Cluster Entropy Profiles

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

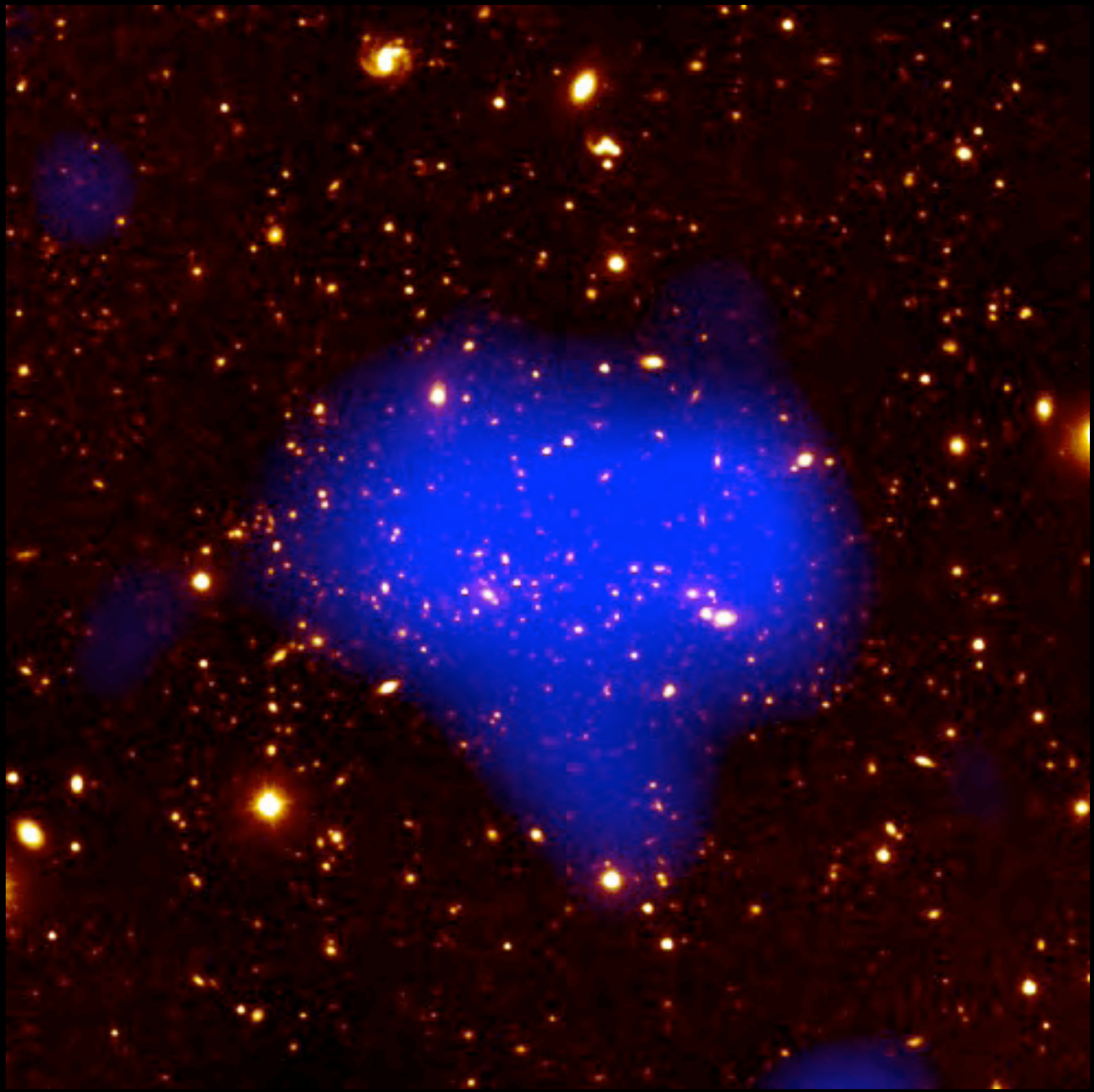
Convective Stability: $dS/dr \geq 0$

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



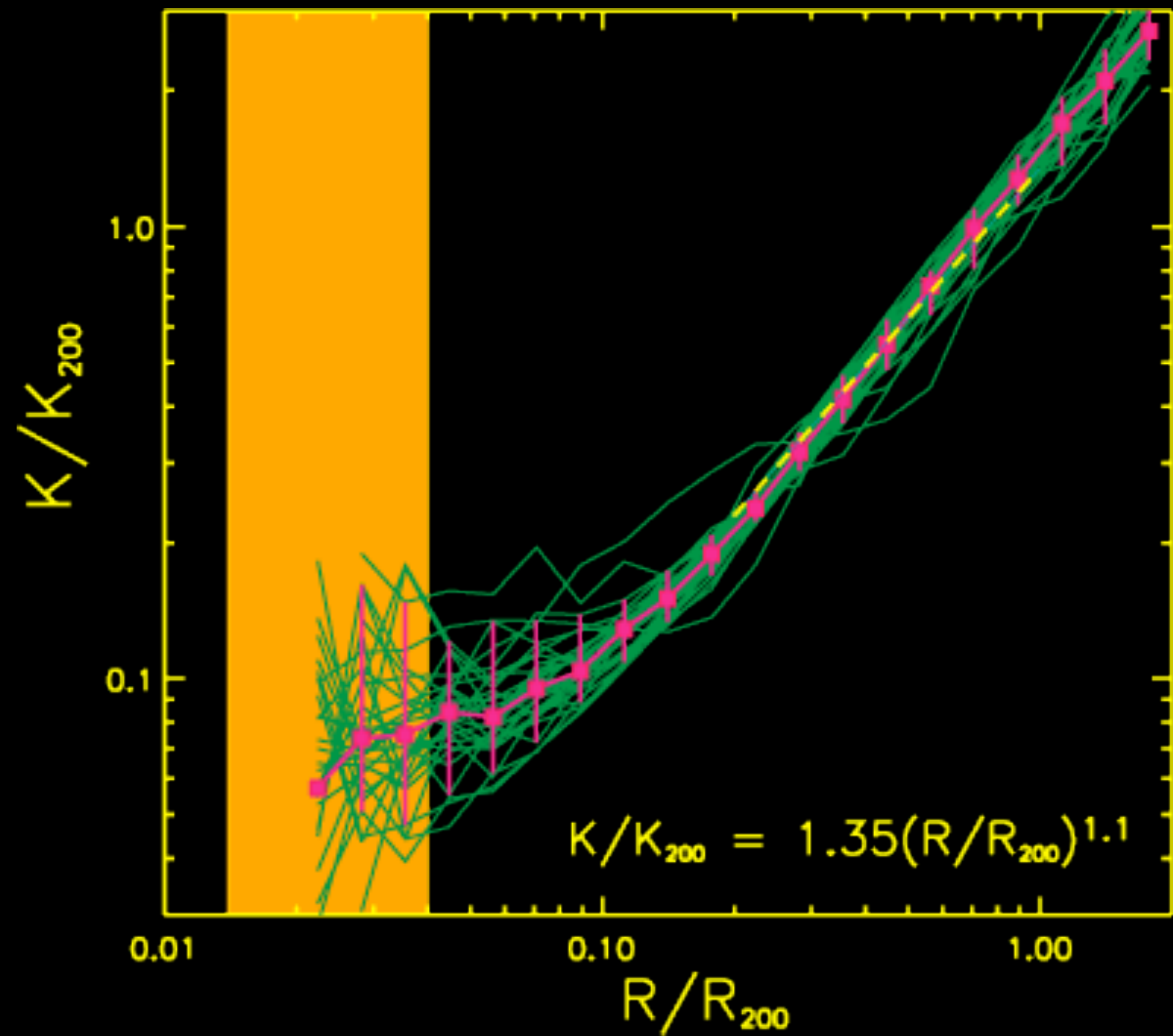
MS 1054-0321 / Donahue et al. (1998)

Properties of relaxed cluster determined by:

- shape of halo
- entropy distribution of intracluster gas

Chandra Core Entropy Survey

Clusters without Feedback



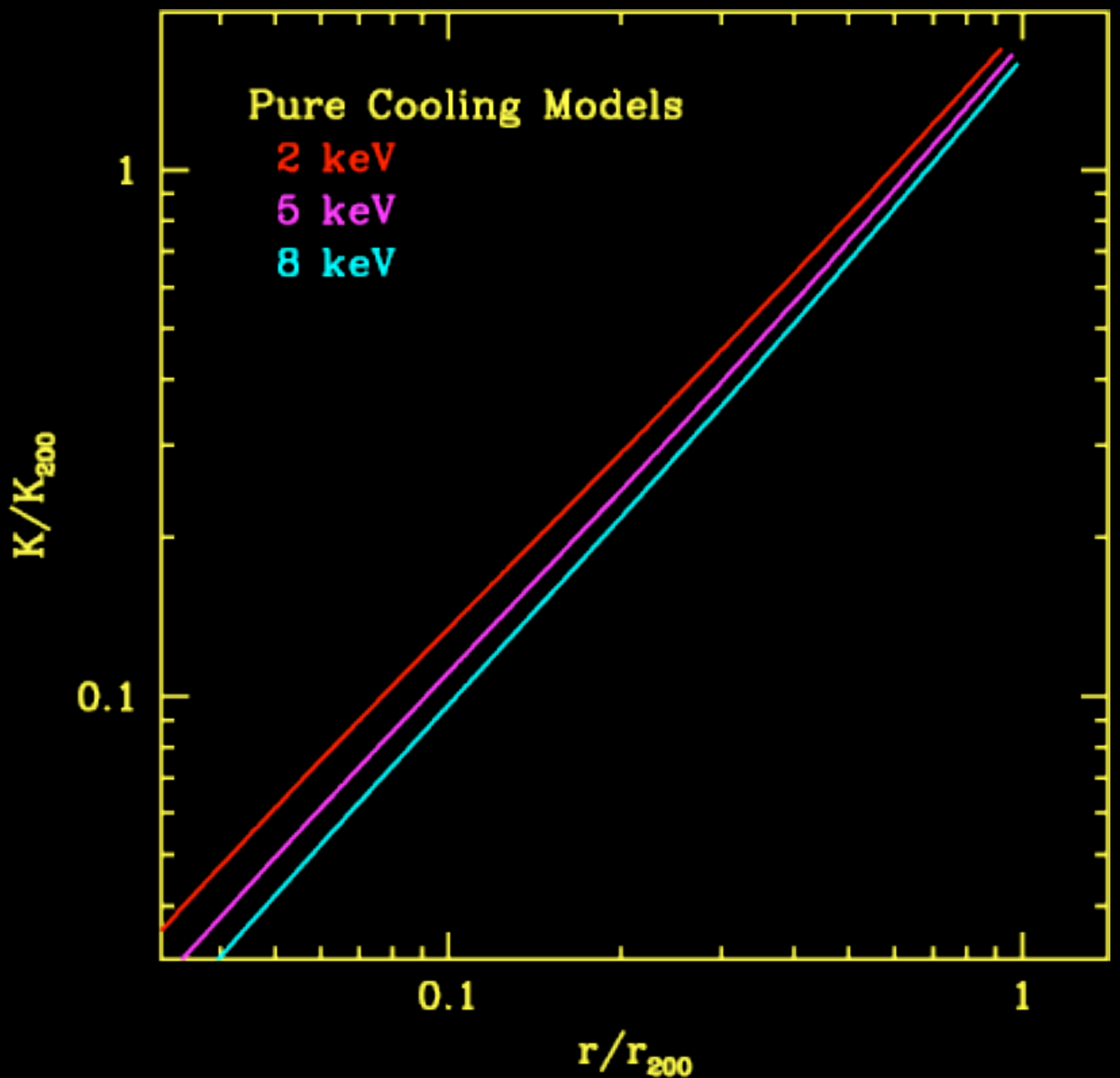
Self-similar entropy profiles in absence of galaxy formation scale with

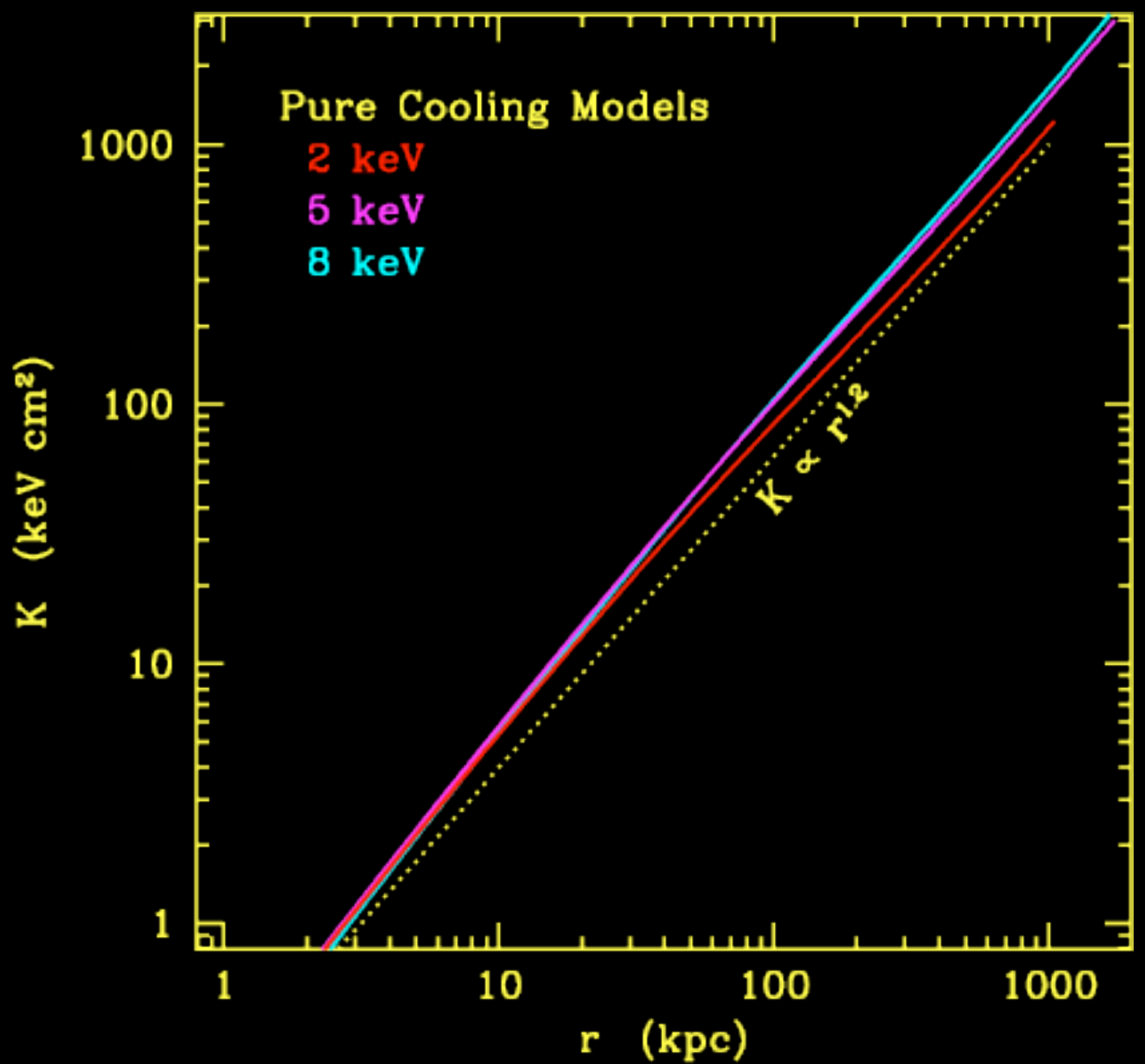
$$K_{200} = \frac{T_{200}}{(200\ f_b\ \rho_{cr})^{2/3}}$$

