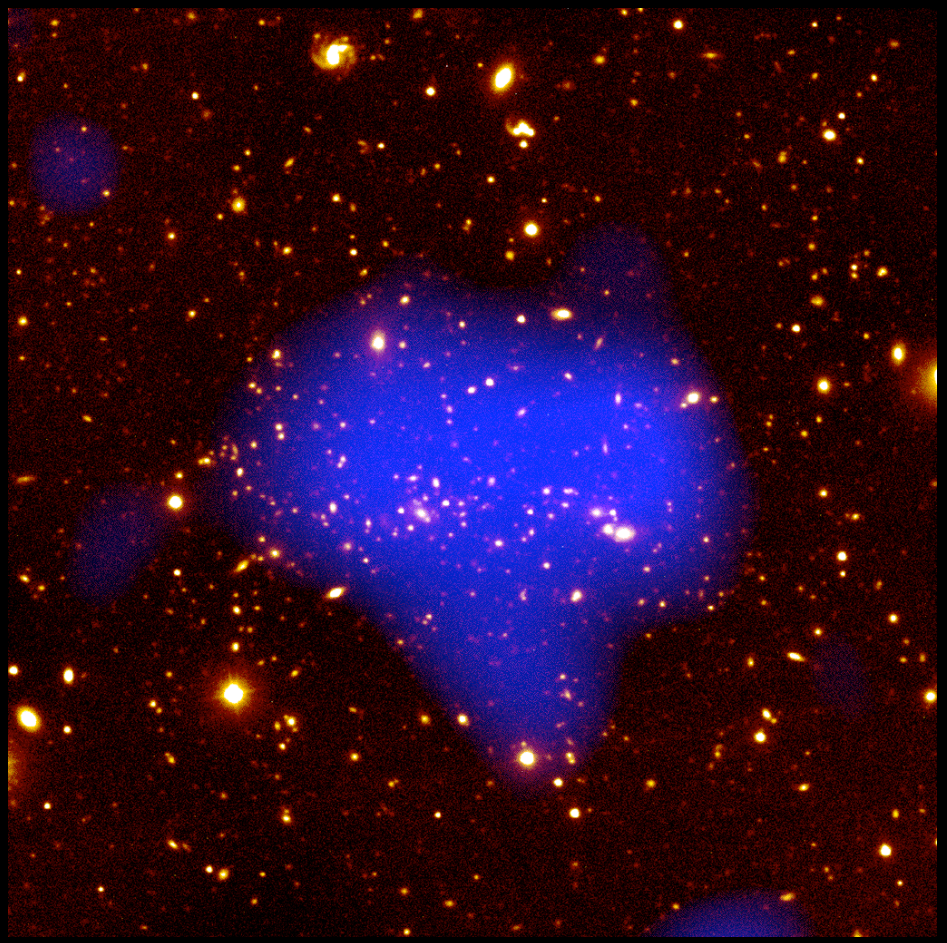
A Framework for AGN Heating in Cluster Cores

Energetics of the ICM



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

kT ≈ 10 keV

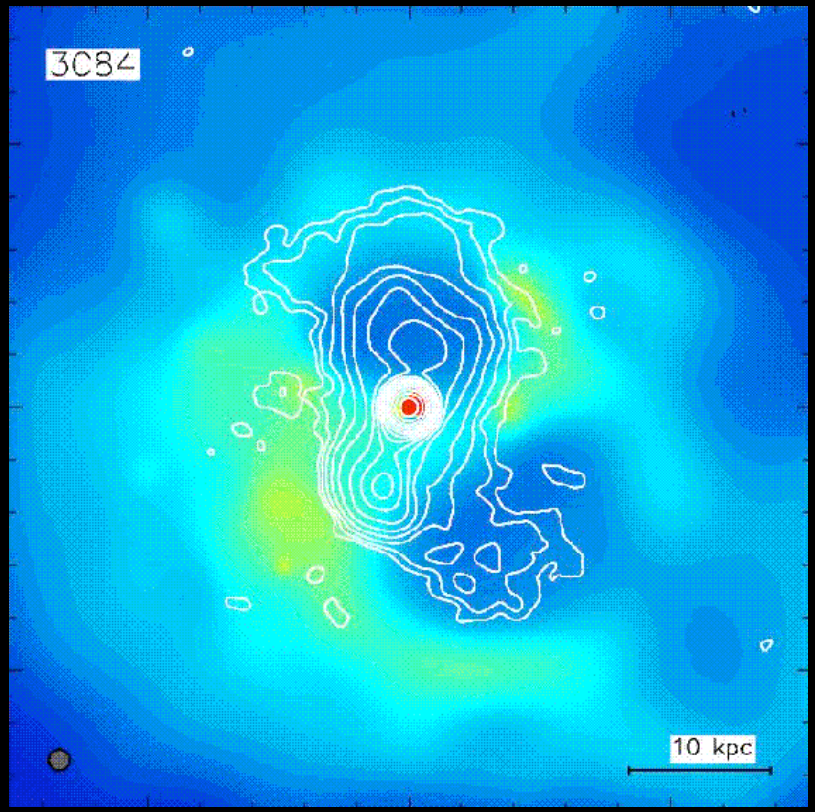
Fe/H ≈ 0.3 solar

z = 0.83

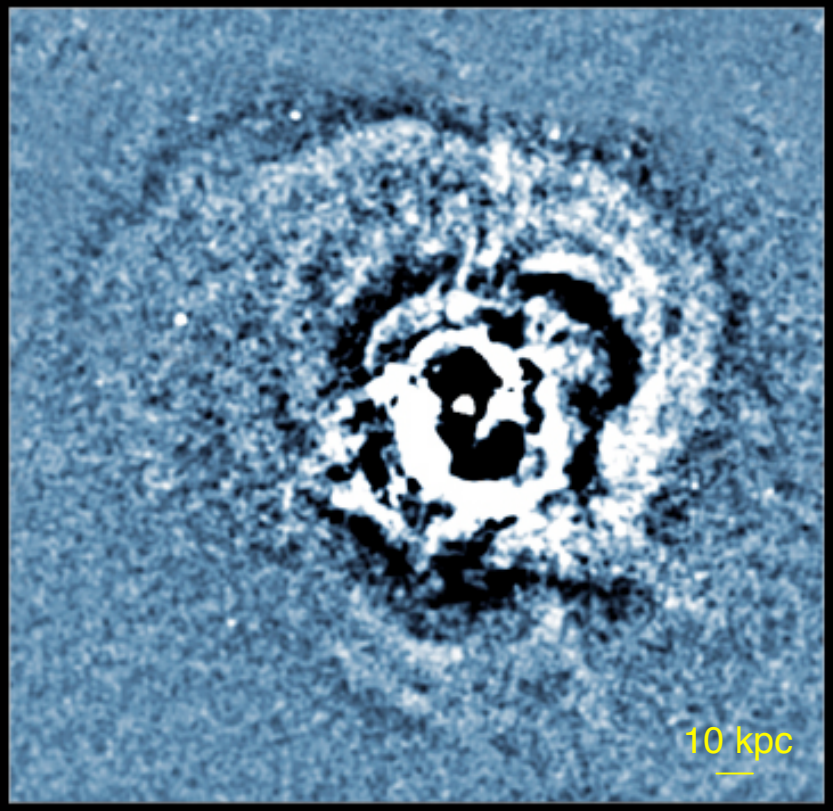
E_{SN} ≈ 1 keV/particle

E_{AGN} ≈ ? keV/particle

Observing AGN Feedback



Perseus Cluster & 3C 84



Sound Waves in Perseus

Motivating Questions

- Is AGN heating necessary to explain cluster properties?
- Does AGN feedback stop star formation in high-mass galaxies?
- What can observations tell us about the characteristics of AGN feedback?

