Gian Luigi Granato

Istituto Nazionale di Astrofisica - Trieste, Italia

The central structure of Intra-Cluster Medium: recent encouraging results from simulations

THE ASTROPHYSICAL JOURNAL LETTERS, 813:L17 (6pp), 2015 November 1 doi:10.1088/2041-8205/813/1/L17

© 2015. The American Astronomical Society. All rights reserved.

COOL CORE CLUSTERS FROM COSMOLOGICAL SIMULATIONS

E. RASIA[1,2], S. BORGANI[1,3,4], G. MURANTE[1], S. PLANELLES[1,3,4], A. M. BECK[5], V. BIFFI[1,3], C. RAGONE-FIGUEROA[6], G. L. GRANATO[1], L. K. STEINBORN[5], AND K. DOLAG[5,7]

[1] INAF, Osservatorio Astronomico di Trieste, via Tiepolo 11, I-34131, Trieste, Italy; rasia@oats.inaf.it

[2] Department of Physics, University of Michigan, 450 Church St., Ann Arbor, MI 48109, USA

[3] Dipartimento di Fisica dell' Università di Trieste, Sezione di Astronomia, via Tiepolo 11, I-34131 Trieste, Italy

[4] INFN, Instituto Nazionale di Fisica Nucleare, Trieste, Italy

[5] Universitäts-Sternwarte München, Scheinerstr.1, D-81679 München, Germany

[6] Instituto de Astronomá Teórica y Experimental (IATE), Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET), Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, X5000BGR, Córdoba, Argentina

[7] Max-Plank-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, D-85740 Garching, Germany

Received 2015 September 7; accepted 2015 October 12; published 2015 October 29

The thermal history of Intra-Cluster Medium (ICM)

- During the hierarchical assembly of galaxy clusters, the ICM is leaded to $T\sim10^8$ K and central $n_e\sim10^{-3}$ cm^{-3}. Thus the cooling time $t_{cool} \propto T^{0.5}/n_e$ is short enough to expect extreme accretion (cooling flows) toward the center and star formation rates $\sim1000\ M_{\odot}/\mathrm{yr}$. These rates are not observed, indicating a substantial heating source and/or efficient redistribution.
- Since about 10 years the prime suspect to provide extra heating is AGN feedback.
- It requires some fine tuning to preserve the observed thermodynamic structure. Main questions:
    1. How the AGN output energy, apparently dictated by conditions on a few pc scale, is tuned to match the cooling on scales $\sim$ 100 kpc?
    2. How the AGN energy is distributed to balance cooling everywhere?

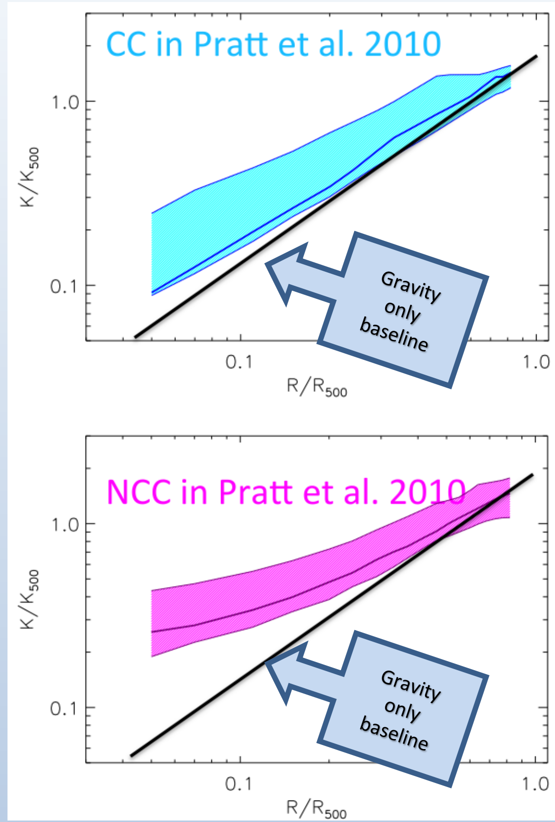
The thermal history of Intra-Cluster Medium (ICM)

- It requires some fine tuning to preserve the observed thermodynamic structure.
- The most studied tracer of the thermal history of clusters is the (pseudo)entropy profile $K = T/n_e^{2/3}$ (the classical thermodynamic entropy per particle is $\ln K^{3/2} + costant$ in an ideal monatomic gas).
- It always rises when heat energy is introduced and always falls when radiative cooling carries heat energy away. By converse the gas temperature can be little affected due to gas expansion (contraction) and conversion of thermal energy into (from) potential energy.
- Another interesting choice would be the cooling time profile $t_{cool} \propto T^{0.5}/n_e$ (Voit+ 2015).

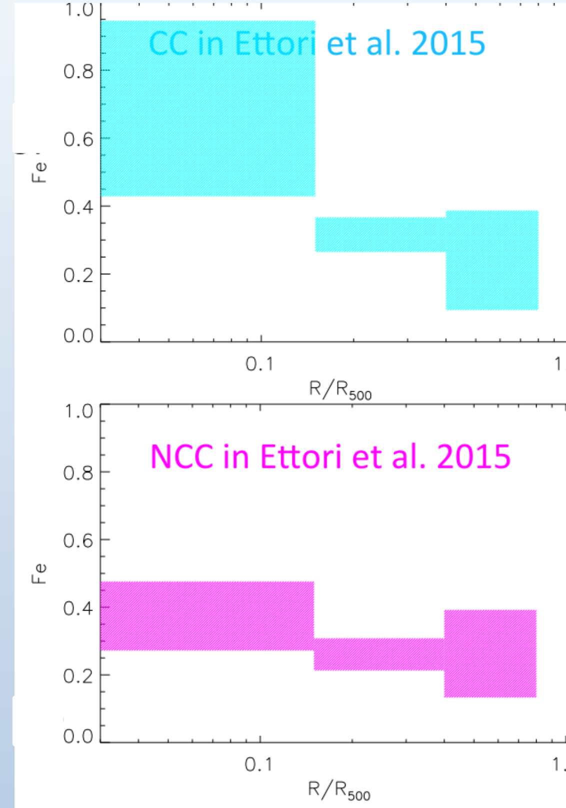
Observational situation: a dichotomy in the core

