Hot gas in galaxy groups: observations vs. simulations

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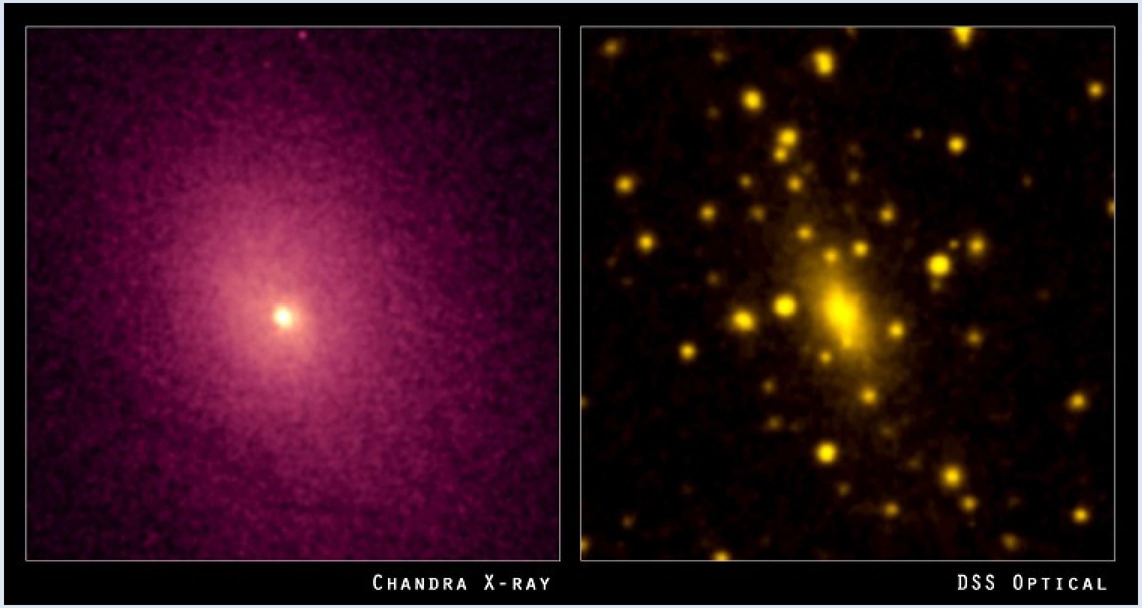
The IGM in groups & clusters

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

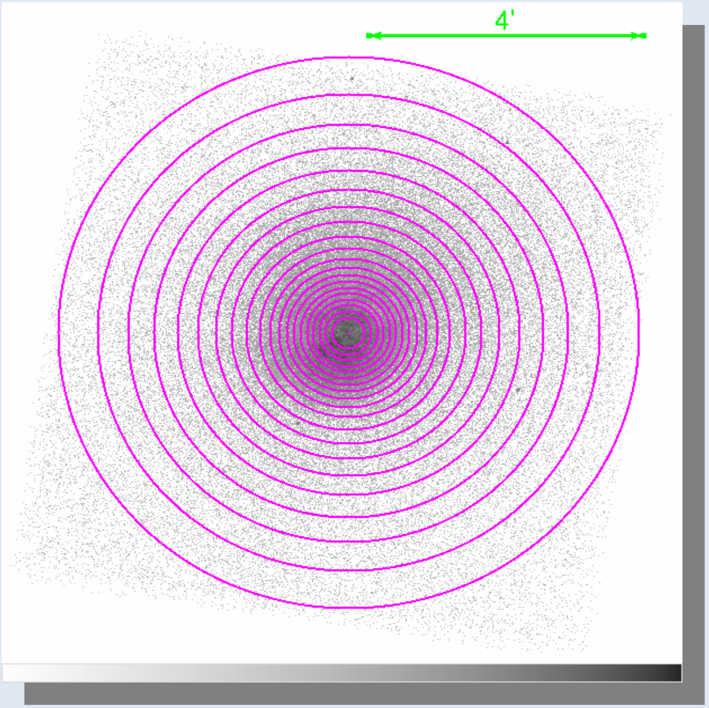
Non-gravitational processes in groups & clusters

