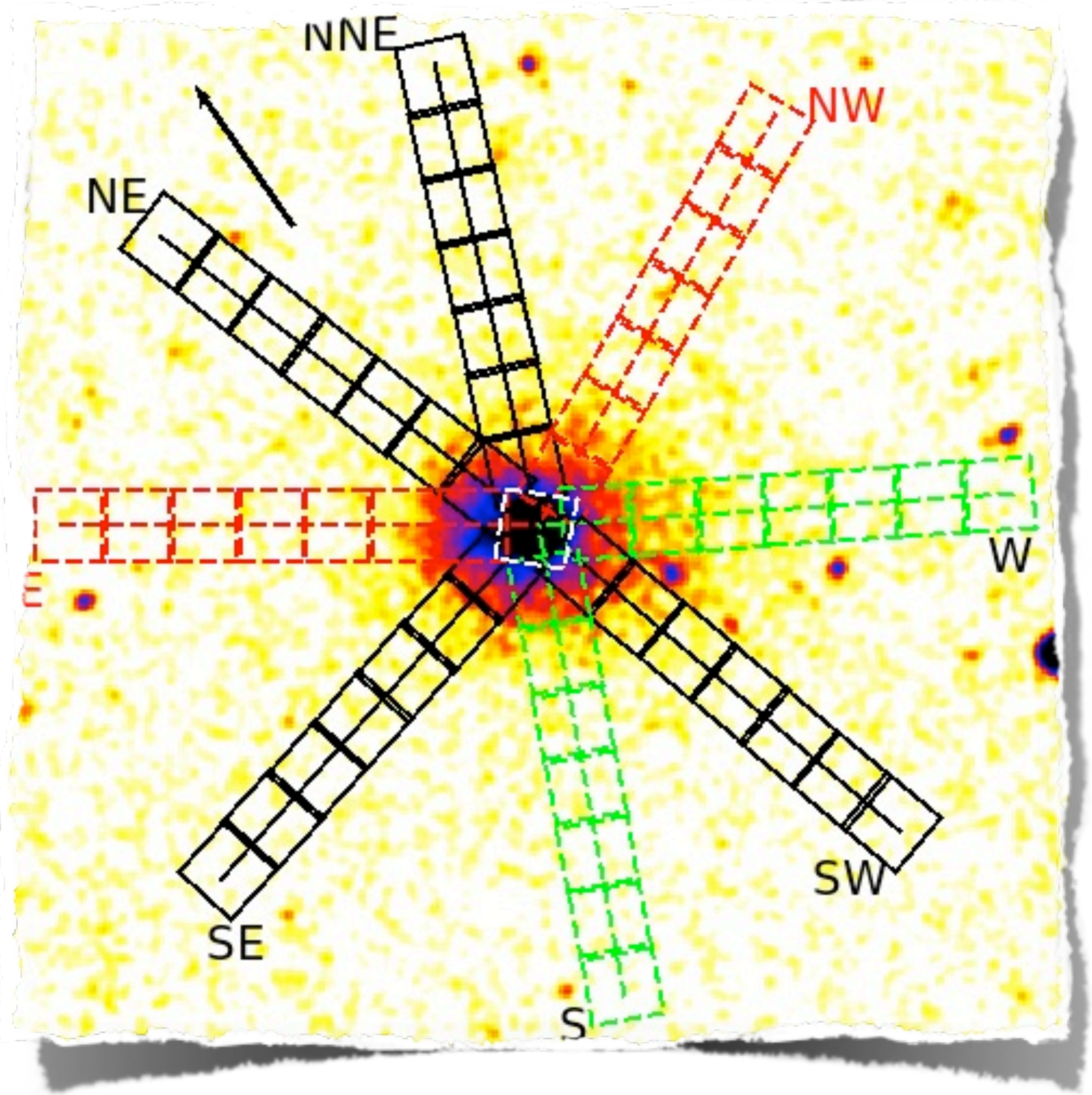
Baryons in the outskirts of the nearest brightest galaxy clusters



Norbert Werner (Stanford)

Aurora Simionescu, Ondrej Urban, Steve Allen, Adam Mantz, Yoh Takei, Glenn Morris, Andy Fabian, Jeremy Sanders, Paul Nulsen, Matt George, Hans Böhringer

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.
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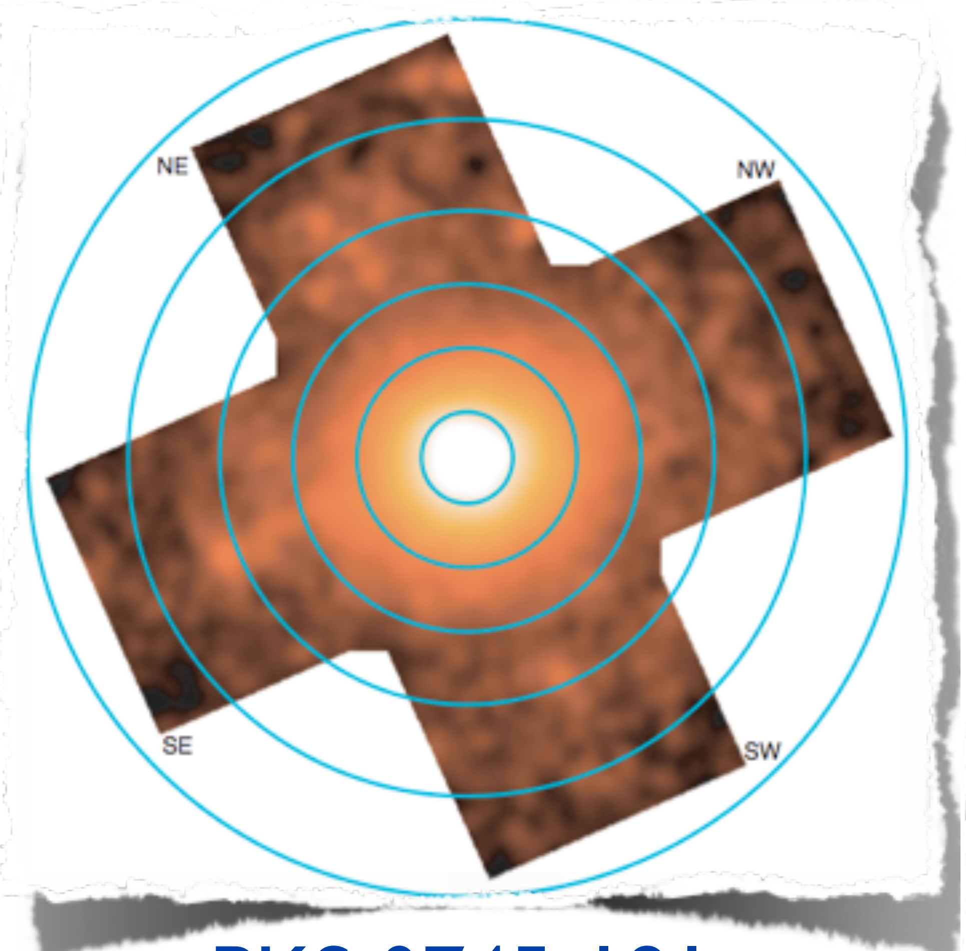
2/3 of cluster volumes practically unexplored!

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

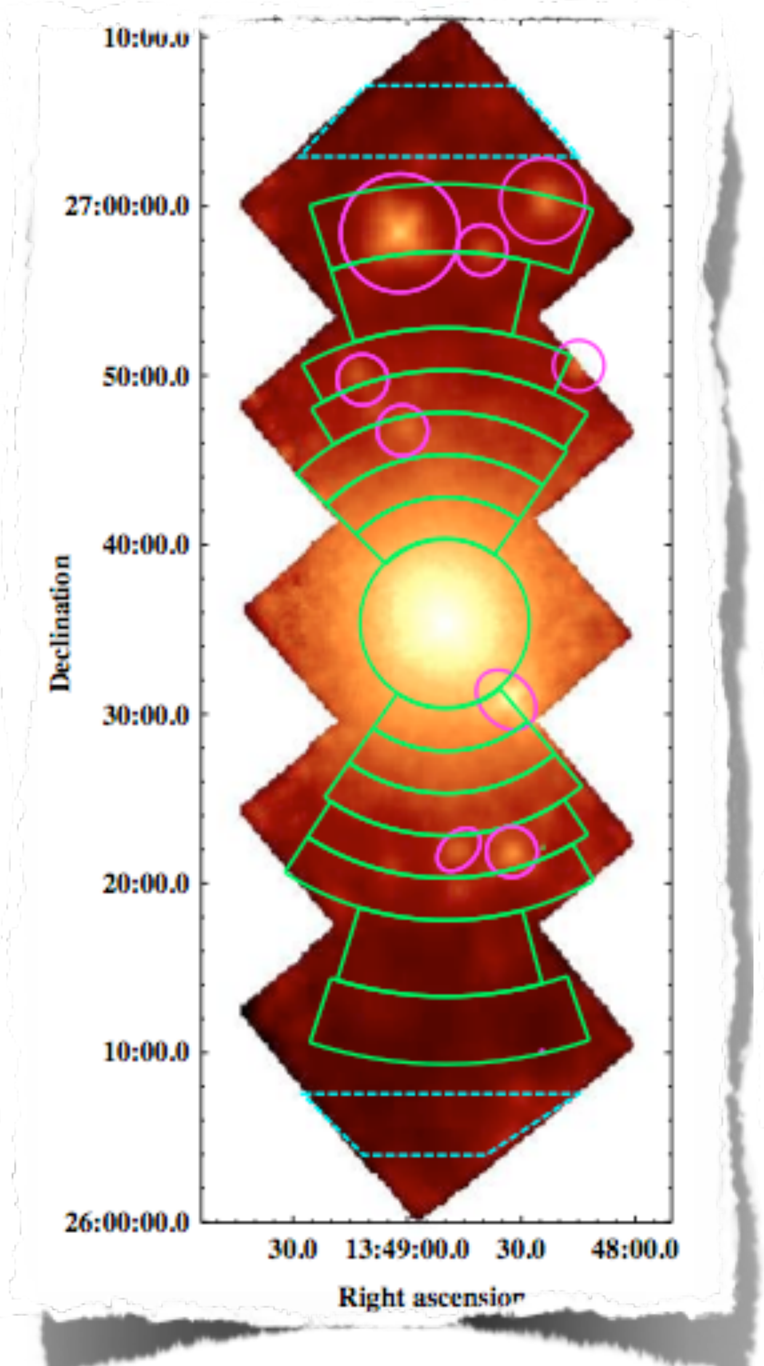
Why study clusters to large radii?

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

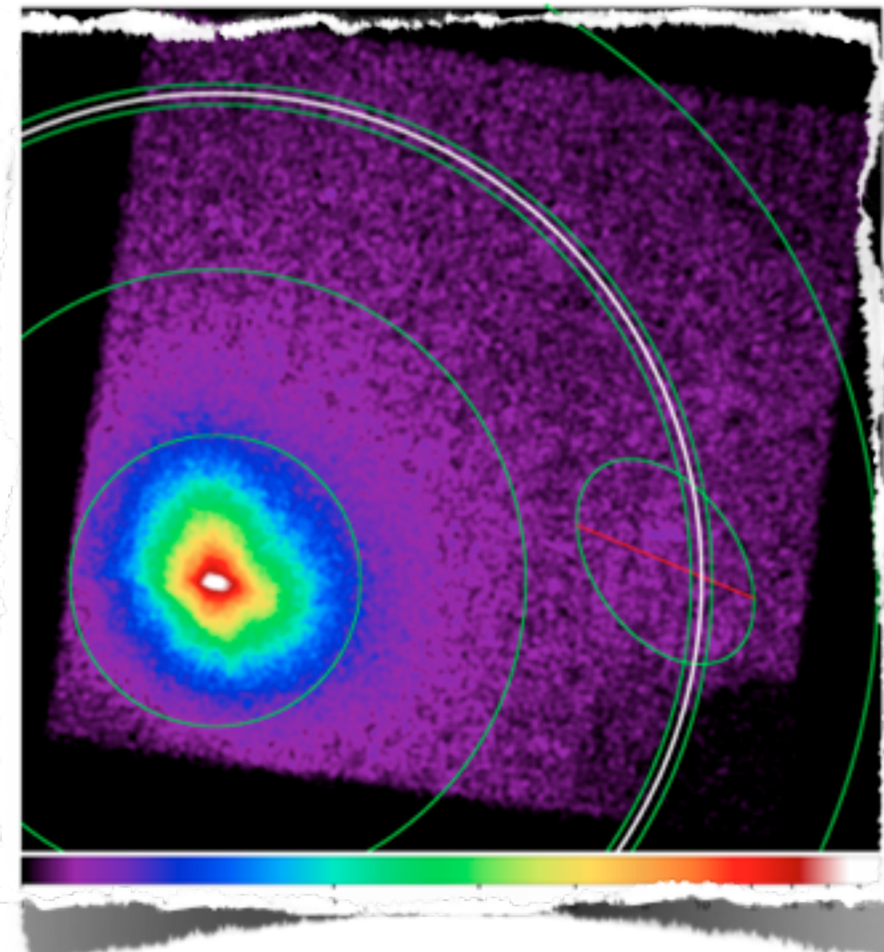
- physics of the ICM and pre-virialized IGM
  (the formation of largest scale structure `as it happens')
- use of clusters as cosmological probes
  (calibration of X-ray mass proxies; benchmark for hydro. simulations)



