Chandra analysis of cool-core groups & clusters: statistical properties

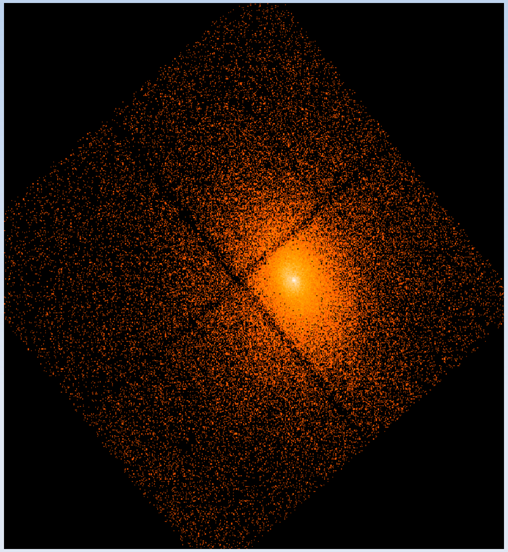
Alastair Sanderson
The University of Birmingham, UK

In collaboration with Ewan O'Sullivan (CfA), Trevor Ponman (B'ham)

Outline

- Introduction
- Cool core properties
  - Radial profiles of $T(r)$, $\rho(r)$, $S(r)$ etc.
  - Statistical Chandra sample of 20 clusters
  - Archival Chandra sample of 14 galaxy groups
- Key issues
  - Cool core fraction and formation/destruction
  - Cool core link to galaxy feedback
- Connection to REXCESS

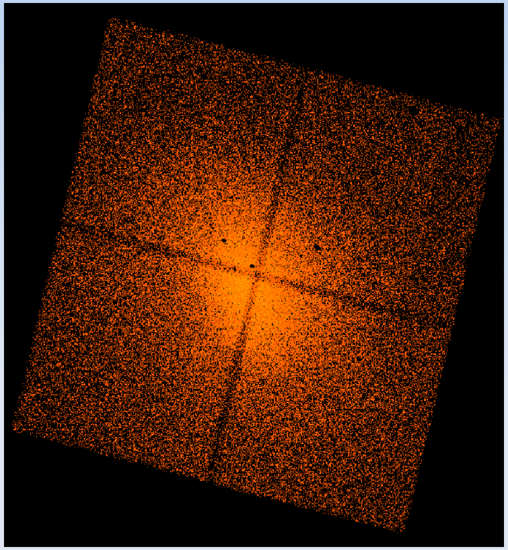
What is a cool core?



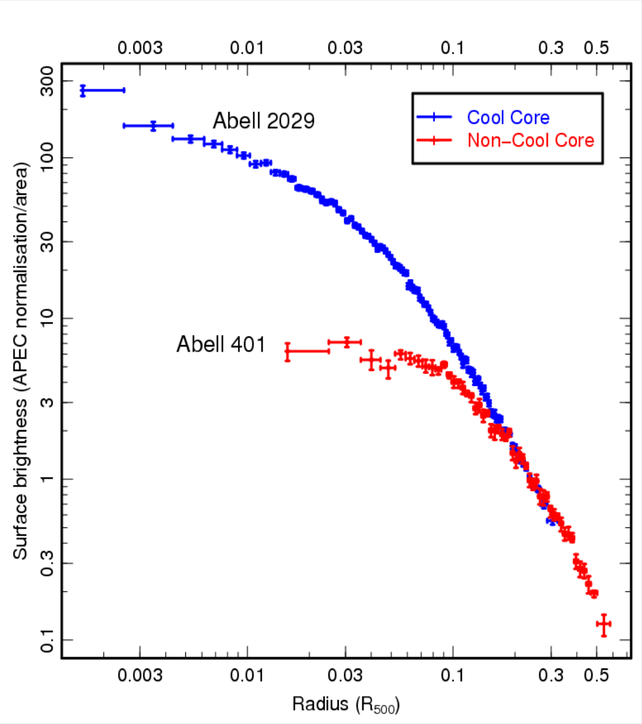
Abell 2029 (T ~ 9 keV, z= 0.077)
COOL CORE

