X-ray observations of the intracluster medium: implications for semi-analytic models

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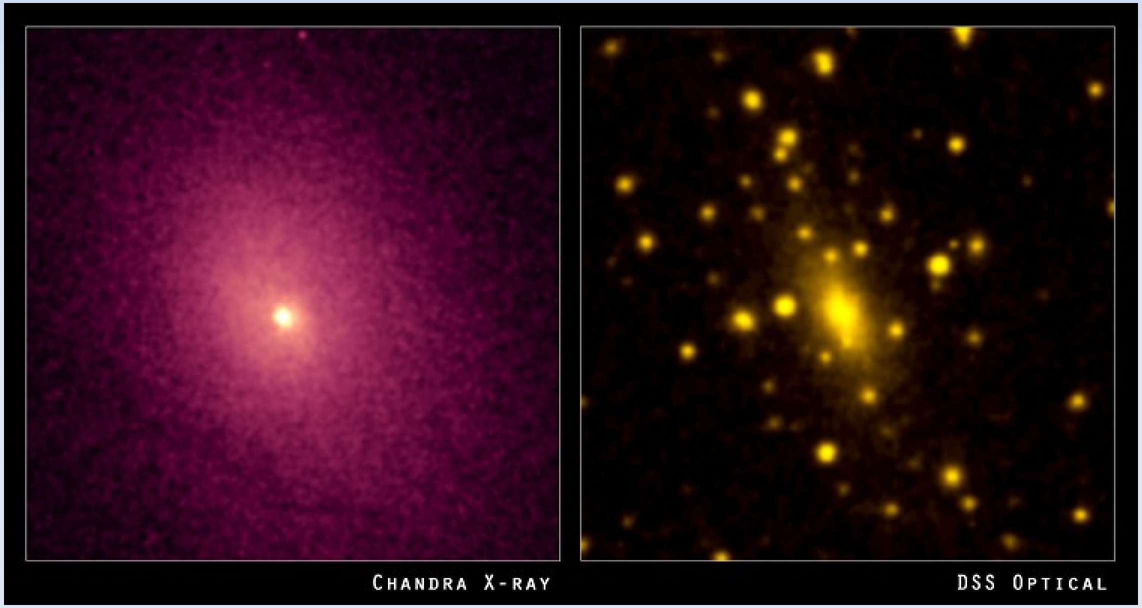
Hot gas in groups & clusters

- Intergalactic medium compressed & shock heated to virial temperature in dark matter halos
  - gas $T \sim 10^7$-10^8 K => $kT \sim$ 1-10 keV *(X-rays)*

hot gas typically:
- $n_e \sim 10^{-3}$ cm^{-3}
- $Z \sim 0.3$ Solar

Abell 2029 cluster



Hot gas (T ~ 10-100 million K)
[**~12% of total mass**]

Thousands of individual galaxies
[**~3% of total mass**]

Held together by dark matter
[**~85% of total mass**]

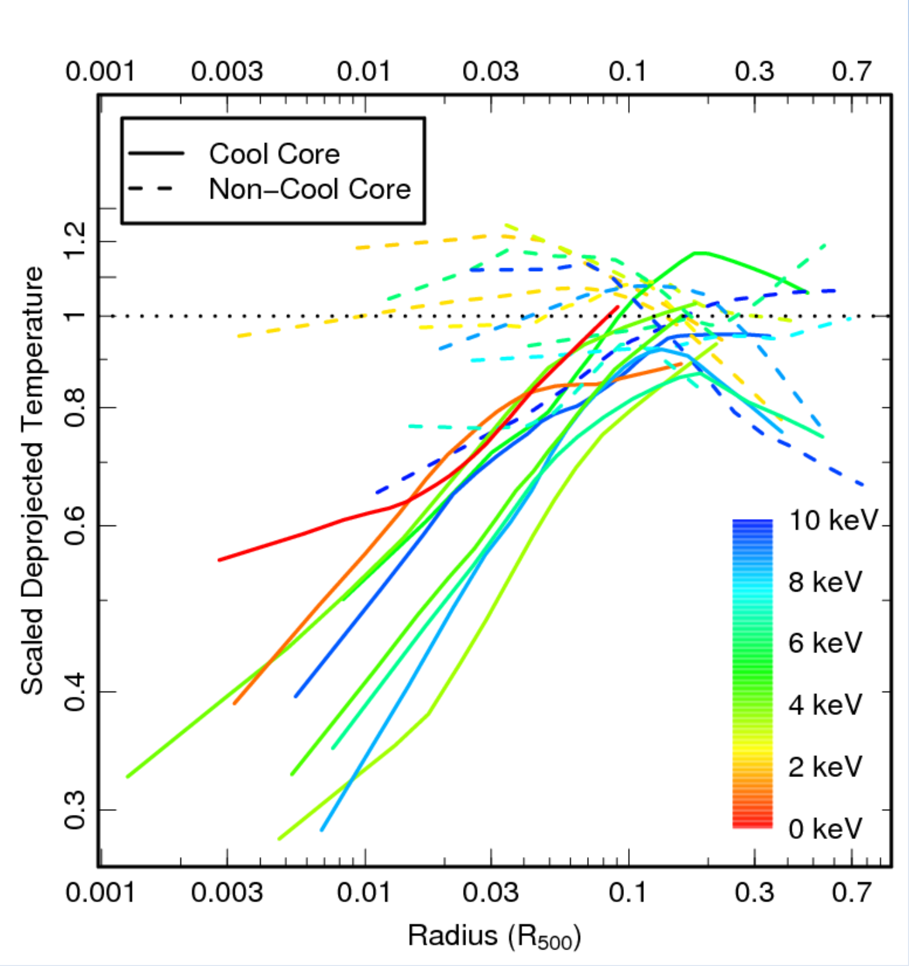
Total cluster masses:
- $M \sim 10^{14} - 10^{15}\ M_{sun}$

Why is the ICM important in semi-analytic models?

- The hot intracluster medium (ICM) serves as a reservoir of baryons:
  - 3-5 times more mass in gas than in stars
  - Cooling gas fuels black hole growth and star formation
- The hot gas can influence galaxies:
  - e.g. ram pressure stripping
- ICM very sensitive to galaxy feedback:
  - Non-gravitational processes modify gas entropy & break cluster self-similarity - the same mechanisms that restrict star formation in galaxies
  - Gas metallicity probes supernova-driven galaxy winds
- X-ray observations of the hot gas are a powerful probe of feedback & an additional constraint on SAMs

Gas temperature profiles: cool-core vs. non-cool core

- Statistical sample of 20 clusters; *Chandra* data, *T(r) normalized by mean T*
- Two distinct classes:
  - Cool-core and non-cool core, in roughly equal proportion
- CC clusters have v. similar *T(r)*
  - CC tend to be more “relaxed” and better studied
  - Non-CC often regarded as disturbed or anomalous; rarely seen in cosmological simulations
- Distinction often made in terms of *cooling time*...

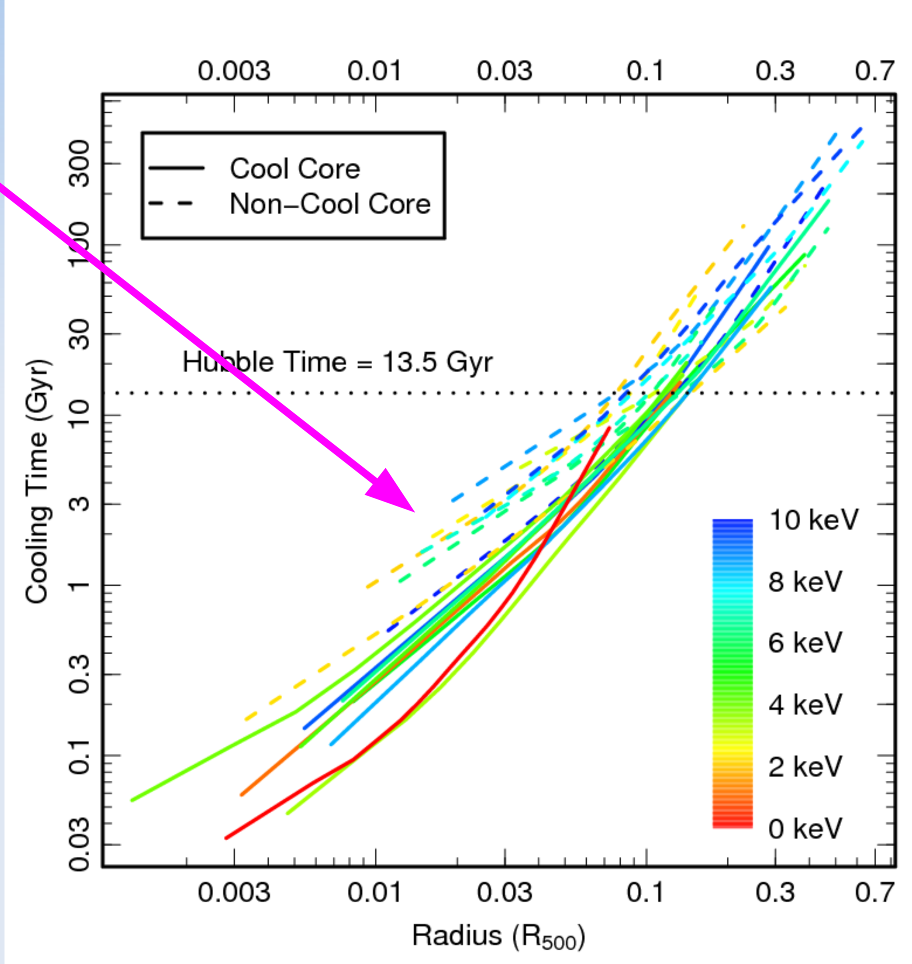


Sanderson et al., 2006

The importance of radiative cooling on the hot gas

t_{cool} < 3-5 Gyr in all cases

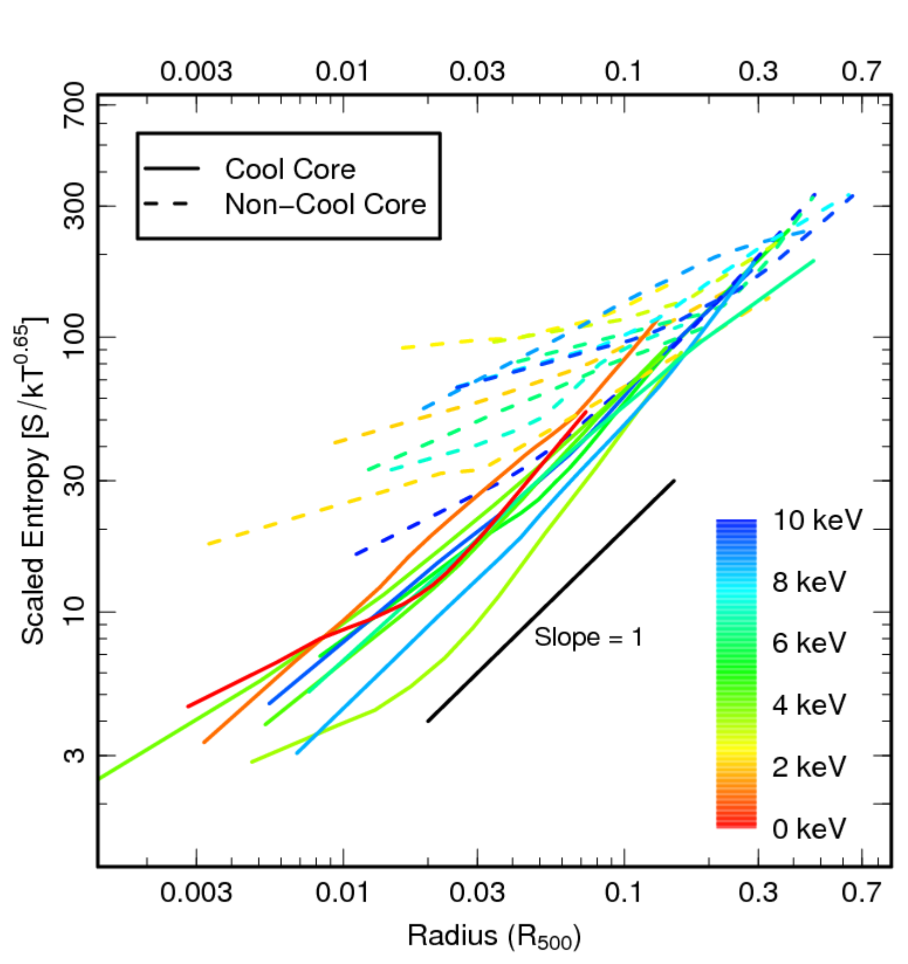
- Cooling time of gas vs. scaled radius (R / R_{500})
- Inside *T(r)* peak ($r \sim 0.15\ R_{500}$) t_{cool} << Hubble time
- ~"Universal" cooling time profile? (i.e. small scatter)
  - cooling very important
- *Even non-cool core clusters have very short cooling times….so why no cool core?*



Sanderson et al., 2006

Gas entropy profiles: cool-core vs. non-cool core

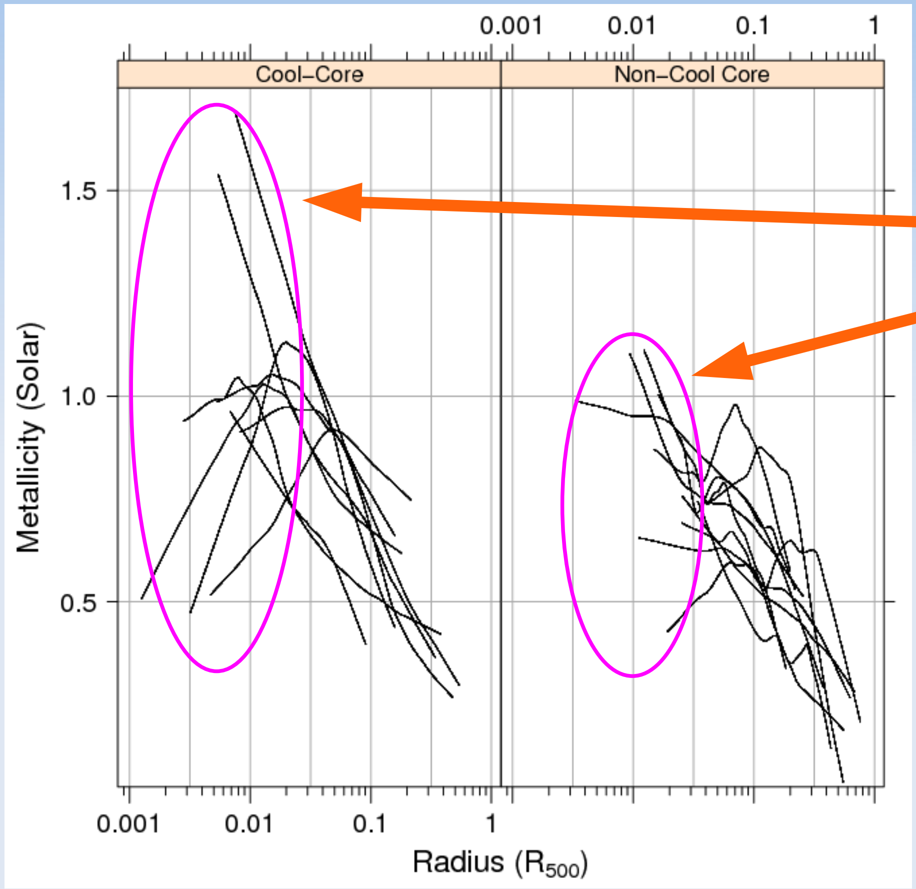
- Gas entropy, $S = kT / \rho^{2/3}$ v. sensitive to non-grav. processes
- Empirical scaling by $kT^{0.65}$ (Ponman et al. 2003)
  - Confirms ***non*** self-similar scaling, *even outside of core*
- Cool core clusters show ~power-law *S(r)* at all radii
  - *T(r)* peak not obvious
- Wide dispersion in core entropy within cooling radius
  - Non-CC clusters have high entropy cores: feedback / cooling



Sanderson et al, in prep.

Cluster gas metallicity profiles (projected)

NB Abundances from Grevesse & Sauval, 1998



Wide dispersion within ~30-50 kpc, i.e. ~2x size of central galaxy

- Both Cool-Core *and Non-Cool Core* clusters show declining *Z(r)* outside inner core (R ~ 0.03 R_{500})
- Some (CC) clusters show sharp central *Z* decline - feedback and/or cooling removing enriched gas?

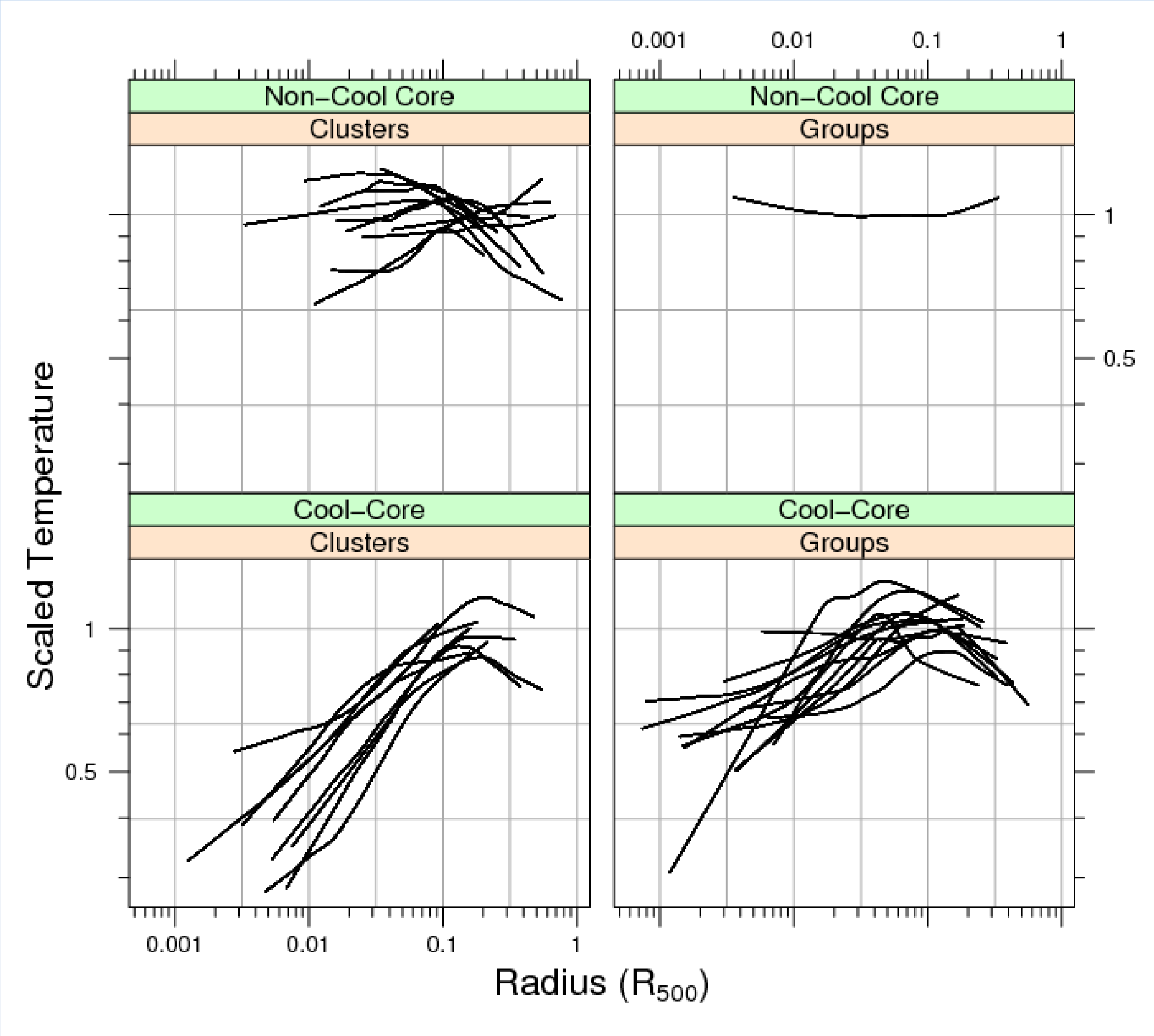
What about galaxy groups? (i.e. low mass halos)

- Flux-selected sample biased towards massive objects...
- But, groups dominate mass function, and massive clusters are rare in simulations
- Also, *groups* are more sensitive to non-gravitational heating as less massive

=> groups provide better constraints on galaxy feedback

Gas temperature profiles: groups vs. clusters

- +14 galaxy groups (archive sample)
- Cluster *T(r)* ~bimodal
  - CC peak ~0.15 R_{500}
- Groups much more diverse
  - Varying peak *T(r)*, but R_{peak} < clus.
  - Flatter, more variable log slope

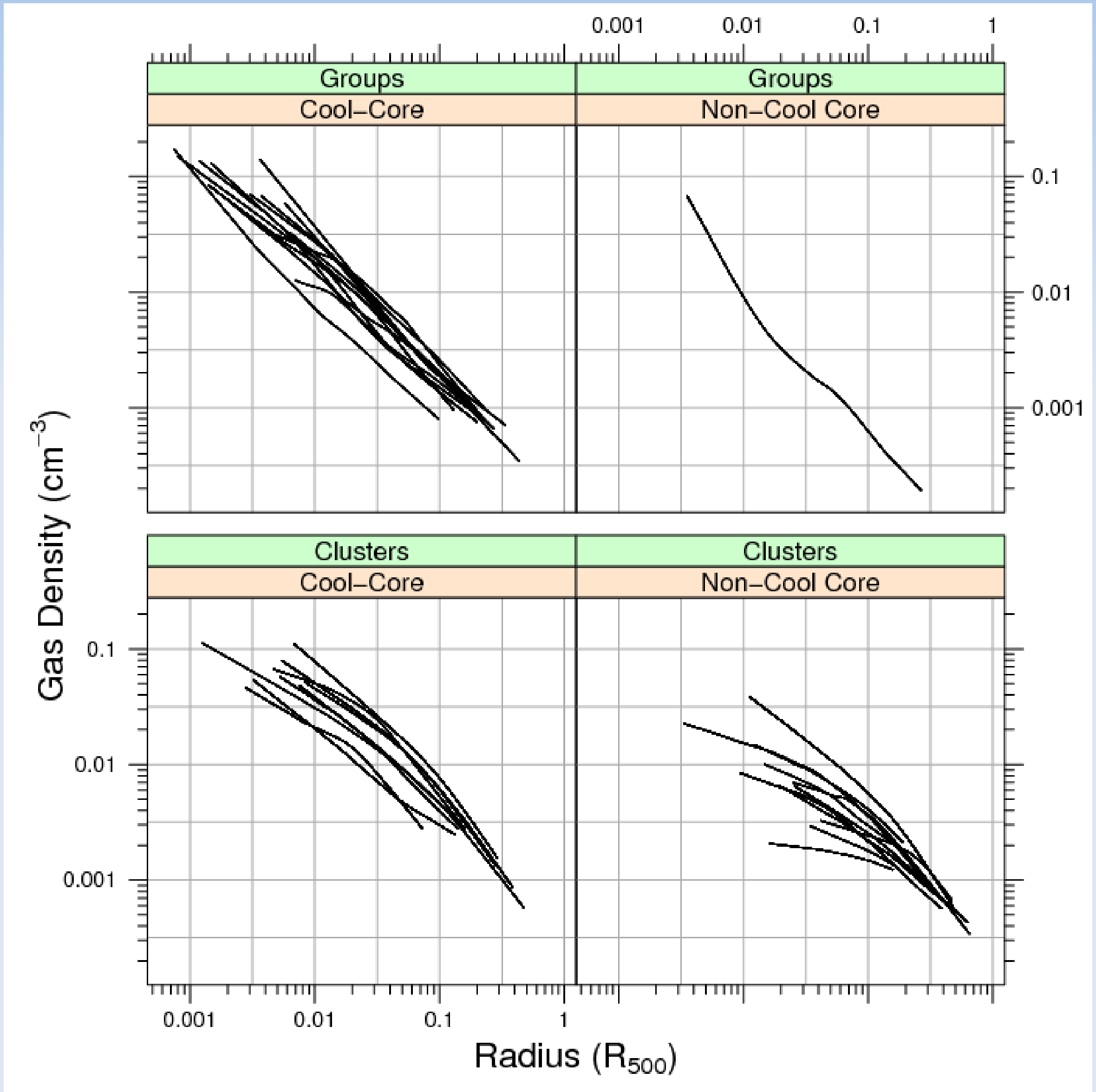


Locally-weighted fits (i.e. smoothed)

Gas density profiles: groups vs. clusters

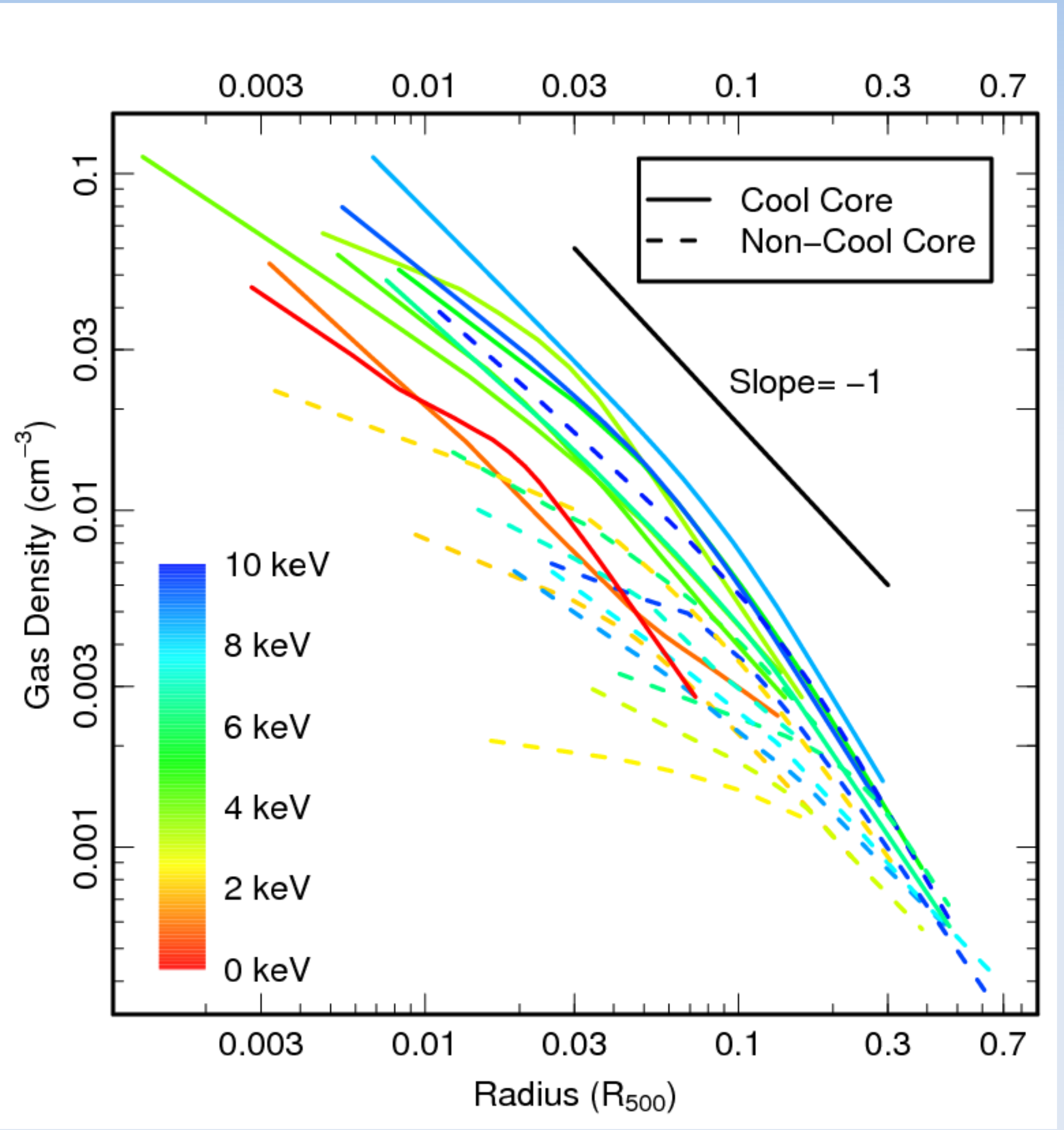
- Cluster $\rho_{gas}(r)$ very diverse within core
  - Diverge < 0.3 R_{500}
  - Flatten in core
- Groups have more uniform core $\rho_{gas}(r)$
  - ~power-law, with similar slope
  - Gas density more cuspy than clusters

Locally-weighted fits (i.e. smoothed)



Cluster gas density profiles trends with mean temperature

- $\rho_{gas}(r)$ lower in cooler clusters => depletion of gas
  - Expulsion to outskirts
  - Condense out of hot phase to form stars
- Density higher in cool-core clusters
  - ρ_{gas} rises as T falls to maintain pressure balance



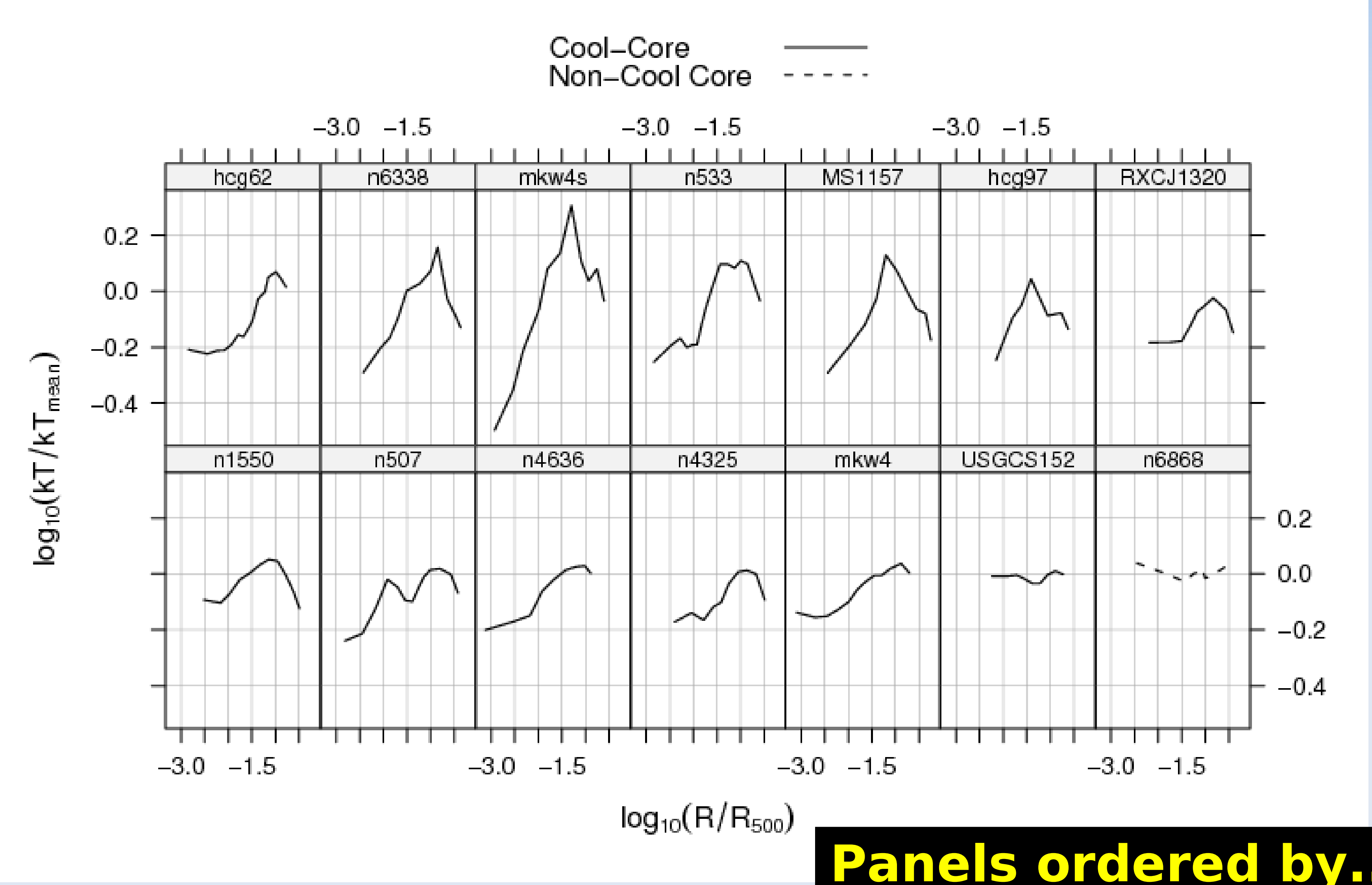
Locally-weighted fits (i.e. smoothed)

What can account for the diversity in groups?

Important clue in the systematic variation of group temperature profiles...

The *shapes* of group scaled temperature profiles

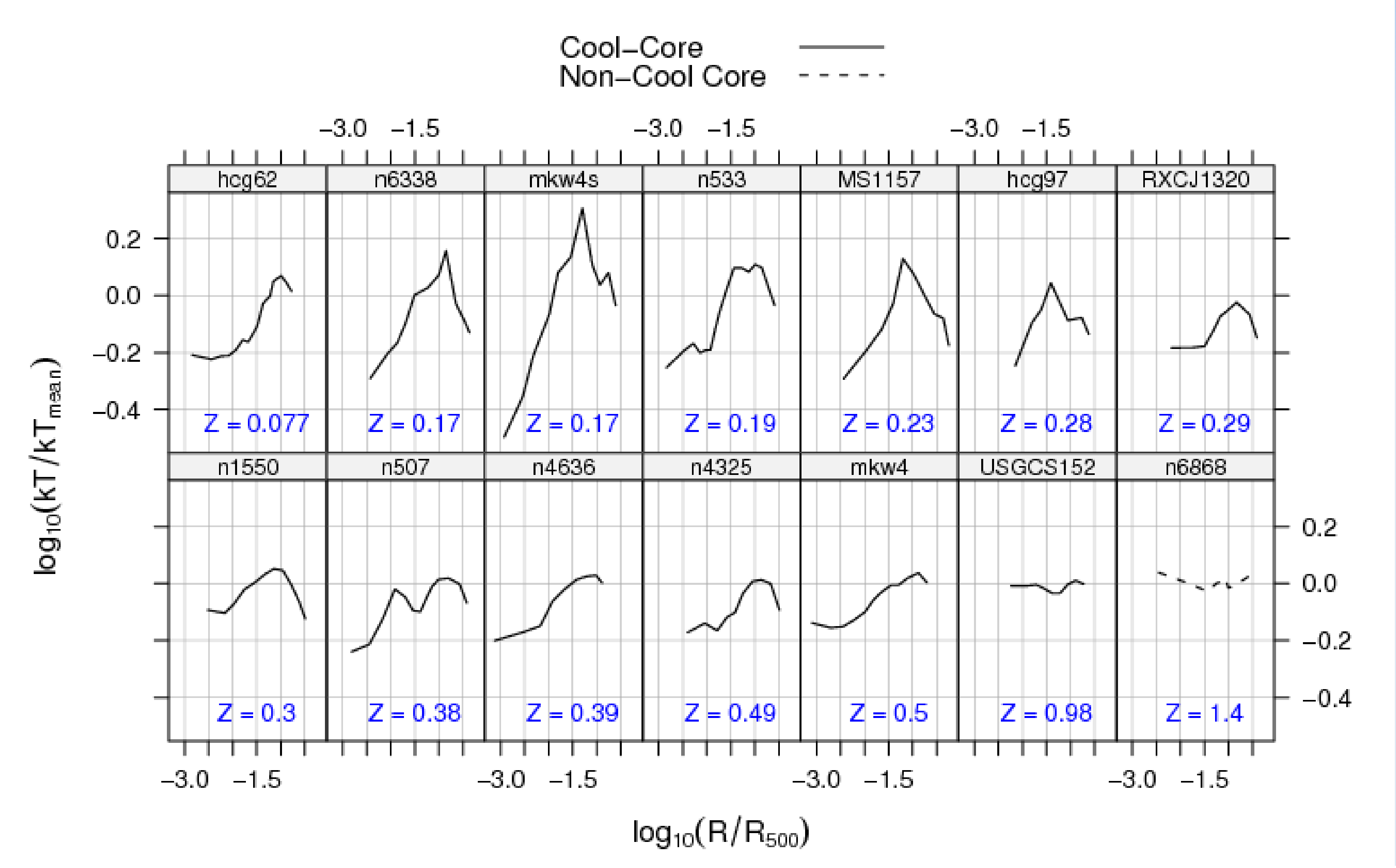
***T(r)* / mean *kT* vs. scaled radius; axes scaled identically**



Panels ordered by...

Systematic trend in group temperature profiles

...Increasing metallicity!



Mean metallicity measured 0.15-0.2 R_{500} (i.e. core-excluded)

Group *T(r)* diversity correlates with metallicity

- Group temperature profiles become flatter, with narrower peak-to-trough range as the gas metallicity rises (measured 0.15-0.2 R_{500})
  - Flatter *T(r)* caused by SN heating, which also enriches the gas?
  - Or, flatter *T(r)* caused by AGN heating, which also lifts enriched gas outwards (*Z* usually higher in core)?
  - Hotter core more easily disrupted by outflows, which carry enriched gas?
- No such trend between *T(r)* & *Z* is evident in clusters
  - ...and cluster *T(r)* less diverse than in groups
  - Larger cluster potential means *T(r)* more resistant to supernova heating and feedback in general

Summary

- Dichotomy in cluster population: cool core vs. non-cool core (roughly equal occurrence)
  - Very obvious in gas *T(r)*, *ρ(r)* and entropy within cooling radius (r_{cool} ~ 100-300 kpc)
  - But, CC & NCC metallicity profiles very similar, outside ~50 kpc
- Gas cooling very important in groups & clusters
  - Even non-cool core systems have t_{cool} << Hubble time
- Galaxy group properties more diverse than clusters; more sensitive to feedback
  - Flatter *T(r)* in core, with wider range of slopes than clusters
  - CC *T(r)* flattens with increasing gas metallicity (outside core)
- Clusters & groups are not self-similar
  - Need AGN feedback to match inner core properties, but supernova feedback may also be important in groups