$\sim$1/3 are Cool Core (CC): low entropy and metal enriched gas in the center. T (n_e) at $\sim$ 10 kpc smaller (larger) than that at $\sim$100 kpc by a factor $\sim$3 (10)

$\sim$2/3 are Non Cool Core (CC): nearly isentropic core, not showing the metallicity spike of CCs



Entropy profile



Metallicity profile

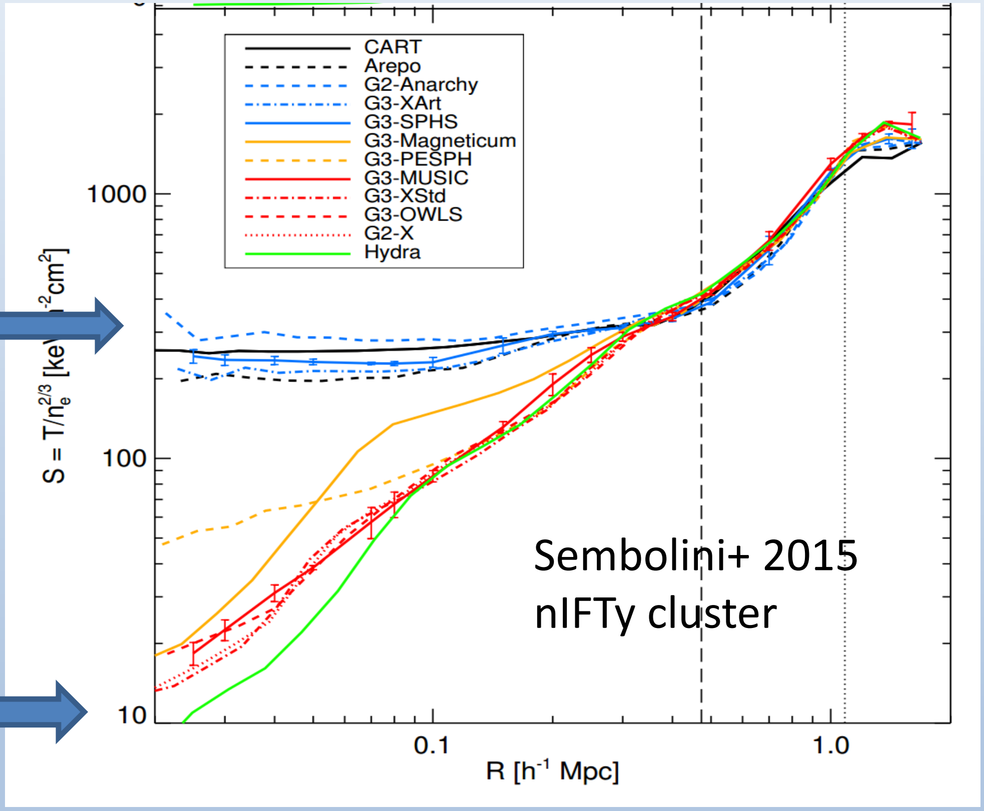
- Entropy profiles results from a delicate balance between heating and cooling processes, possibly including thermal conduction;
- Metal profiles results from enrichment by stellar evolution and redistribution processes such as galactic winds, ram pressure stripping, AGN bubbles, mergers;
- In most cases, CC clusters show regular X-ray morphology while the opposite is true for NCC systems, suggesting a correlation with cluster merging events.

CC and NCC cluster dichotomy in simulations

Non radiative simulations (no cooling, no SF) produce power law entropy profiles in the outskirts $k(r) \propto r^{\alpha}$ with $\alpha \approx 1-1.1$, but differing in the center depending on the hydro solver (a "numerical method dichotomy"): ….