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

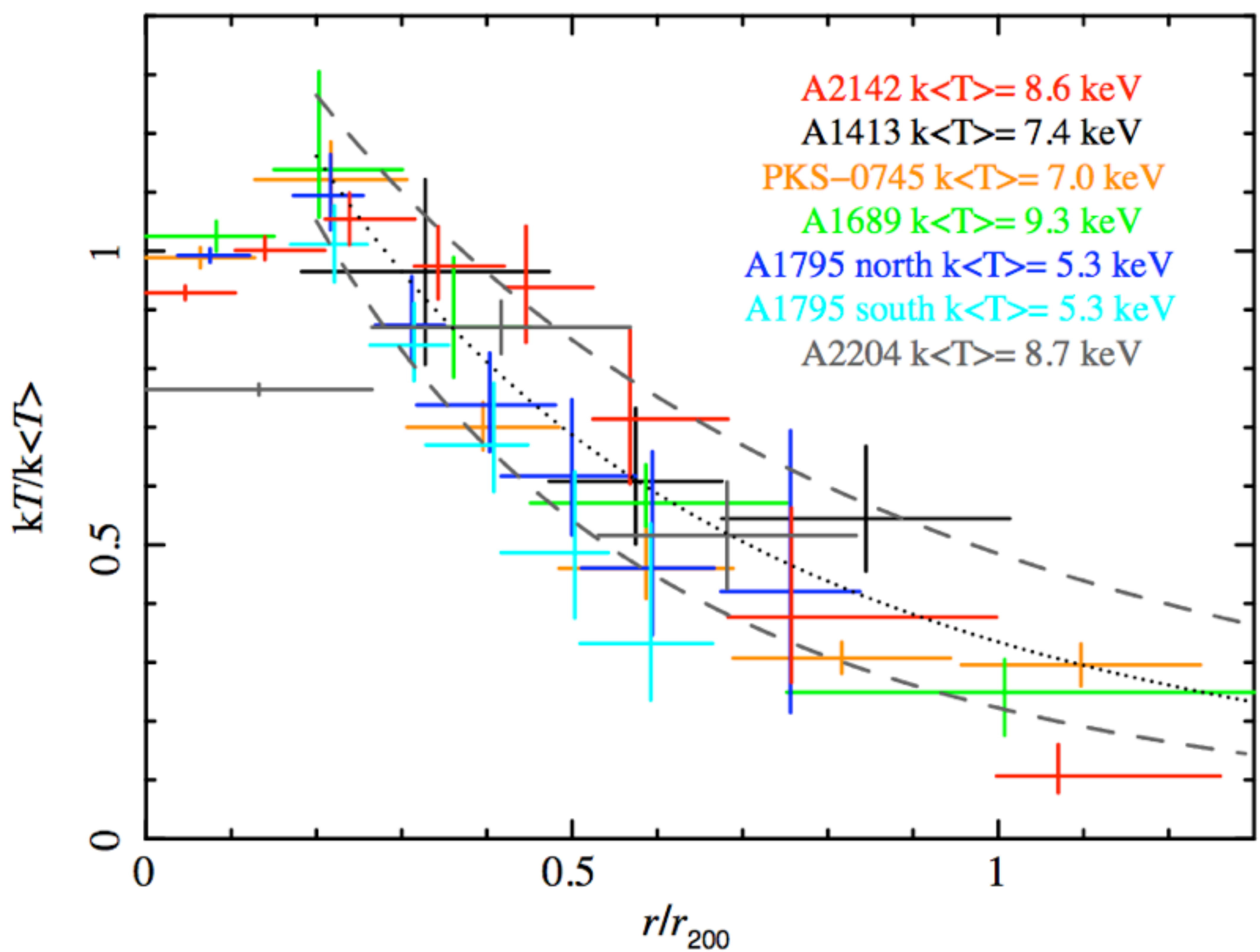


A1795,
Bautz et al. 2009,
z=0.06



A2204,
Reiprich et al. 2009
z=0.15

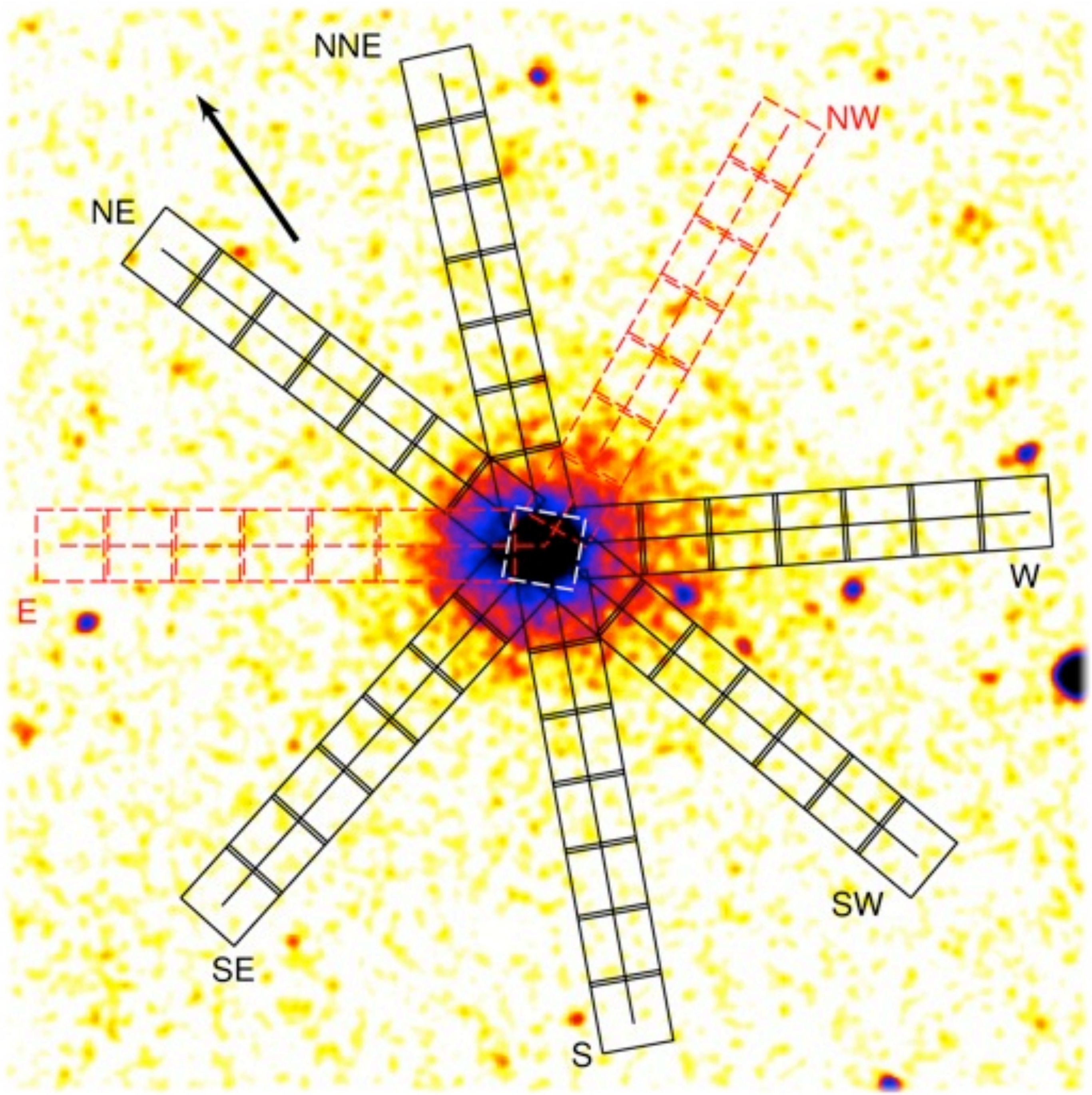
also: Hoshino et al. 2010, Kawaharada et al. 2010, Sato et al. 2010



From Akamatsu et al. 2011 (additional data from Hoshino et al. 2010, George et al. 2009, Kawaharada et al. 2010, Bautz et al. 2009, Reiprich et al. 2009)

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

Results from the Perseus Cluster observations:

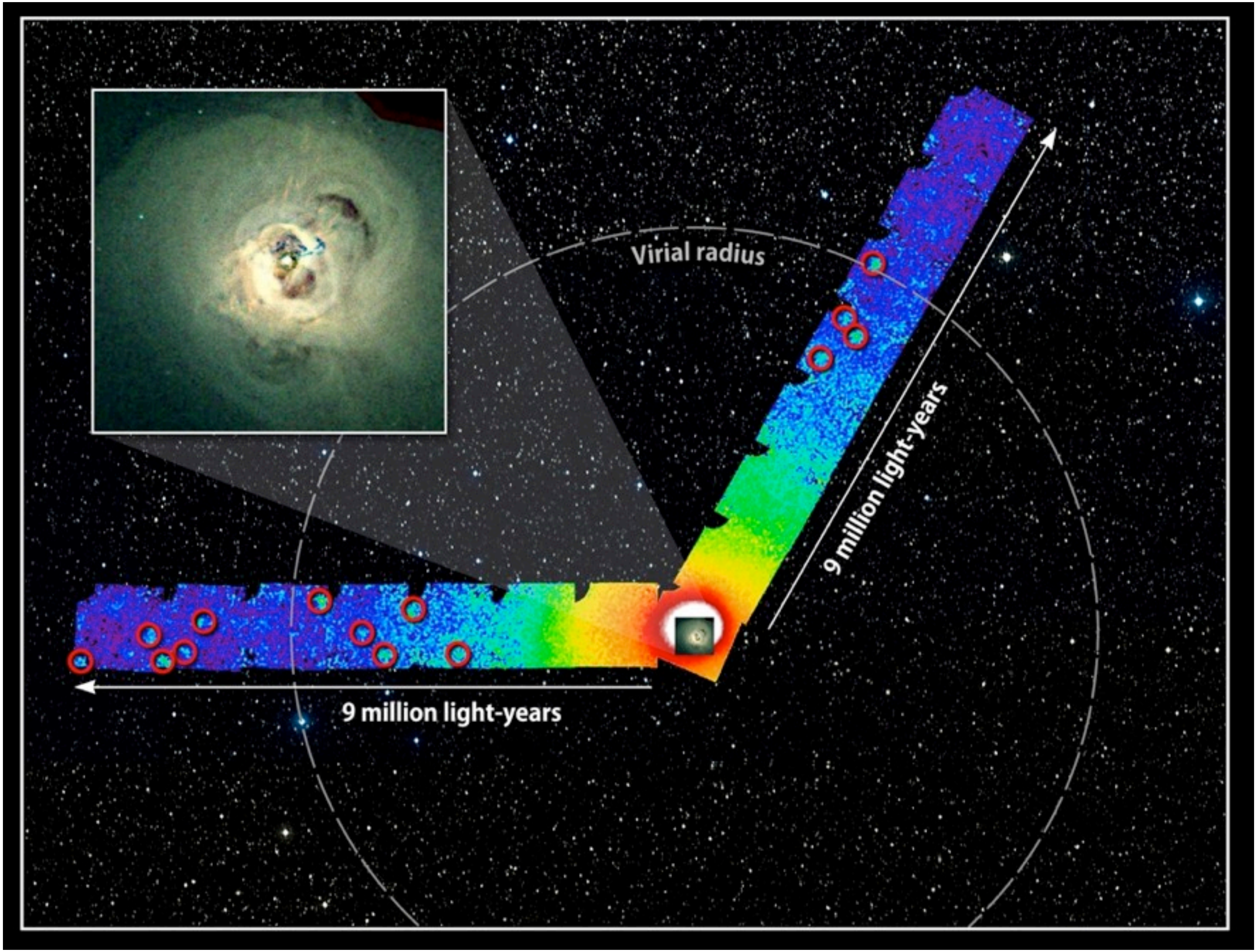


The first two arms:

analysis of E & NW mosaics (total 260 ks) reported by

Simionescu et al. 2011, Science, 331, 1576

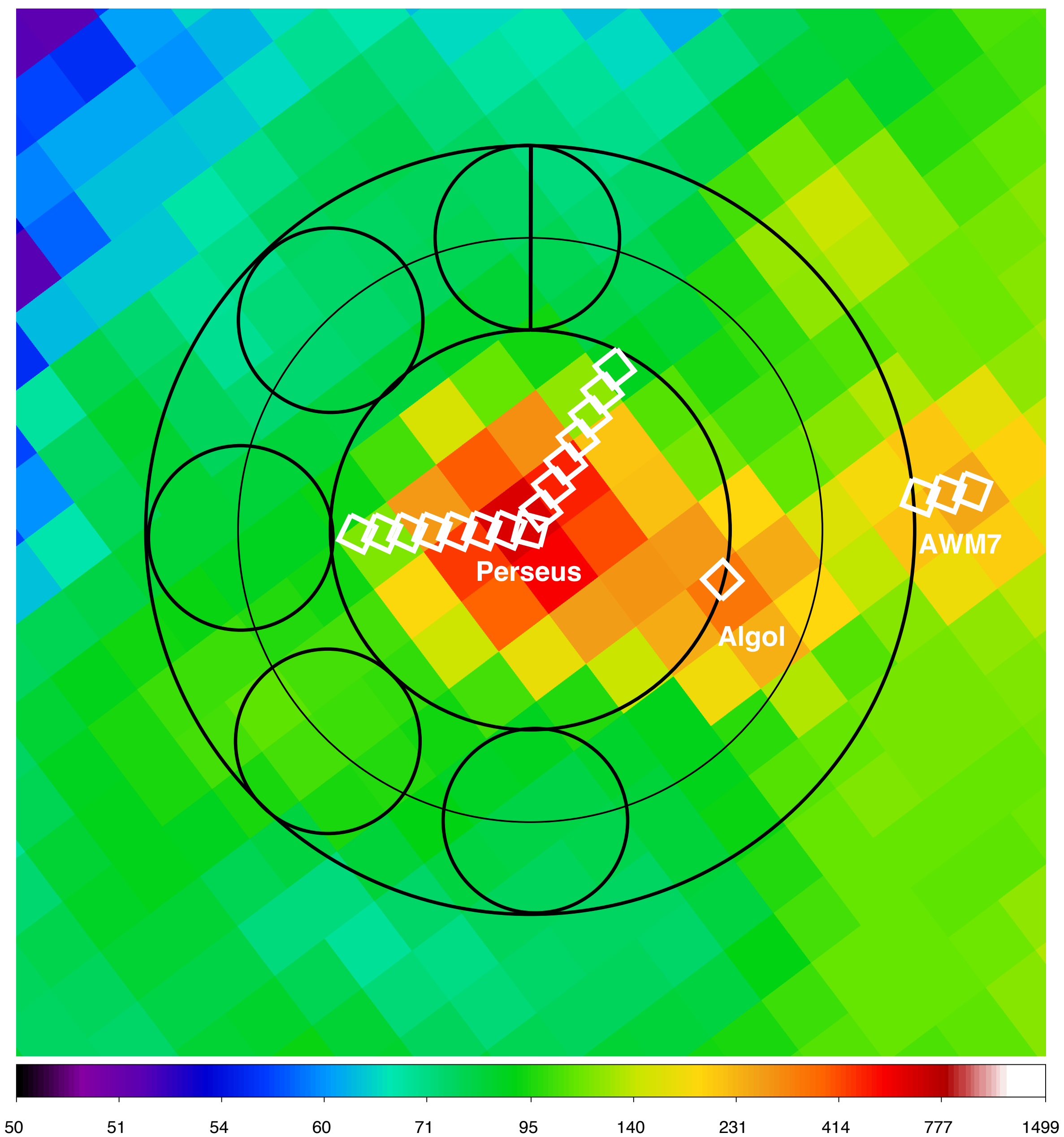
Surface brightness images of the NW and E arms:



Spectral analysis

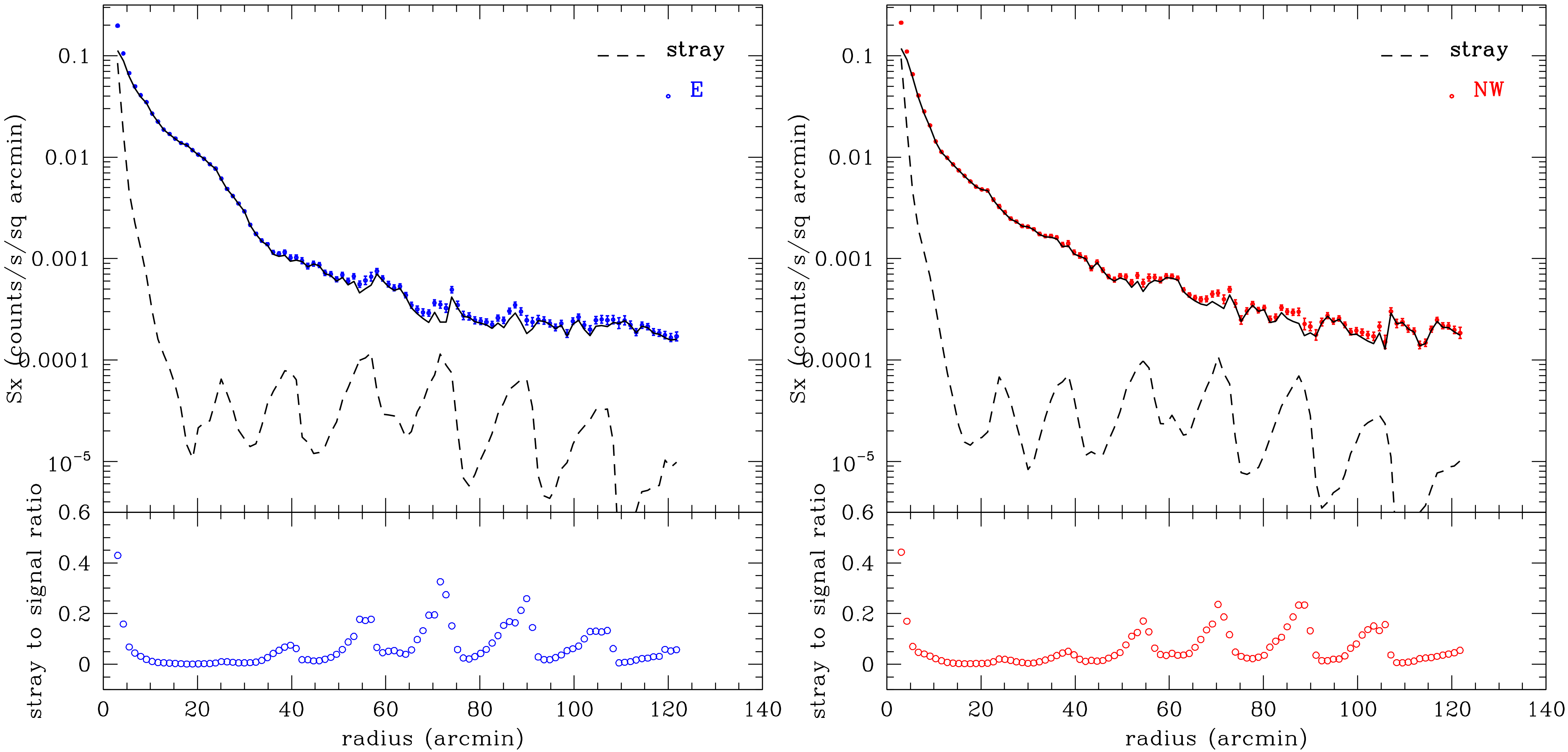
Spectral analysis I: background

Background model based on fits to ROSAT and Suzaku outer pointings



- unabsorbed LHB 0.1 keV thermal
- absorbed GH 0.2 keV thermal
- absorbed 0.6 keV thermal
- absorbed Γ=1.41 power law
- expected particle background (subtracted)

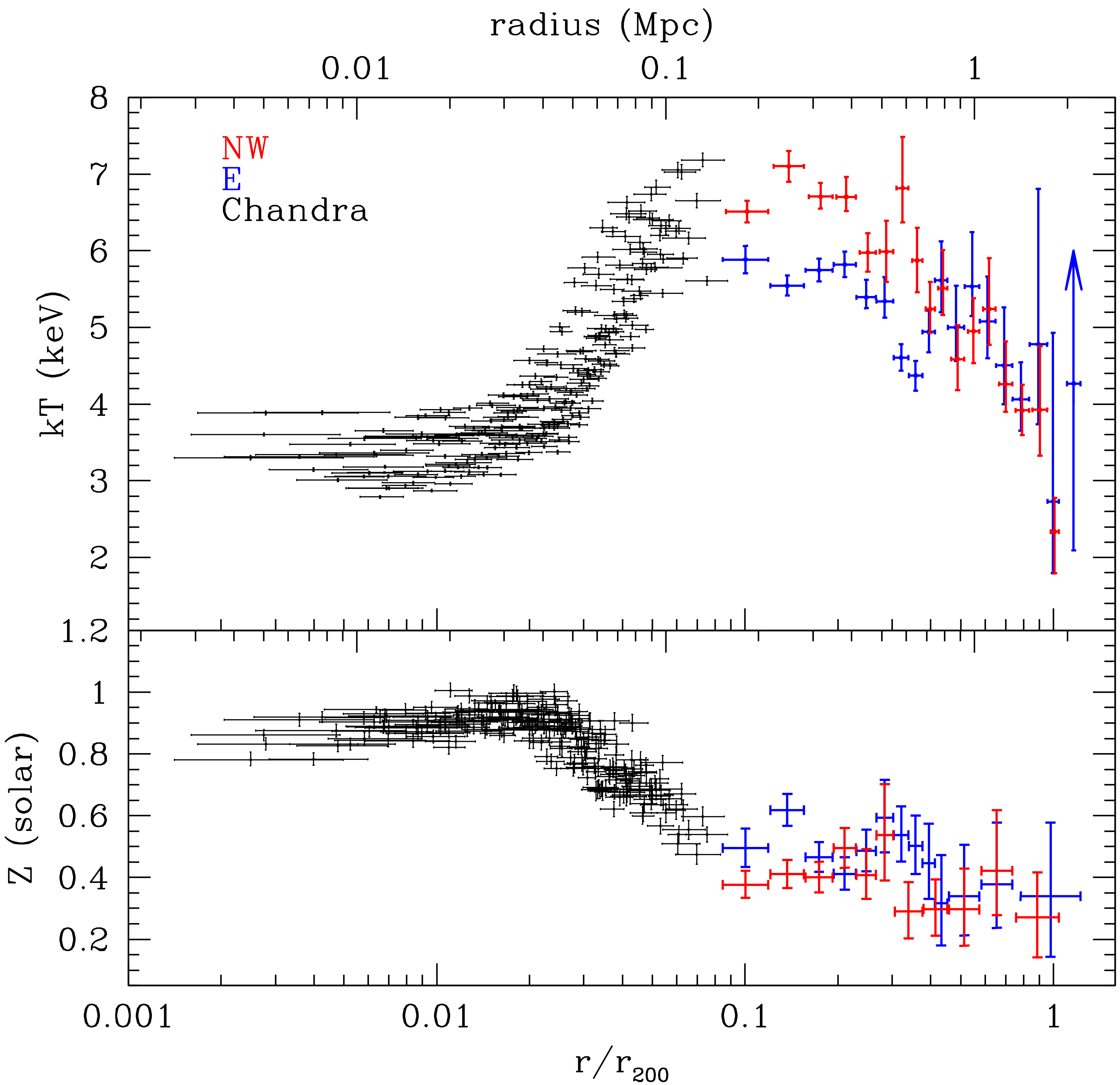
Spectral analysis II: stray light



Stray light spectrum softens with radius
Exclude parts of each spectrum where
stray>0.2*(data-modelCXB) - usually >1.5 keV

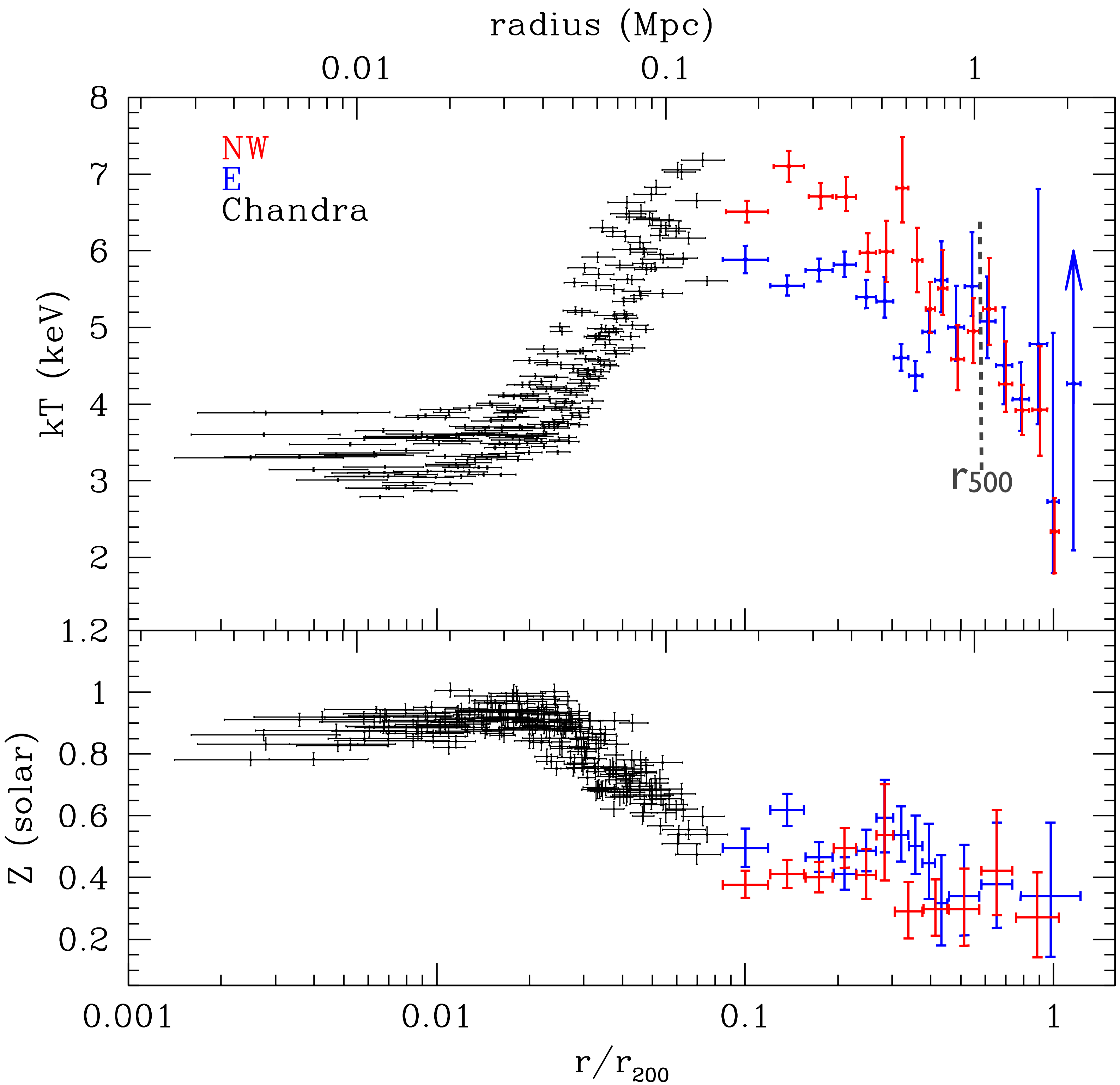
Results

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

Projected temperature and metallicity profiles:



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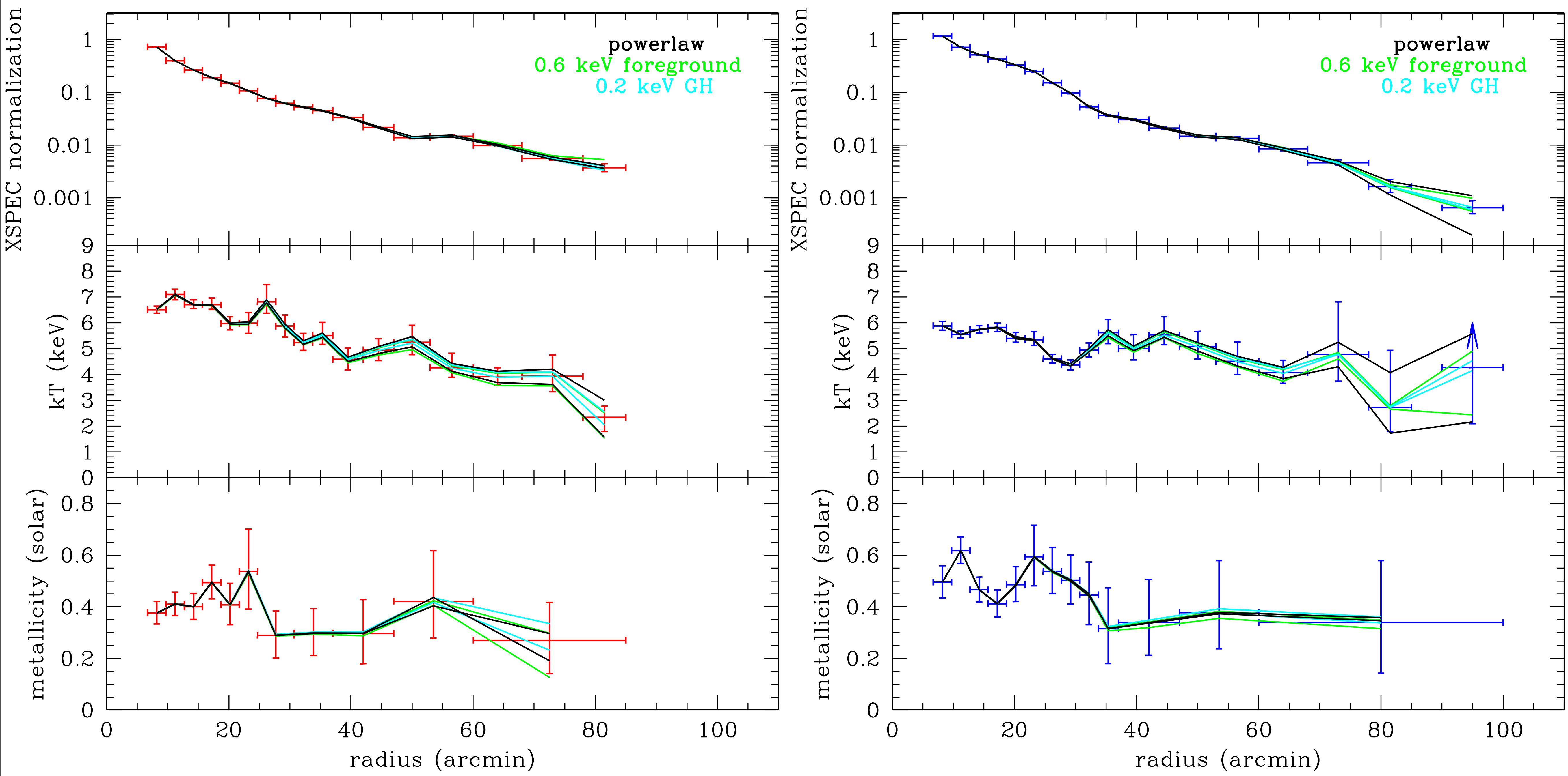
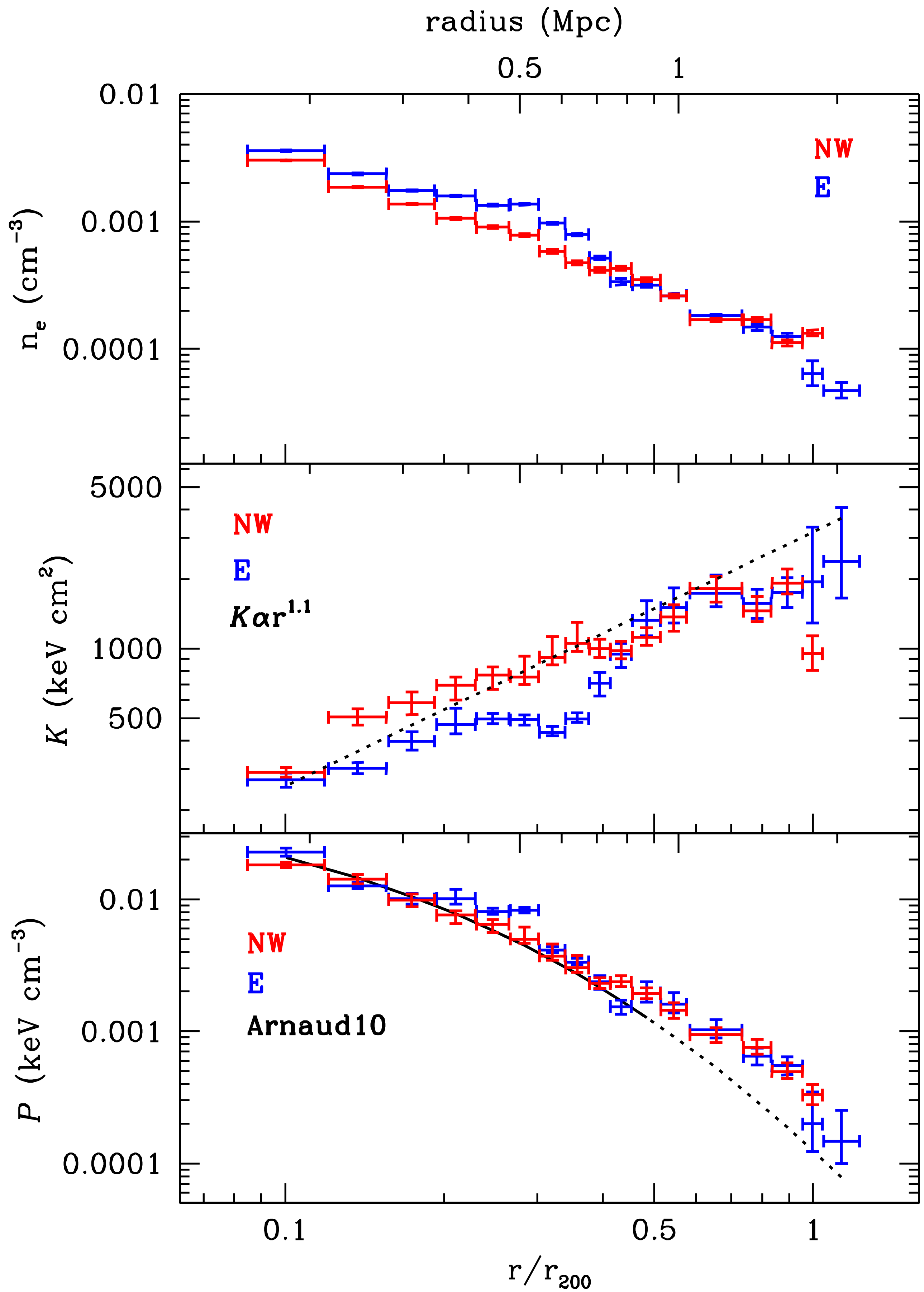
metallicity profile measured for the first time until the virial radius

CXB systematics are small:



Deprojected thermodynamic profiles:



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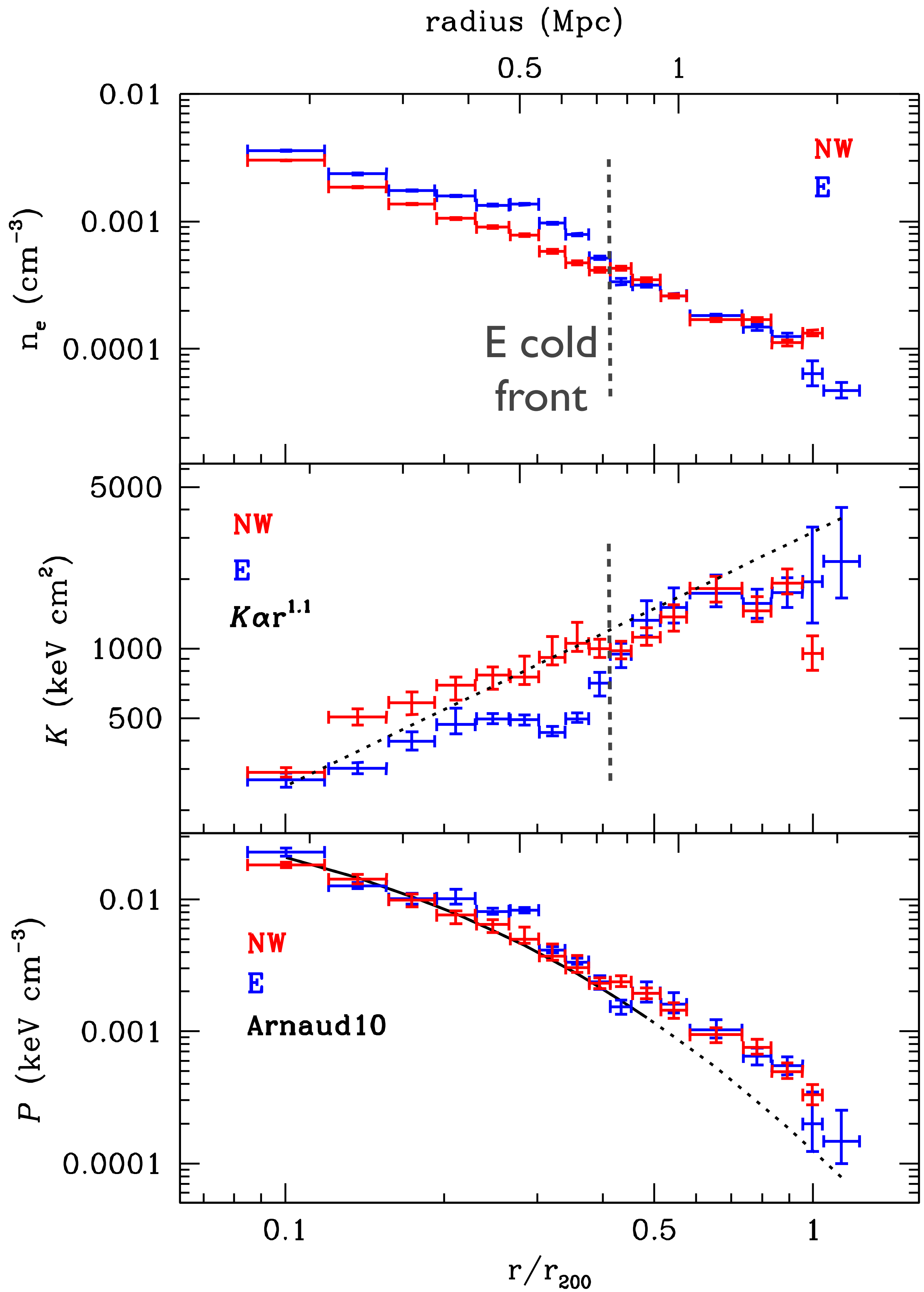

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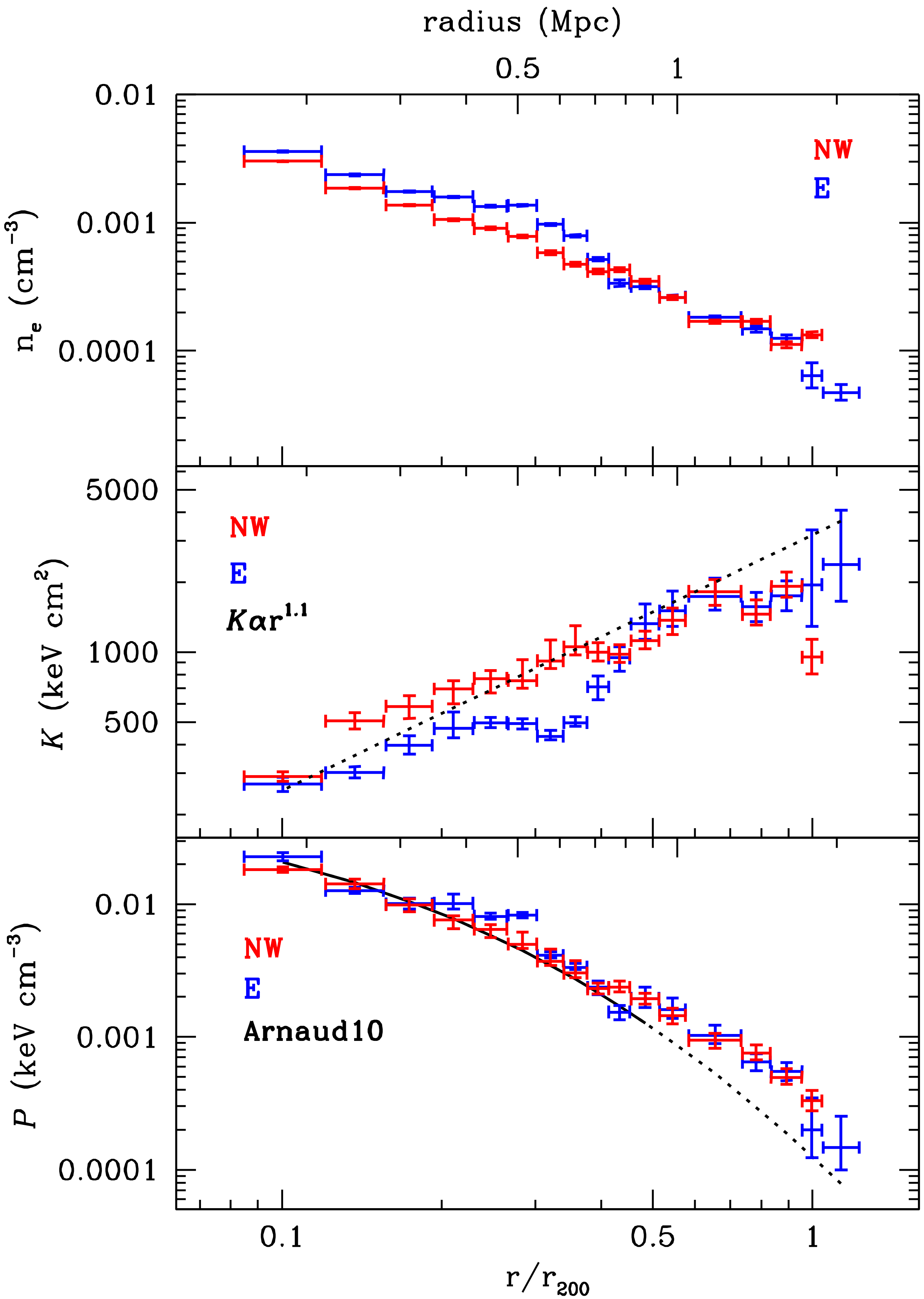
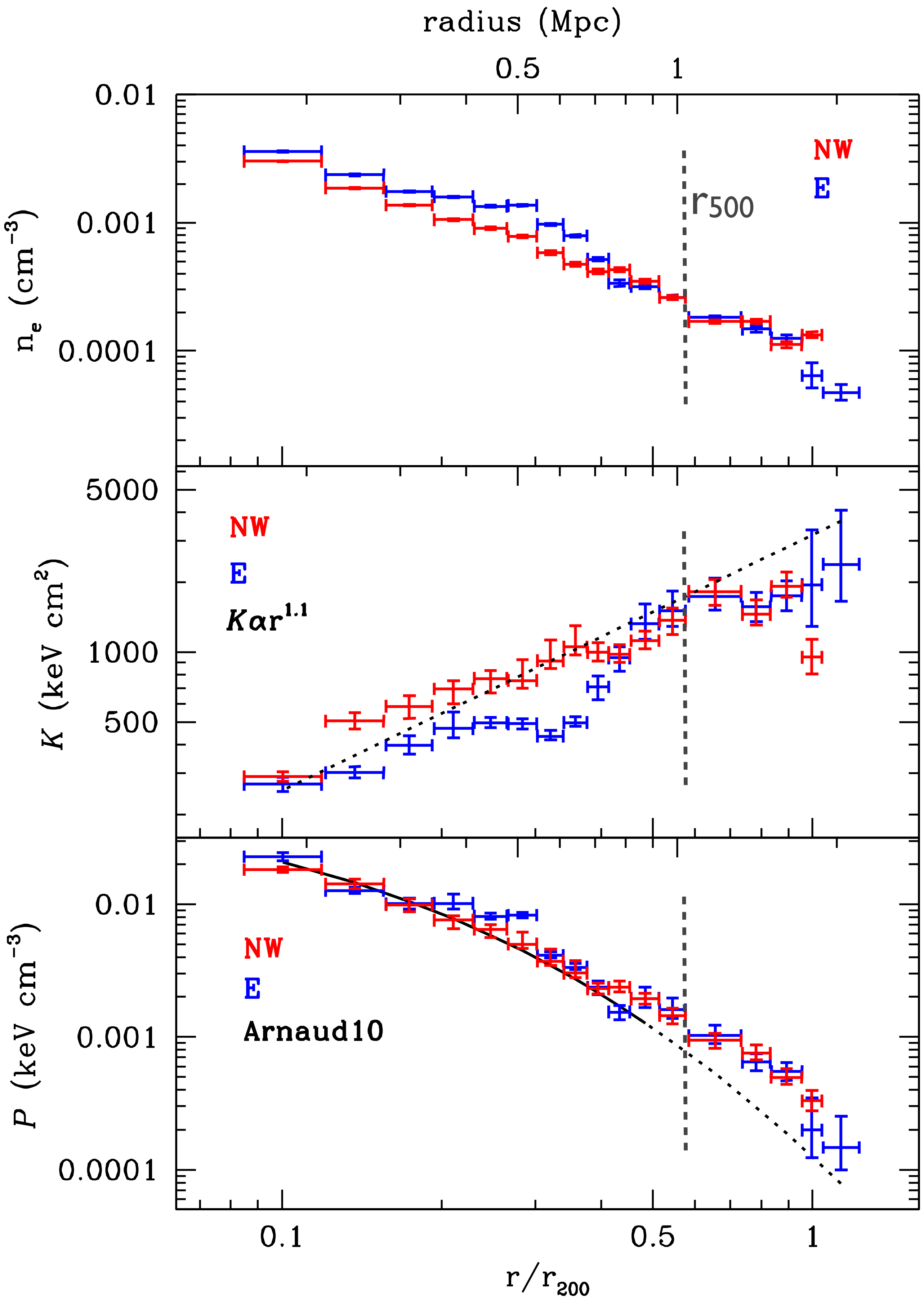
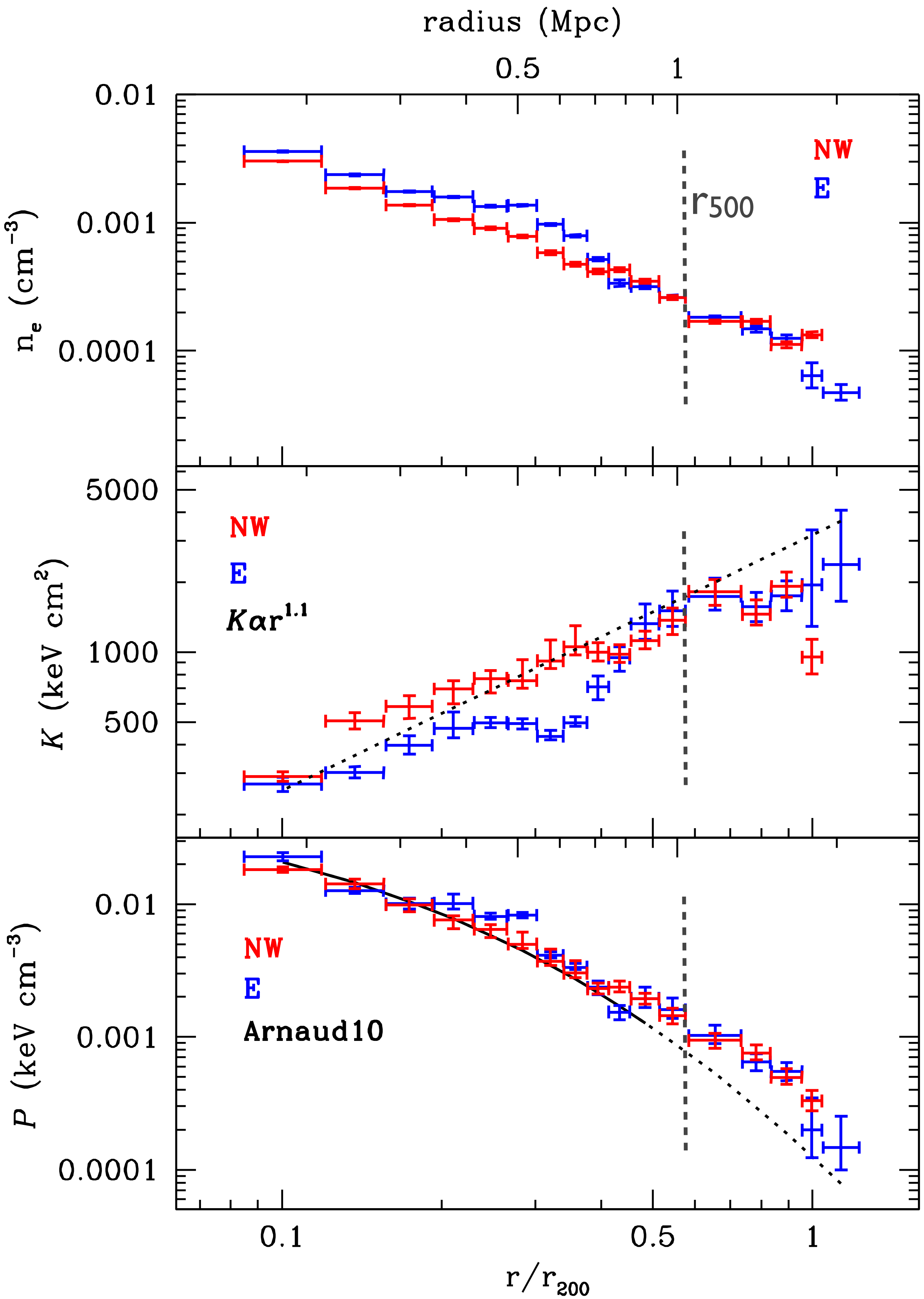


Deprojected thermodynamic profiles:



Deprojected thermodynamic profiles:

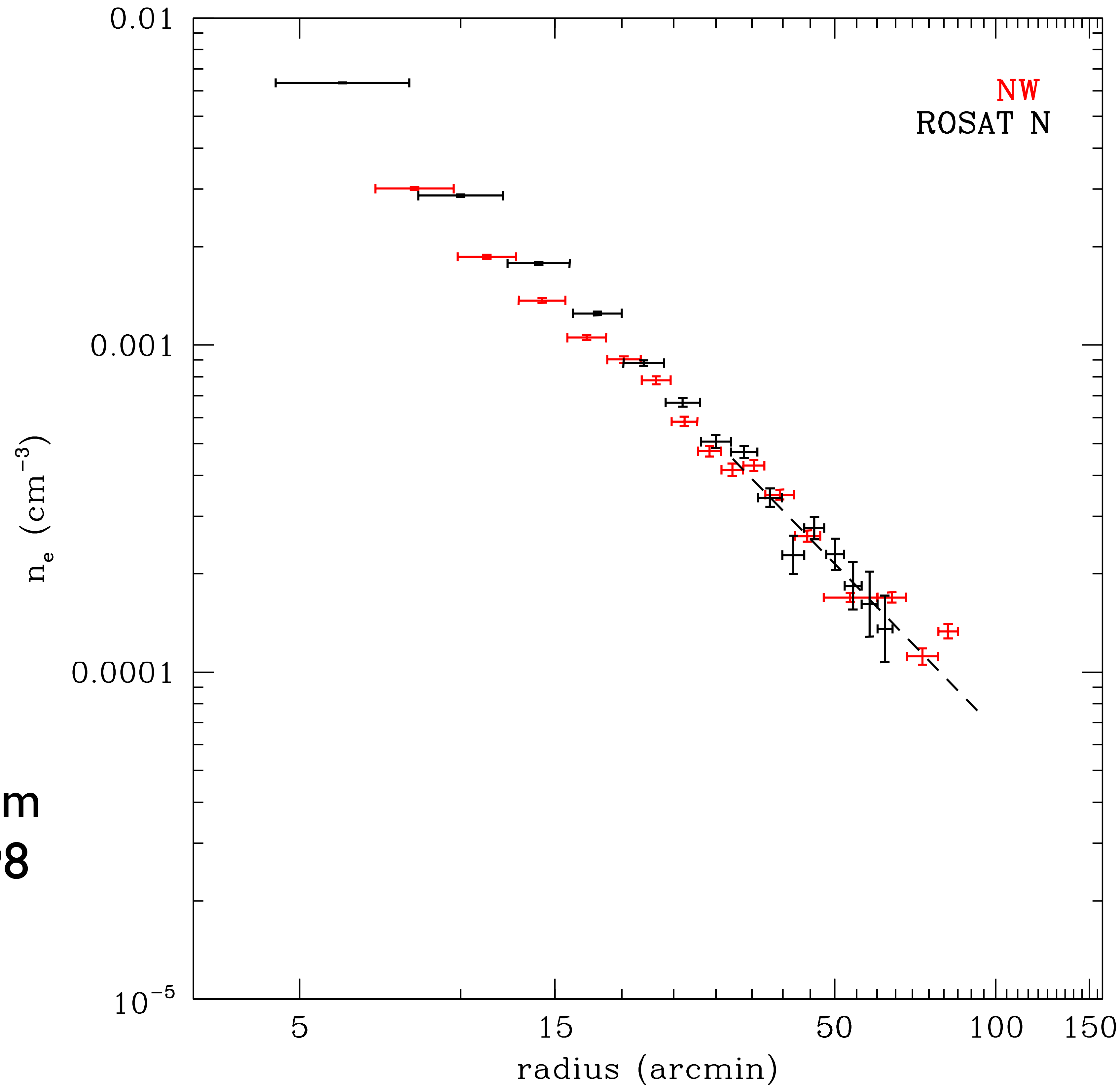


shallow decline of electron density at large radii

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

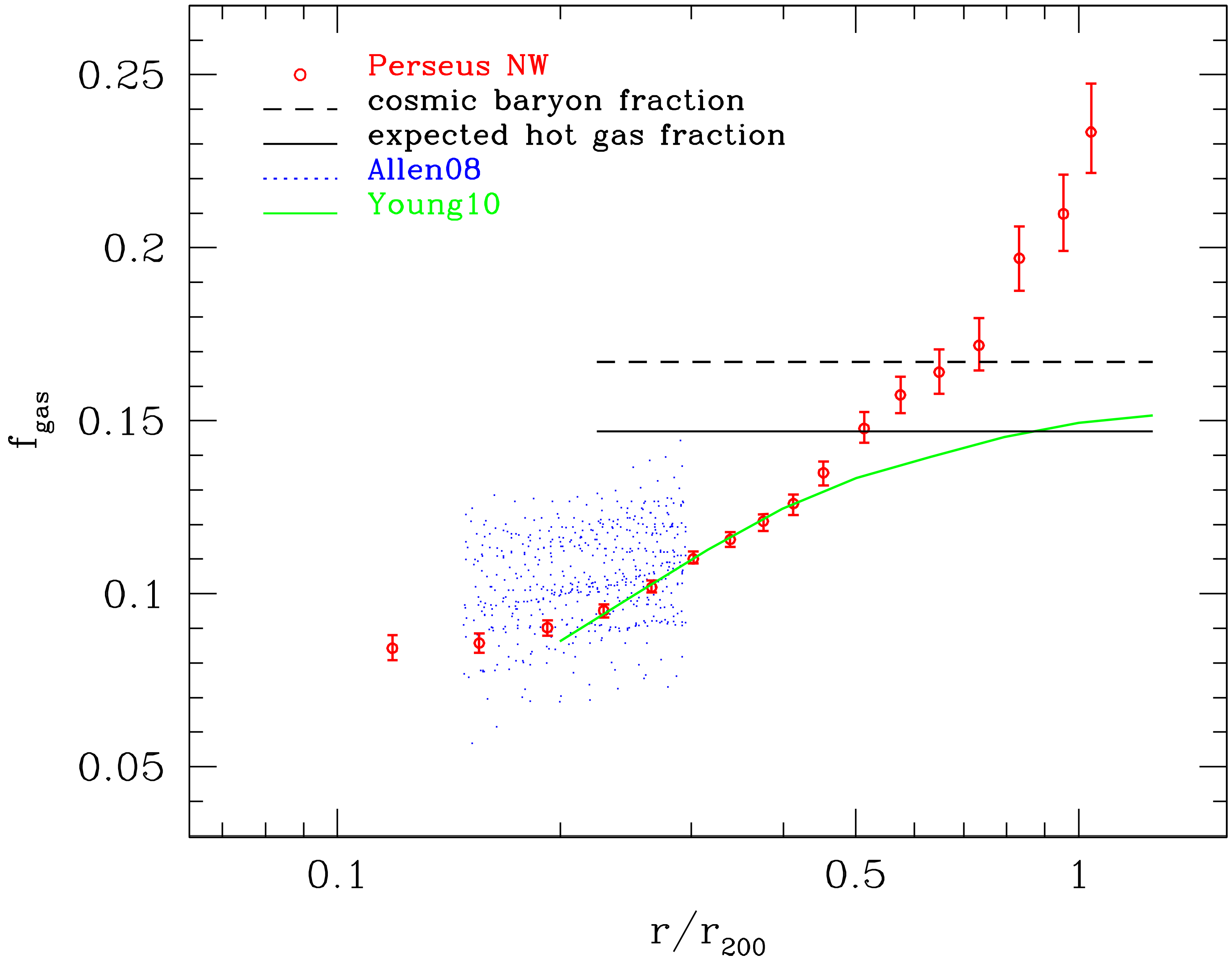
pressure at large radii greater than predicted by numerical simulations (fitted to XMM data inside r_{500} by Arnaud et al. 2010)

Comparison with ROSAT



ROSAT data from Ettori et al. 1998

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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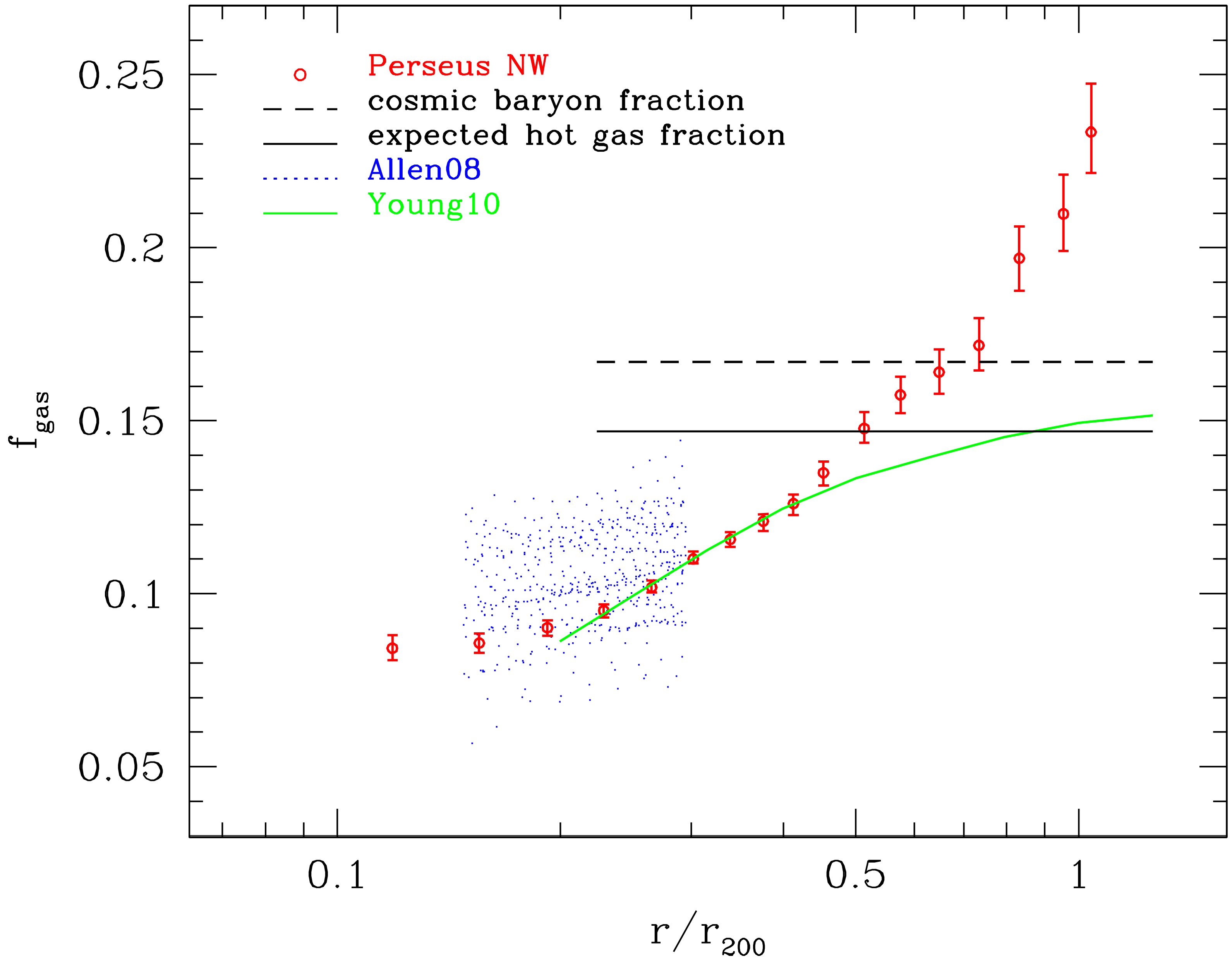


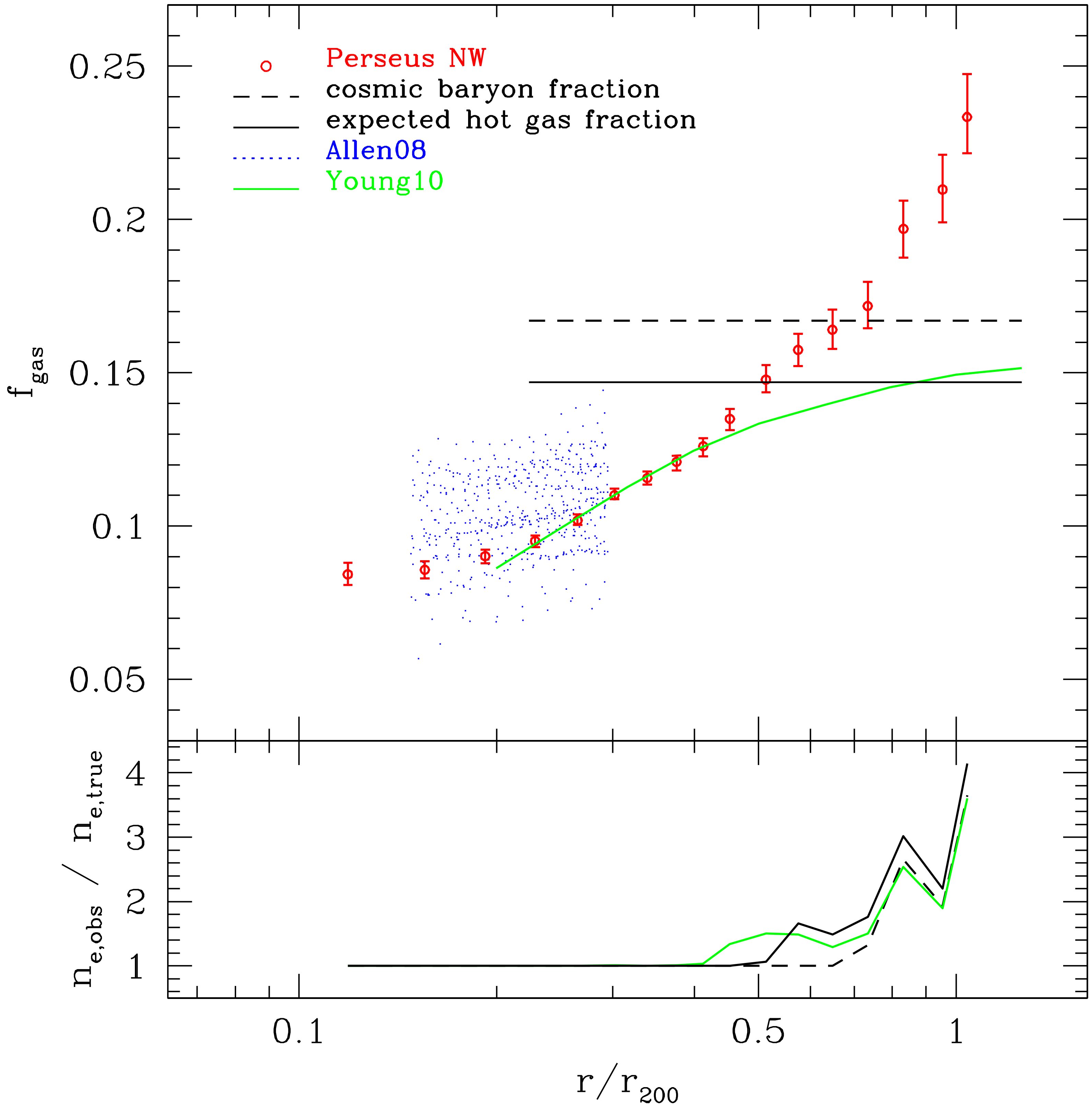
NW arm highly relaxed ➛ use hydrostatic equilibrium to infer gas and total mass profiles (E arm excluded due to cold front at 30')

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

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

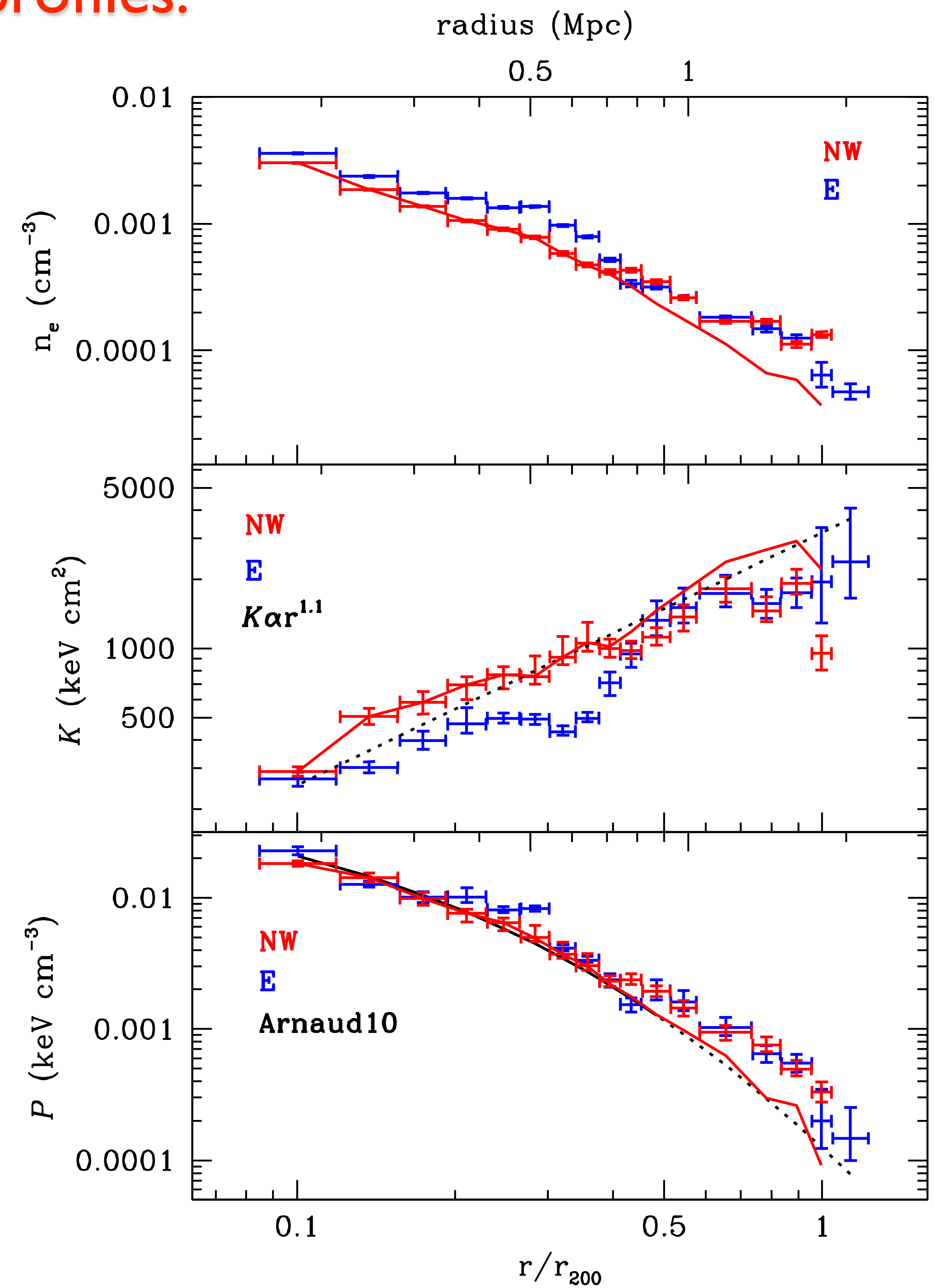
important implications for future studies at very large radii in clusters, e.g. X-ray+SZ

Corrected thermodynamic profiles:

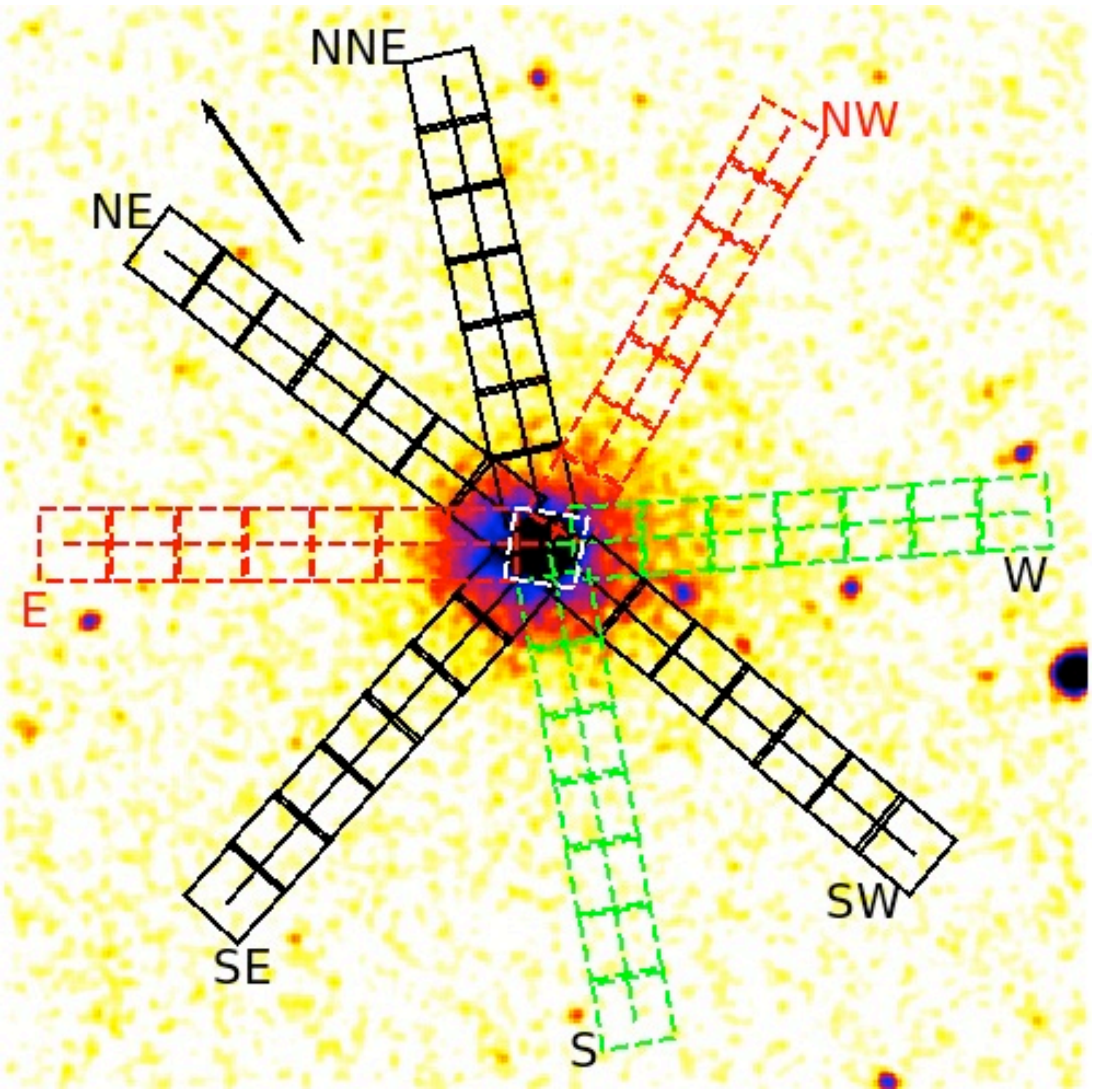
correcting for clumping (red lines) brings measurements into agreement with expected trends

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

simulations predict azimuthal variations in clumping



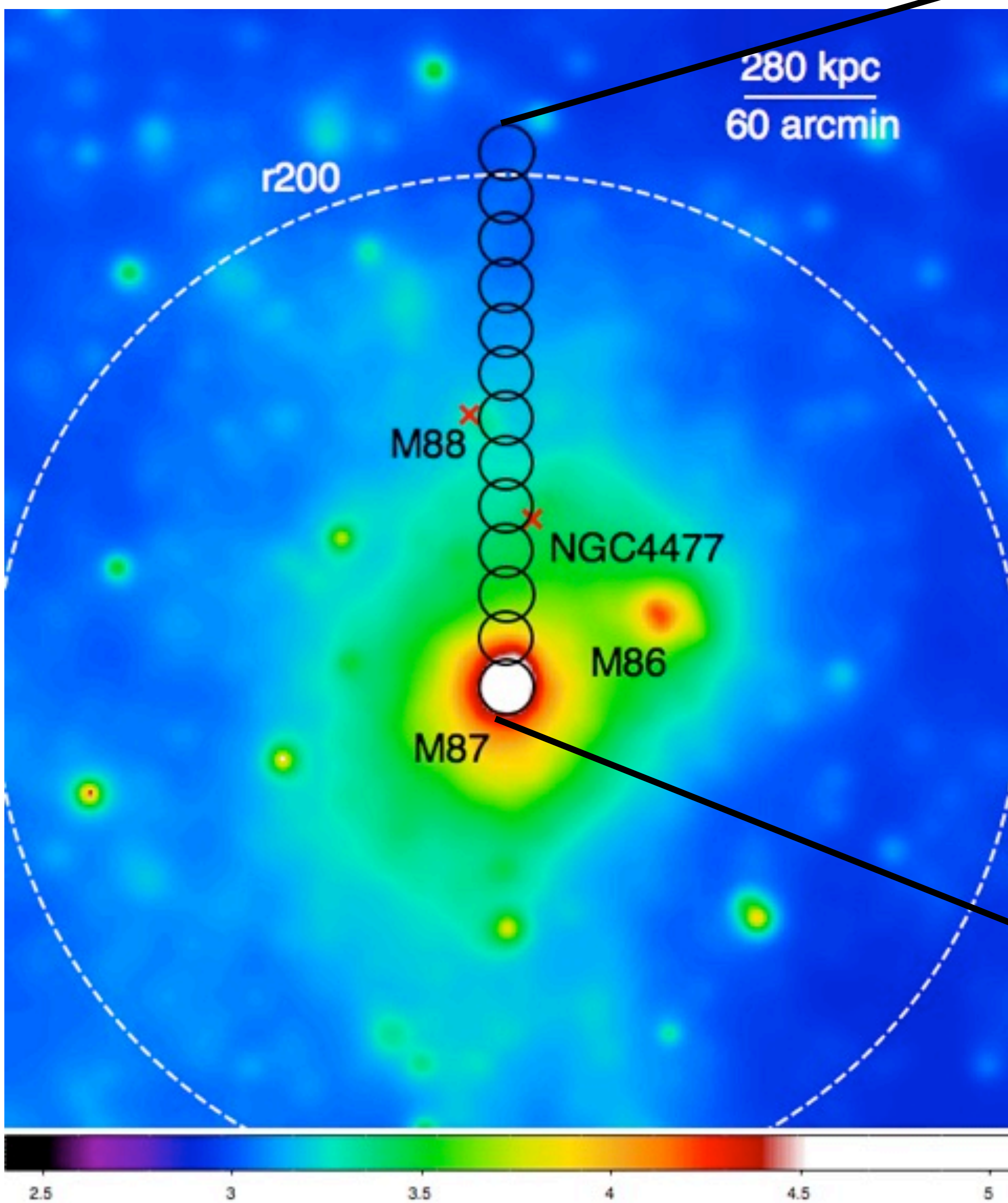
Look forward to:



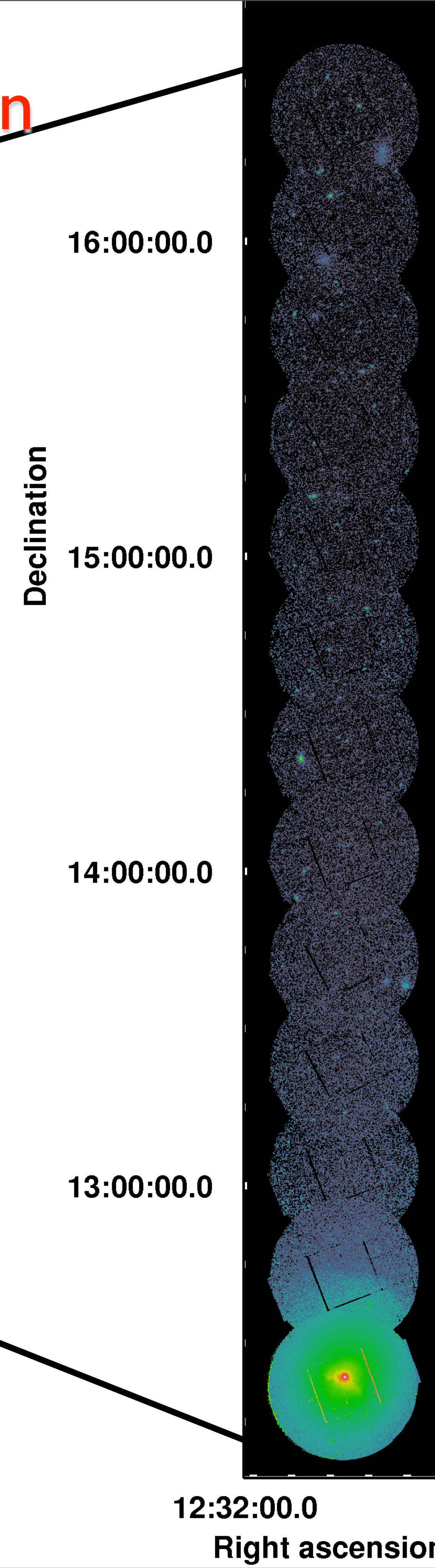
S and W arms have been observed - data reduction is under way

NNE, NE, SE, SW arms will be observed in August.

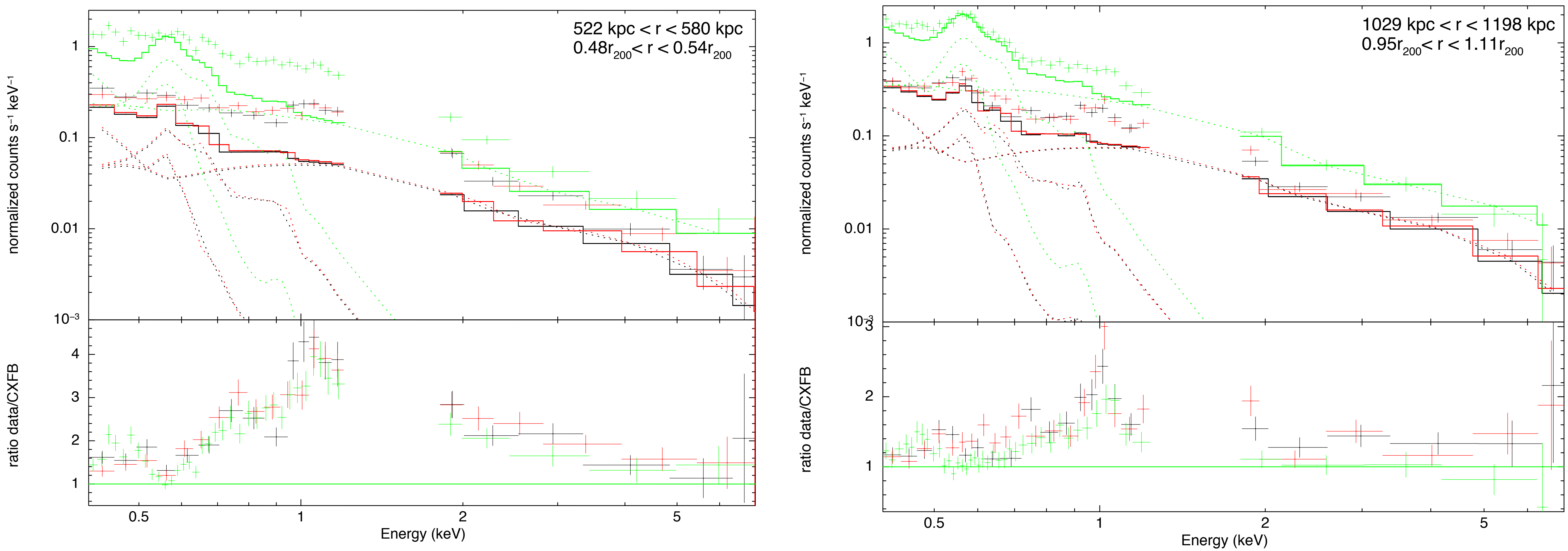
To the virial radius of Virgo with XMM-Newton



Urban et al. 2011

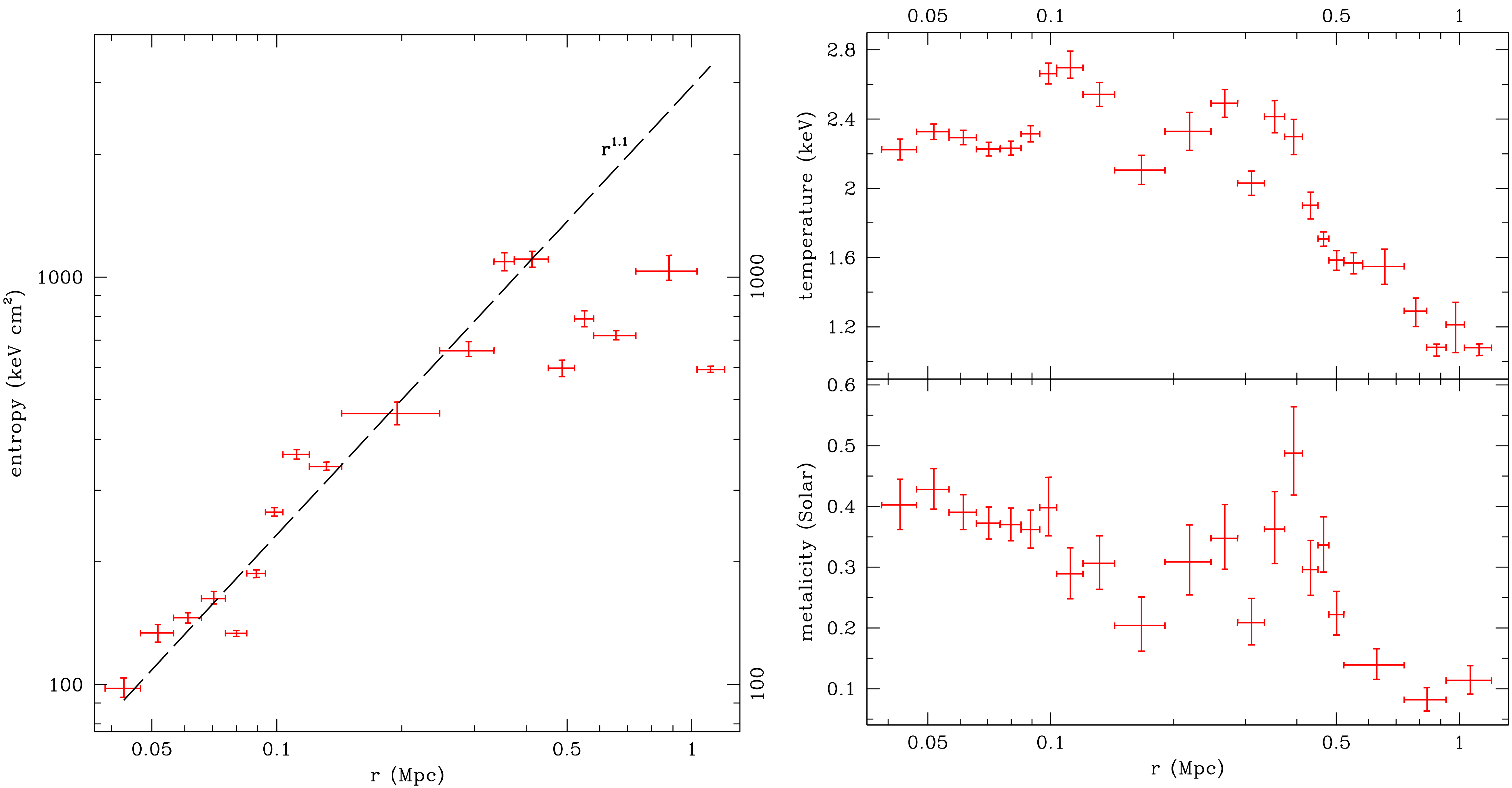


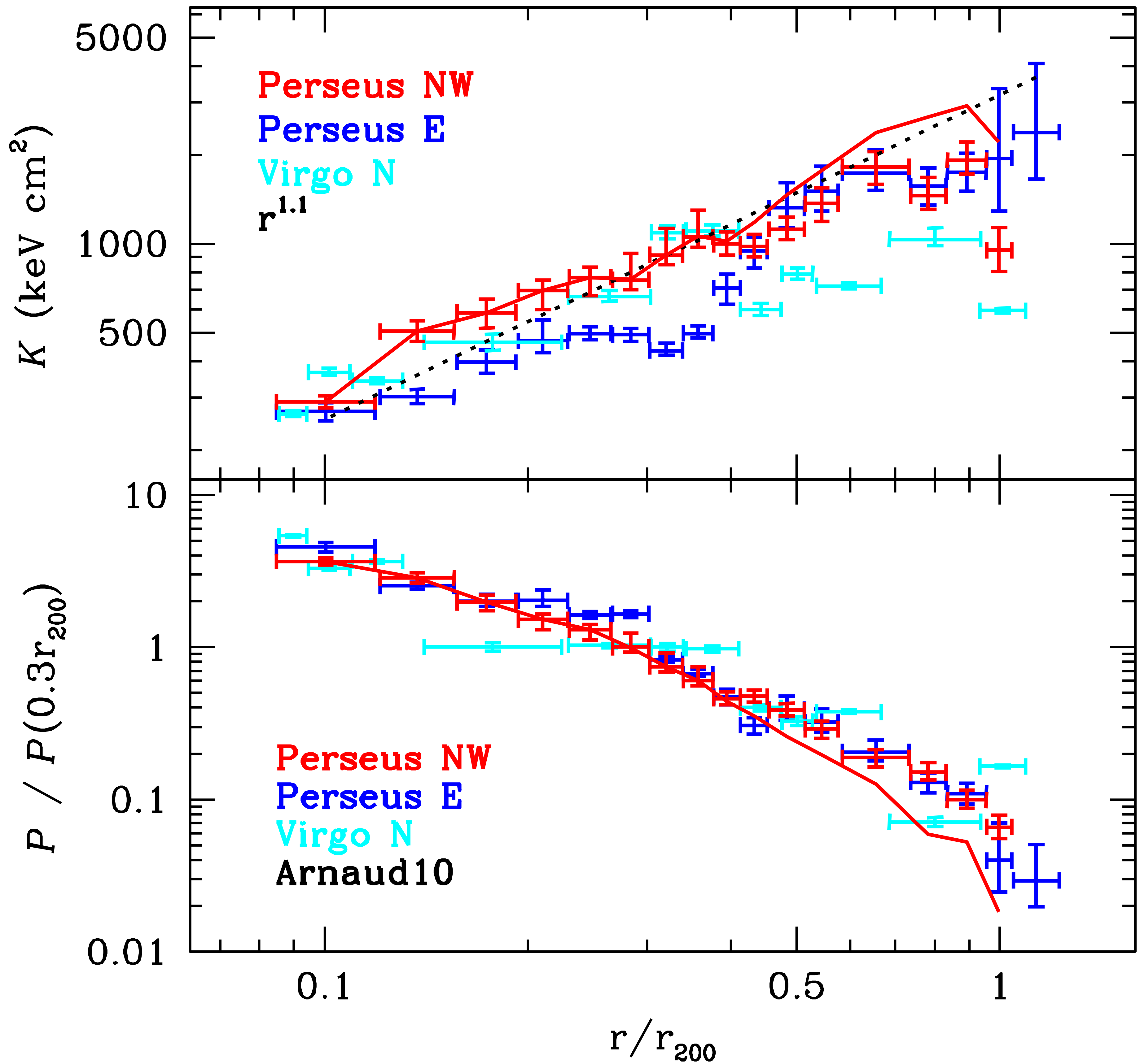
Line emission at ~1 keV



The favorable temperature range of the Virgo ICM allows us to measure the temperature and metallicity even in this background dominated regime.

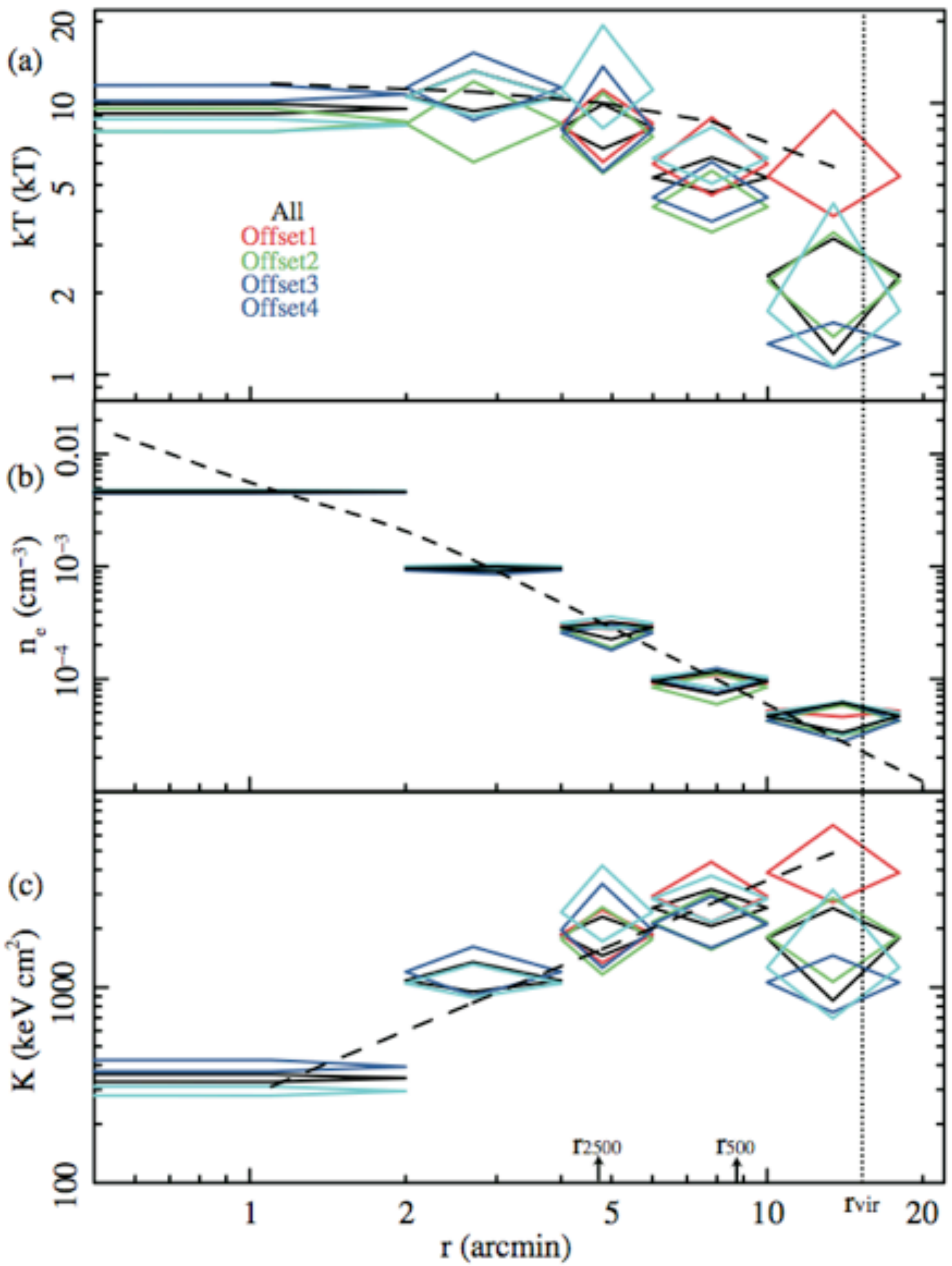
Evidence for gas clumping in the outskirts of the Virgo Cluster