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

Voit, Kay, & Bryan (2005)

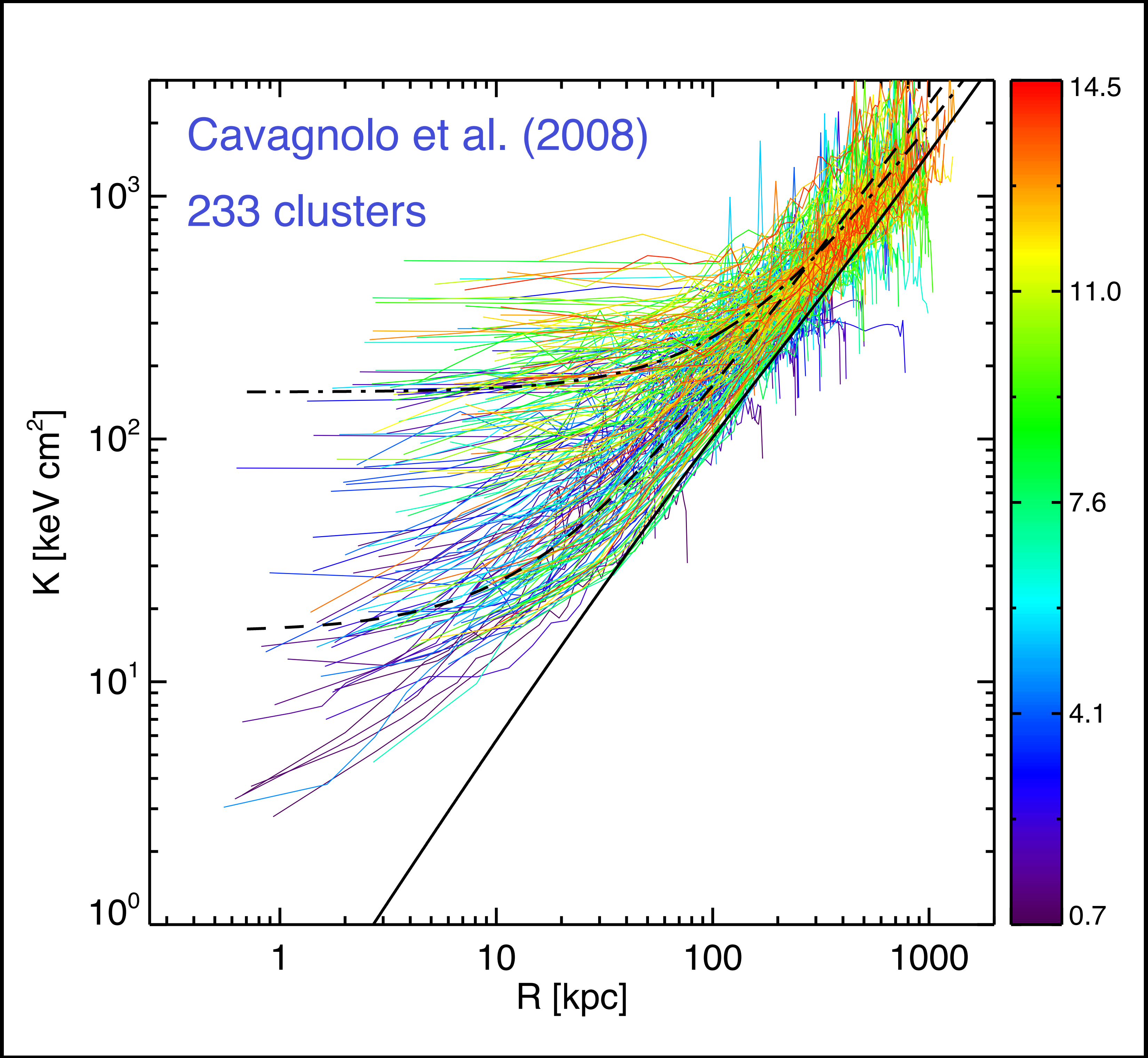
Pure Cooling Model





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

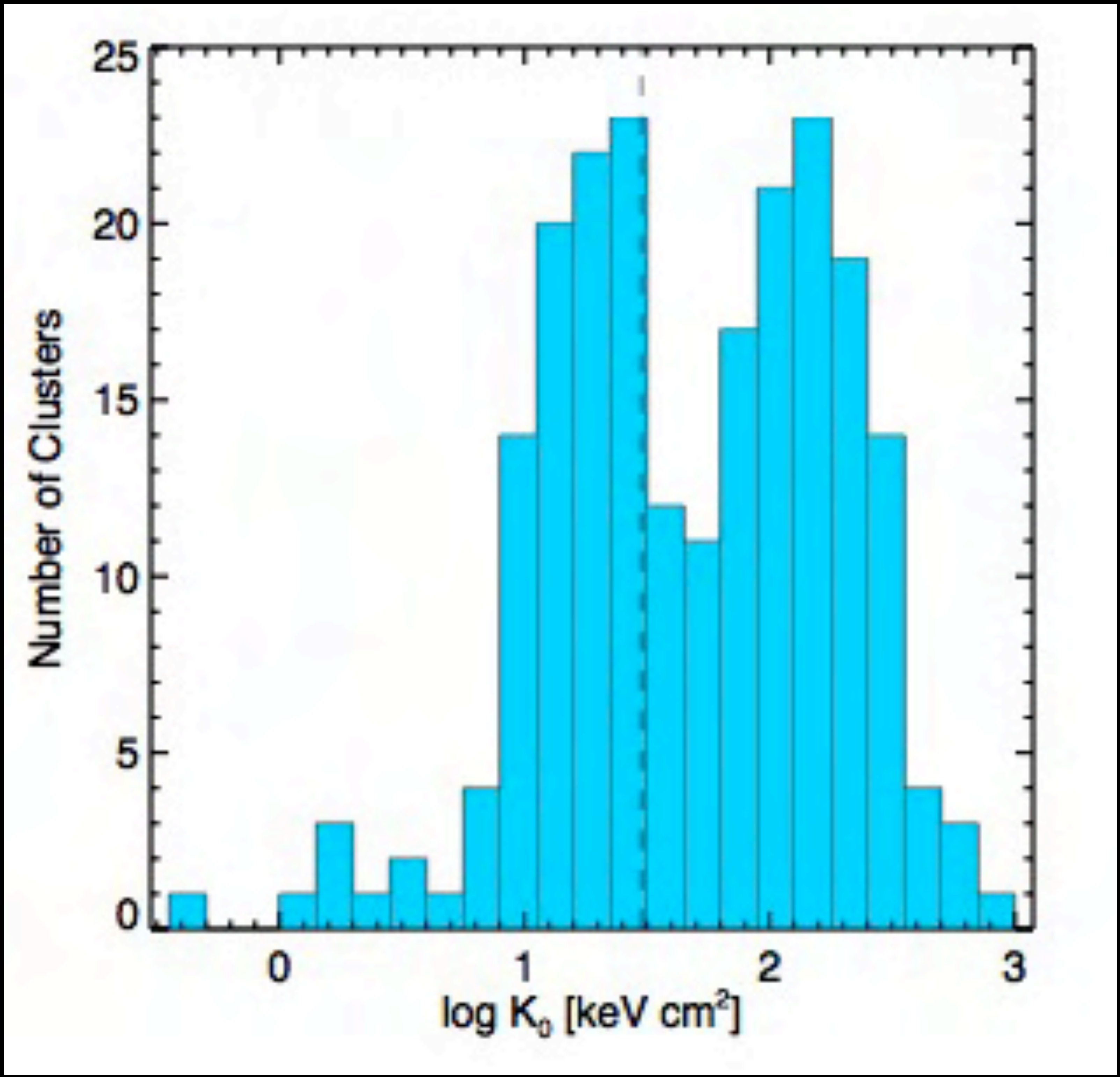
Most profiles are well fit with:

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

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

$\alpha \sim 1.2$

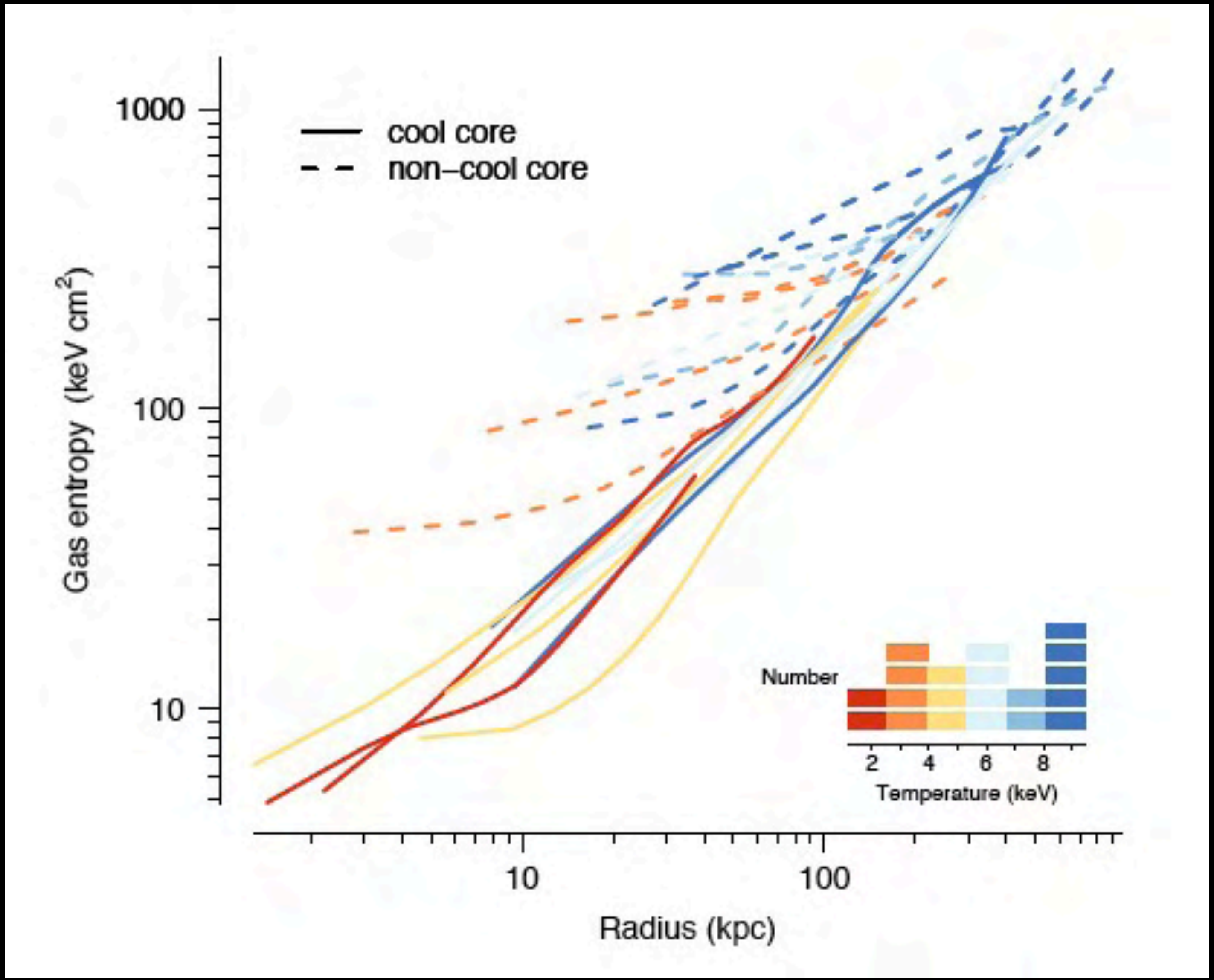
Distribution of Core Entropy



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

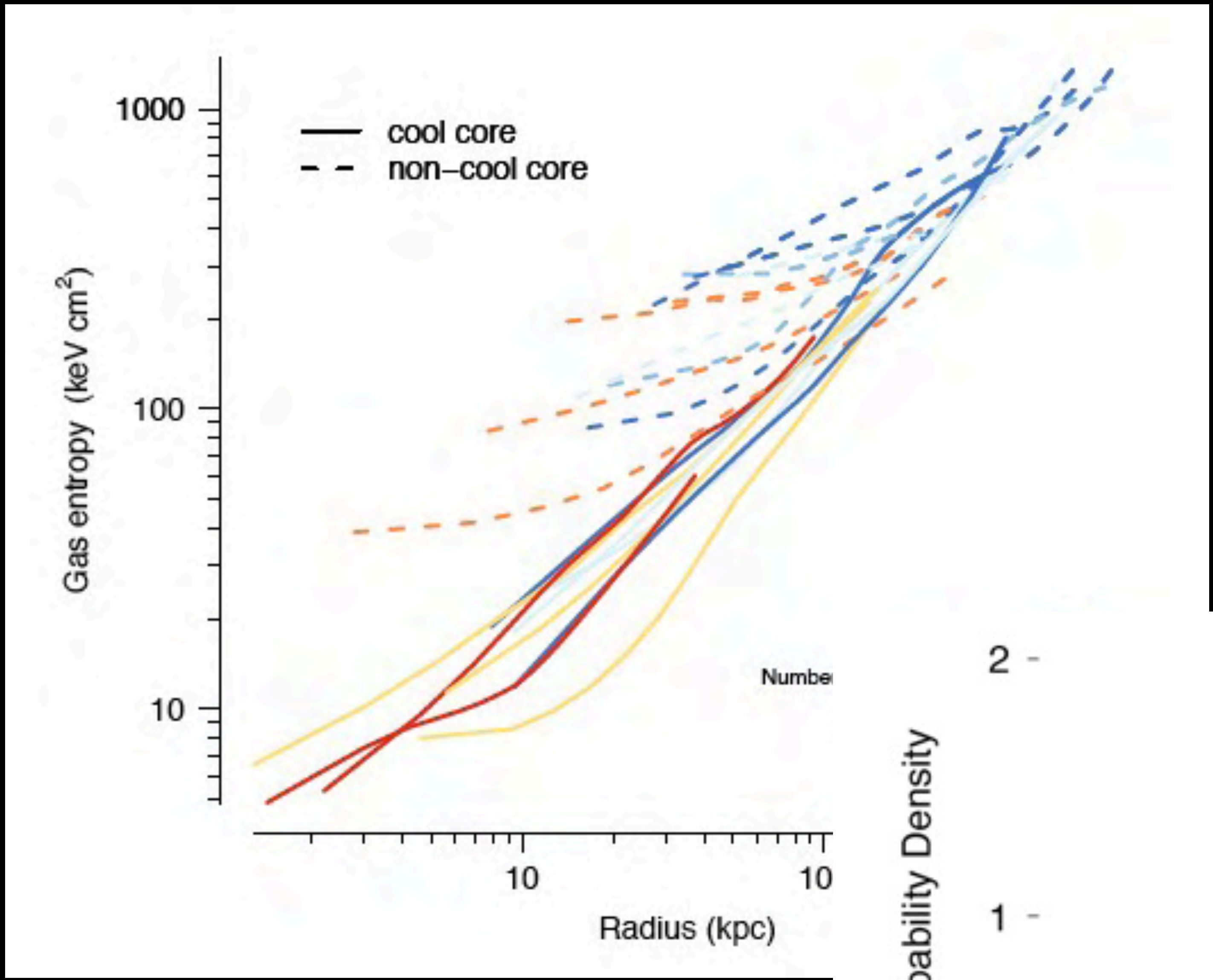
Cavagnolo et al. (2008, 2009)
See also:
Sanderson et al. (2009)
Hudson et al. 2010
(HIFLUGGS)

Sanderson et al. 2009



Cool cores have steeper entropy slopes than non-cool core clusters

Sanderson et al. 2009



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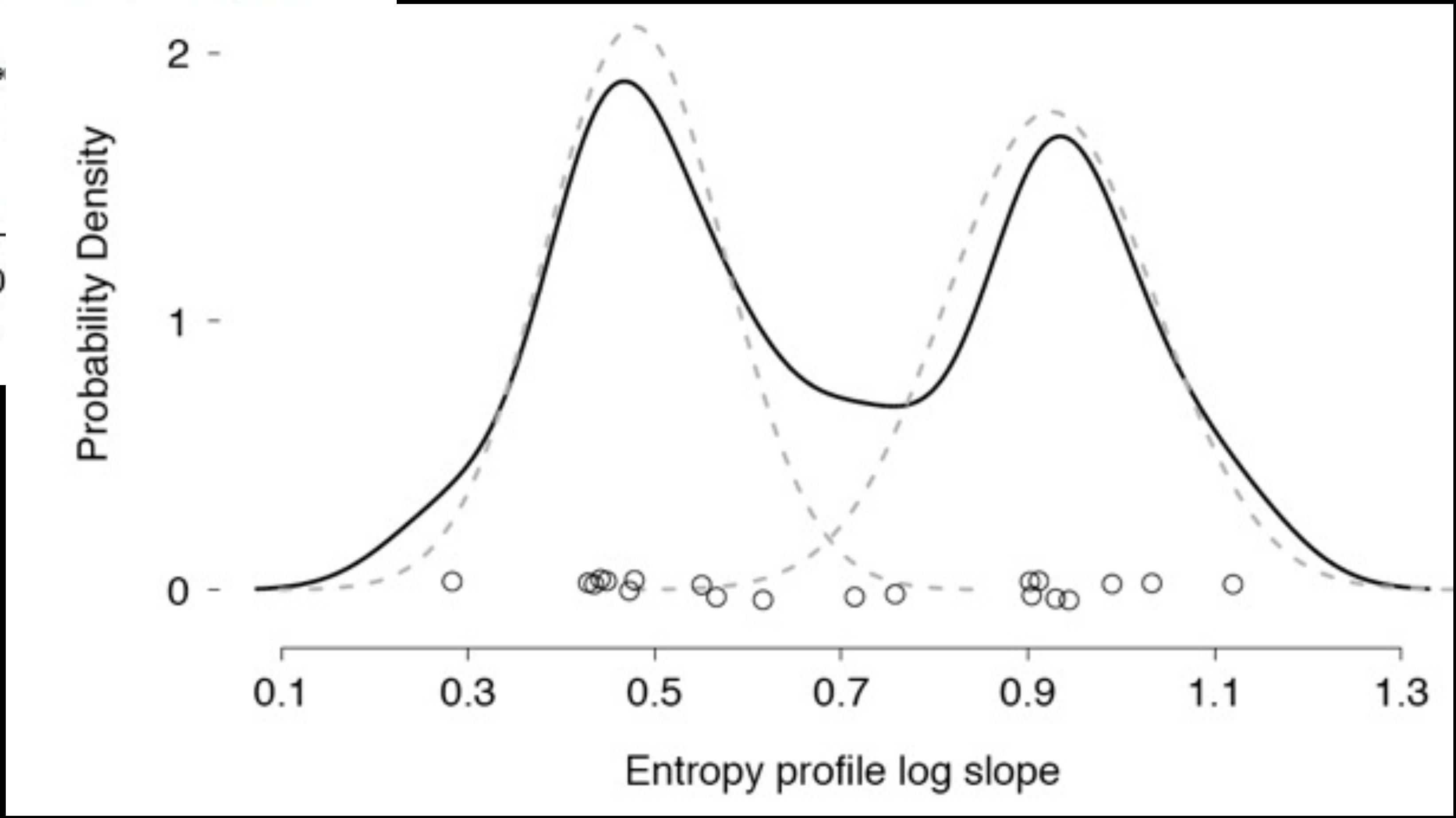
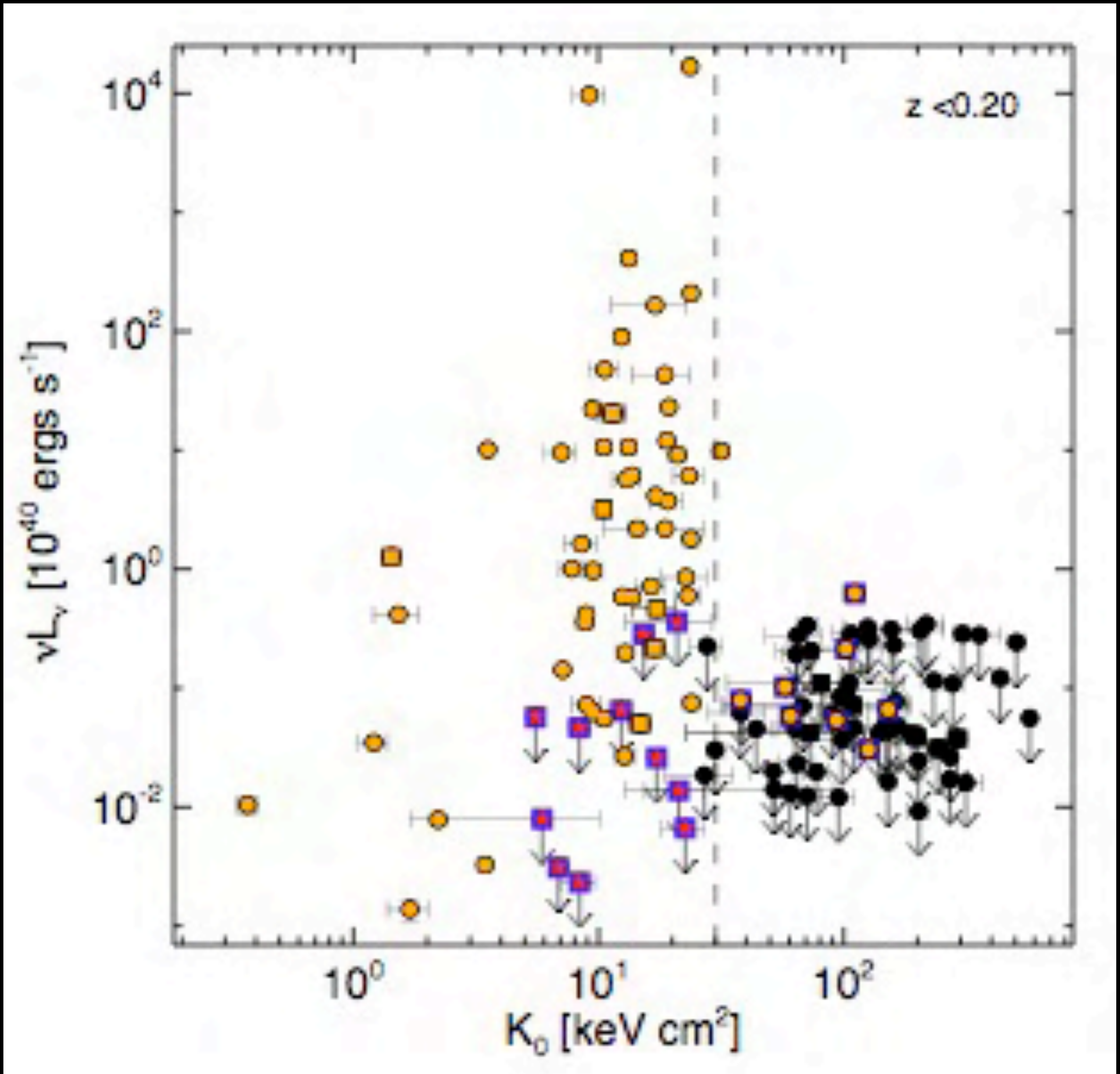


How is core entropy related to feedback signatures?

K_0 and Radio Power



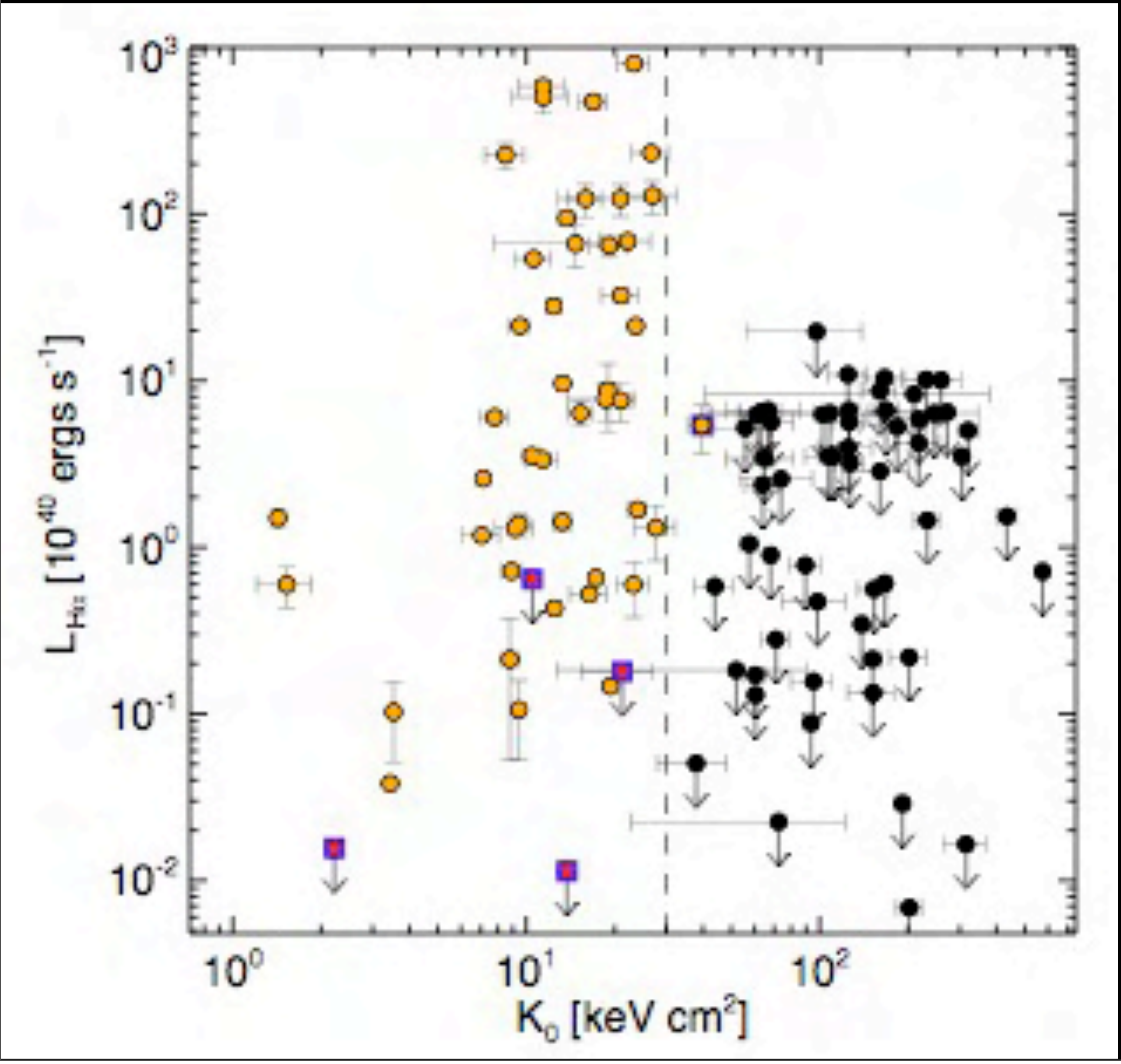
Central galaxy of a *z* < 0.2 cluster can be a strong radio source only if