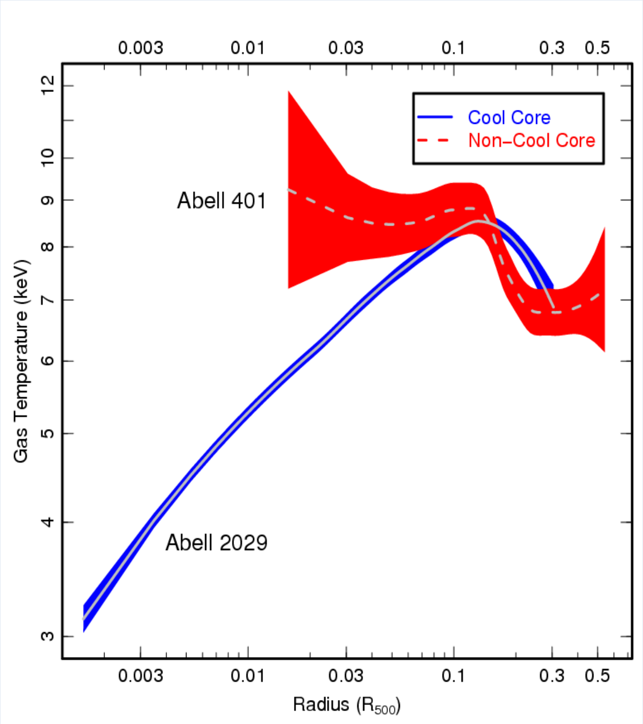
Chandra X-ray images

Abell 401 (T ~ 8.4 keV, z=0.074)
NO COOL CORE



Surface brightness profiles





Smoothed gas temperatur e profiles

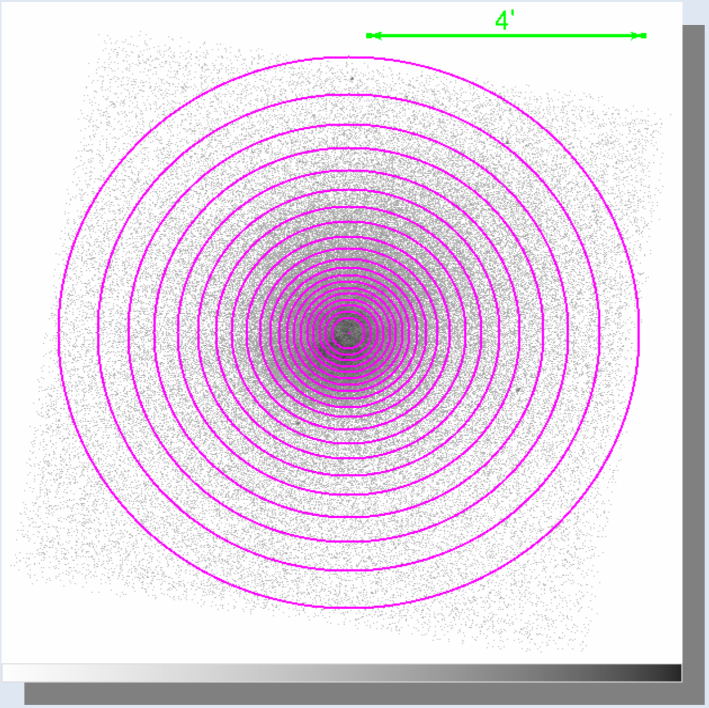
Why are cool cores important?

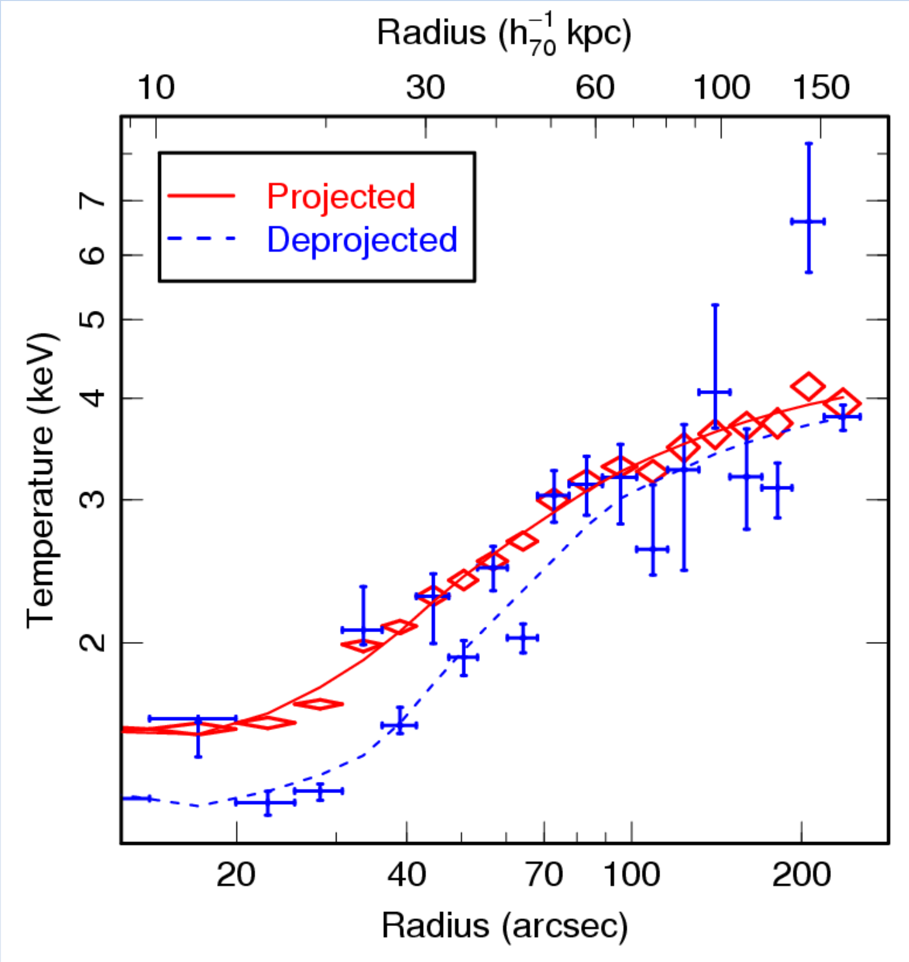
- Gas has a short t_{cool} & can drop out of hot phase:
  - Cool cores can fuel AGN & star formation [**feedback**]
- Cool cores are compact and dense:
  - Can affect merger & accretion-driven cluster evolution
  - More effective ram pressure stripping of galaxies
- CC associated with more relaxed, regular clusters:
  - Common in the most “ideal” clusters for detailed study
- Cool cores are luminous (and cool!):
  - Can bias global cluster luminosity and mean temperature
  - Have cuspy surface brightness profiles (harder to model)

X-ray analysis method

- Non-parametric deprojection
- Assume spherical geometry

2A0335+096 Cluster (z=0.035)