….cored with Eulerian codes or modern SPH,

…declining with standard SPH

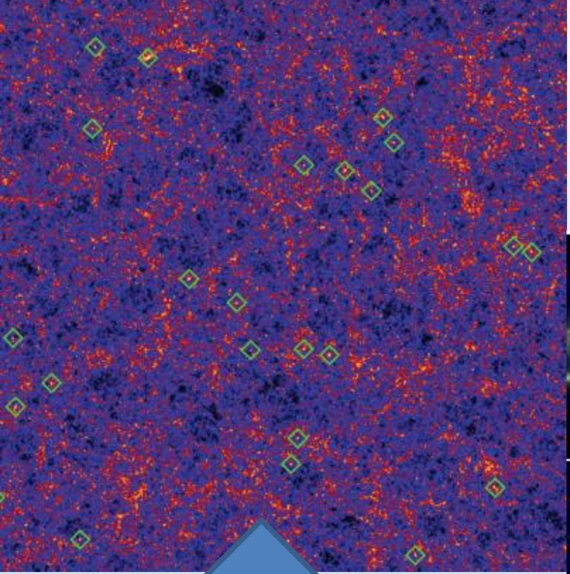


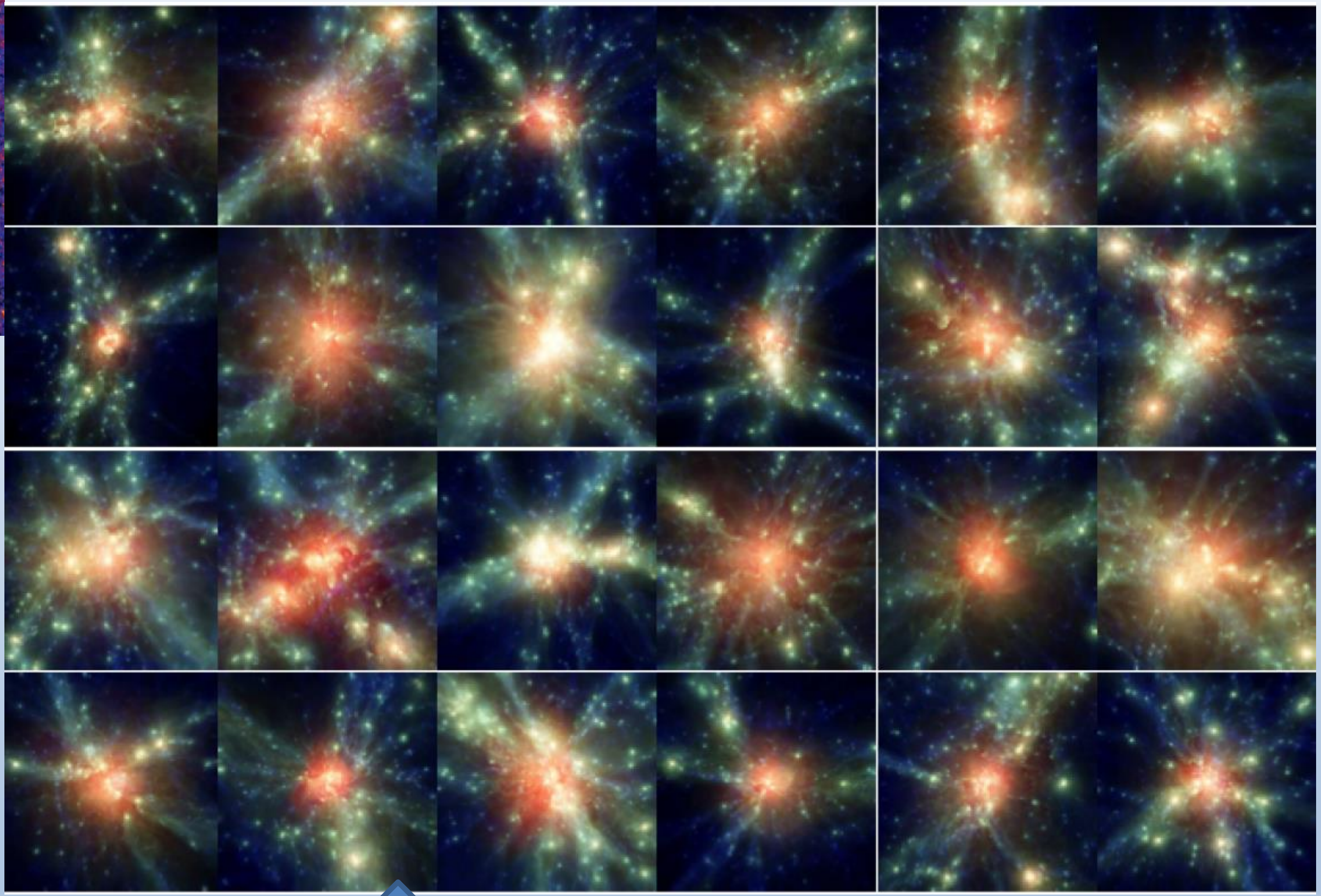
Conventional wisdom is to consider more "real" the results of Eulerian codes. The absence of cores in standard SPH is attributed to the lack of mixing. For sure, the adopted hydro solver matters.

CC and NCC cluster dichotomy in simulations

- Radiative processes (cooling and star formation), have the somewhat counterintuitive effect of raising ICM entropy in the central region, by removing gas with low entropy and short cooling time from the gas phase to fuel star formation.
- If this effect were properly counteracted by some form of feedback (stellar, AGN), one could expect to produce the observed diversity of situations.
- What about mergers? Earlier numerical work predicted a "primeval" origin of the two classes (e.g. Burns+2008, Poole+2008), with CC being destroyed only by early mergers at $z > 0.5$, in conflict with observations. However these works did not include AGN feedback, a serious limitation likely leading to too strong cool cores.
- Overall, until now, cosmological simulations of clusters have been unable to satisfactorily reproduce the diversity of features and relative abundance of CC and NCC clusters.

Our "Dianoga" zoom in sims





Parent gravity only sims, box 1 Gpc h^{-1}. Diamonds on position of 24 most massive clusters

24 most massive clusters ($M_{200} > 1e15\ h^{-1}\ M_{\odot}$ at z=0) re-simulated at higher resolution in boxes of about 60 Mpc, including baryonic physics (images of 15 Mpc/h, color code T gas)

DIANOGA SIMULATION: The Clusters Sample

The 24 most massive clusters $M_{200} > 1e15\ h^{-1}\ M_\odot$ at z=0) and 5 poorer clusters ($1e14\ h^{-1}\ M_\odot < M_{200} < 5e14\ h^{-1}\ M_\odot$), extracted from a parent simulation (gravity only) with box of 1 Gpc h^{-1}.