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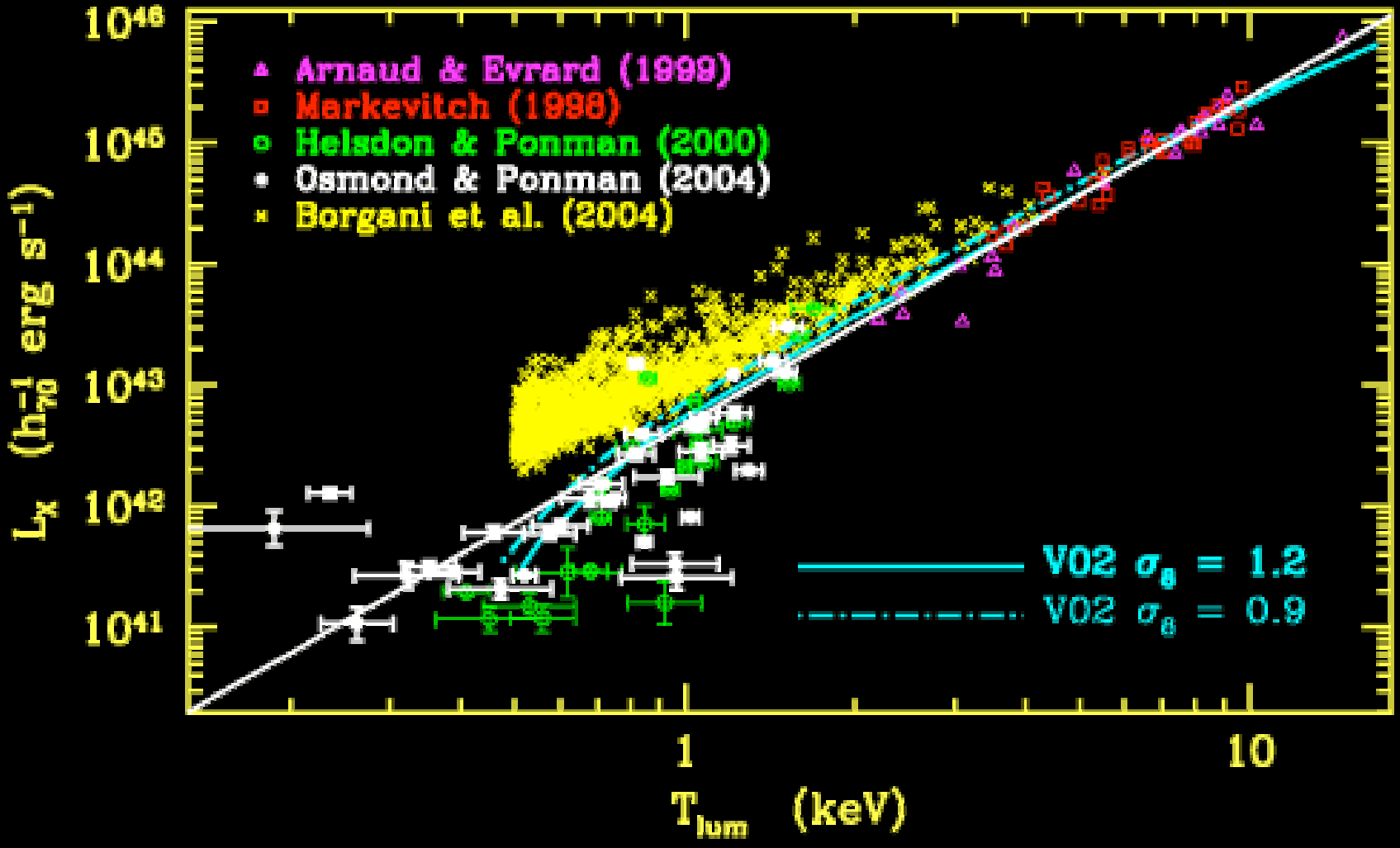
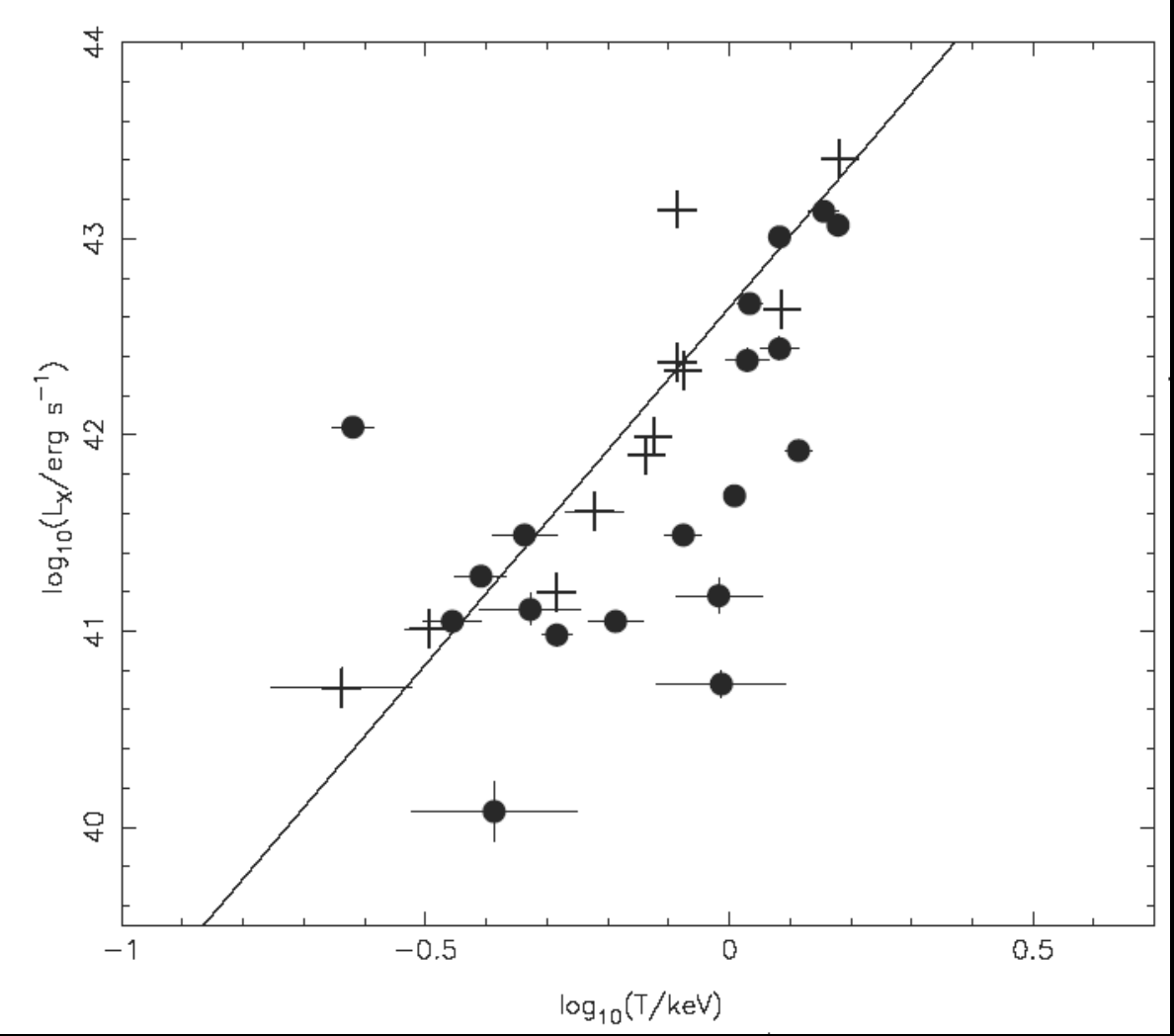
Evidence for AGN Heating

