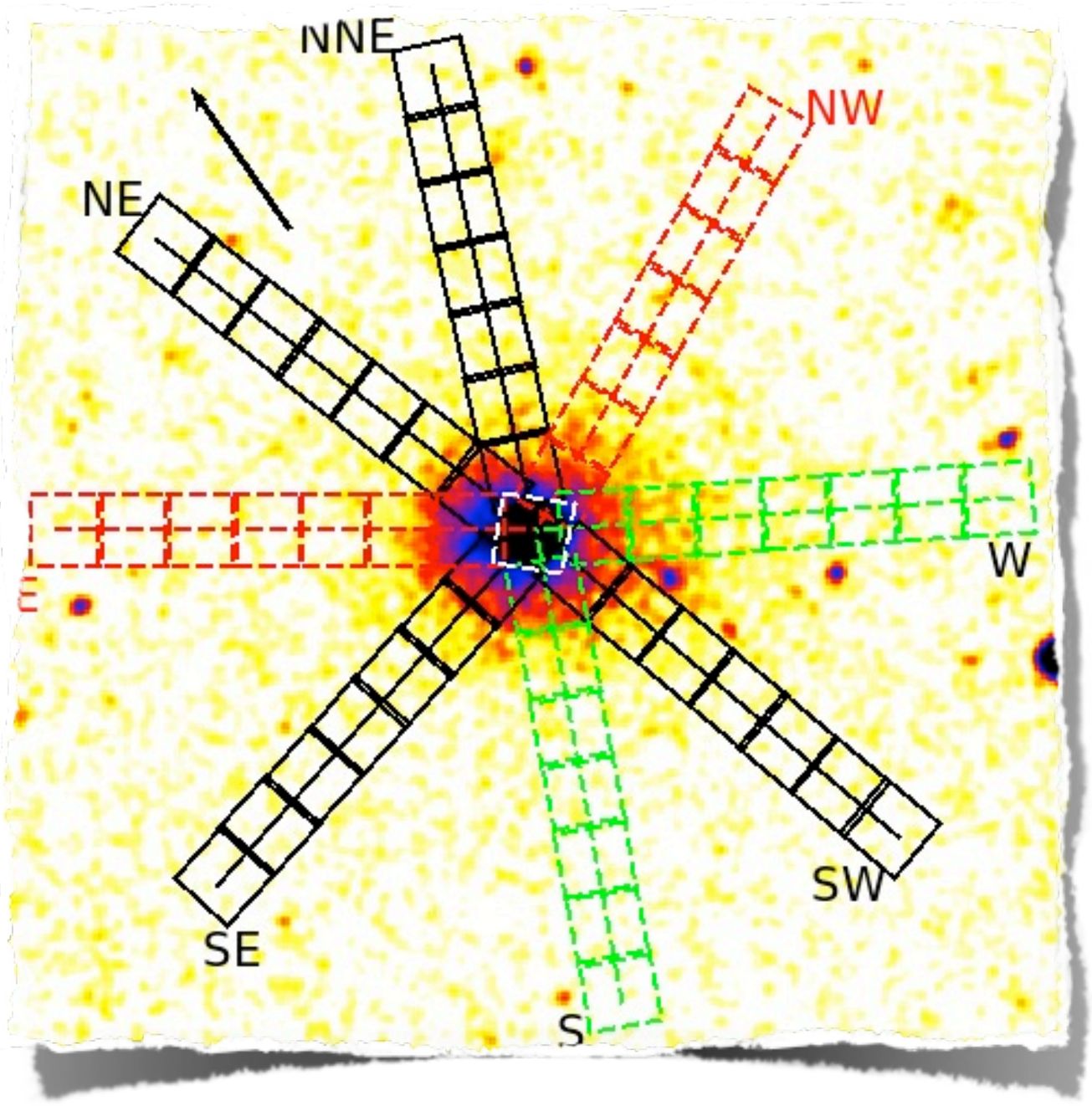
Baryons in the outskirts of the X-ray brightest galaxy clusters



Aurora Simionescu (KIPAC)

Steve Allen, Adam Mantz, Norbert Werner, Yoh Takei, Ondrej Urban, Glenn Morris, Andy Fabian, Jeremy Sanders, Paul Nulsen, Matt George, Hans Böhringer, Greg Taylor, Takaya Ohashi

Suzaku enables these studies by providing a lower and more stable background.

Until recently, detailed thermodynamic studies of clusters out to $r \sim r_{vir}$ have proved extremely challenging

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- inherently low surface brightness of cluster outskirts.
- relatively high particle backgrounds of Chandra/XMM-Newton.

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2/3 of cluster volumes practically unexplored!

Suzaku enables these studies by providing a lower and more stable background.

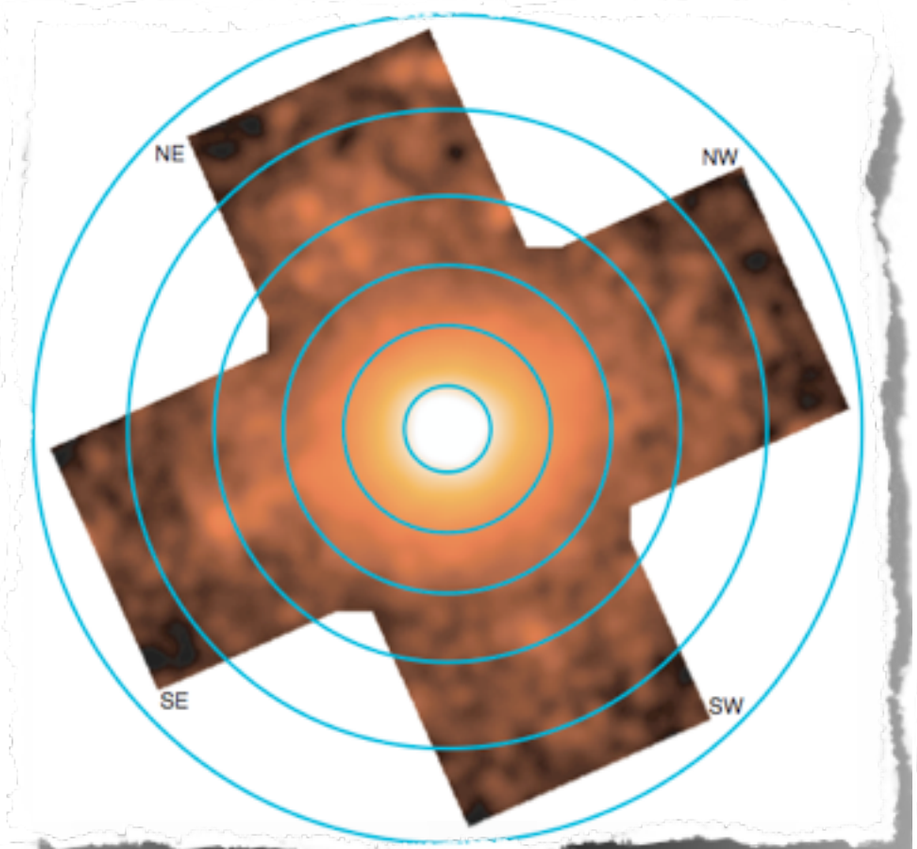
Why study clusters to large radii?

Accurate measurements of the properties of galaxy clusters out to large radii provide critical insight into

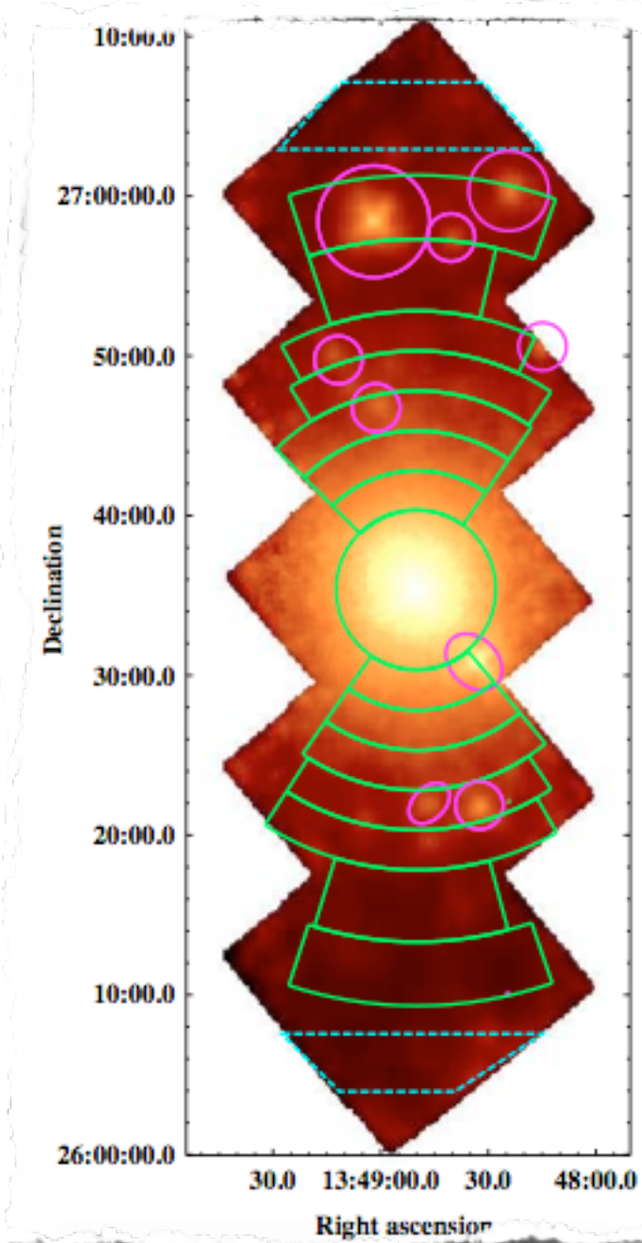
- physics of the ICM and pre-virialized IGM
  (the formation of largest scale structure `as it happens')

- use of clusters as cosmological probes
  (calibration of X-ray mass proxies; benchmark for hydro. simulations)

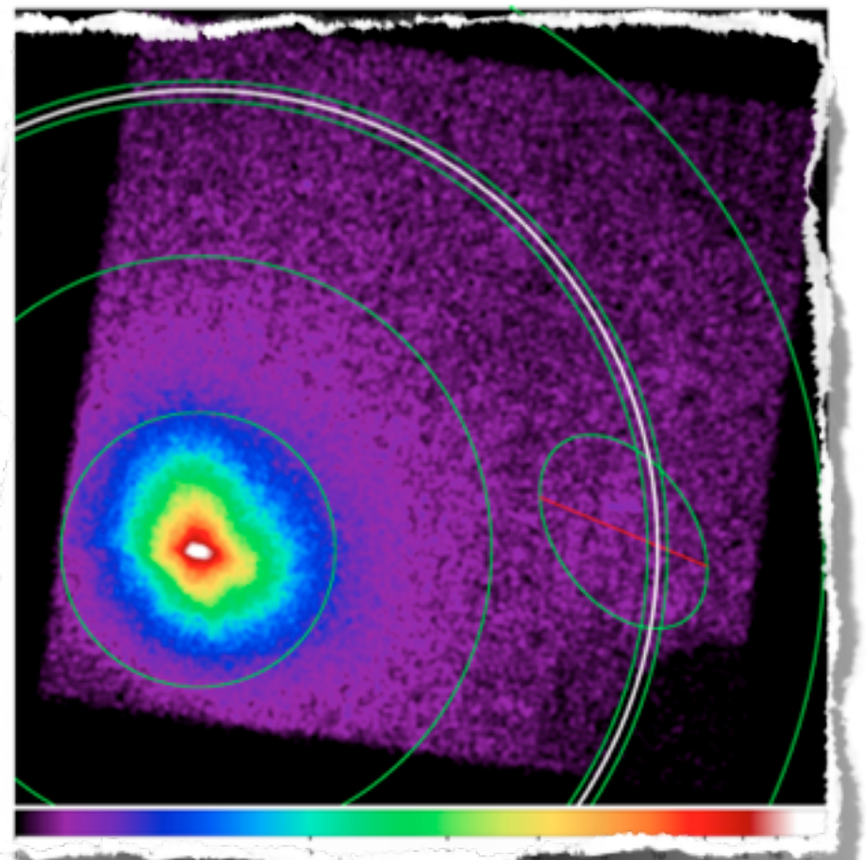
- galaxy formation and evolution
  (history of star formation; ICM interactions; AGN evolution etc)