The 29 Lagrangian regions around these objects zoom-in re-simulated with our custom version of Gadget-3, including hydrodynamics and sub-resolution baryonic physics:
Cooling, Star Formation, SN Feedback, AGN Thermal Feedback

softening old 5/now 3.5 h^{-1} kpc; $M_{DM} = 8.5e8\ h^{-1}\ M_\odot$; $M_{gas,ini}=1.5e8\ h^{-1}\ M_\odot$

Runs with 3 levels of physics included (NR, CSF, AGN)

Comparison with observations for the pre-2015 version(s):

- Planelles et al. 2014 ("On the role of AGN feedback on the thermal and chemodynamical properties of the hot intracluster medium")
- Ragone-Figueroa et al. 2013 ("Brightest cluster galaxies in cosmological simulations: achievements and limitations of active galactic nuclei feedback models")

+ Fabjan et al. 2010, Planelles et al. 2013, Killedar et al. 2013; Cui et al. 2014, Rasia et al. 2014 +

DIANOGA 2015: what's new wrt 2013

OLD vs NEW

"Standard" Gadget3 SPH → Revised SPH scheme (Beck+ 2015), better treats problems related with mixing of different gas phases:

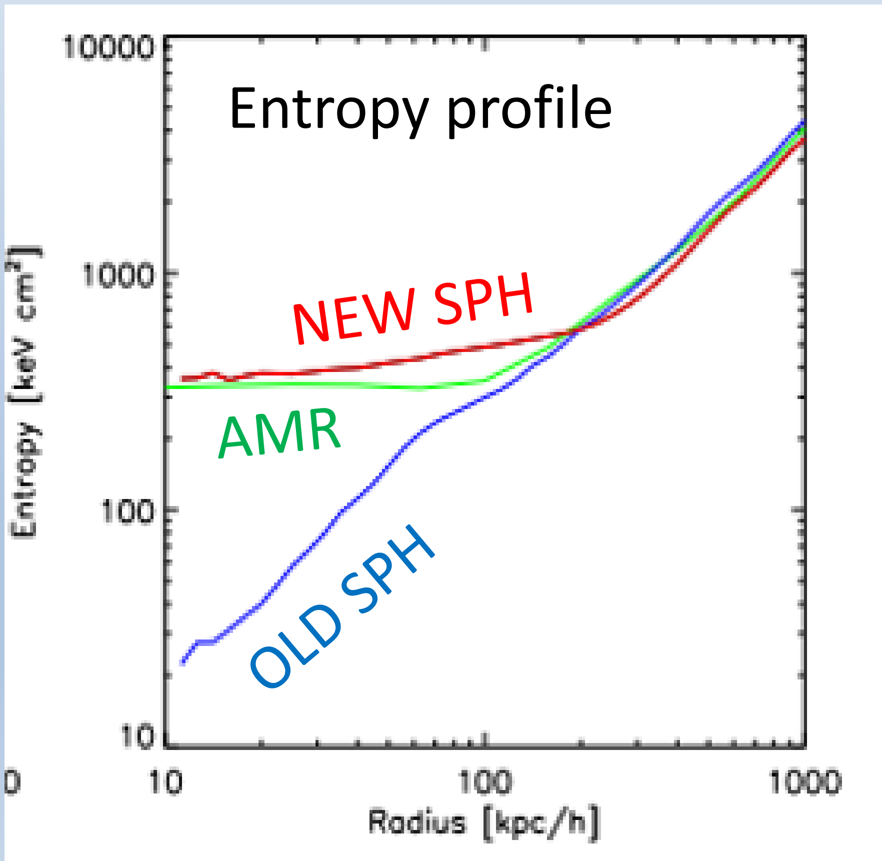
- Artificial conduction term reducing spurious surface tension
- High order interpolating kernel
- Time dependent artificial viscosity

AGN thermal feedback (Springel+ 2005, modifications in Ragone+ 2013) → New AGN feedback prescription (Steinborn+ 2015)

- Phenomenological dependence of accretion efficiency $\varepsilon(M_{BH}, \dot{M}_{BH})$

Non Radiative test of new SPH scheme on the "Santa Barbara Cluster" (Beck+ 2015)

In keeping with results of Eulerian AMR codes, using the new scheme, an entropy core forms and the cold blobs are destroyed. The spurious complexity of ICM is reduced.



