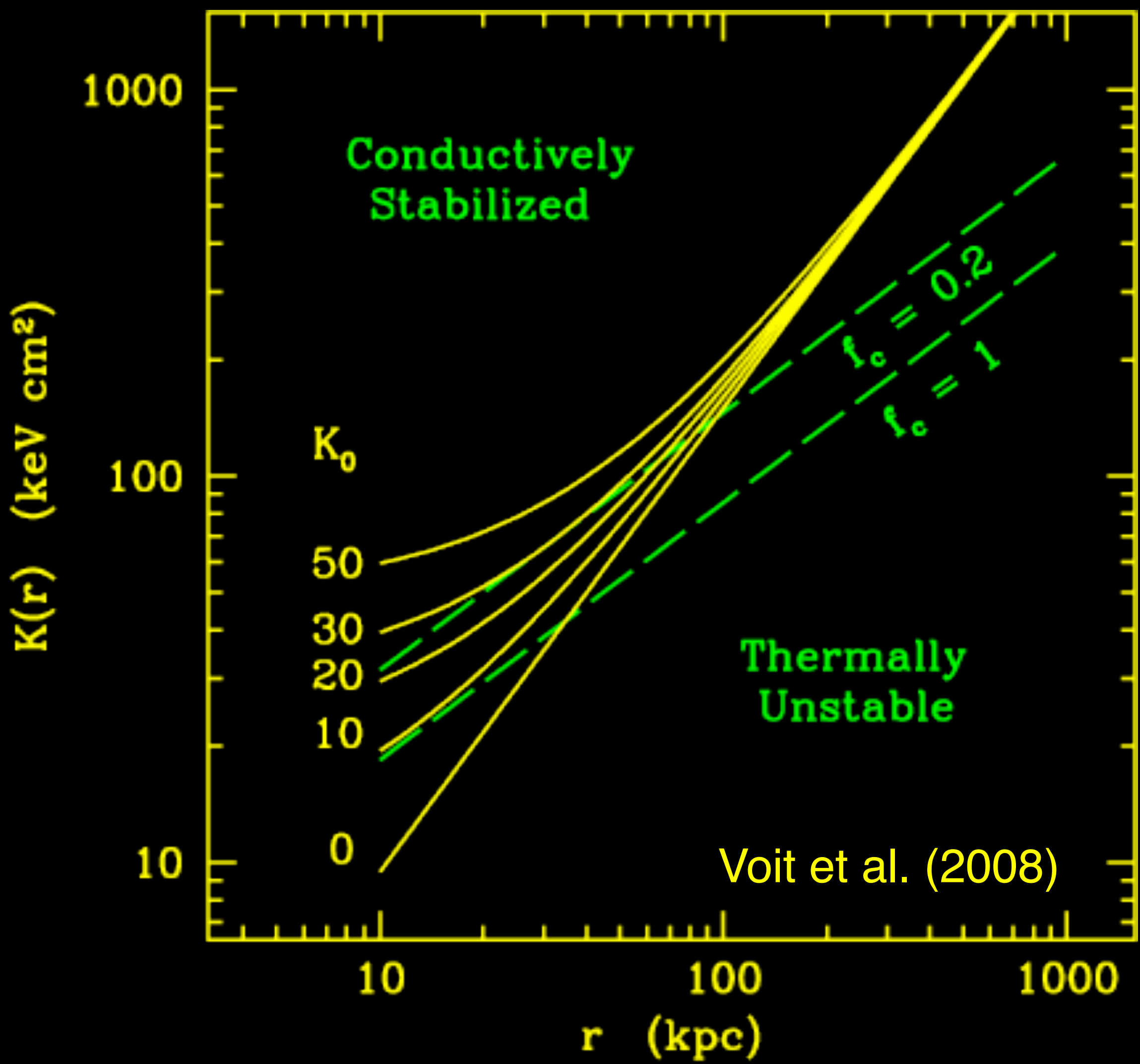
Conductive Stabilization of ICM



High-entropy gas can be stabilized by conduction

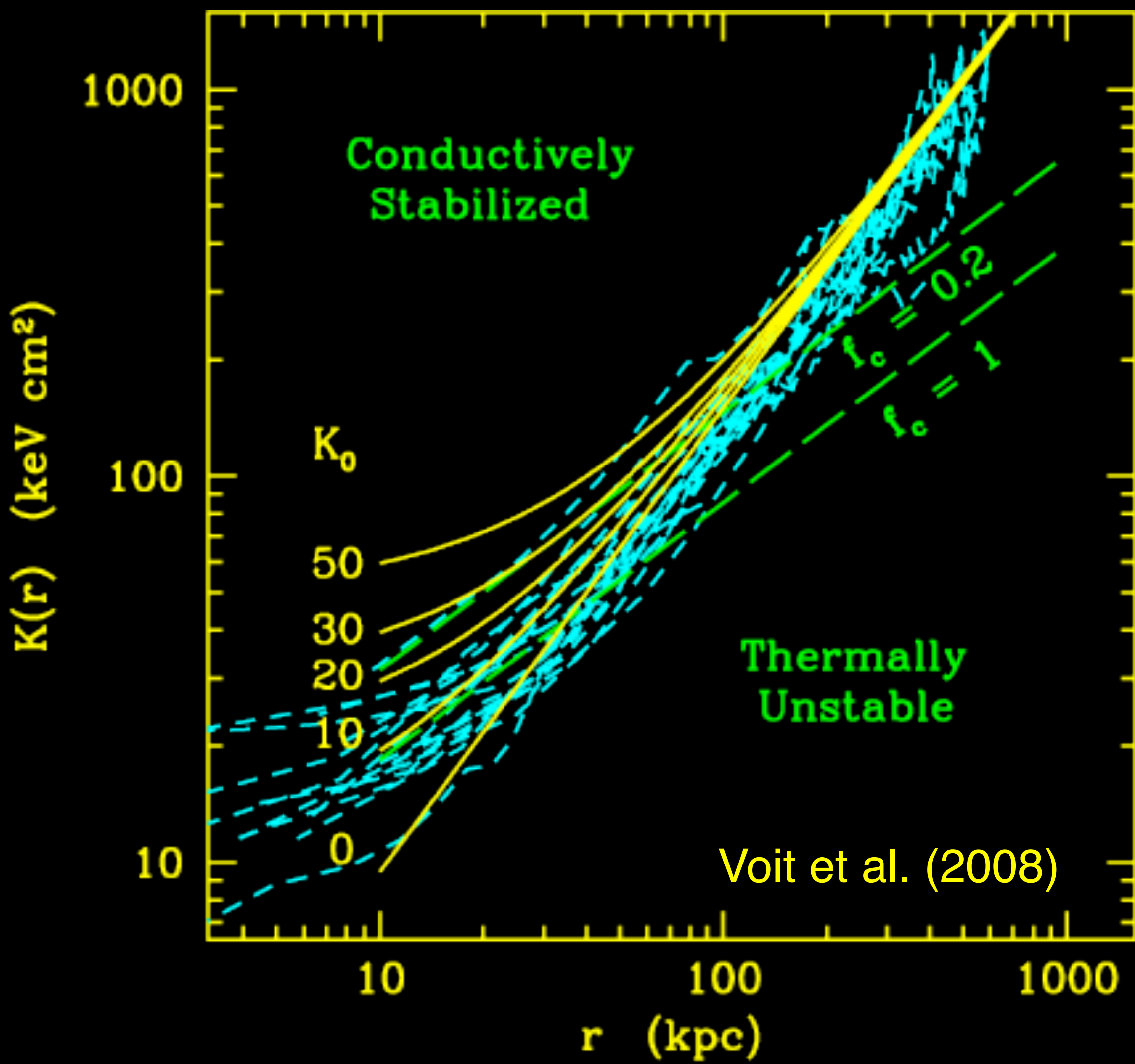
Low-entropy gas is thermally unstable

Conductive Stabilization of ICM



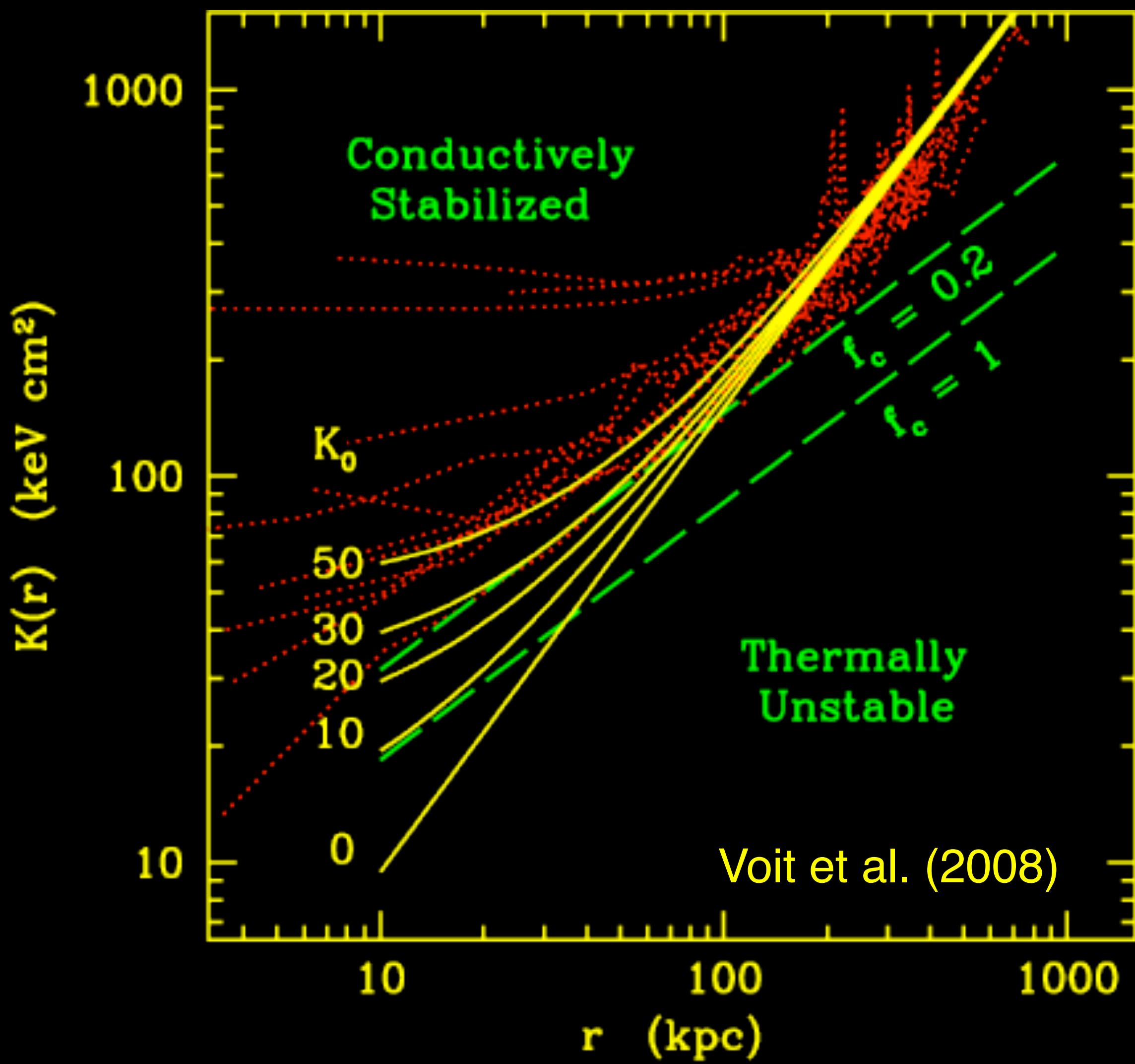
Thermal conduction can stabilize cooling in clusters with $K_0 > 30$ keV cm^2 as long as $f_c \sim 0.2$

