Cluster Thermodynamics: Entropy

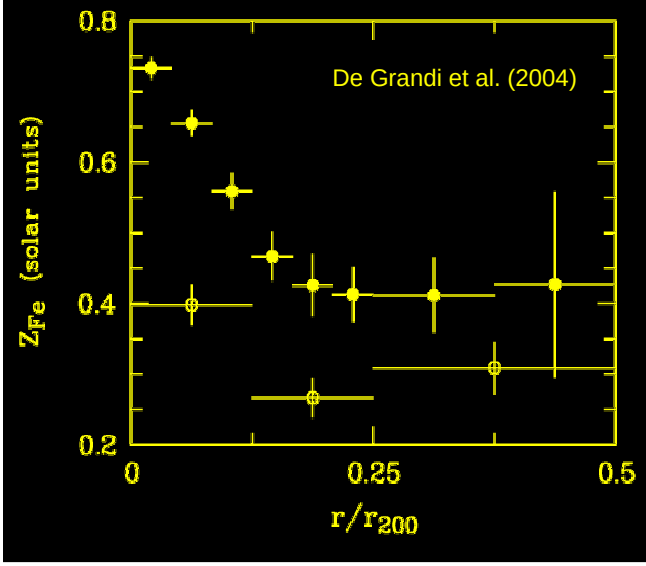
Intracluster Entropy

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

- 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*

How much energy have galaxies put into the ICM?

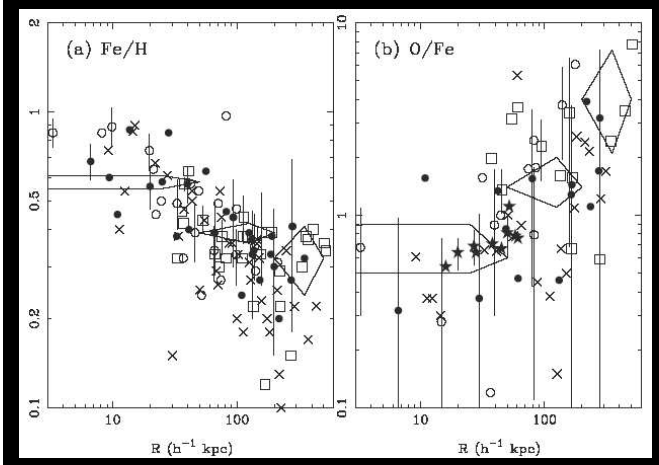
Iron Abundance Profiles



Z_{Fe} ~ 0.3 solar out to half the virial radius

Cool-core clusters (filled circles) have central Fe excess consistent with Type Ia SNe in central galaxy

Oxygen Abundance Profiles



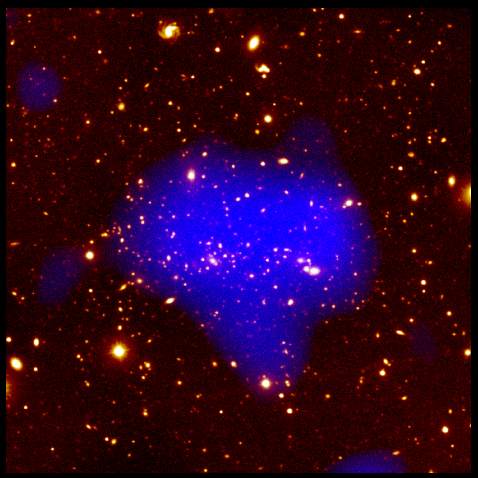
Tamura et al. (2004)

O abundance does not show core excess – different origin from Fe in core

O/H ~ 0.3 solar

E_{SN} ~ 0.5 keV/part

Energetics of the ICM



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

kT ≈ 10 keV

Fe/H ≈ 0.3 solar

z = 0.83

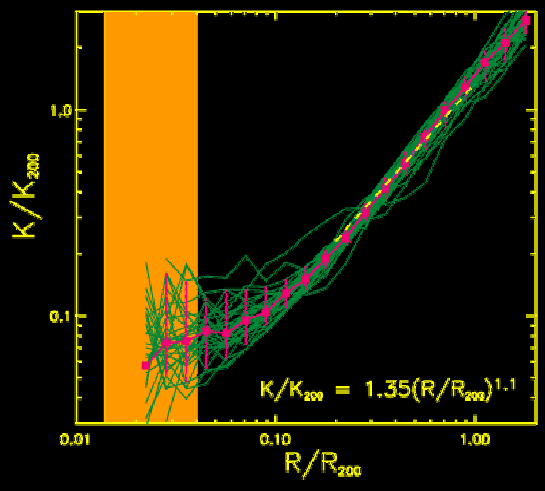
(Fe/H ~ 0.3 @ z > 1; Tozzi et al. 2003)

E_{SN} ≈ 0.5 keV/particle

E_{AGN} ≈ ? keV/particle

How does galaxy feedback alter cluster structure?