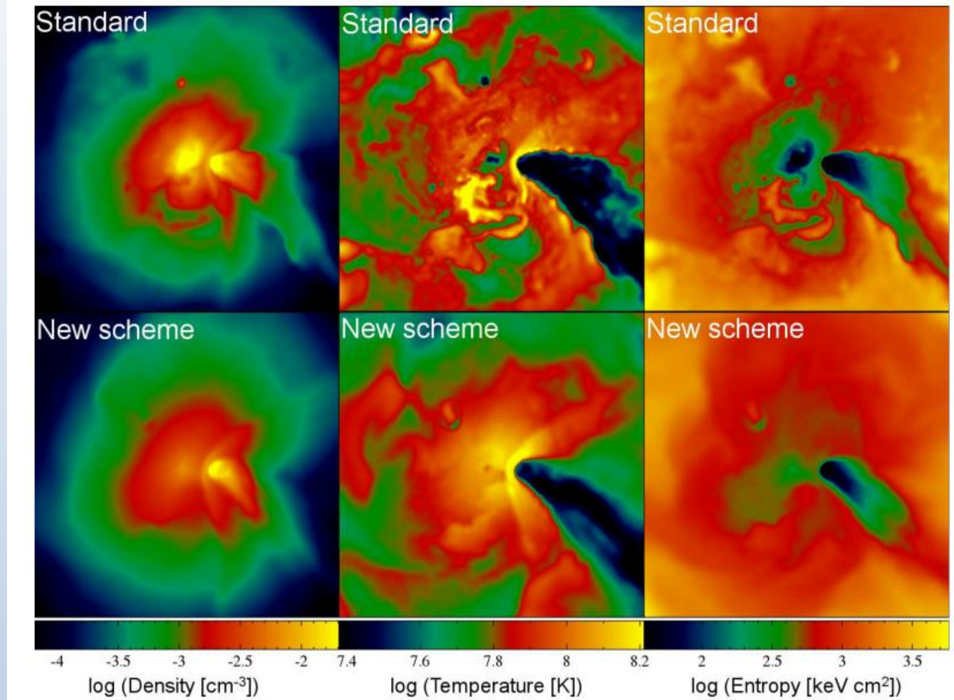
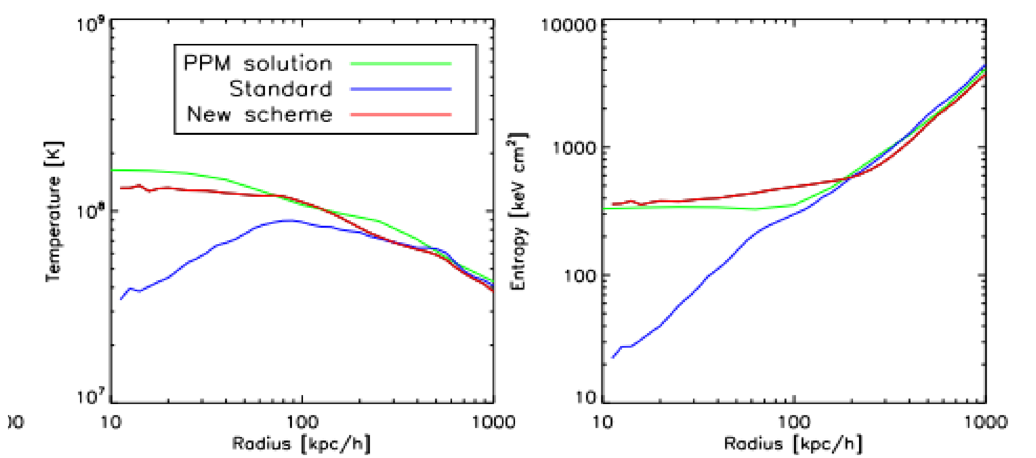


Figure 20. Santa Barbara Cluster. In boxes with 1 Mpc/h side length, we show this slices of gas density (left panels), temperatur (middle panels) and entropy (right panels) at redshift $z = 0$ for the 'standard' scheme (top row) and the 'new' scheme (bottom row) In the 'new' scheme significantly less dense and cold gas blobs are present, as AC promotes fluid mixing and blob dissociation. Thi promotes a smoother distribution of higher temperatures and entropies at the halo centre, which reduces the ICM complexity.



