Feedback from Central Black Holes in Clusters of Galaxies

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X-ray Signatures of Feedback

1. Metals in the intracluster medium (ICM)
2. The ICM Luminosity - Temperature relationship.
3. ICM entropy patterns and ICM bubbles generated by active galactic nuclei (AGN) in the brightest central galaxy (BCG).

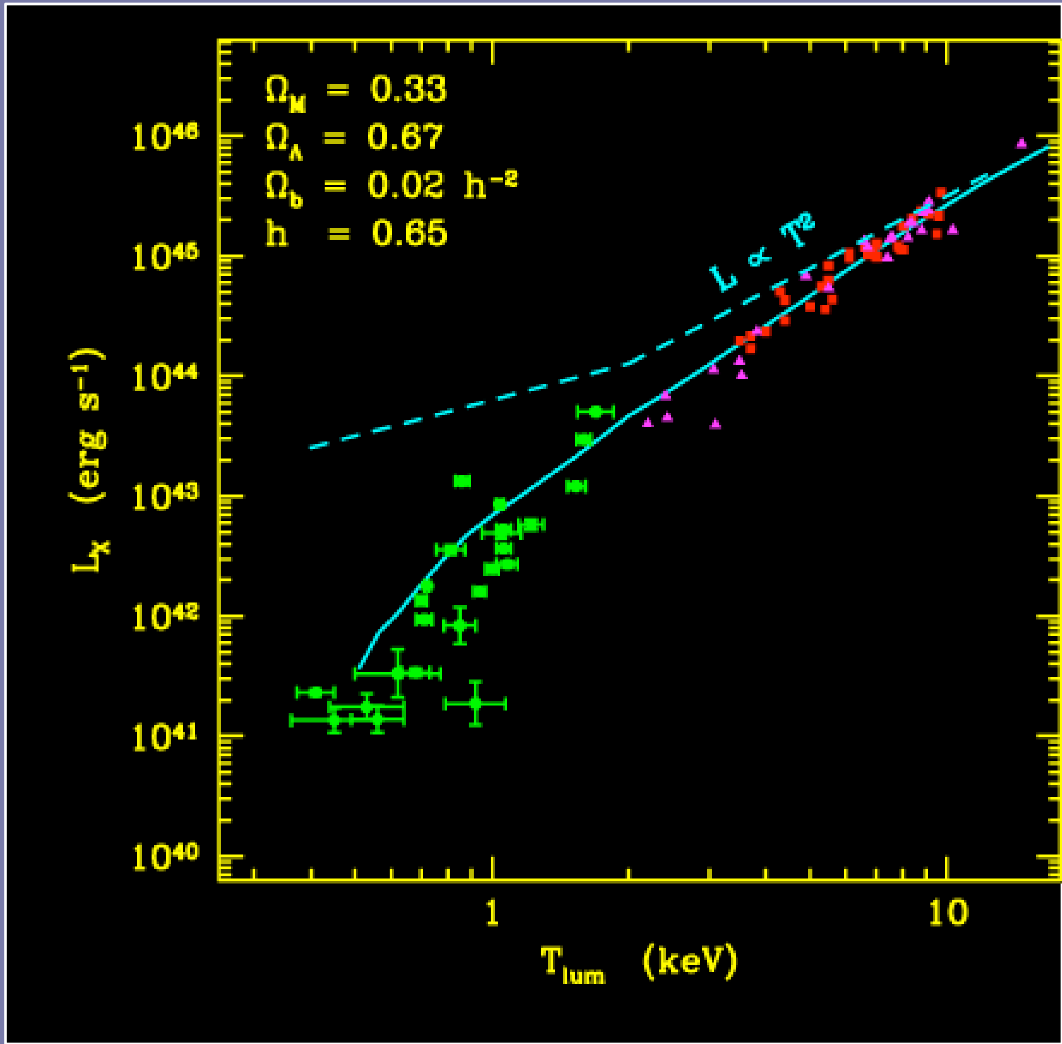
Does galaxy formation affect the thermodynamics of the ICM?

ICM Luminosity - Temperature Relation

Structure formation without feedback predicts L ~ T^2.

Including cooling modifies the relation

e.g. Voit & Bryan 2001



Galaxy Formation and the ICM

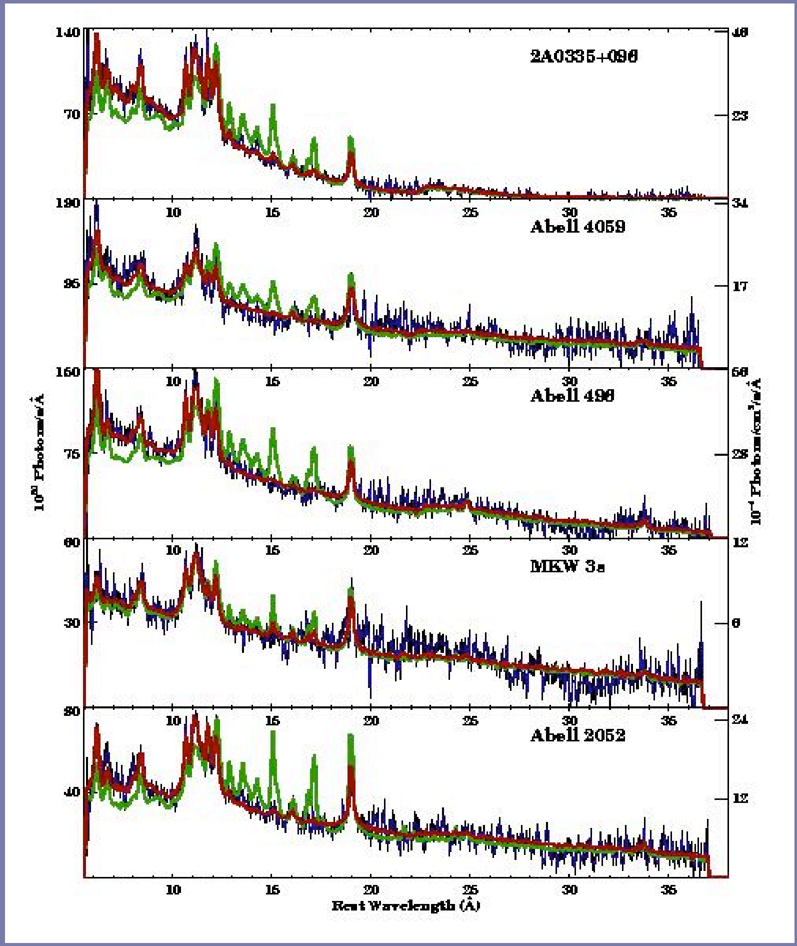
- ✓ Cooling and condensation into stars brings the L-T relation into agreement w/ observations.
- However, cooling alone produces too many stars (Rees & White 1978; Balogh 2001).
- ✓ Star formation contributes metals and energy to the ICM: this feedback alone may regulate star formation in most galaxies.