$K_0 < 30$ keV cm^2

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

Cavagnolo et al. (2008)

K_0 and Hα Emission



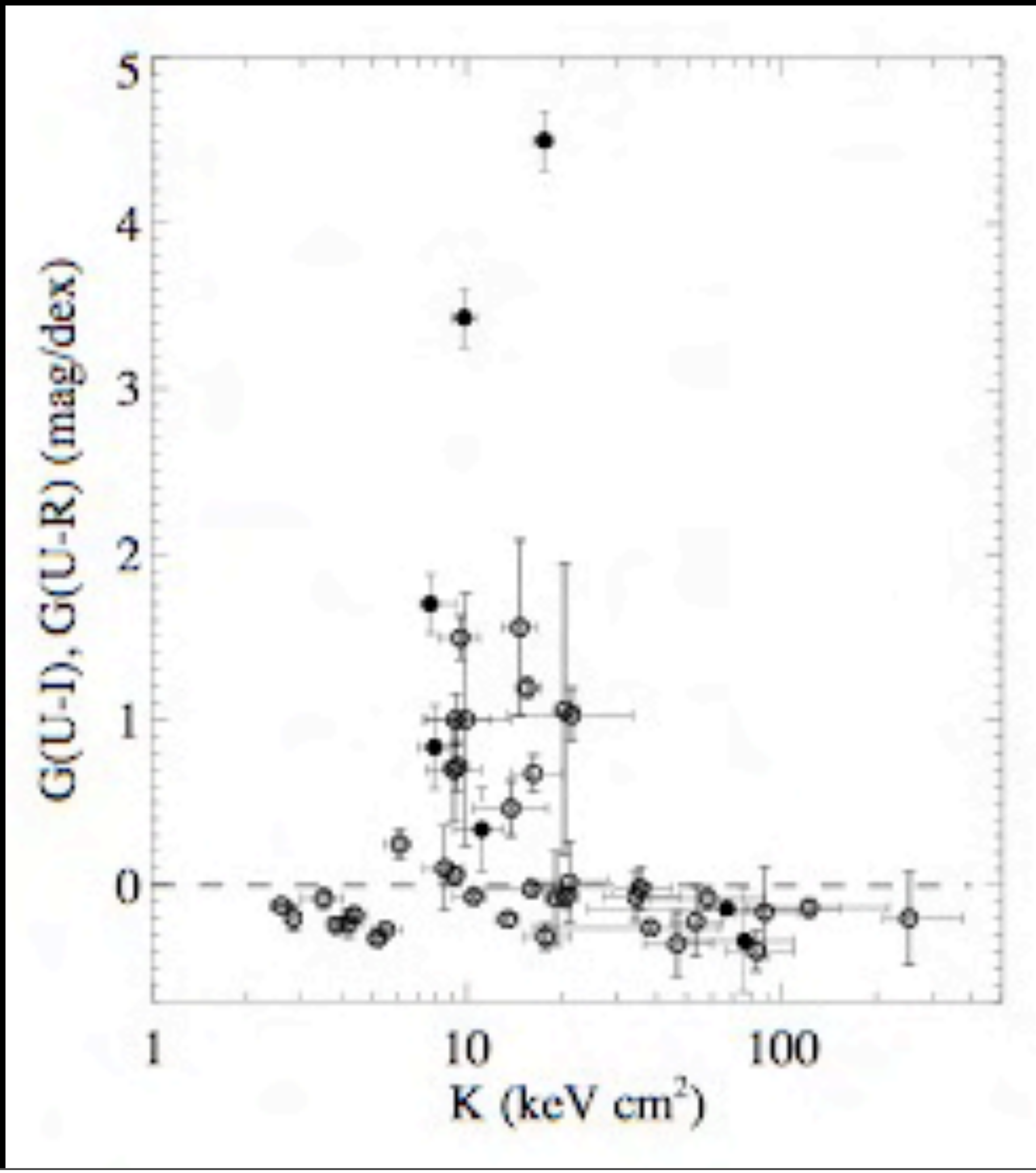
Central galaxy can have emission-line nebulosity only if

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

Hα data from many diverse sources

Cavagnolo et al. (2008)

K_0 and Central Blue Gradient

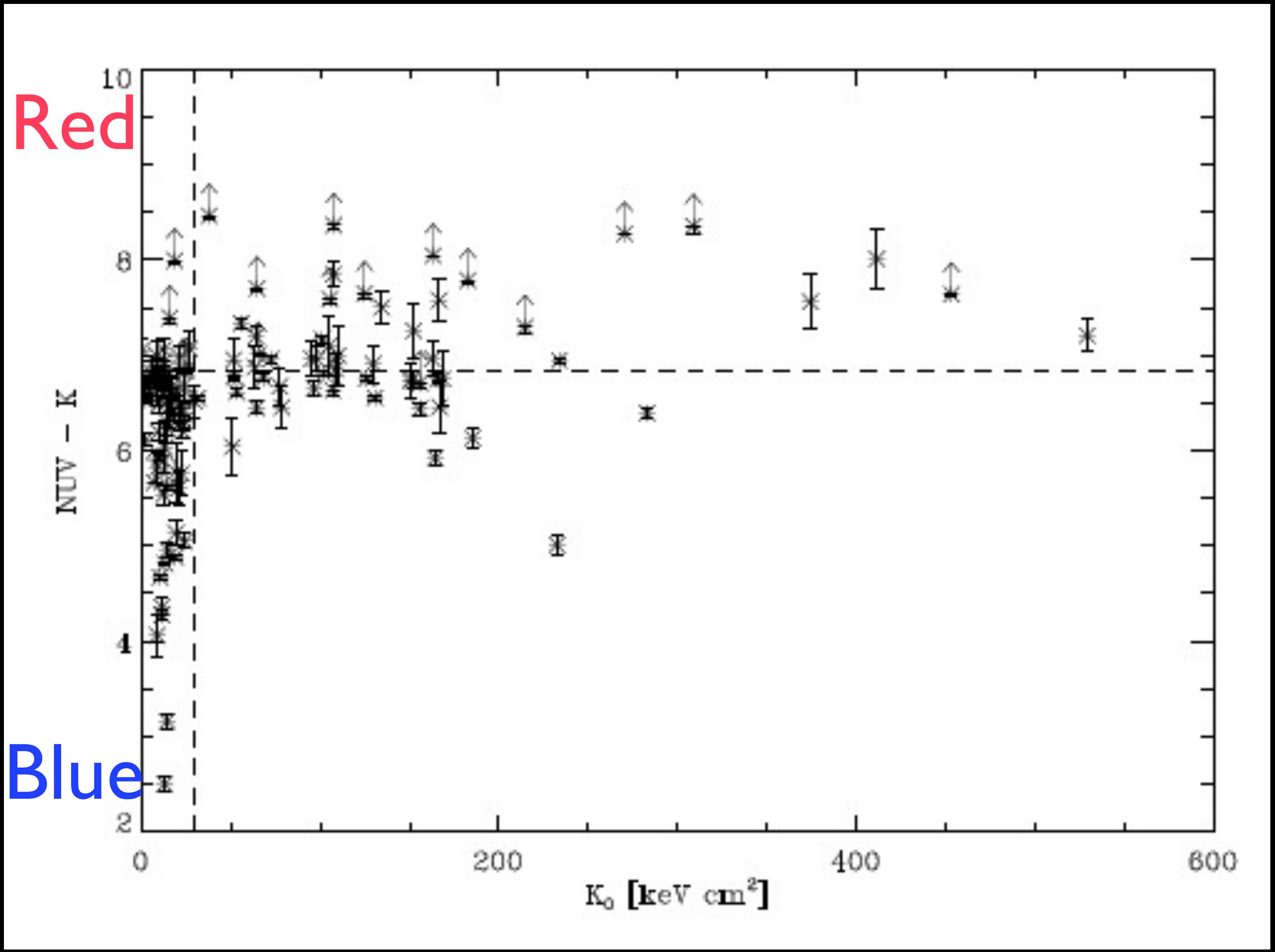


Central galaxy can have blue gradient indicating star formation only if

$K_0 < 30$ keV cm^2

Rafferty et al. (2008)