Comparing with observations: how to define degree of "cool coreness"

Two joint criteria extensively applied to observational data (eg Rossetti+ 2011):

1) A "pseudo-entropy ratio between the inner and the outer region of the cluster:

$$\sigma = \frac{(T_{\rm IN}/T_{\rm OUT})}{(\mathrm{EM_{IN}}/\mathrm{EM_{OUT}})^{1/3}},$$

where IN is $r < 0.05\ R_{180}$ and OUT is $0.05\ R_{180} < r < 0.15\ R_{180}$

2) The value of the central entropy K_o derived from a parametric fit

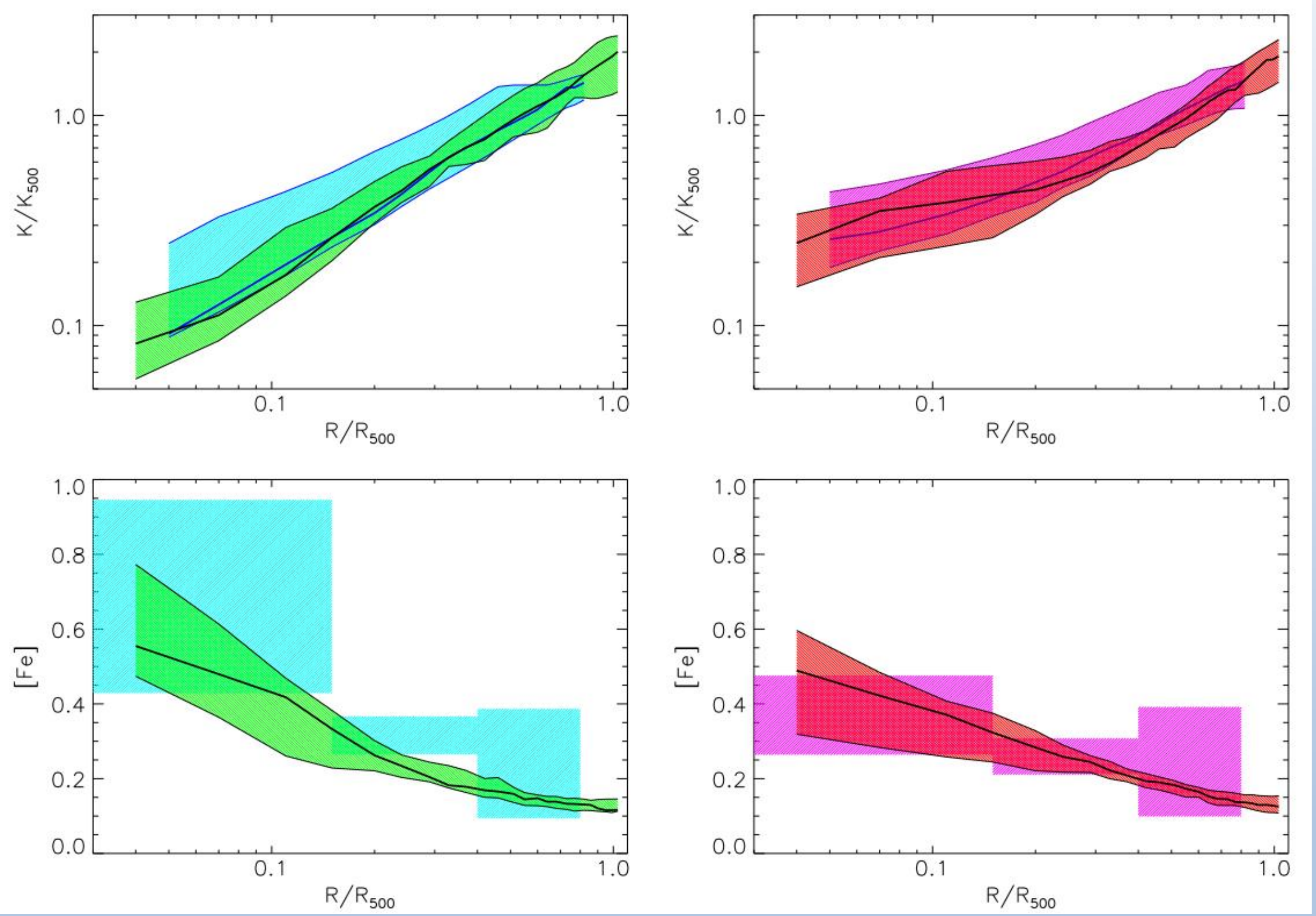
a cluster is defined CC if $\sigma < 0.55$ AND $K_o < 60$ KeV cm^{-2}