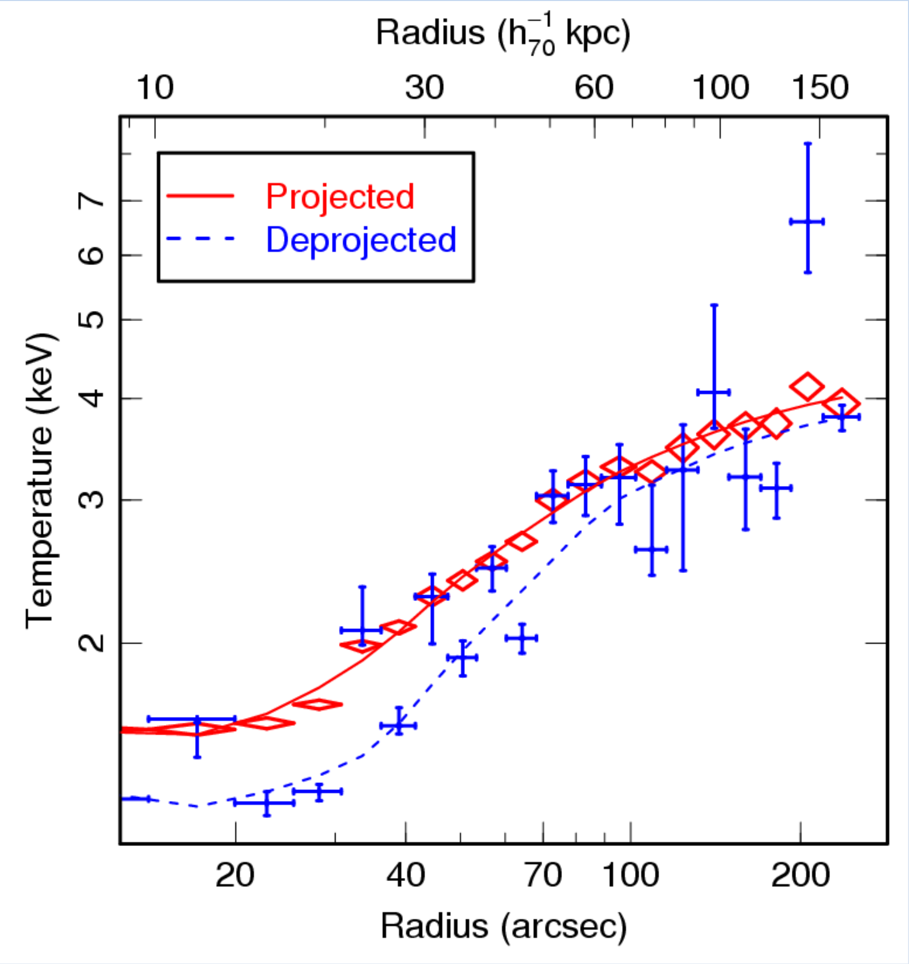
- IGM is affected by galaxy feedback before *and* after collapse into groups/clusters:
  - supernova-driven galaxy winds
  - Active Galactic Nuclei (AGN) outbursts
- This non-gravitational energy breaks self similarity and offsets cooling losses:
  - best studied by comparing X-ray scaling properties of hot gas in galaxy clusters & especially groups
- Further insight provided by comparing observations with simulations:
  - deduce impact of different physical processes on cluster properties
  - refine models of feedback so as to match observations

X-ray analysis method

- Non-parametric deprojection
- Assume spherical geometry

2A0335+096 Cluster (z=0.035)