Conductive Stabilization of ICM



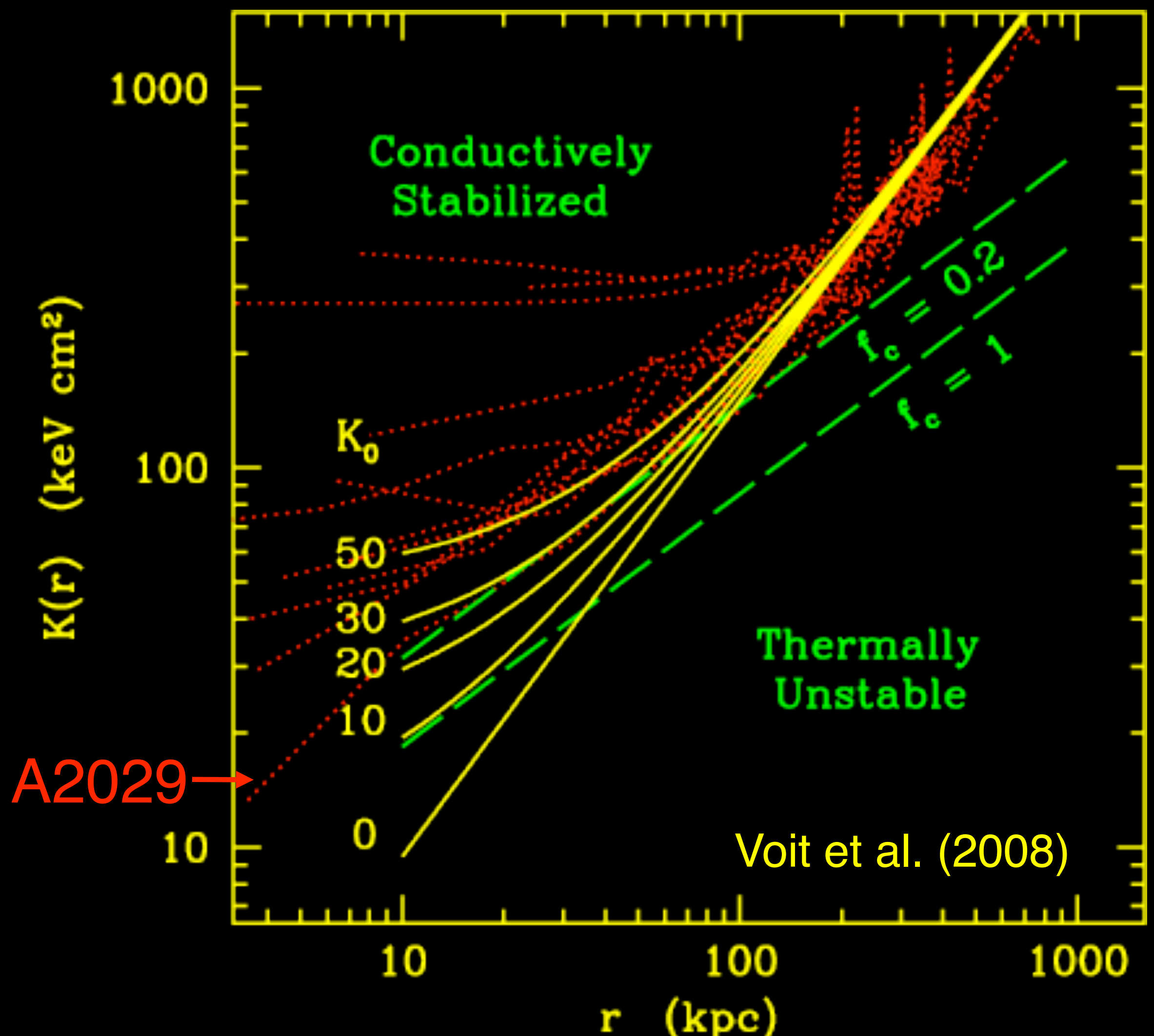
Star forming BCGs from Rafferty et al. (2008) are in clusters with entropy profiles that dip below this stabilization threshold

Conductive Stabilization of ICM



Clusters from Rafferty et al. (2008) that host BCGs without star formation or Hα emission have entropy profiles that remain above the threshold