PKS 0745-191,
George et al. 2009
z=0.1



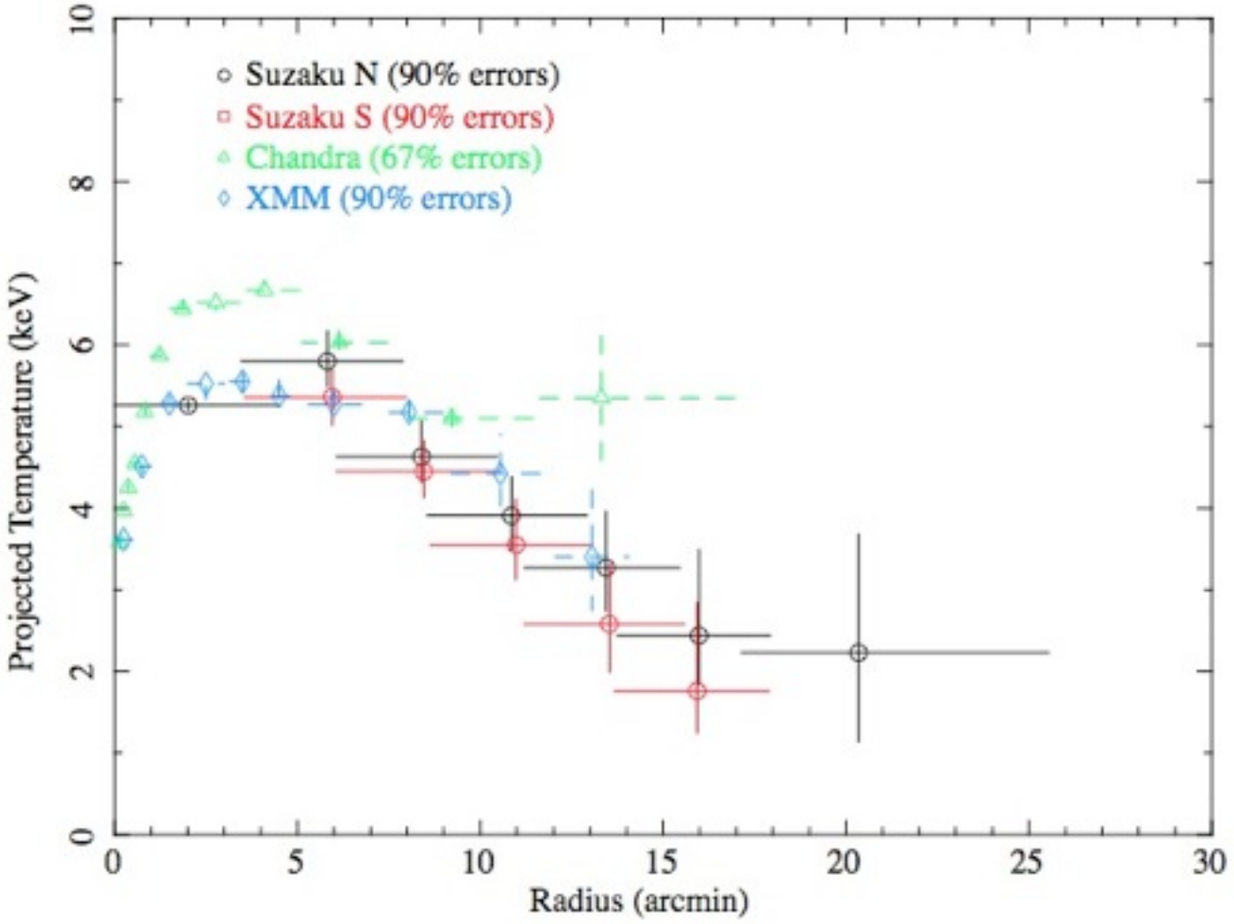
A1795,
Bautz et al. 2009,
z=0.06



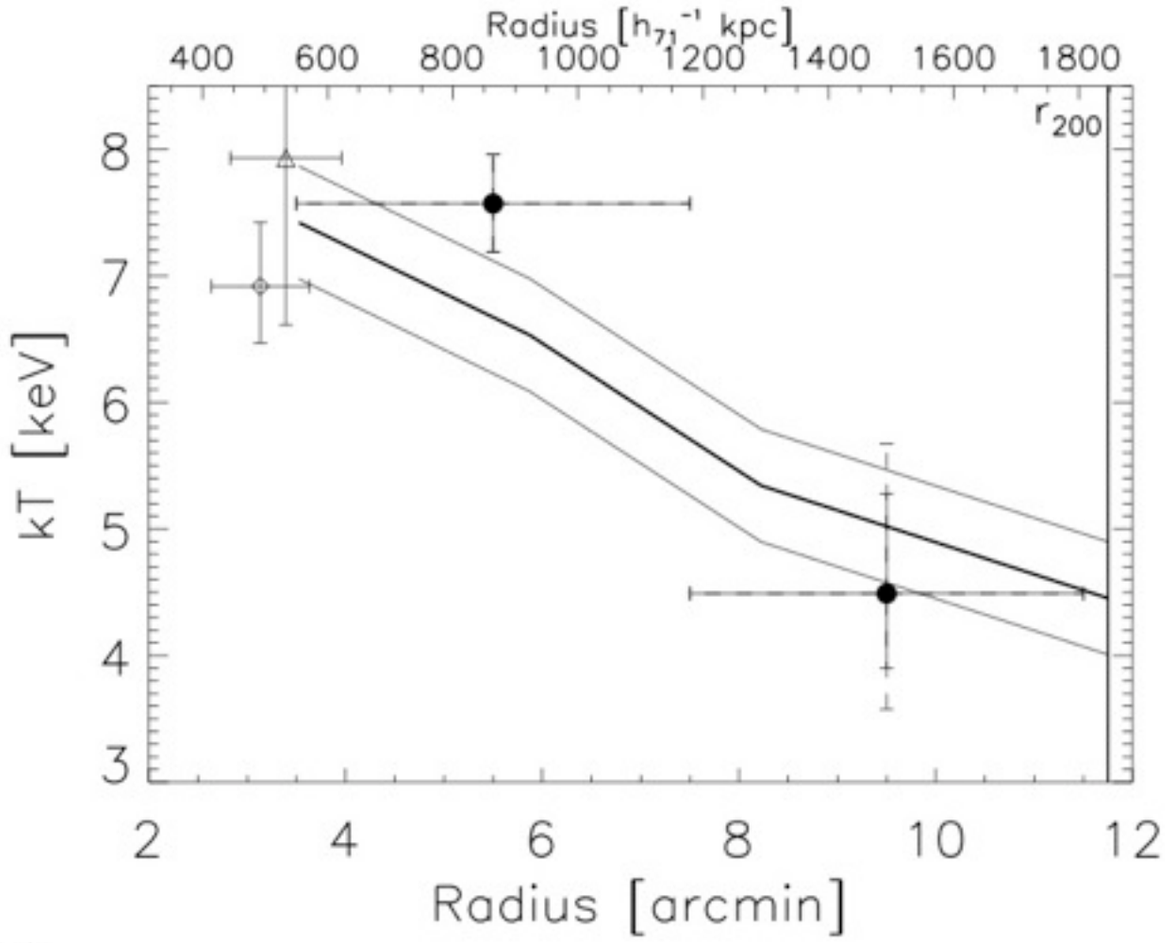
A2204,
Reiprich et al. 2009
z=0.15

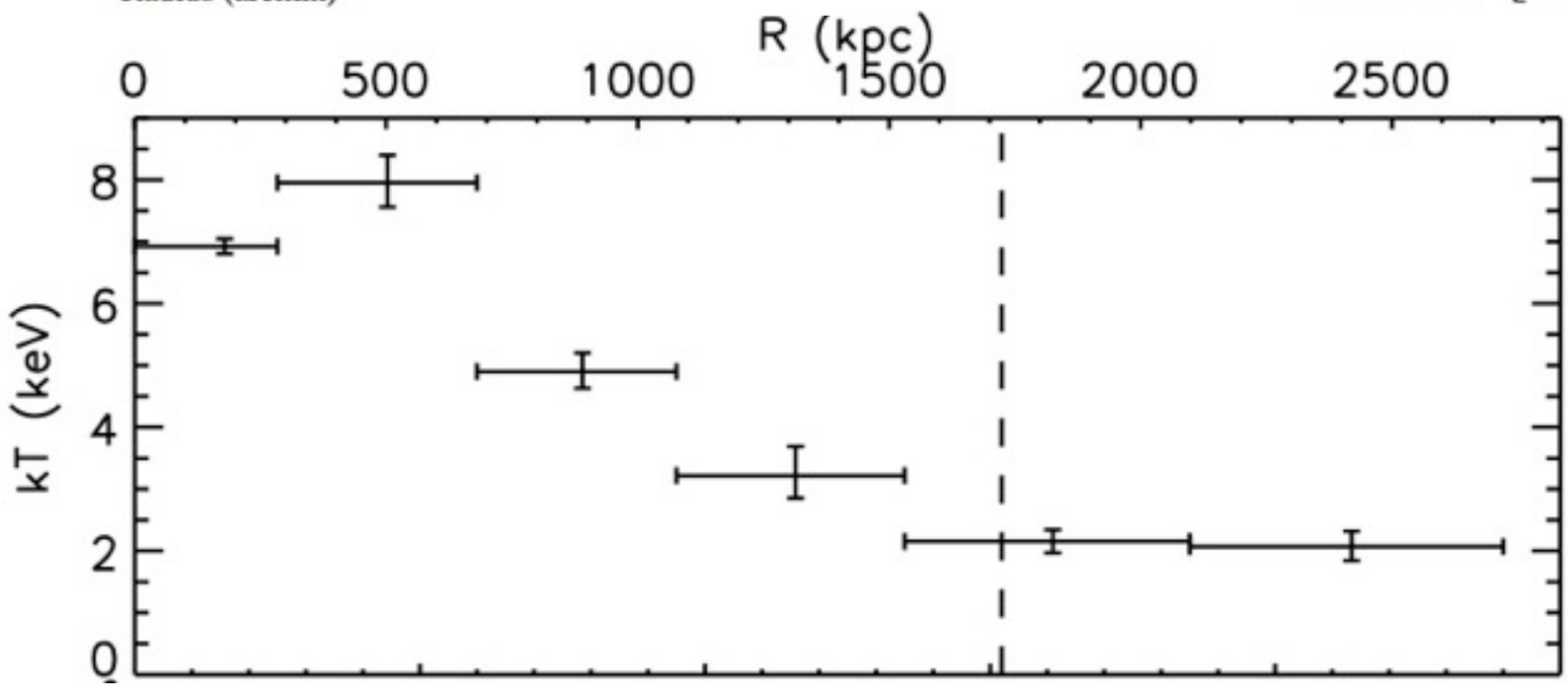
also: Hoshino et al. 2010, Kawaharada et al. 2010, Sato et al. 2010