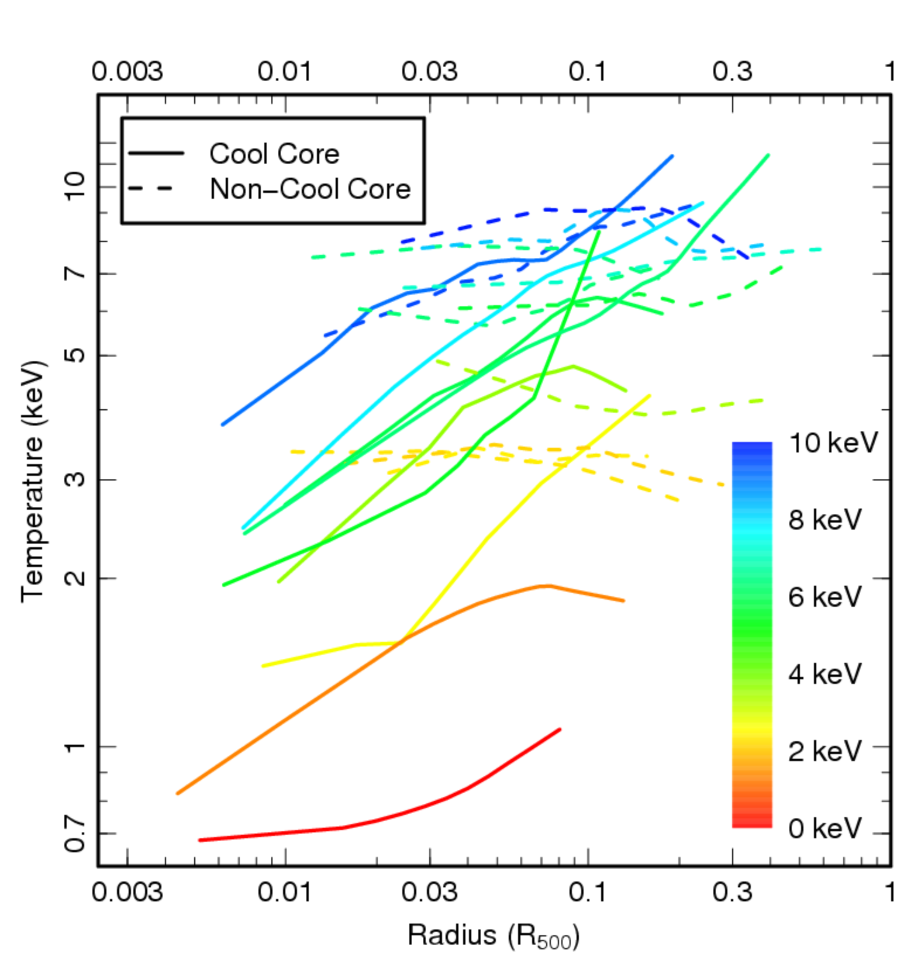




Local fit curves, to smooth data

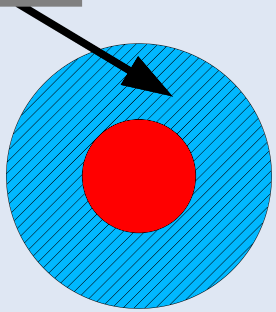
Gas temperature profiles

- Statistical Chandra sample of 20 clusters
- 9 / 20 clusters have CC
- *T*(r) slope very similar within cool core
- Non-CC roughly isothermal



Sanderson et al., 2006

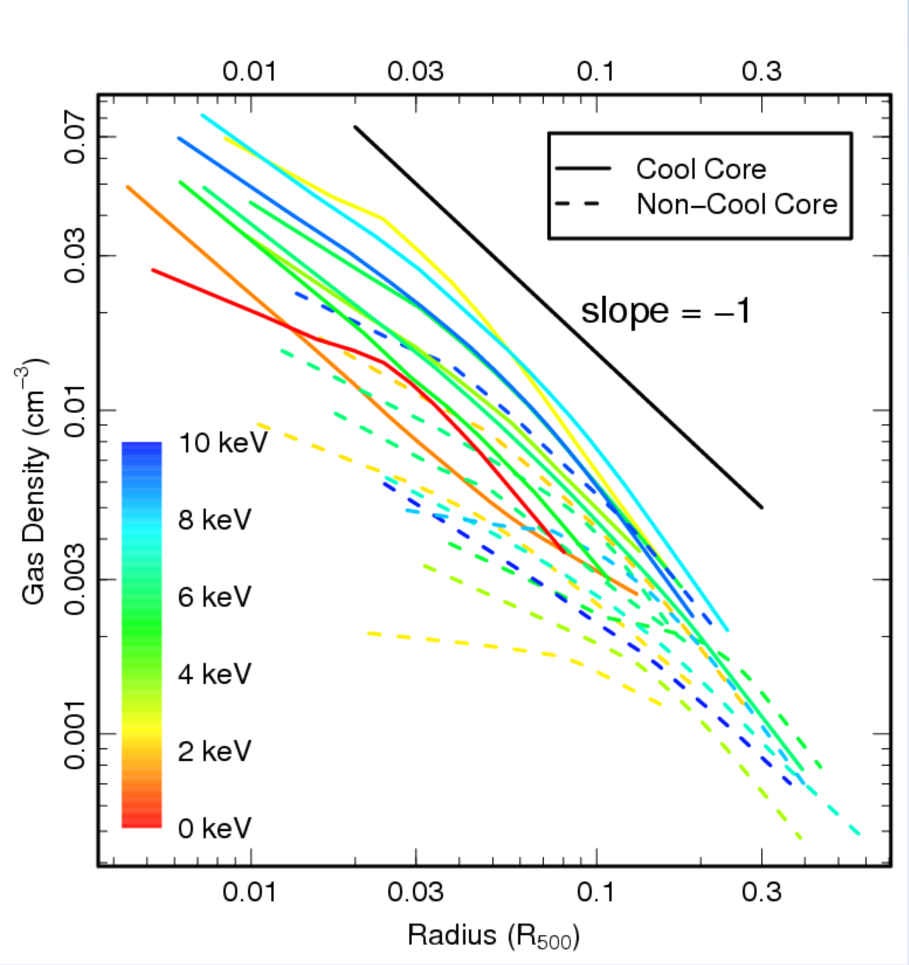
Profiles colour-coded by mean (core-excluded) gas temperature



mean T measured within 0.1-0.2 R_{500}

Gas density profiles

- Gas in cool cores is denser and more cuspy
  - Density increases to maintain pressure as *T* decreases
- Density profiles converge beyond cool core
  - Need wider FOV: ***REXCESS***
- In general, hot gas is less dense in cooler (less massive) clusters
  - (Pre)heating breaks similarity

