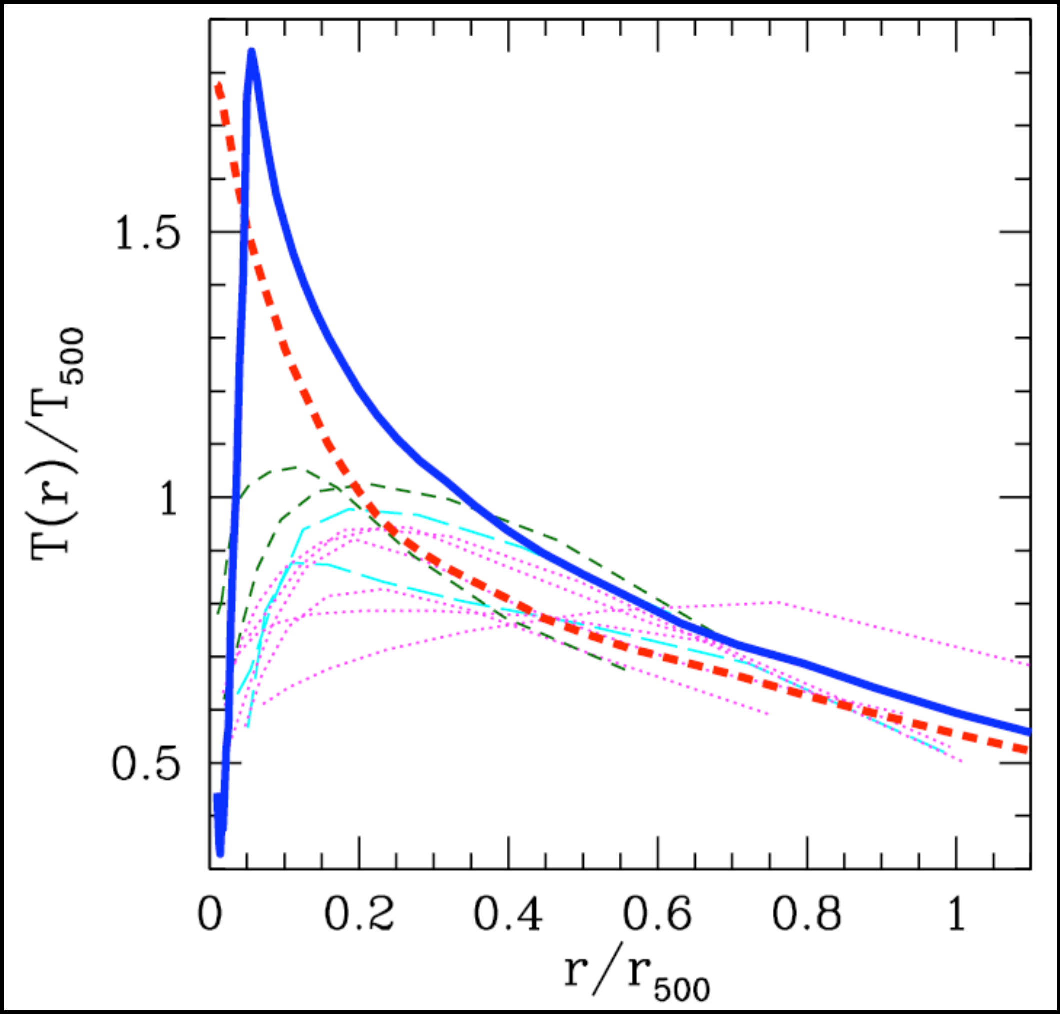
Conduction and Multiphase Structure in the ICM

Disclaimer

- This talk will ***not*** claim that conduction solves the cooling-flow problem
- Conduction might be important for
  - Determining when AGN feedback is triggered
  - Distributing AGN feedback energy
  - Regulating star formation in brightest cluster galaxies (BCGs)

Thermodynamics of Cluster Cores

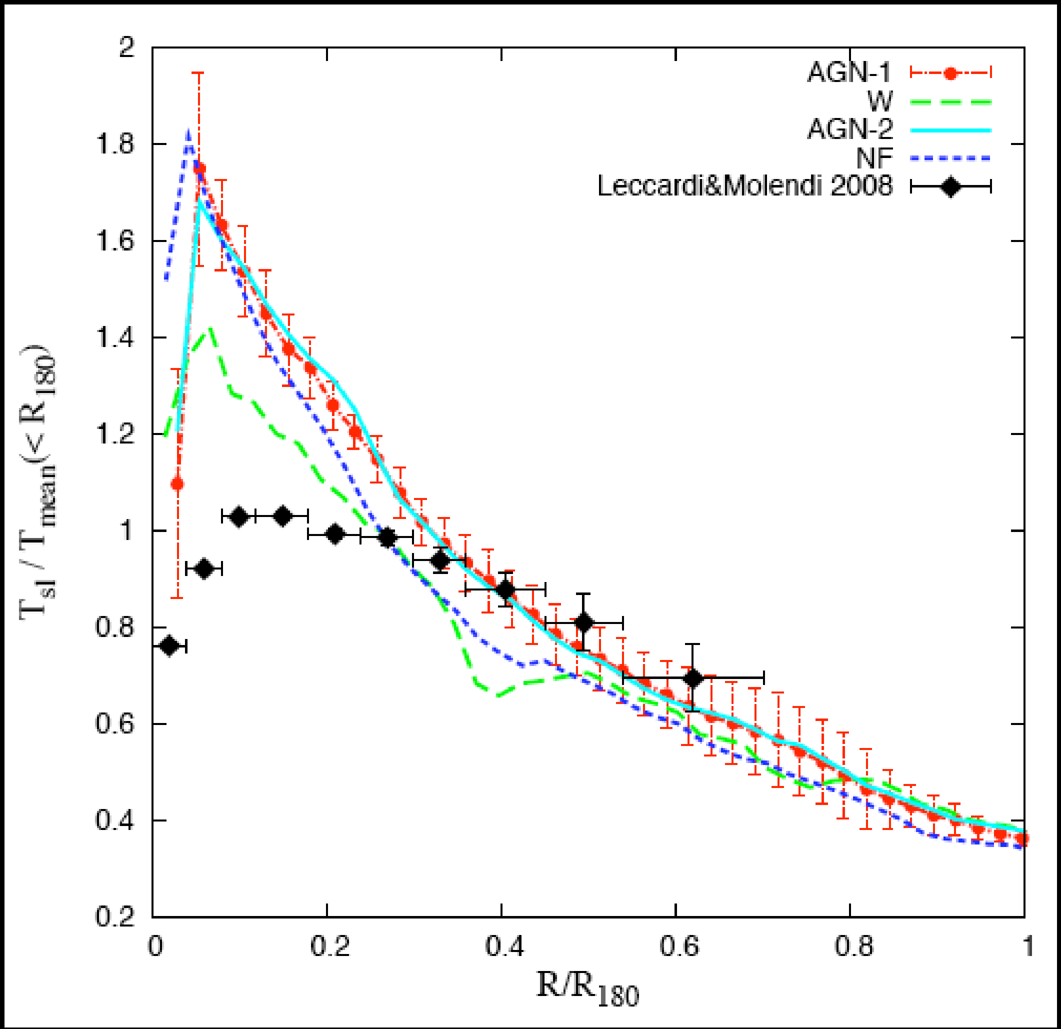
Core Temperature Profiles



Simulations have difficulty producing core temperature profiles that agree with observations

Nagai et al. (2007)

Core Temperature Profiles



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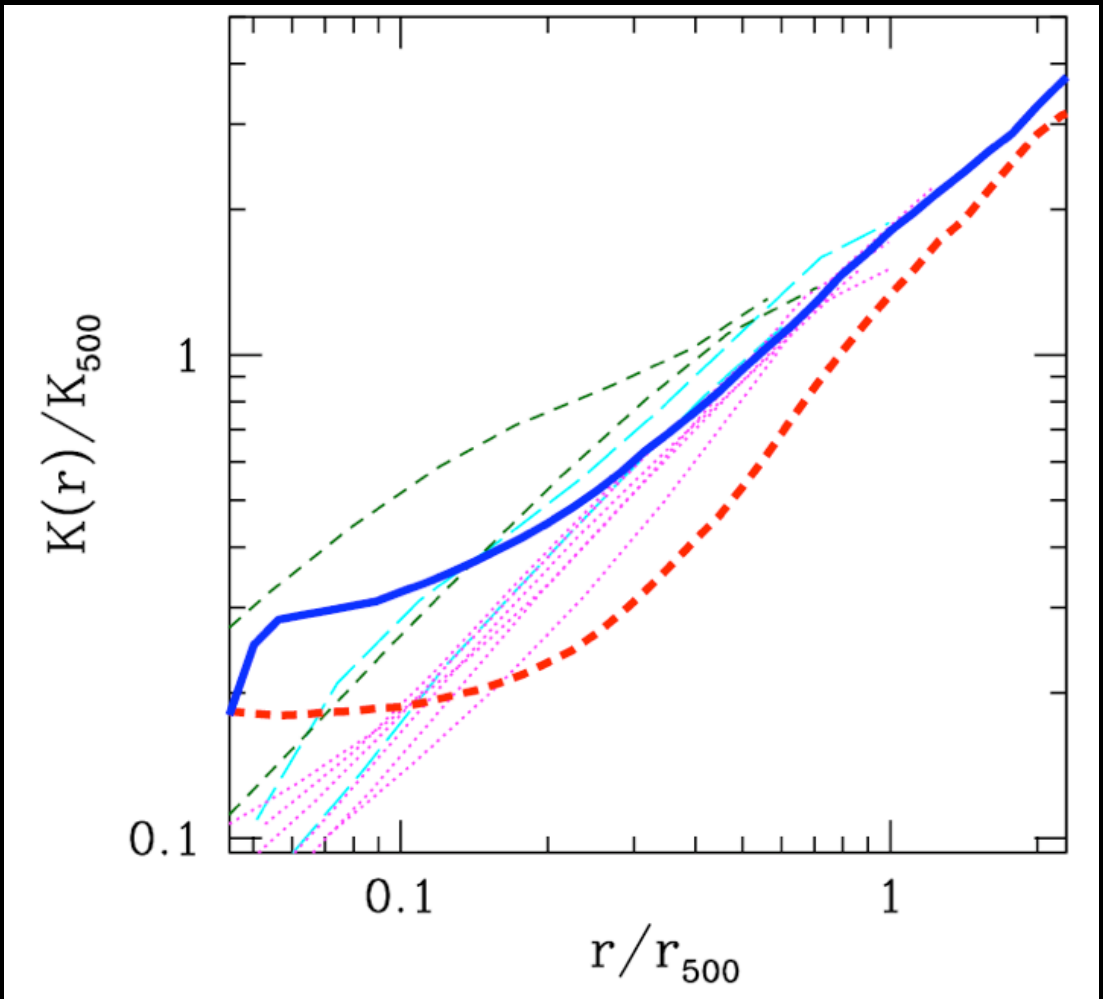
Fabjan et al. (2009)

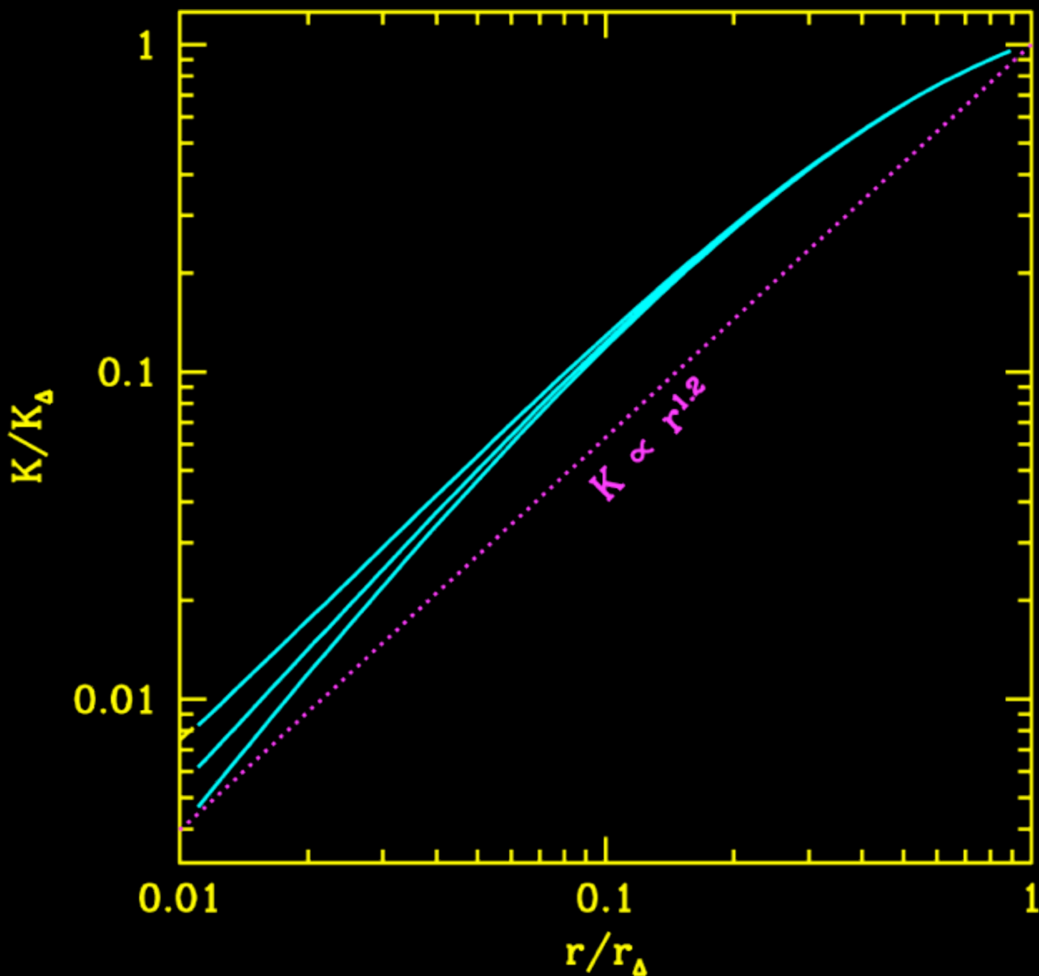
Core Entropy Profiles



Inhomogeneous cooling and condensation in simulations may be producing an unrealistic entropy plateau

Nagai et al. (2007)

Analytical Cooling Solution

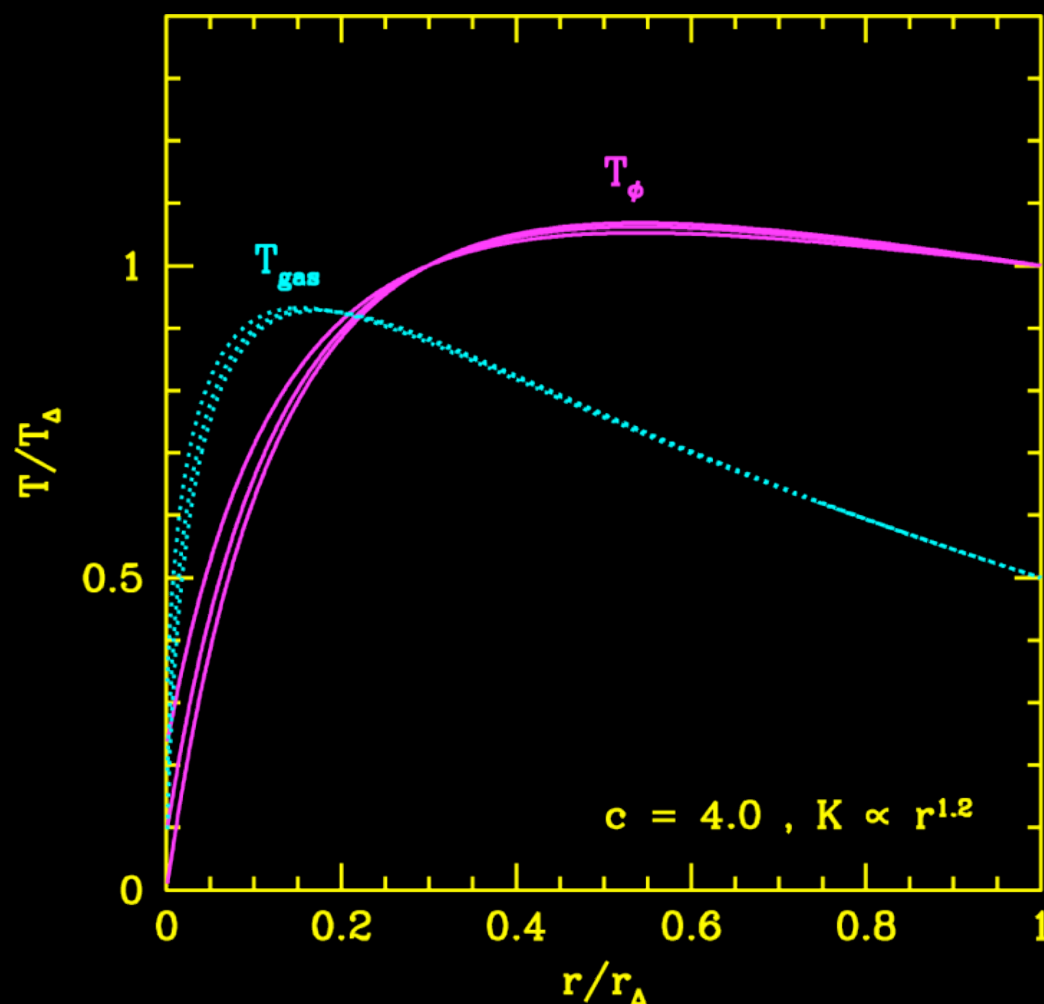


Steady-state free-free cooling in an NFW potential would produce a nearly power-law entropy profile with

$$K \sim r^{1.2}$$

Analytical solution forces gradients to be smooth

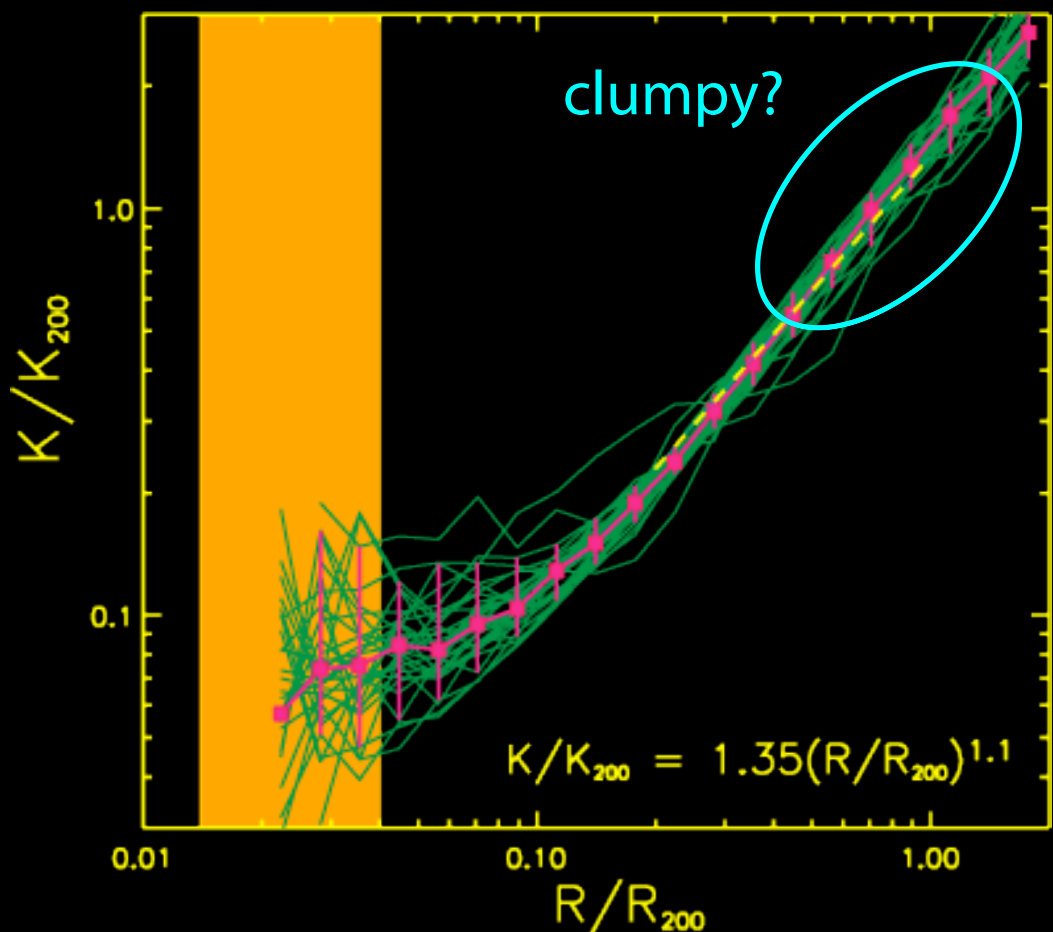
Analytical Cooling Solution



If core entropy is low enough, gas temperature profile reflects the gravitational potential

$T_\phi \sim M(r)/r$

Clusters without Cooling



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

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

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

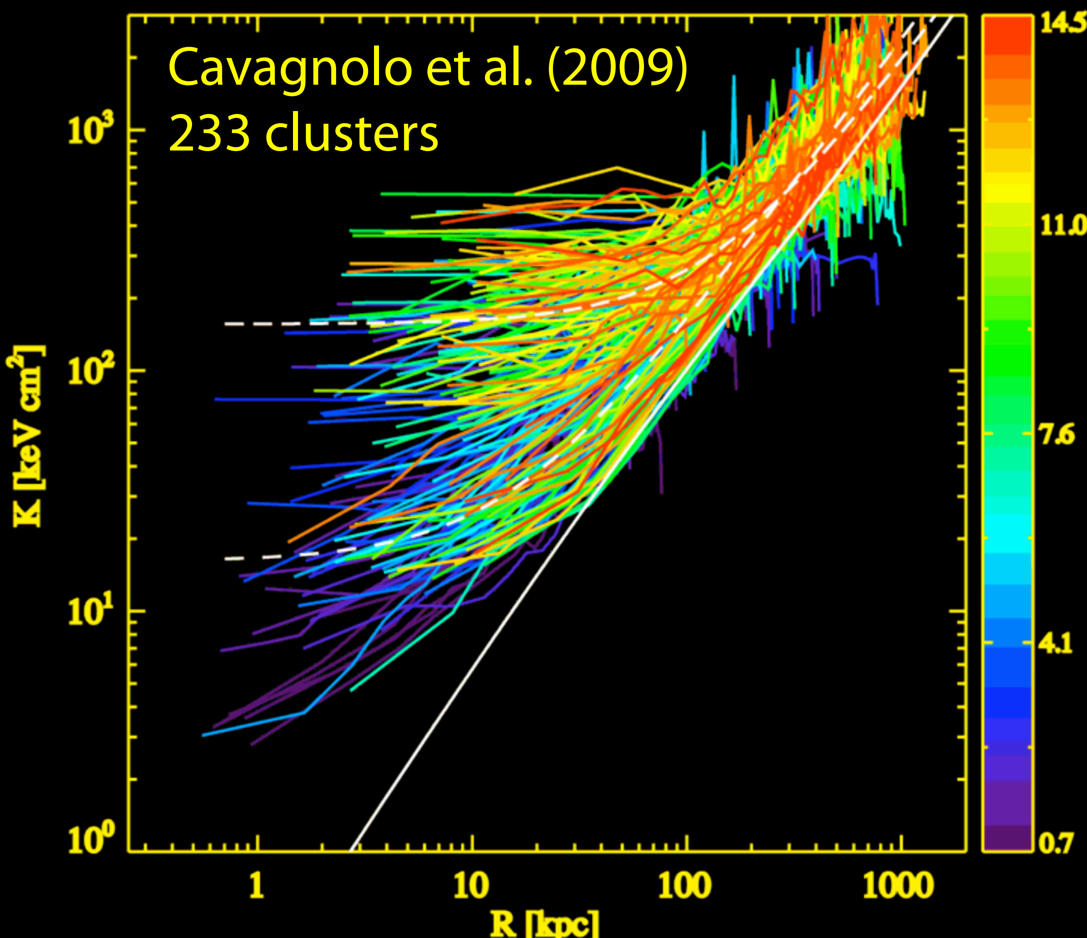
Voit, Kay, & Bryan (2005)

Chandra Core Entropy Survey

Motivation

- How do the entropy profiles of real clusters deviate from the no-cooling profiles?
- What do those deviations reveal about the influence of non-gravitational processes on the ICM?
- How do characteristics of entropy profiles relate to signatures of feedback?

Chandra Entropy Profiles



Pure cooling model is lower limit to observed profiles

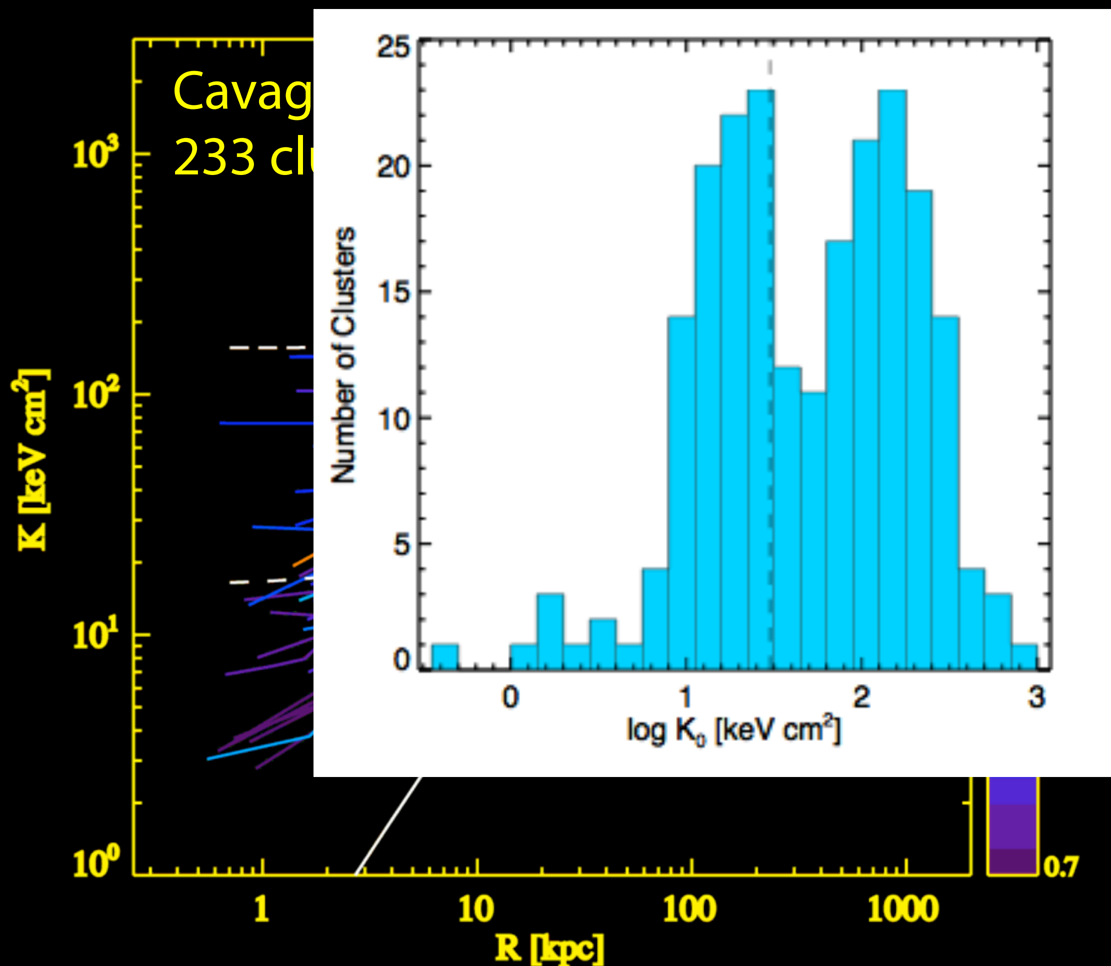
Most profiles are well fit with:

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

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

$\alpha \sim 1.2$

Chandra Entropy Profiles



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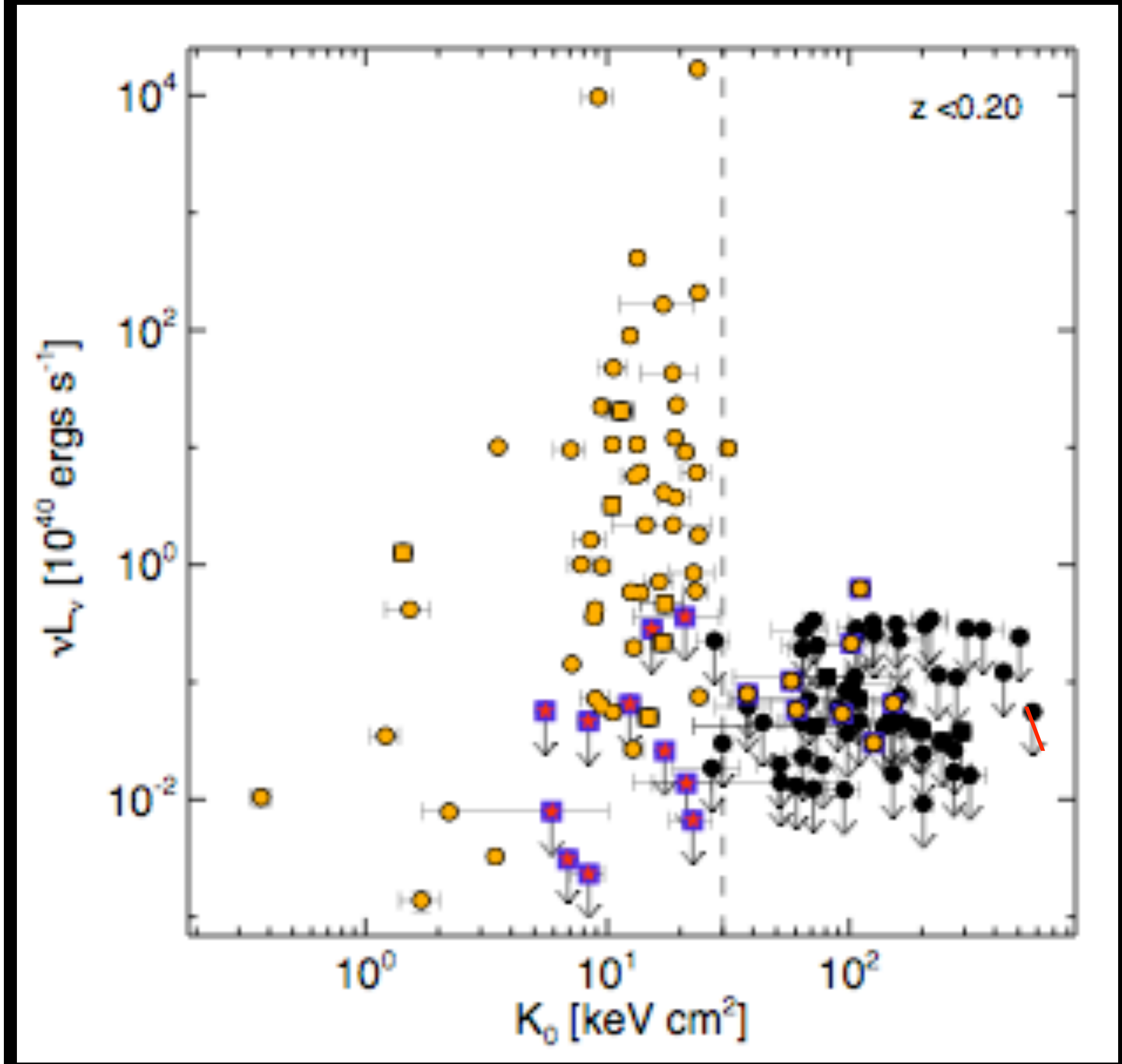
K_0 *and Radio Power*



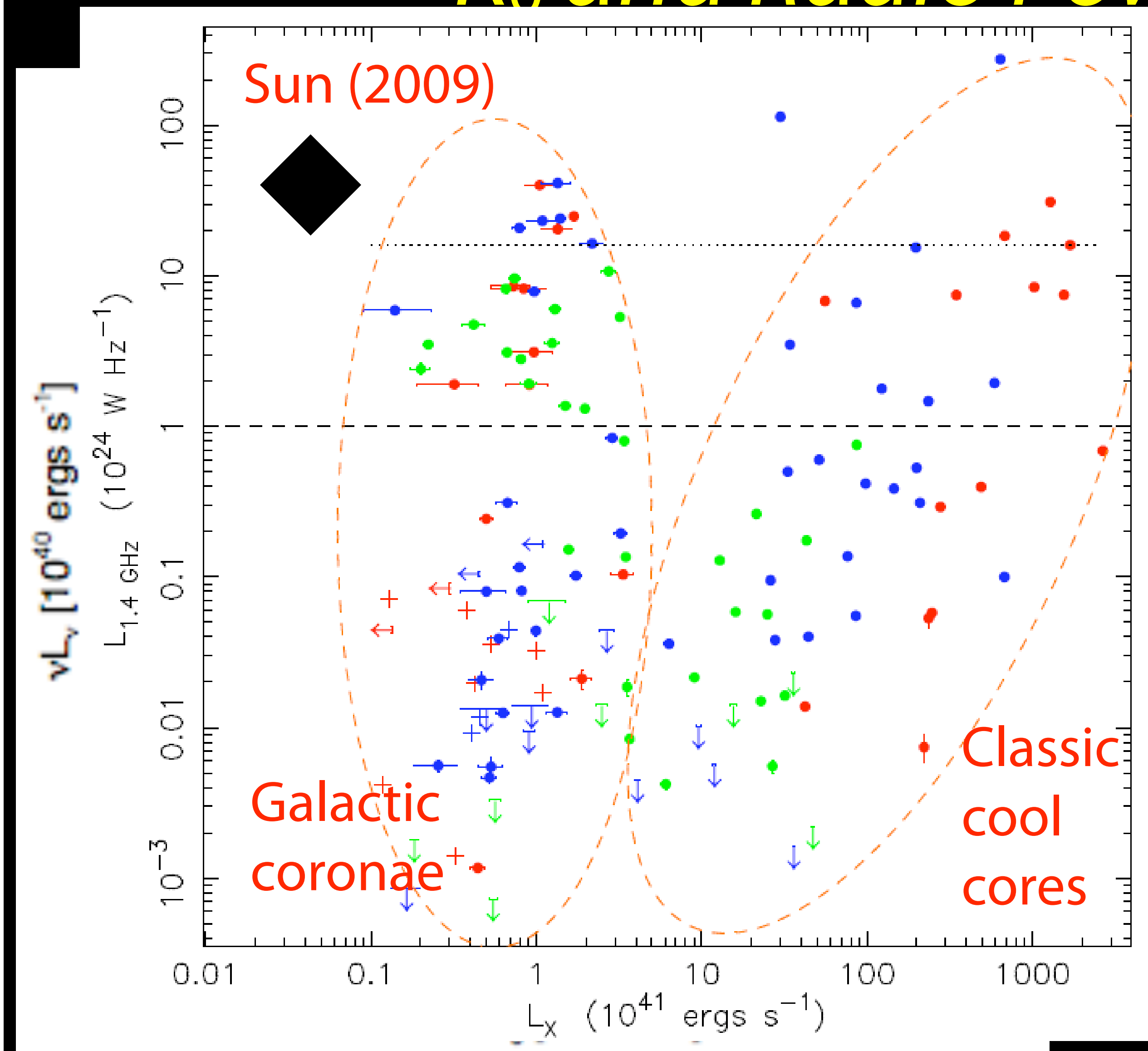
Central galaxy of a $z < 0.2$ cluster can be a strong radio source only if

$K_0 < 30$ keV cm^2

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

Cavagnolo et al. (2008)

K_0 and Radio Power



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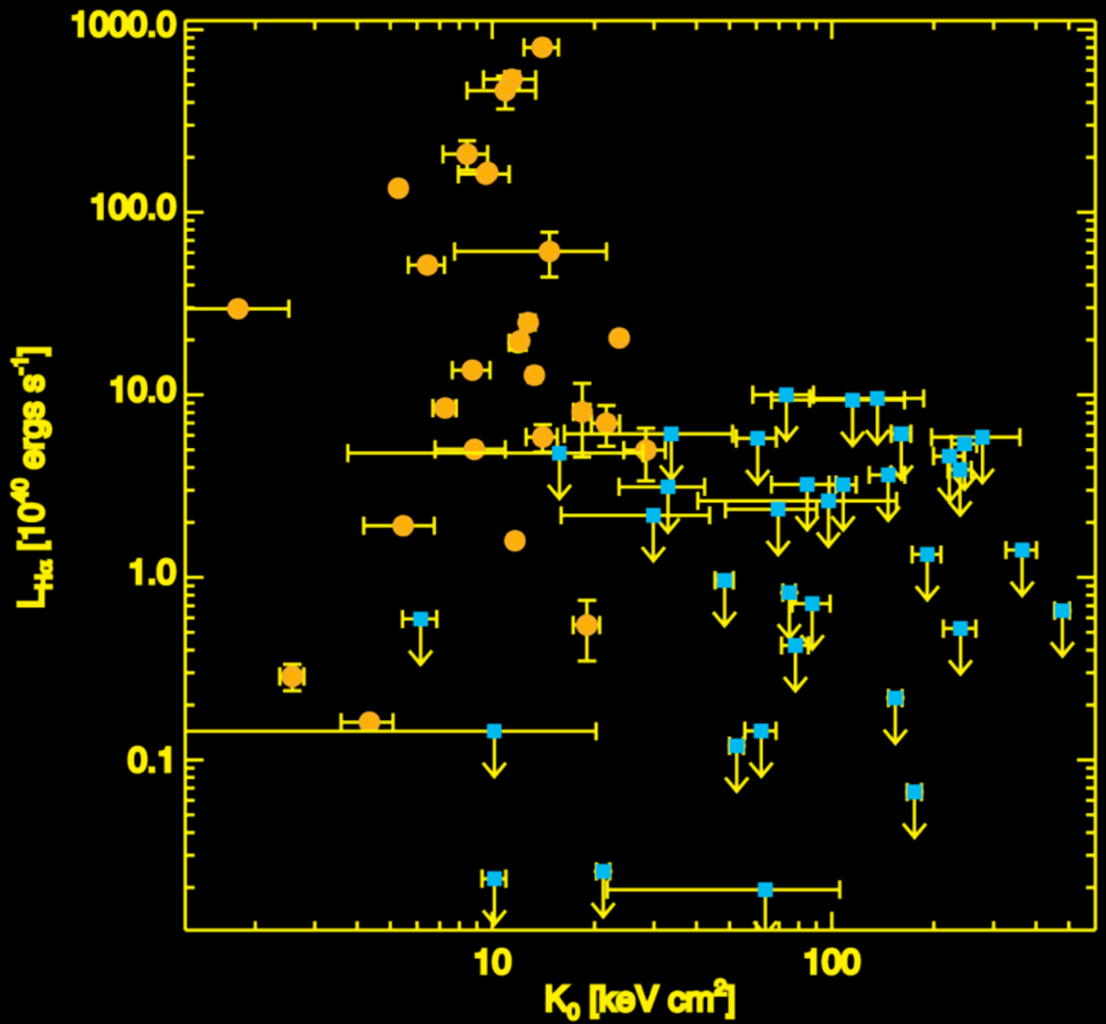
K_0 and Hα Emission



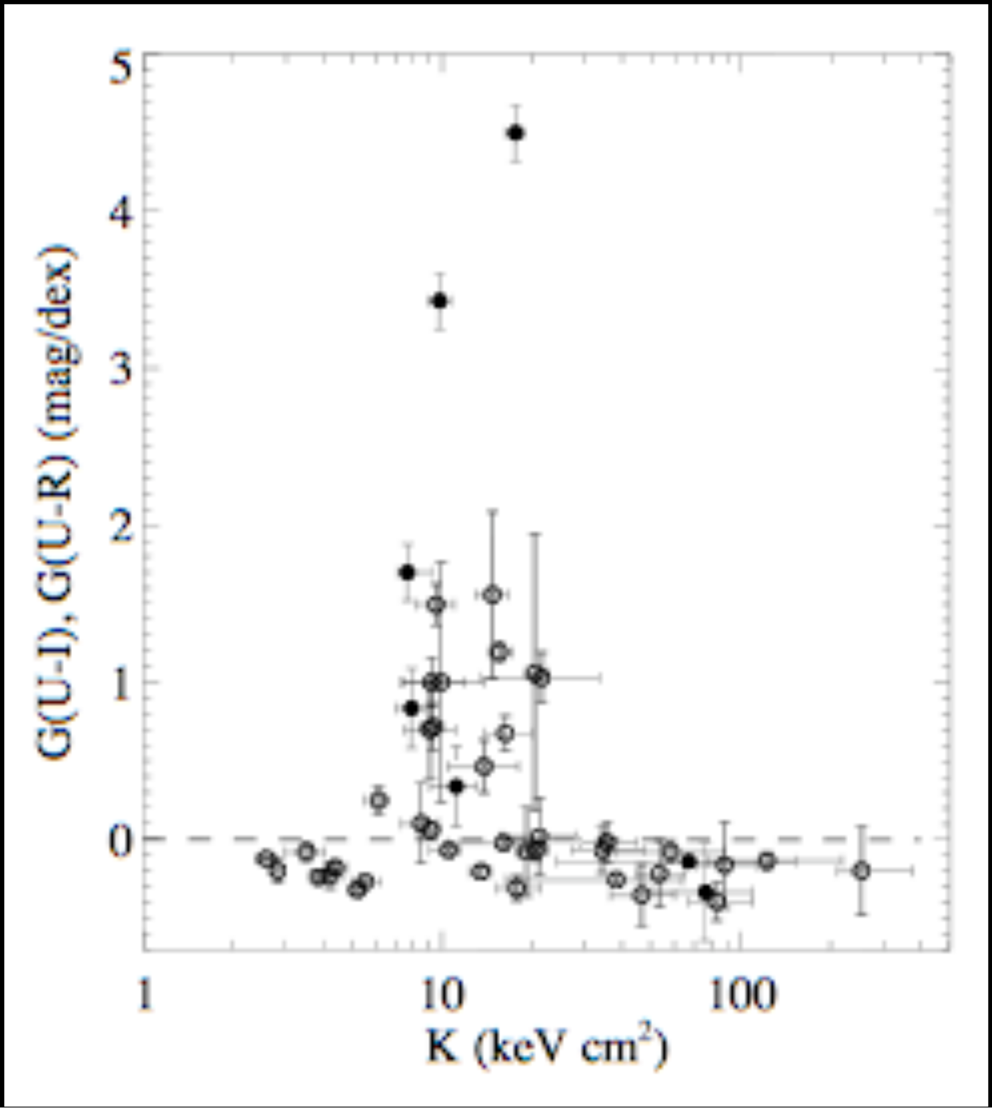
Central galaxy can have emission-line nebulosity only if

$K_0 < 30$ keV cm^2

Hα data from many diverse sources

Cavagnolo et al. (2008)

K_0 and Star Formation

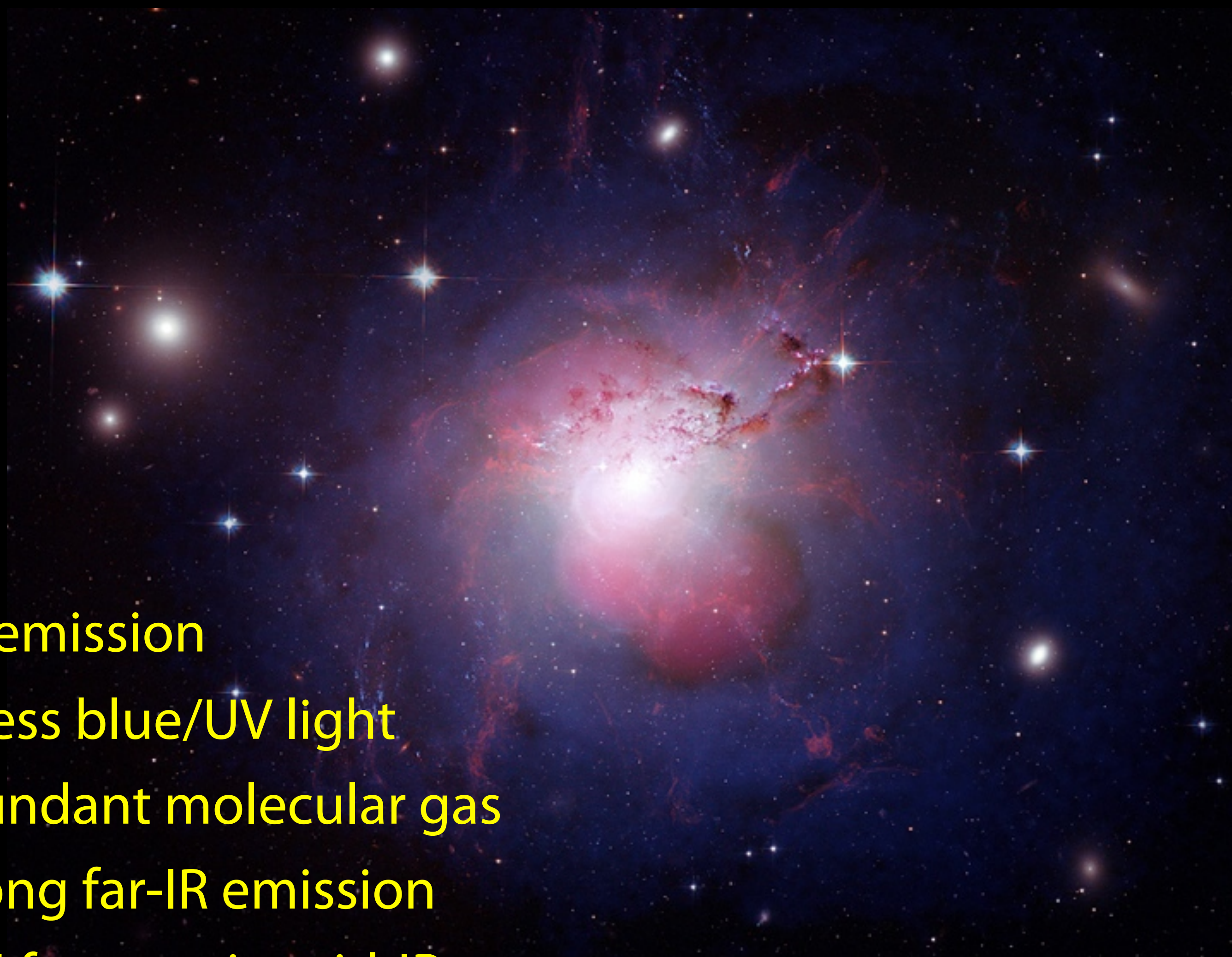


Central galaxy can have blue gradient indicating star formation only if

$K_0 < 30$ keV cm^2

Rafferty et al. (2008)

Star Formation in BCGs



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

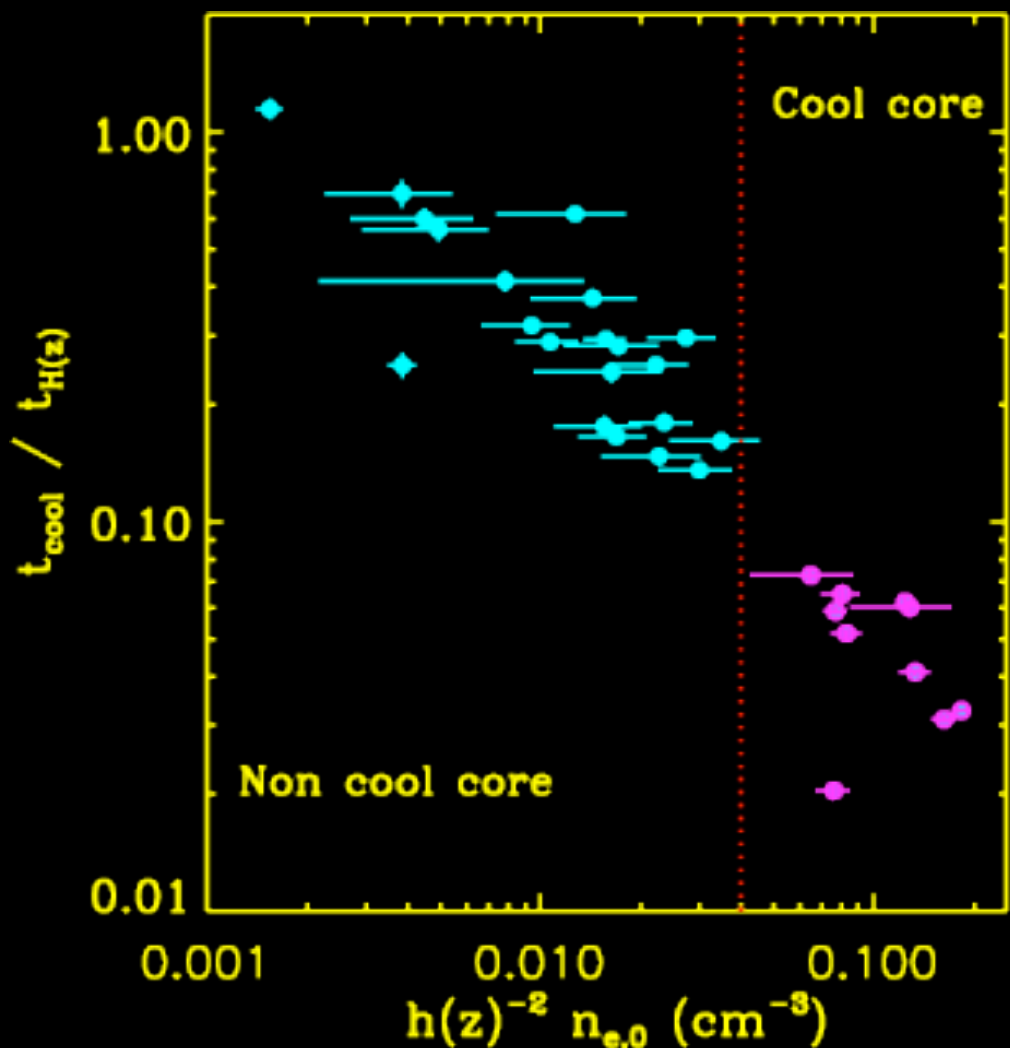
NGC 1275: Perseus

Transition to Multiphase ICM

- Presence of AGN feedback, cool gas, and star formation in BCG are closely coupled to state of hot ICM
- Threshold: $t_c <$ 1 Gyr or $K_0 <$ 30 keV cm^2
- Conditions needed to trigger AGN feedback are nearly identical to those that promote multiphase ICM and star formation in BCG

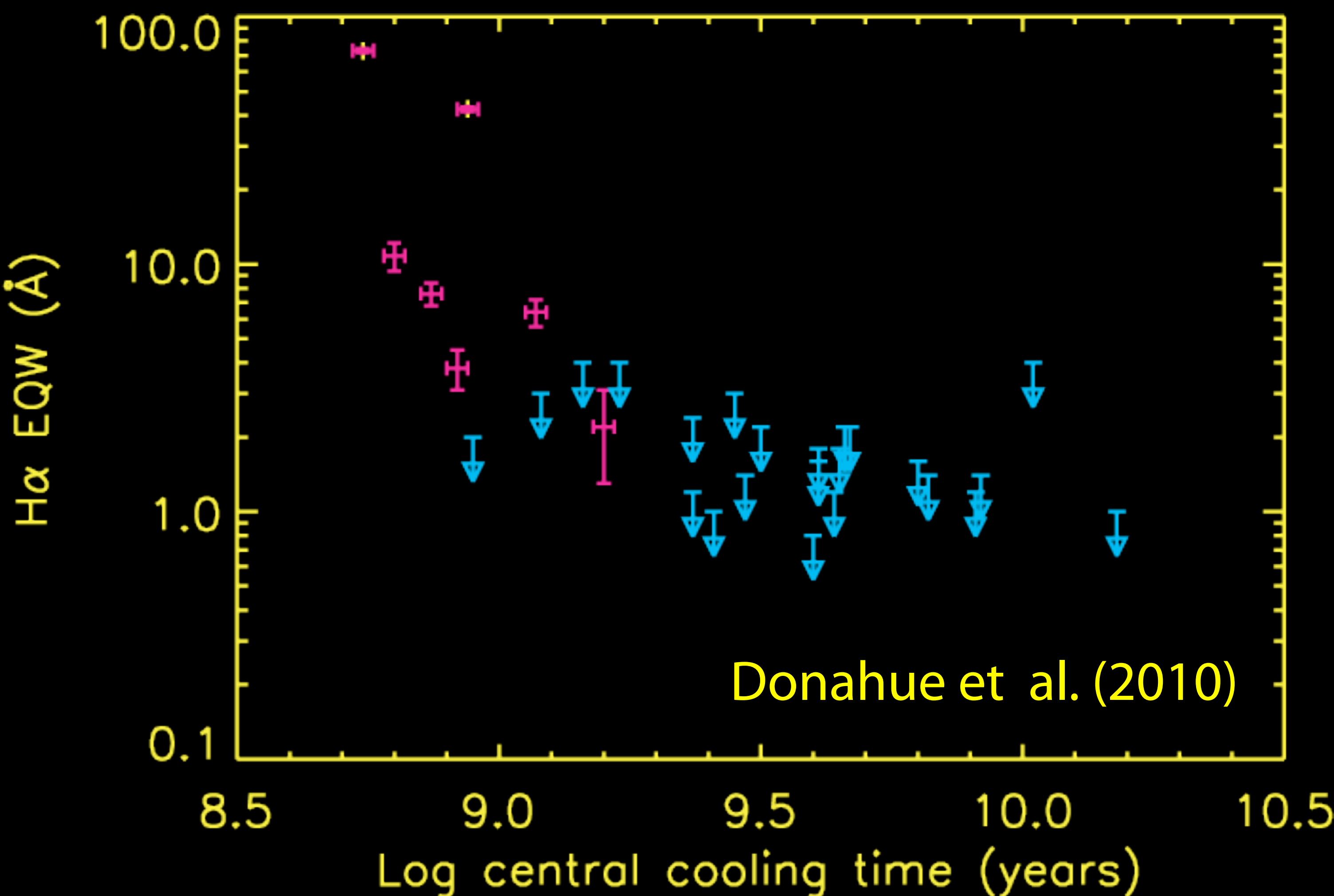
Hα & UV in REXCESS BCGs

REXCESS Cooling Times

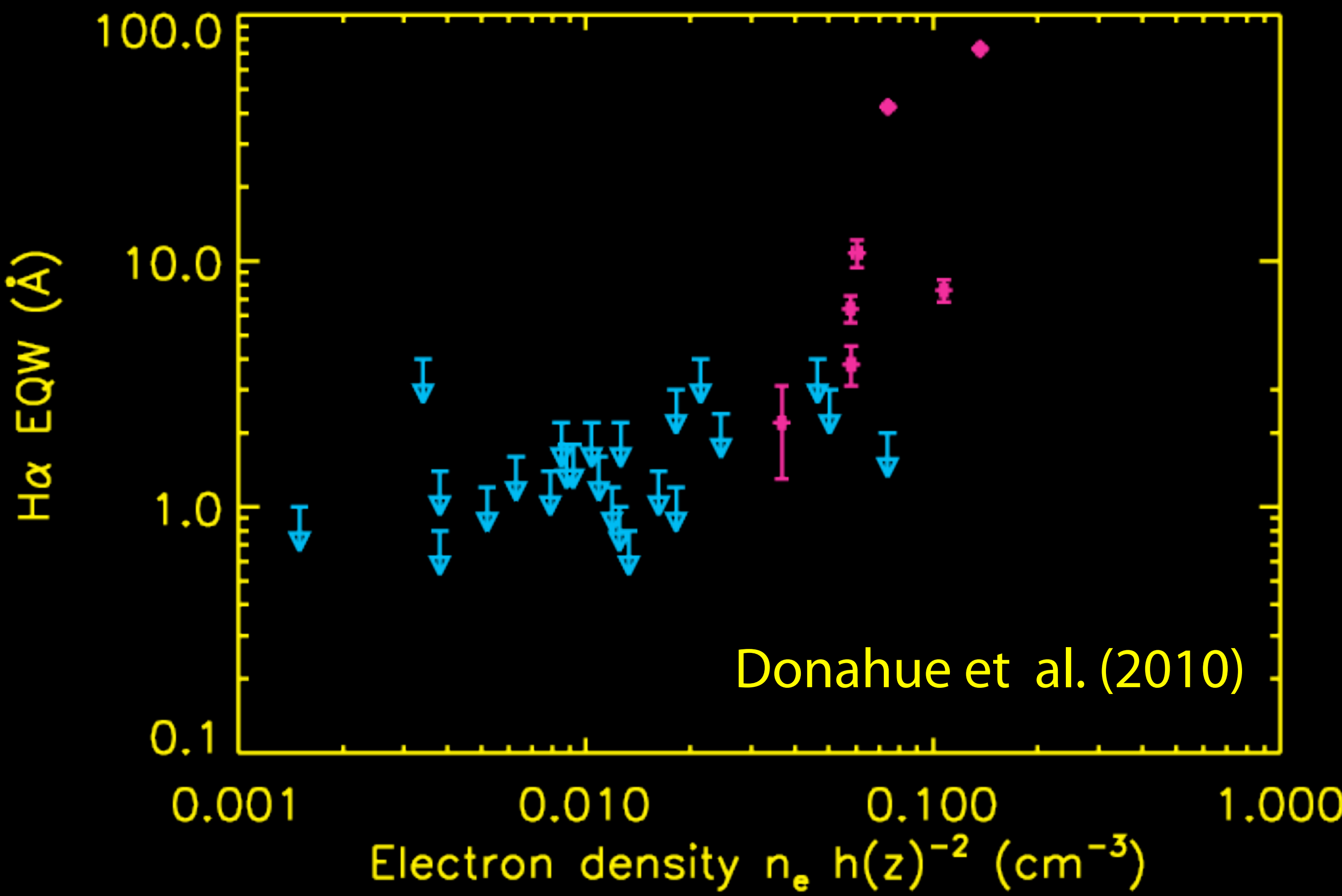


REXCESS cool-core classification based on t_{cool} at 0.003 R_{500}

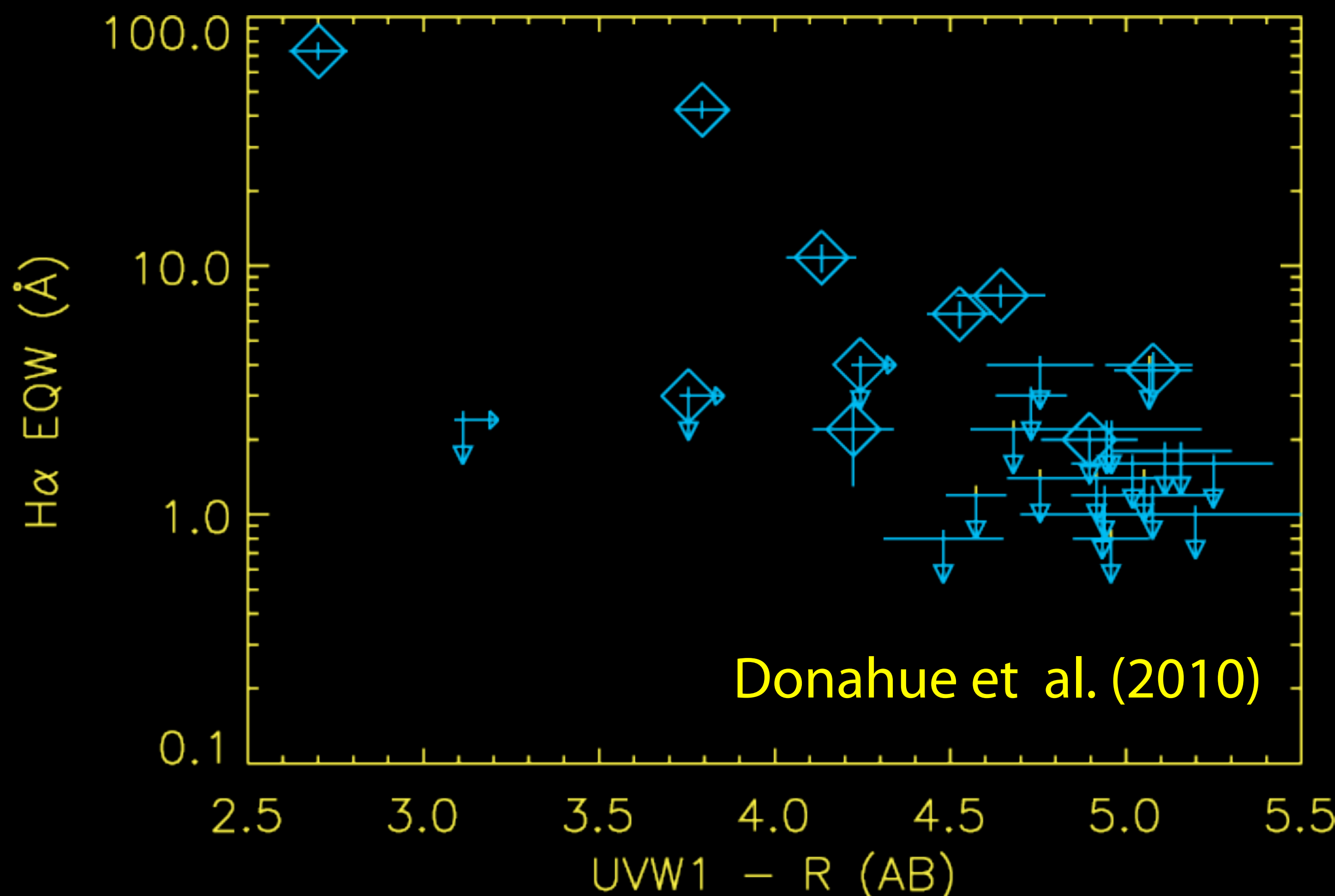
Cooling-Time Threshold for Hα



Central Density Threshold for Hα

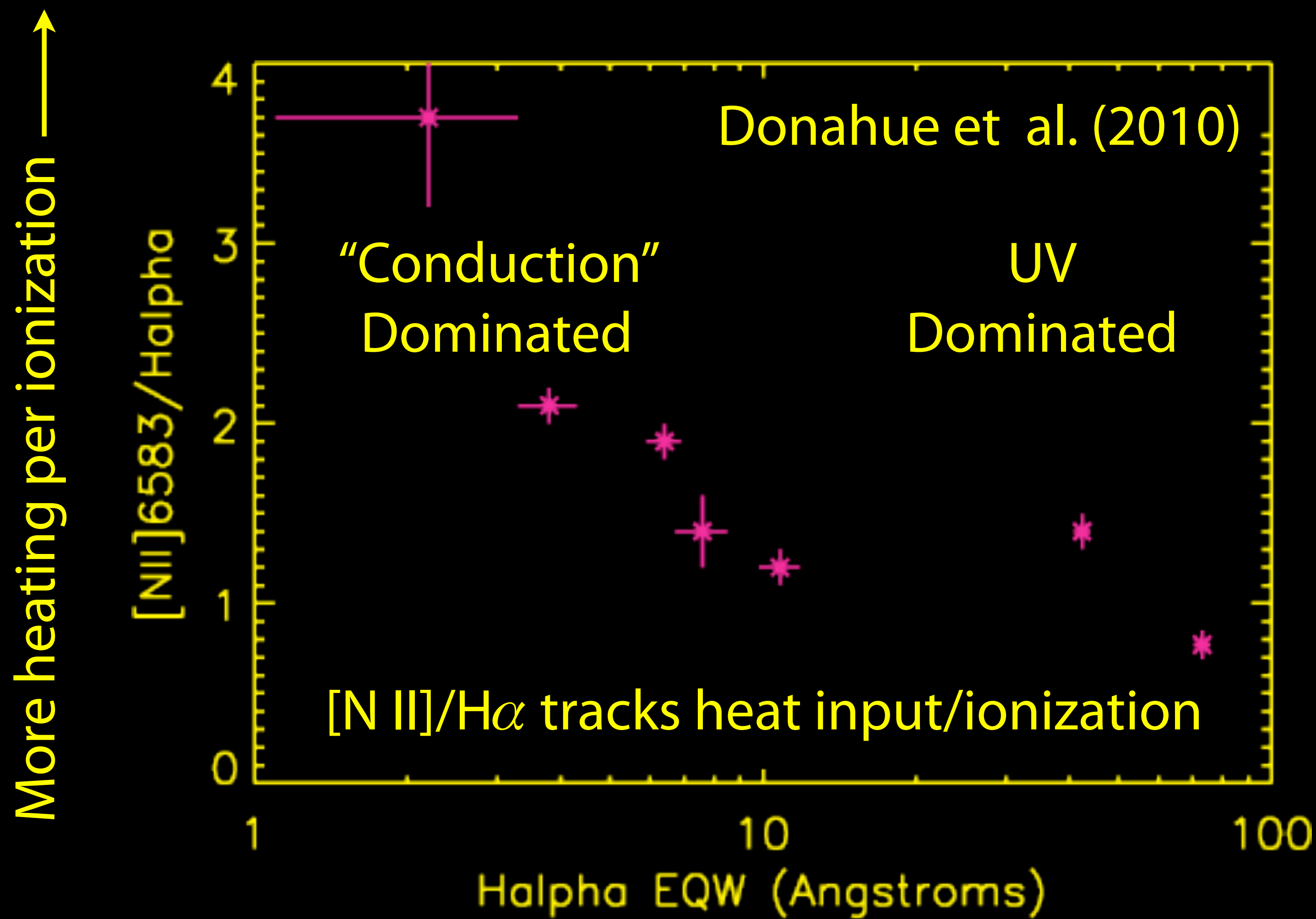


UV-Hα Correlation

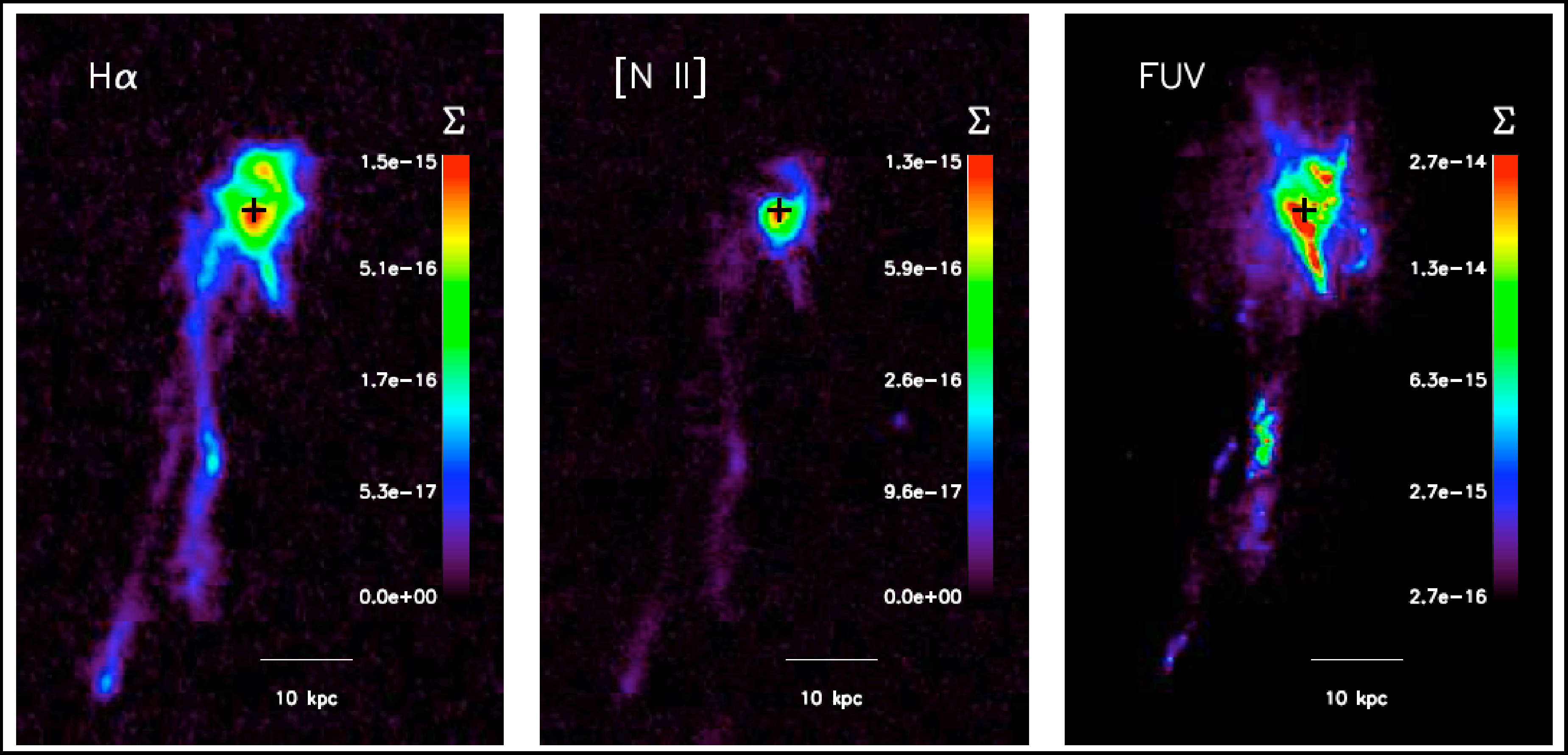


Donahue et al. (2010)

[N II]/Hα and Filament Heating

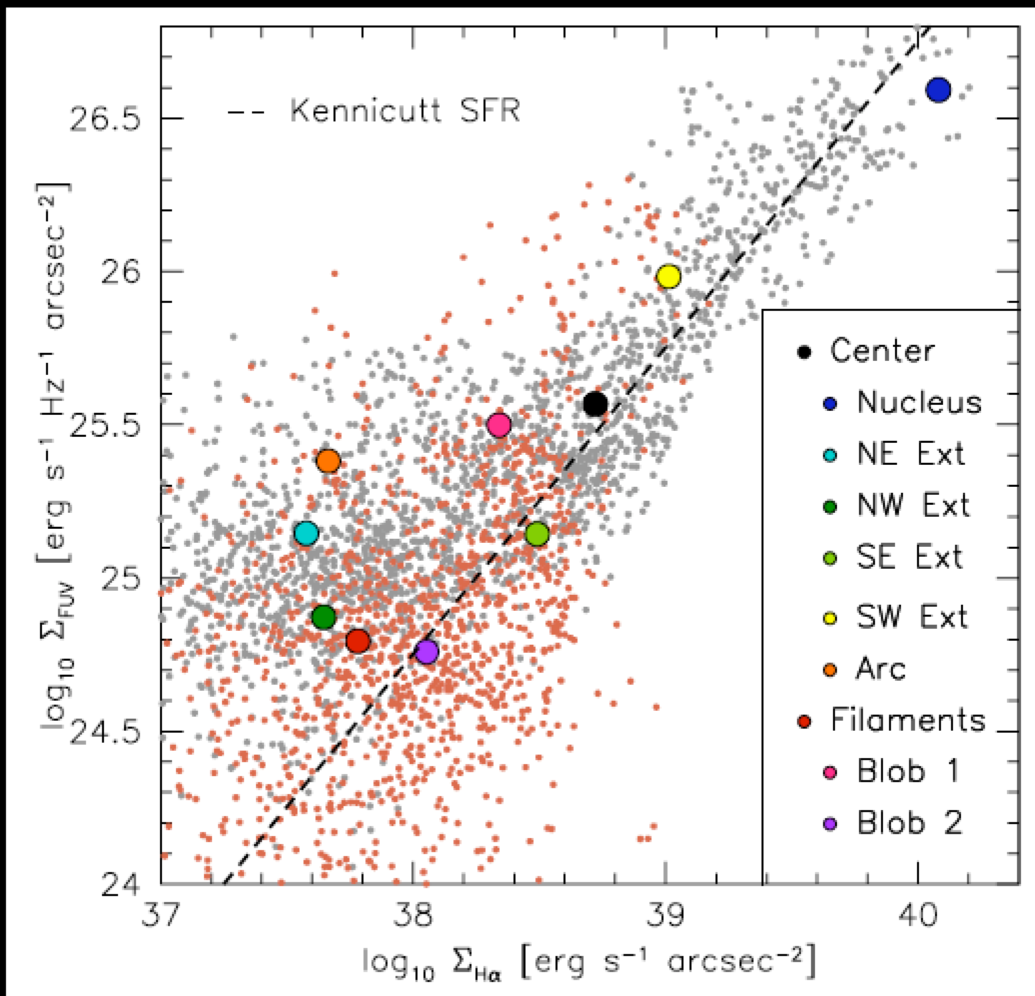


Hα & UV in Abell 1795



McDonald & Veilleux (2009)

Hα-UV Spatial Correlation



In Abell 1795, correlation is strong in bright regions and poor in dim regions

McDonald & Veilleux (2010)

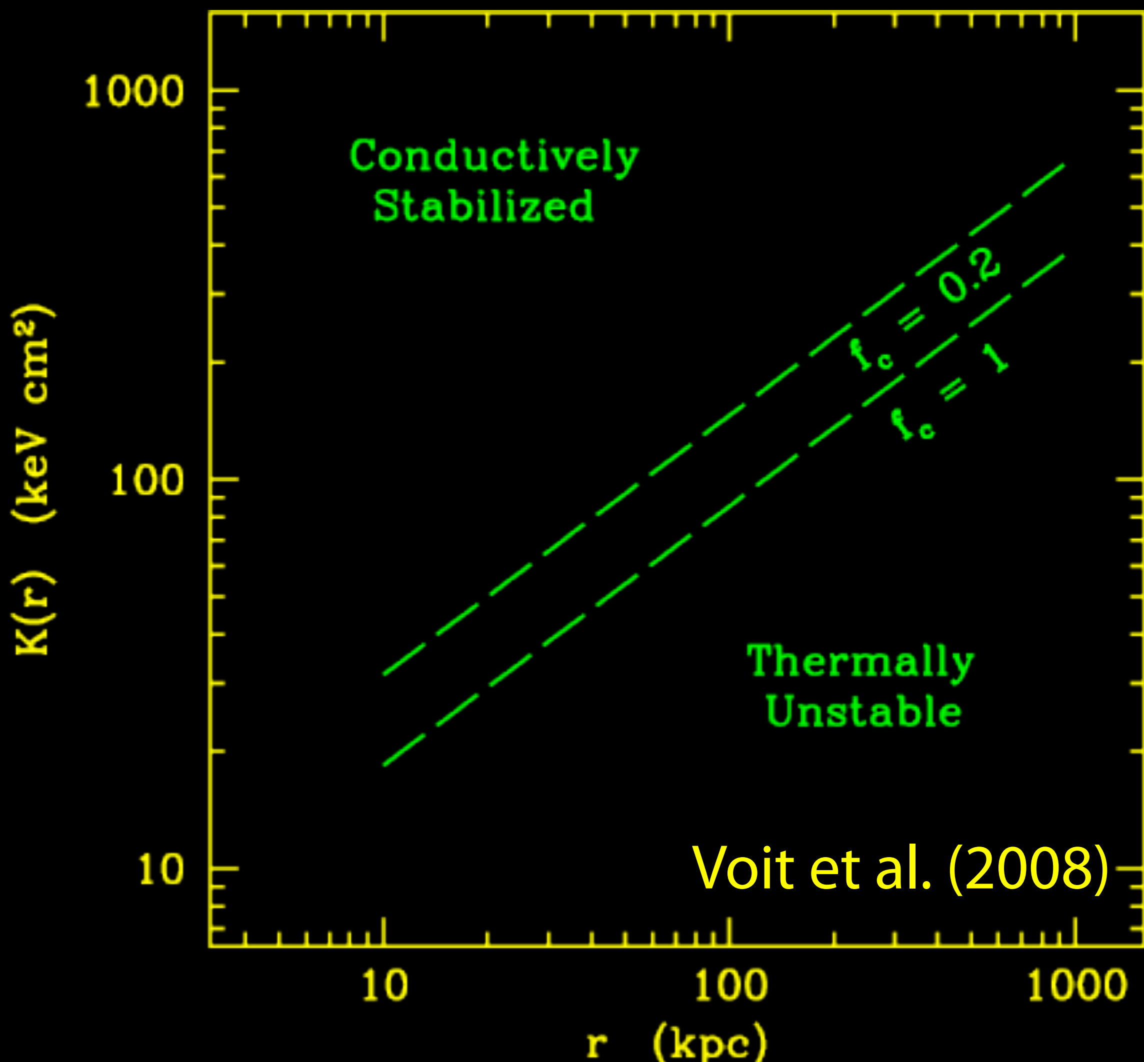
Conduction & Multiphase Structure

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 λ_F depends uniquely on K for free-free cooling
- Conduction cannot erase inhomogeneity of core gas if λ_F is too small
- Tug of war between cooling and conduction may produce a bifurcation in cluster properties (Donahue et al. 2006)

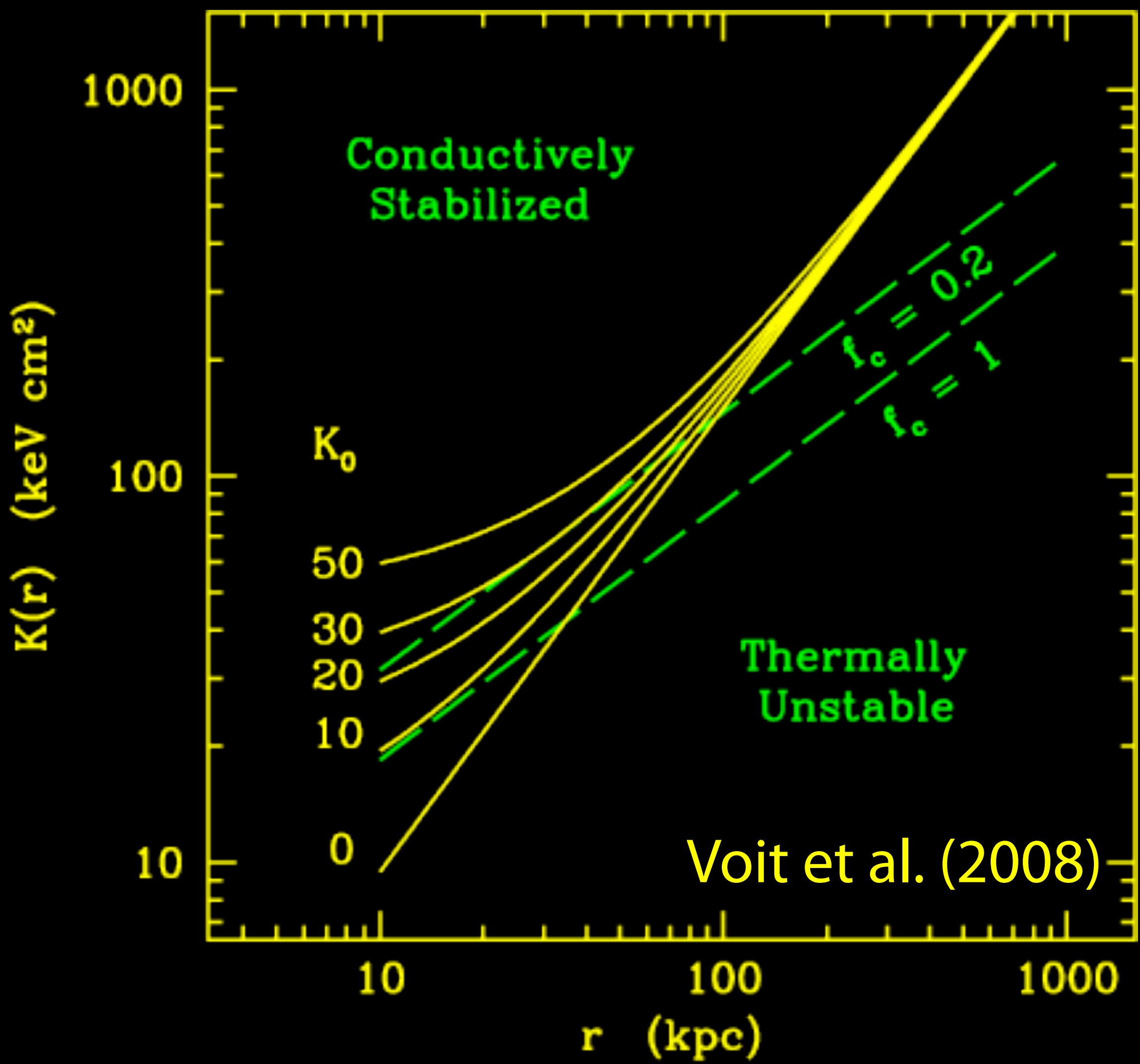
Conductive Stabilization of ICM



High-entropy gas can be stabilized by conduction

Low-entropy gas is thermally unstable

Conductive Stabilization of ICM

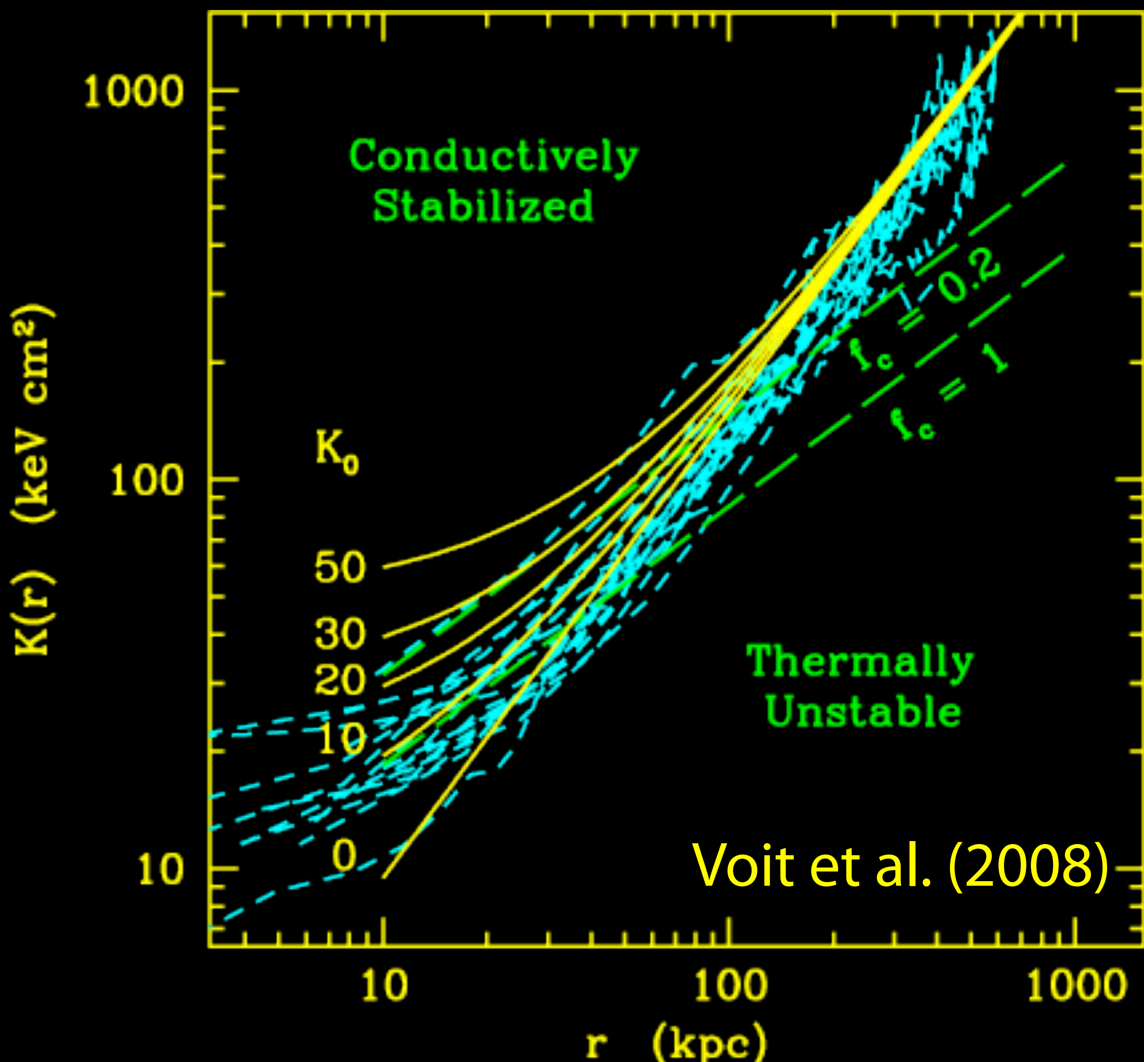


Thermal conduction can stabilize cooling in clusters with

$K_0 > 30$ keV cm^2

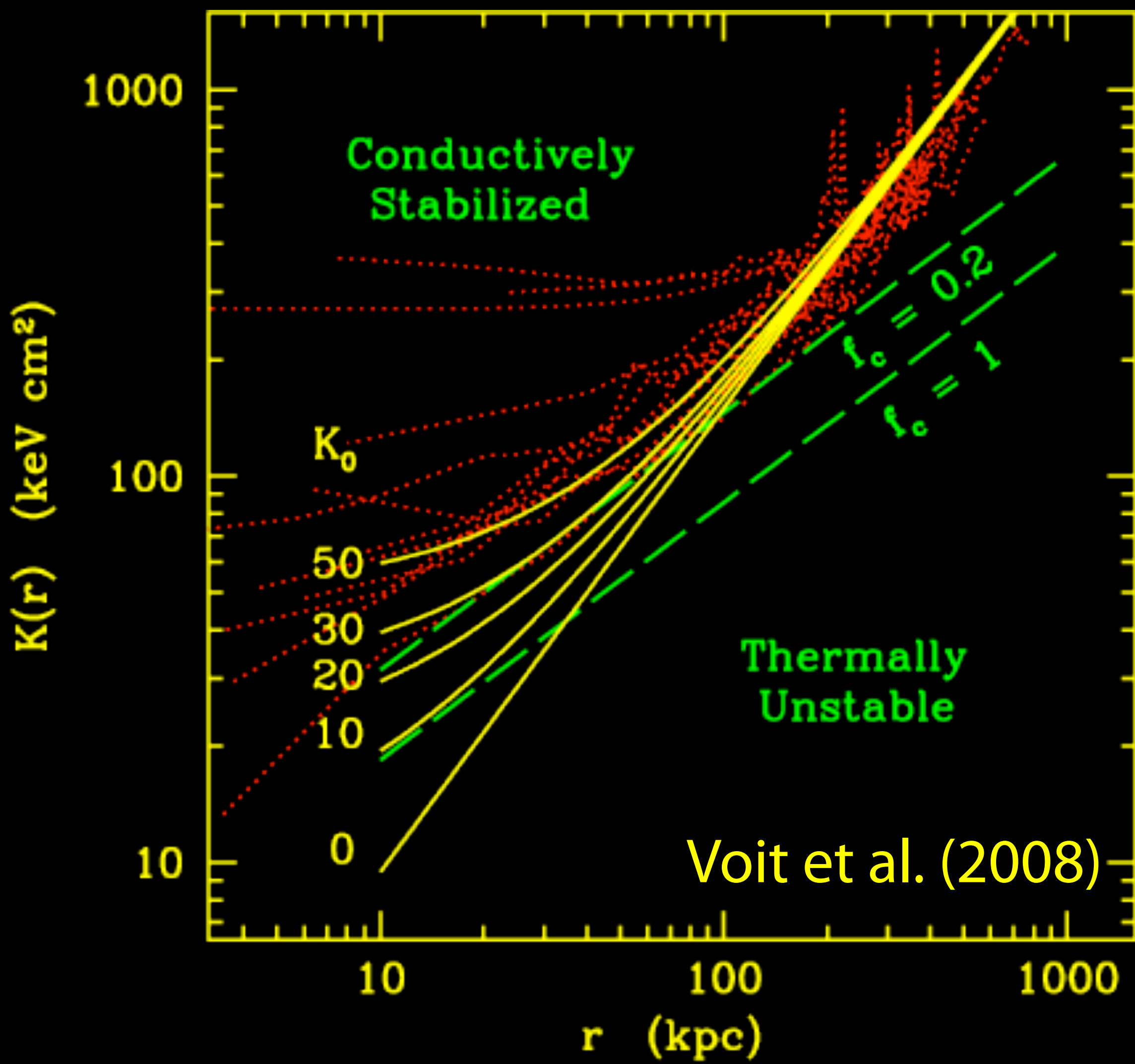
as long as $f_c \sim 0.2$

Conductive Stabilization of ICM



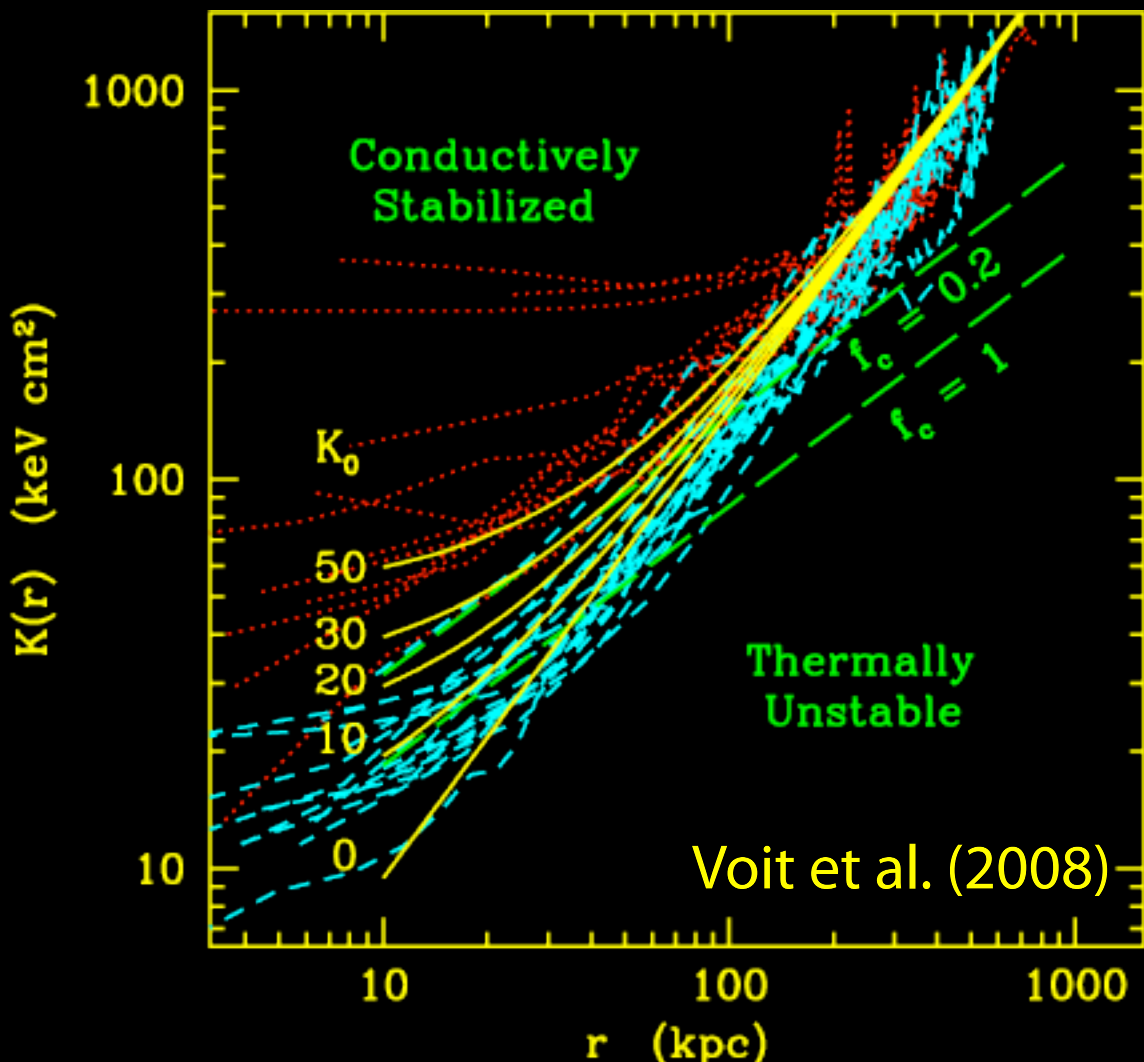
Star forming BCGs from Rafferty et al. (2008) are in clusters with entropy profiles that dip below this stabilization threshold

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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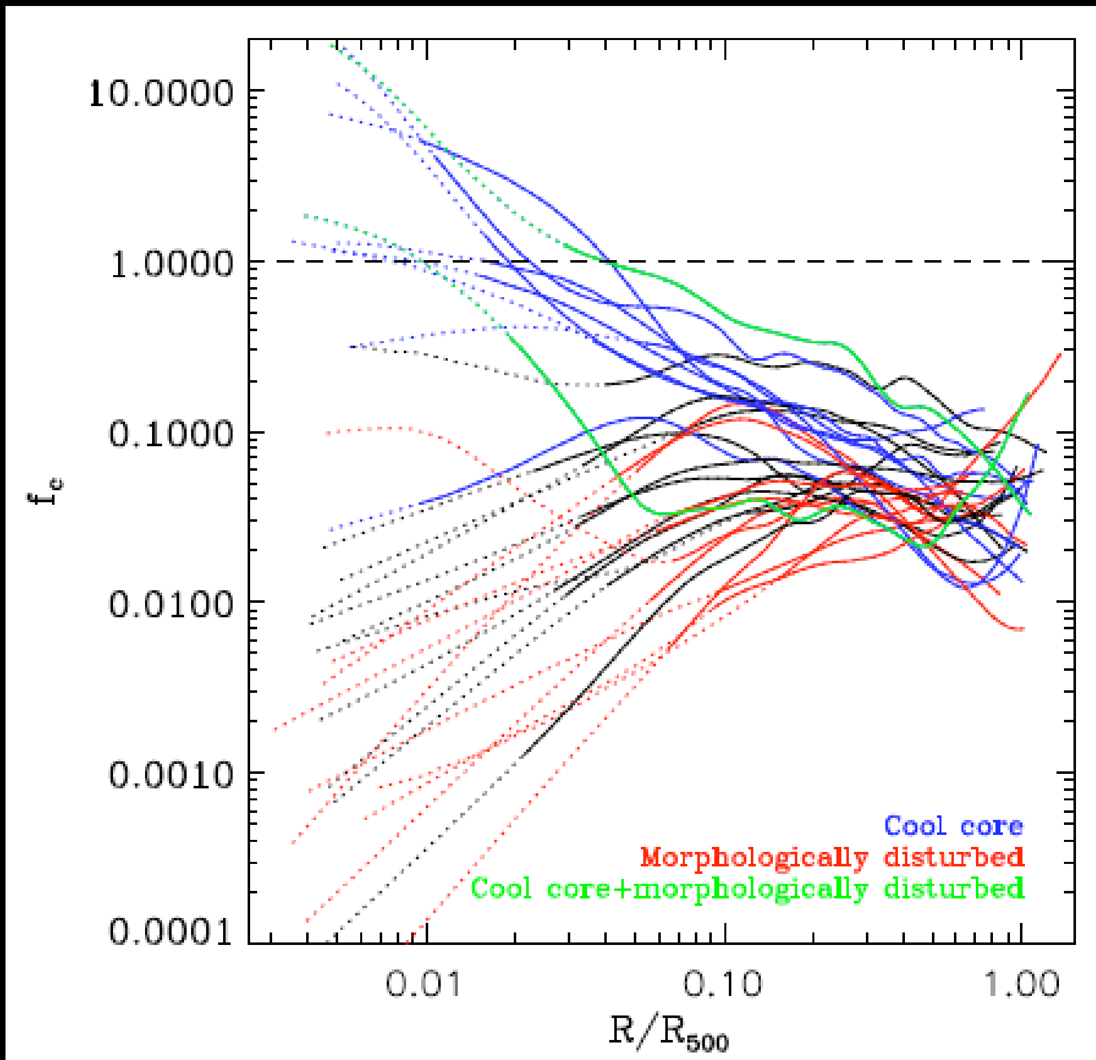


More evidence for bimodality: effective f_c profiles of REXCESS clusters avoid $f_c \sim 0.2$ within core

Pratt et al. (2010)

Conduction & Feedback

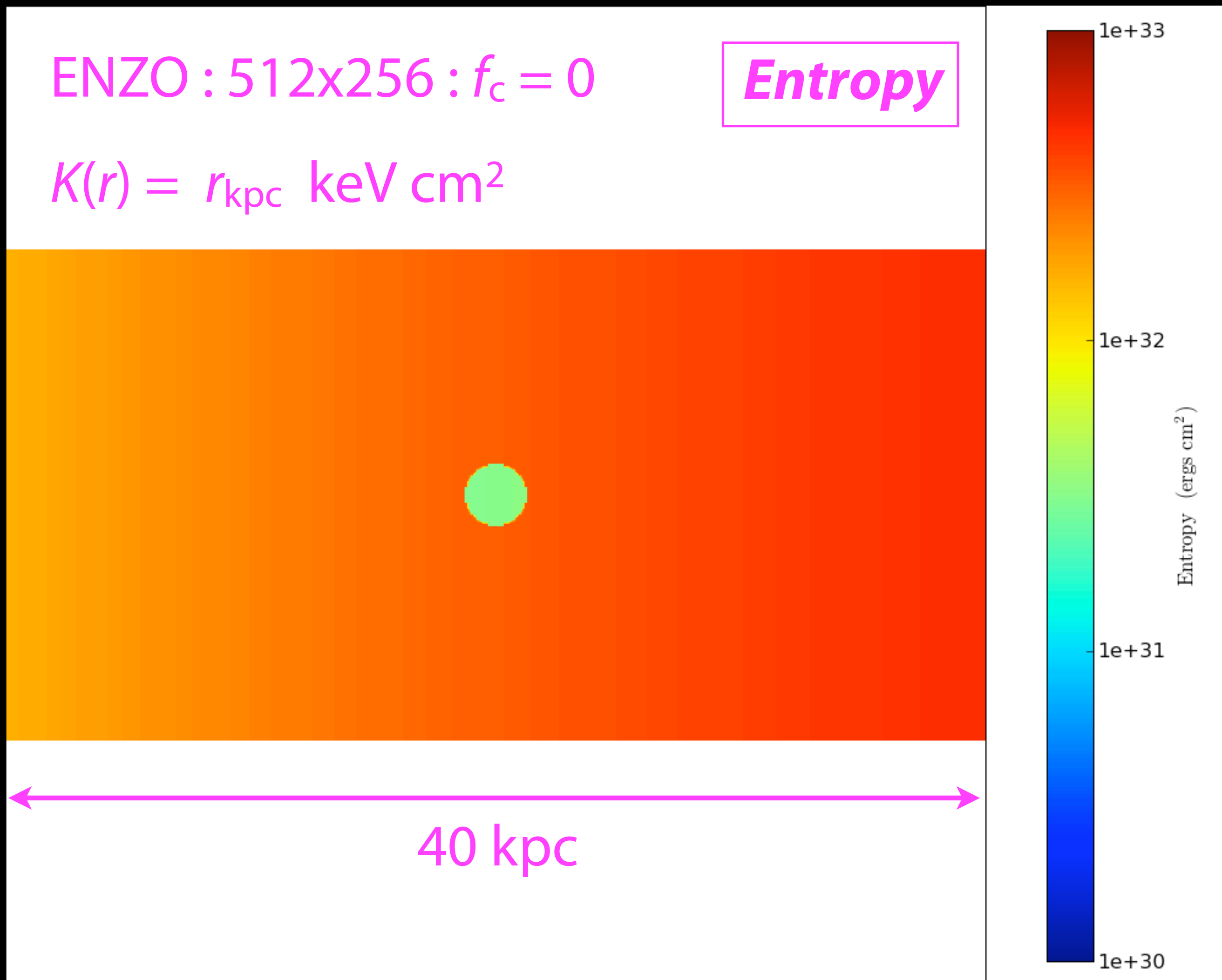
- Conduction with $f_c \sim 0.2$ plausibly accounts for lack of multiphase structure in high-entropy clusters

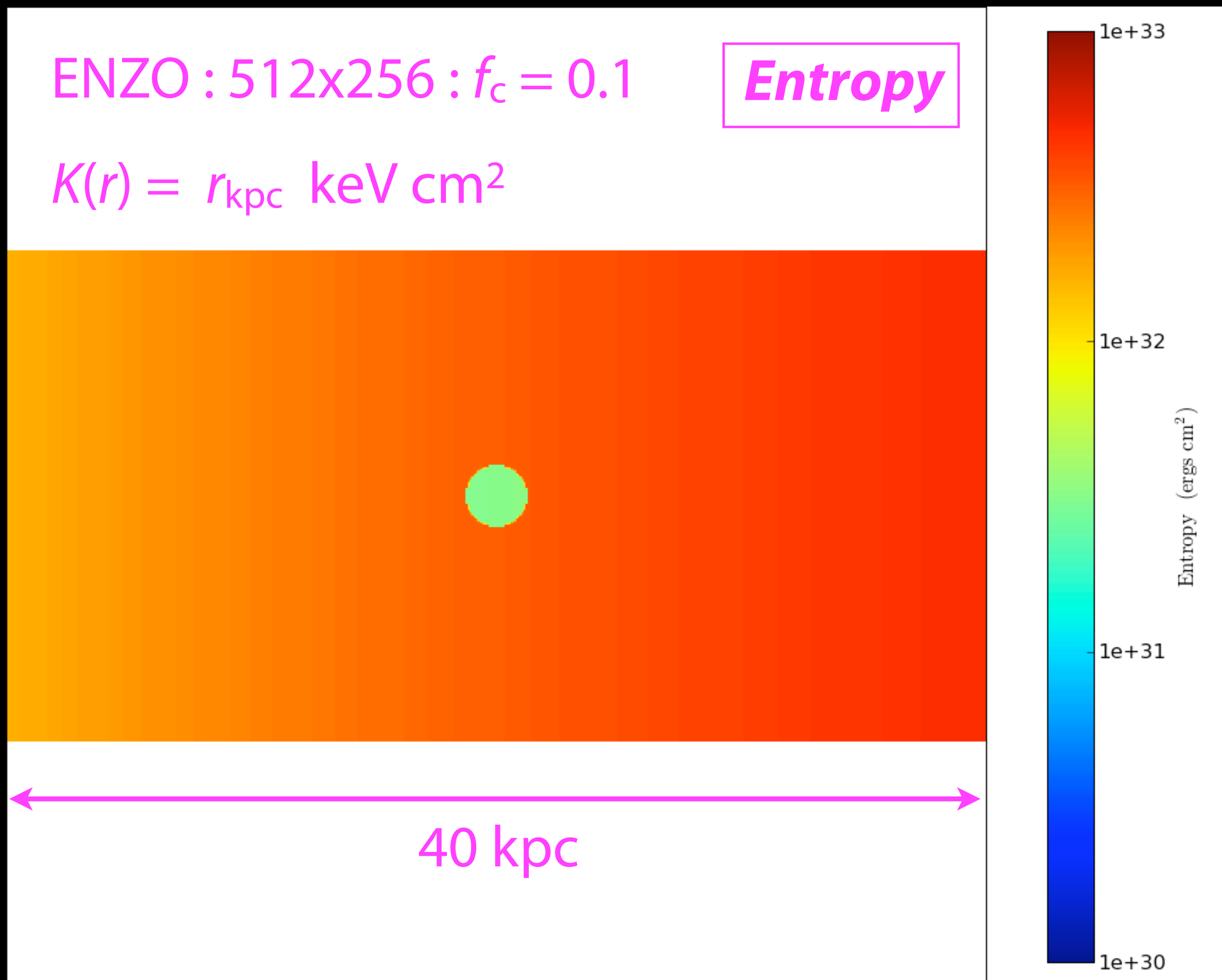
- If conduction is present, it may be important for distributing energy input throughout the cluster core very preliminary

ENZO Simulations of Multiphase ICM Structure

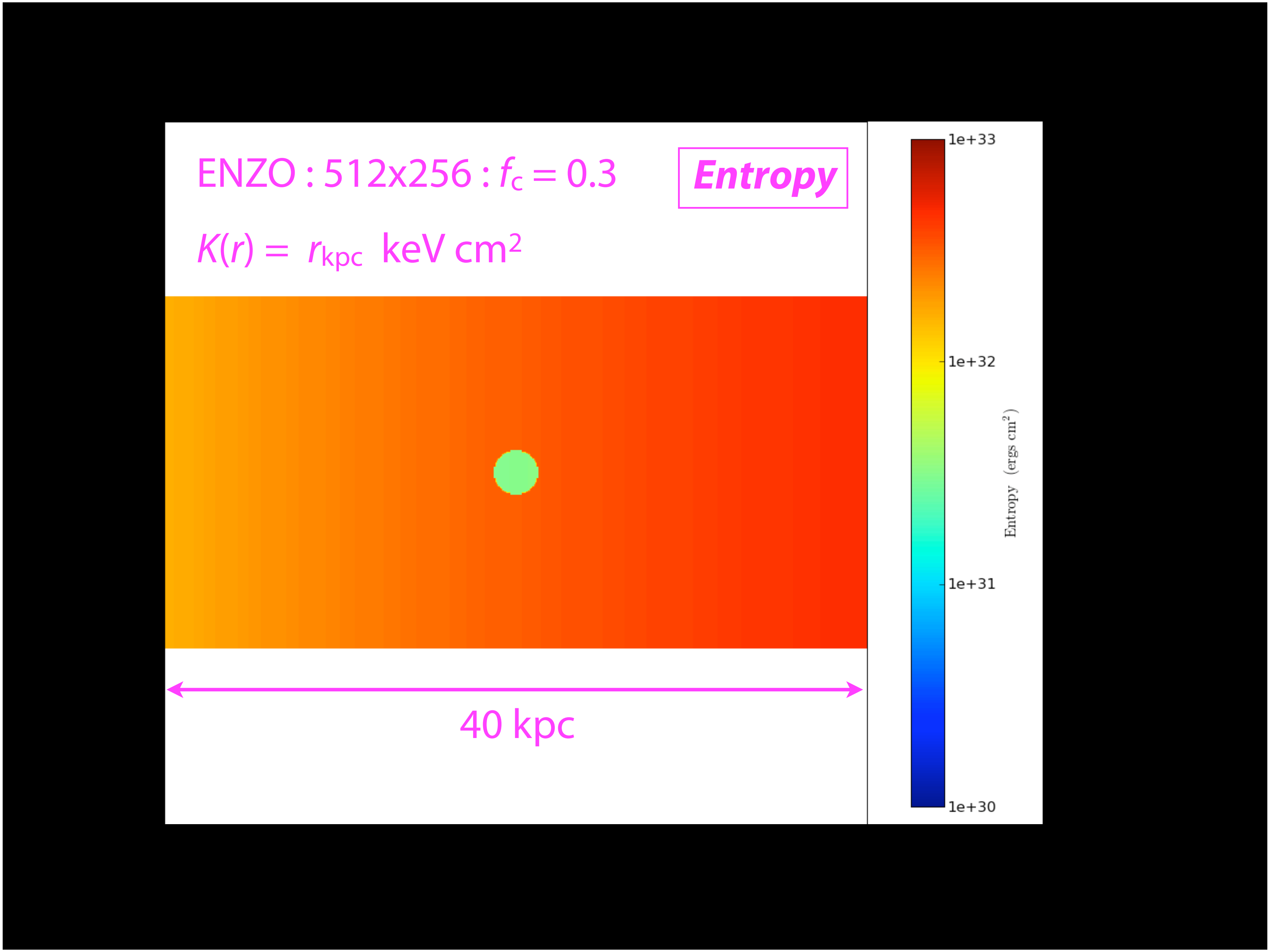
ENZO Modifications

- Isotropic conduction implemented by Brian O'Shea
- MHD version of ENZO now exists
- Implementation of anisotropic conduction on the way

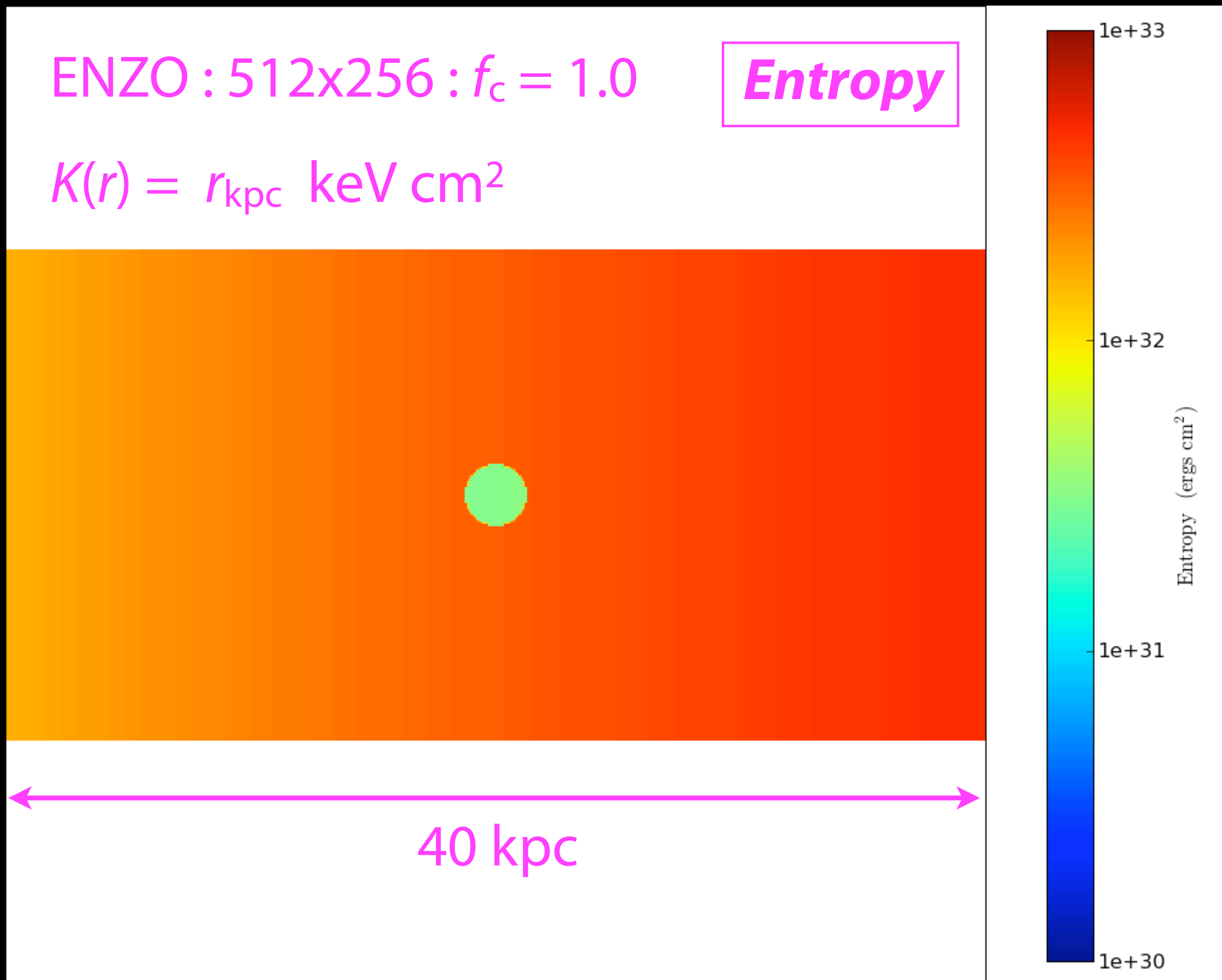

ENZO : 512x256 : $f_c = 0$
Entropy
$K(r) = r_{kpc}$ keV cm^2
40 kpc
1e+33
1e+32
1e+31
1e+30
Entropy (ergs cm^2)

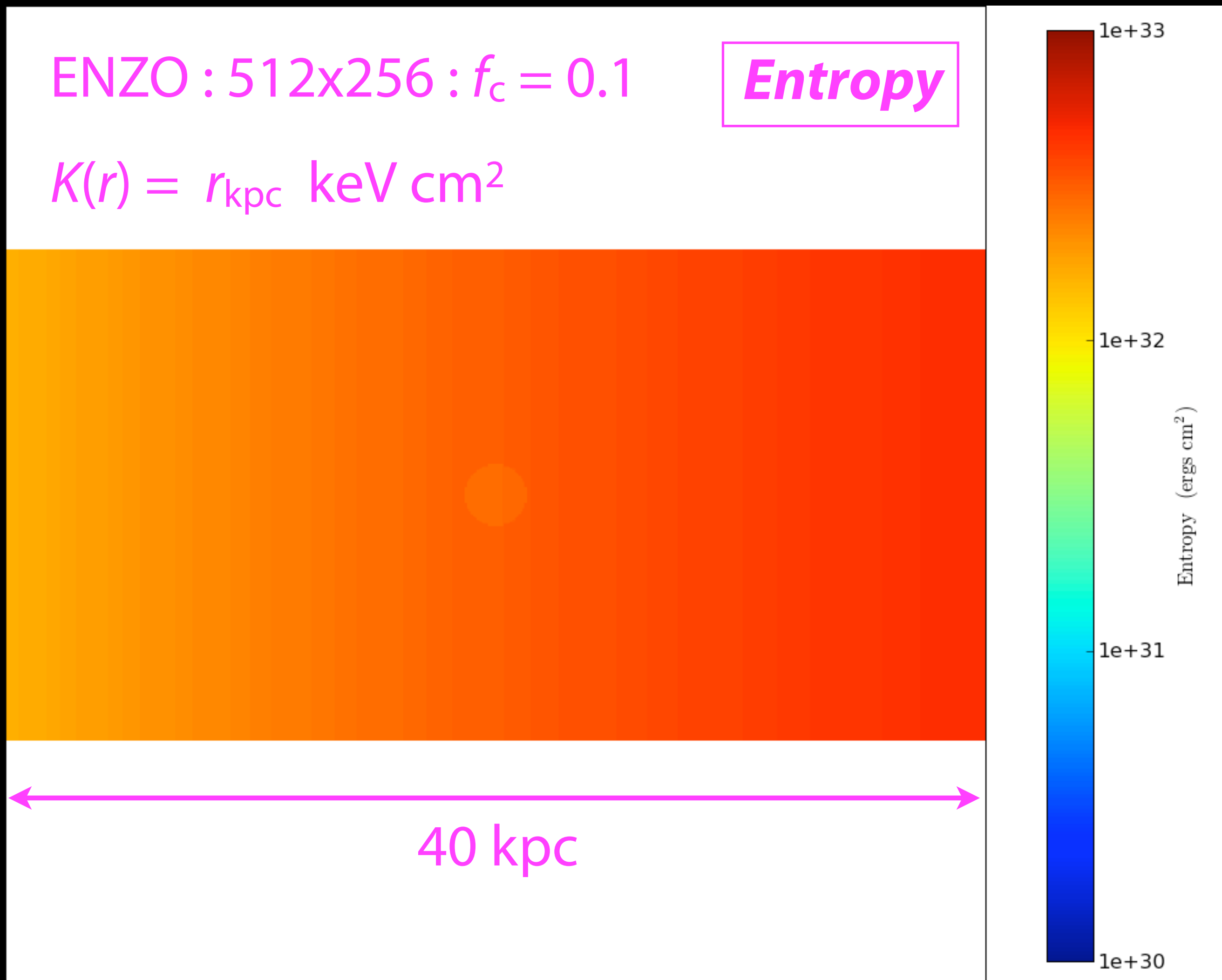


ENZO : 512x256 : $f_c = 0.1$
Entropy
$K(r) = r_{kpc}$ keV cm^2
40 kpc
1e+33
1e+32
1e+31
1e+30
Entropy (ergs cm^2)



ENZO : 512x256 : $f_c = 0.3$
Entropy
$K(r) = r_{\mathrm{kpc}}$ keV cm^2
40 kpc
1e+33
1e+32
1e+31
1e+30
Entropy (ergs cm^2)


ENZO : 512x256 : $f_c = 1.0$
Entropy
$K(r) = r_{kpc}$ keV cm^2
40 kpc
1e+33
1e+32
1e+31
1e+30
Entropy (ergs cm^2)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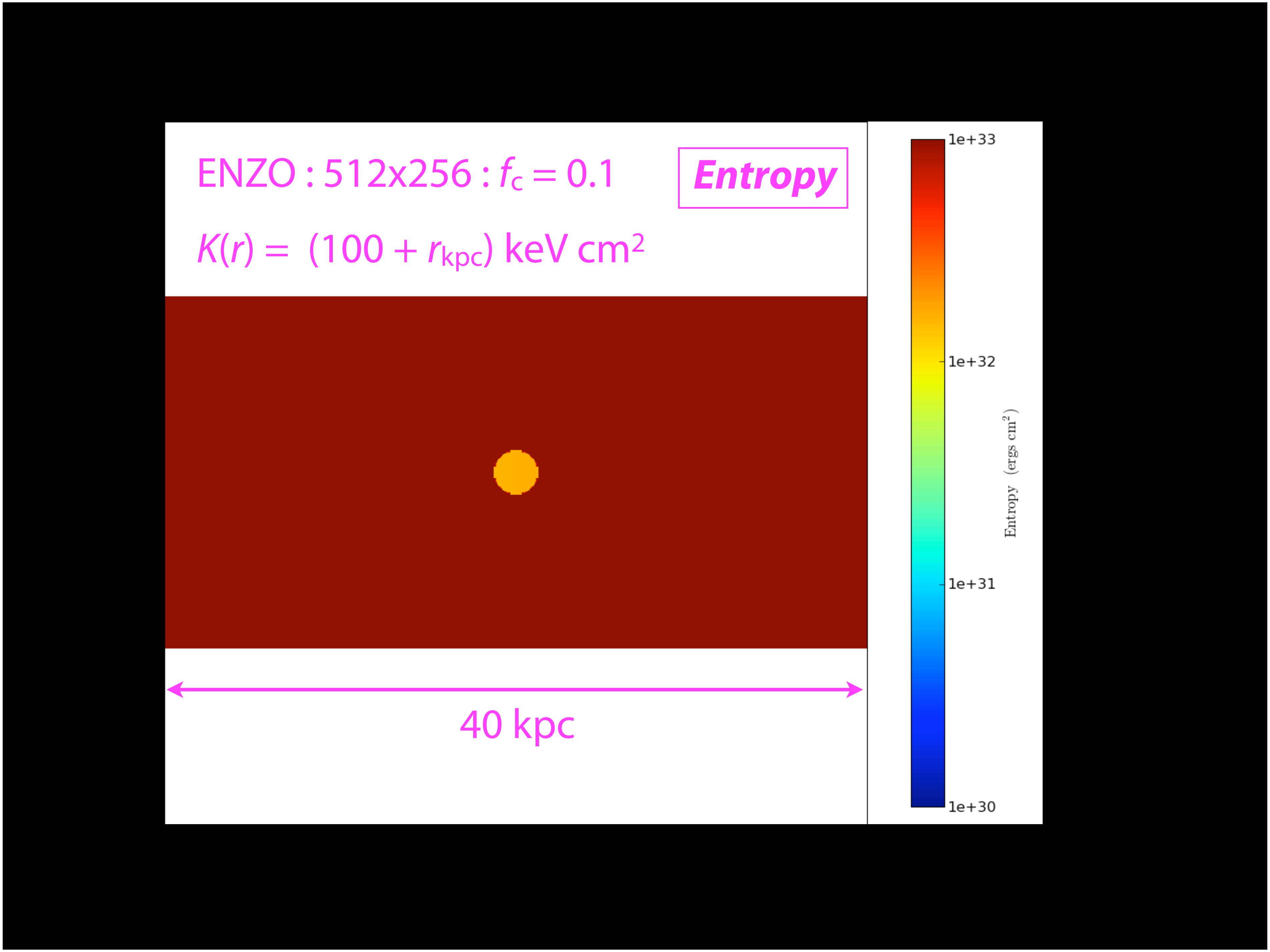

ENZO : 512x256 : $f_c = 0.1$
Entropy
$K(r) = (100 + r_{kpc})$ keV cm^2
40 kpc
1e+33
1e+32
1e+31
1e+30
Entropy (ergs cm^2)

Summary

- AGN feedback and multiphase gas is directly linked to the state of the hot ICM
- Presence of multiphase gas may be governed by conduction, indicating $f_c \sim 0.2$
- Condensation of ICM is qualitatively different if conduction is present