A 1795, Bautz et al. 2009



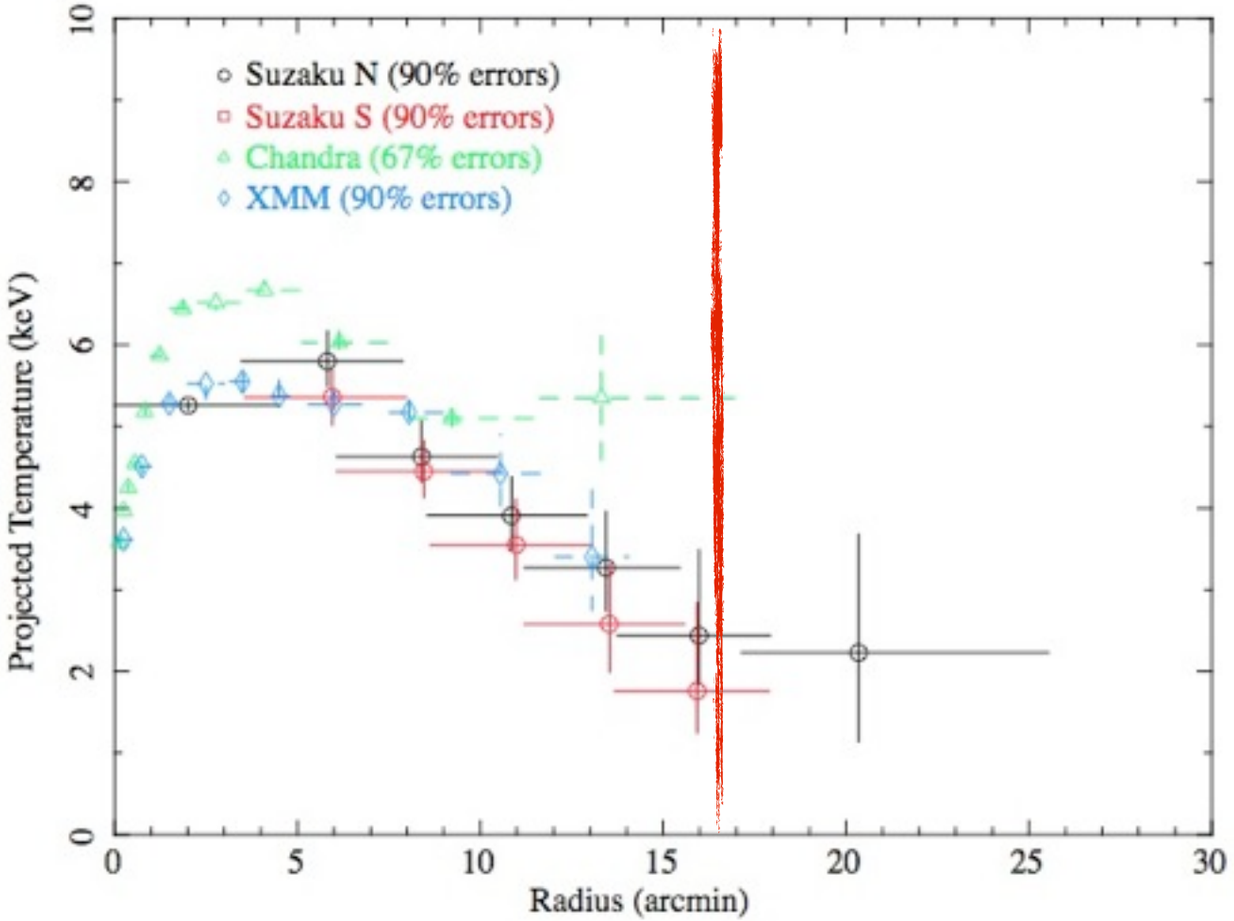
A 2218, Reiprich et al. 2009





PKS 0745-191, George et al. 2009

A 1795, Bautz et al. 2009



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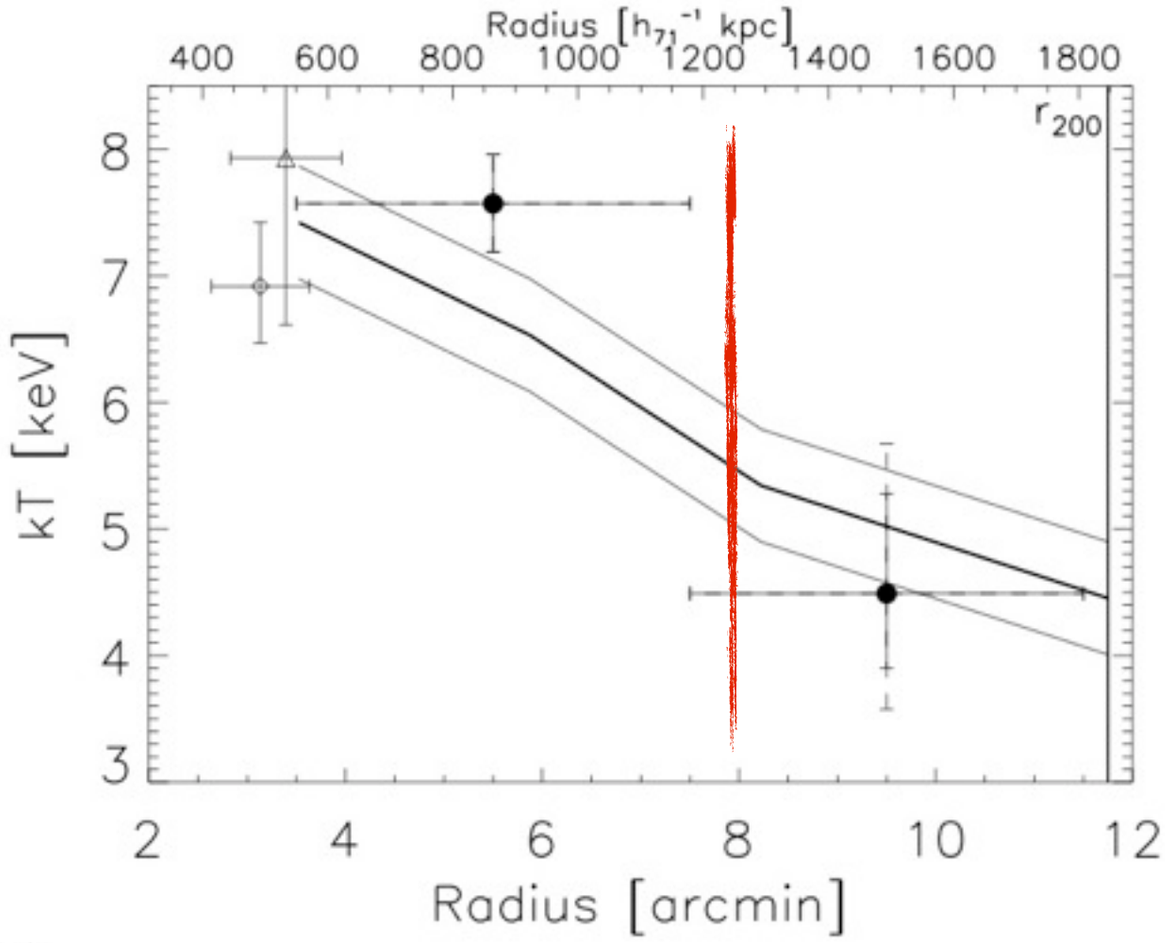
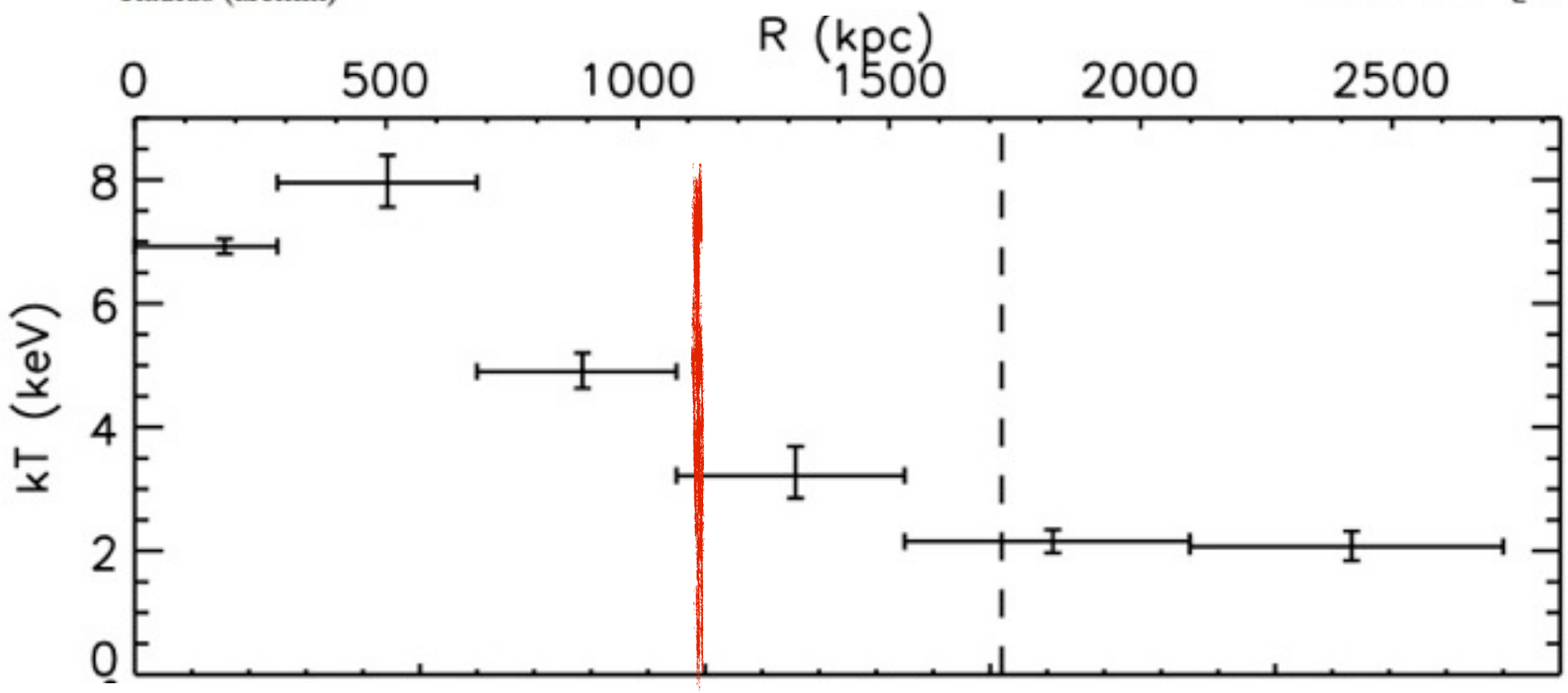
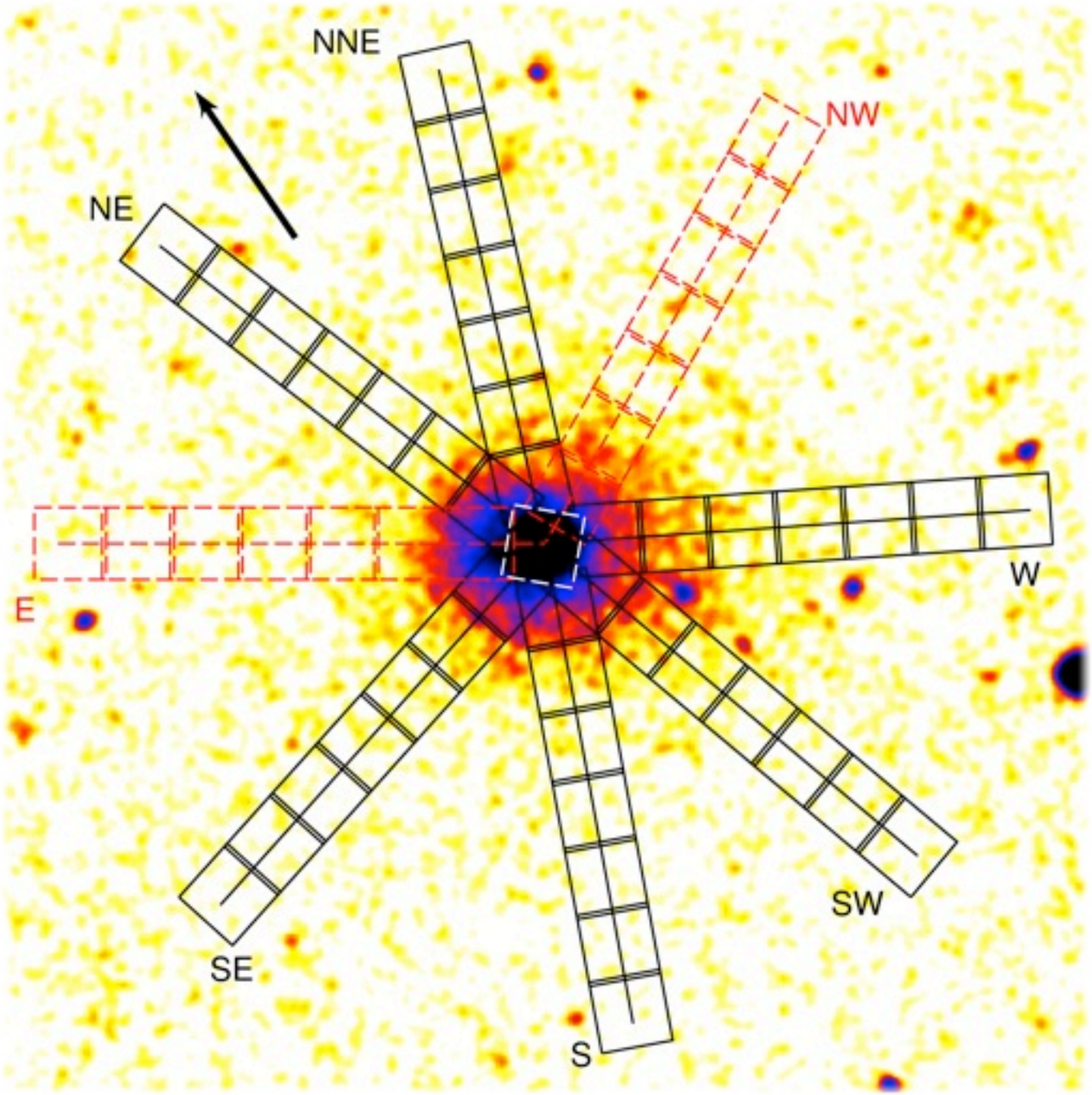




PKS 0745-191, George et al. 2009

To maximize the signal-to-noise and minimize the systematics related to the modest PSF of Suzaku, we must observe the outskirts of the **nearest, brightest clusters,** making the Perseus Cluster an ideal target.

Results from the Perseus Cluster observations:

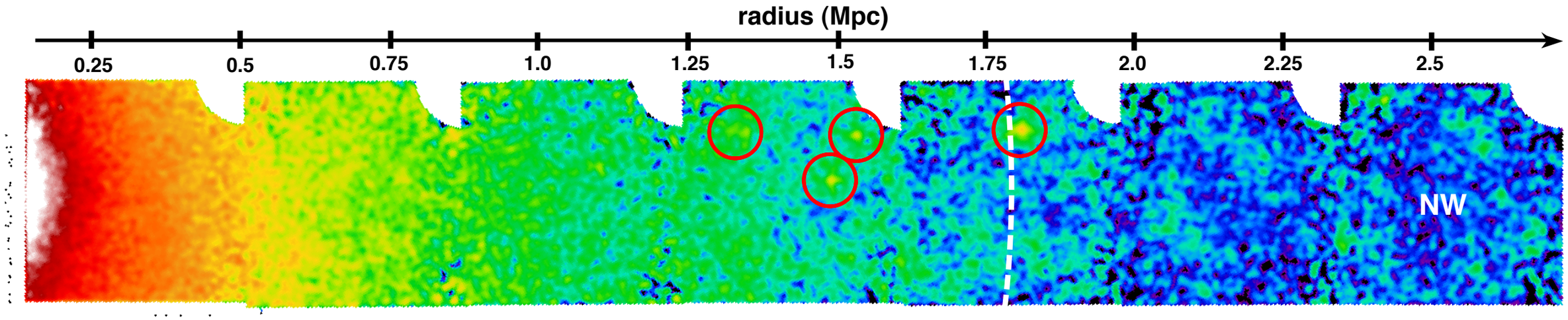


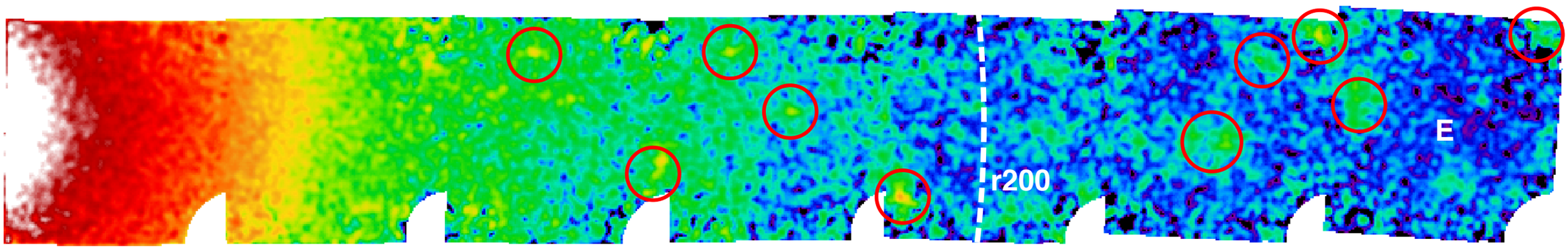
The first two arms:
analysis of E & NW mosaics (total 260 ks) reported by

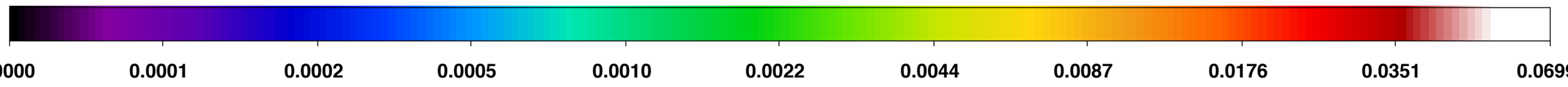
Simionescu et al. 2011, accepted to Science

arXiv 1102.2429

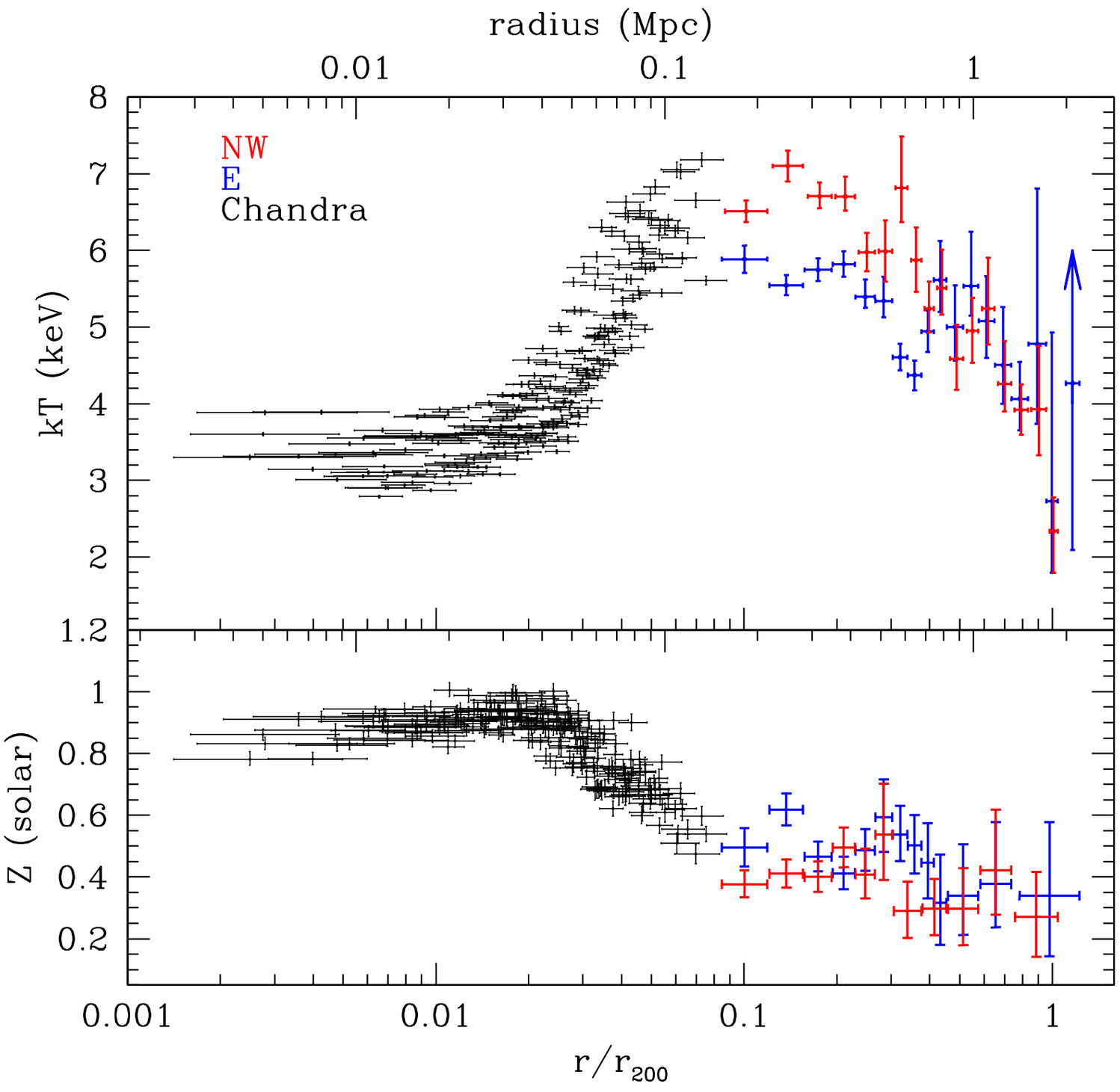
Surface brightness images of the NW and E arms:







Projected temperature and metallicity profiles:



excellent agreement with Chandra data

detailed profiles spanning 3 decades in radius

profiles between r_{500} and r_{200} resolved for the first time

metallicity profile measured for the first time until the virial radius

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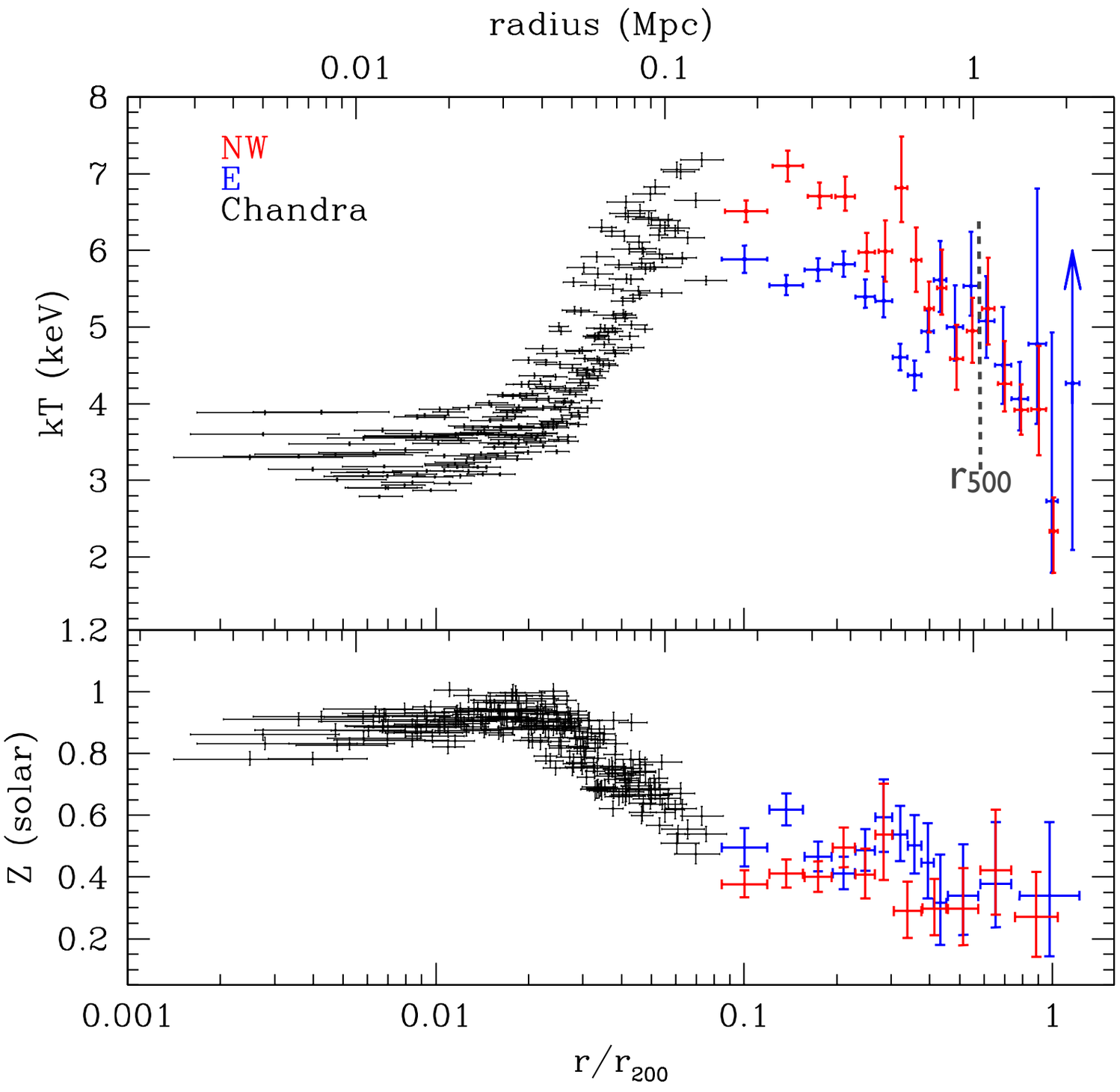

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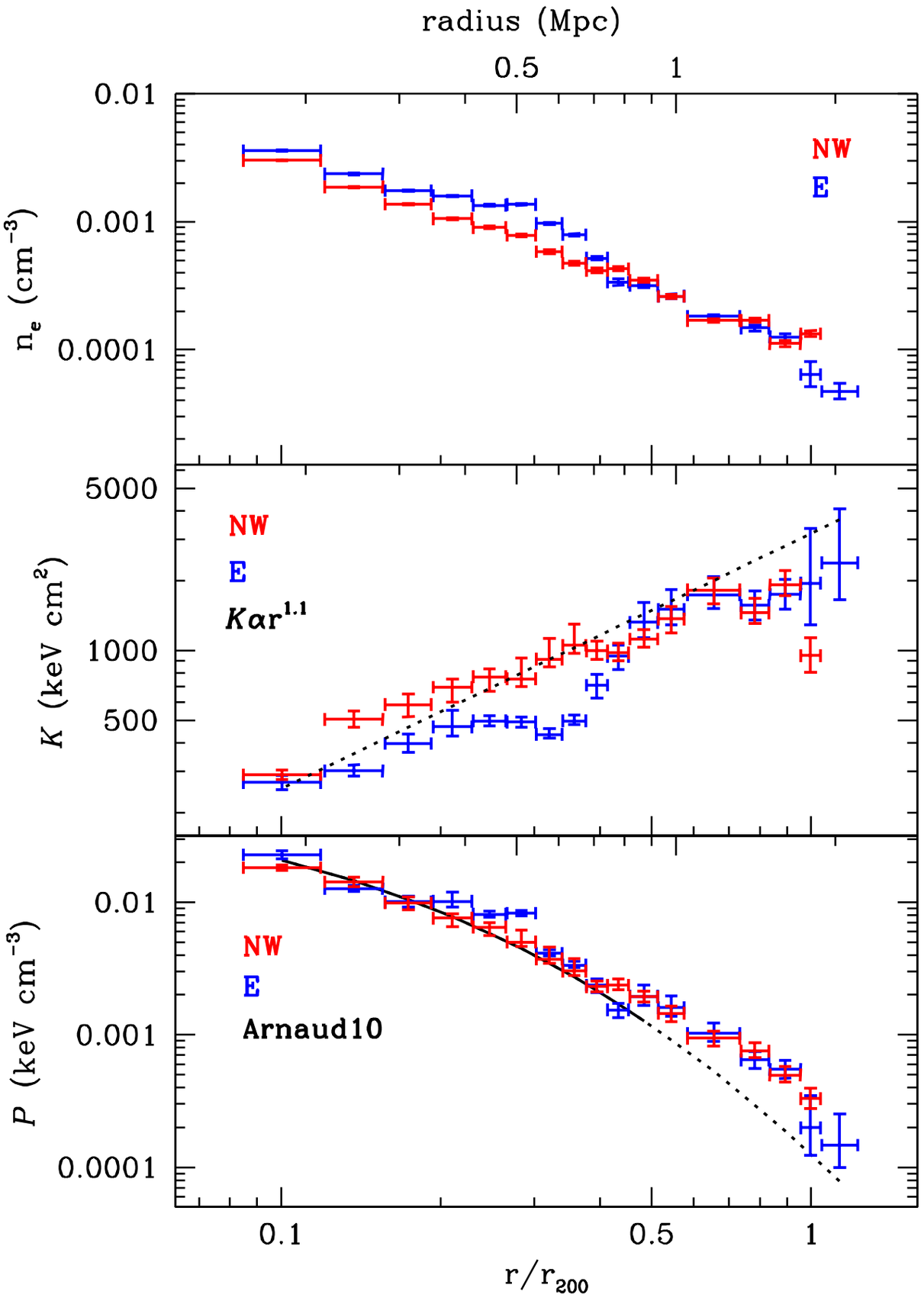
Deprojected thermodynamic profiles:



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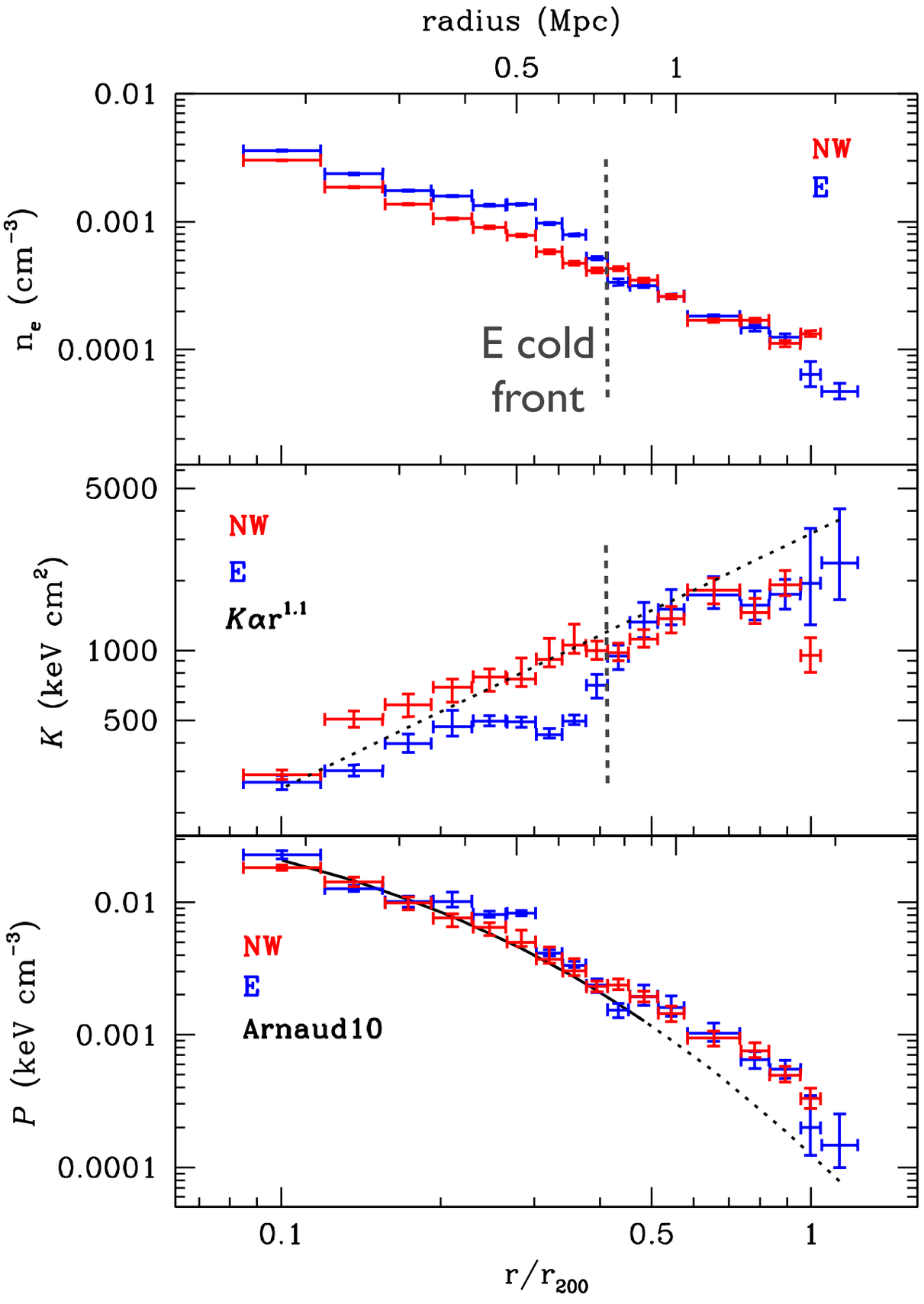