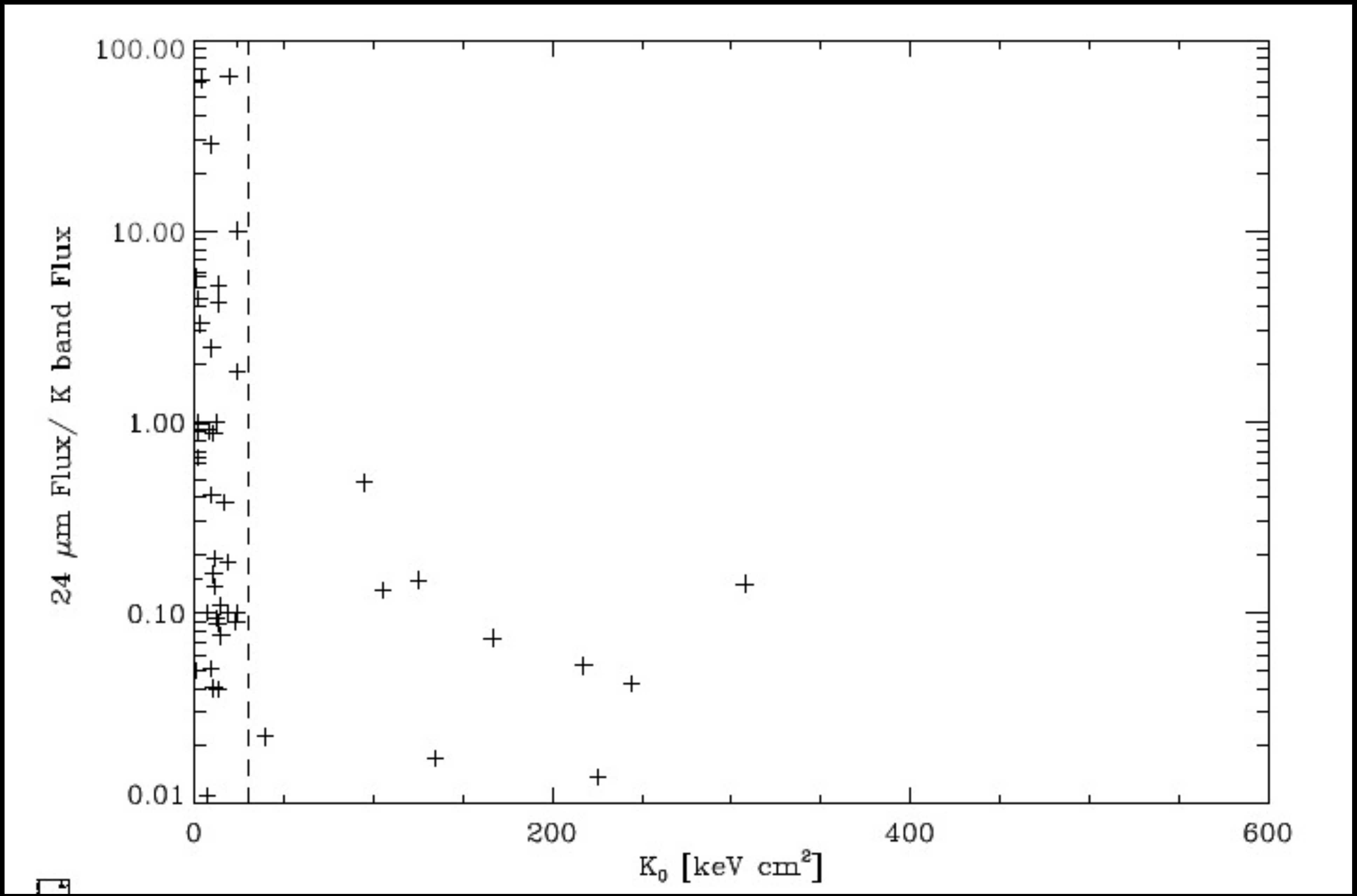
K$_0$ and UV color



124 BCGs
GALEX-2MASS
colors

Hoffer, Donahue et al. 2011, in prep

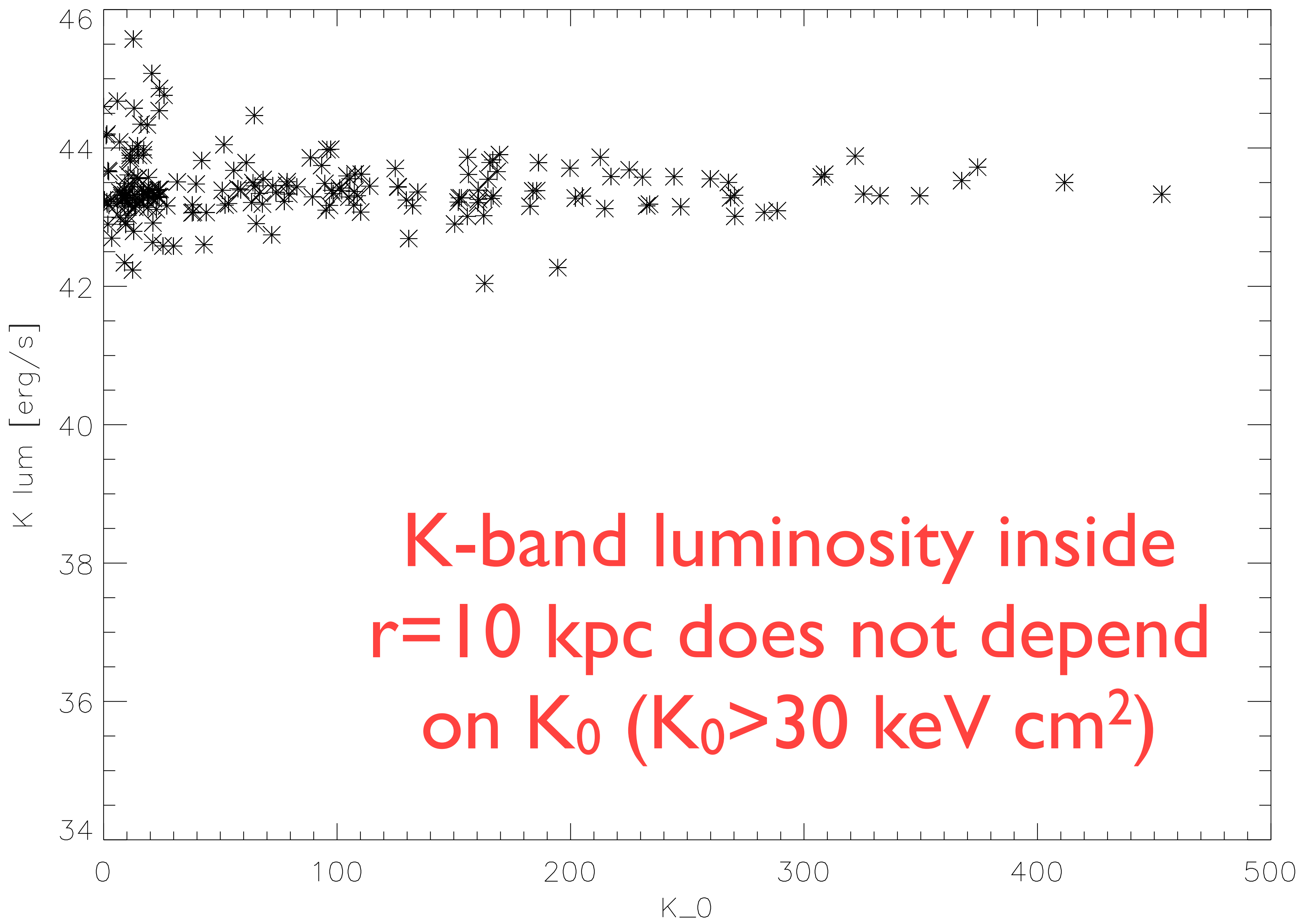
K_0 and Spitzer 24 micron excess



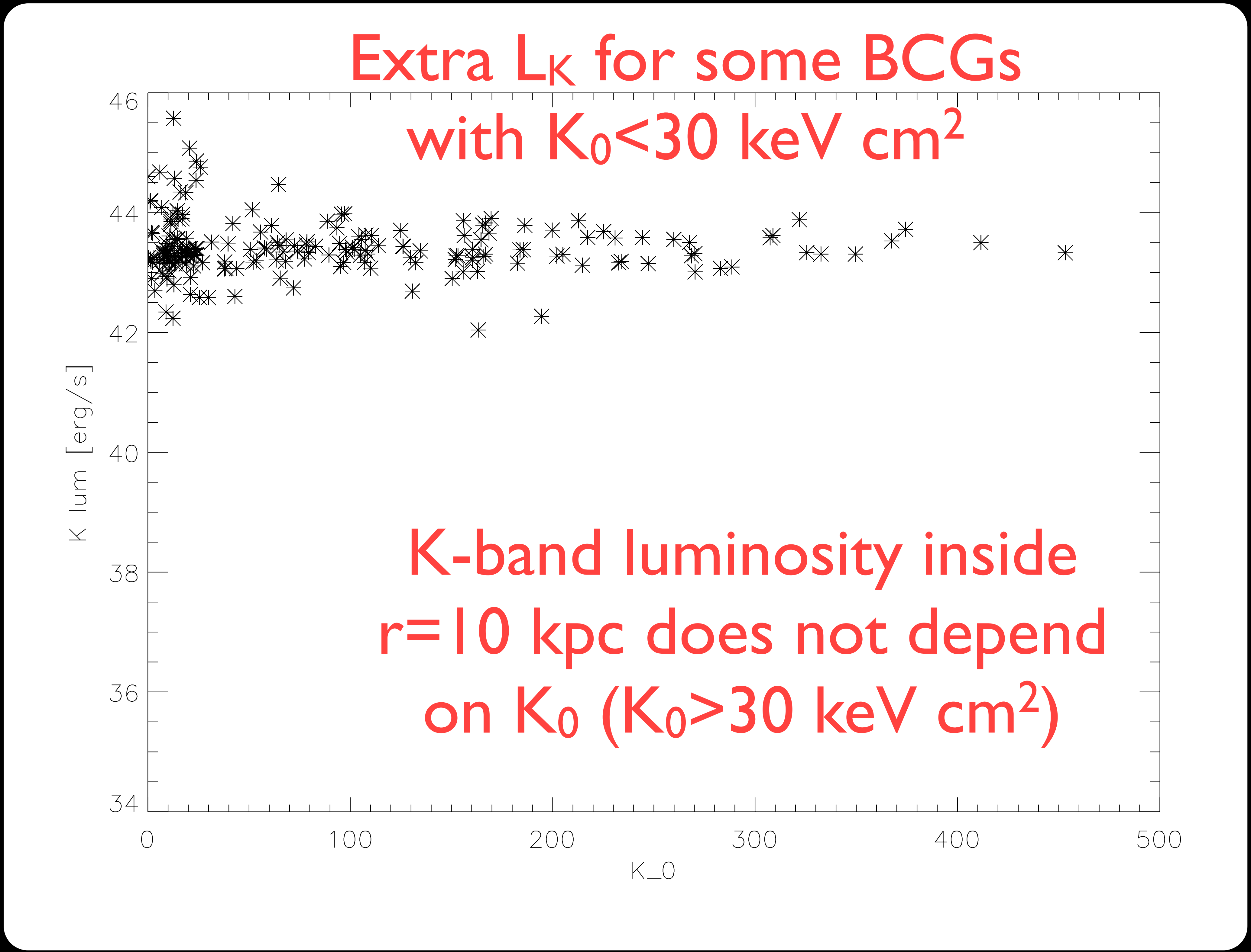
83 BCGs with Chandra + MIPS 24 micron

Hoffer, et al. 2011, in prep

K_0 and L_K

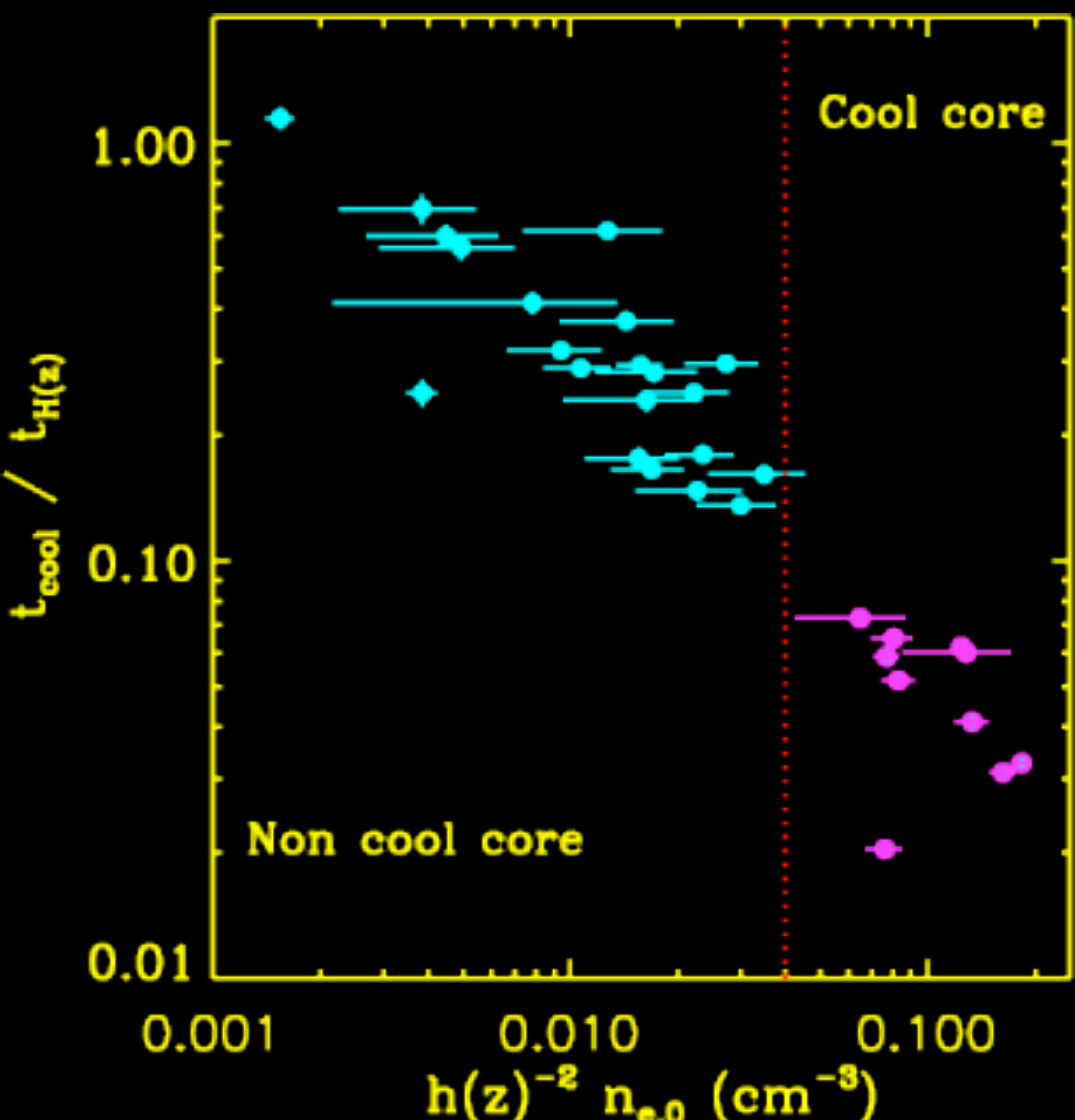

46
44
42
40
38
36
34
K lum [erg/s]
0
100
200
300
400
500
K_0
K-band luminosity inside
r=10 kpc does not depend
on K0 (K0>30 keV cm2)

K_0 and L_K


Extra L_K for some BCGs
with K_0<30 keV cm^2
K-band luminosity inside
r=10 kpc does not depend
on K_0 (K_0>30 keV cm^2)
K lum [erg/s]
K_0
46
44
42
40
38
36
34
0
100
200
300
400
500