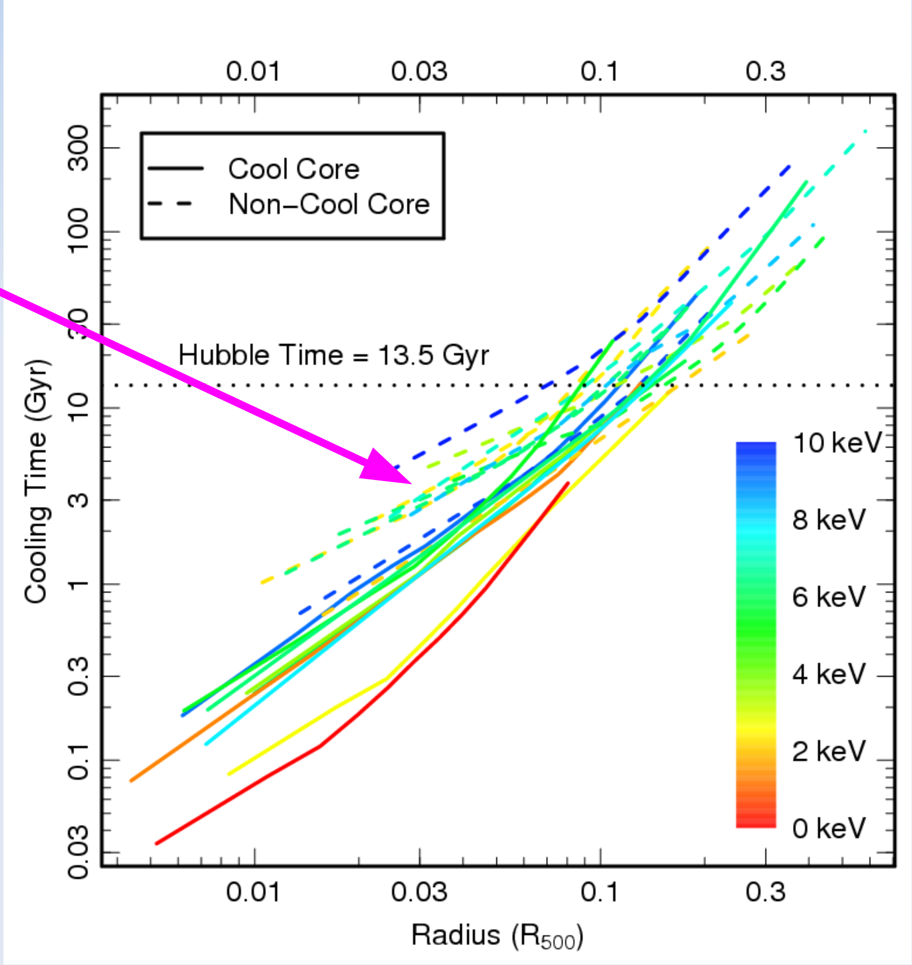


Sanderson et al. in prep.

Gas cooling time profiles

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

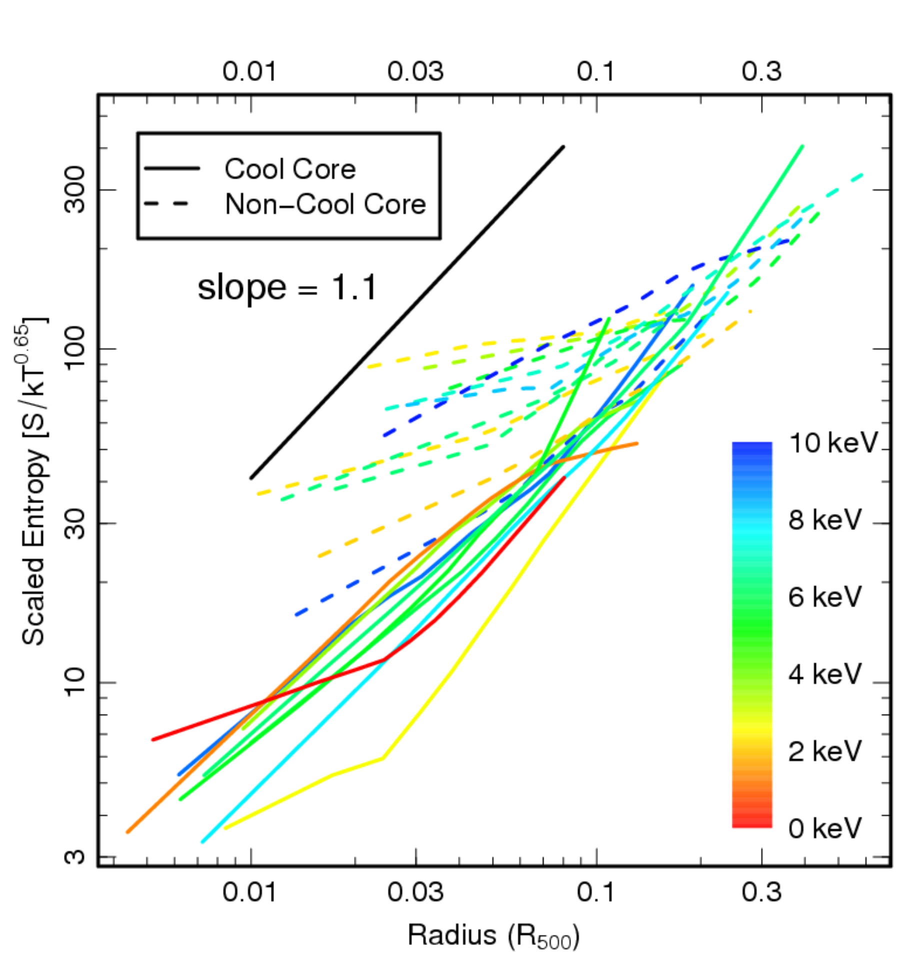
- Cooling time of gas vs. physical radius
  - t_{cool} = energy / luminosity
- Similar shaped profiles, but CC clusters lower norm.
  - cooling very influential
- *Even non-cool core systems have v. short cooling times*