Conductive Stabilization of ICM



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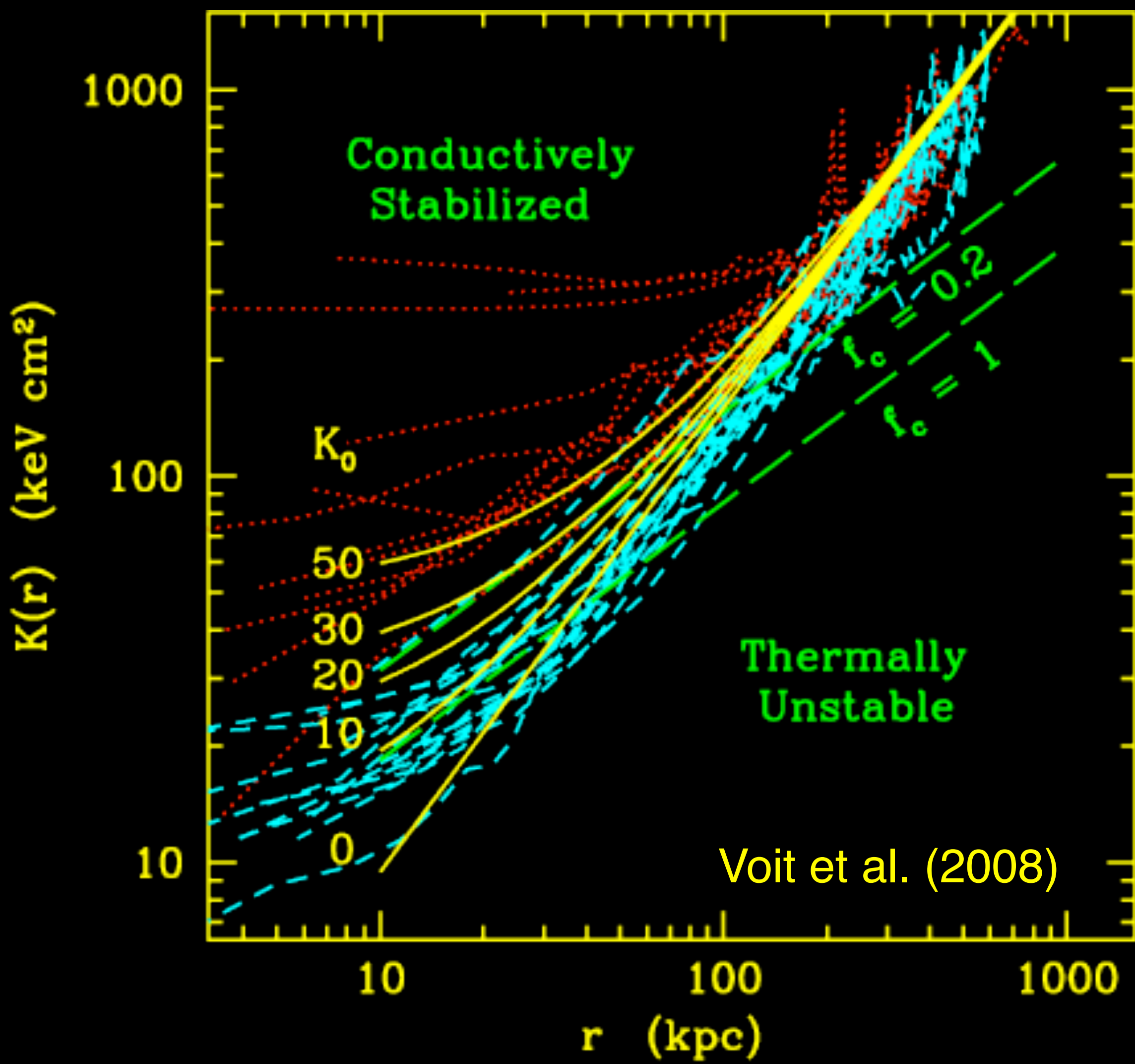

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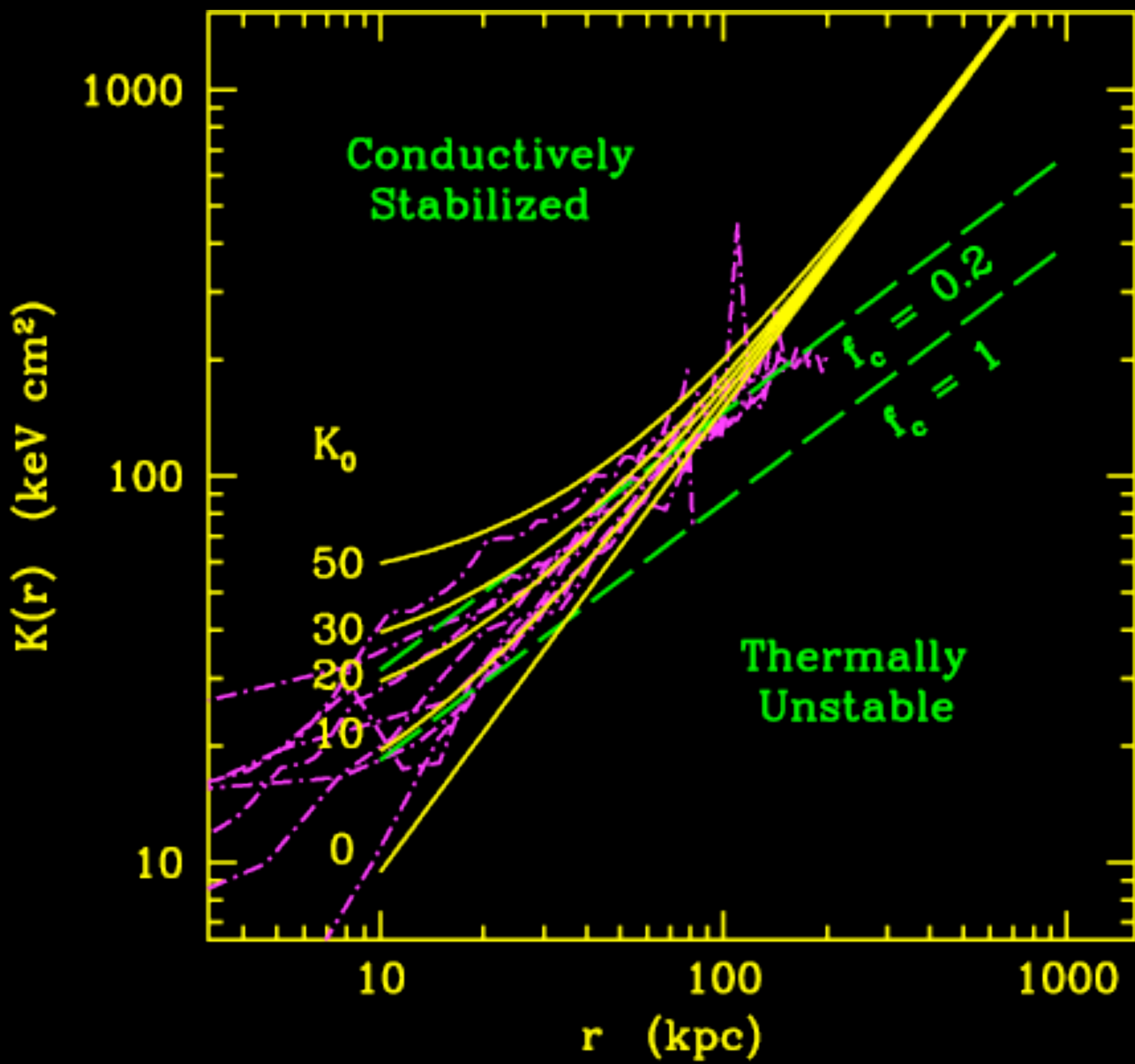
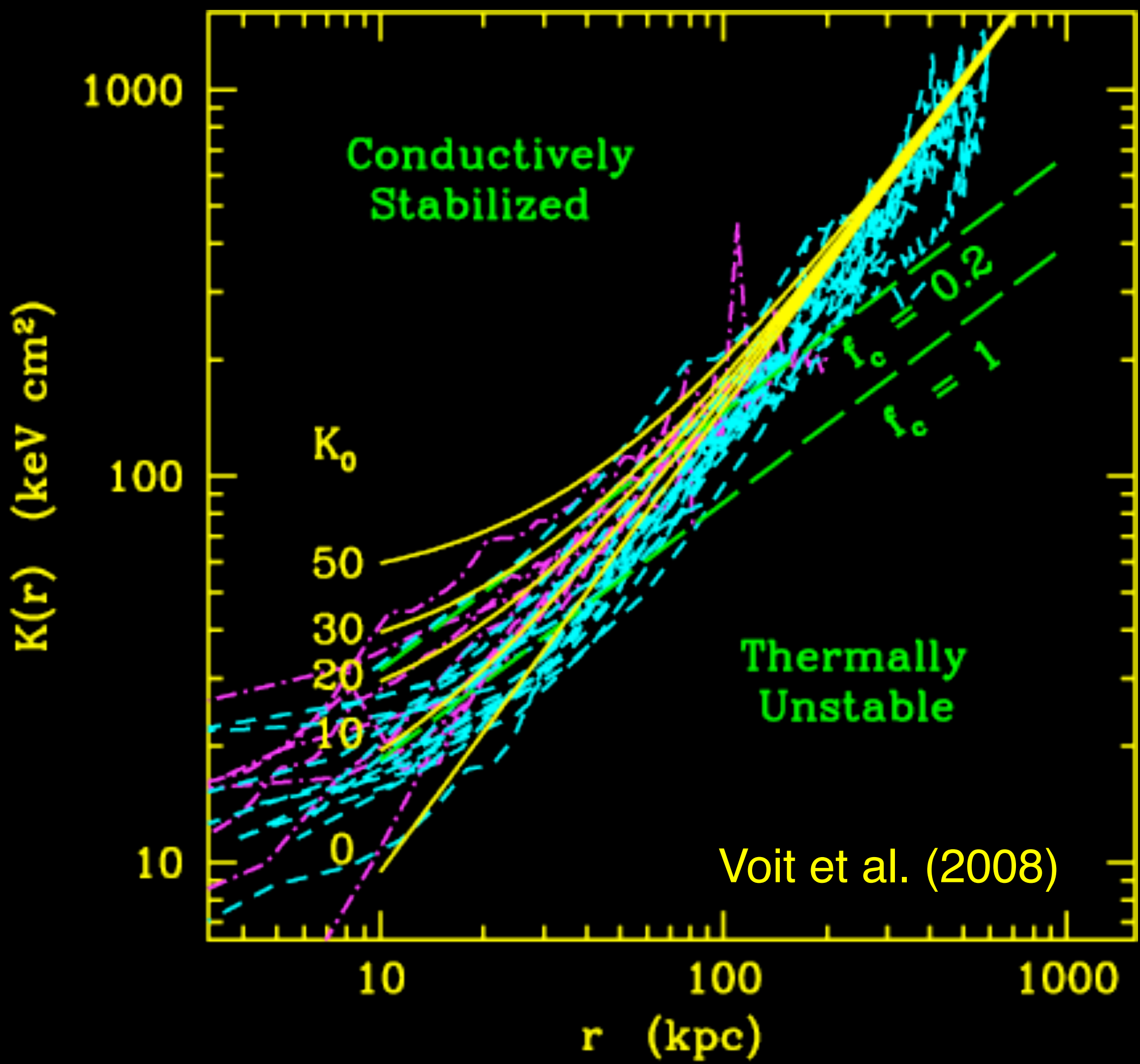