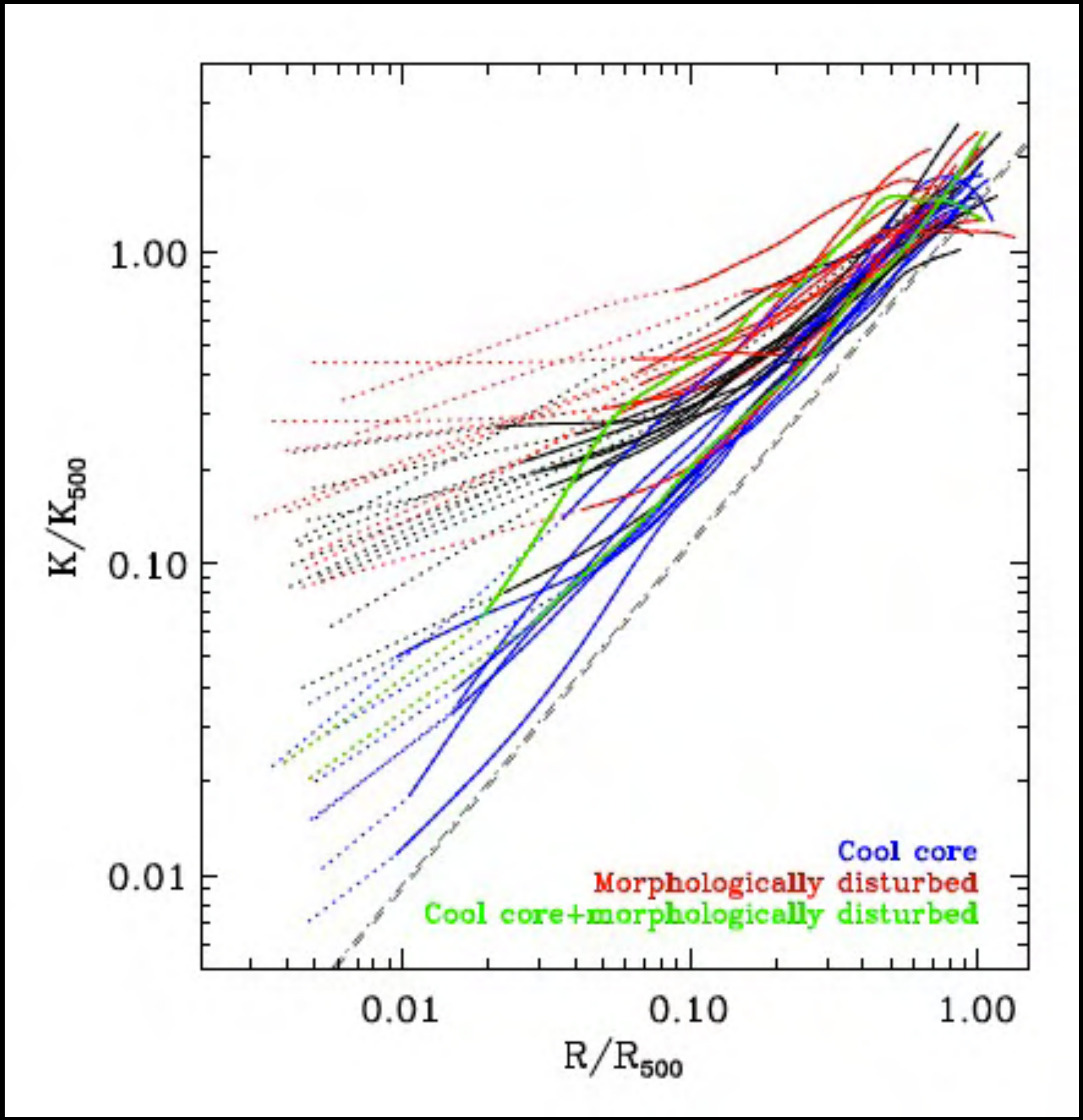
Multiphase Gas in REXCESS BCGs

REXCESS Cooling Times



REXCESS cool-core classification based on t_{cool} at 0.003 R_{500}

REXCESS Entropy Profiles



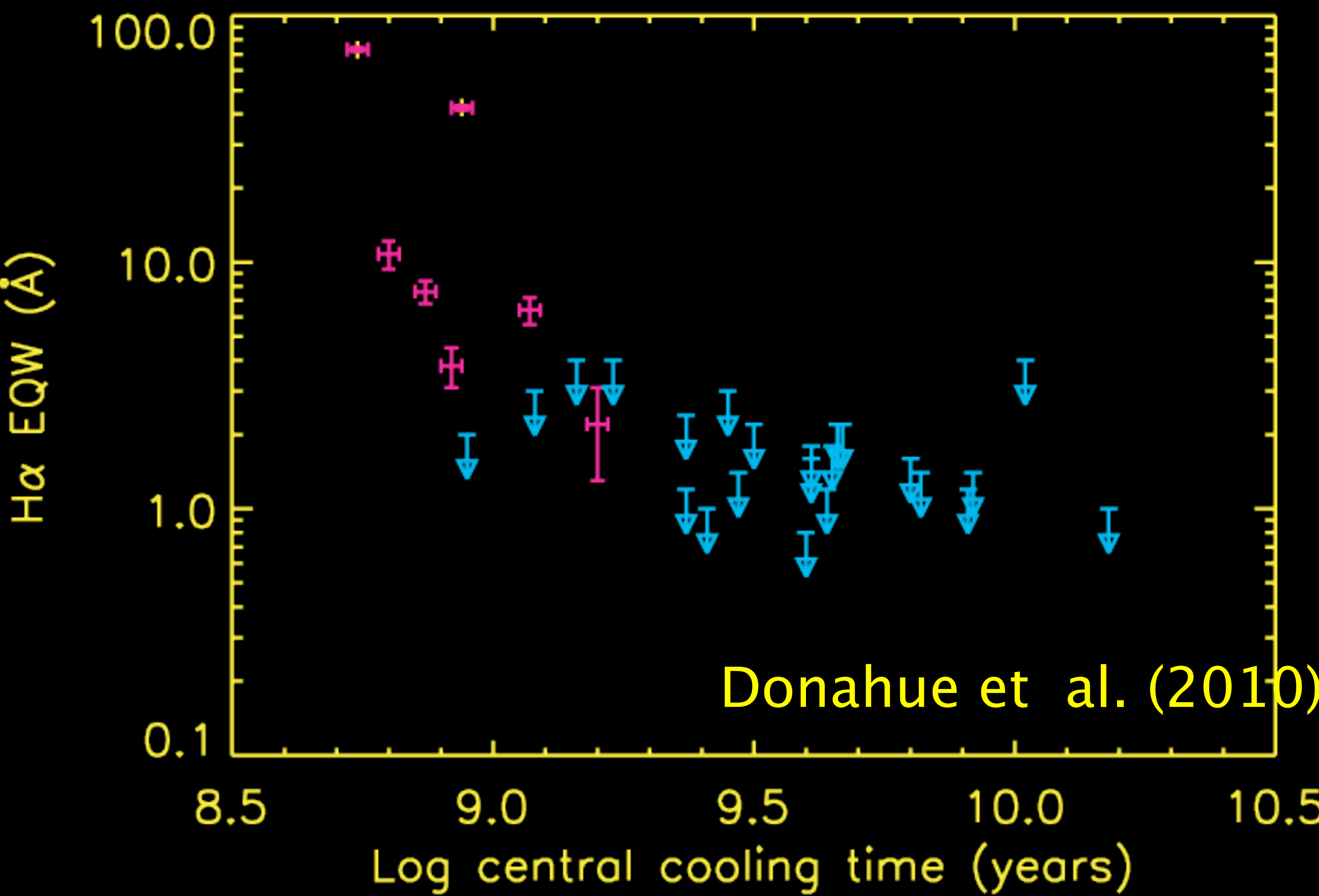
Entropy profile depends on cluster morphology.

Pratt et al. 2010

BCGs in REXCESS

- Haarsma et al. 2010: no correlation with BCG luminosity and central cooling time or K0.
- Donahue et al. 2010: only BCGs in REXCESS CC's exhibited excess UV and/or Hα emission ($f_{H\alpha}$ = 70% of REXCESS CCs)

Cooling-Time Threshold for Hα

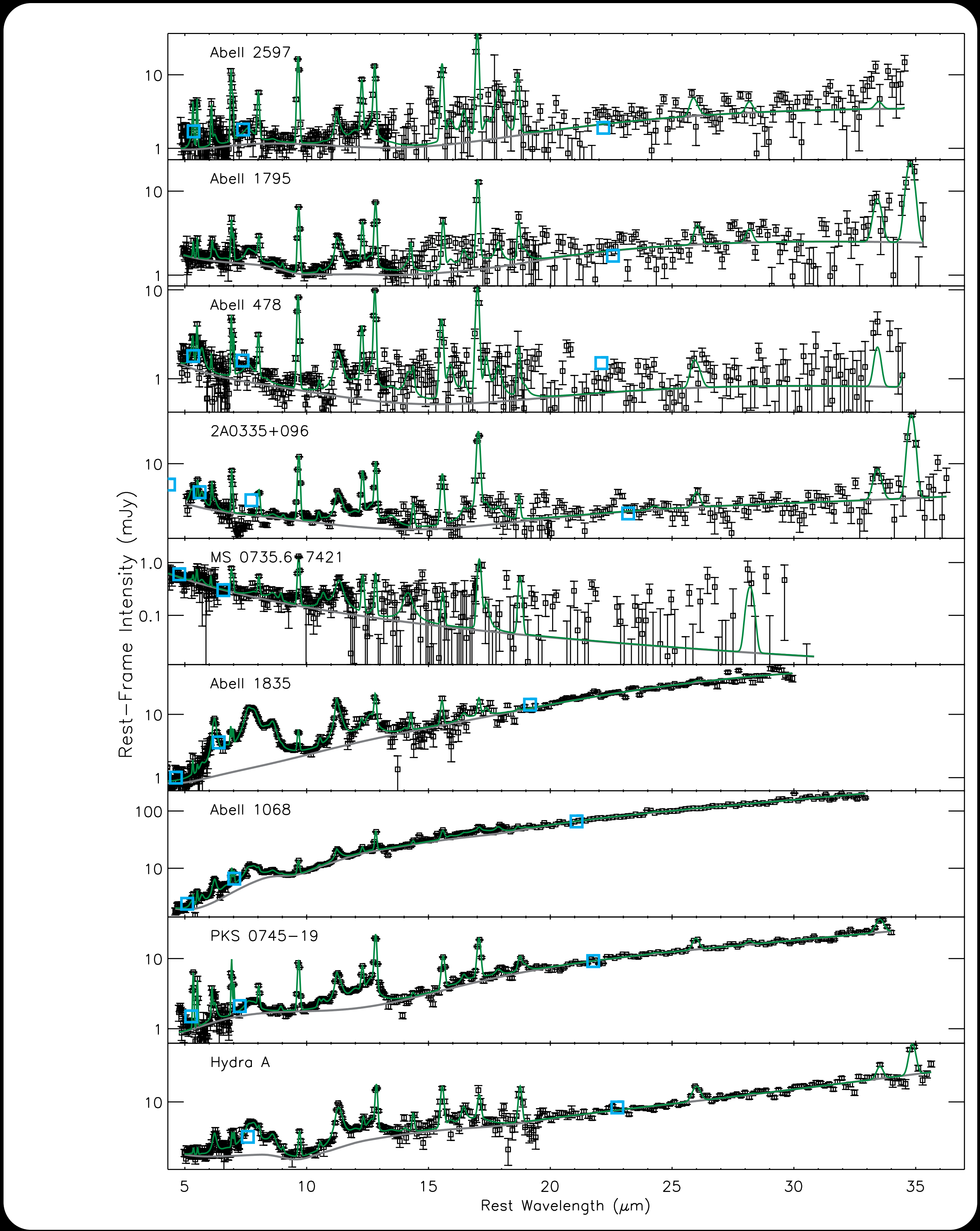


Donahue et al. (2010)

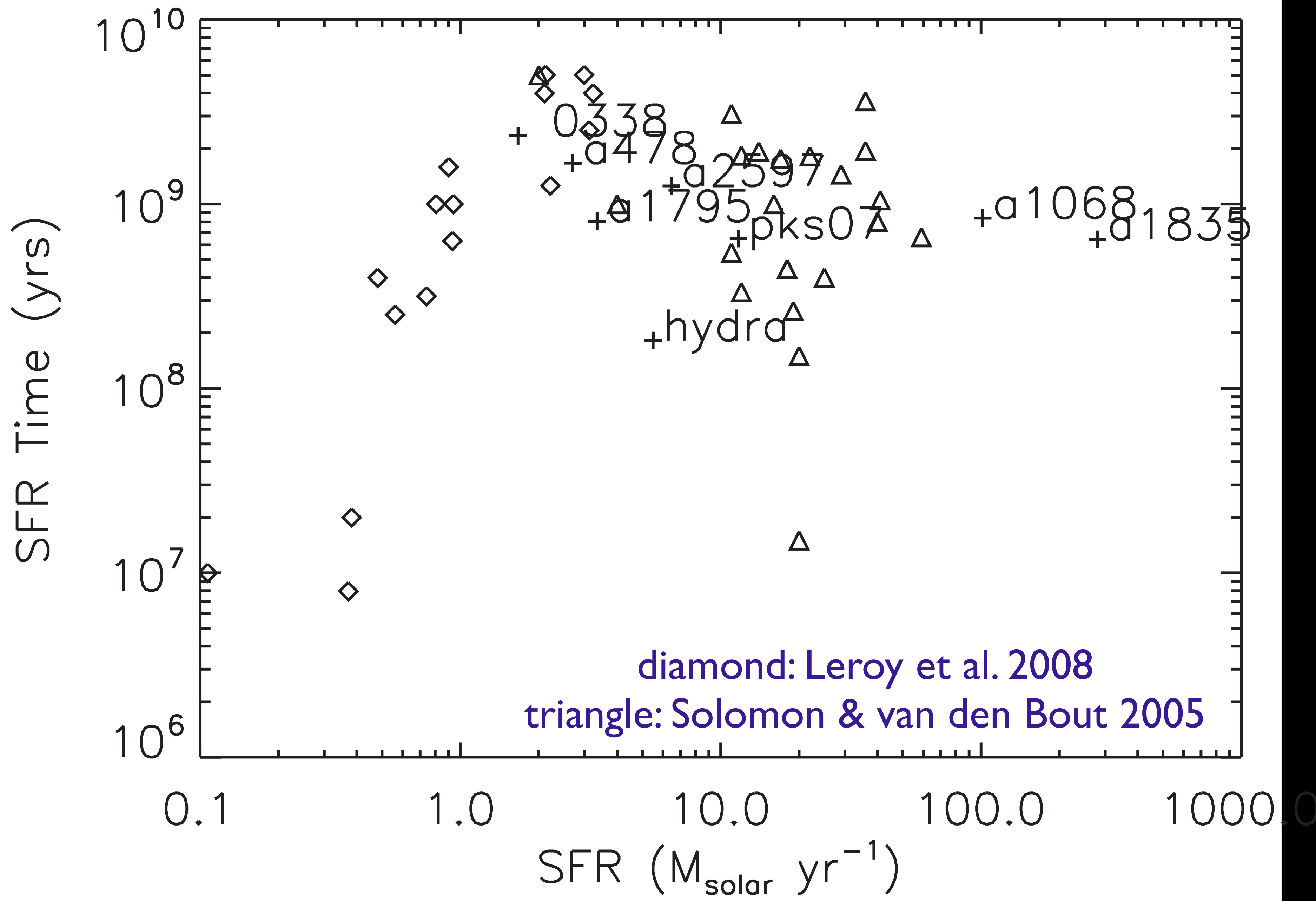
Spitzer studies of emission-line BCGs

Spitzer IRS Spectra of 9 cool-core BCGs

- Show PAHs, [Ne II], strong H2 lines
- PAH/IR and PAH/PAH ratios similar to star forming galaxies (Donahue et al. 2011)
- H_2 consumption timescales 1 Gyr or less, similar to star-forming galaxies and starbursts