Sanderson et al., 2006

Gas entropy profiles

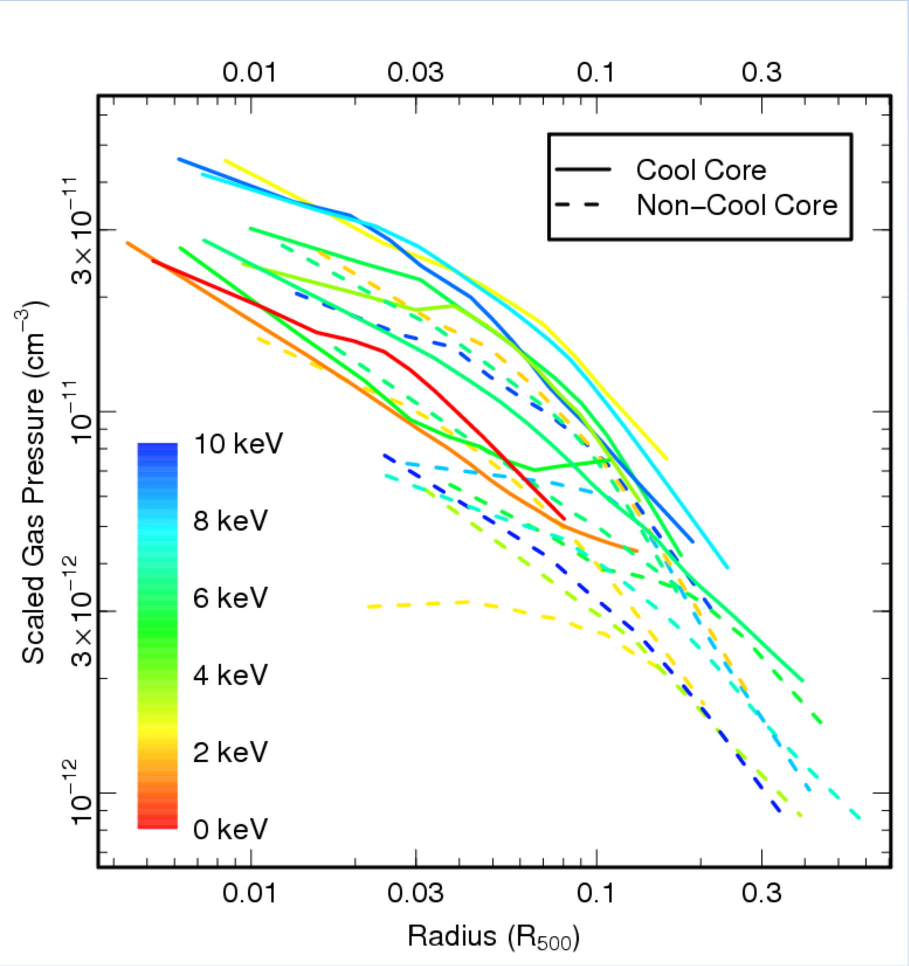
- Entropy = $kT / \rho^{2/3}$
- Scaled by empirical factor of $kT^{0.65}$ (from Ponman et al. 2003)
  - CC profiles show low scatter
- CC entropy ~r *at most radii*
  - *S* set by accretion shock in outskirts vs. cooling in core
- Non-CC profiles are flatter
  - cooling lowers entropy
  - non-CC (pre)heated more?



Sanderson et al. in prep.

Gas pressure profiles

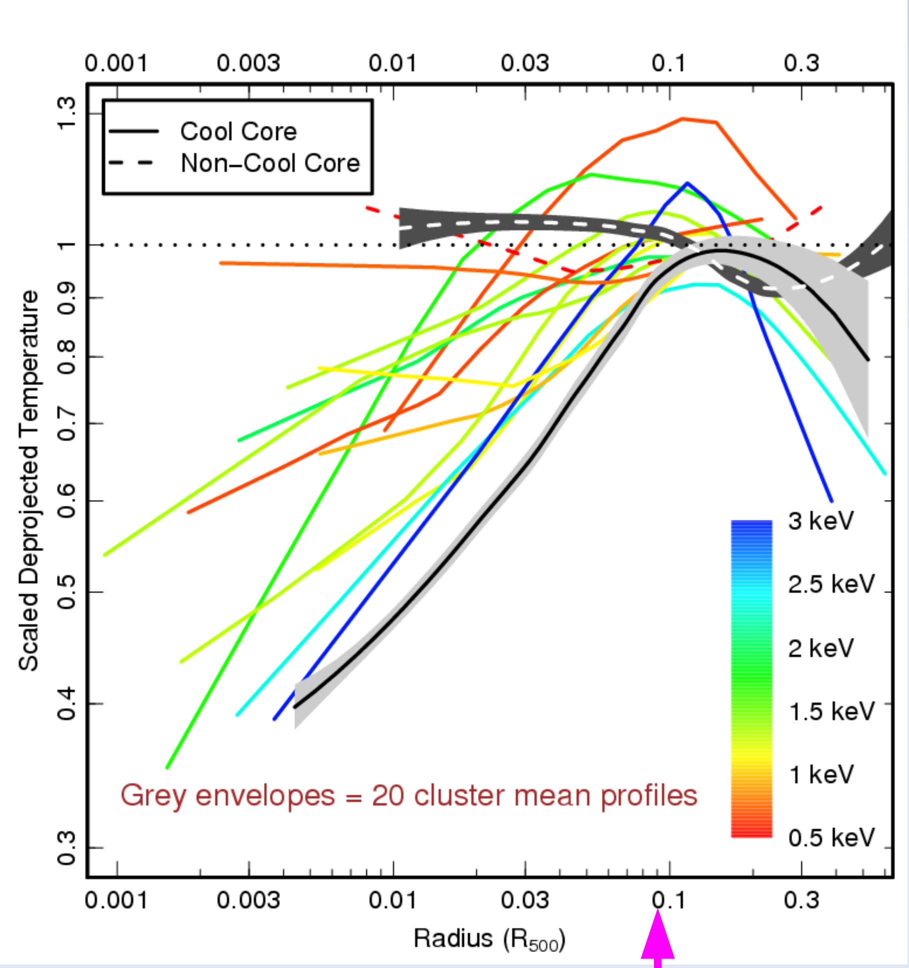
- Pressure = *kT* * *ρ*
- Scaled by mean *kT*
- Less difference between CC & non-CC
  - factor ~3 scatter in norm.
- No obvious trend with mean temperature
- CC P(r) may be more cuspy
  - but could just be resolution effect