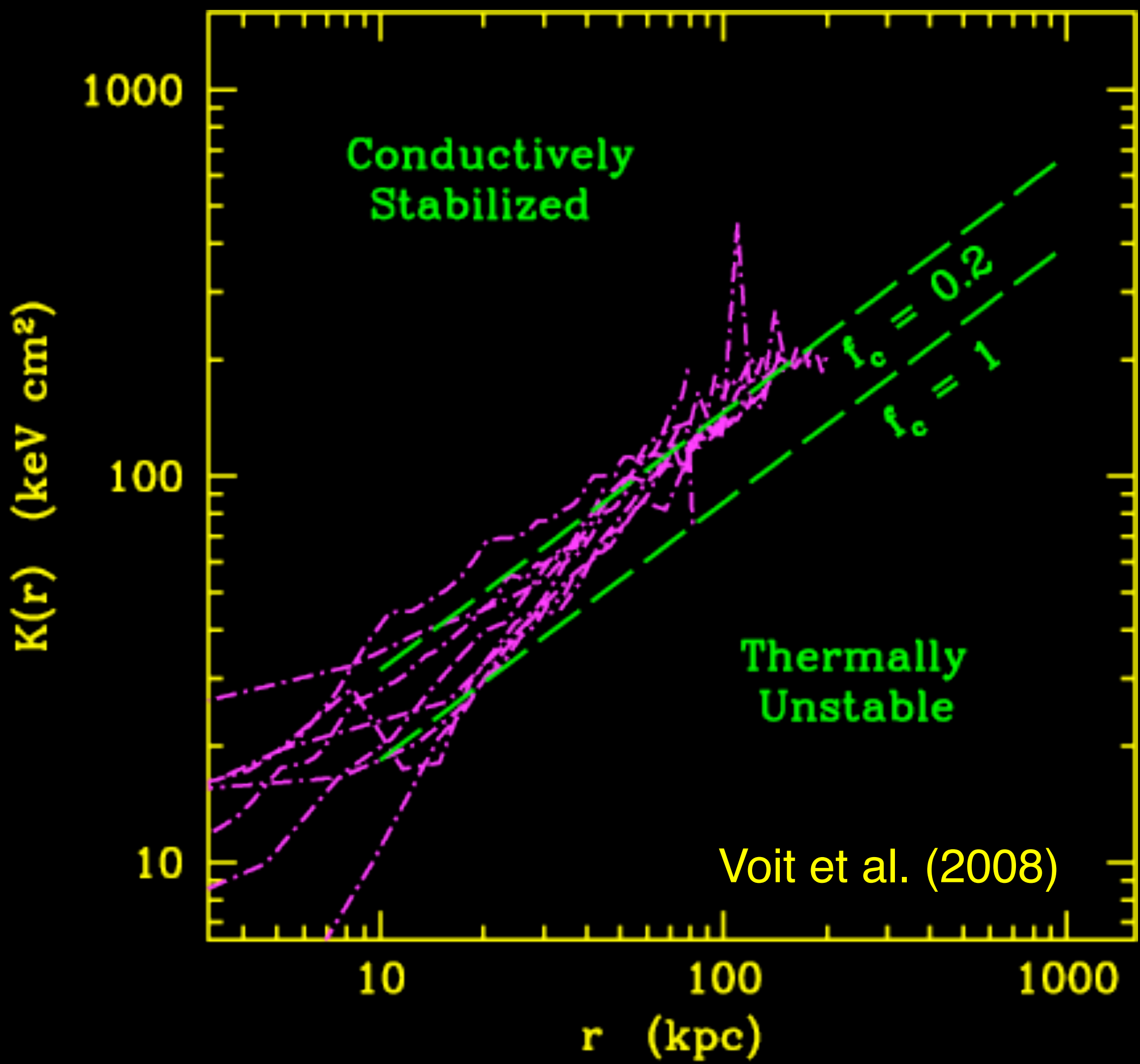
Clusters from Rafferty et al. (2008) with Hα but no star formation also dip below threshold …

Conductive Stabilization of ICM



… but their core entropy profiles suggest systematic differences from star-forming BCGs

Conductive Stabilization of ICM



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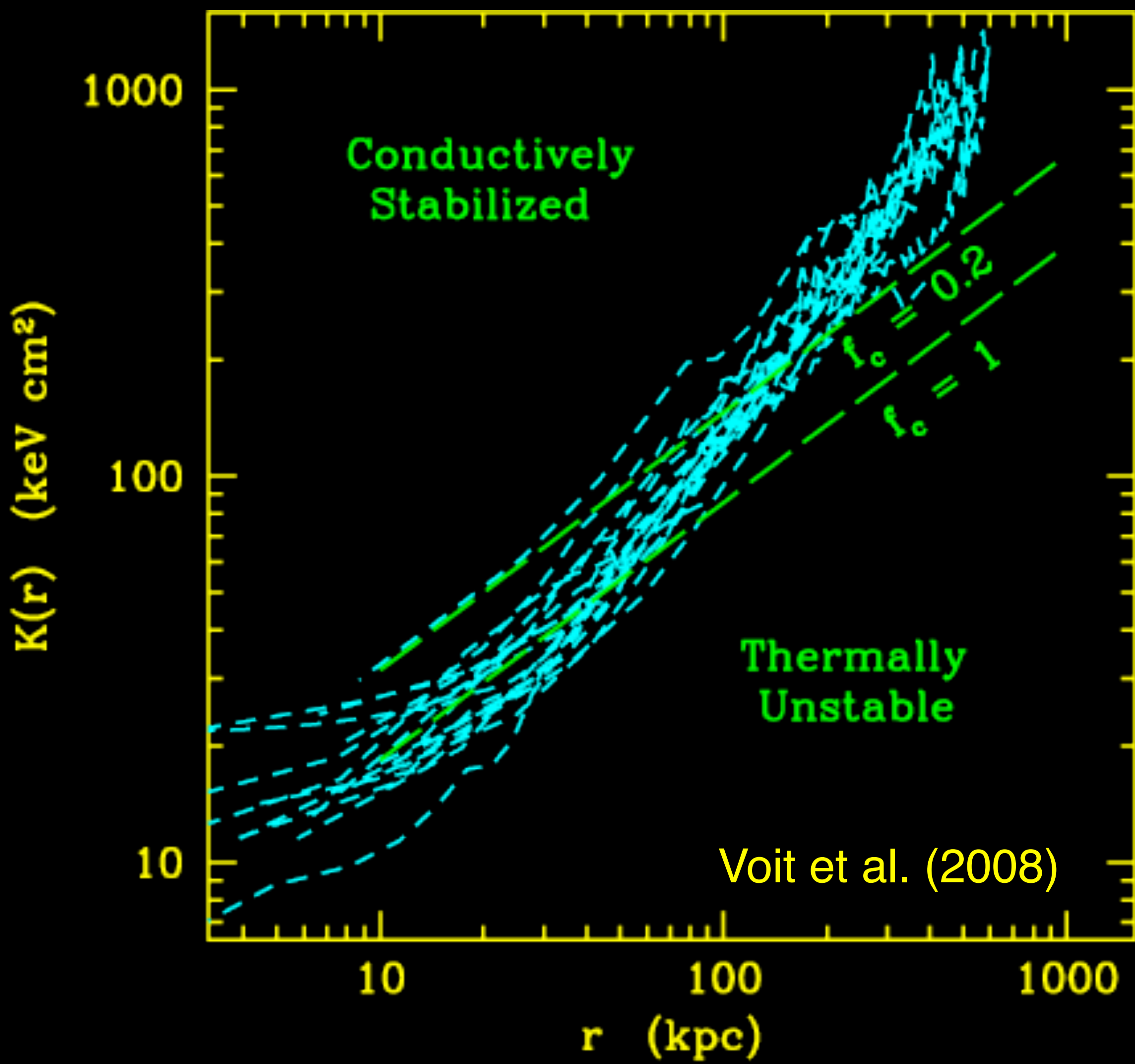


… but their core entropy profiles suggest systematic differences from star-forming BCGs

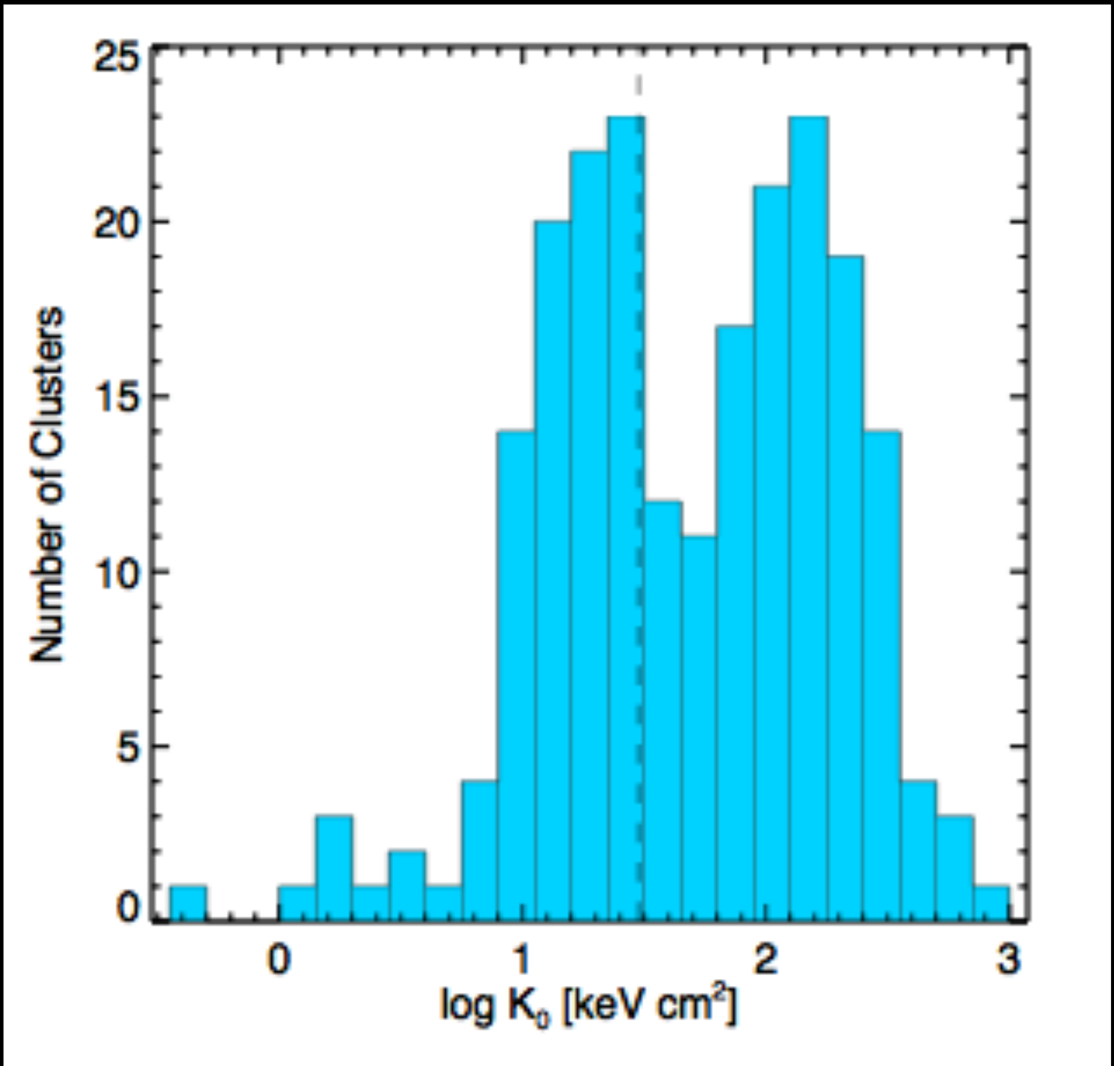
Conduction & Feedback

- AGN feedback, nebulosity and BCG star formation appear where conduction can no longer compensate for cooling

- If conduction is present, it may be important for distributing AGN energy input throughout the cluster core

How do cluster cores evolve?

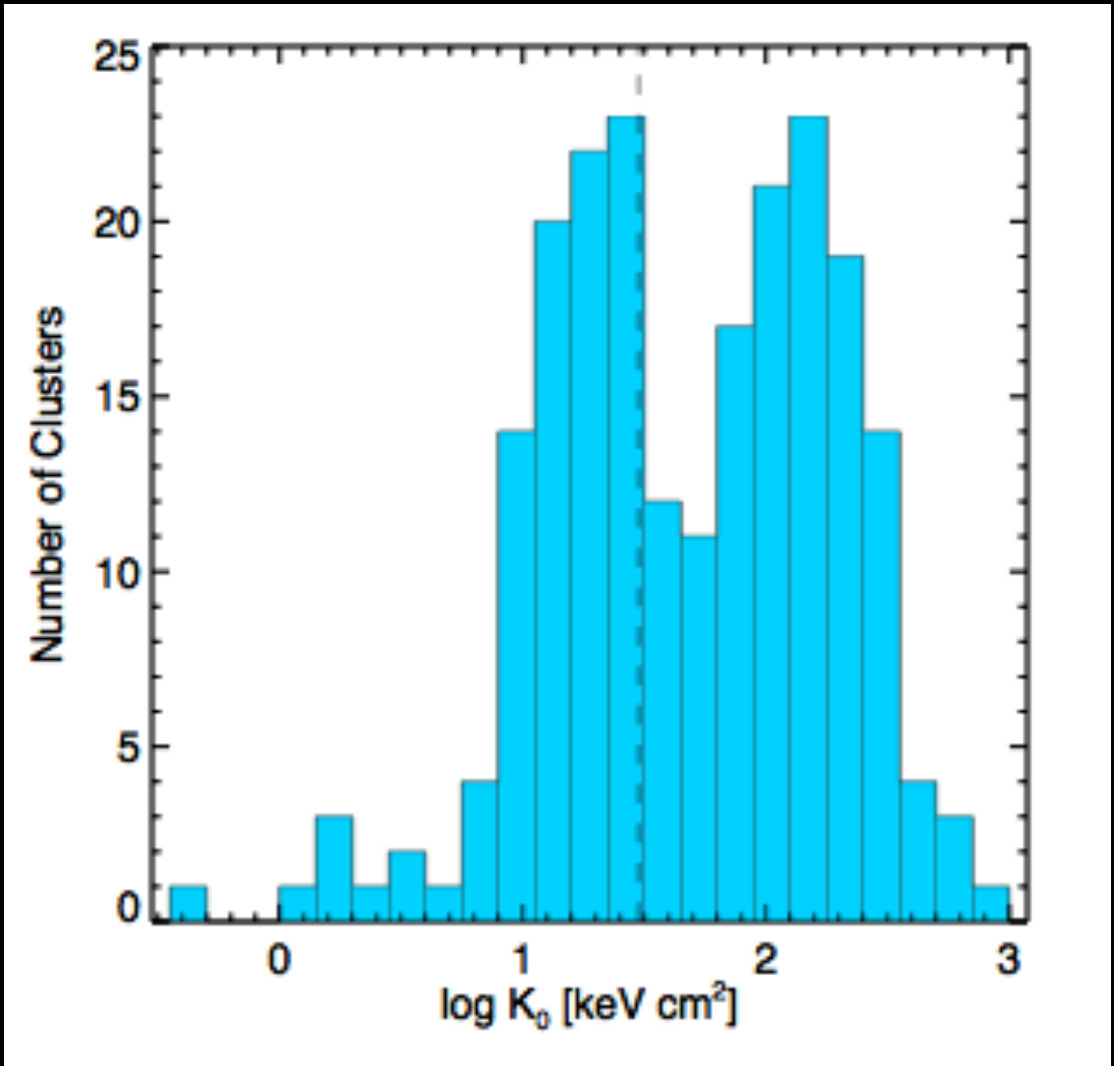
Distribution of Core Entropy



Distribution of K_0 is bimodal with deficit at K_0 ~ 30-50 keV cm^2 corresponding to a cooling time ~ 1 Gyr

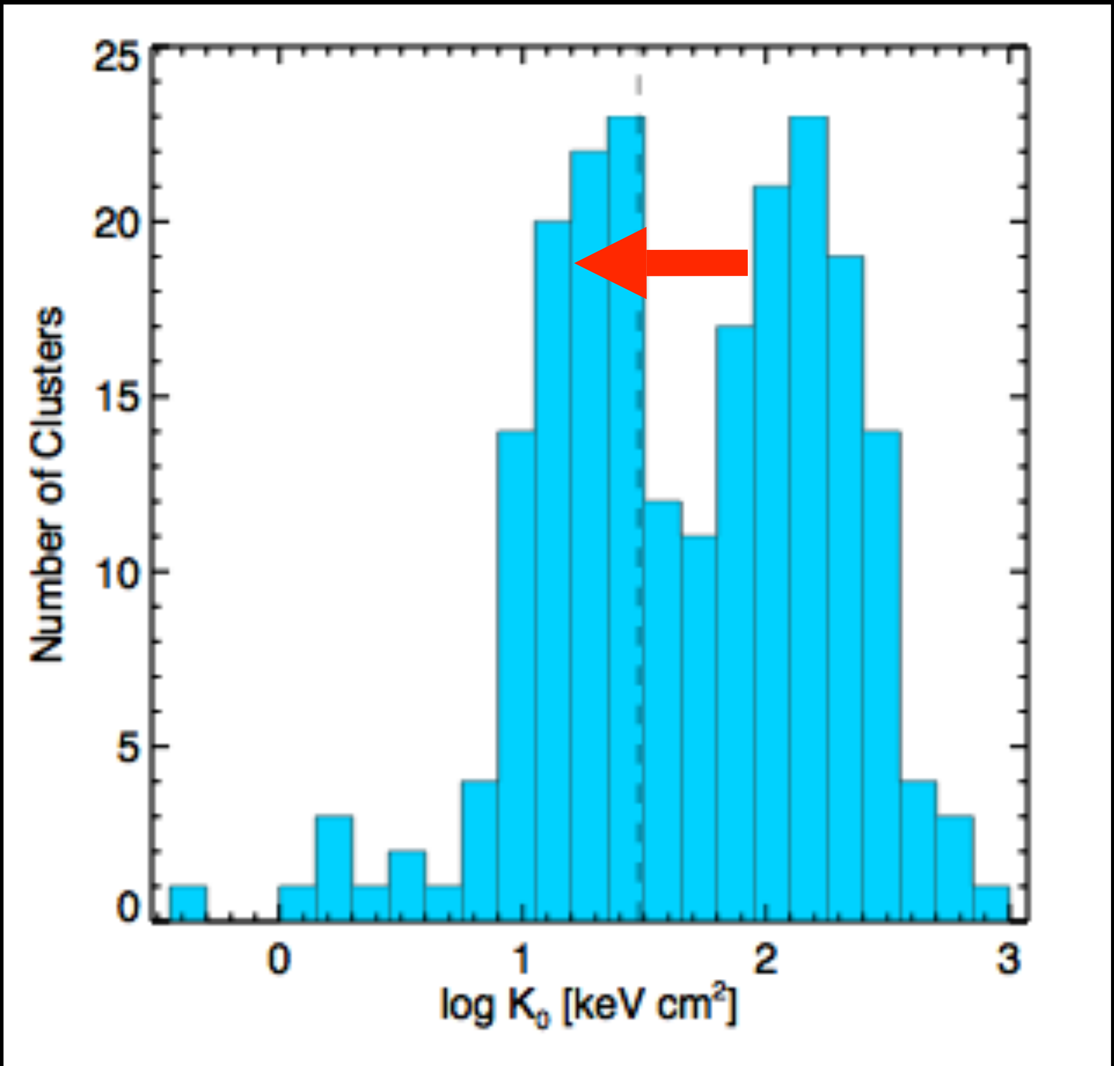
Cavagnolo et al. (2008)
See also Hudson & Reiprich

Distribution of Core Entropy



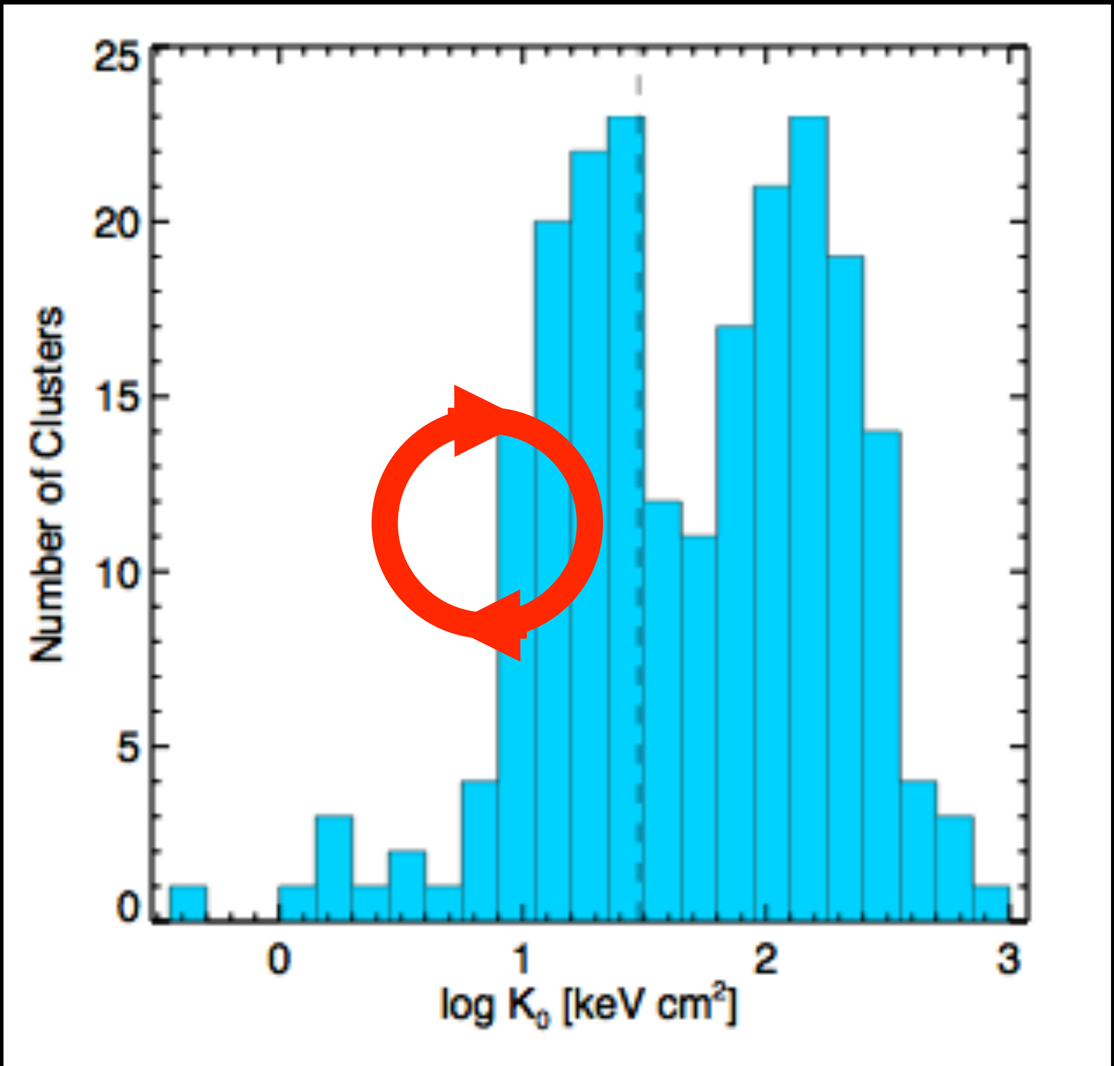
No consensus from simulations on distribution of K_0 without cooling & feedback

Distribution of Core Entropy



If conduction is inefficient, cooling causes clusters with t_c < few Gyr to migrate to lower K_0

Distribution of Core Entropy

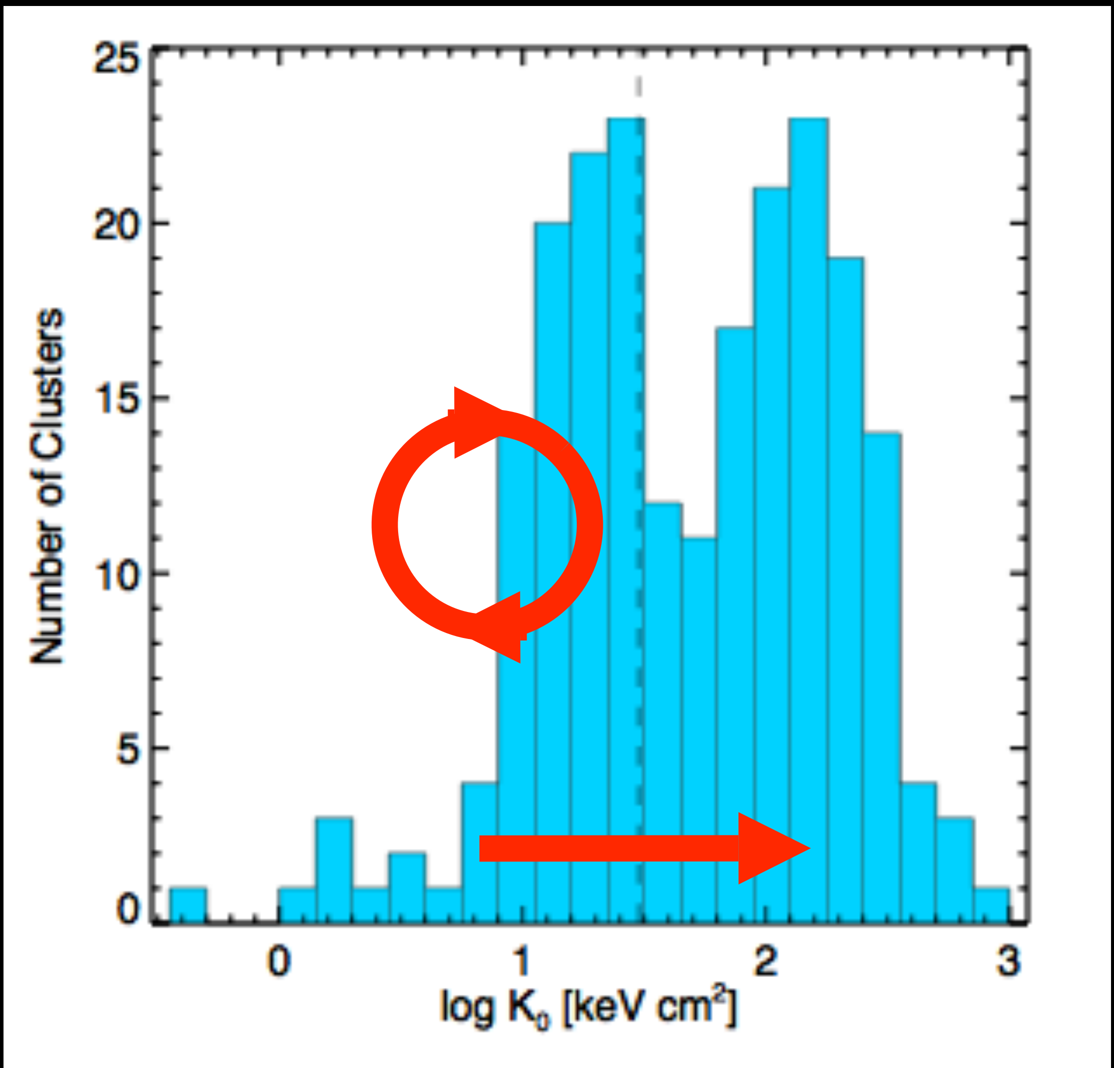


Episodic AGN feedback can plausibly maintain clusters in a quasi-steady state with