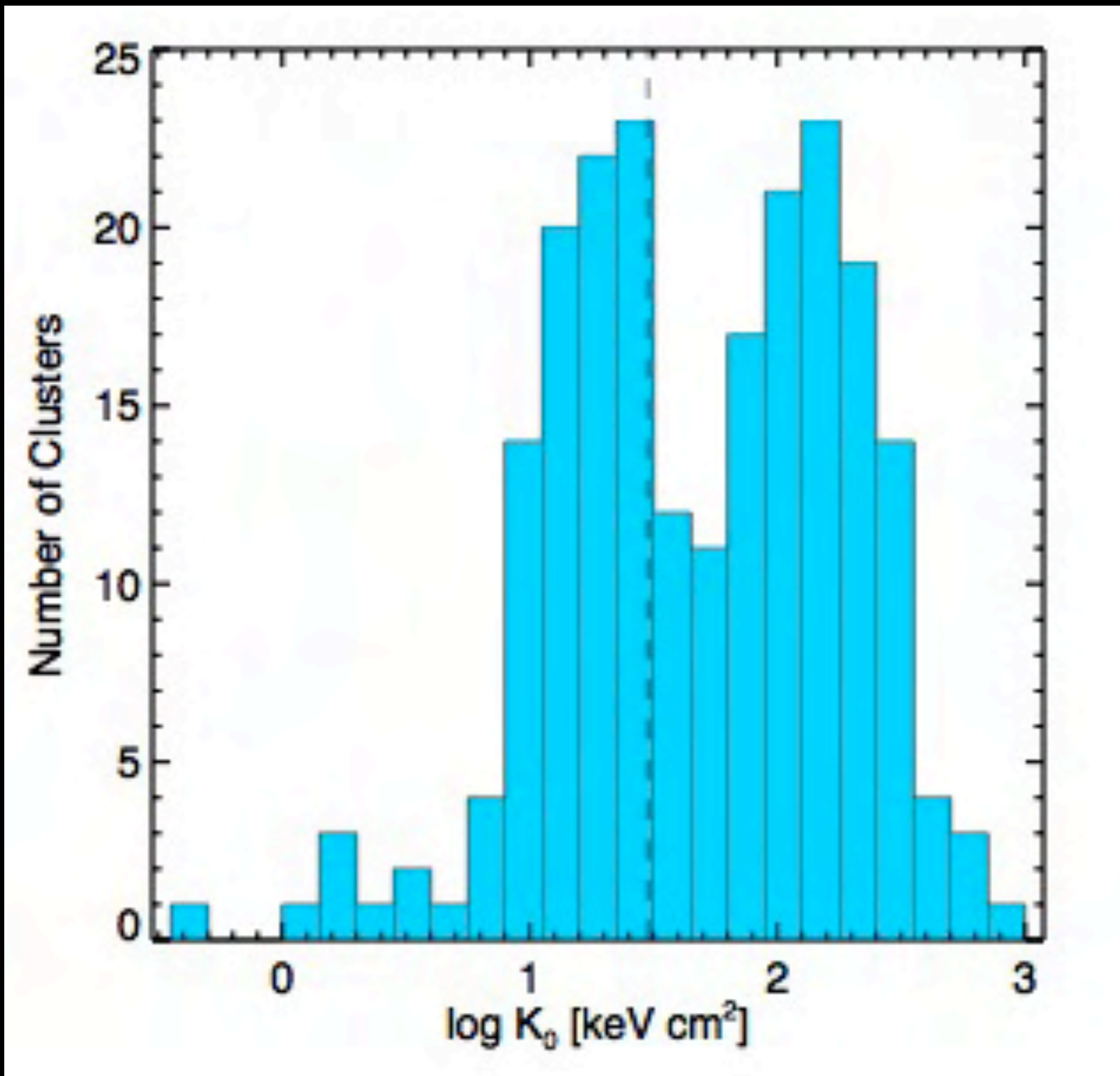


H_2 depletion ~ Gyr



speculations about the distribution of K_0

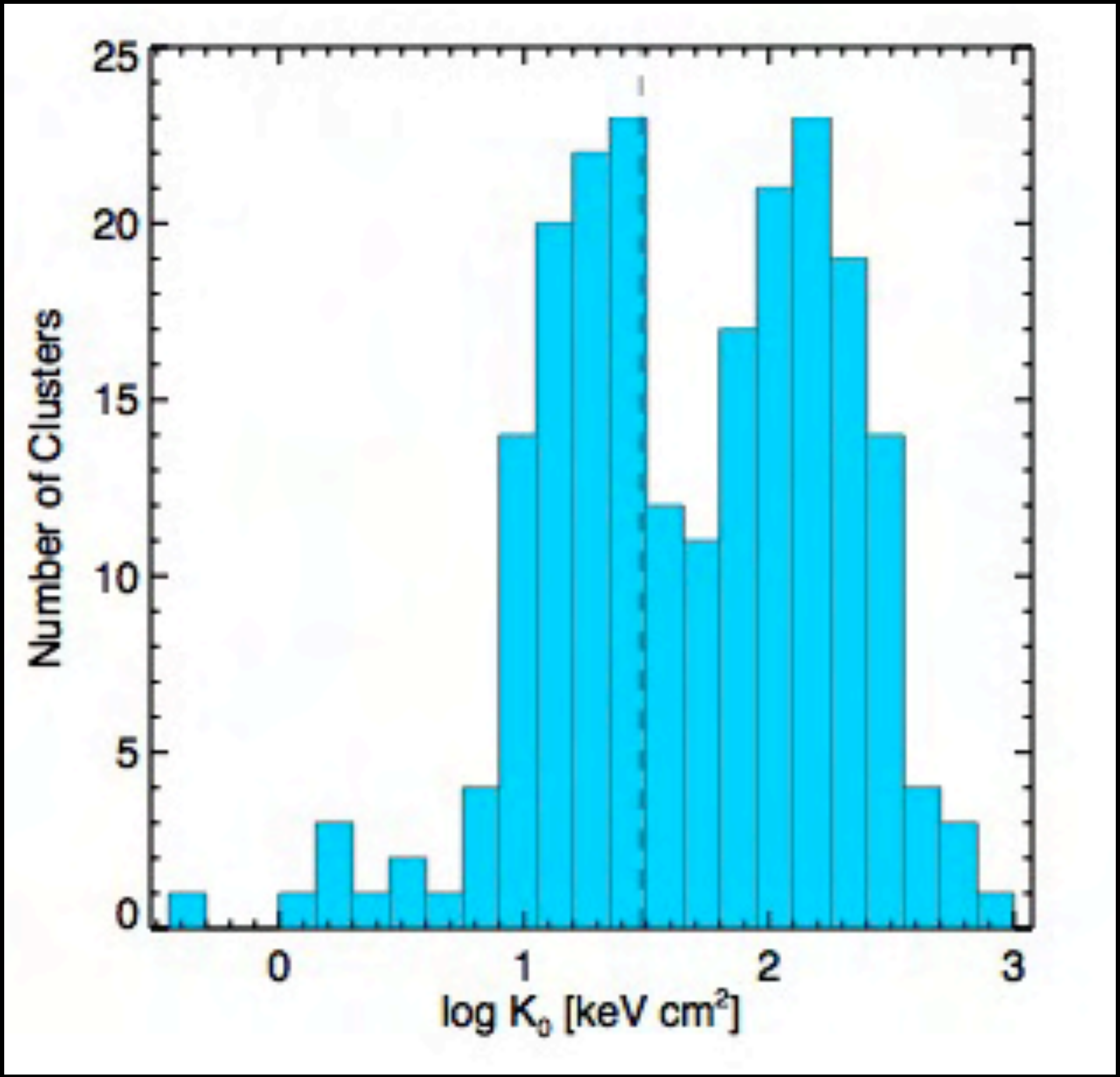
Distribution of Core Entropy



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

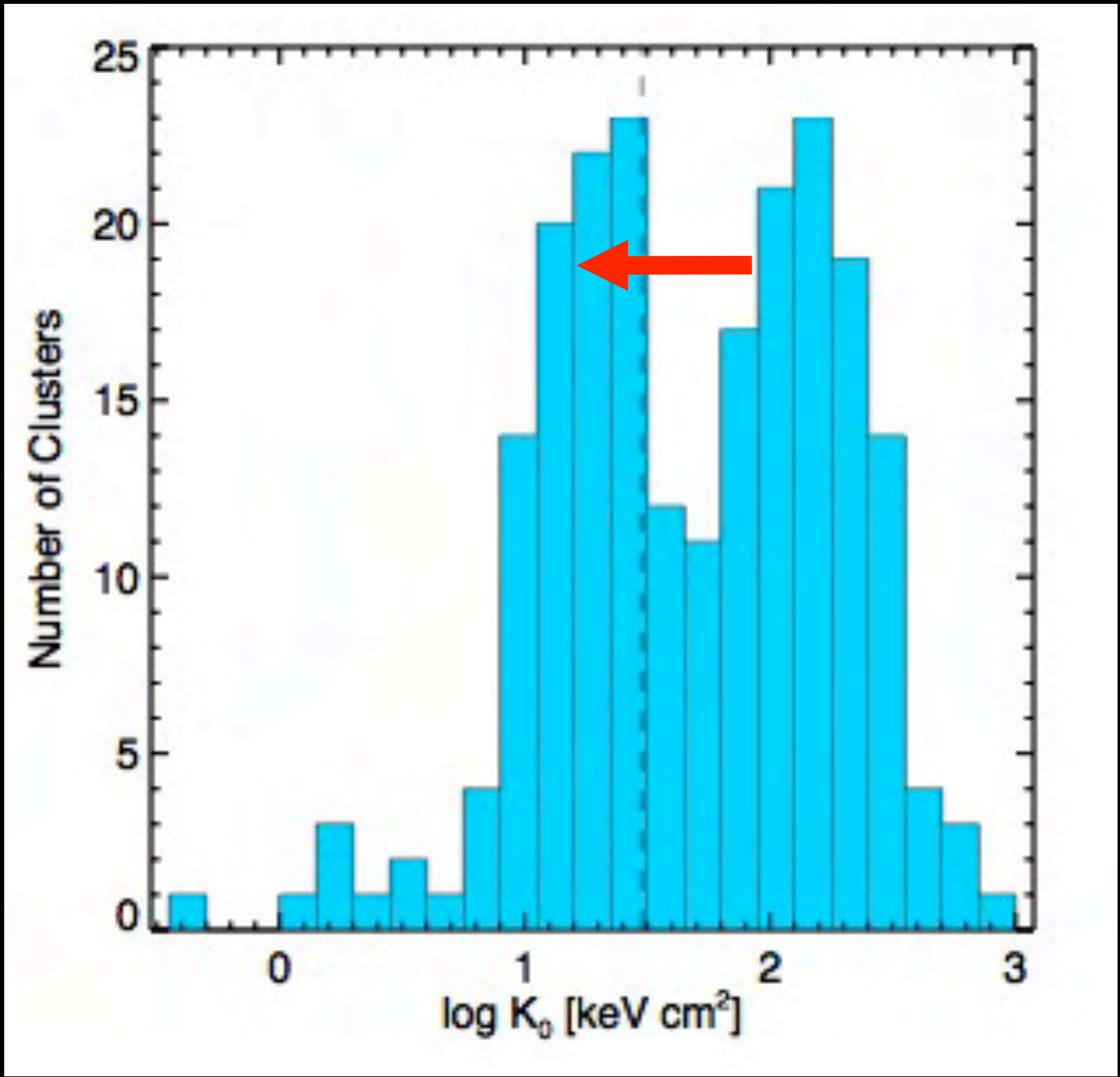
Cavagnolo et al. (2008)
See also Hudson & Reiprich

Distribution of Core Entropy



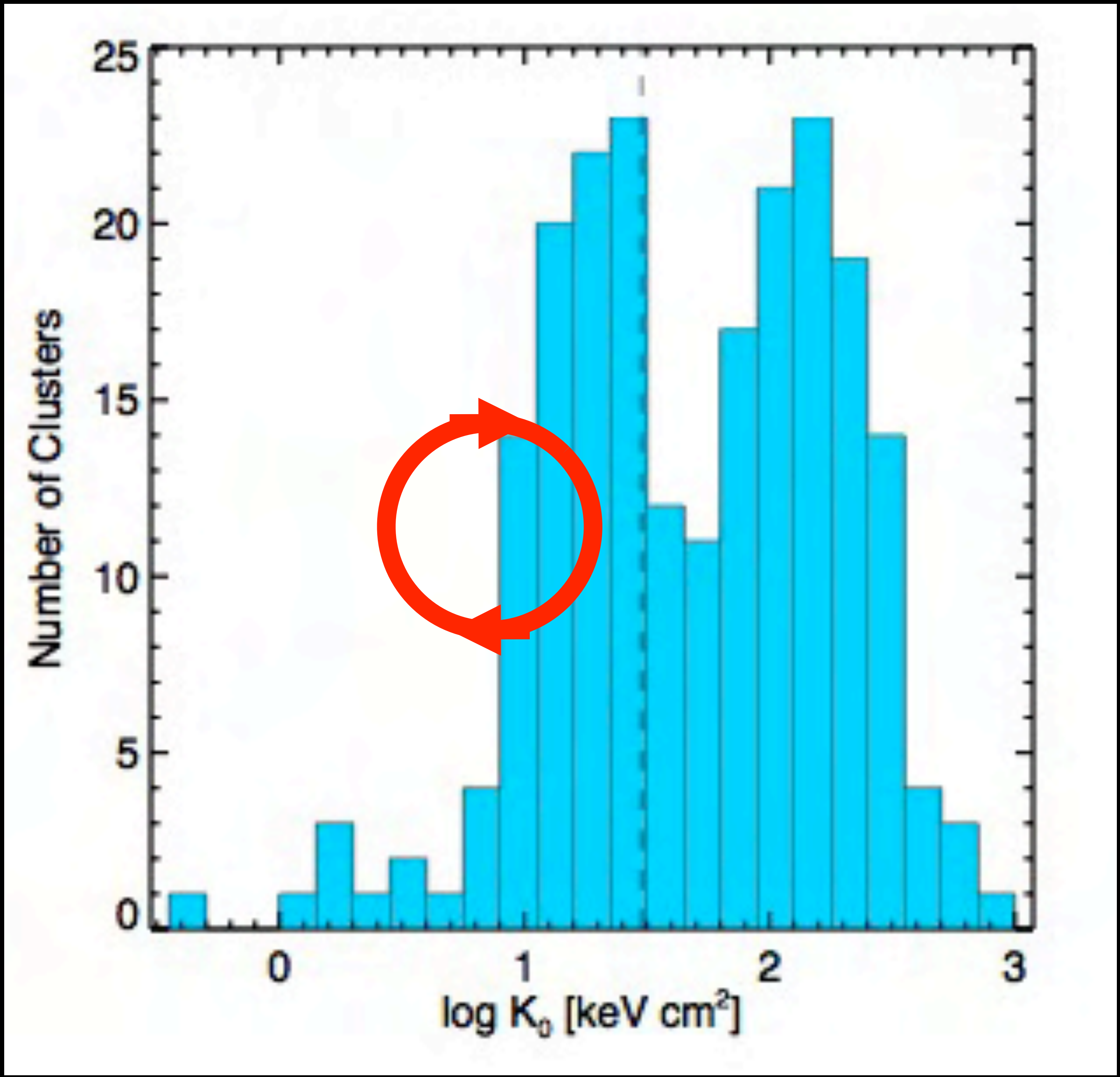
No consensus from simulations on distribution of K_0 without cooling & feedback

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

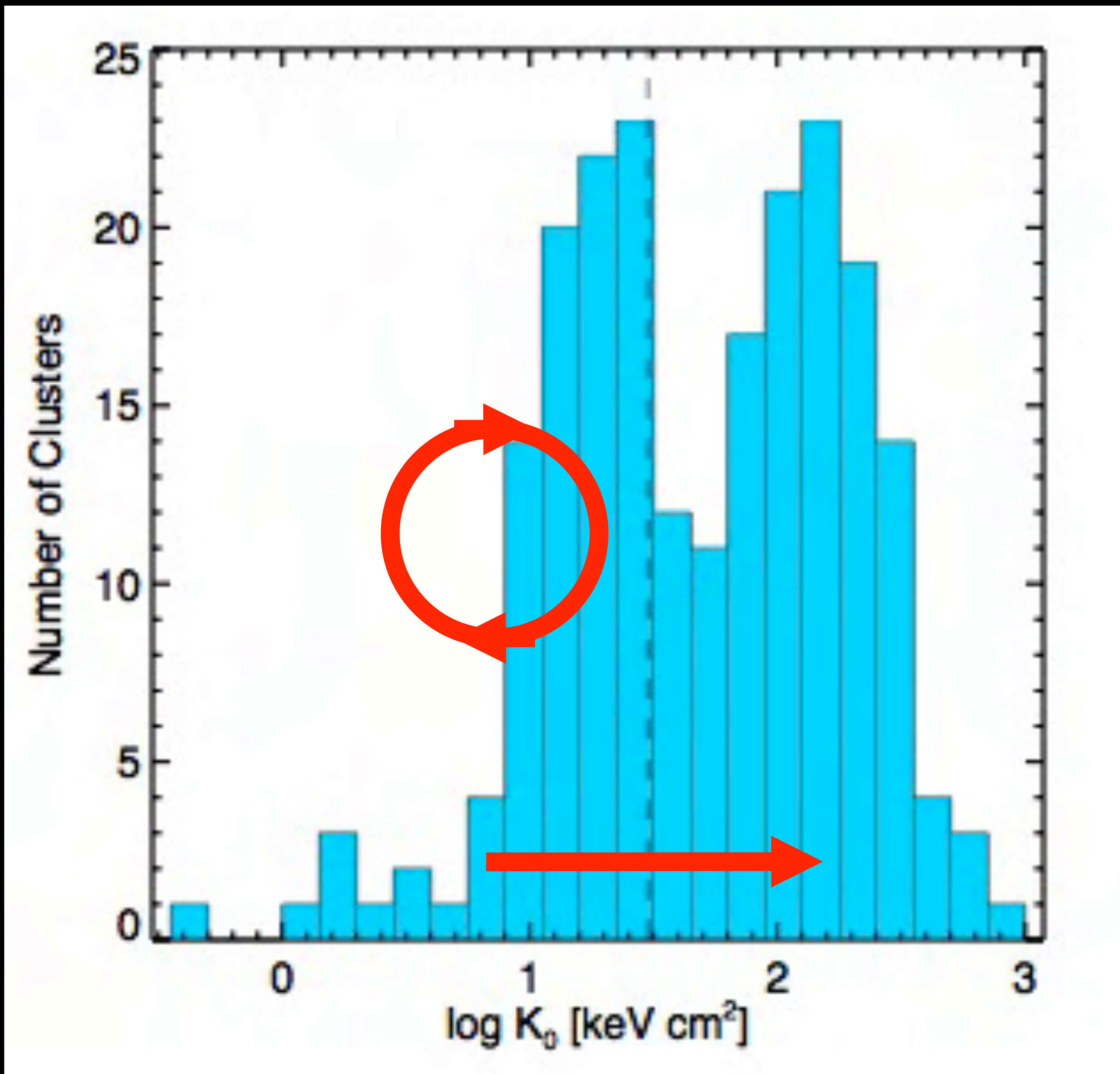


Episodic AGN feedback can plausibly maintain clusters in a quasi-steady state with

K_0 ~ 10-20 keV cm^2

Voit & Donahue (2005)
See also Kaiser & Binney

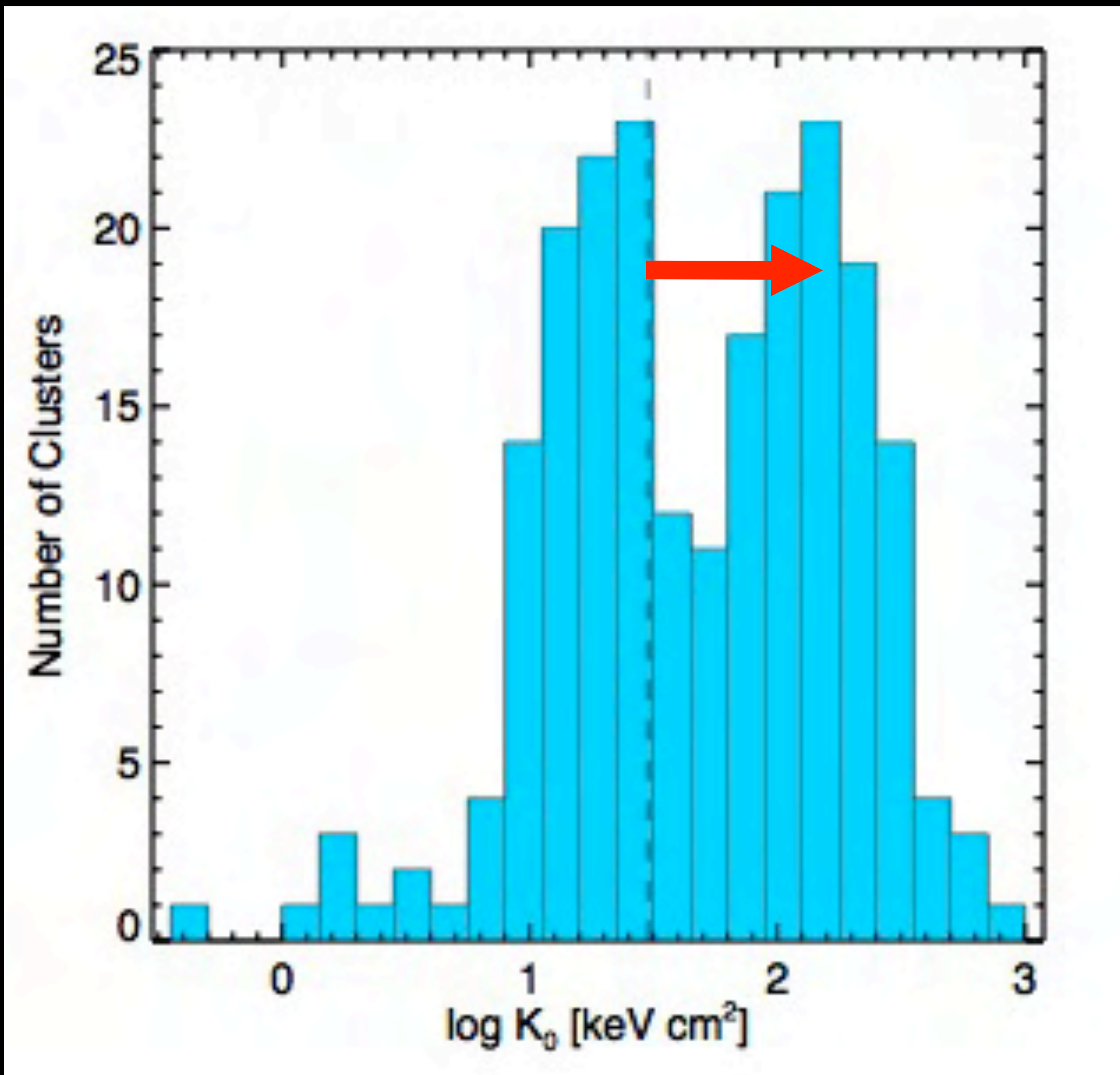
Distribution of Core Entropy



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

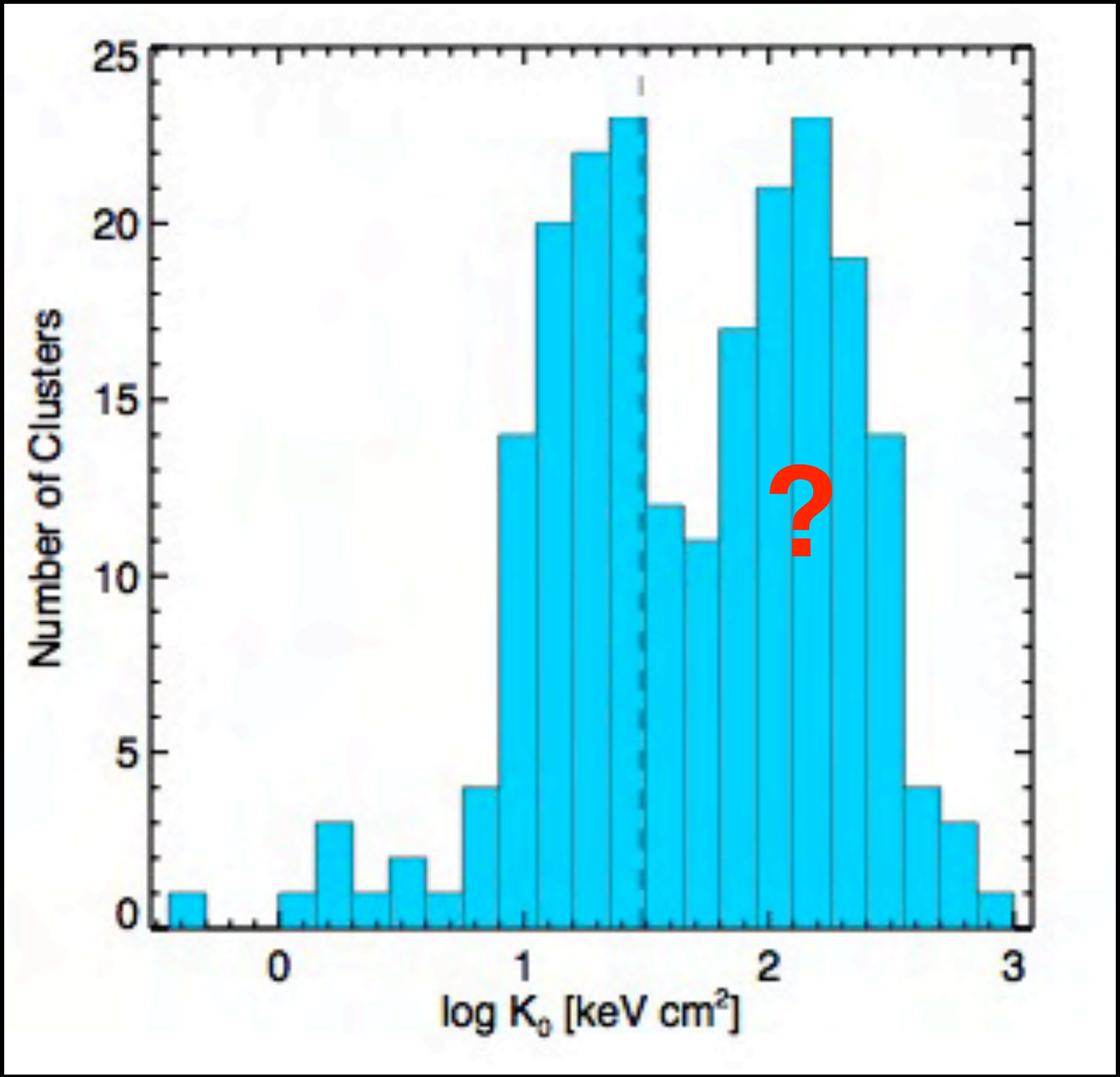
Mergers are also ineffective at producing large K_0 jumps

Distribution of Core Entropy



If conduction is operating, mergers can more easily cause clusters with $K_0 > 30$ keV cm² 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?

Summary

- Cluster population is bimodal (may include an intermediate mode)
- Central AGN and BCG star formation activity responds to state of ICM
- ICM is multiphase for low K_0
- High K_0 seems more common in disturbed clusters