Sanderson et al. in prep.

Scaled gas temperature profiles: ***galaxy groups***

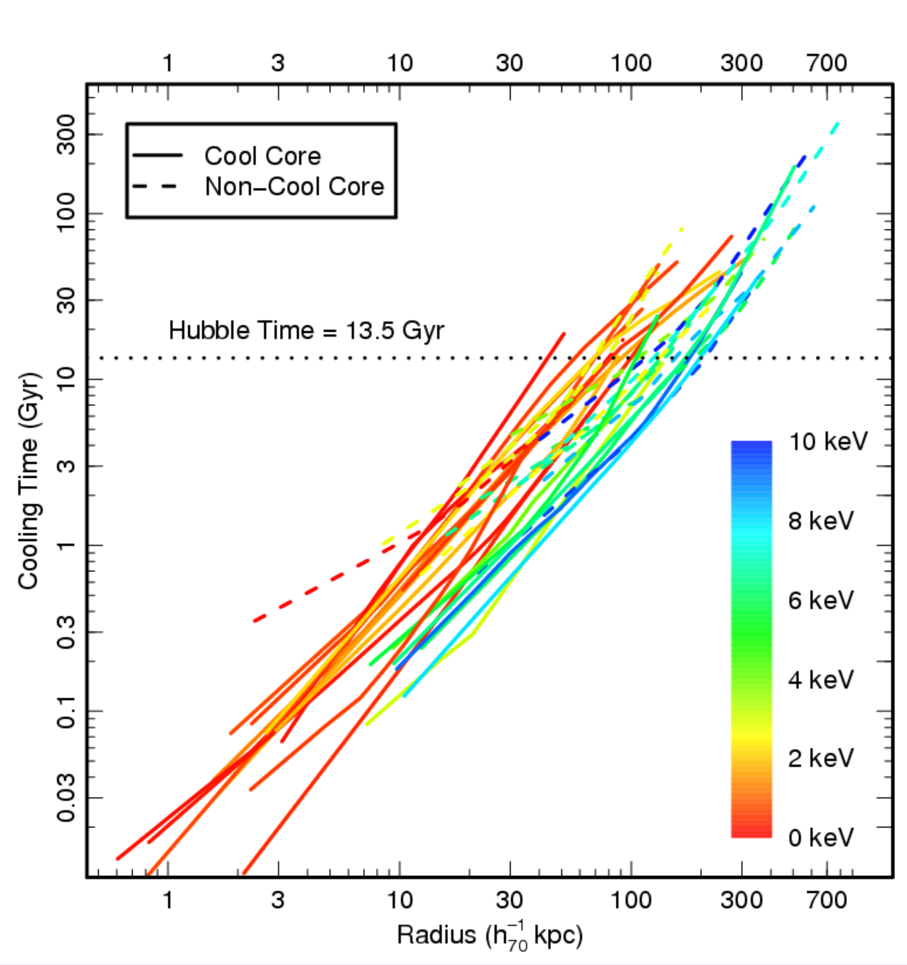
- Chandra sample of 14 groups, *scaled T(r)*
  - potentially biased towards bright/unusual systems
- All but one has cool core:
  - cooling v. effective in groups
  - but, smaller r_{cool} than clusters
- Group *T(r)* more diverse than clusters
  - varied feedback history?
- But, cooling still prominent:
  - feedback coupled to cooling?