$K_0 \sim$ 10-20 keV cm^2

Voit & Donahue (2005)
See also Kaiser & Binney

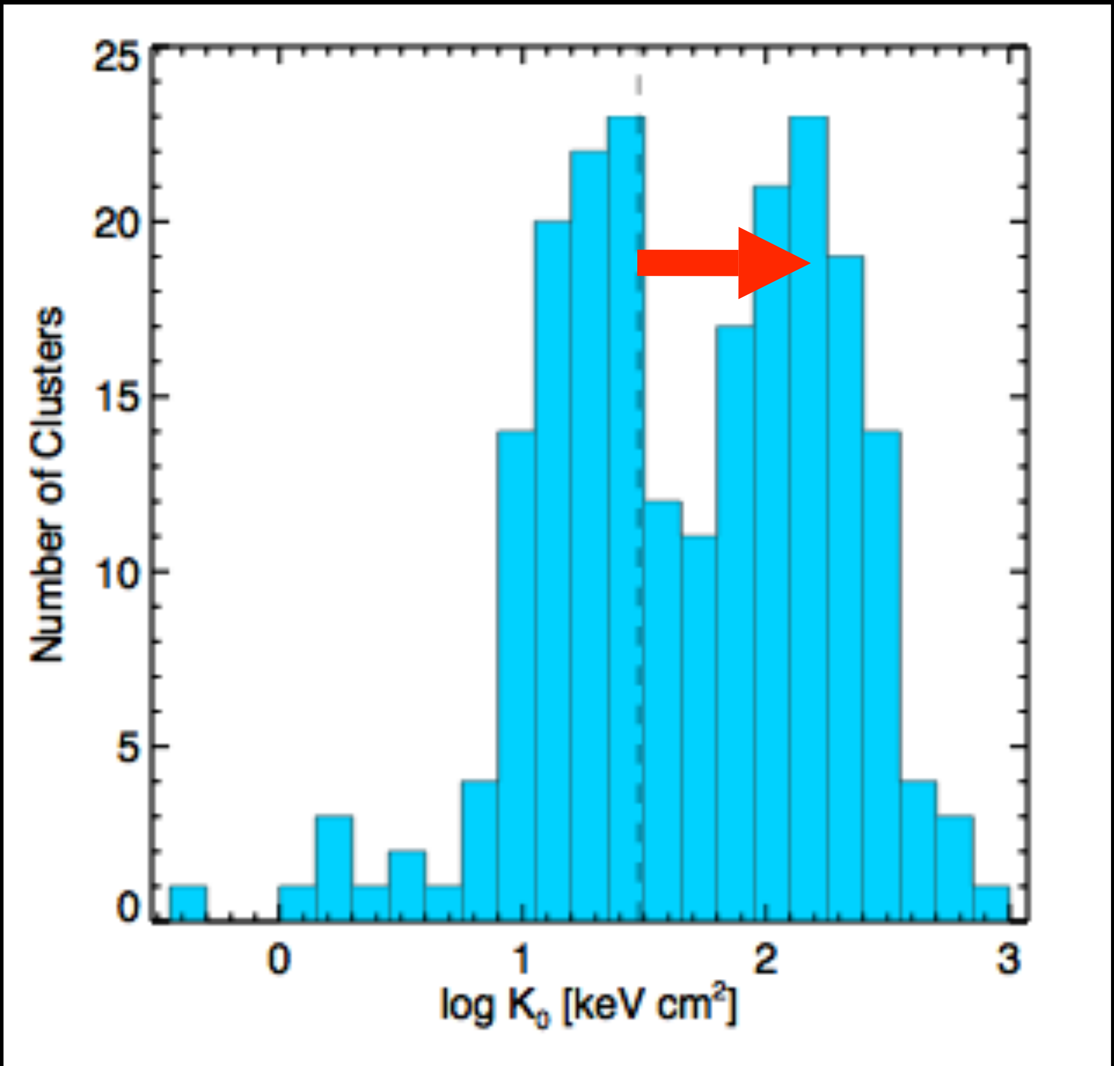
Distribution of Core Entropy



Raising K_0 by a large factor requires an implausibly large AGN outburst

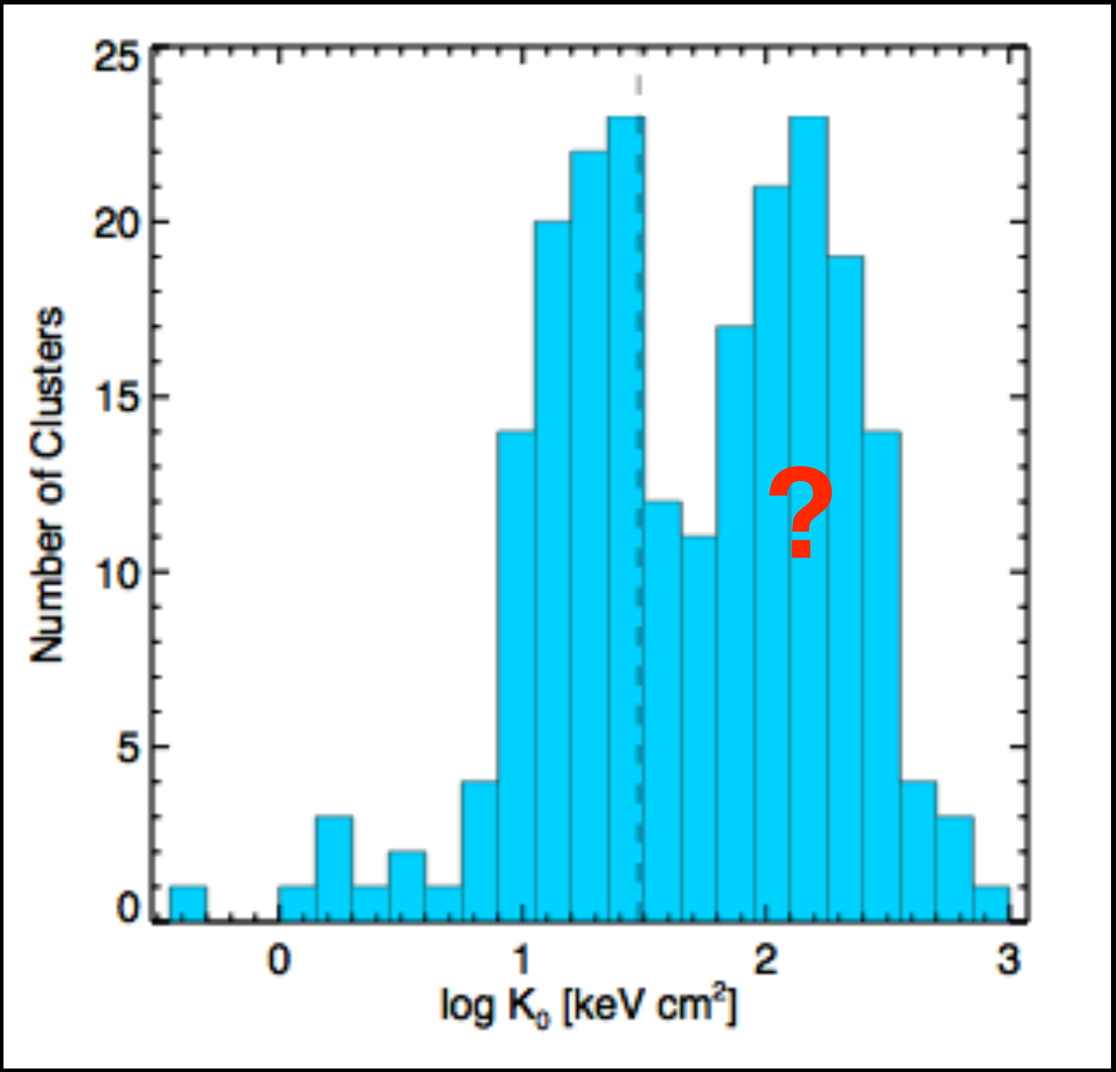
Mergers are also ineffective at producing large K_0 jumps

Distribution of Core Entropy



If conduction is operating, mergers can more easily cause clusters with $K_0 > 30$ keV cm^2 to migrate to greater K_0

Distribution of Core Entropy



How many clusters with $K_0 > 100$ keV cm^2 are mergers in progress that will eventually relax to a low K_0 state?

Answers

- Cluster population is bimodal
- Central AGN responds to state of ICM
- ICM seems to be multiphase for low K_0
- Conduction may be important in ICM

Questions

- Why are some clusters in a high K_0 state?
- How do cluster cores evolve?
- How does cluster astrophysics affect f_b?
- What is minimal physics set needed for cosmological cluster simulations?
- How should we parameterize scatter in mass-proxy relations?