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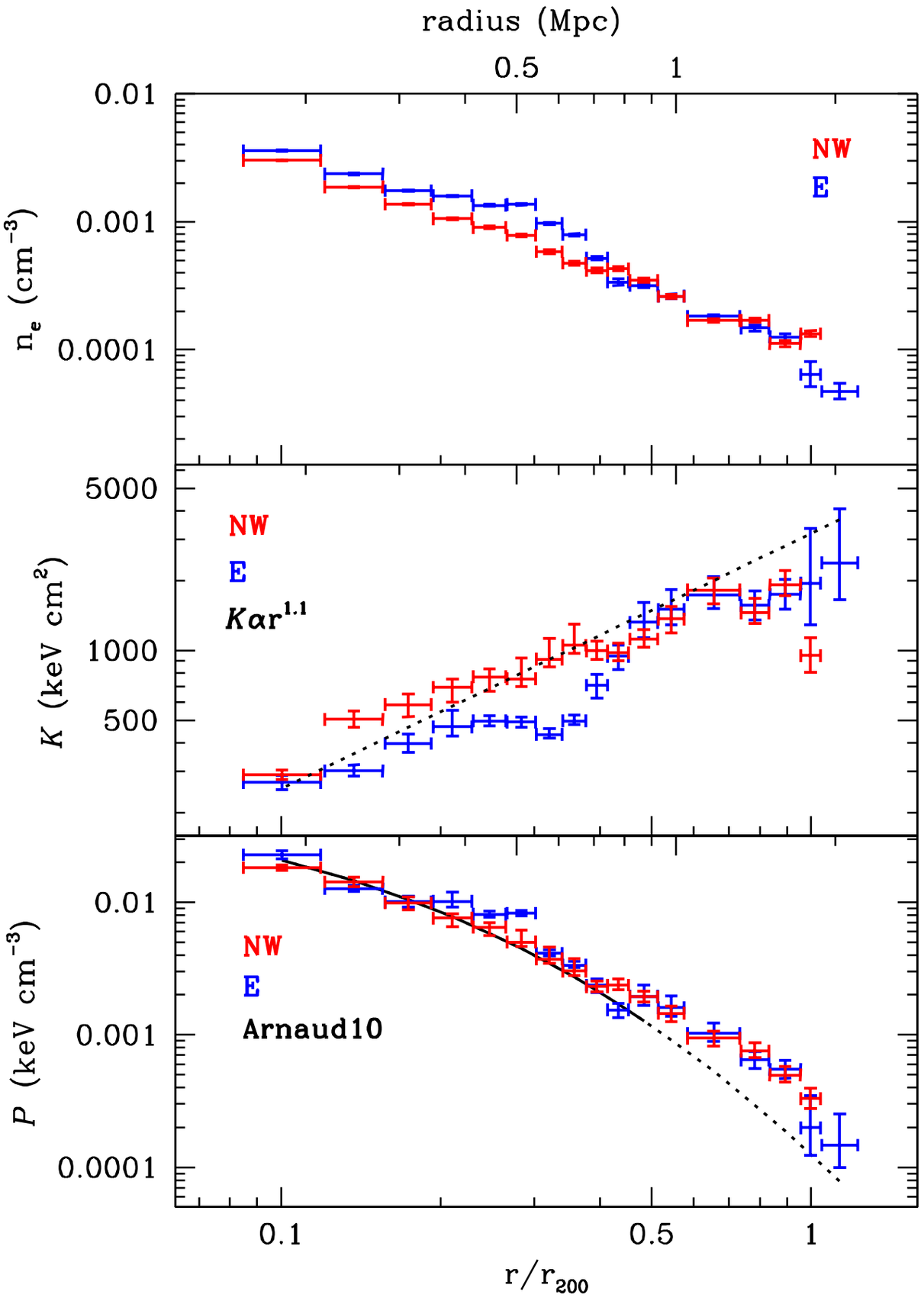

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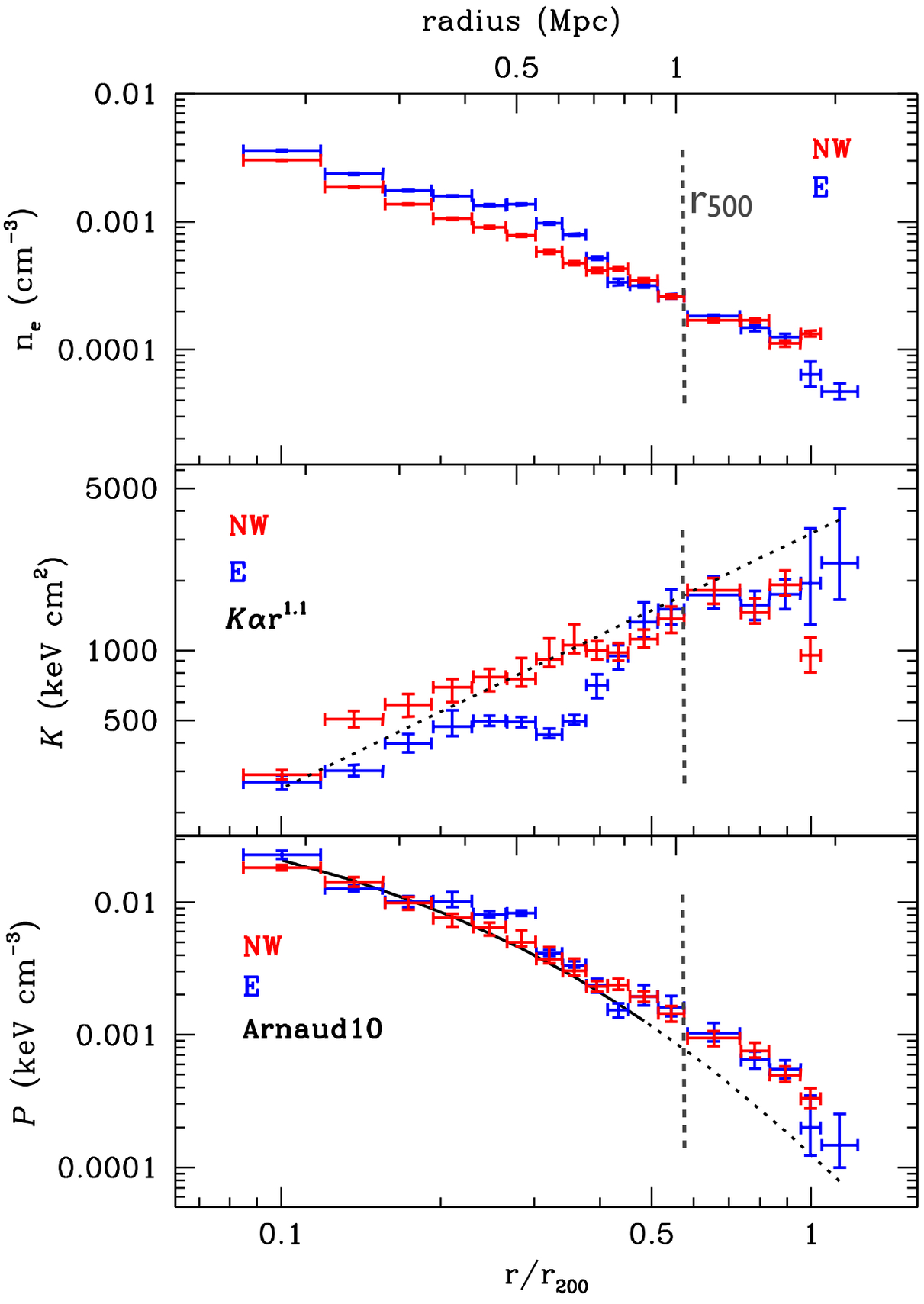

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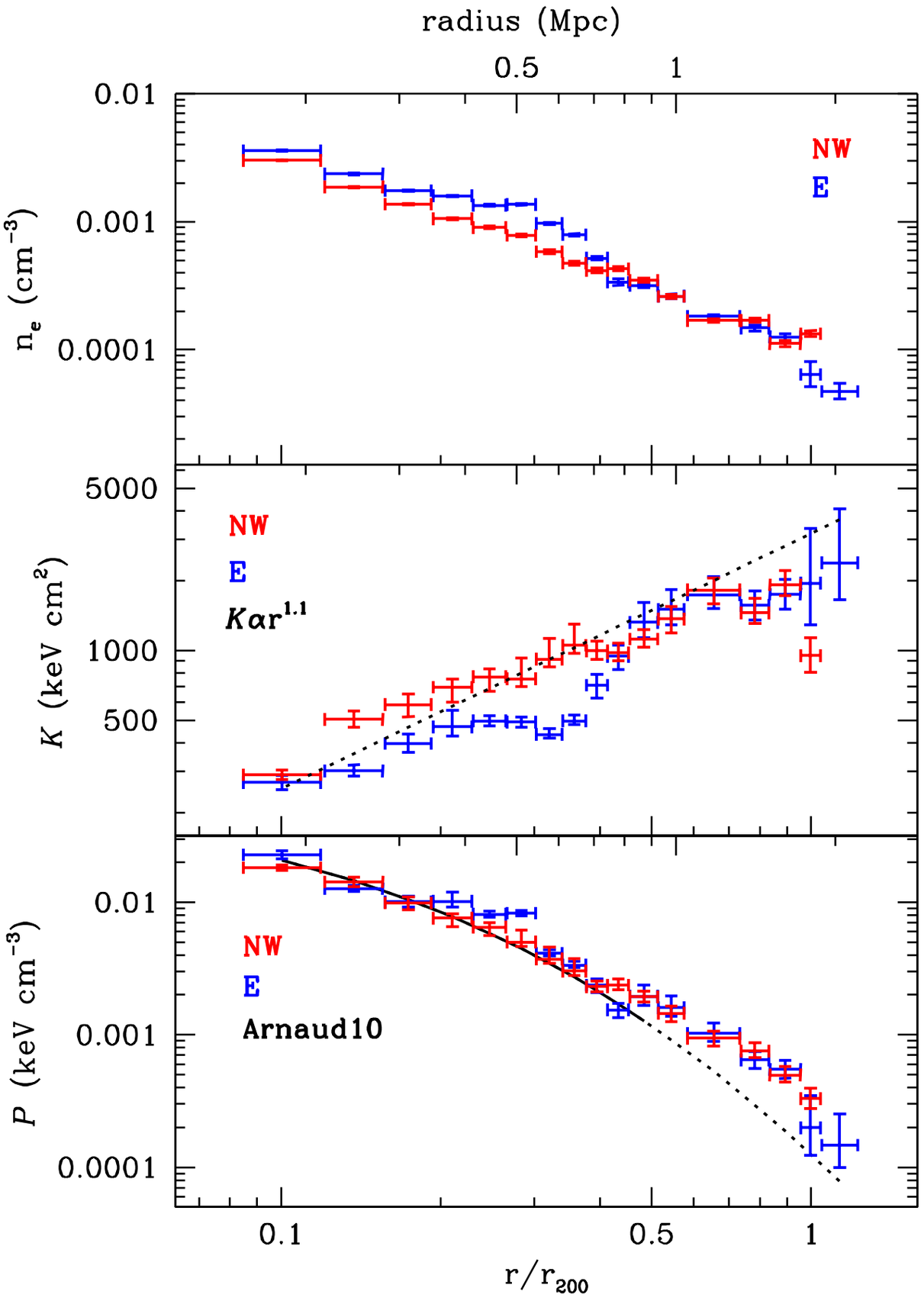

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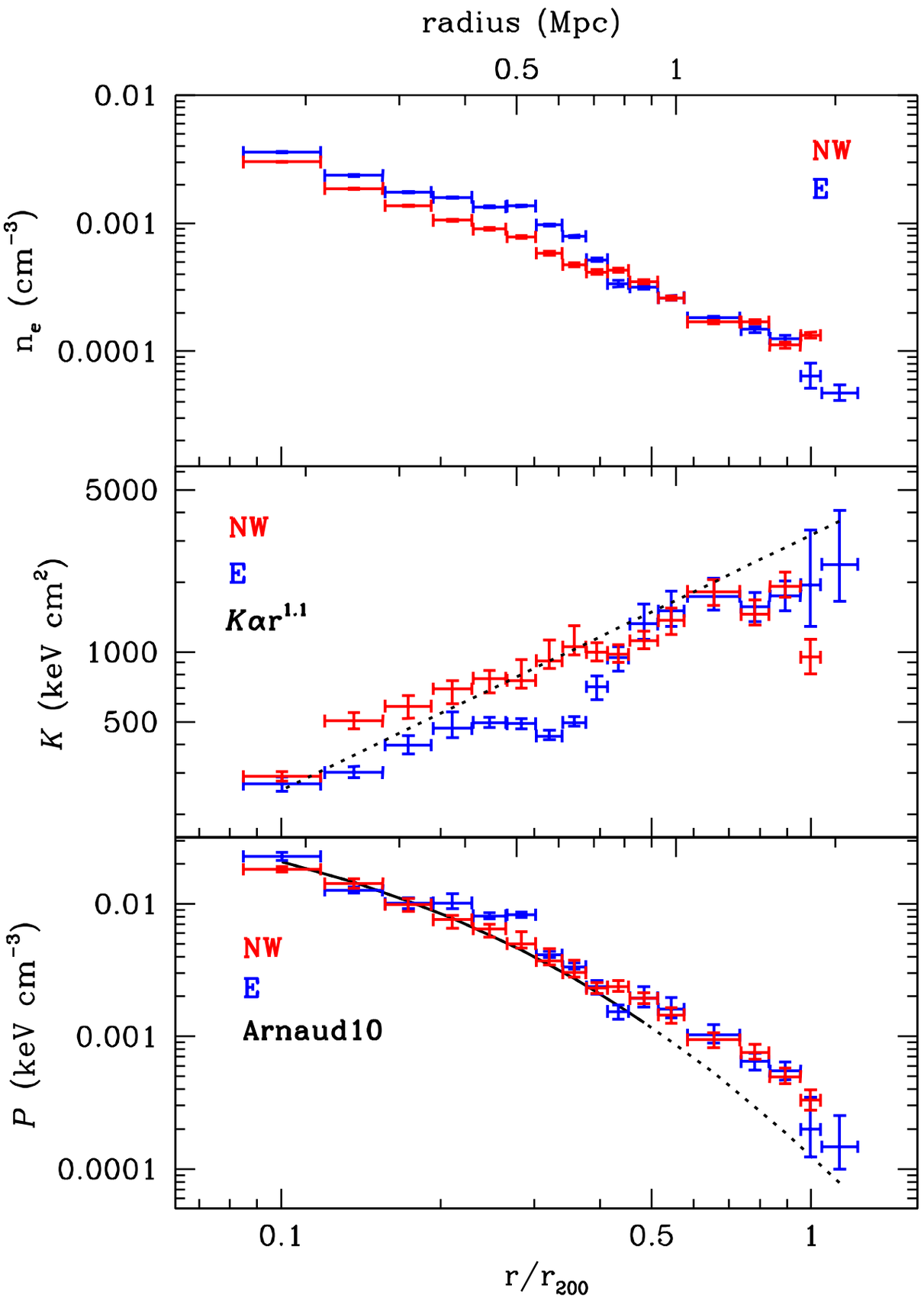
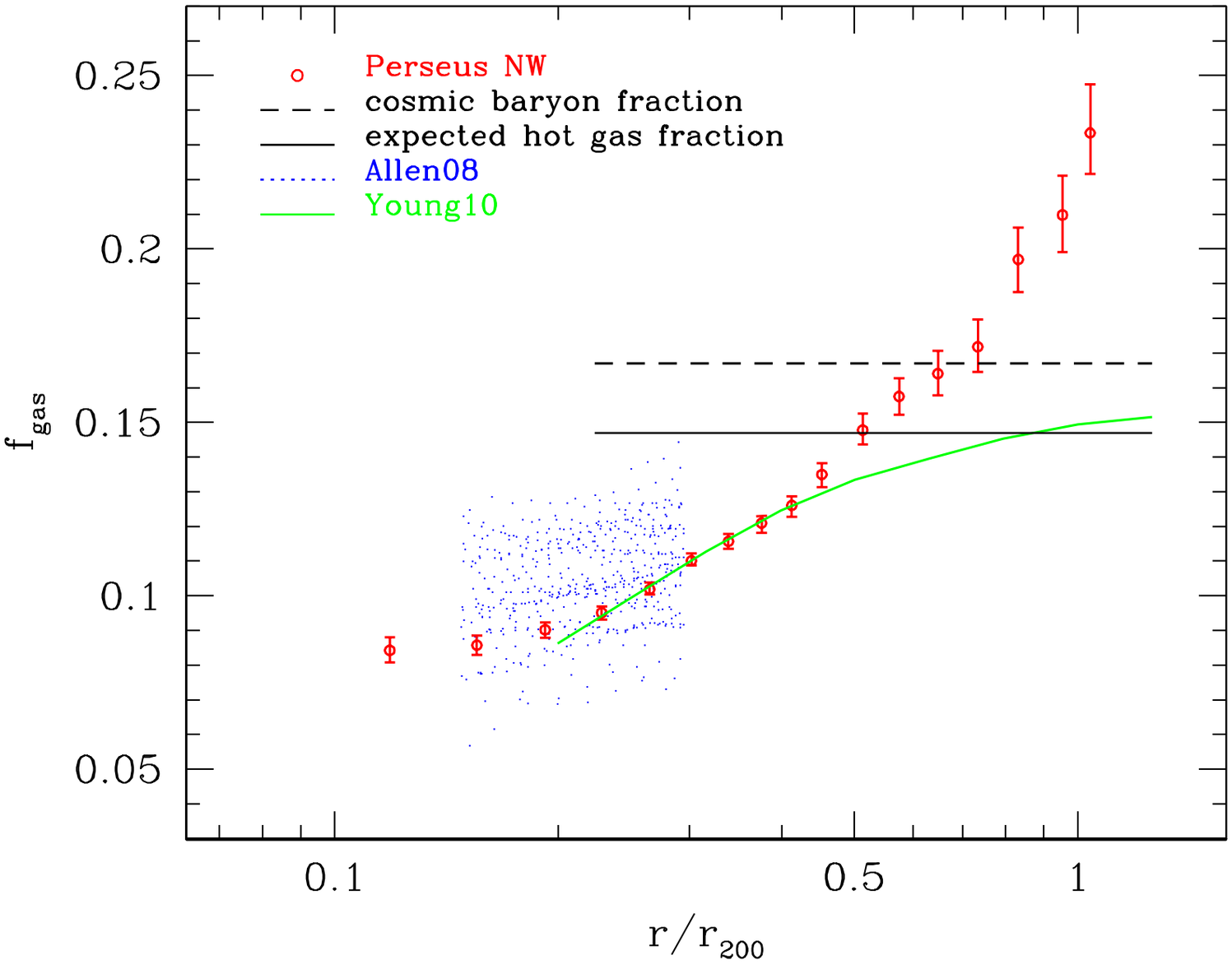