radius of *T(r)* peak smaller in groups than clusters

The importance of radiative cooling on the hot gas

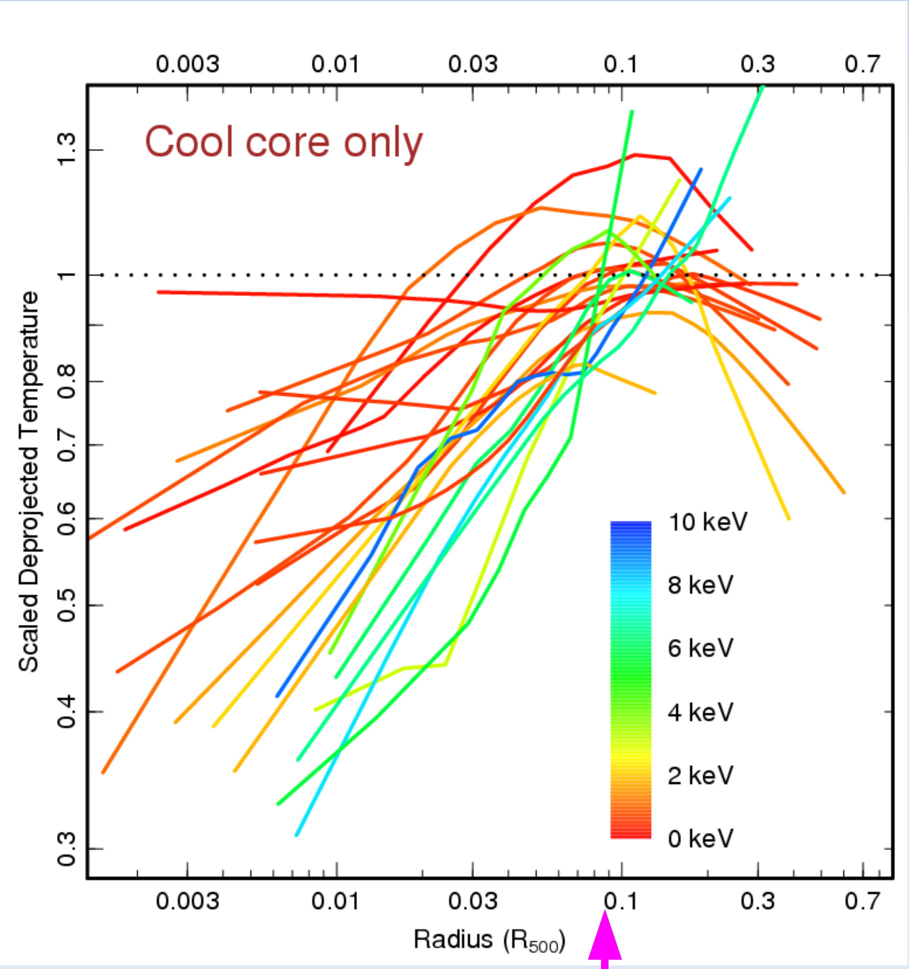
- 15 groups + 20 clusters, t_{cool} vs. *physical radius*
  - less scatter than vs. R_{500}
- "Universal" cooling time profile?
  - cooling very important
- Non-CC show steep profiles
  - need high resolution & S/N to probe short t_{cool}
  - e.g. 1 Gyr @ < 10 kpc → arcsec scales



Sanderson et al., 2006 + groups

Cool core groups vs. clusters

- Flatter group *T*(r) in cool core with a range of slopes
  - more diverse feedback history than clusters?
  - wider range of formation epochs?
- Peak *T*(r) at smaller scaled radius
  - smaller CC, due to greater impact of AGN feedback?
  - could be scaling bias, due to overestimate of R_{500}



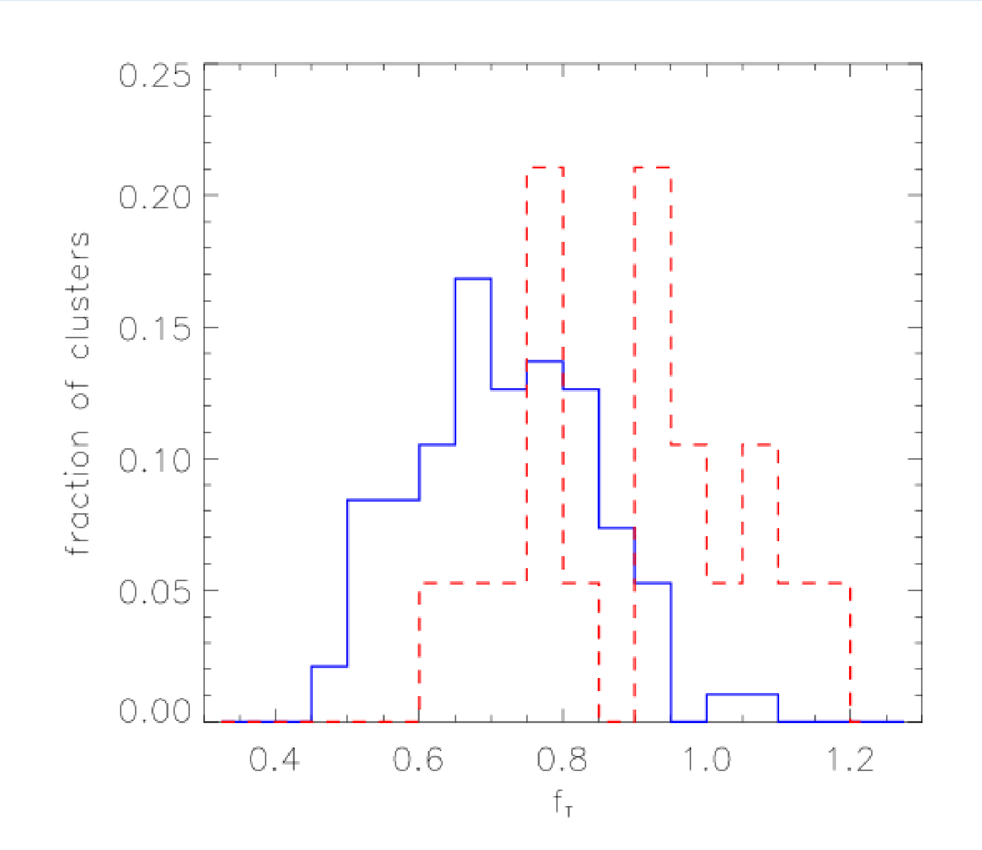
Sanderson et al., 2006 + groups

radius of *T(r)* peak is smaller in galaxy groups (red lines)

Why don't all clusters have a cool core?

- Radiative cooling v. unstable:
  - bremsstrahlung emissivity ~ $\rho^2 T^{0.5}$
- Cooling times are short in ~all clusters
  - gas is capable of cooling, but does not always do so
- Need heating and/or mixing mechanism
  - AGN outbursts?
- Non-CC clusters often show signs of disruption
  - mergers could disrupt cool cores
  - but, detailed simulations indicate that CC can't be destroyed in this way (e.g. Poole et al., 2006)...

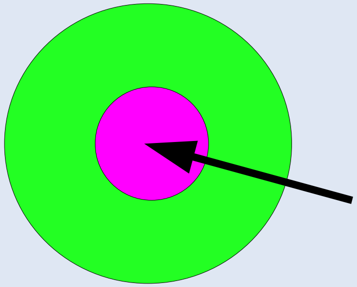
How many cool core clusters are found in cosmological simulations?



- Histograms of cool core strength, f_T for simulated clusters (Kay et al., 2007) vs. observed clusters

Blue solid curve is simulated clusters
Red dashed curves = 20 observed clusters

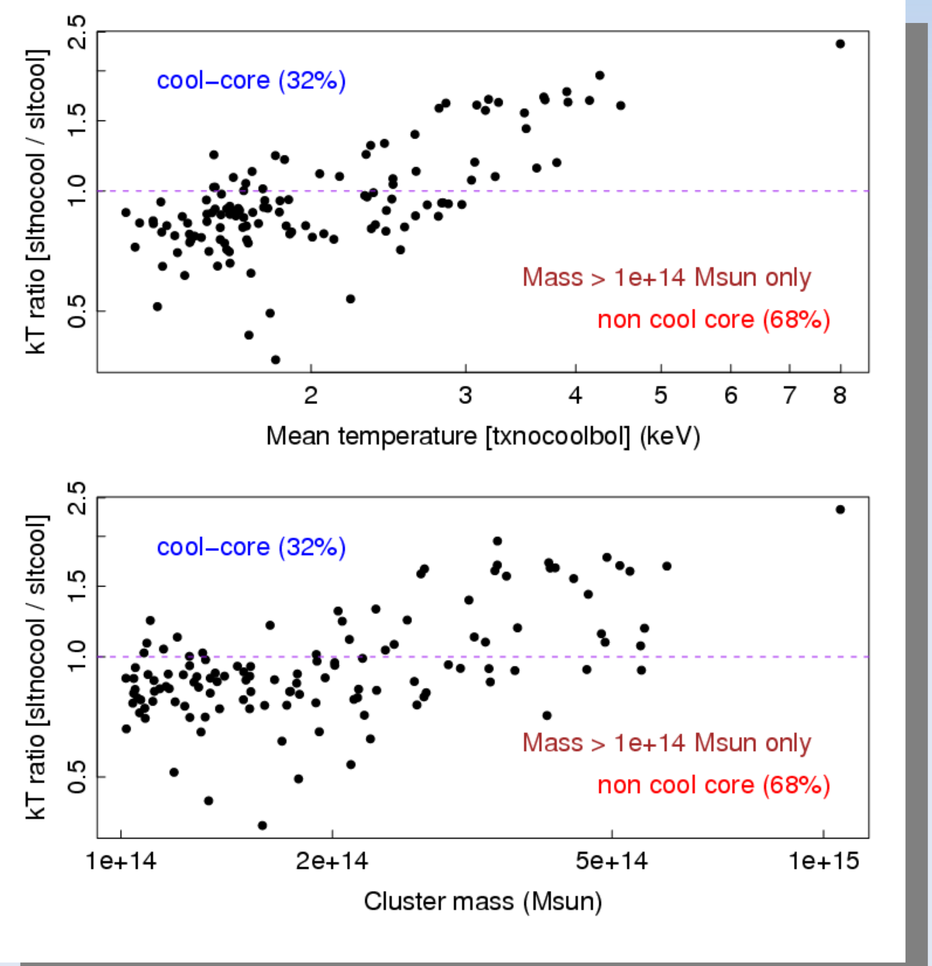
f_T is ratio of temperature within purple region ($0.1\ R_{500}$) to that in green region (0.1-$0.2\ R_{500}$)



- *Almost all these simulated clusters have cool cores*
- But, only around half the observed clusters have cool cores -> simulations are missing some key physics (AGN heating)

Cool core fraction in simulated clusters

- CC if T<0.1 R_{500} cooler than 0.1-0.2 R_{500}
- Simulation predicts cool cores more common in clusters
- But, 13/14 observed groups have cool core! (~50% CC fraction in clusters)
  - Selection effect?
  - Too much preheating?



slt = "spectroscopic-like temperature"
→ more like observed, emission-weighted T

simulated cluster data courtesy of Lorena Gazzola & Frazer Pearce (U. Nottingham)

Cool cores & REXCESS

- REXCESS is larger sample (34 clusters), with more rigorous selection criteria:
  - better understanding of range of cool core properties
- Can probe REXCESS clusters out to ($\sim R_{500}$)
  - link core properties to outskirts & global properties
  - are clusters more self-similar outside the core?
  - can trace $M(r)$ to large radius: better measurement of R_{500}
- Need to complement X-ray data with other wavelengths & with numerical simulations:
  - improved understanding of feedback, AGN fuelling, star formation, metal enrichment, etc.

Summary

- 2 types of cluster: cool core & non-cool core
  - ~50% clusters have CC; seems to be much higher in groups
- Gas cooling very important in groups & clusters
  - Universal cooling time profile?
  - Even non-cool core systems have t_{cool} << Hubble time
- Galaxy group properties more diverse than clusters
  - Flatter *T(r)* in core, with wider range of slopes
  - Cooling radius ~0.1 R_{500} vs. ~0.15 R_{500} in clusters
- Cool core properties sensitive to (pre)heating history as well as formation & evolutionary history
- REXCESS sample will be very important here