Galaxy Formation and the ICM: Questions

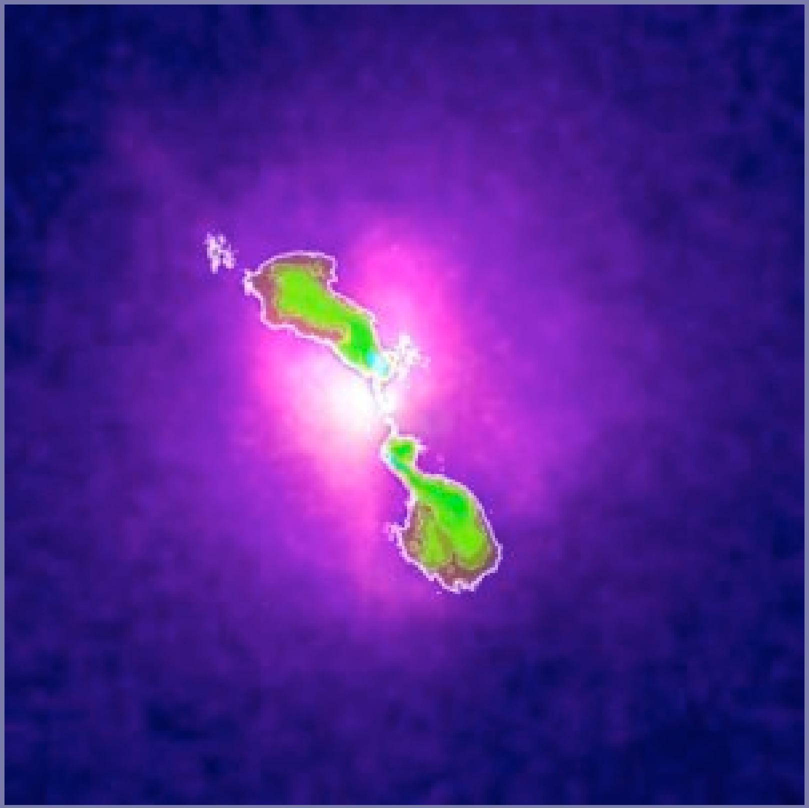
- Even with feedback from star formation, simulations still predict too much star formation in brightest central galaxies in clusters (e.g. Kravtsov 2005).
- The ICM in the centers of most X-ray clusters is radiating too quickly to persist without additional energy input: the “cooling flow” problem.

Cool cores in clusters

- XMM RGS results show little or no gas cooler than 1 keV
- Temperature gradients from Chandra and XMM observations: “cool” cores
- The radiative cooling times are short.



Is another source of feedback necessary to explain cluster cores?



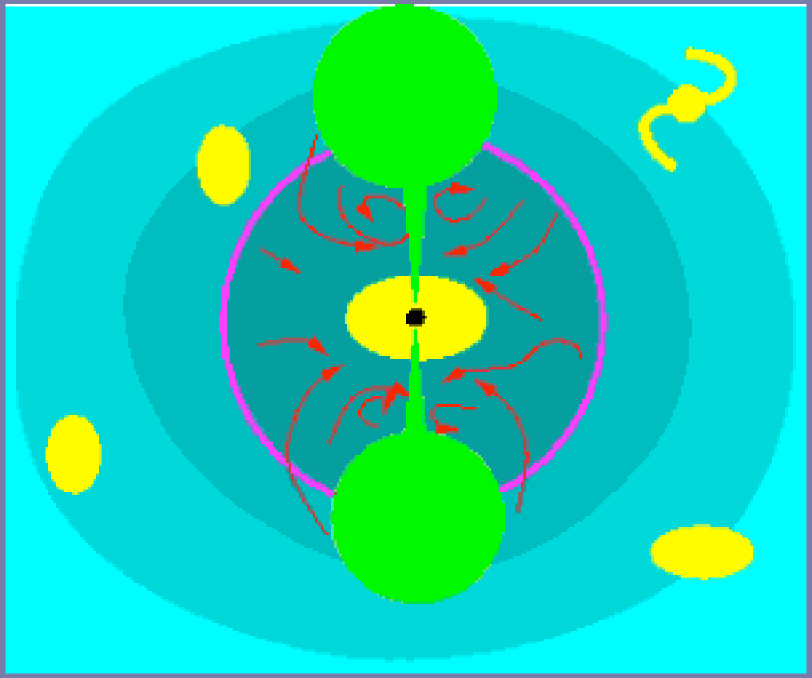
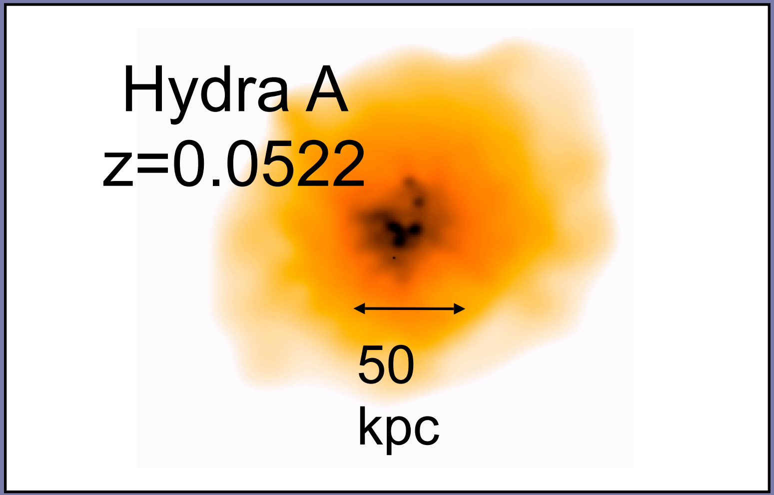
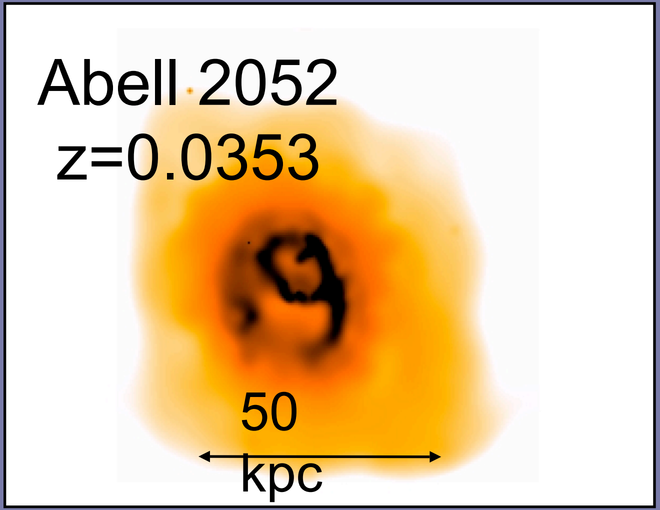


Figure source: Max-Planck-Institute

Radio Sources & Cluster Cores



- Bubbles in the ICM (McNamara, Sarazin, Blanton)
- Heating occurs, but it's not clear how the AGN compensates for radiative losses.



How does the presence of an AGN affect a cluster core?

Chandra Archive Analysis

- A comparison sample of 9 X-ray clusters, radio “loud”, 8 with optical emission line systems, were analyzed in the same way

Donahue, Horner, Cavagnolo, & Voit 2005, submitted

T(r), Z(r) In Systems with Radio Sources

- Cool cores in all these systems.
- Significant iron gradients, increasing toward the core.
- Evidence for a relatively undisturbed recent history:
  - ✓ The center (and peak) of the X-ray source aligns with the center of the brightest central galaxy (BCG).
  - – The presence of an iron gradient.

ICM Entropy

- ICM X-ray temperature is related to a cluster's gravitational potential.
- X-ray luminosity