shallow decline of electron density at large radii

entropy appears to flatten at large radii compared to the expected power-law

pressure at large radii greater than predicted by numerical simulations (fitted to XMM data inside r_{500} by Arnaud et al. 2010)

Gas mass fraction profile towards the NW:



NW arm highly relaxed ➔ use hydrostatic equilibrium to infer gas and total mass profiles (E arm excluded due to cold front at 30')

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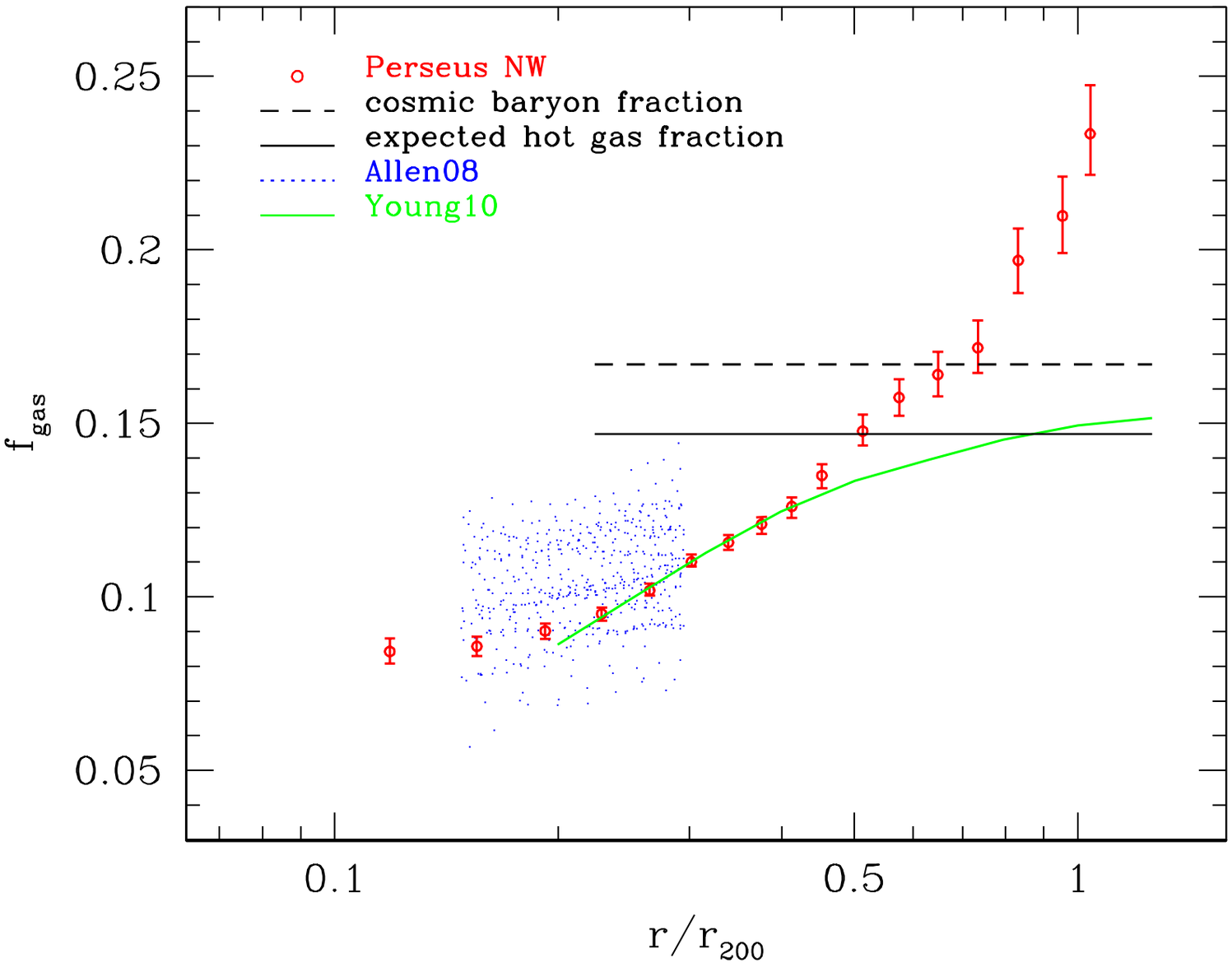


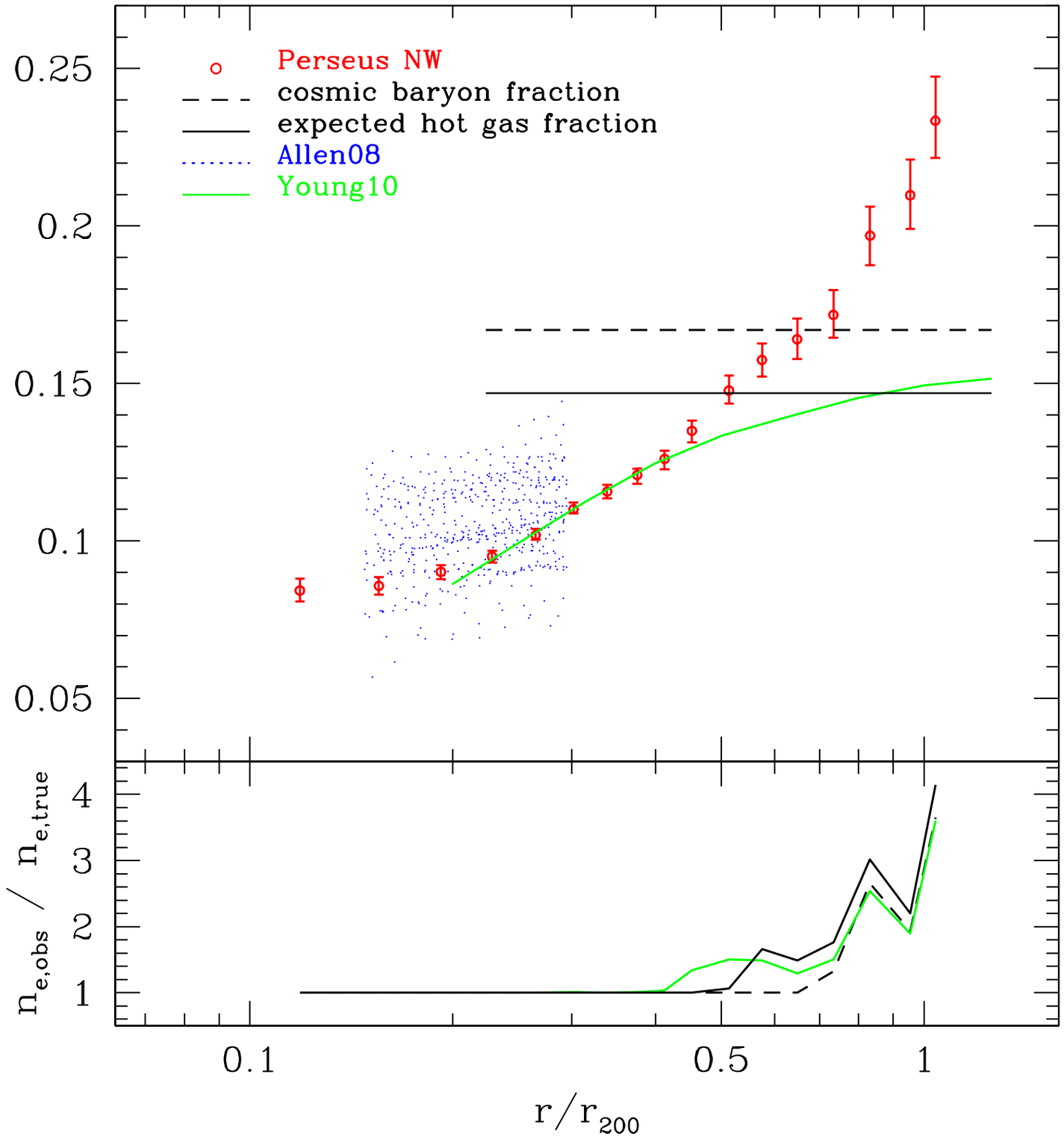
NW arm highly relaxed ➔ use hydrostatic equilibrium to infer gas and total mass profiles (E arm excluded due to cold front at 30')

good agreement with previous observations and numerical simulations at $r<0.4r_{200}$

f_{gas} value matches cosmic mean at $r\sim r_{500}$

no missing baryons in clusters - good news for cluster cosmology!

Gas mass fraction profile towards the NW:



f_{gas} exceeds cosmic mean at large radii ($r>0.6$-$0.7r_{200}$)

most likely cause: the gas is clumpy, thus n_e predicted from the X-ray surface brightness is biased high

bottom panel shows the first measurements of the gas clumping factor

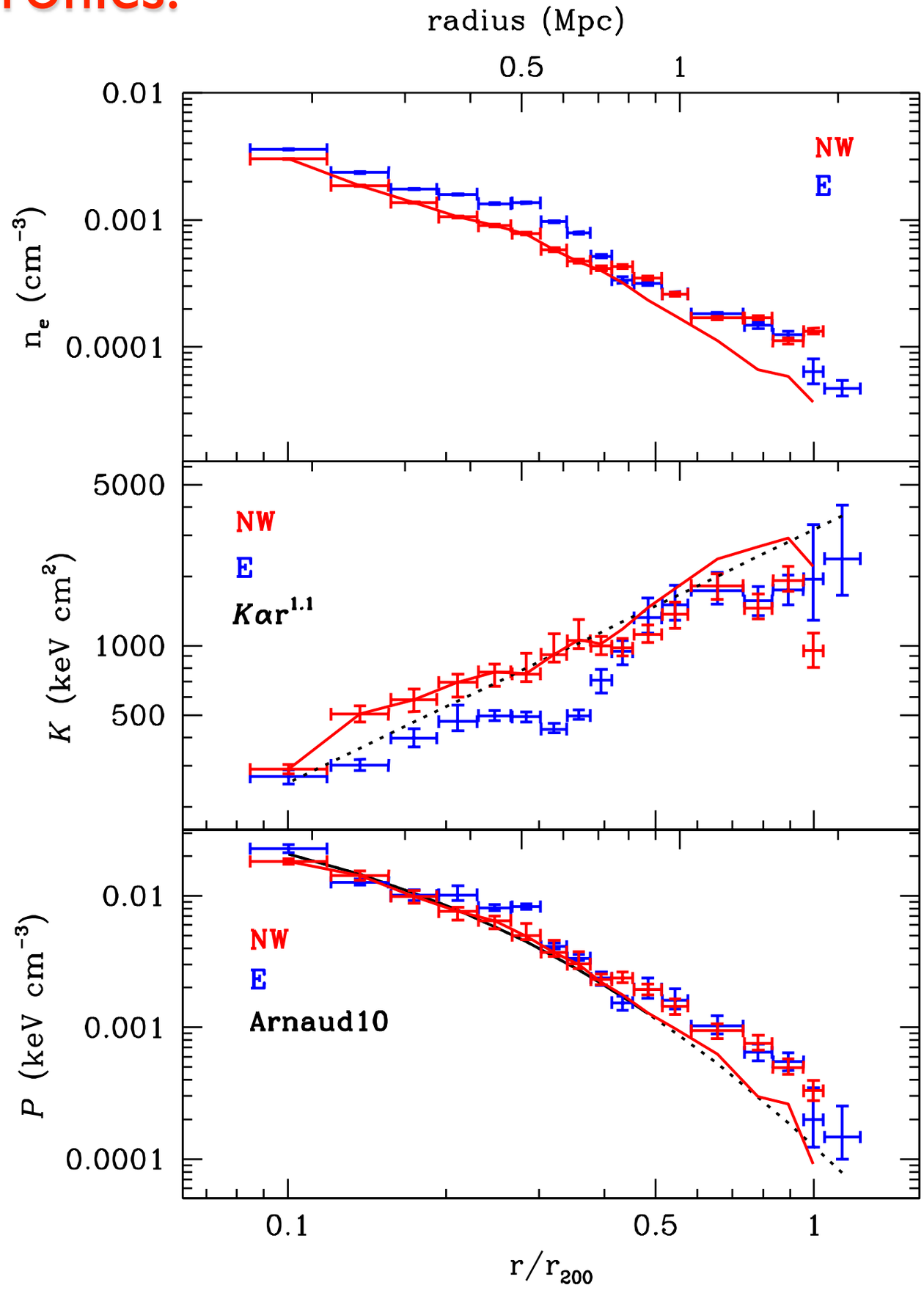
important implications for future studies at very large radii in clusters, e.g. X-ray+SZ