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, $K(r) \sim r^{1.1}$

Voit, Kay, & Bryan (2004)

Entropy Floor: The Good

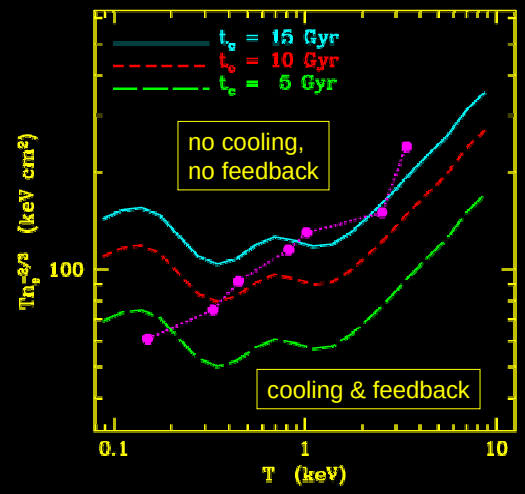
- Self-similar clusters: $L \sim T^2$
- Observed clusters: $L \sim T^3$
- Excess entropy in low-*T* systems suppresses core luminosity
- Universal entropy floor in early universe would lead to $L \sim T^3$
- Requires floor ~ 100-200 keV cm^2

(Evrard & Henry 1991; Kaiser 1991)

Entropy Floor: The Bad

- Universal floor at z~3 implies $T_{IGM} > 10^5$ K
- Imposing floor at z~3 in virialized systems requires ~ 1 keV part^{-1}
- XMM data do not show isentropic cores in groups

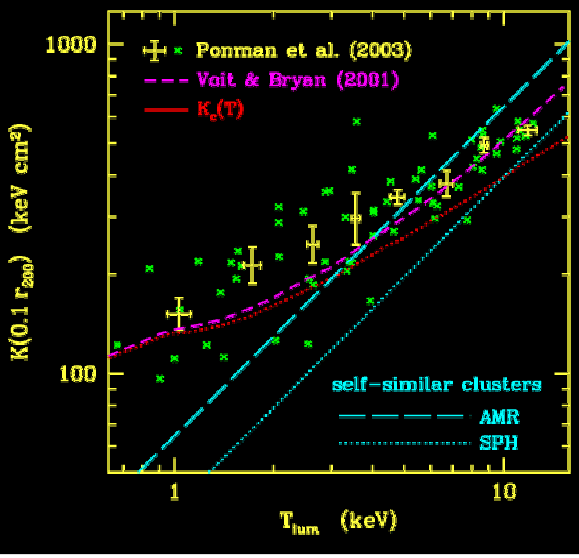
Entropy Threshold for Cooling



Gas that remains above threshold does not cool and condense.

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

Entropy Threshold for Cooling



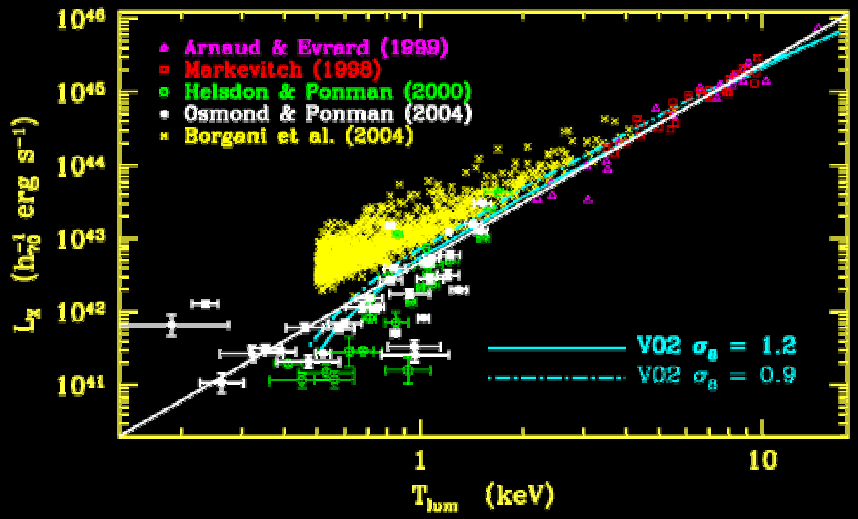
Measurements show that entropy at $0.1r_{200}$ scales as