CC and NCC in simulations vs observations

Cool Core 38% | Non Cool Core 62%

Data Pratt+ 2010

Data Ettori+ 2015



The simulated sample cluster contains CC and NCC clusters, with fractions close to observations. The mean entropy and metallicity profiles of the two classes are also in keeping with the data.

Transformations NCC ↔ CC
A variety of situations. Examples

Slow development of a CC in a NCC cluster

Destruction of a CC due to the merger of a sub-clump

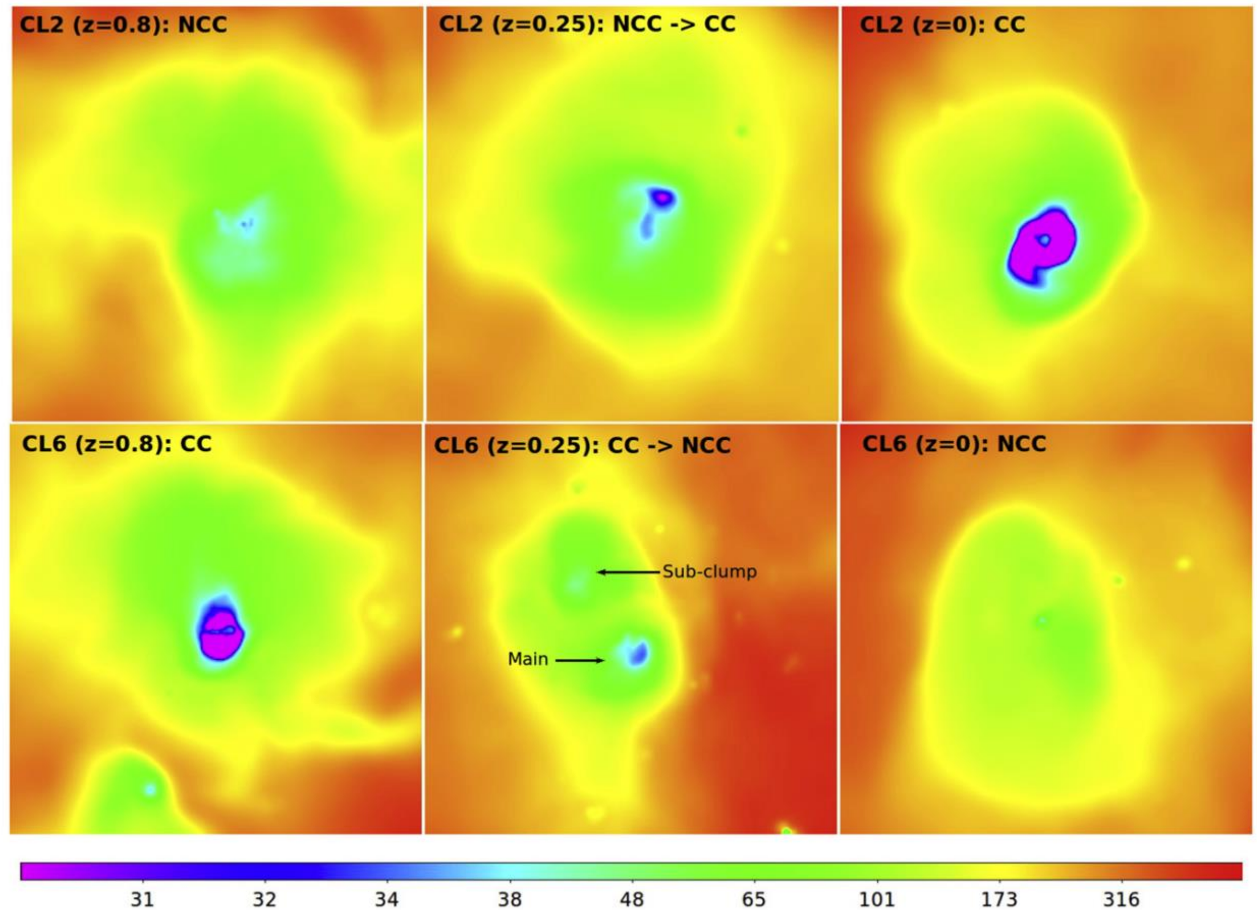
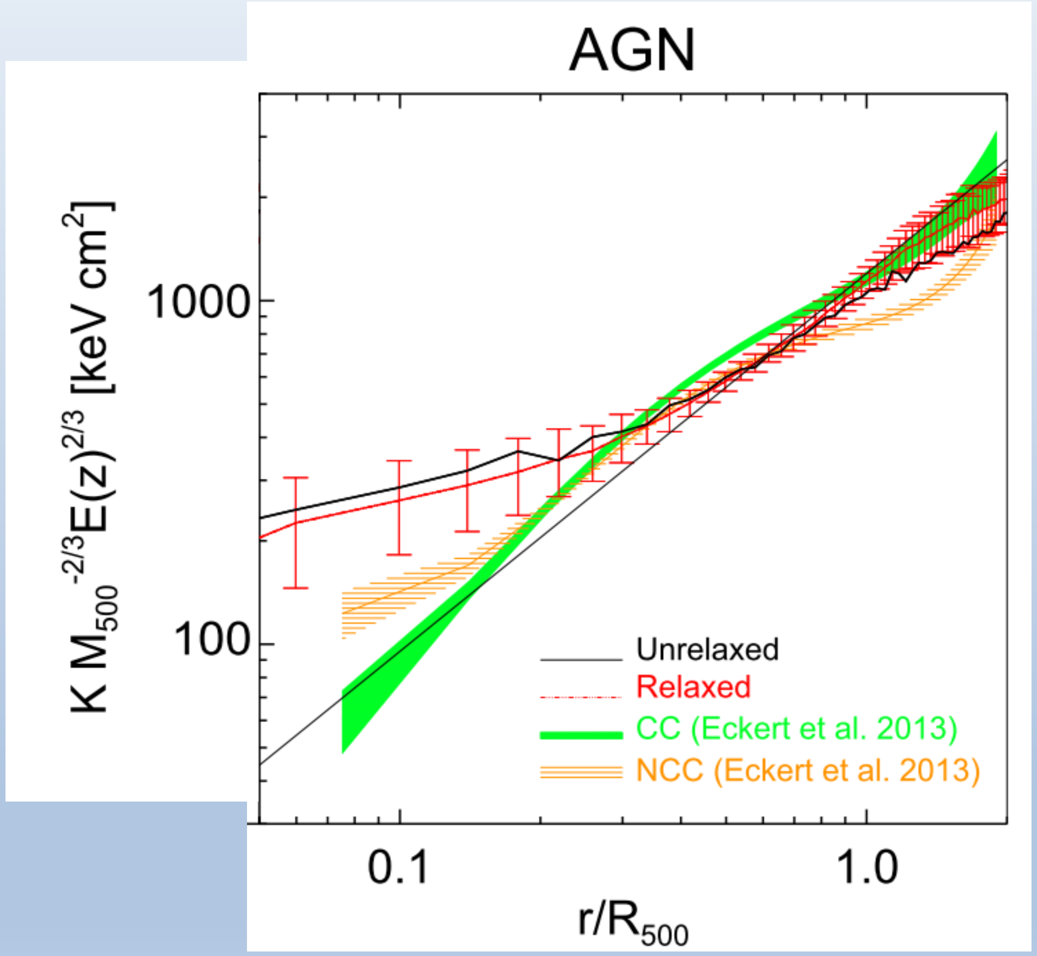


Figure 2. Maps of pseudo entropy of two simulated clusters with masses $M_{500} = 2.4 \times 10^{14}\, h^{-1}\, M_{\odot}$ (upper panels) and $M_{500} = 7.3 \times 10^{14}\, h^{-1}\, M_{\odot}$ (lower panels) $z = 0$. The size of the images is 1 Mpc and the line-of-sight integration is for 10 Mpc.

At variance wrt previous claims that CC would be very resilient against low-z mergers (e.g. Poole+ 2008; Burns+ 2008). Based on simulations not including AGN fb, likely overcooling originated stronger cores.

Dianoga 2013 no-dicothomy situation: all NCC (Planelles+20014)

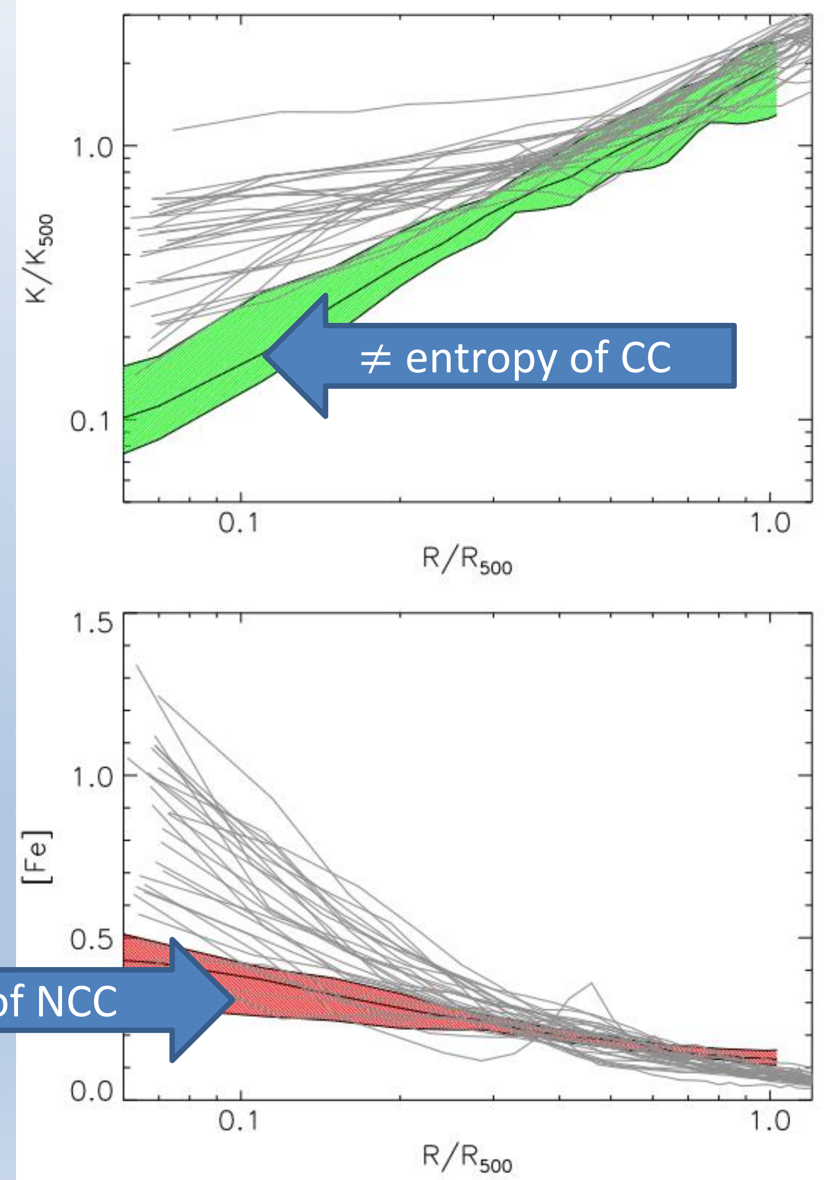


The key role of AGN feedback (introduced to avoid overcooling)

With AGN switched off (grey lines) our clusters behaves similarly to NCC in the entropy profile and similarly to CC in the metallicity profile

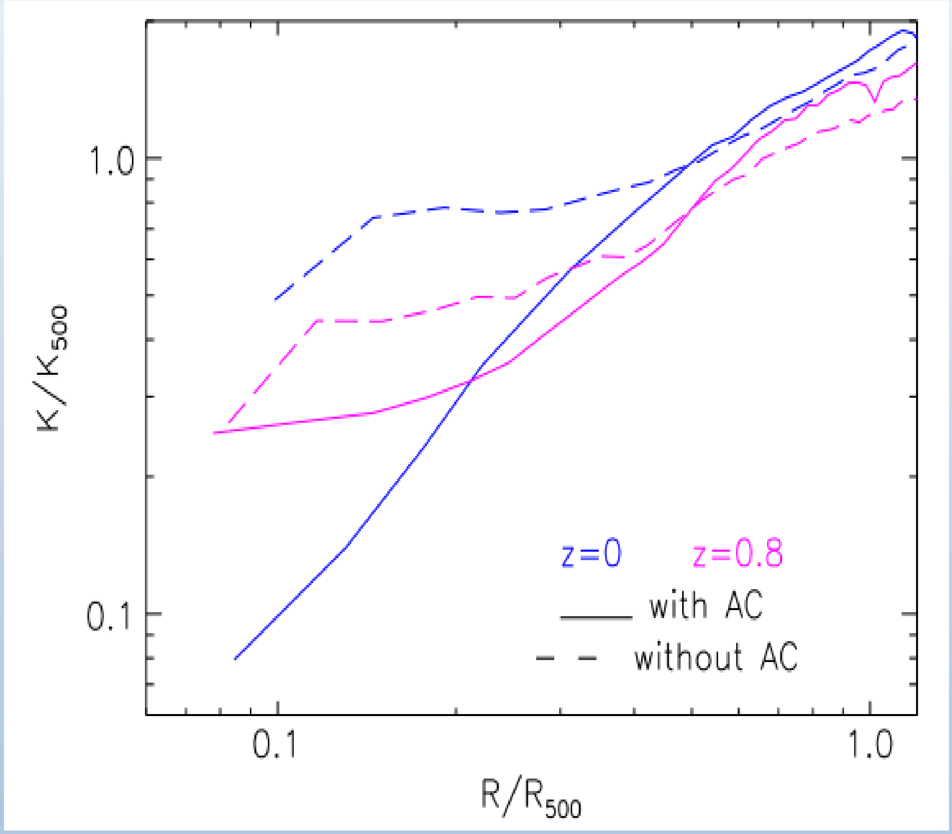
AGN fb in sims has a twofold effect:

- Prevents low entropy gas to drop out from ICM, so that the mean entropy stays lower;
- Raises metals from the central region, lowering central Z;



The key role of artificial conduction (introduced to overcame numerical limitations of SPH)

With AGN artificial conduction switched off (dashed) clusters do not develop a CC.



Summary of Rasia+15

- Our simulations produce a population of CC and NCC clusters having a reasonable thermal and chemical structure in the ICM;
- Also the relative fraction of CC and NCC cluster is similar to observations;
- A cluster may develop or lose its CC during all its assembly history;
- The result depends on the combined effect of AGN feedback and a better hydro treatment;
- However we are aware that this is just an *effective* descriptions of several physical processes related to the cool-coreness (e.g. inflation of bubbles by AGN jets, turbulence, *physical* thermal conduction, magnetic fields) difficult or impossible to capture in similar cosmological simulations;
- A poetic way to say that we are likely getting the right answer for the wrong reasons;