Corrected thermodynamic profiles:

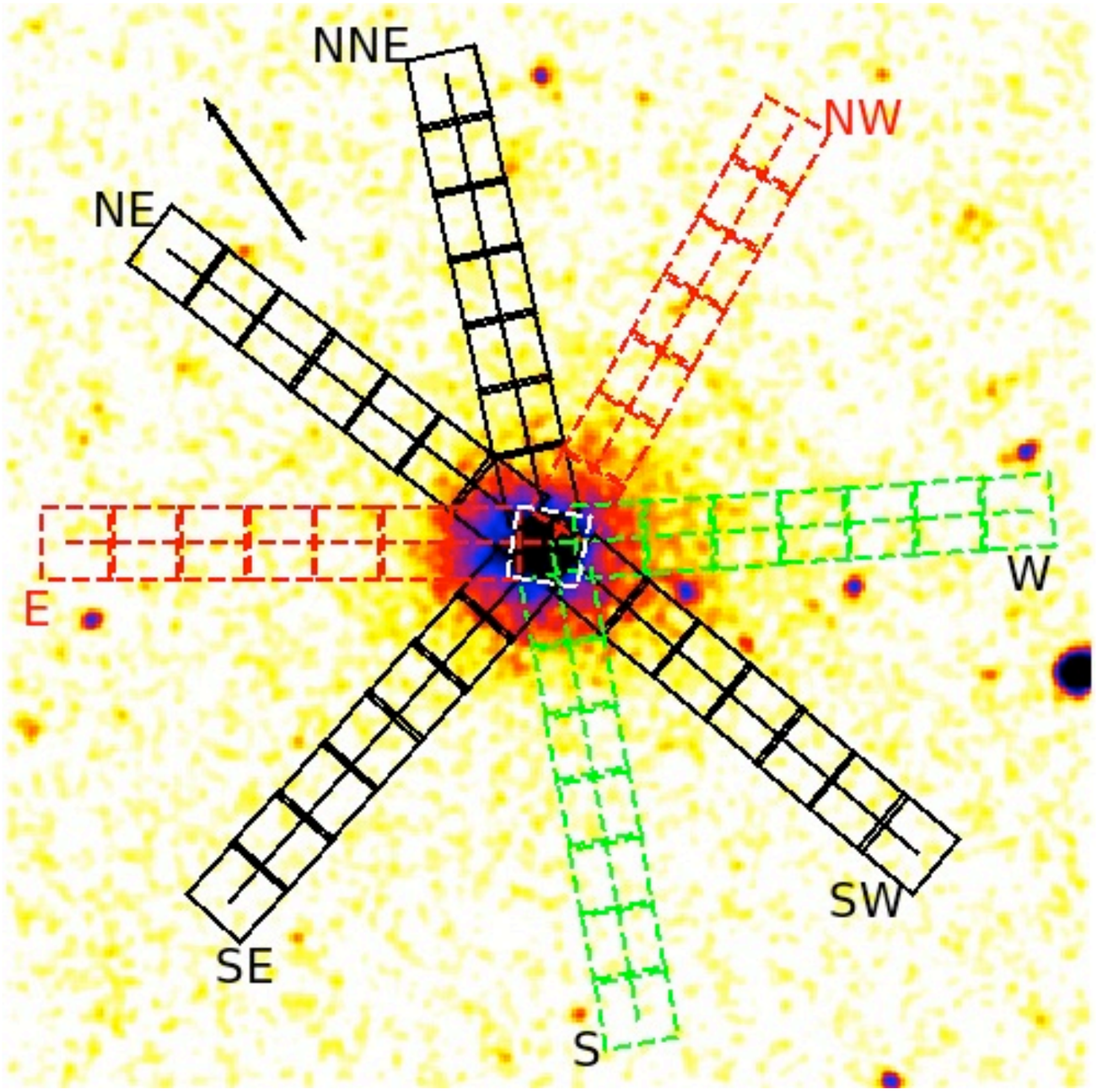
correcting for clumping (red lines) brings measurements into agreement with expected trends

crucial to verify this along other directions / in other systems!

simulations predict azimuthal variations in clumping



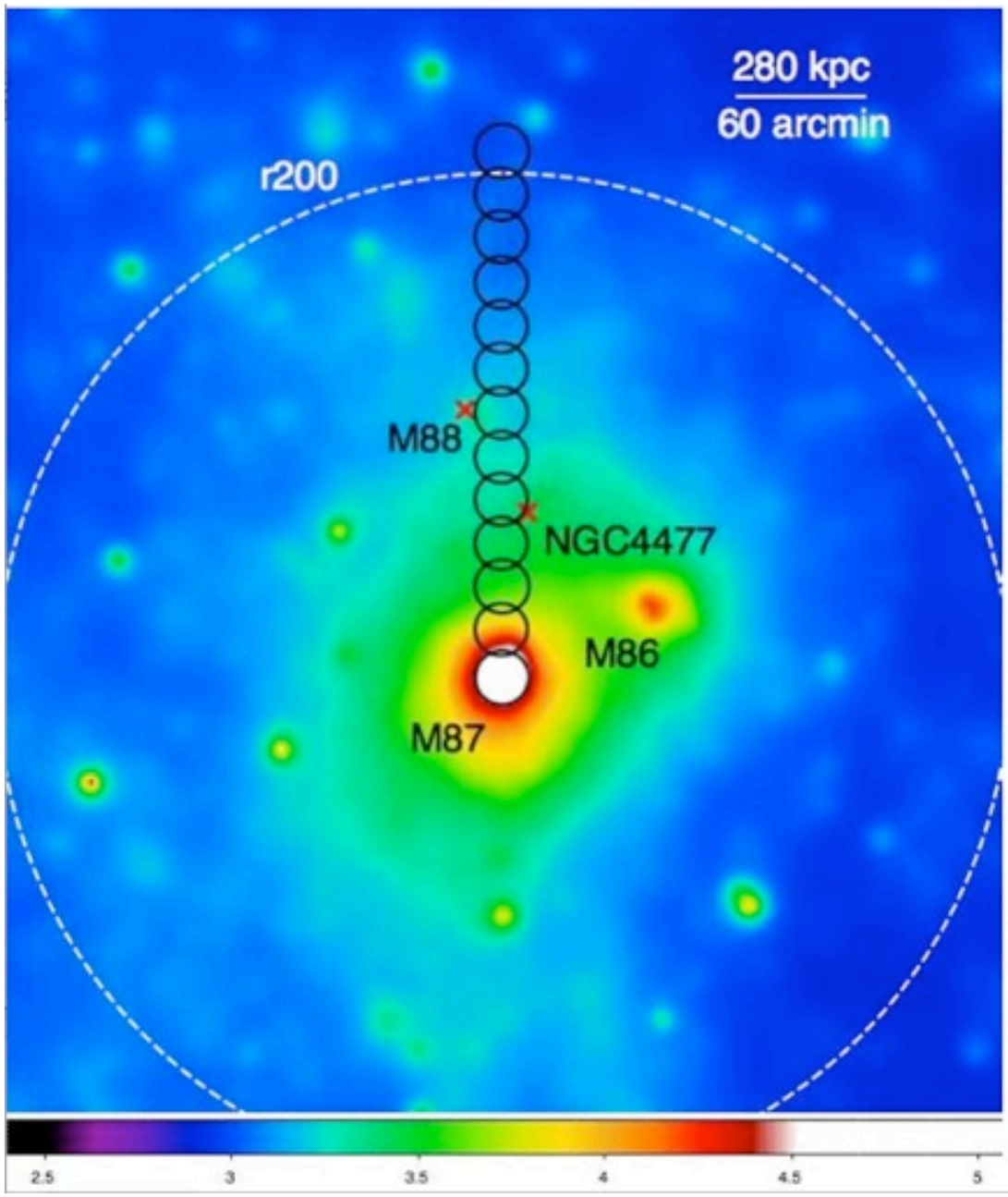
Look forward to:



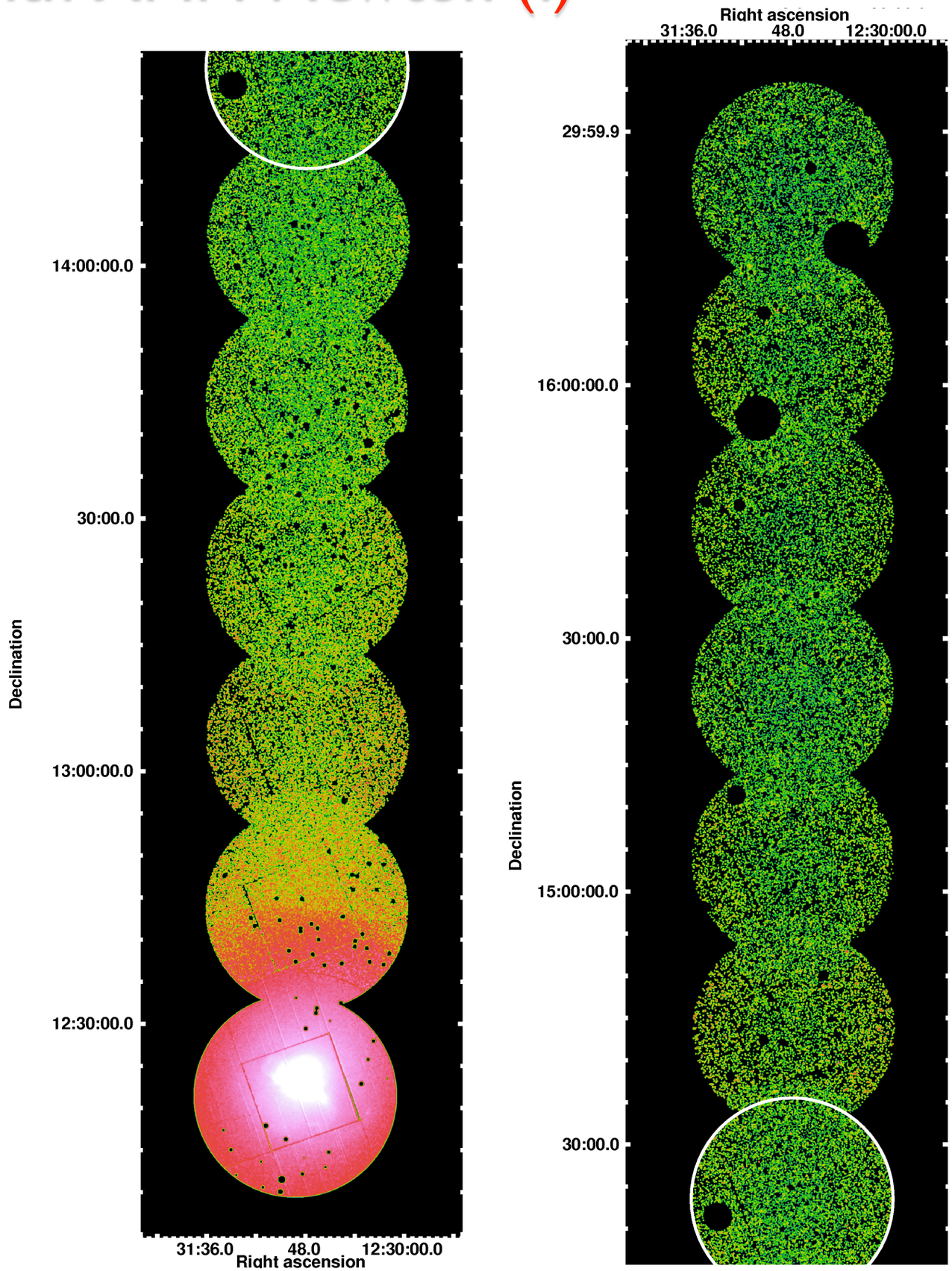
S and W arms have been observed - data reduction is under way