$$L_x \propto n_e^2 T^{1/2}$$

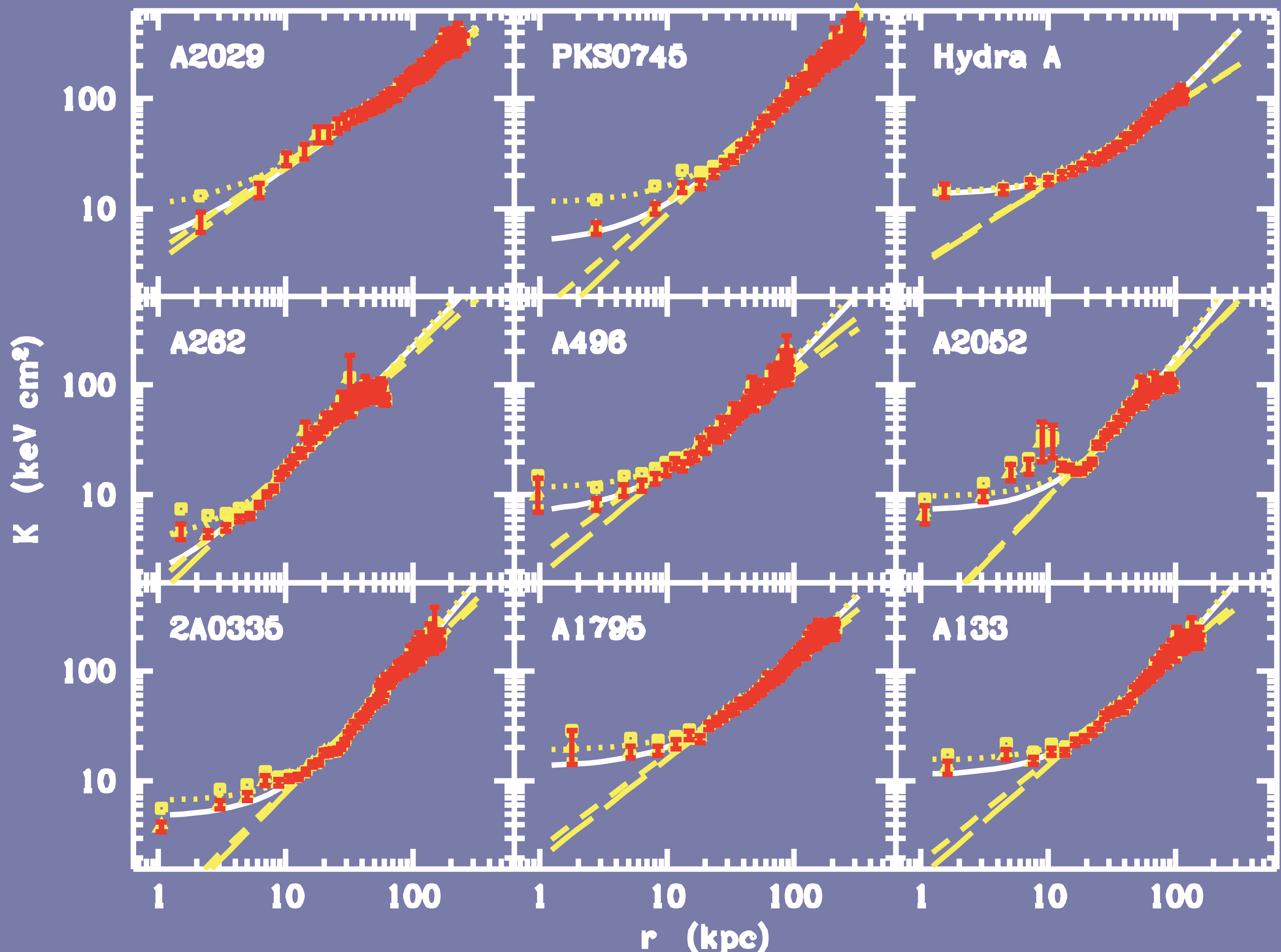
- Density of the ICM is determined by the ICM entropy

$$K = T\, n^{-2/3}$$

Cluster Entropy Profiles

- ICM entropy can be changed by feedback processes from the member galaxies: galactic winds, AGN.
- Different cooling and feedback histories lead to different entropy profiles.
- ?

Clusters With Radio Sources



Donahue, Horner, Cavagnolo and Voit 2005

Entropy Gradients

- Cool cores ***with*** feedback evidence show a remarkable consistency in their entropy profiles:
- $K(r) = K_0 + K_{100}(r/100\ \mathrm{kpc})^{\alpha}$
  - $K_0 \sim 10$ keV cm^2

    $\alpha \sim 0.9 - 1.3$
- If there were no feedback, models predict $\alpha = 1.1$
- Almost all have non-zero K_0.
- Cooling time $t_c = (100\ \mathrm{Myr})\ (K/10\ \mathrm{keV\ cm^2})^{3/2}\ (T_{keV})^{-1}$

Interpretation of profiles

- Similarity of profiles implies similarity in feedback history.
- No entropy inversions $r > 10$ kpc: suggests energy injection happens over a large volume, not just in the center.

What about clusters without radio sources?

Radio-quiet cluster cores

Peres et al. 1998:

- 23 clusters with short cooling times in the cores.
- 13: emission line nebulae & strong central radio source
- 2: strong central radio source but no optical line emission (A2029, A3112)
- 3: emission lines but weak central radio source. (A478, A496, A2142)
- 5: no emission lines and little or no radio activity. (A644, A1650, A1651, A1689, A2244)

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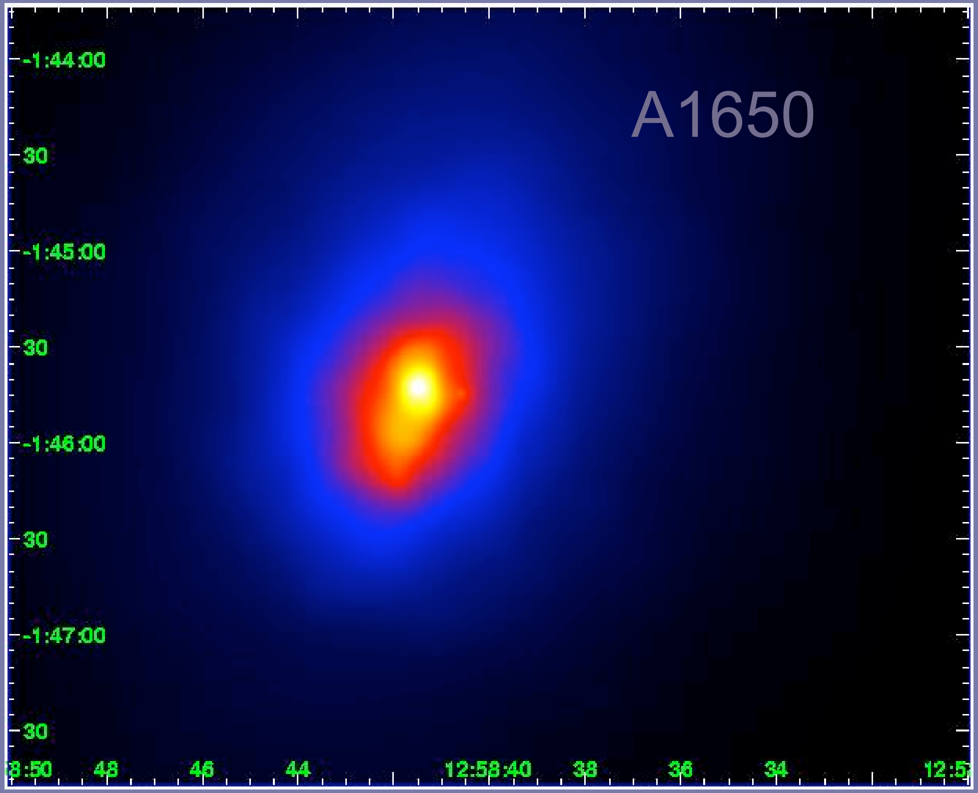
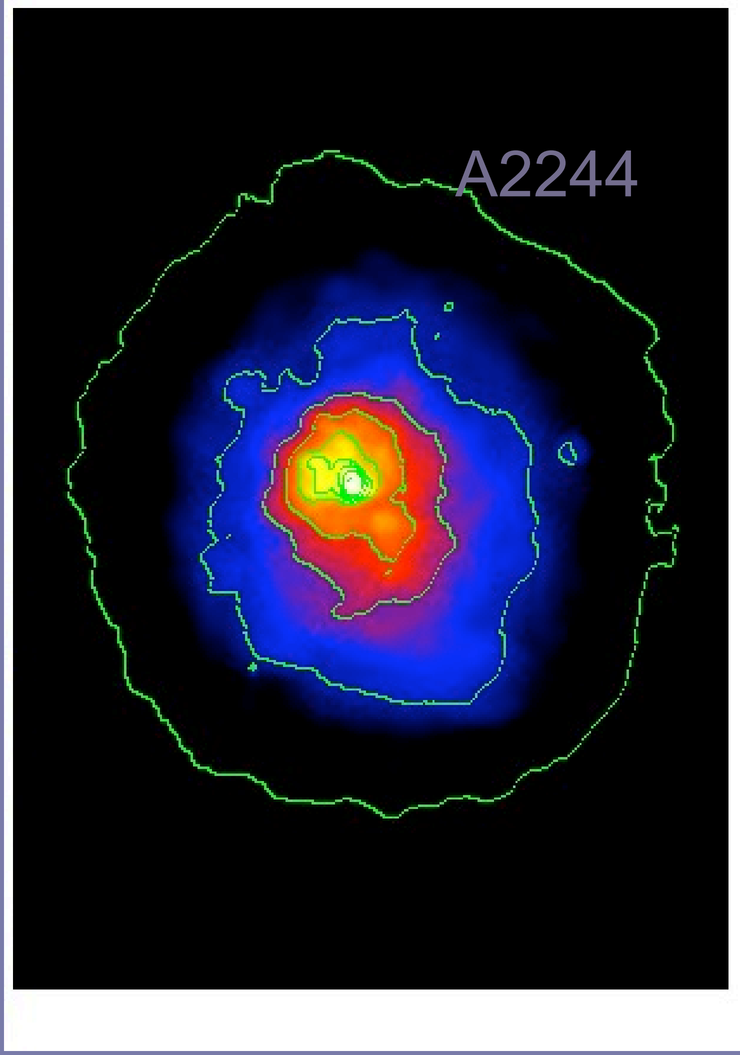
What might have been:

- Fossil radio bubbles and/or X-ray cavities suggestive of earlier radio activity.
- Very low central entropy values, suggesting that these clusters are on the verge of a heating episode.

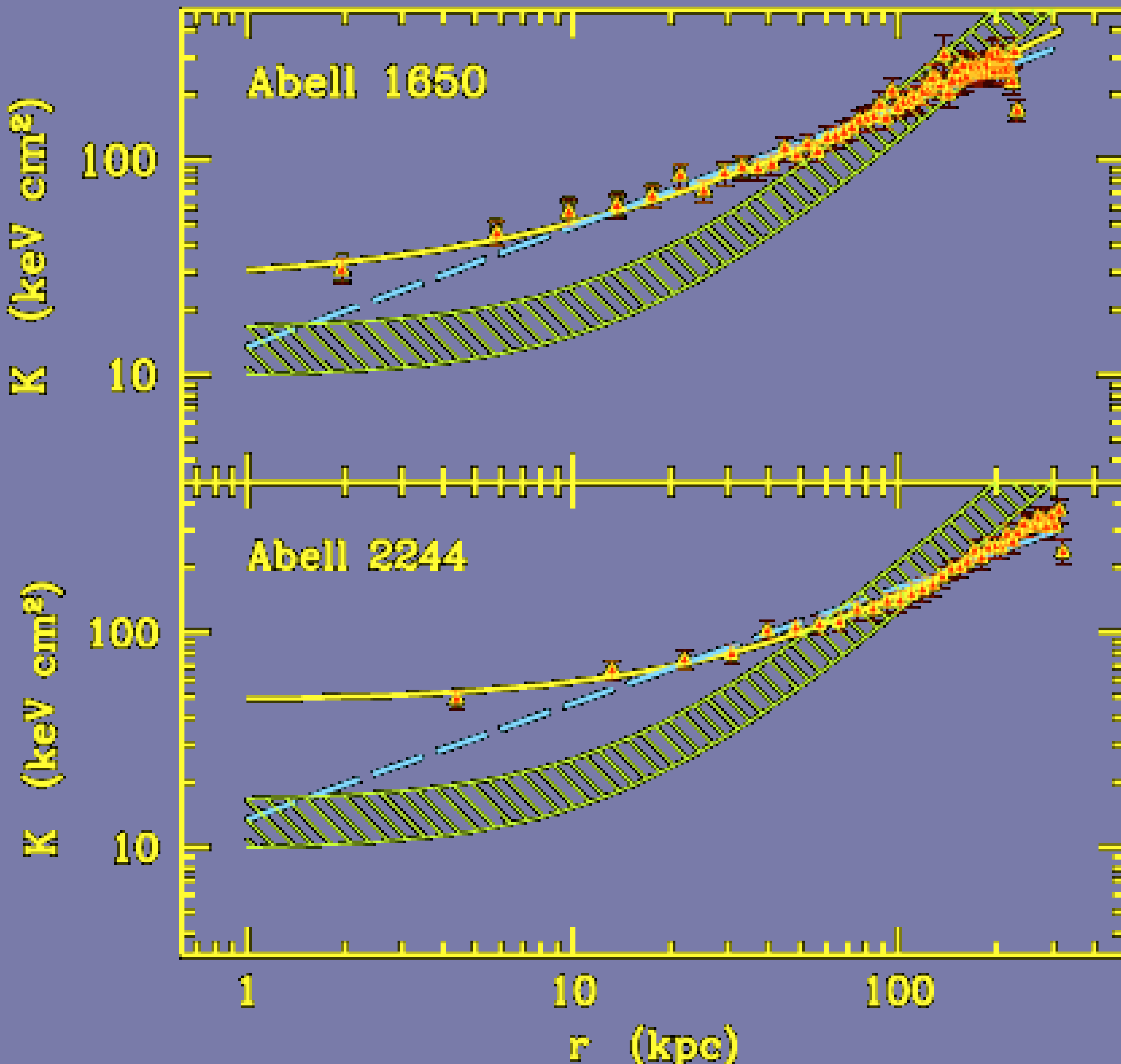
What is

- No fossil bubbles out to ~100 kpc
- Little or no temperature gradients





Donahue, Voit, O'Dea, Baum & Sparks 2005

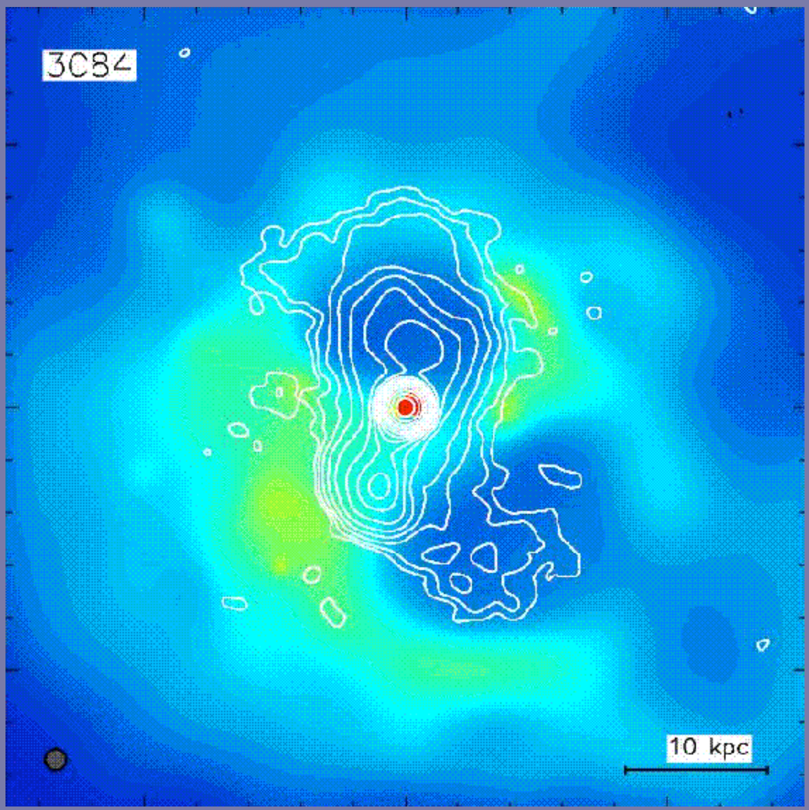


Abell 1650
Abell 2244
K (keV cm^2)
100
10
1
10
100
r (kpc)