L-T Relation


Arnaud & Evrard (1999)
Markevitch (1998)
Helsdon & Ponman (2000)
Osmond & Ponman (2004)
Borgani et al. (2004)
V02 σ_8 = 1.2
V02 σ_8 = 0.9
10^{46}
10^{45}
10^{44}
10^{43}
10^{42}
10^{41}
L_X (h_{70}^{-1} erg s^{-1})
1
10
T_{lum} (keV)

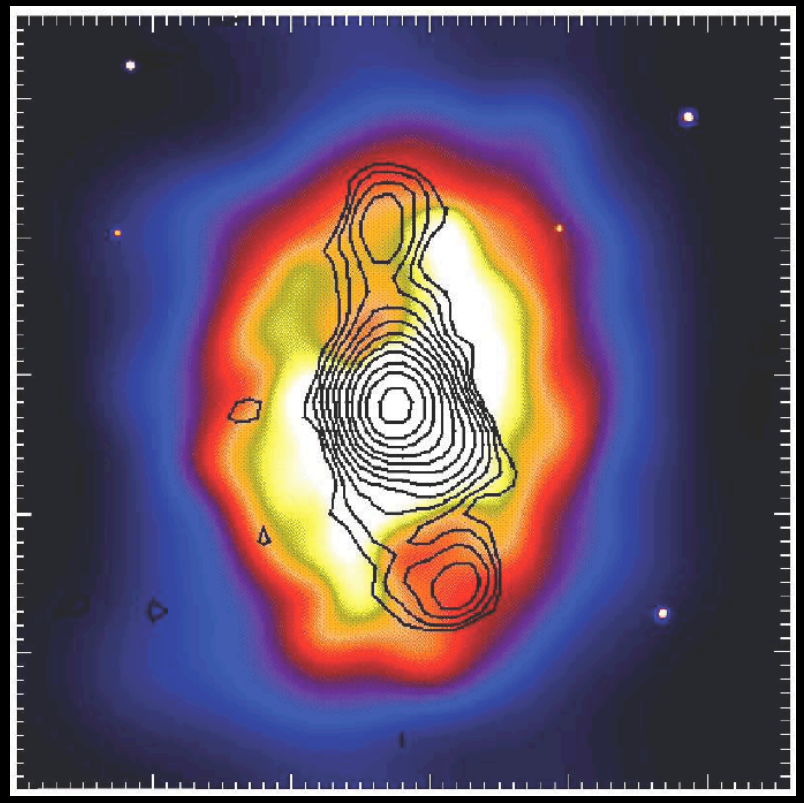
AGN Heating in Groups



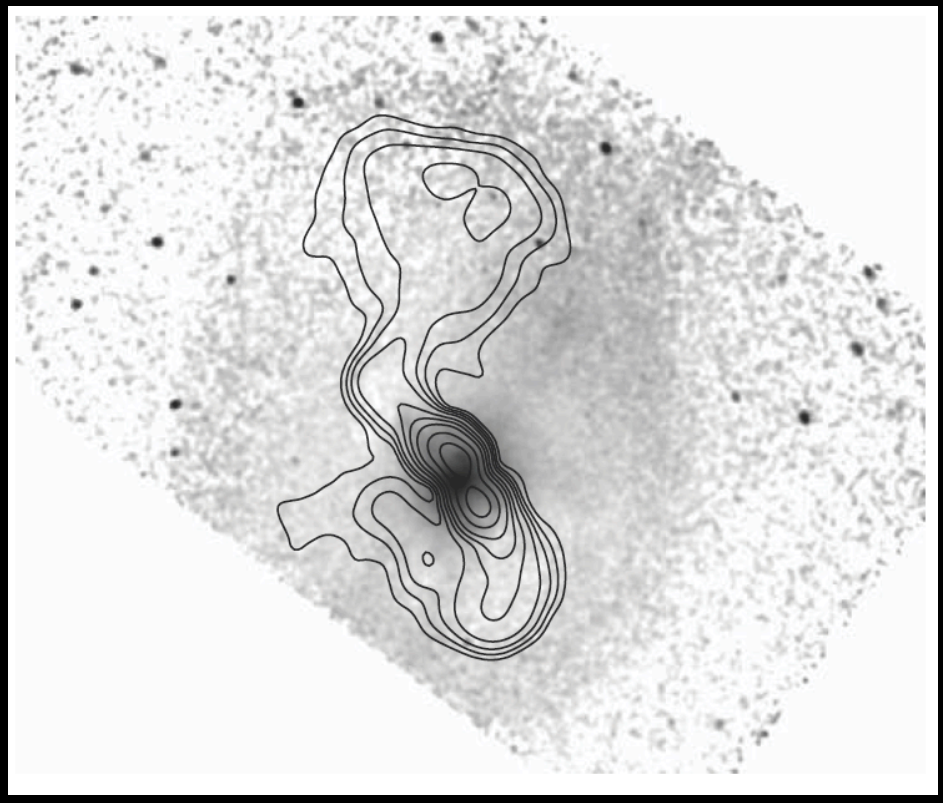
Radio-loud groups (circles) tend toward the low-L, high-T side of L-T relation

Croston et al. 2004

Dramatic Heating Events



MS0735 (McNamara et al.)



Hydra A (Nulsen et al.)

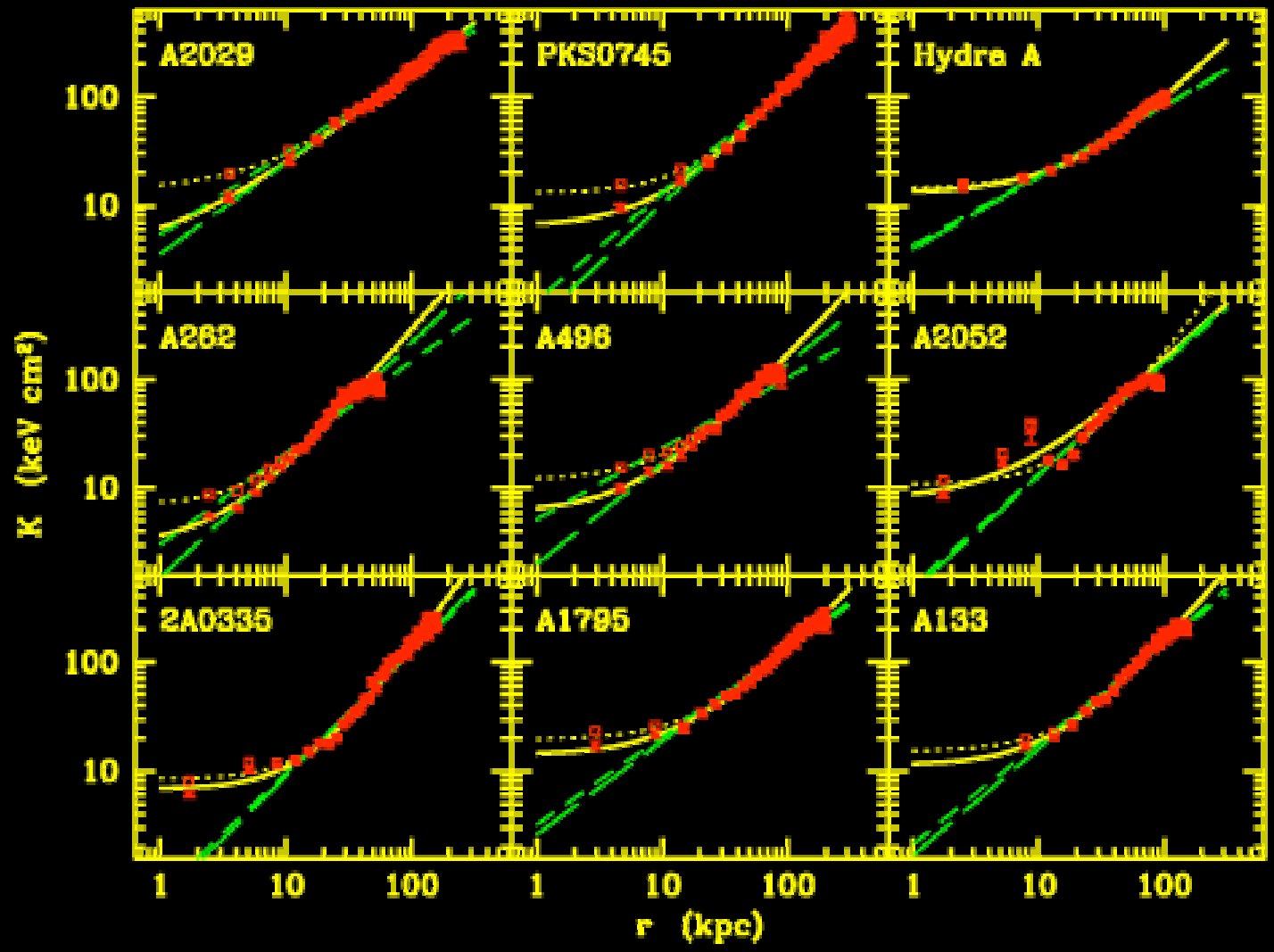
Entropy in Cluster Cores

Intracluster Entropy

$$K = P\rho^{-5/3} \propto Tn_e^{-2/3} \quad (\mathrm{keV\ cm^2})$$

- Entropy distribution in ICM determines a cluster's equilibrium structure
- Entropy distribution retains information about cluster's thermodynamic history
- Feedback changes *K* more than *T*

Entropy Profiles of "Active Clusters"



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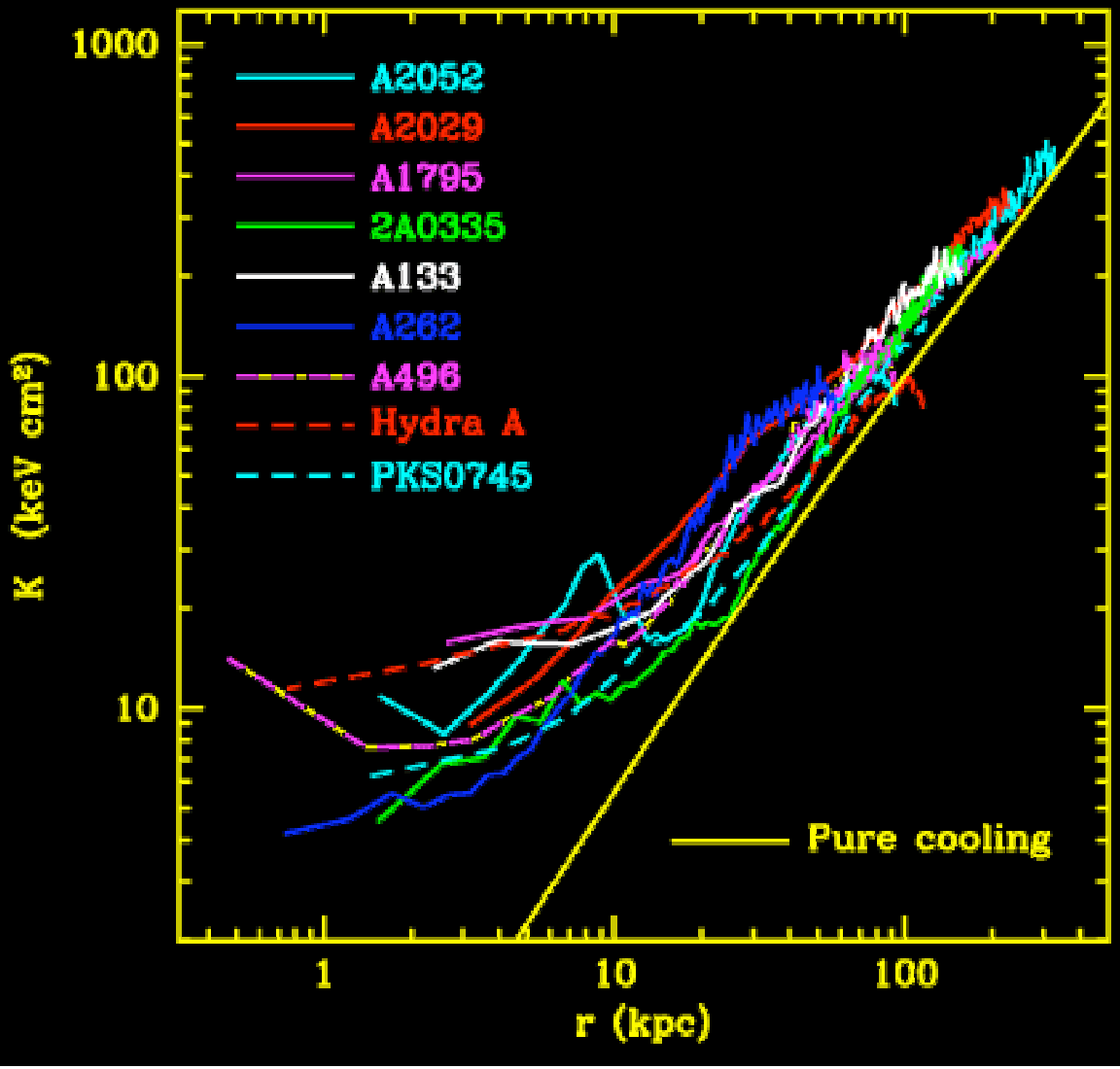

Core entropy profiles very regular

Entropy inversions are minor and lie at $r < 10$ kpc

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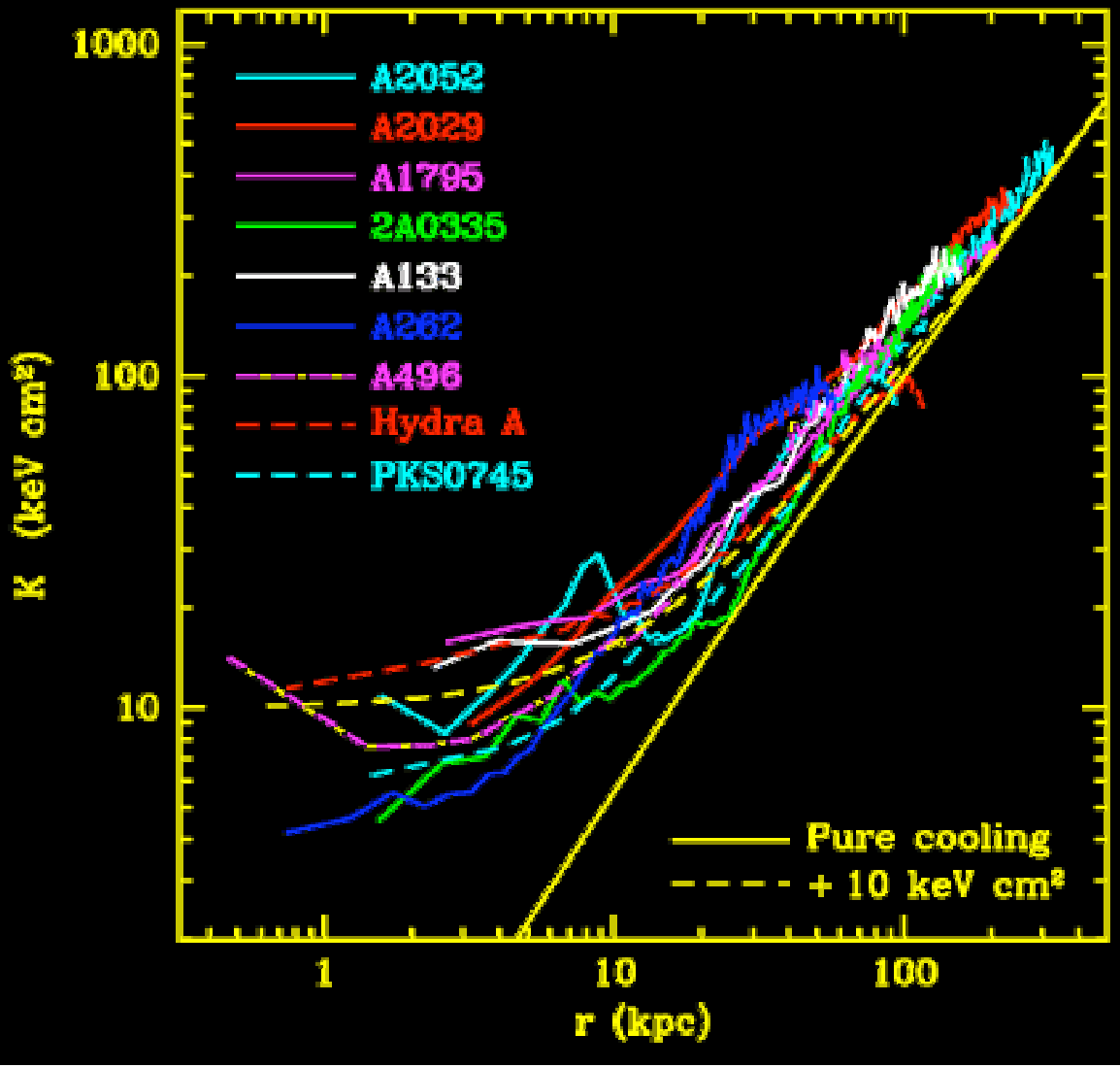


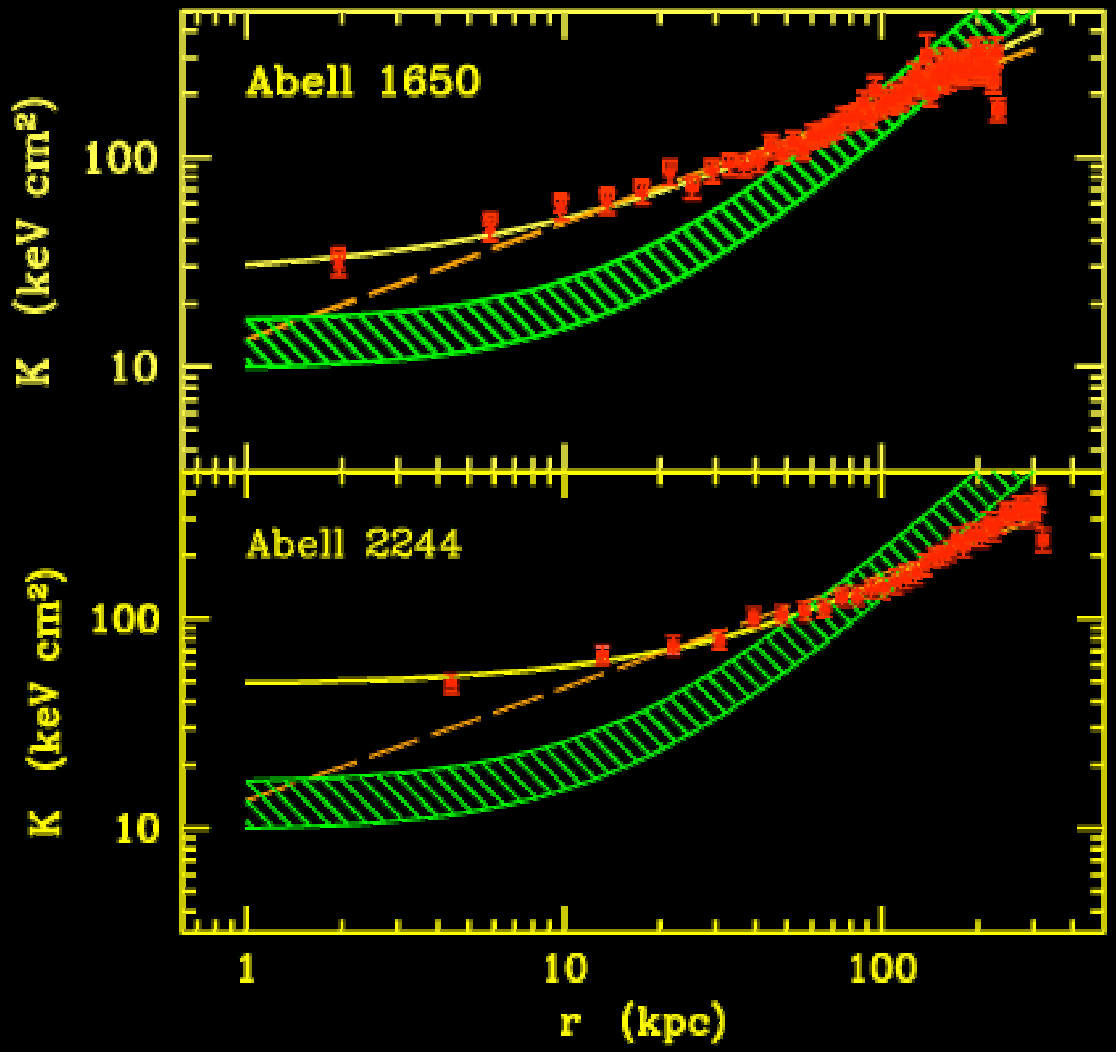
Pure cooling model plus a 10 keV cm^2 pedestal reproduces observed profiles

Episodic Heating

$\Delta t \approx 10^8$ yr $(K / 10 \text{ keV cm}^2)^{3/2}$ $(T / 5 \text{ keV})^{-1}$

- Heating episodes required every ~10^8 yr
- Central entropy level remains near input level for most of duty cycle
- Central entropy input cannot greatly exceed 10-20 keV cm^2

Entropy Profiles of "Passive Clusters"



"Cooling flow" clusters without signs of feedback appear to have high central entropy and cooling time ~ 1 Gyr

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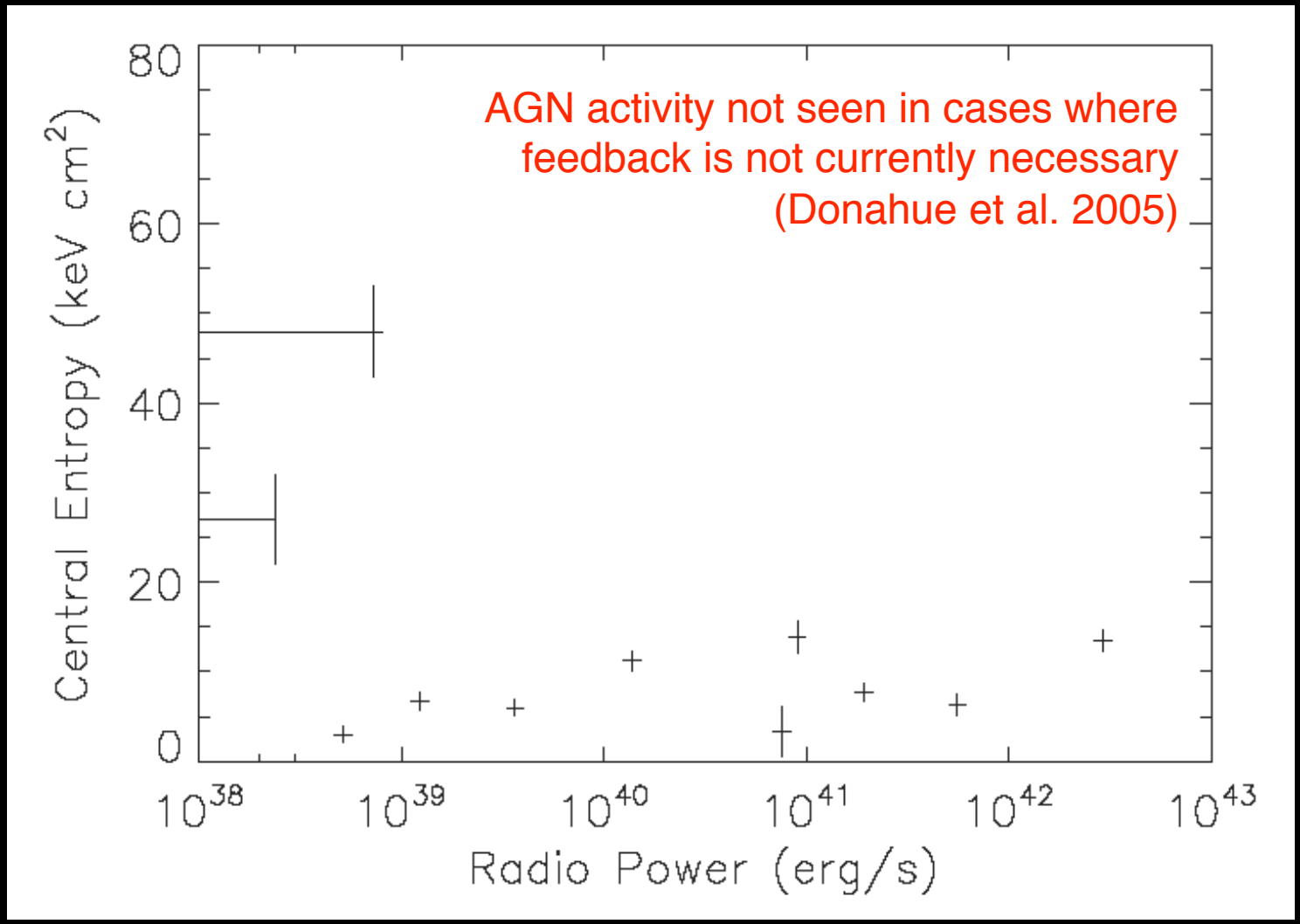

Heating of Cluster Cores

Constraints on Heating

- Entropy inversions are rare
- Iron gradients monotonically decrease
- Central entropy input ~ 10-20 keV cm^2

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Consistent with AGN outbursts of:

- *kinetic power ~10^{45} erg s^{-1}*
- *lasting for > 2 x 10^7 yr*
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~ 10^{60} erg

Independent of inferences from X-ray cavities

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Zones of AGN Heating

- Outflow dominated: $L \sim \rho r^2 v^3$, $v \approx f_P (L/\rho r^2)^{1/3}$
- Energy dominated: $E \sim \rho r^3 v^2$, $v \approx f_E (E/\rho r^3)^{1/2}$
- Bubble dominated: $\Delta E \approx V_{bub}$ |dP/dr| Δr

Pre-Outburst Configuration

$K(r) \approx 150 \text{ keV cm}^2 \, (r / 100 \text{ kpc})$

$T(r) \approx T_{5,100} \, (r / 100 \text{ kpc})^{1/3}$

$n_e(r) \approx 0.006 \text{ cm}^{-3} \, T_{5,100}^{3/2} \, (r / 100 \text{ kpc})^{-1}$

Entropy Jump Condition

$$K_2 \approx \frac{v^2}{3(4\rho)^{2/3}} + 0.84\, K_1$$

$$\Delta K \approx \frac{v^2}{3(4\rho)^{2/3}} - 0.16\, K_1$$

$$M \approx 2.1\, (\Delta K / K_1)^{1/2}$$

Zones of AGN Heating for $\rho \propto 1/r$

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  – Constant power naturally produces $\Delta K(r) \sim$ const.

  – No entropy inversion; no convective mixing

  – Inner entropy scale directly related to power input

$$\mathcal{M}(r) \approx \sqrt{\frac{\Delta K}{10\ \mathrm{keV\ cm^2}} \frac{30\ \mathrm{kpc}}{r}}$$

Zones of AGN Heating for $\rho \propto 1/r$

- Outflow dominated: $L \sim \rho r^2 v^3$, $v \approx f_P (L/\rho r^2)^{1/3}$

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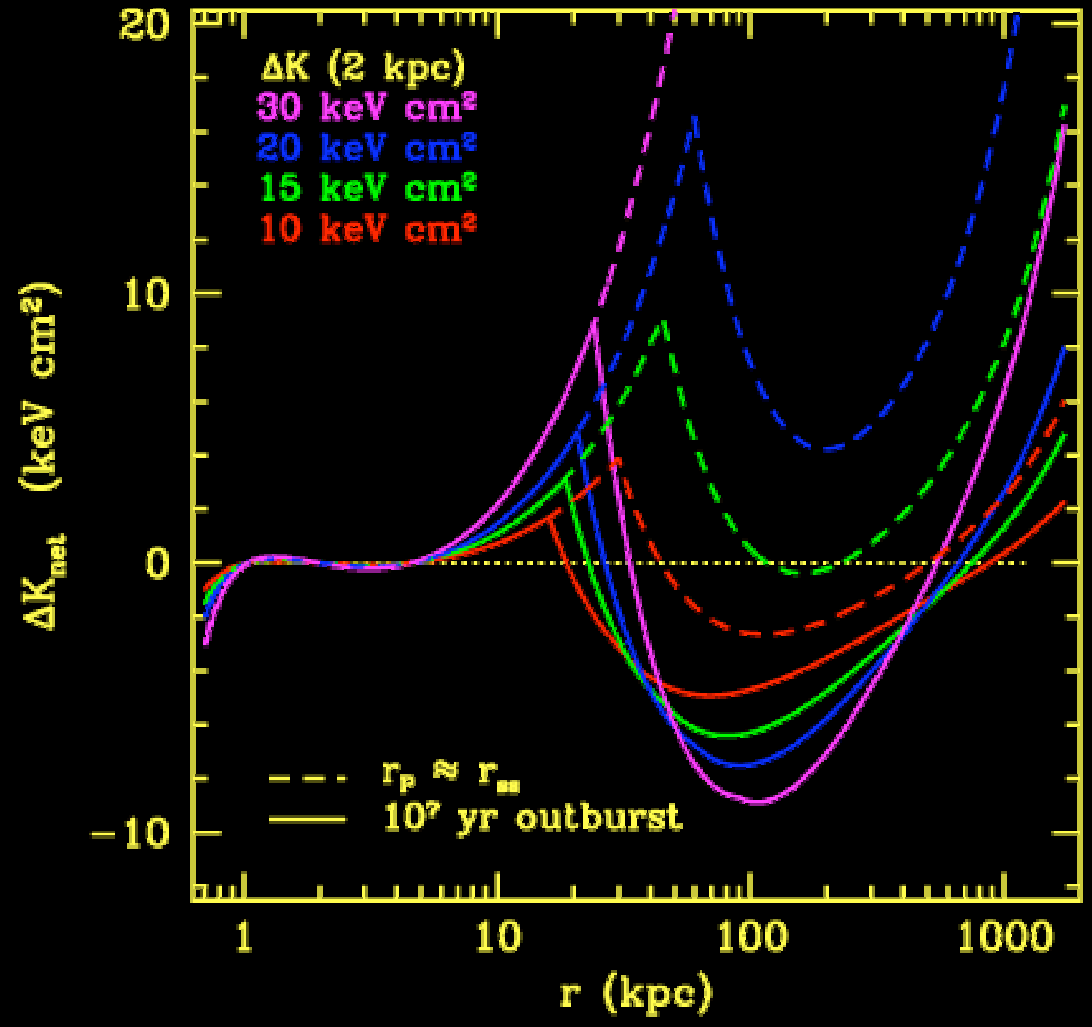
Net Entropy Change Per Cycle

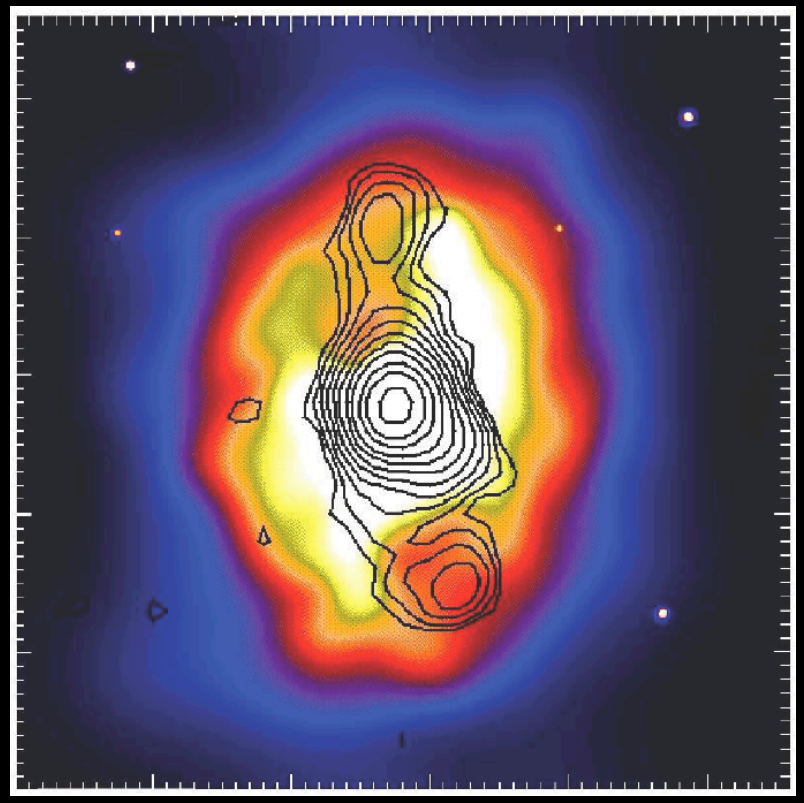


Use pure cooling model as initial state

Time between outbursts set by balancing heating and cooling at 2 kpc

Heating beyond the Core

Dramatic Heating Events



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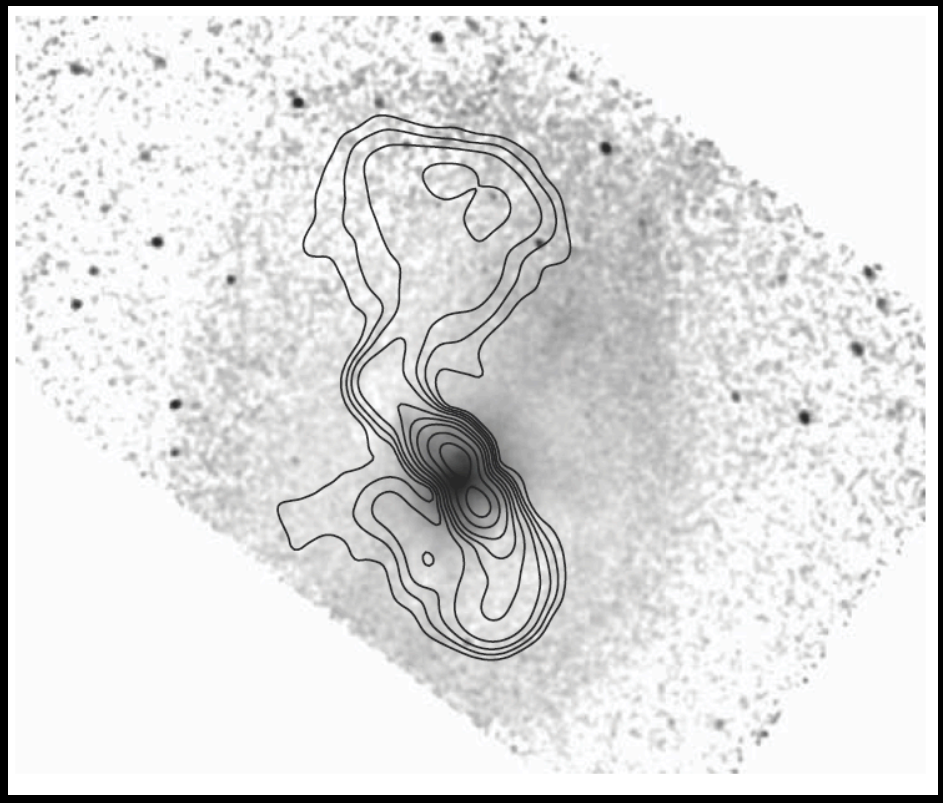

Hydra A (Nulsen et al.)

Beyond the Core ($\rho \propto 1/r^2$)

- Sustained Luminosity: $L \sim \rho r^2 v^3$

$v \sim 1600 \text{ km s}^{-1} \; L_{46}^{1/3} \; (T/5 \text{ keV})^{-1/3}$

$\Delta K / K \sim 0.4 \; L_{46}^{2/3} \; (T/5 \text{ keV})^{-5/3}$

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Preserves shape of original K profile!

A Role for Conduction?

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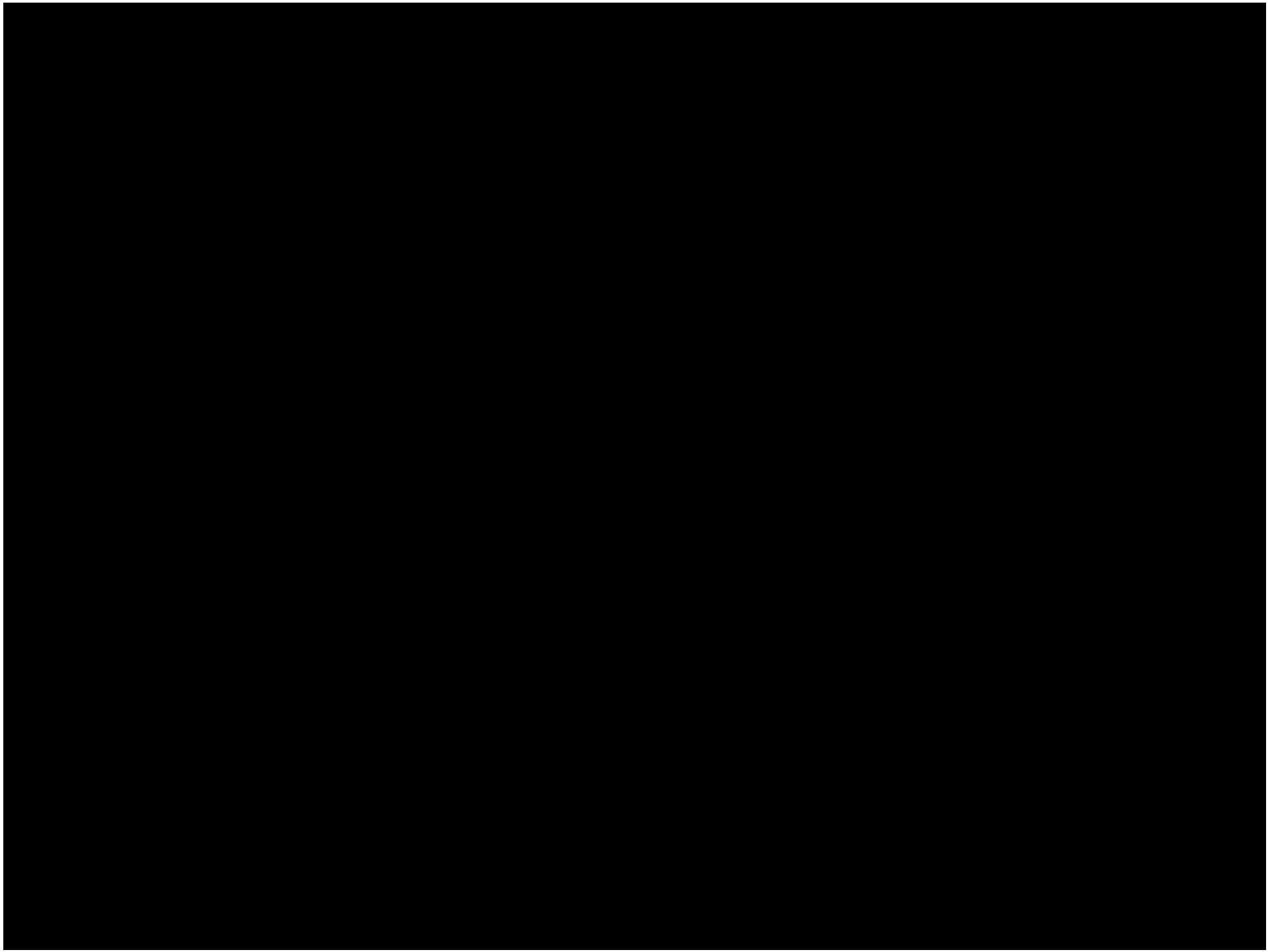
$$\lambda_F = \sqrt{\frac{\kappa T}{n_e^2 \Lambda}} \sim 10 \text{ kpc } (K / 18 \text{ keV cm}^2)^{3/2} \; f_c^{1/2}$$

- Conduction cannot stabilize radiative cooling in “active clusters”
- Conductive stabilization is possible in “passive clusters” for $f_c \sim 0.3$ - 1
- Large AGN outburst can raise core to conductively stabilized state (bifurcation?)

AGN Heating in Cluster Cores

- Entropy Profile Shapes:
  - "Active clusters" have ~10 keV cm^2 pedestal
  - "Passive clusters" have higher central entropy

- Heating by AGN Outflows:
  - Constant-power outflow can produce $\Delta K \sim$ const.
  - Core profiles imply ~10^{45} erg/s for ~ 30 Myr
  - Bubble heating (or wave heating) at > 30 kpc
  - Conduction may cause bifurcation in cores



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