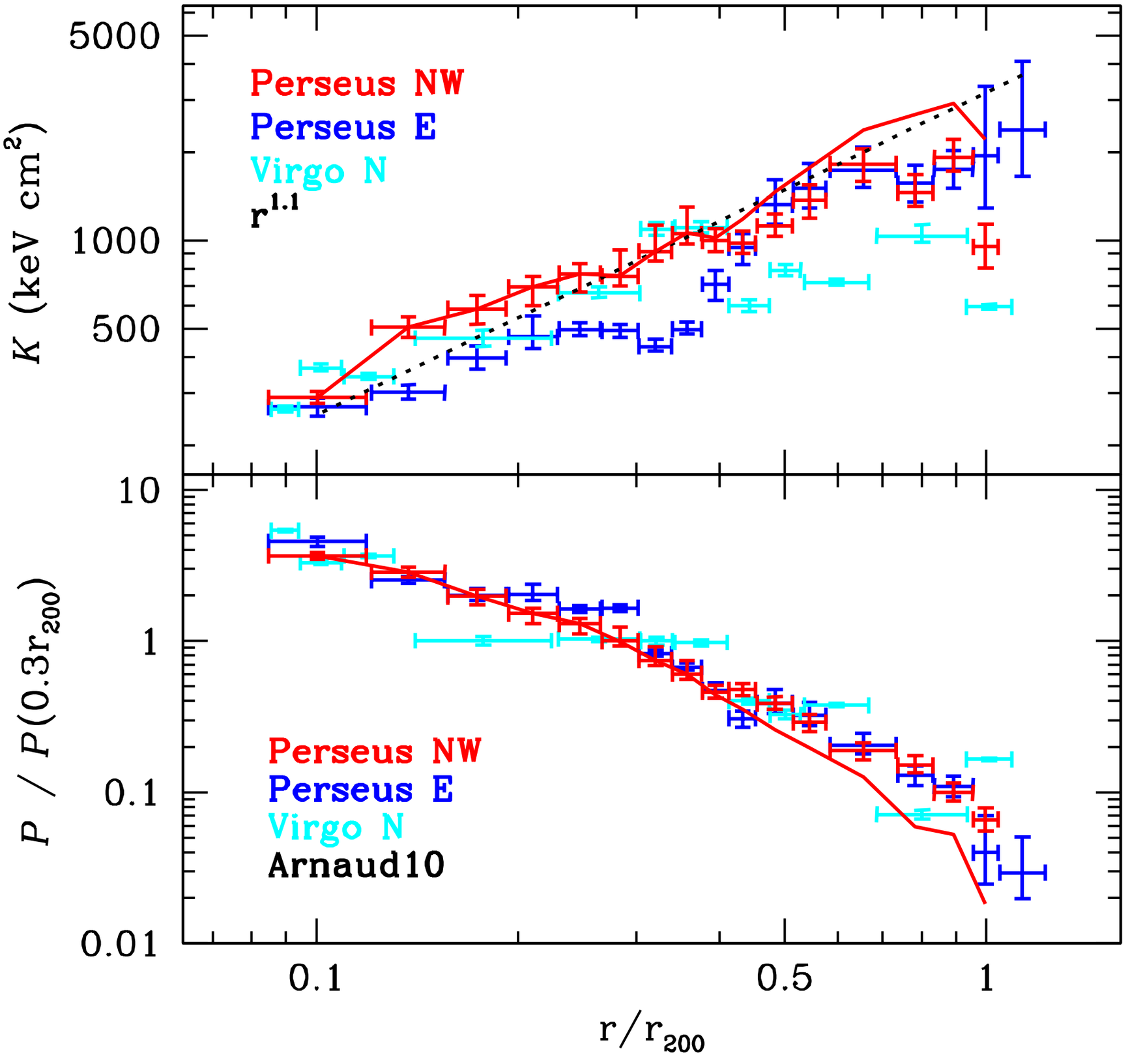
NNE, NE, SE, SW arms will be observed in the upcoming AO.

To the virial radius of Virgo with XMM-Newton (!)

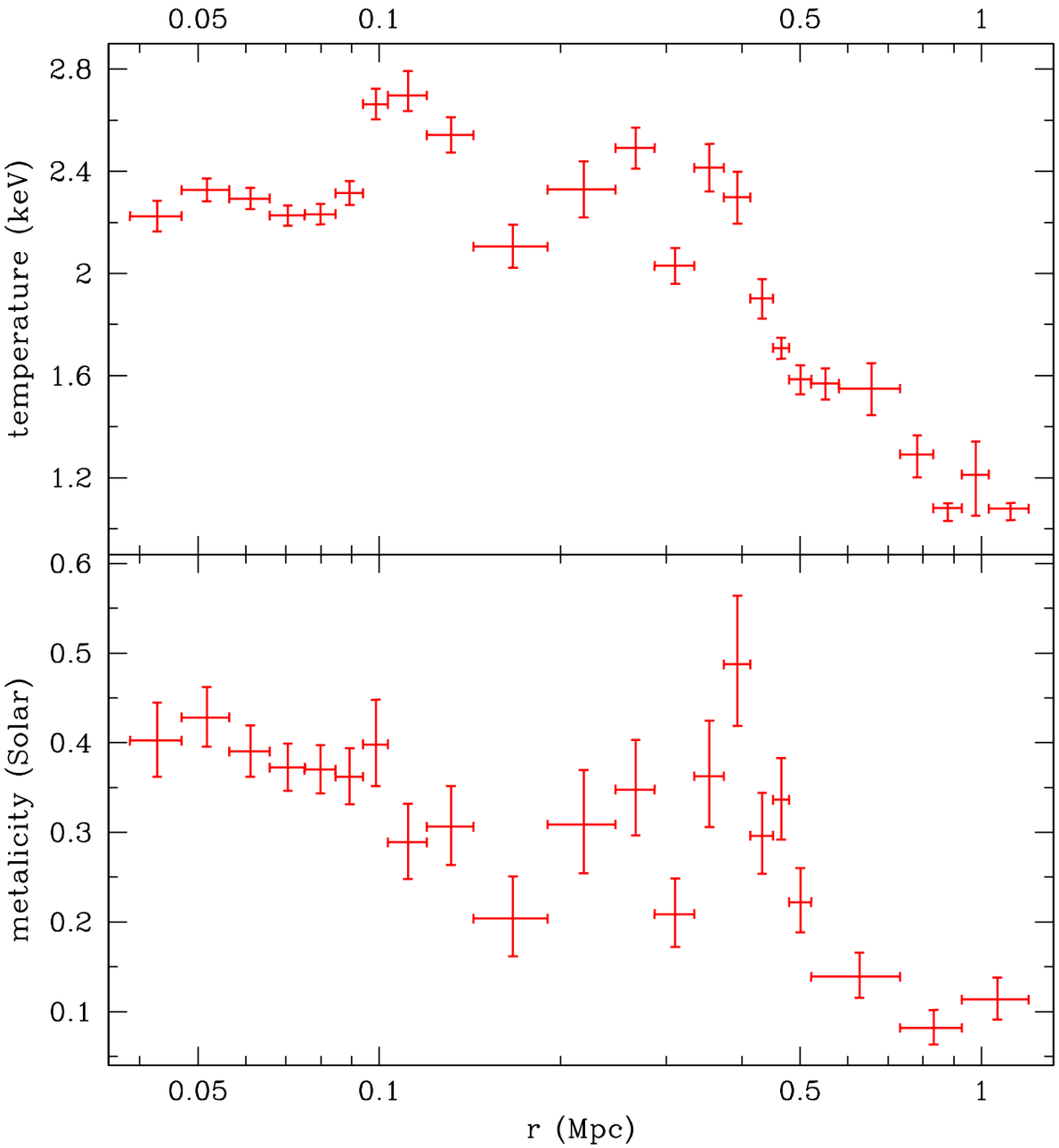


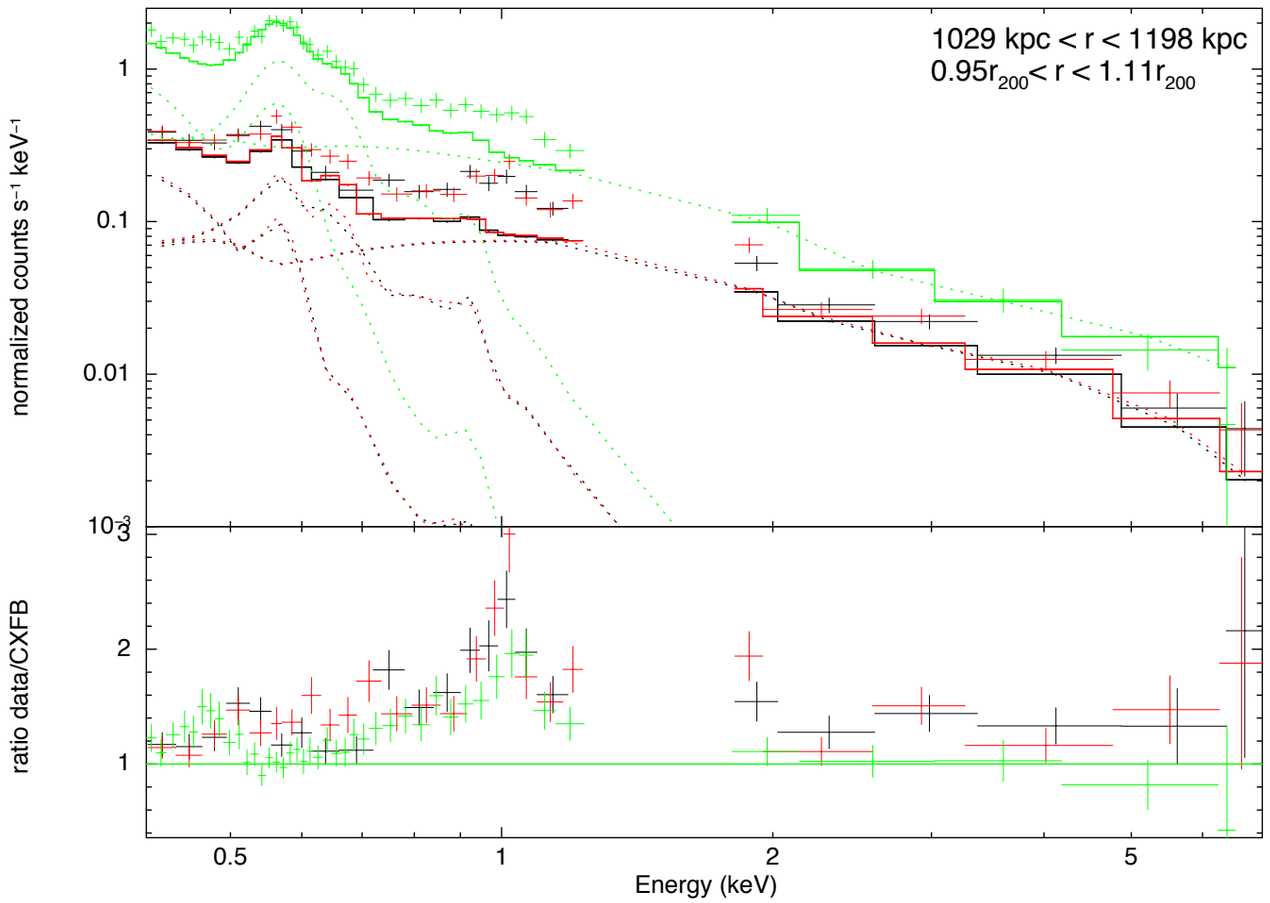
Urban et al. 2011




5000
1000
500
10
1
0.1
0.01
K (keV cm²)
P / P(0.3r200)
Perseus NW
Perseus E
Virgo N
r^1.1
Perseus NW
Perseus E
Virgo N
Arnaud10
0.1
0.5
1
r/r200

Temperature and metallicity to the virial radius of Virgo





Urban et al. 2011

Conclusions:

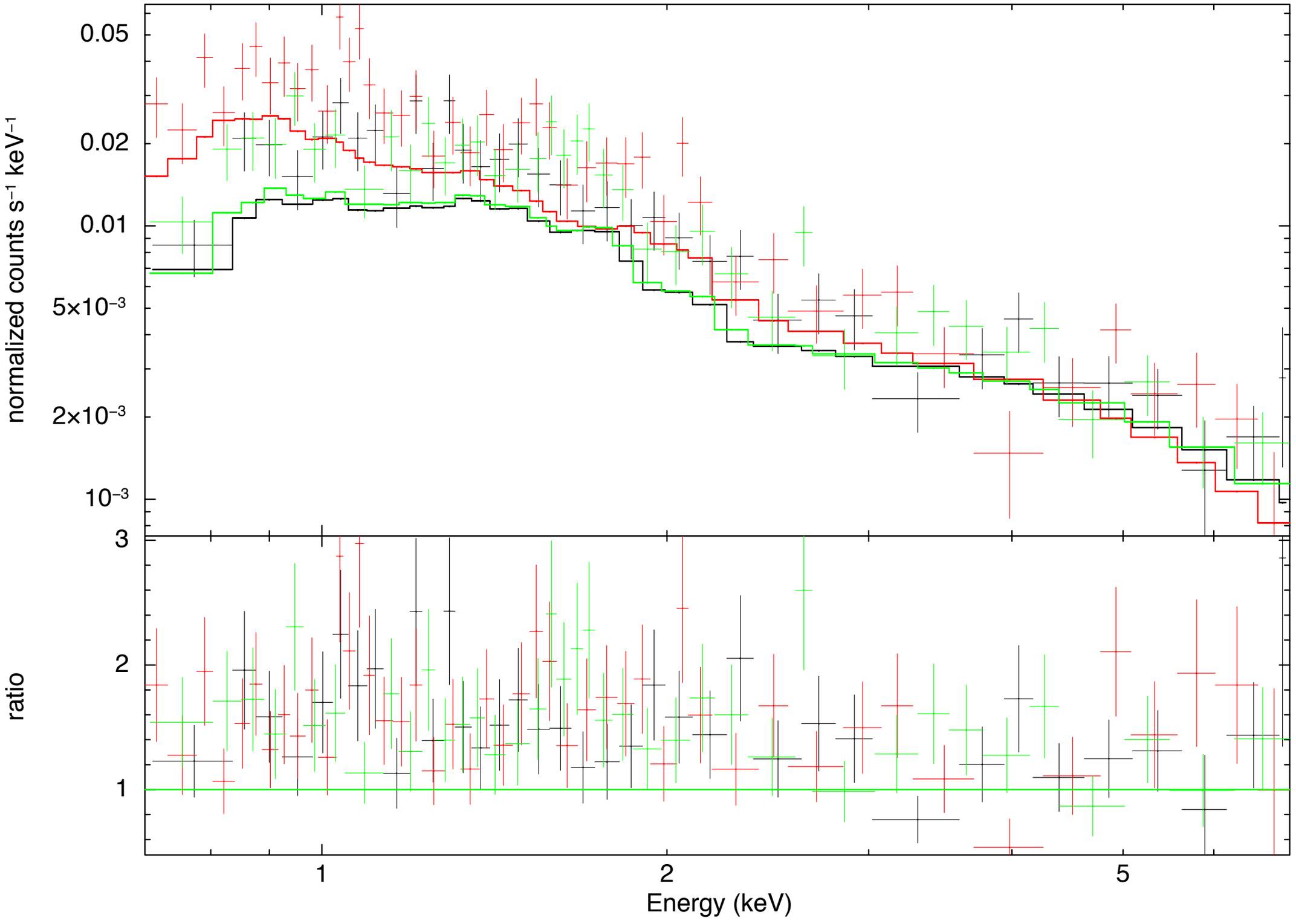
- We have obtained the first observational proofs for gas clumping in cluster outskirts.

- Clumping provides a new window onto the virialization and equilibration processes and the physics of cluster outskirts -> numerical simulations will be a key to understand this further.

- Knowledge of the radial dependence and azimuthal *variance* of clumping is critical for robust measurements of thermodynamic quantities, e.g. density, entropy, pressure.

- Along one relaxed arm of Perseus, we have measured a very accurate gas mass fraction profile. Our results indicate that there are no "missing" baryons in clusters.

Perseus NW spectrum 0.95-1.05r_{200}



CXB systematics are small: