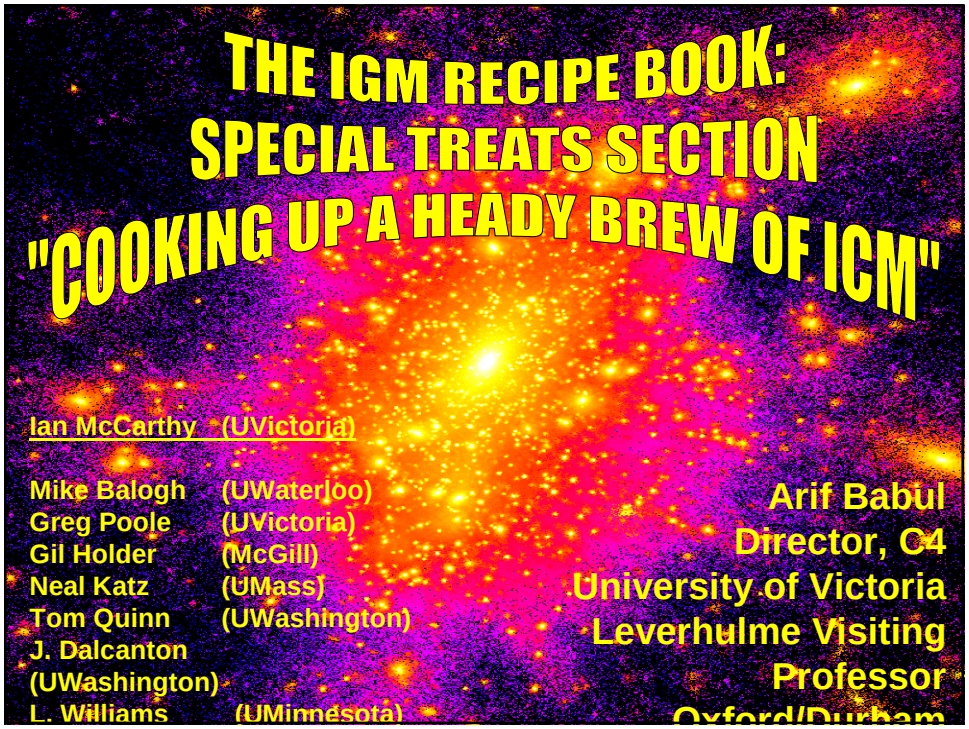
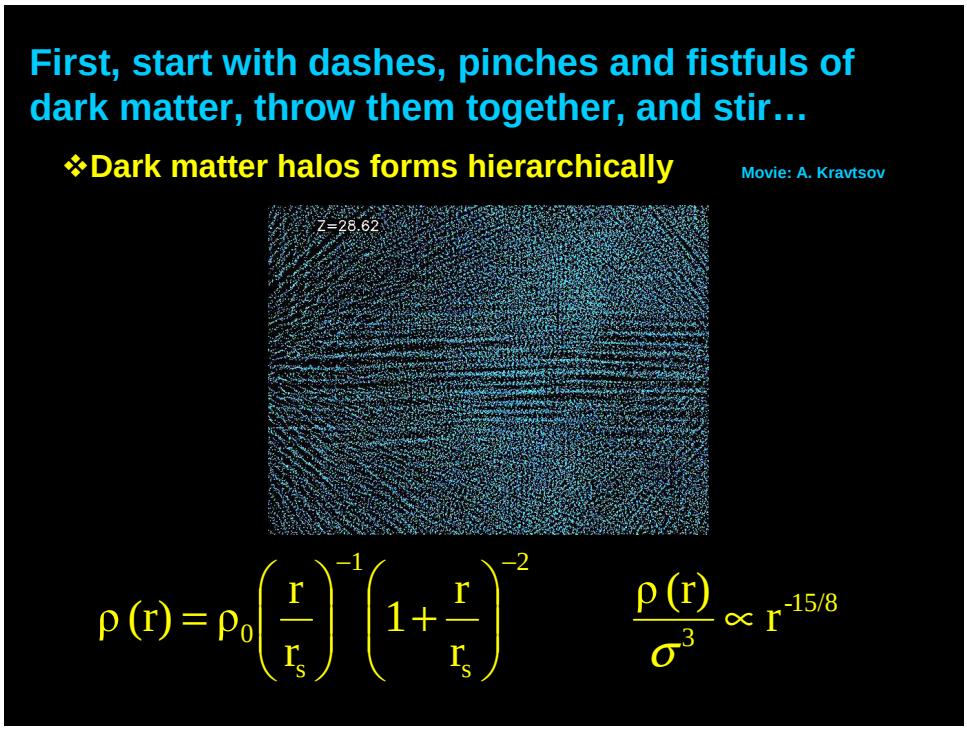
Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters

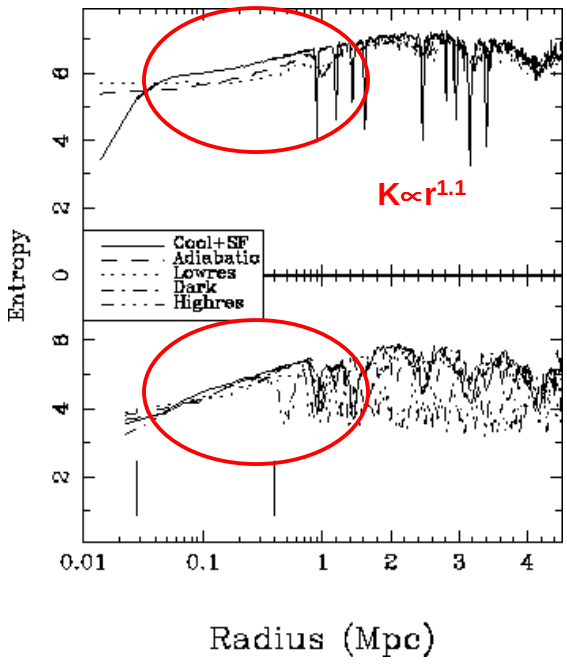




First, mix in gas in proportion. Do not stop stirring, otherwise…

- In the standard model, gas falls in with dark matter and in the absence of any energy transport, will trace the dark matter
  ➔ entropy due to accretion:

$$\frac{\rho(r)}{\sigma^3} \propto r^{-15/8} \Rightarrow \frac{KT}{n_e^{2/3}} \propto r^{1.25}\ [1.1\text{-}1.2]$$



$K \propto r^{1.1}$

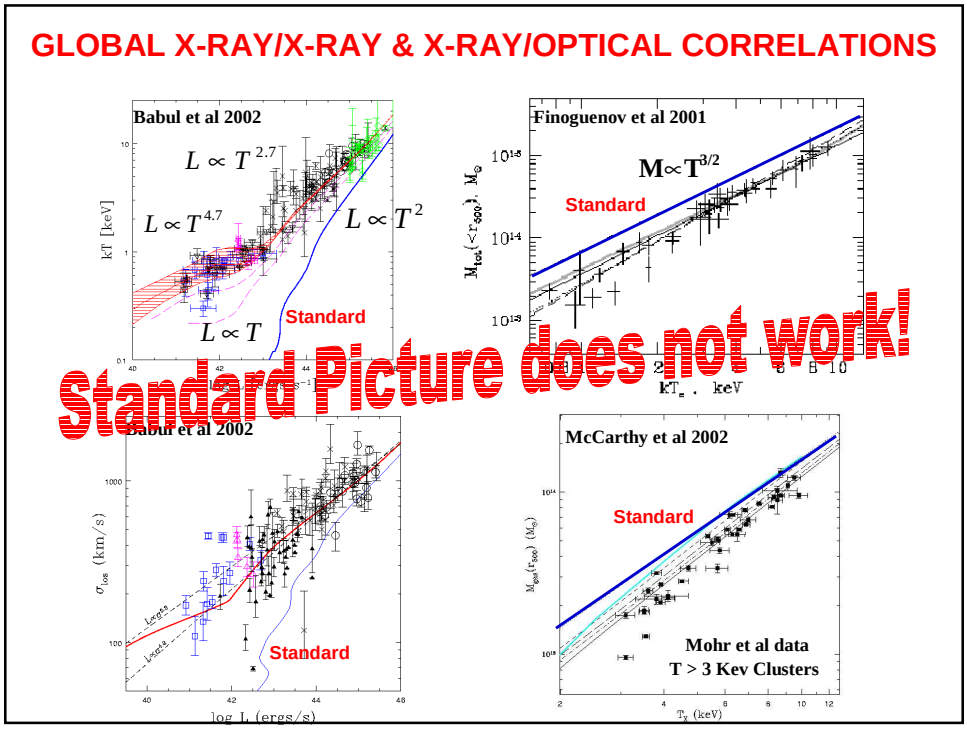
If gas traces DM, and solve for T to ensure hydro..eq.,

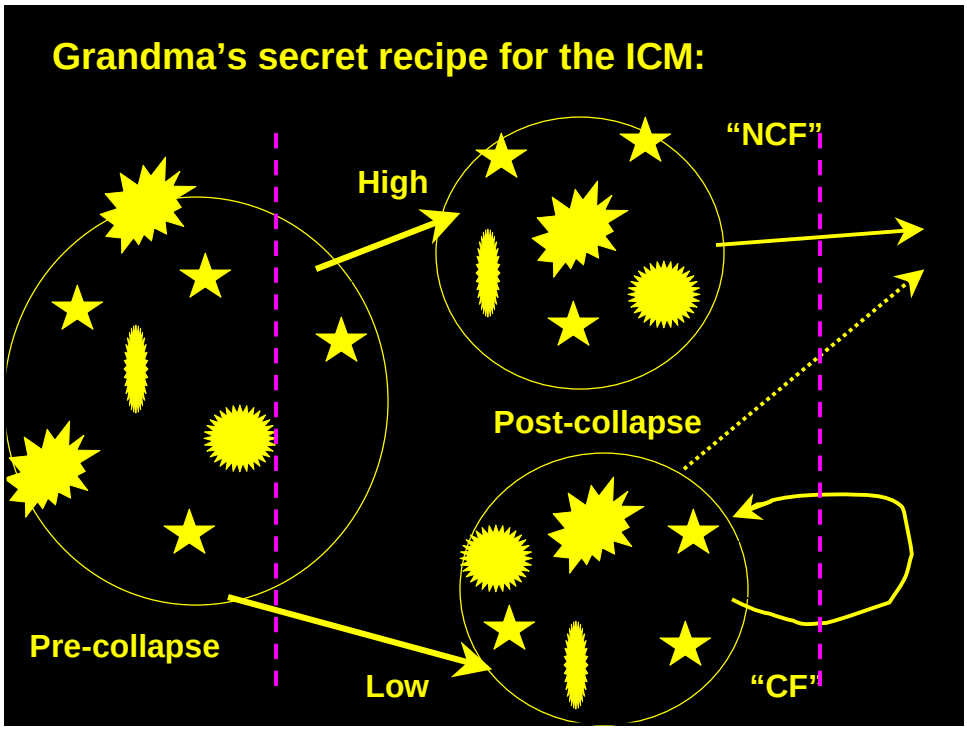
Get $K \propto r^{1.1}$

Shocks & stirring by infalling objects tends to make the gas in the inner regions nearly isothermal (no cooling)

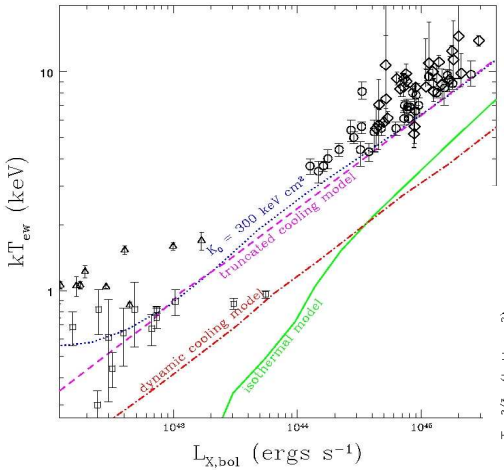
Lewis et al 2000

Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters





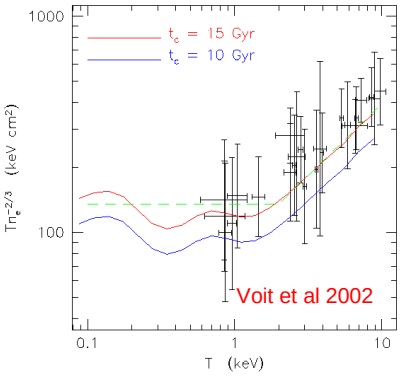
Why Heating?

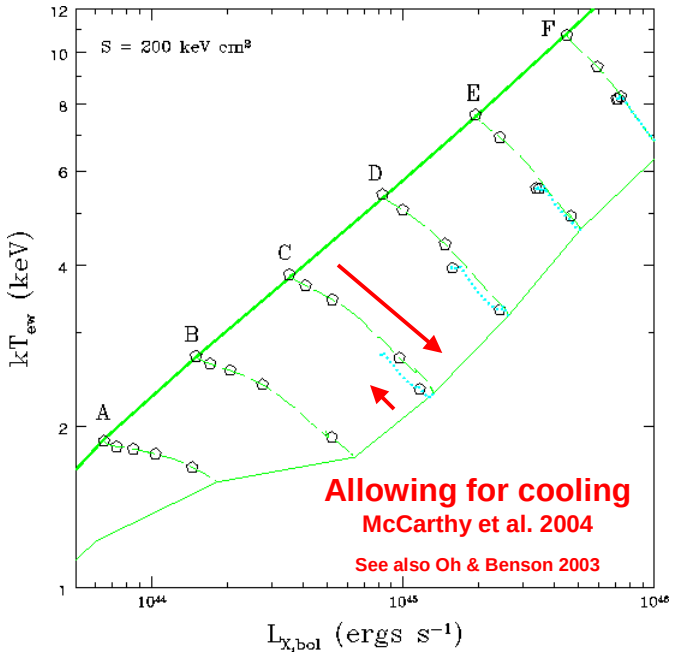


Lx-Tx from Cooling?
We know cooling is occuring!

Truncated vs Dynamic Cooling

- **Inward flow → compression**
- **Quasi-adiabatic → density and T increases**
- **Cooling efficiency increases**

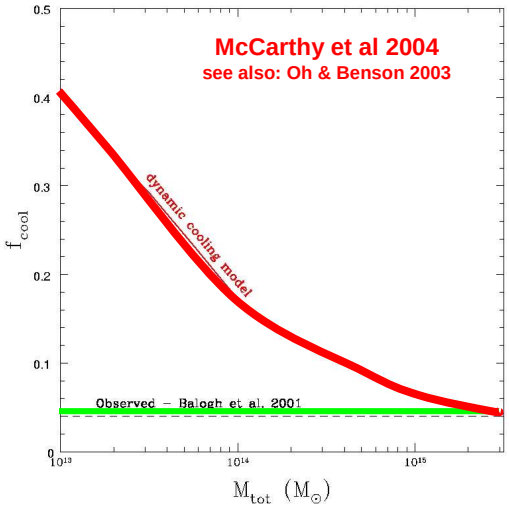




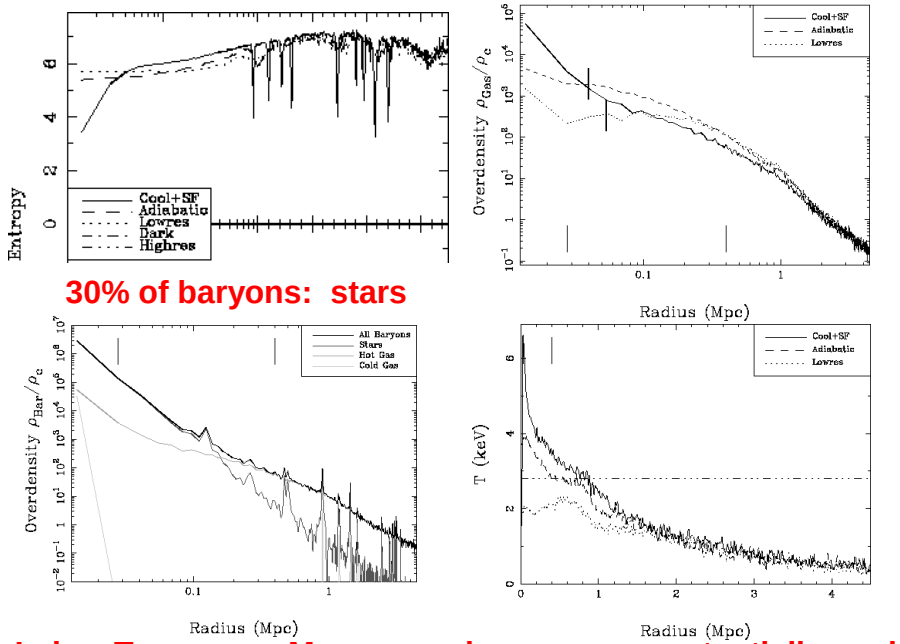
Allowing for cooling
McCarthy et al. 2004
See also Oh & Benson 2003

Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters

For Λ-CDM Universe:

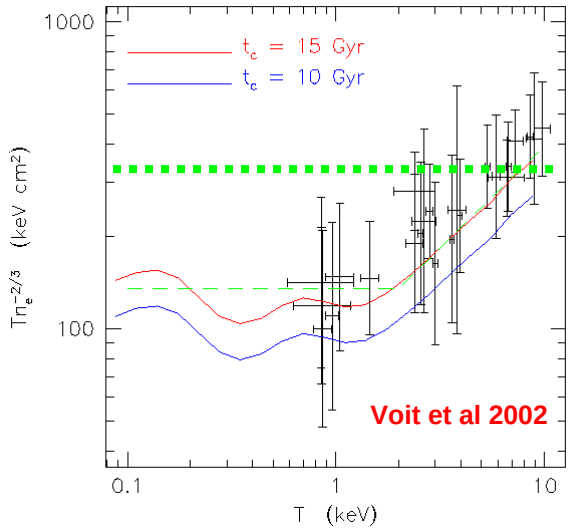


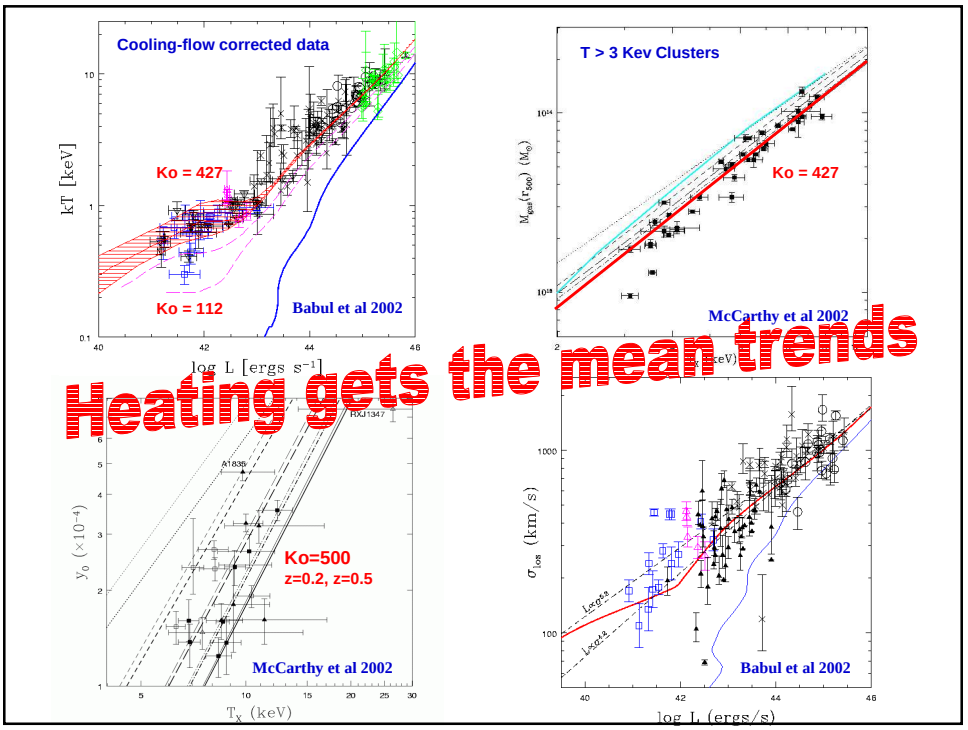
Lewis et al 2000: **PSEUDO-VIRGO** **w. cooling**



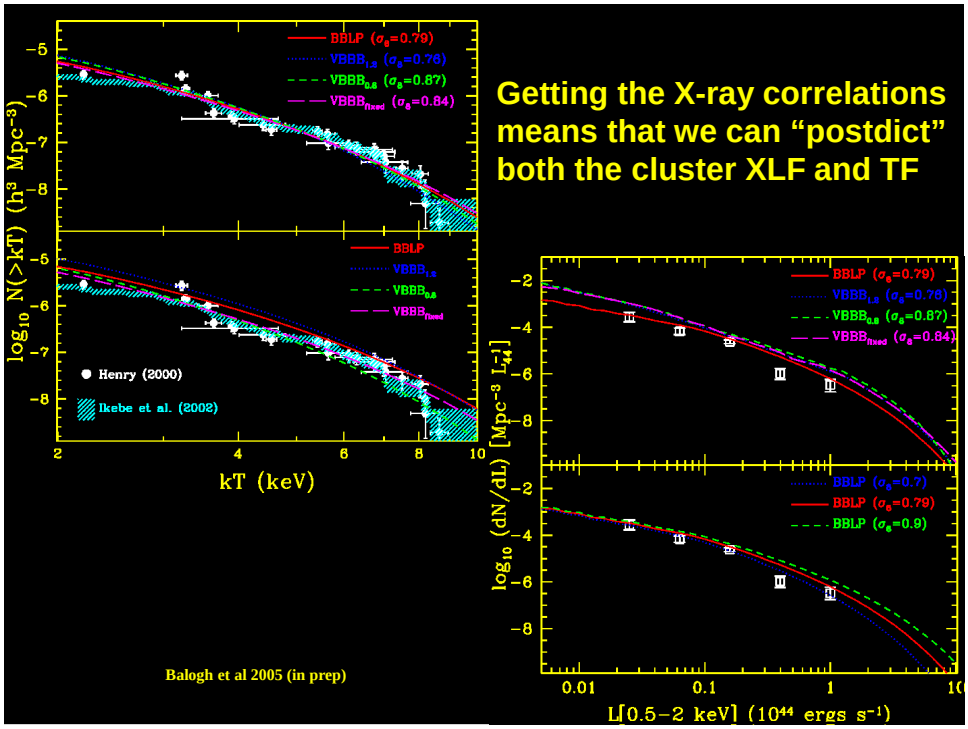
In low T groups: Many more baryons can potentially cool

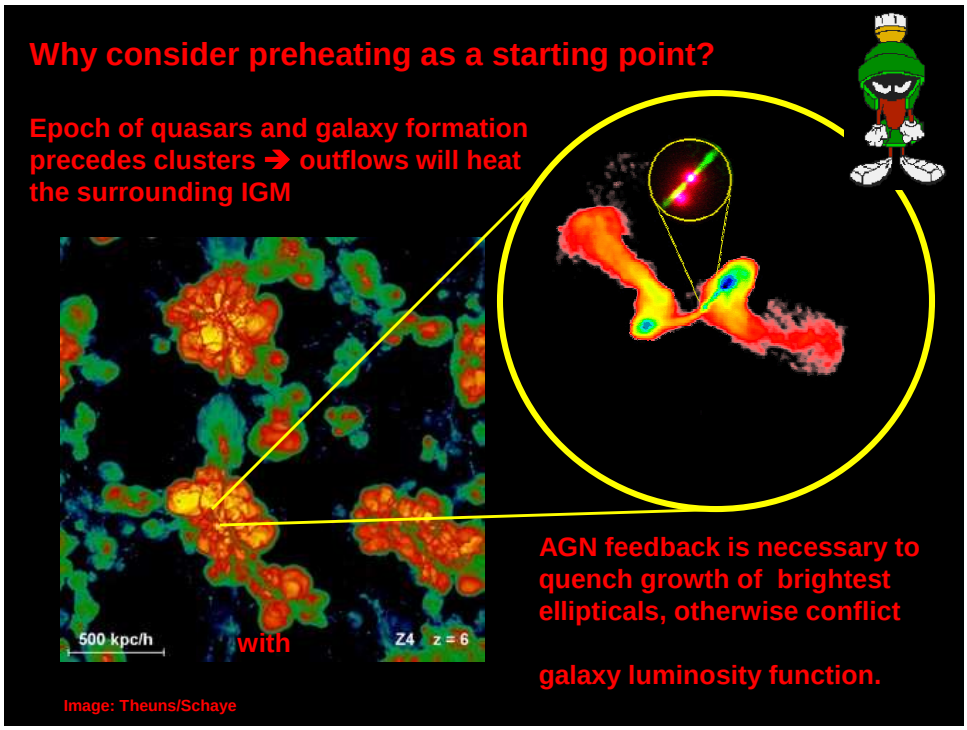
Sufficient heating can quench cooling



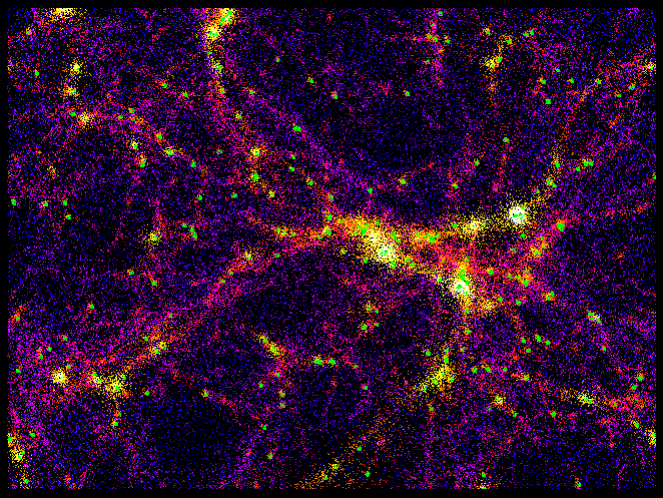


Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters





Regions of highest energy injection will coincide
With regions of high galaxy density:



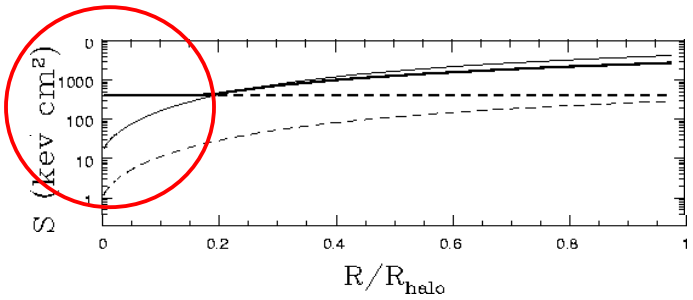
Galaxy Formation at z=2: Weinberg et al.

POSTULATE:

There is a variation in the heating of the gas from cluster-to-cluster ➔ range of "minimum entropy"

- ❖variations in the BH energy output
- ❖ star-formation histories
- ❖ timing

Entropy injection will move the lower entropy gas onto higher adiabat

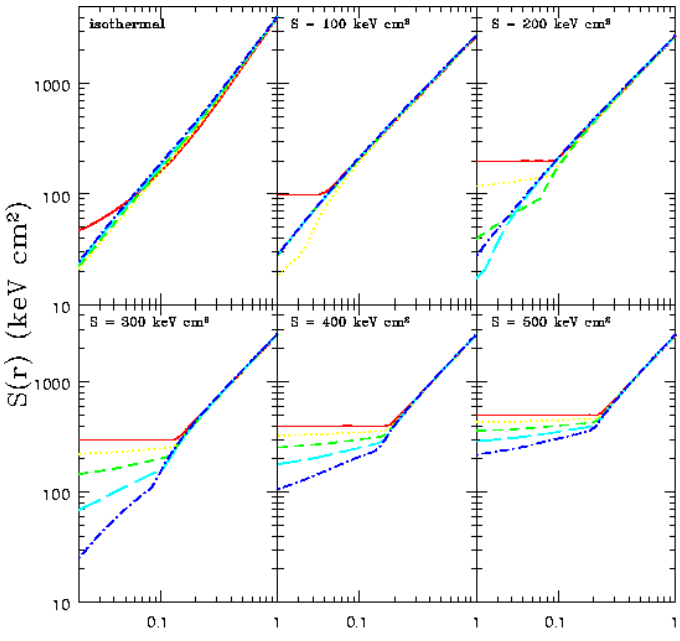


Gas in the clusters will also lose energy via cooling

The impact of cooling will depend on:

(a) "preheating" level

(b) time available for cooling

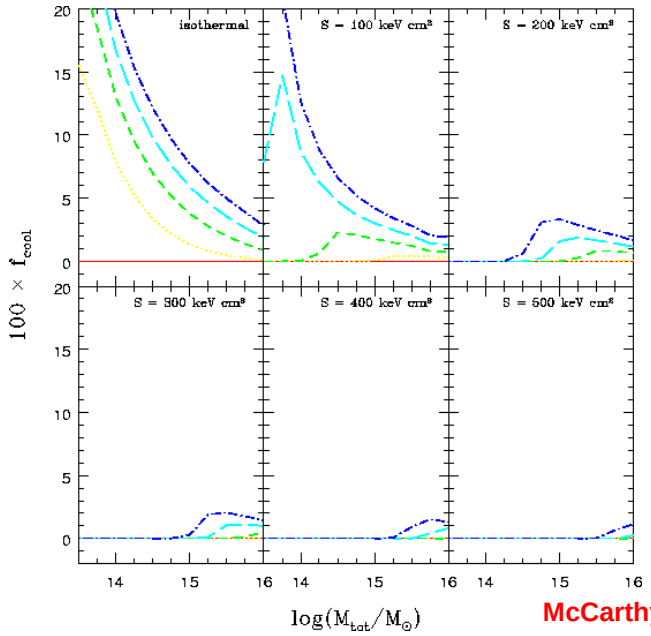


t = 0, 3, 6, 9, 12 Gyrs

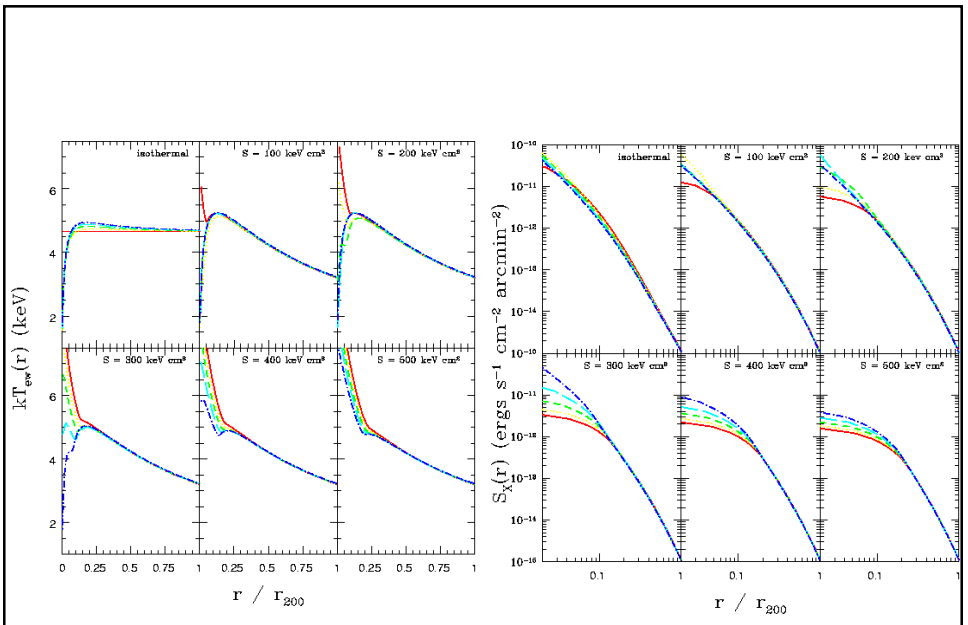
McCarthy et al 2004

Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters

Cool fraction: 0, 3, 6, 9, 12 Gyrs

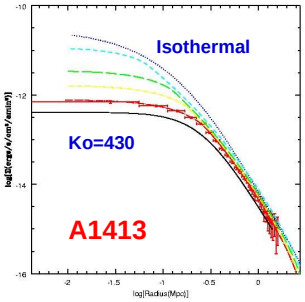


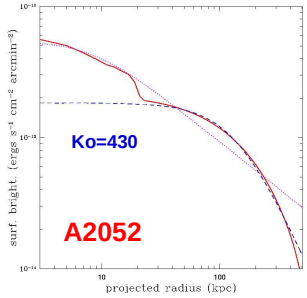
McCarthy et al 2004



McCarthy et al 2004

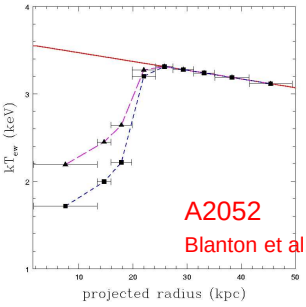
"flat-core (NCF)" vs "peaked (CF)"





Cluster X-ray SF profiles range from having flat cores of size R=150 kpc to strongly peaked systems.

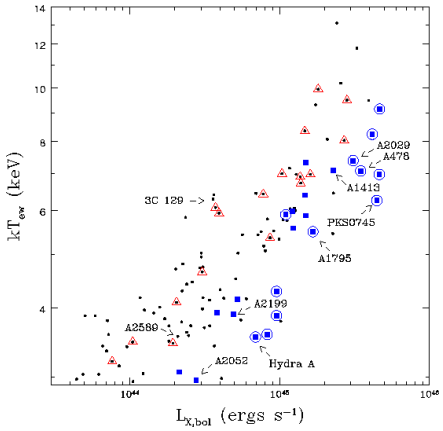
NCF = high heating systems
CF = low heating systems



A2052
Blanton et al.

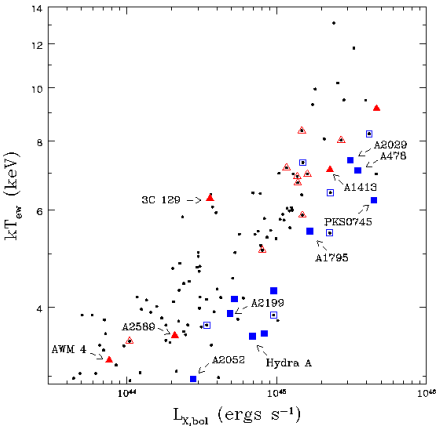
Back to the X-ray correlations – WYSIWYG:

Old Definitions



△ **no significant cooling flow**
■ **small cooling flow**
◉ **massive cooling flow**

New Definitions

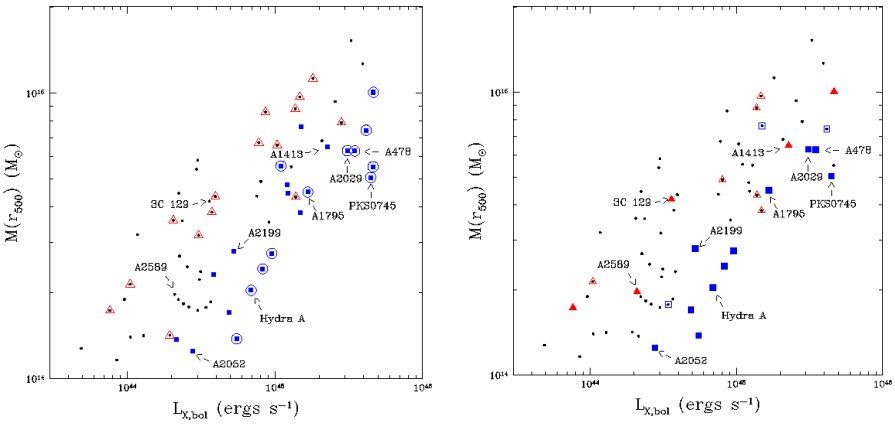


△□ **peaked/flat: disturbed**
▲■ **peaked/flat: relaxed**

McCarthy et al 2004

Back to the X-ray correlations – WYSIWYG:

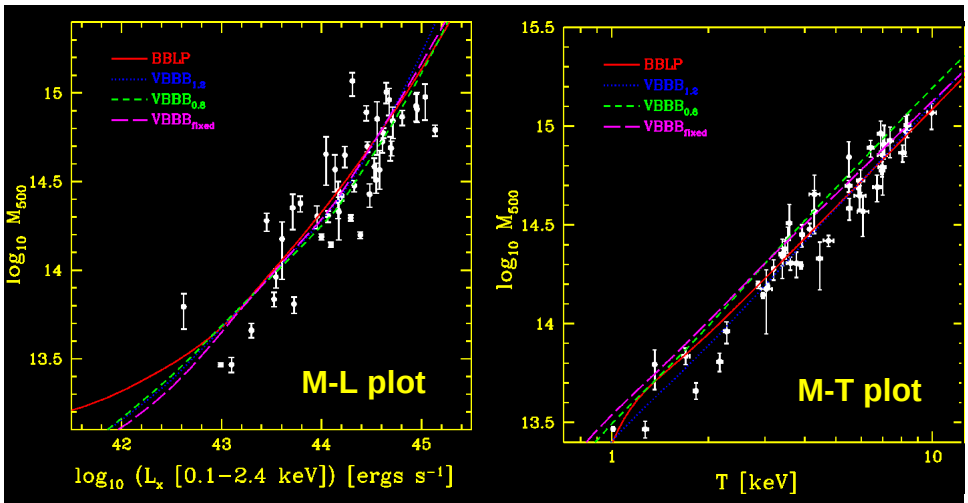
Old Definitions | **New Definitions**



△ no significant cooling flow
■ small cooling flow
◉ massive cooling flow

△□ peaked/flat: disturbed
▲■ peaked/flat: relaxed

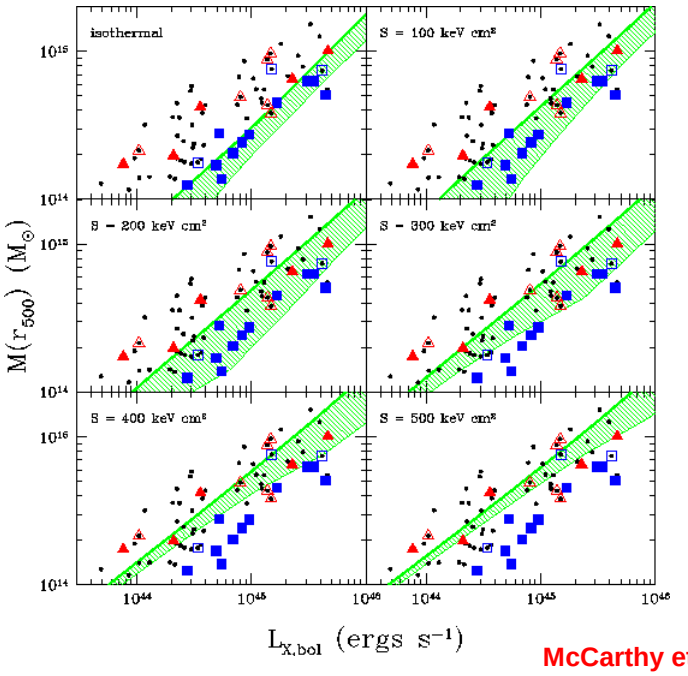
McCarthy et al 2004



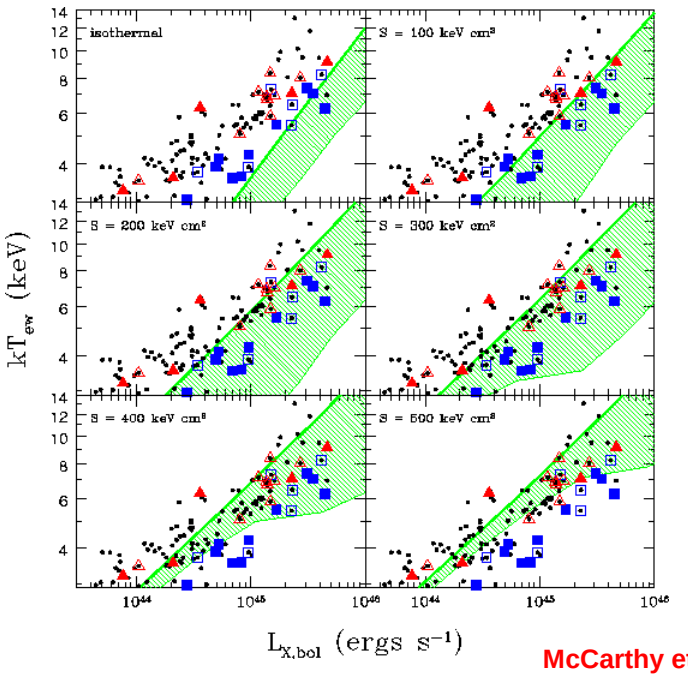
Heating affects the slope of M-T and M-L trend but The impact on T is minimal.

For given M, scatter in L is factor ~10 and in T is ~2

Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters

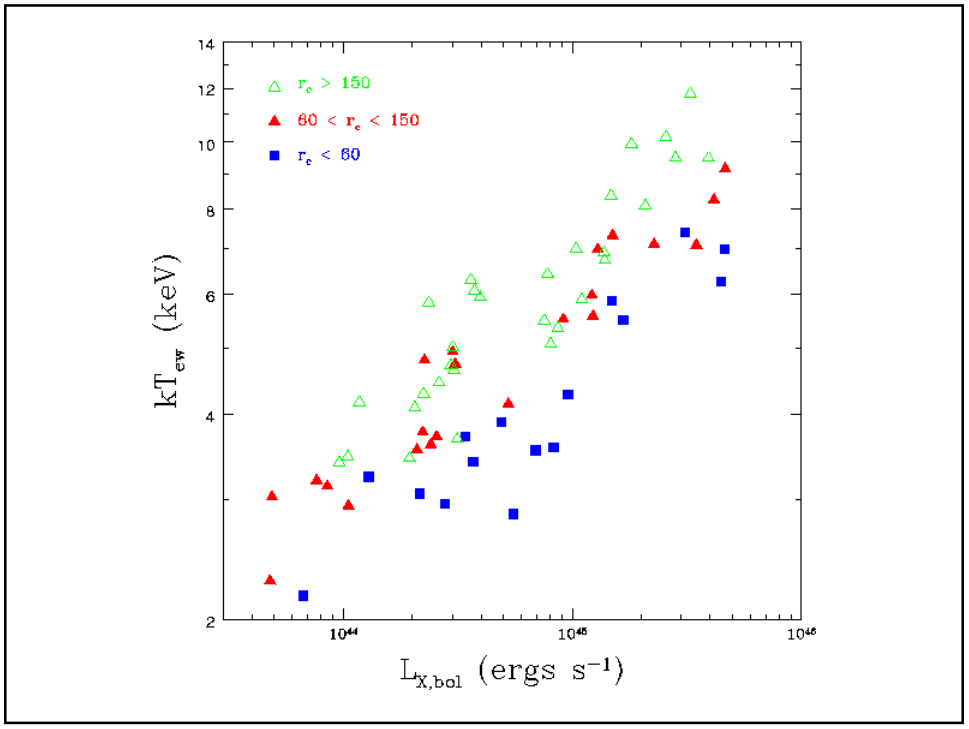


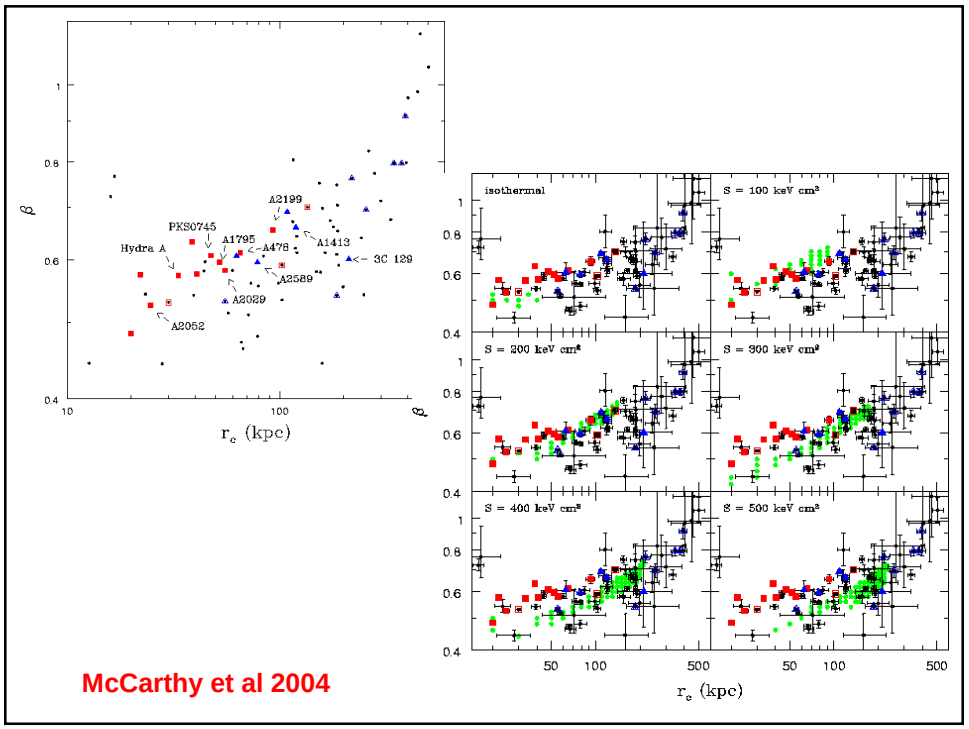
McCarthy et al 2004



McCarthy et al 2004

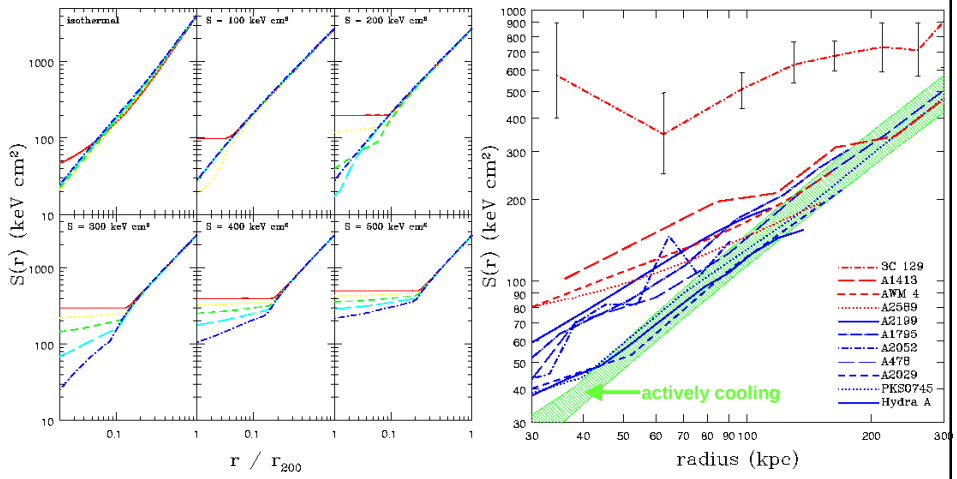
Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters





McCarthy et al 2004

Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters

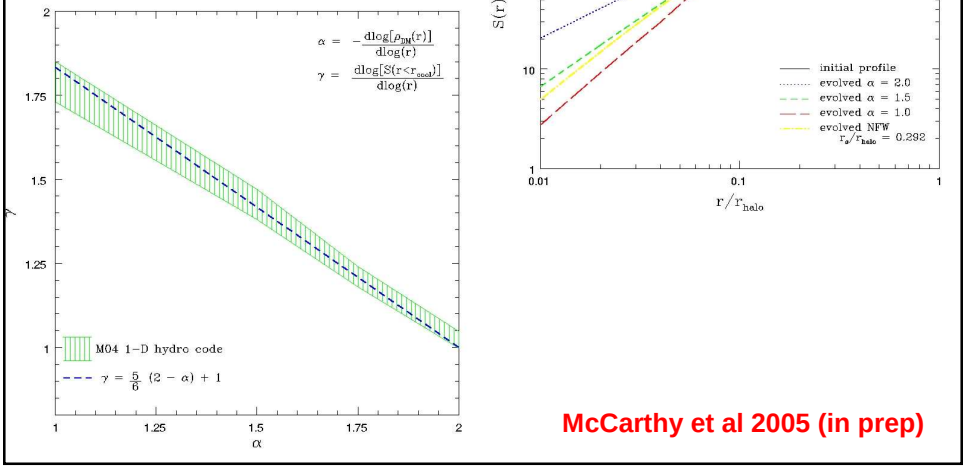


McCarthy et al 2004

An aside:

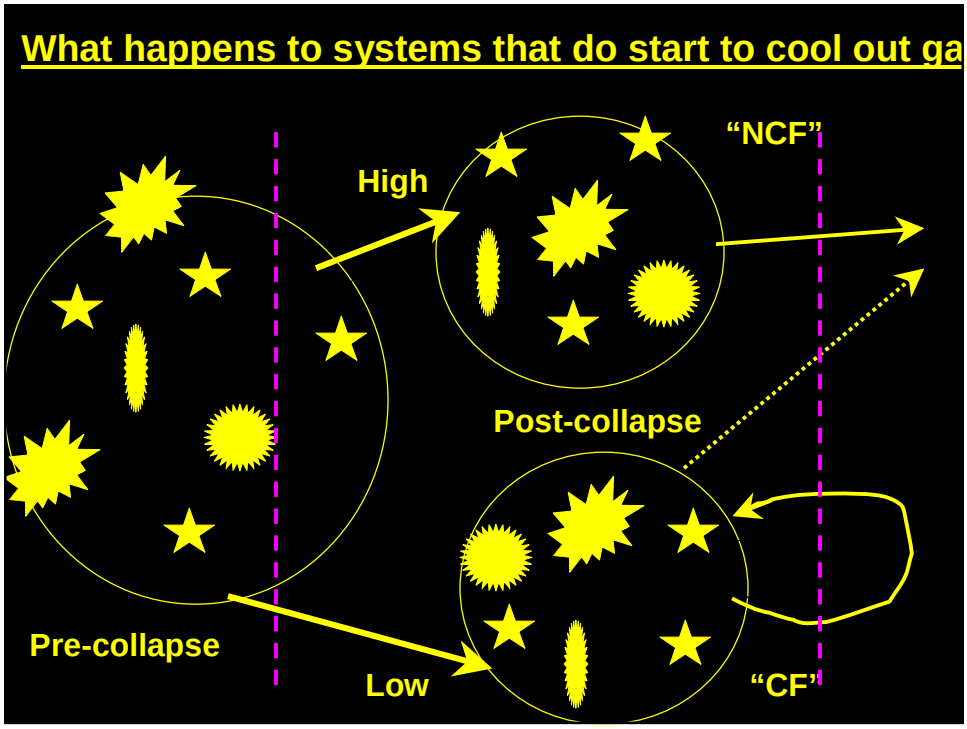
The entropy power-law interior to the cooling radius is set primarily by the gravity.

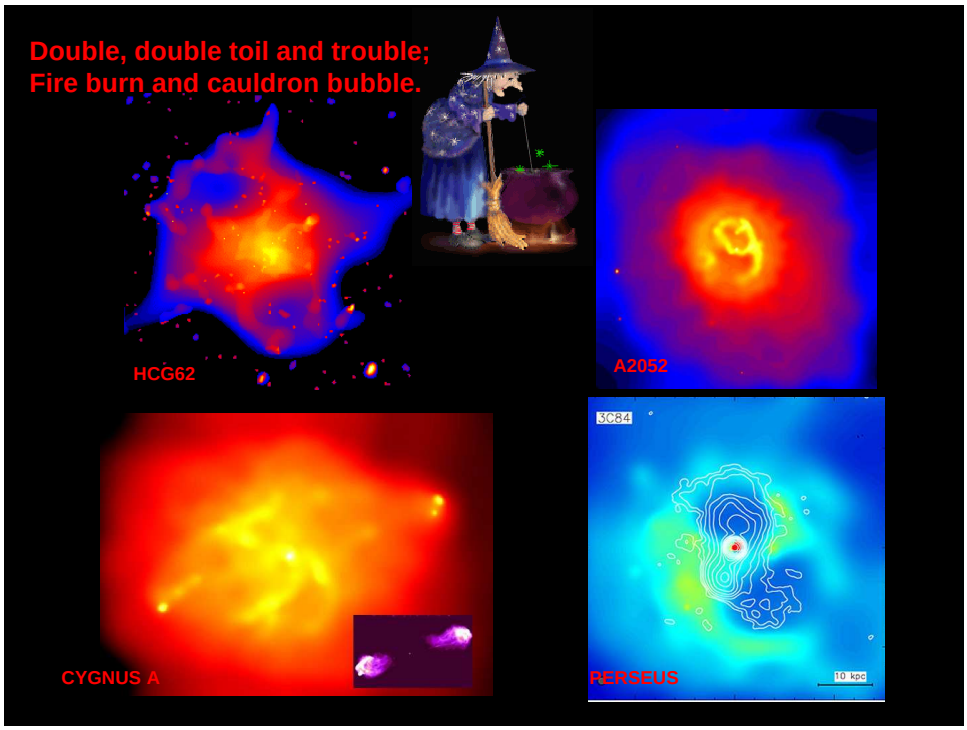
(Bertschinger)



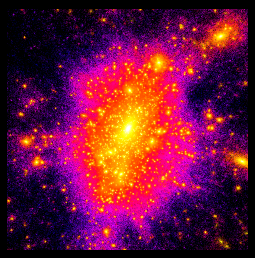
McCarthy et al 2005 (in prep)

Progress Towards Understanding the Global and Structural X-Ray Properties of Galaxy Clusters





Click image for Quicktime Movie



In our picture, the two classes of clusters are the result of variations in the initial entropy injection.

Traditionally, the tacit belief is that NCFs are effectively CF systems that have been stirred up by mergers.

This is based on anecdotal claims that NCF systems tend to have substructure. This is true, but there are also NCF systems that have *NO* visible substructure and which really do look relaxed. There are also CF clusters actively assimilating mergers (Perseus).

Theoretical studies of mergers and their effects on central regions of clusters are few and far in-between, and the outcomes are confusing.

WORK IN PROGRESS

- 3:1 or greater – fraction of these is rare.
- During disruption, systems look like NCF for ~2 Gyrs.

Conclusion: Heating and Cooling

✓ Heating at the level of S_{min}~200 keV cm^2 is needed to prevent excessive cooling of baryons

✓ Radiative cooling tends to establish $S \sim r^{1.1}$

✓Depending on amount of entropy injection and the time elapsed since entropy injection, the model can account for variations in the internal (structural) properties of clusters such as X-ray surface brightness profiles and cluster temperature profiles

mild entropy (S~200): CF (peaked)
high entropy (S~400): NCF (flat-core)

✓NCF clusters: the “heating” vs “merger” hypotheses

Conclusion: Heating and Cooling

- ✓ Variations in level of entropy injection and time since this event can account for the dispersion in the M-T, L-T relations, as well as the the distribution in the size of the X-ray core radius.
- ✓This picture suggest a direct correlation between the cluster's entropy profile and its location on the M-L, L-T and R_c-β plots.
- ✓Model is testable! A preliminary study of Chandra and XMM-Newton data supports this assertion.

Available vs anticipated data