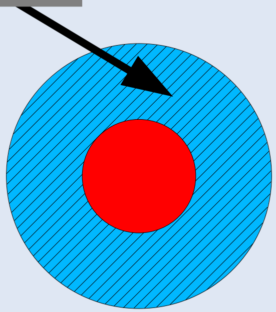


Local fit curves, to smooth data

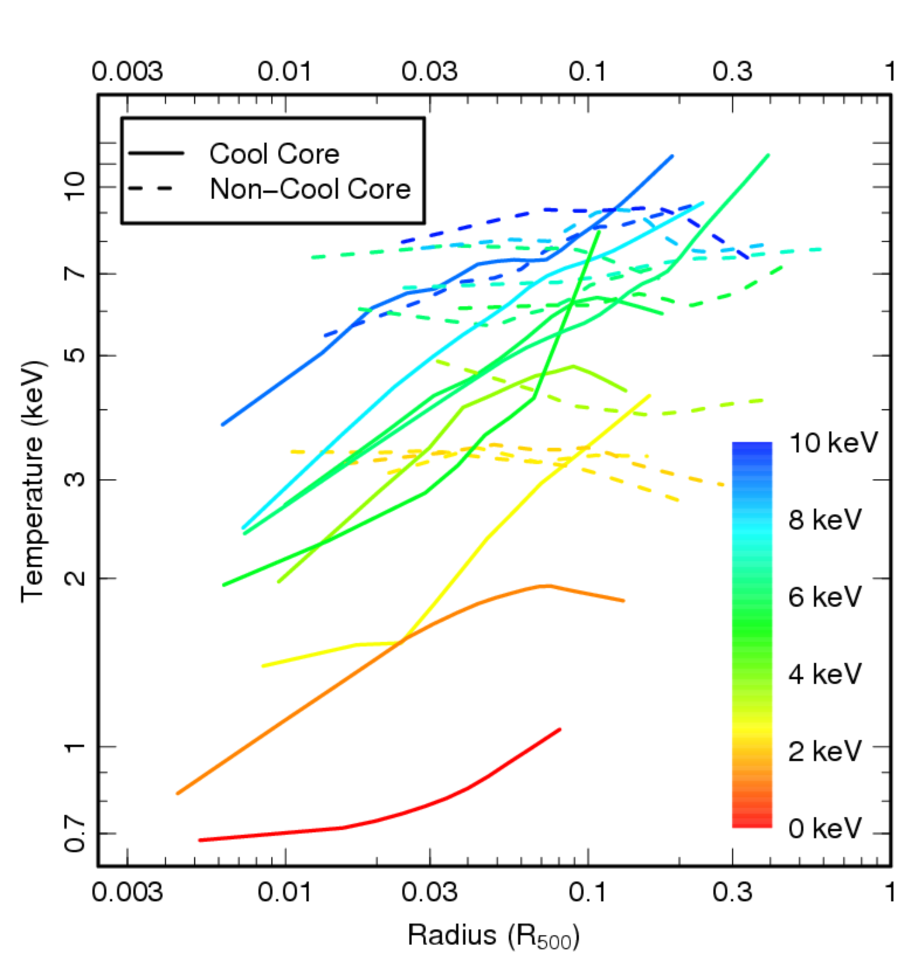
Observed gas temperature profiles: ***galaxy clusters***

- Statistical sample of 20 clusters
  - Chandra X-ray data
- Two types of cluster:
  - cool core (9/20)
  - non-cool core (11/20)

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



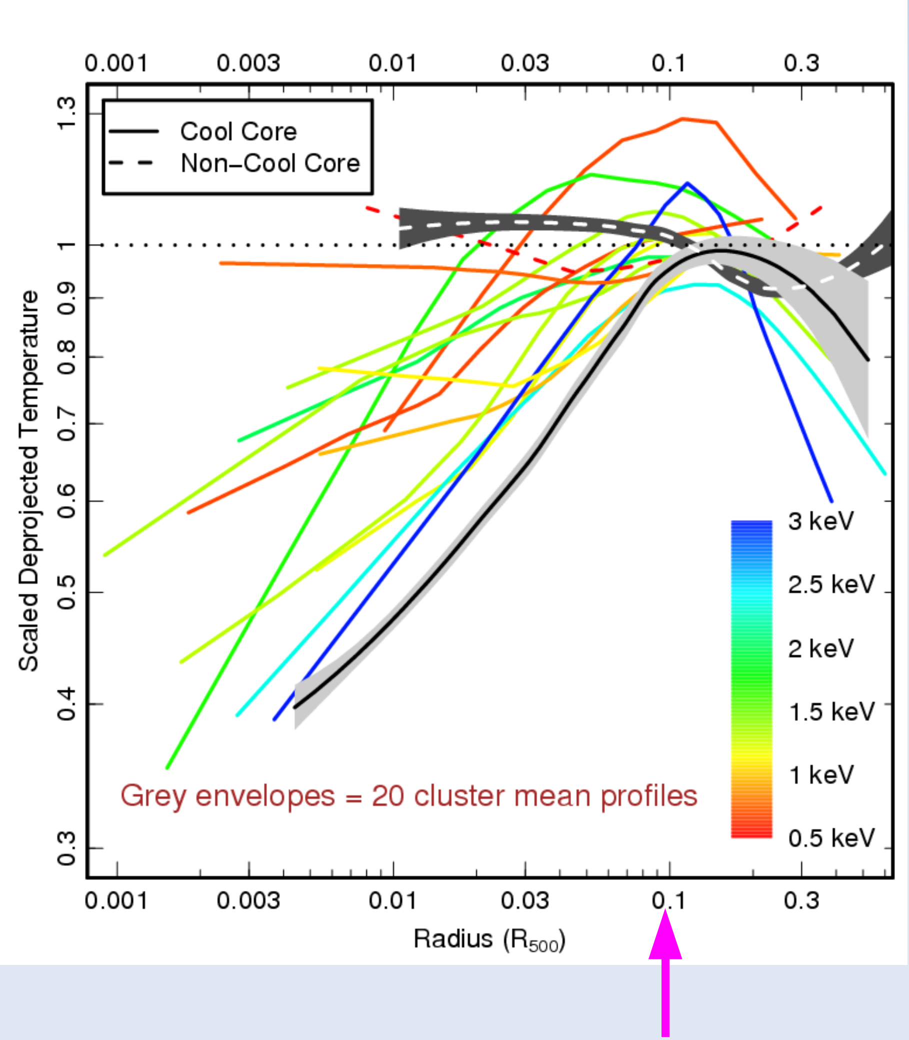
mean T measured within 0.1-0.2 R_{500}



Sanderson et al., 2006

Observed 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?

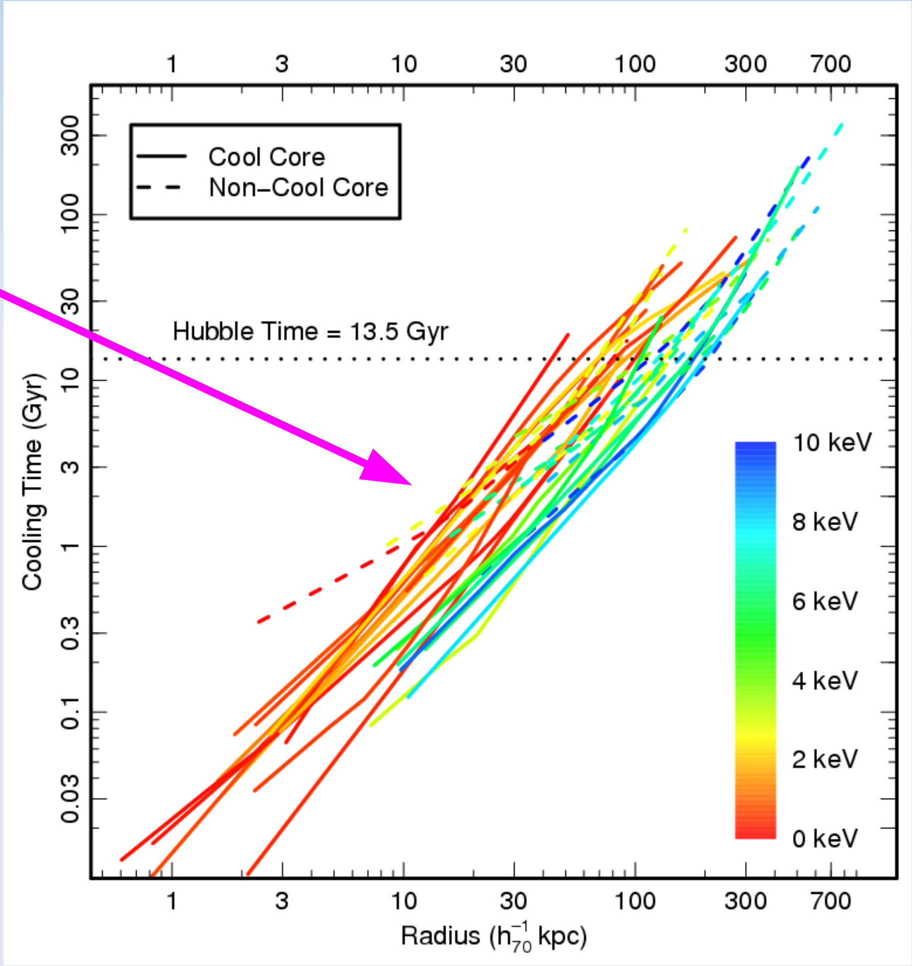


radius of *T(r)* peak smaller in groups than clusters

The importance of radiative cooling on the hot gas

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

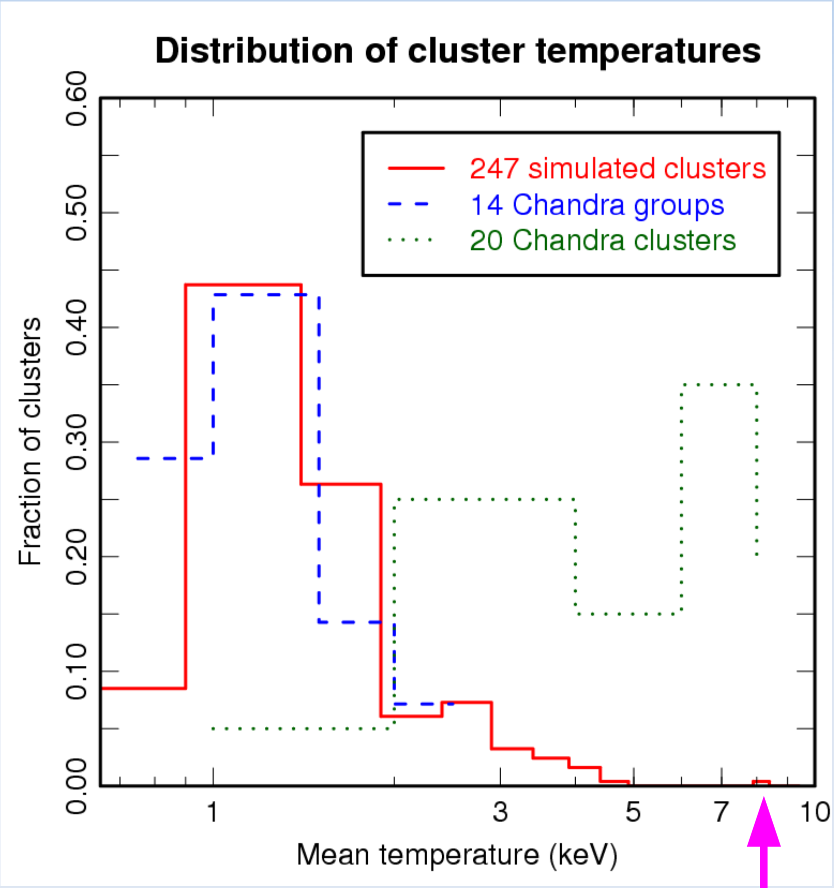
- Cooling time of gas vs. physical radius
  - t_{cool} = energy / luminosity
- "Universal" cooling time profile?
  - cooling very important
- *Even non-cool core systems have v. short cooling times*



Sanderson et al., 2006 + groups

The Millennium Gas Simulation

- 256x256 Mpc box; 25 kpc softening scale, 3.12×10^9 M_{sun} gas particle size
  - 1/8 total simulation volume
- 247 clusters extracted
- Preheating prescription used to mimic star formation & SN heating:
  - SF & energy injection when $T < 10^5$ K and overdensity > 2500
  - Matches L_X-T_X relation
- ***No AGN feedback***



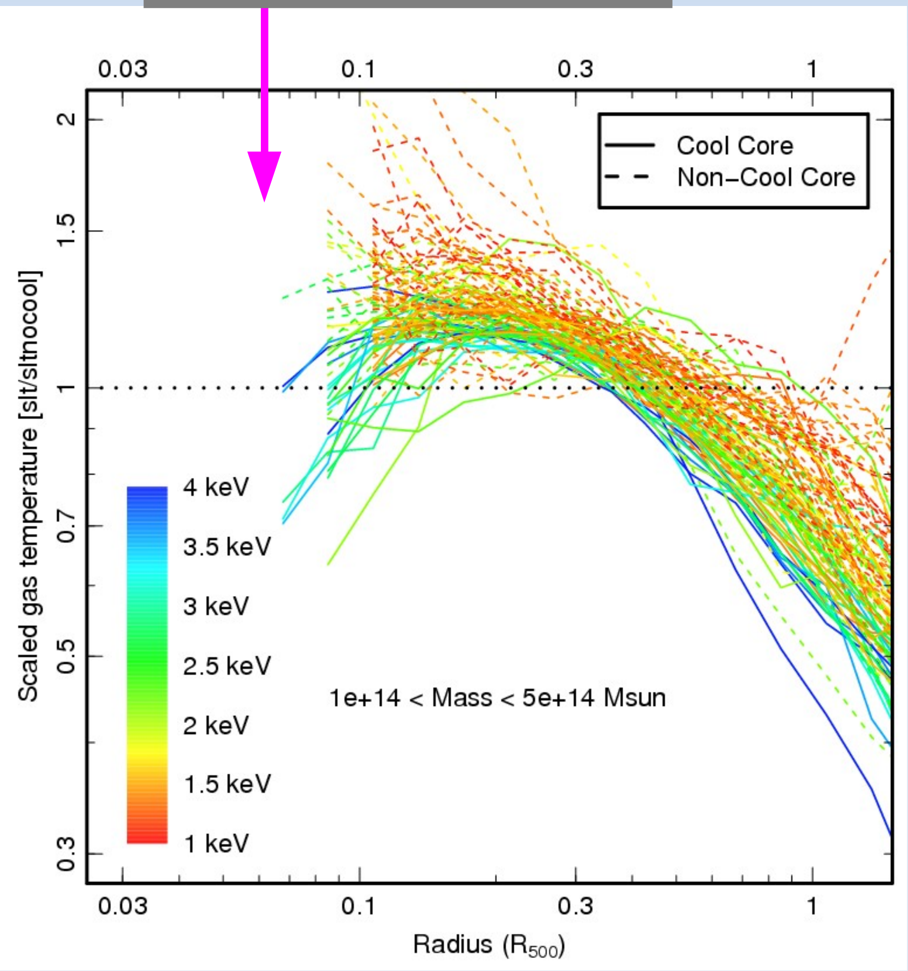
Single ~8 keV simulated cluster

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

Simulated gas temperature profiles

- Excluding massive clusters, to highlight trend
- Cooler clusters have higher scaled *T(r)*
  - effect of preheating?
- *T(r)* drops beyond ~0.2 R_{500}
  - Universal temperature profile

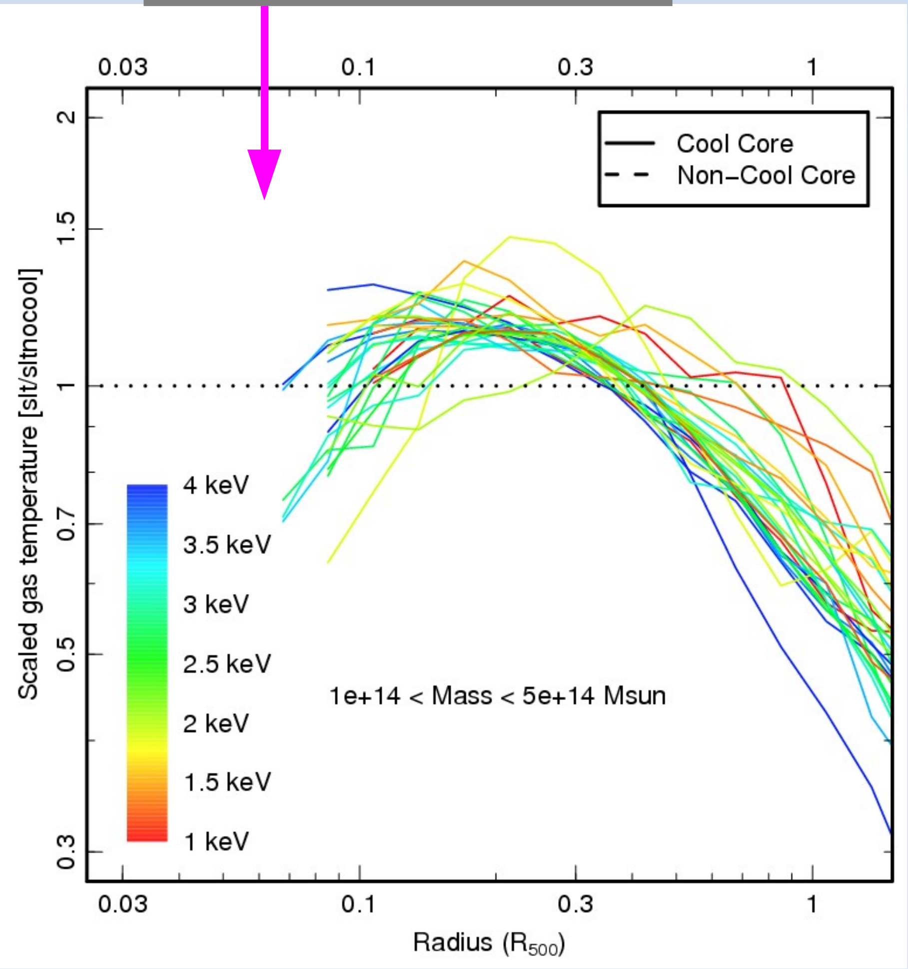
Excluding r < 70 kpc



Simulated gas temperature profiles (cool core only)

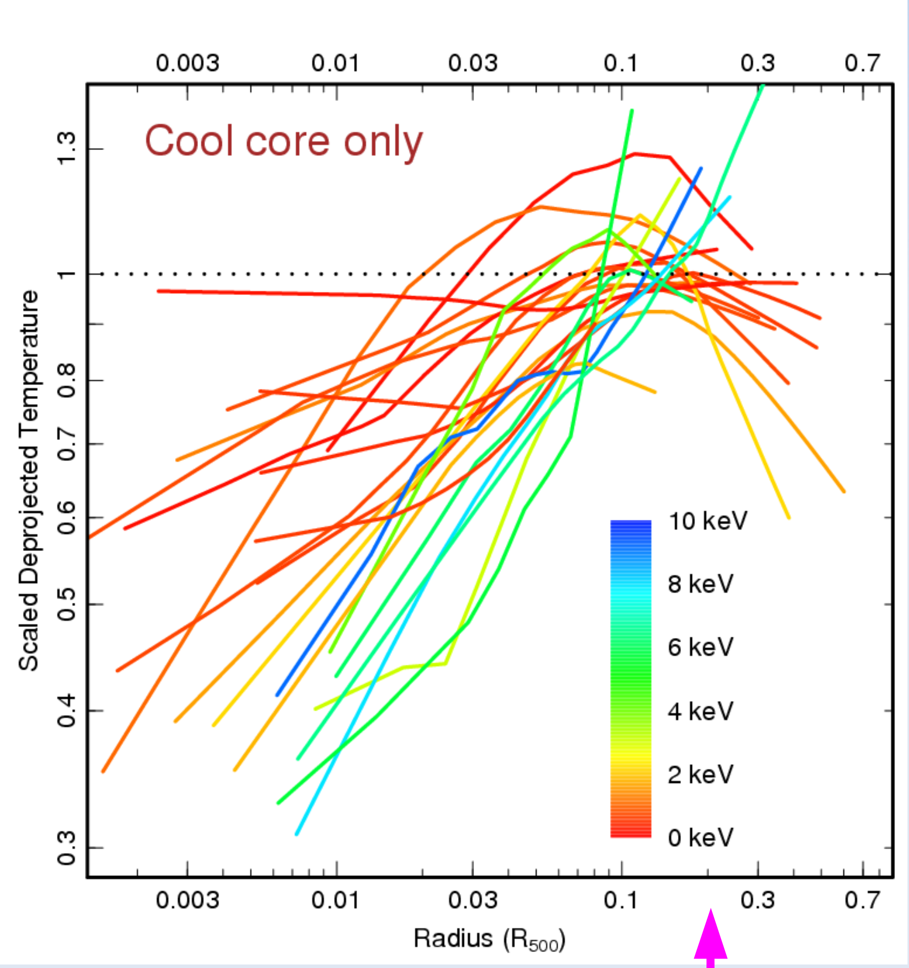
- Excluding massive clusters, to highlight trend
- Cooler clusters have higher scaled *T(r)*
  - effect of preheating?
- *T(r)* drops beyond ~0.2 R_{500}
  - Universal temperature profile
- Peak T(r) ~0.2 R_{500}
  - Larger cool core than observed groups/clusters

Excluding r < 70 kpc



Observed vs. simulated gas temperature profiles

- Cool core systems only
- Observations: 13 groups, 9 clusters
- Simulations:
  - Mass > $1 \times 10^{14}\ M_{sun}$
- Simulated T(r) similar to clusters in core, but steeper than groups (although comparison limited by resolution)
  - AGN heating?



Sanderson et al., 2006 + groups

radius of *T(r)* peak larger in simulated clusters

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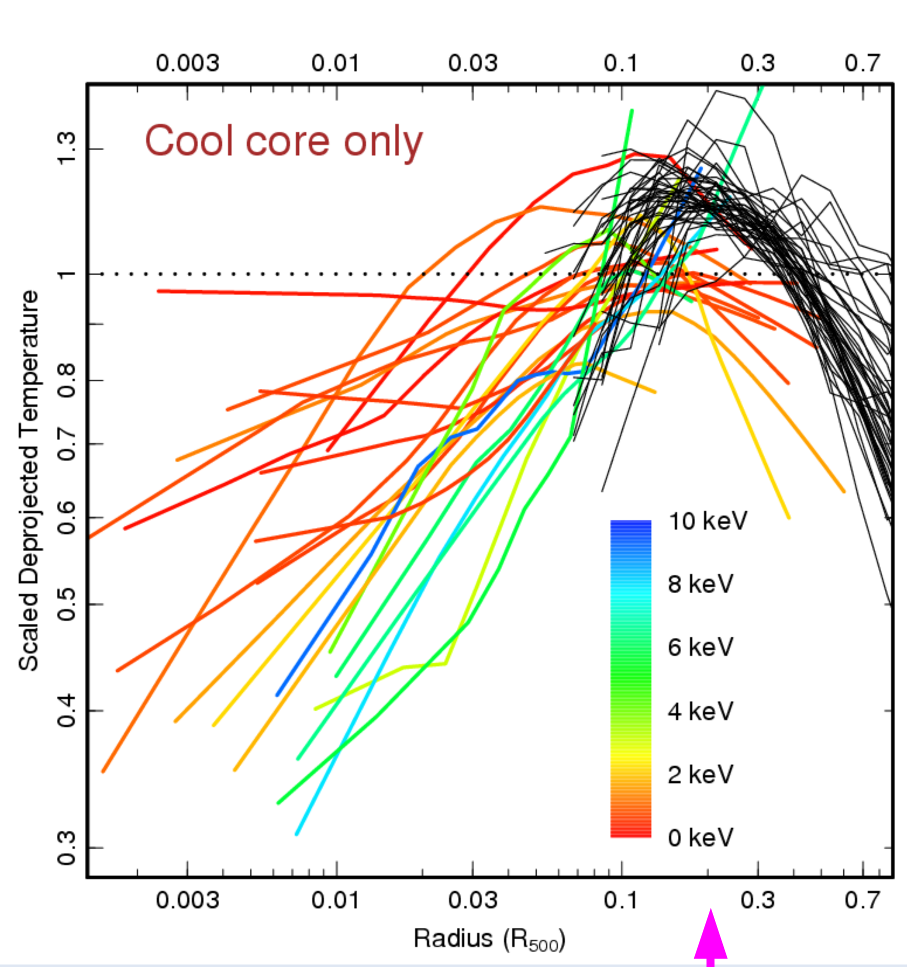
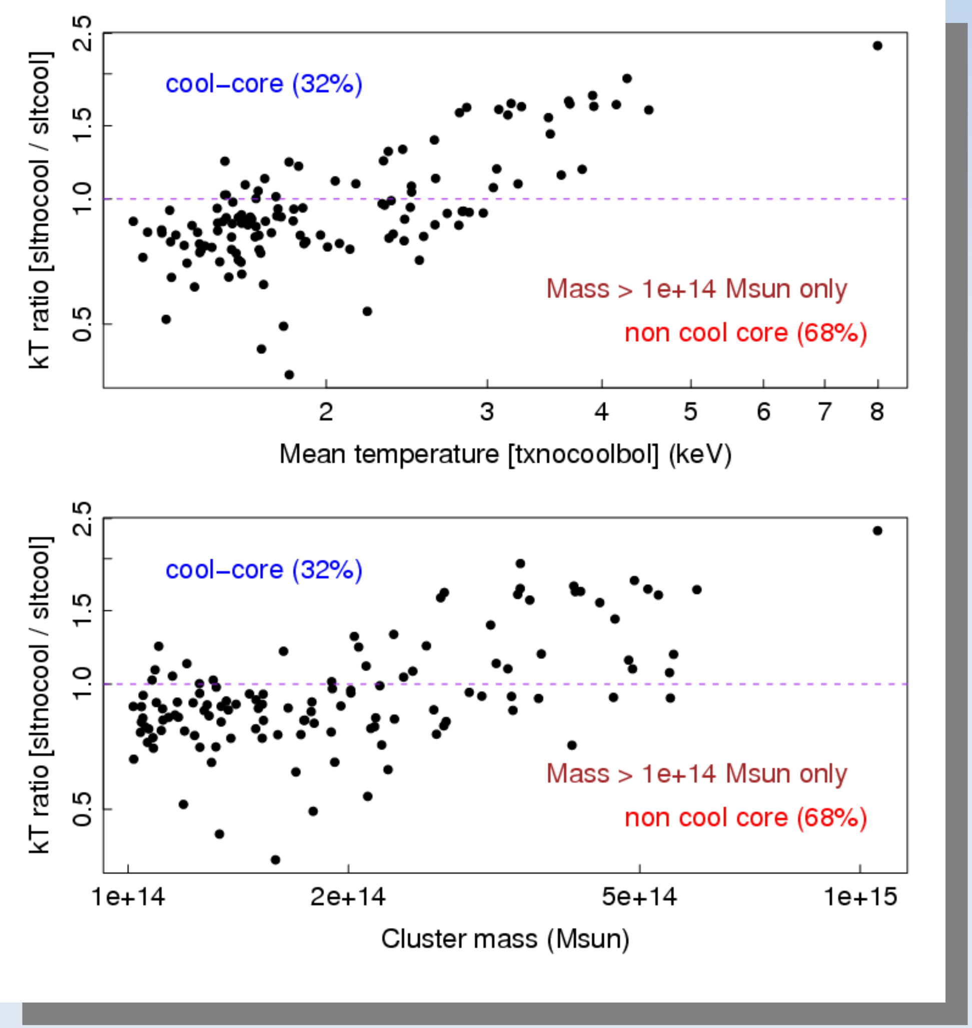


Sanderson et al., 2006 + groups + simulated clusters

radius of *T(r)* peak larger in simulated clusters

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

Summary

- 2 types of cluster: cool core & non-cool core
  - ~50% clusters have CC; only 1/14 groups doesn't
- Gas cooling very important in groups & clusters
  - Even non-cool core systems have t_{cool} << Hubble time
- Galaxy group properties more diverse than clusters
  - Flatter *T(r)* in core
  - Cooling radius ~0.1 R_{500} vs. ~0.15 R_{500} in clusters
- Cosmological simulations match observations over wide range, using preheating and radiative cooling prescriptions
  - But, *T(r)* peak radius too large, core *T(r)* too steep c.f. groups
  - Probably need AGN feedback to match inner core properties