$$K_{0.1} \propto T^{2/3}$$

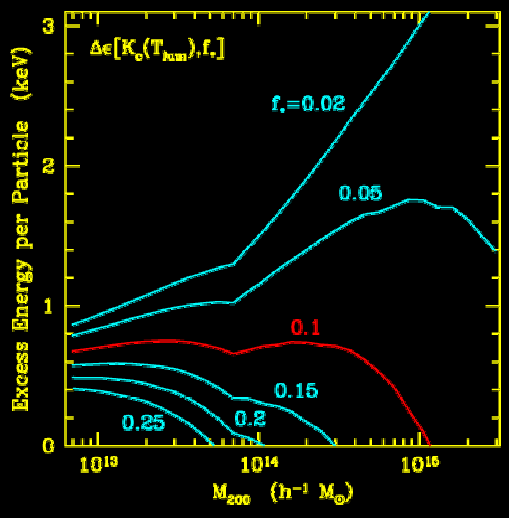
in agreement with cooling threshold models

Ponman et al. (2003)
Voit & Ponman (2003)
Voit, Kay, & Bryan (2004)

L-T Relation



Heating-Cooling Tradeoff



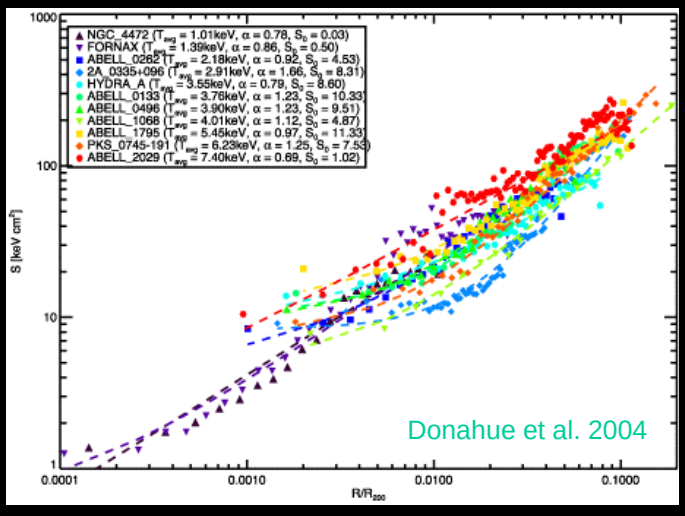
Many mixtures of heating and cooling can explain *L-T* relation

If only 10% of the baryons are condensed, then ~0.7 keV of excess energy implied in groups

Voit et al. (2002)

What can cluster structure tell us about galaxy feedback?

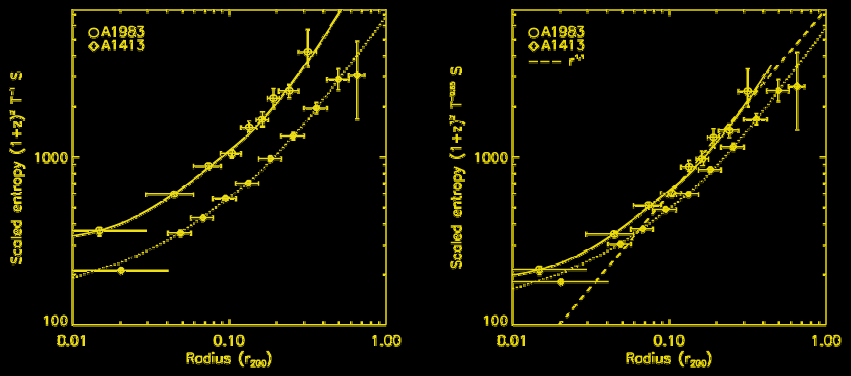
Chandra Entropy Profiles



Core entropy profiles very regular

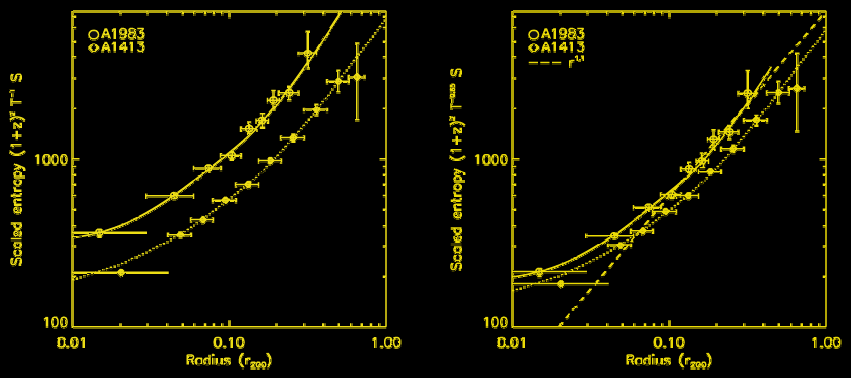
No entropy inversions indicating central heating