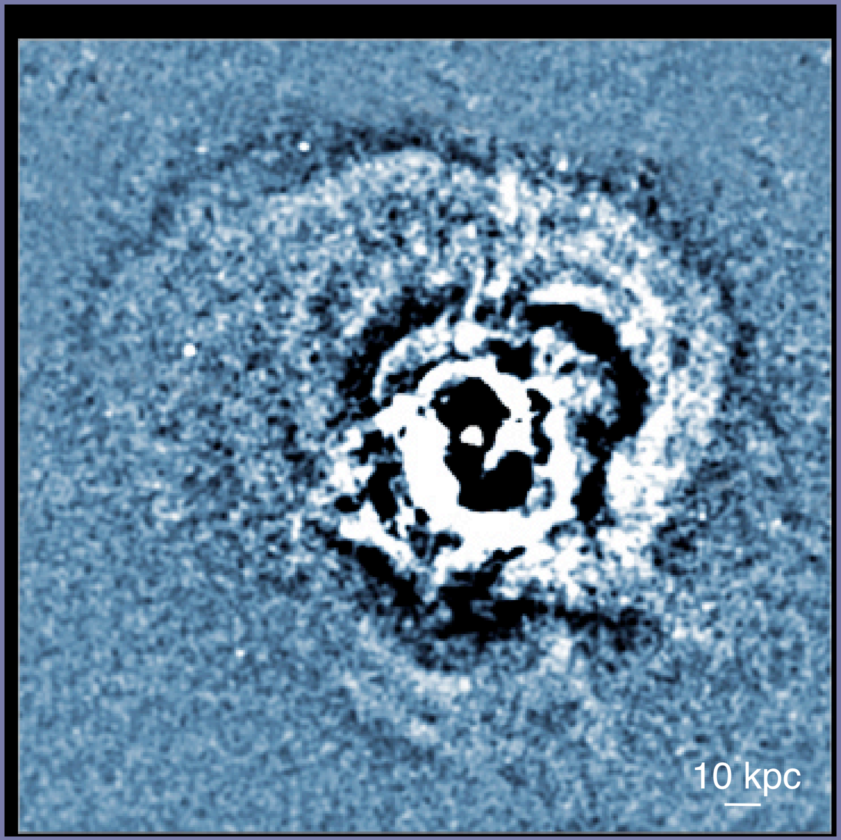
Summary

- High central entropies instead of low central entropies: 35-50 kev cm^2 compared to 6-10 keV cm^2
- Shallow temperature gradients.
- Longer central cooling times: 10^9 years compared to 10^8 years, but still less than the age of the system.

How do AGNs regulate core entropy?

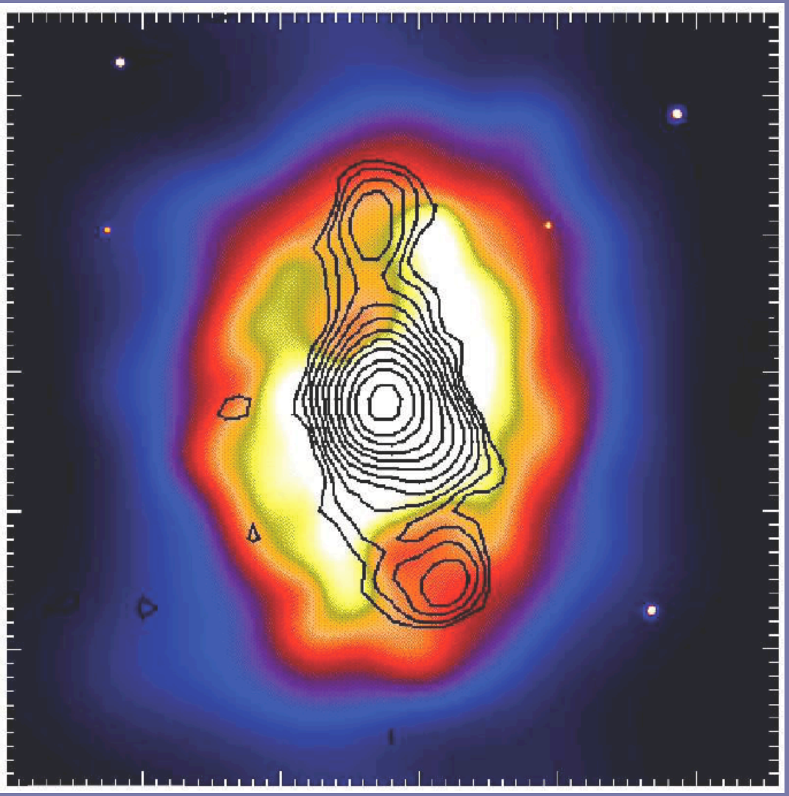


Perseus Cluster & 3C 84

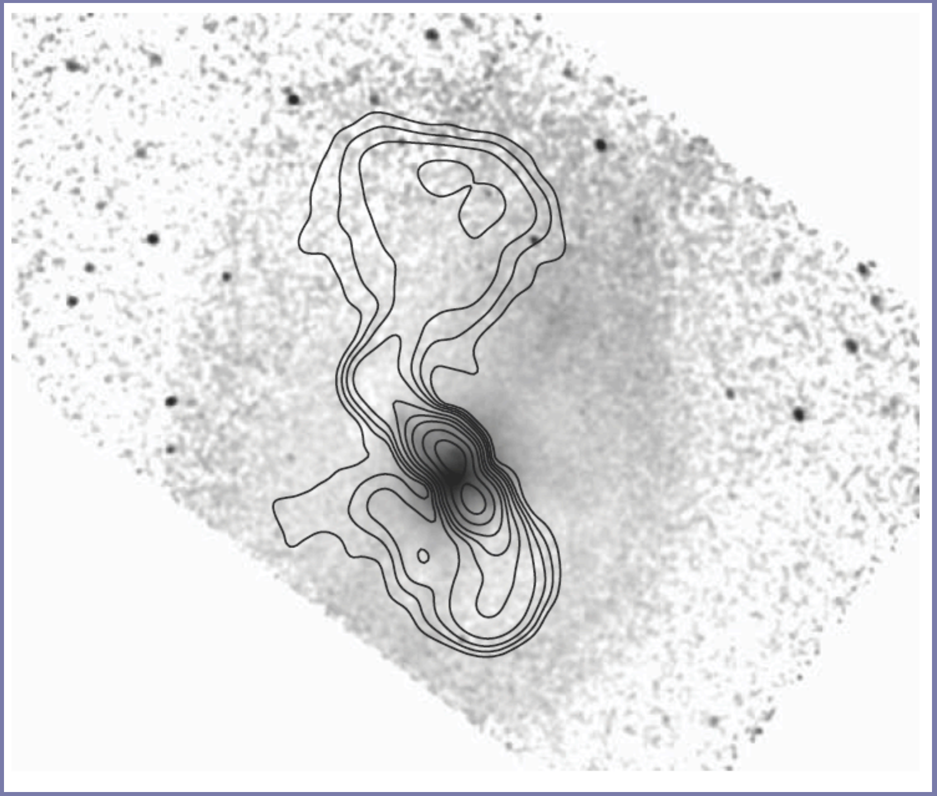


Sound Waves in Perseus

Dramatic Heating Events



MS0735 (McNamara et al.)



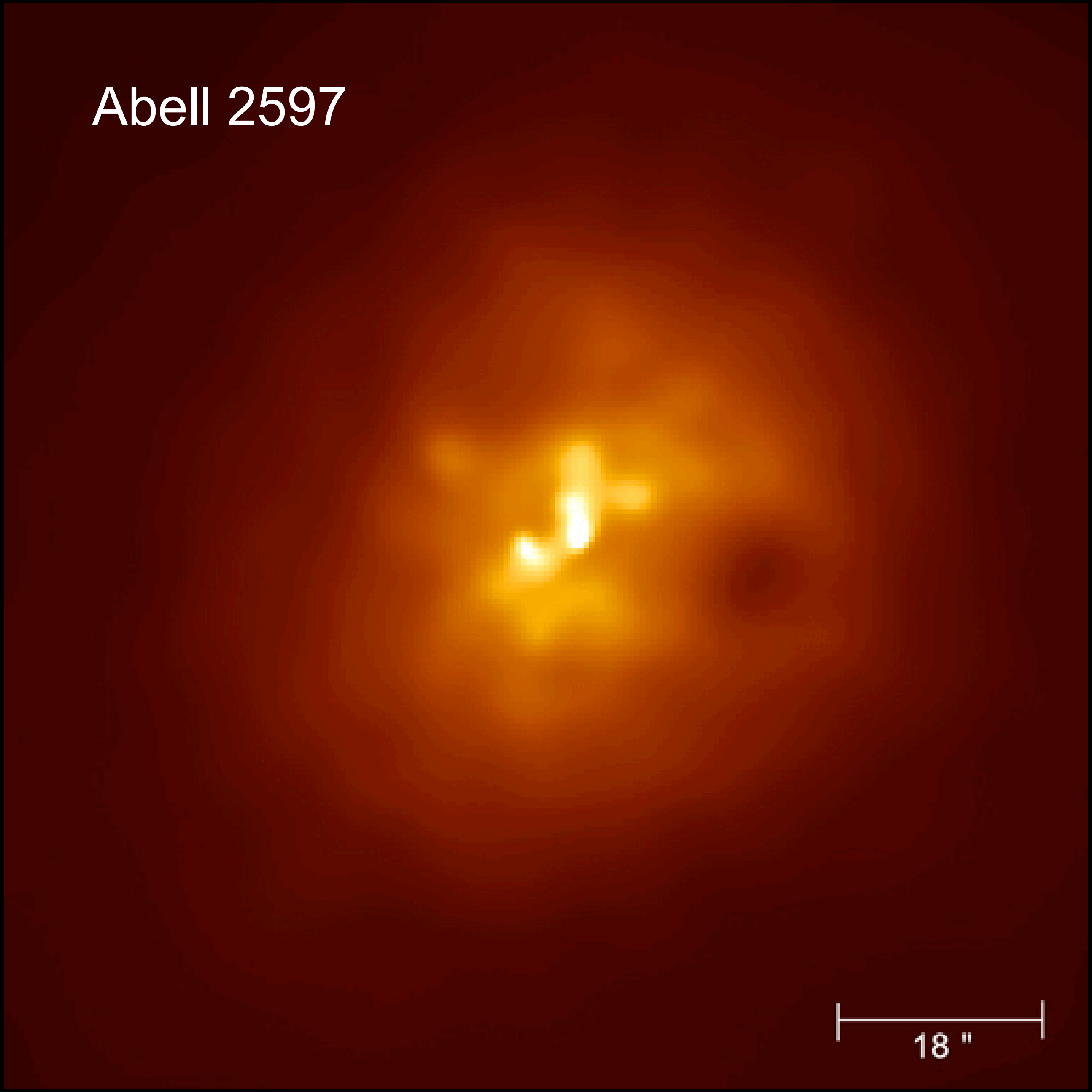
Hydra A (Nulsen et al.)

Episodic Heating

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

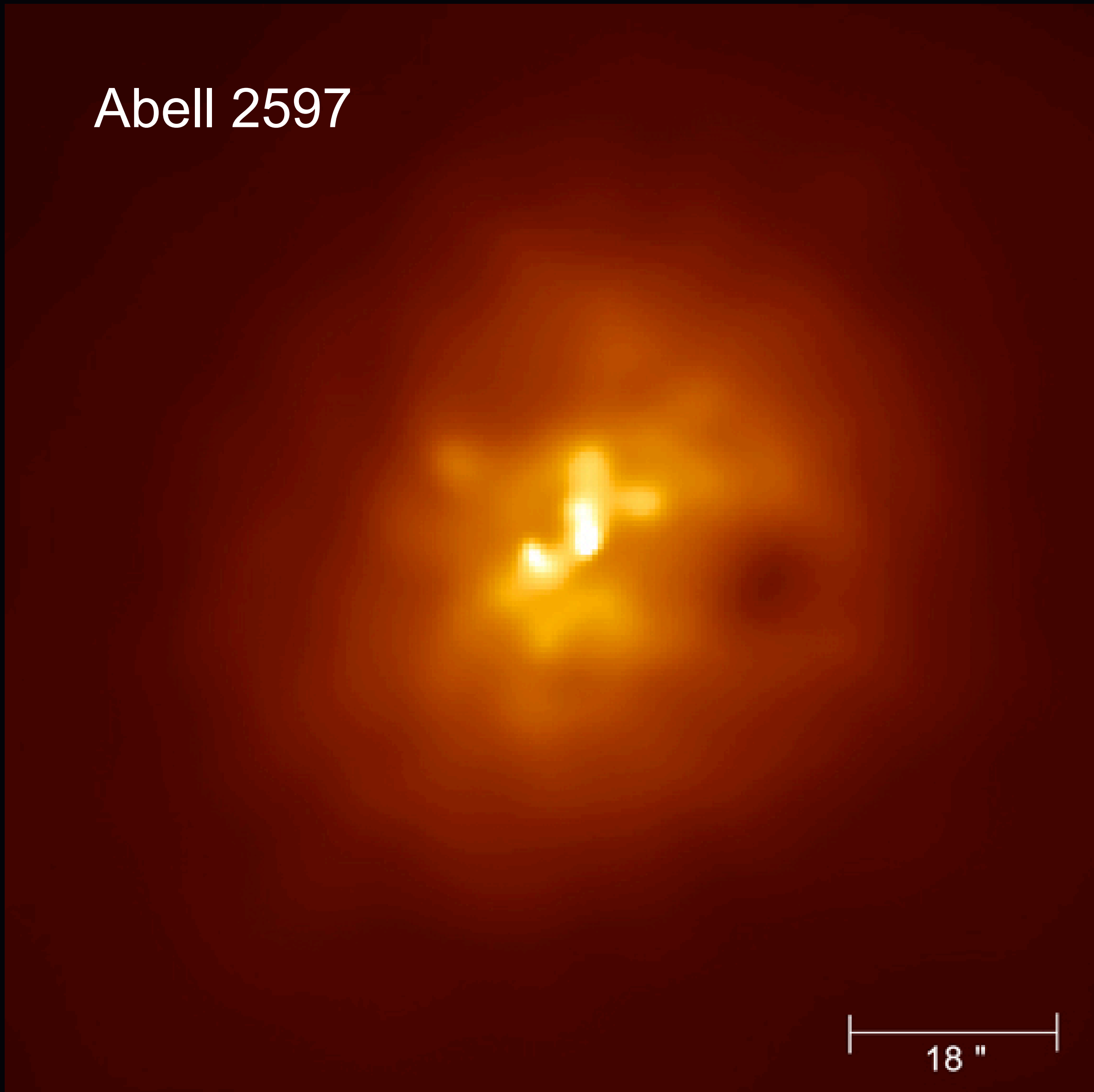
- Heating episodes required every $\sim 10^8$ yr
- Heating source is “on” for a significant fraction of that time
- Central entropy input cannot greatly exceed 10-20 keV cm^2

Voit & Donahue 2005



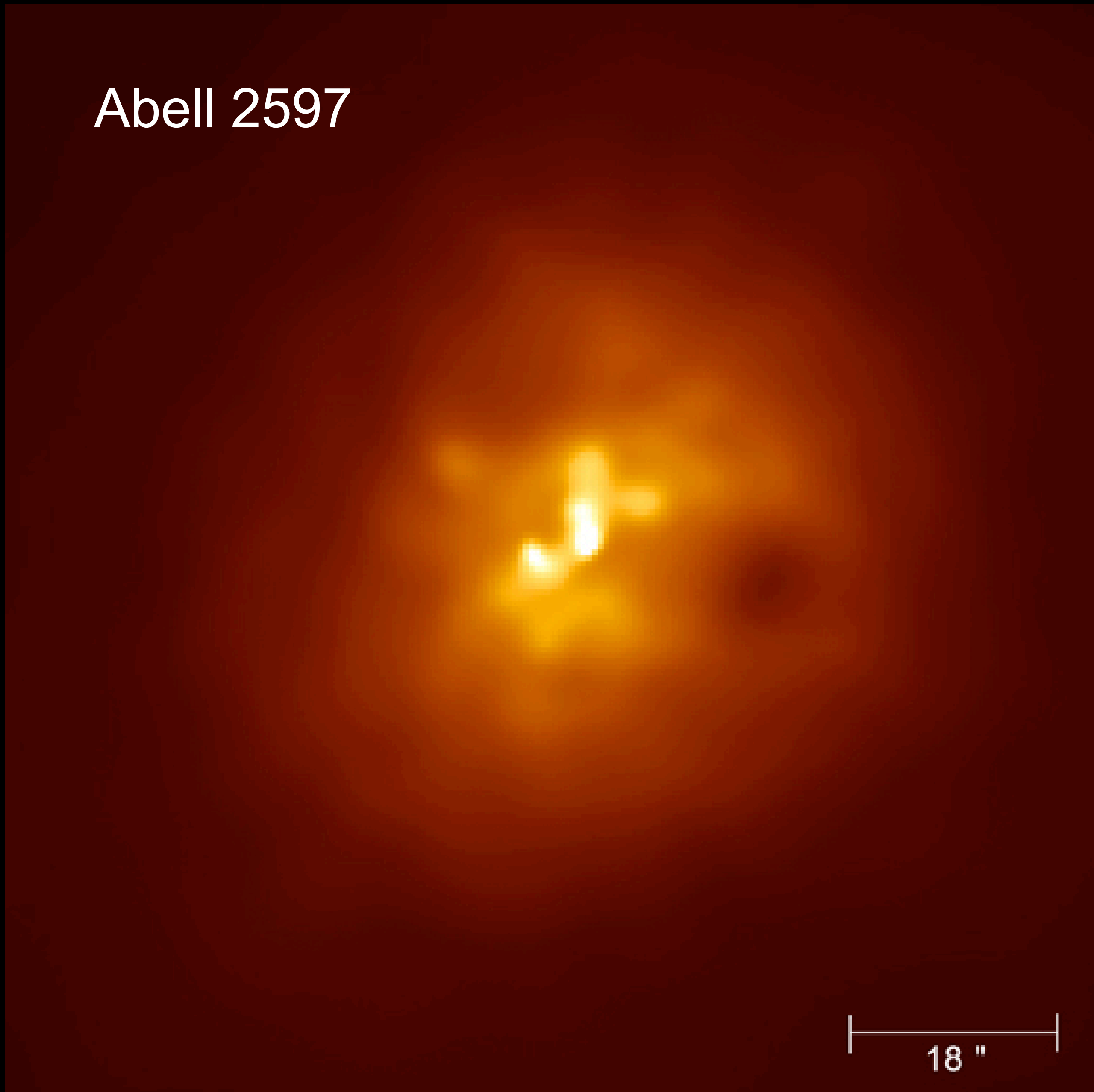
3 phases:
Power
Energy
Bubble

When density drops like r^{-1}, the change in entropy scales with AGN power only



3 phases:
Power
Energy
Bubble

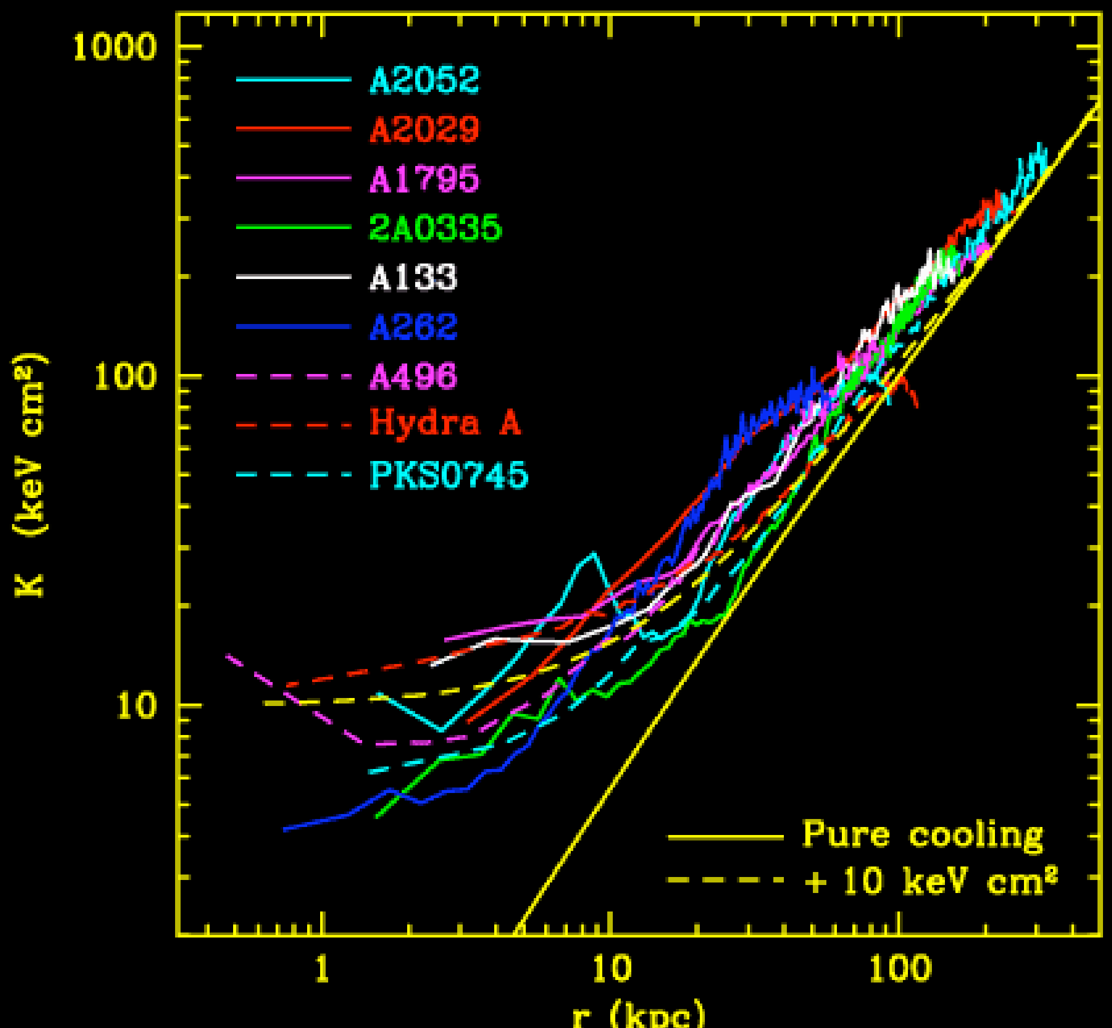
When density drops like r^{-1}, the change in entropy scales with $E\ r^{-4/3}$



3 phases:
Power
Energy
Bubble

The bubble can heat the ICM as it rises: heat and entropy are increased over a large region.

Chandra Entropy Profiles



Core entropy profiles very regular

Entropy inversions are minor and lie at r < 10 kpc

Beyond the Core $(\rho \sim r^{-2})$

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

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

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

Preserves shape of original K profile; no entropy inversions!

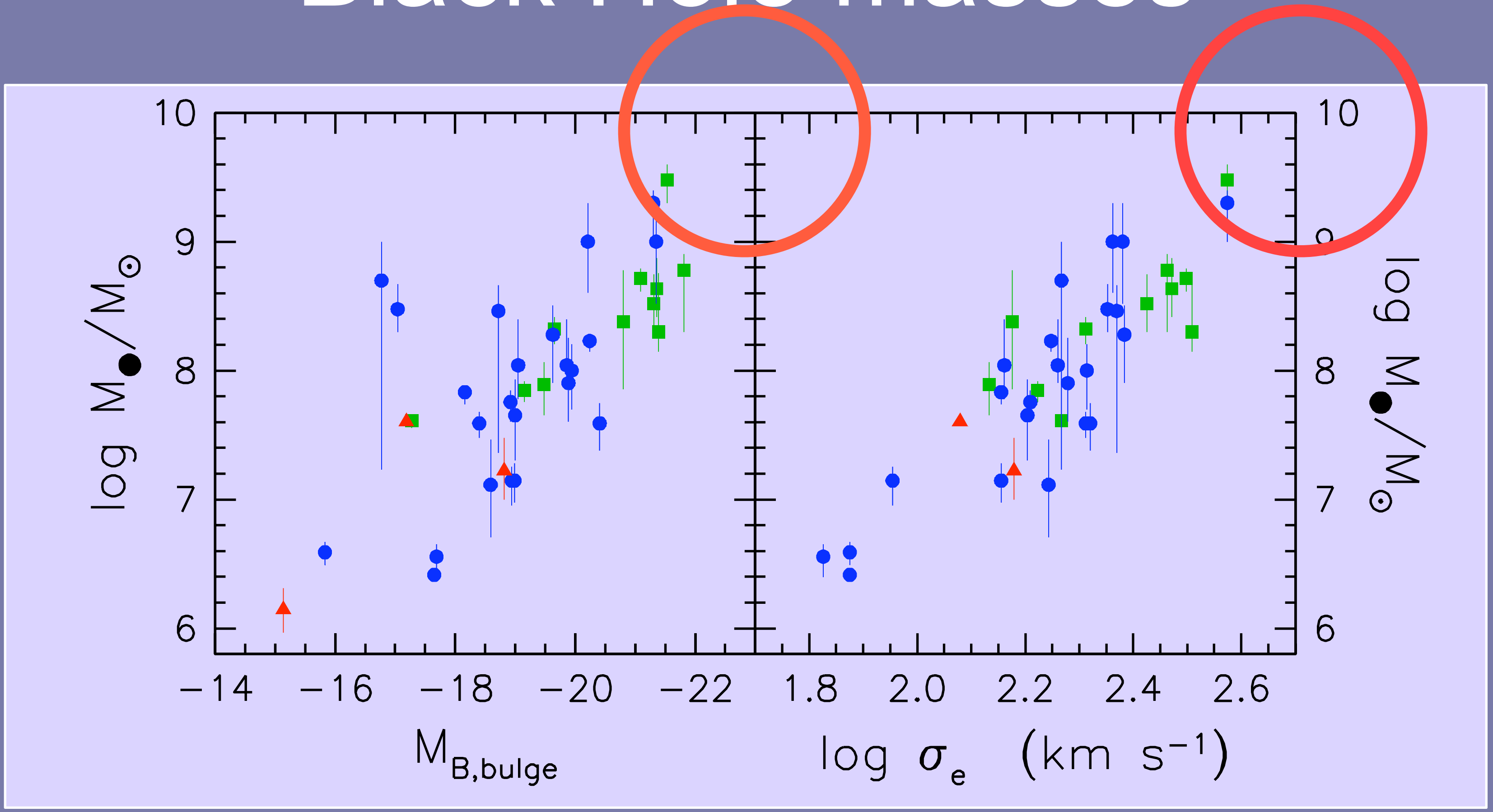
Voit & Donahue, 2005

AGN heating?

- *Yes!*
- *AGN are almost certainly the primary stabilizing mechanisms for cool cores in clusters at z~0.*

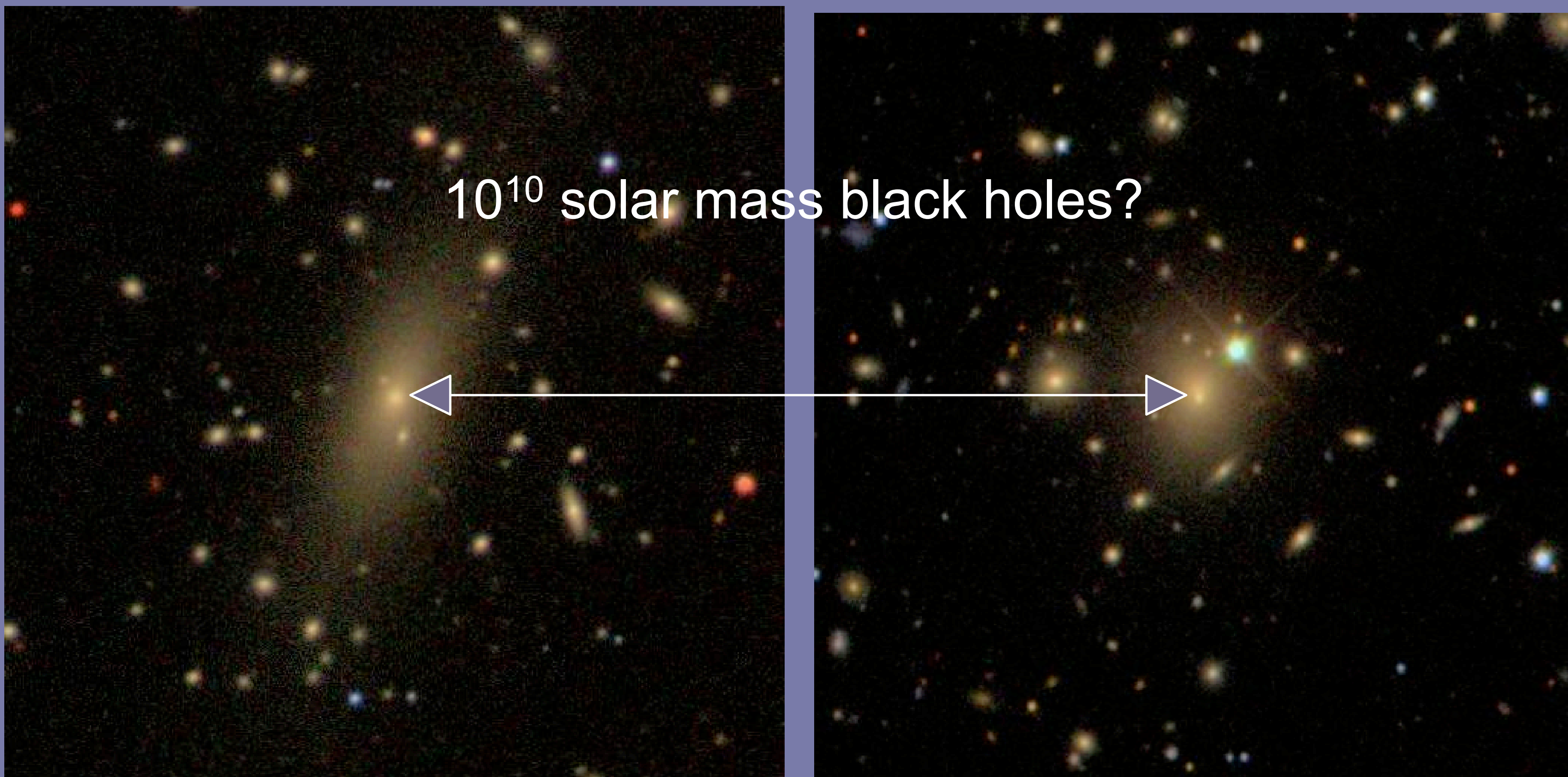
Is AGN feedback consistent with what we know about black holes in galaxies?

Black Hole masses



Gebhardt et al. 2000

Do the brightest galaxies host the most massive black holes?



Abell 1650 $M_I \sim -24$ Abell 2244

Conclusions

- *Star formation has enriched the ICM gas and contributed at least some entropy.*
- *Cooling and star formation explain the ICM L-T relation (for T>3 keV).*
- *But galactic winds from star formation are not sufficient to explain the most massive galaxies.*
- *Central entropies of nearby clusters with short central cooling times are higher in clusters without radio sources.*
- *AGN are required to complete the story to regulate star formation in BCGs and stabilize cool core clusters.*