XMM Entropy Profiles



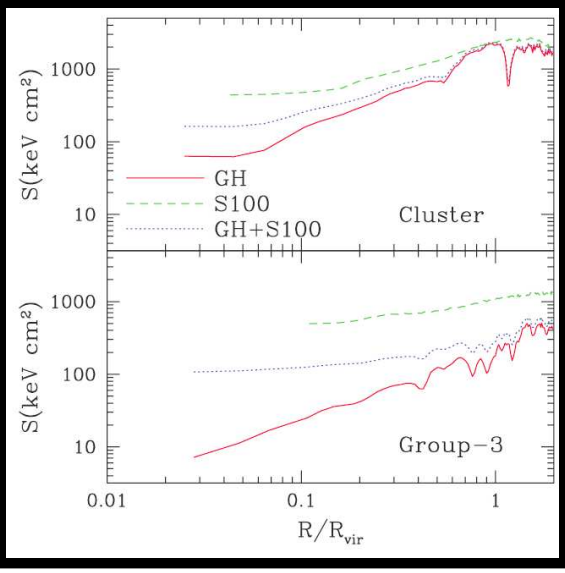
Pratt & Arnaud (2003): Entropy profiles of Abell 1963 (2.1 keV) and Abell 1413 (6.9 keV) coincide if scaled by $T^{0.65}$

Evidence for IGM Smoothing?



Smoothing an accretion flow can boost entropy generation in shocks: $K \sim v_{sh}^2 \rho^{-2/3}$

Entropy Amplification in Simulations

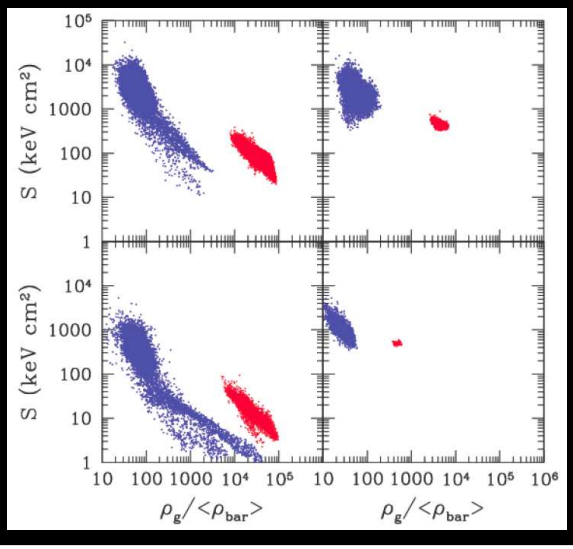


GADGET-2 with no cooling

Structure formation amplifies entropy floor introduced at z=3

Borgani et al., in prep.

Entropy Amplification in Simulations



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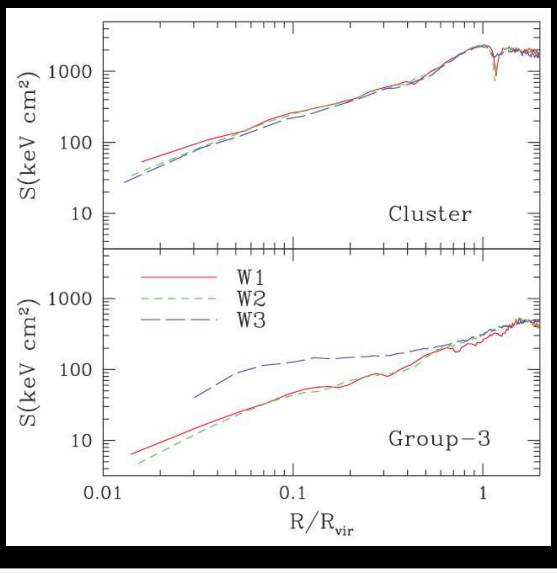

GADGET-2 with cooling & winds

Winds fail to boost the entropy profile

W1: 341 km/s
W2: 484 km/s
W3: 720 km/s

Borgani et al., in prep.

Intracluster Thermodyamics

- ICM enrichment to 0.3 solar via SN II extends beyond $0.5r_{200}$ and occurred at $z > 1$
- Core Fe enrichment from SN Ia
- *L*-*T* governed by cooling & feedback
- Large *L*-*T* dispersion in groups (AGN?)
- Core Fe & entropy structure appears quiescent
- Entropy excess extends over entire ICM
- Does entropy amplification require AGN?