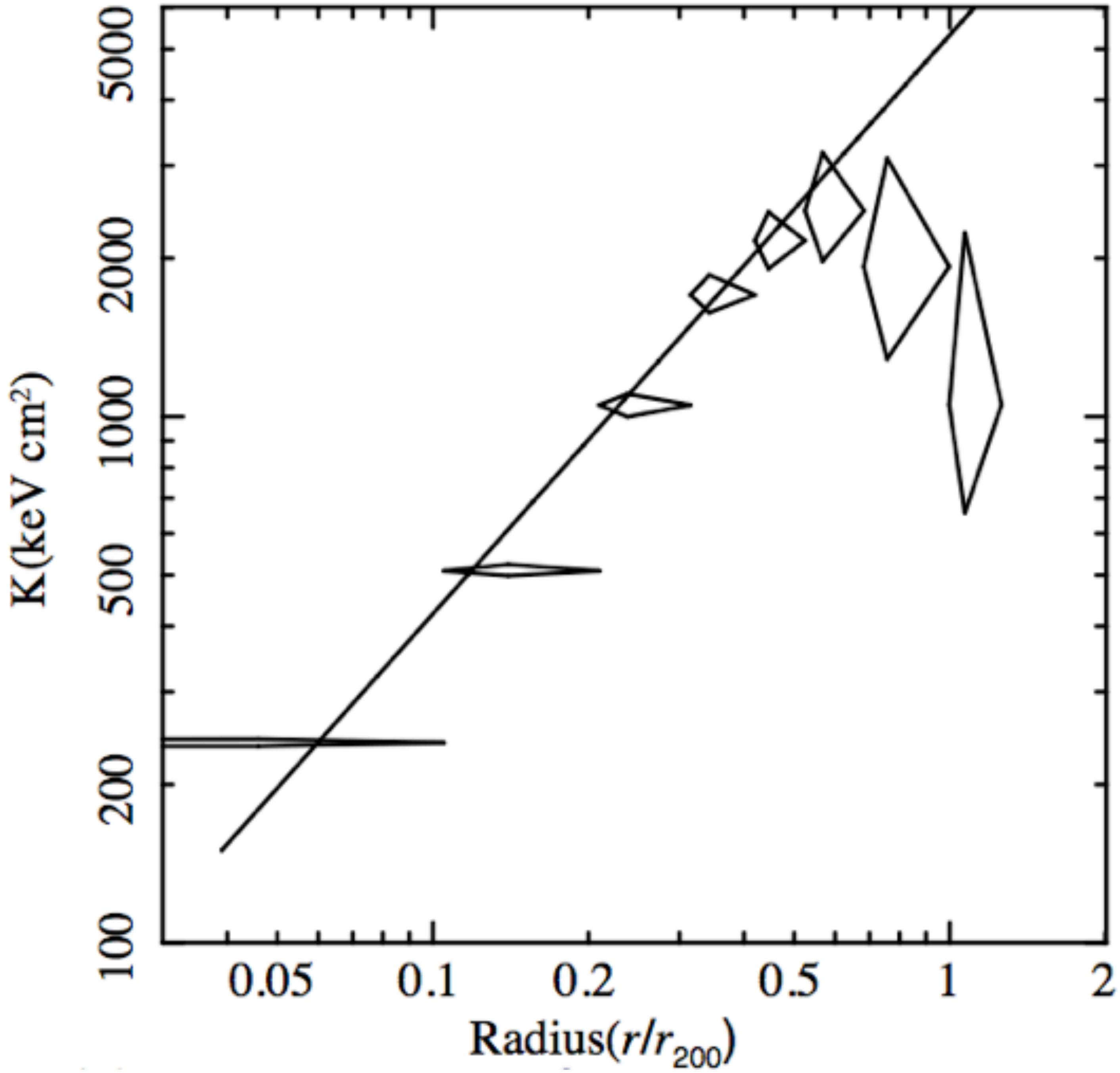
5000
1000
500
10
1
0.1
0.01
Perseus NW
Perseus E
Virgo N
r^1.1
K (keV cm^2)
Perseus NW
Perseus E
Virgo N
Arnaud10
P / P(0.3r200)
0.1
0.5
1
r/r200

A 1689



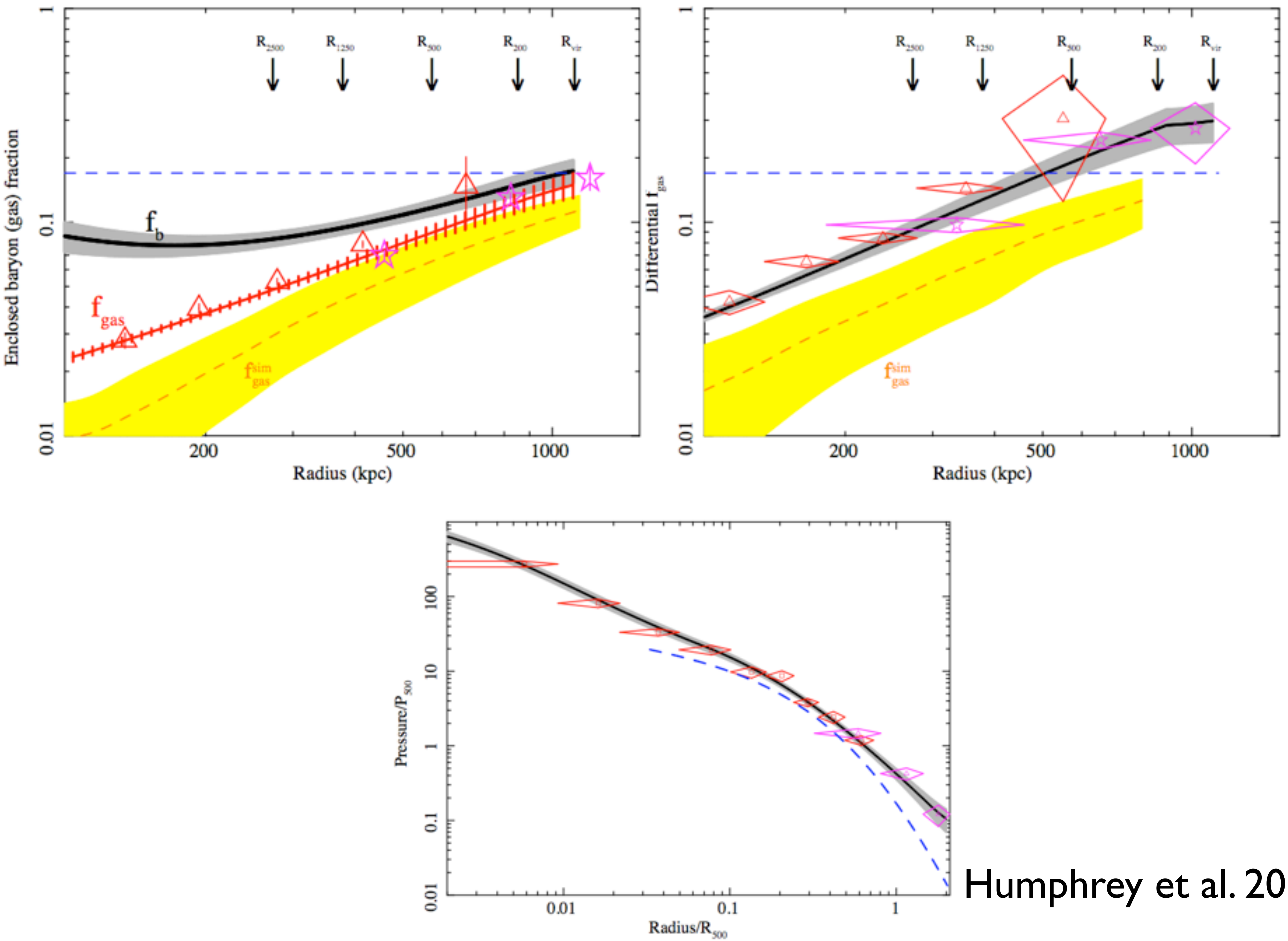
Kawaharada et al. 2010

A 2142



Akamatsu et al. 2011

Fossil group RXJ 1159+5531

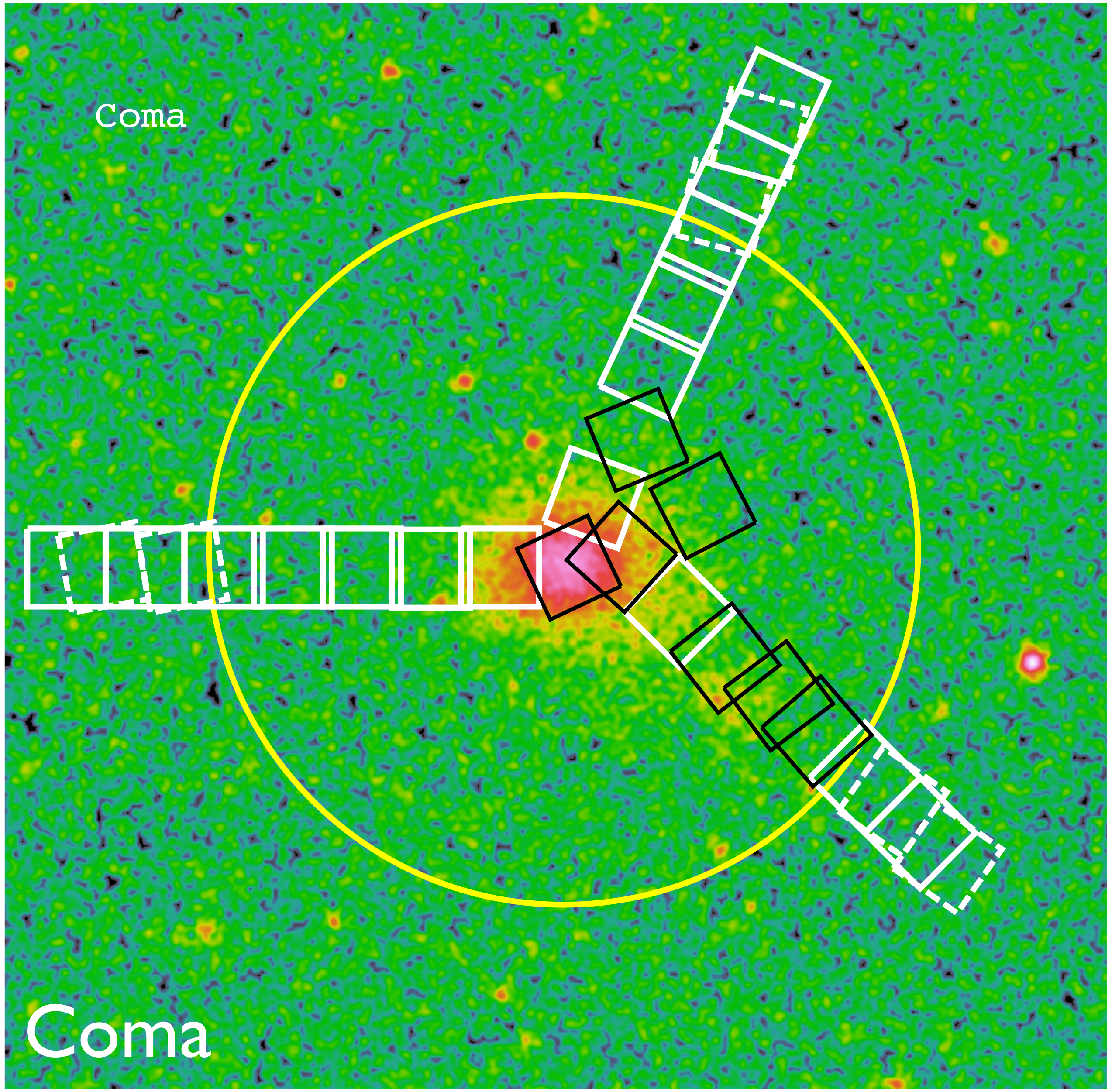


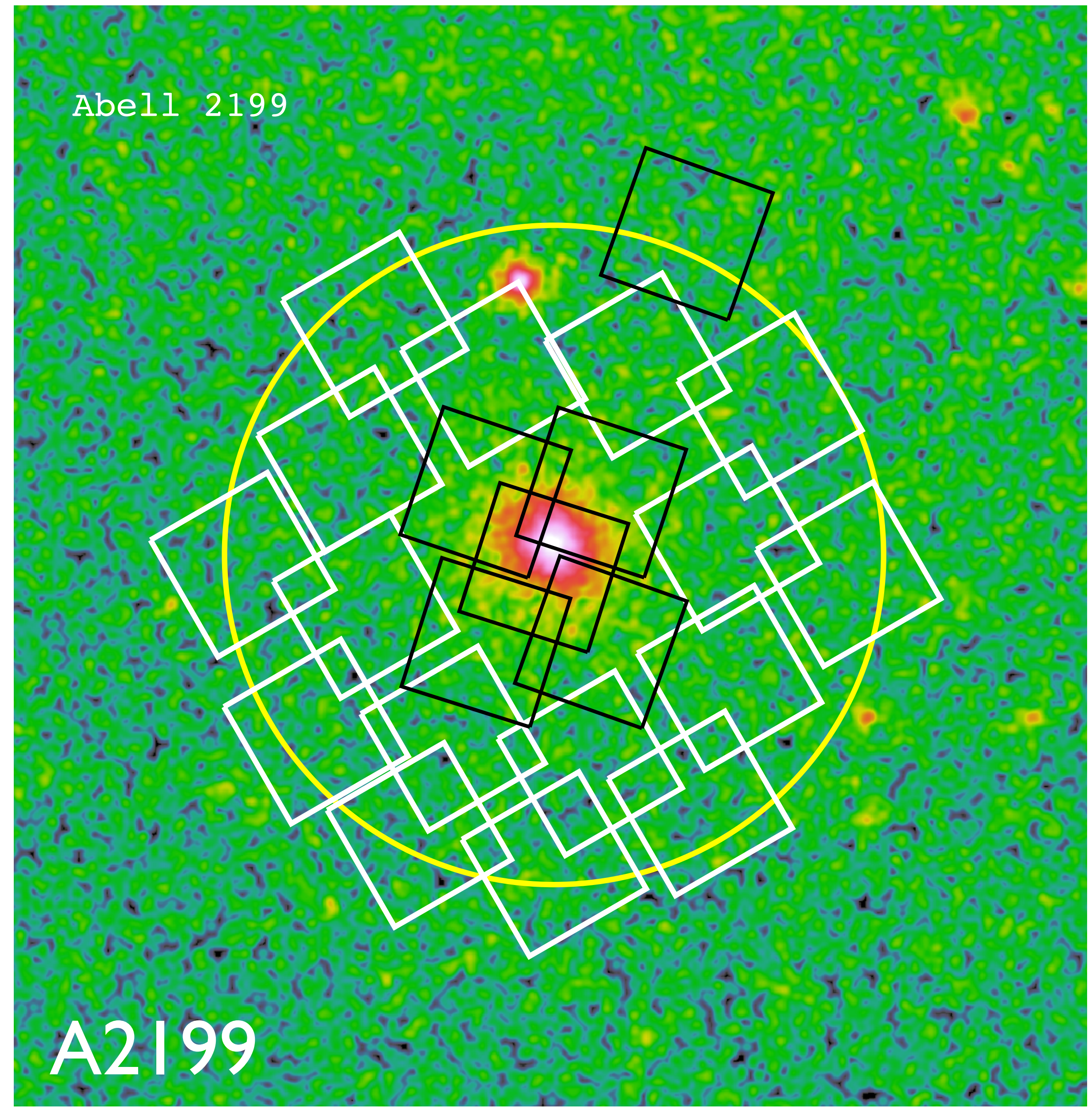
Humphrey et al. 2011

To confirm gas clumping, we need to directly detect and study the clumps with *Chandra*

(See the talk by Alexey Vikhlinin)

The next stage (Suzaku AO-6)





- extension to other nearby, bright clusters (Coma, A2199) to study *system-to-system* variations

Conclusions:

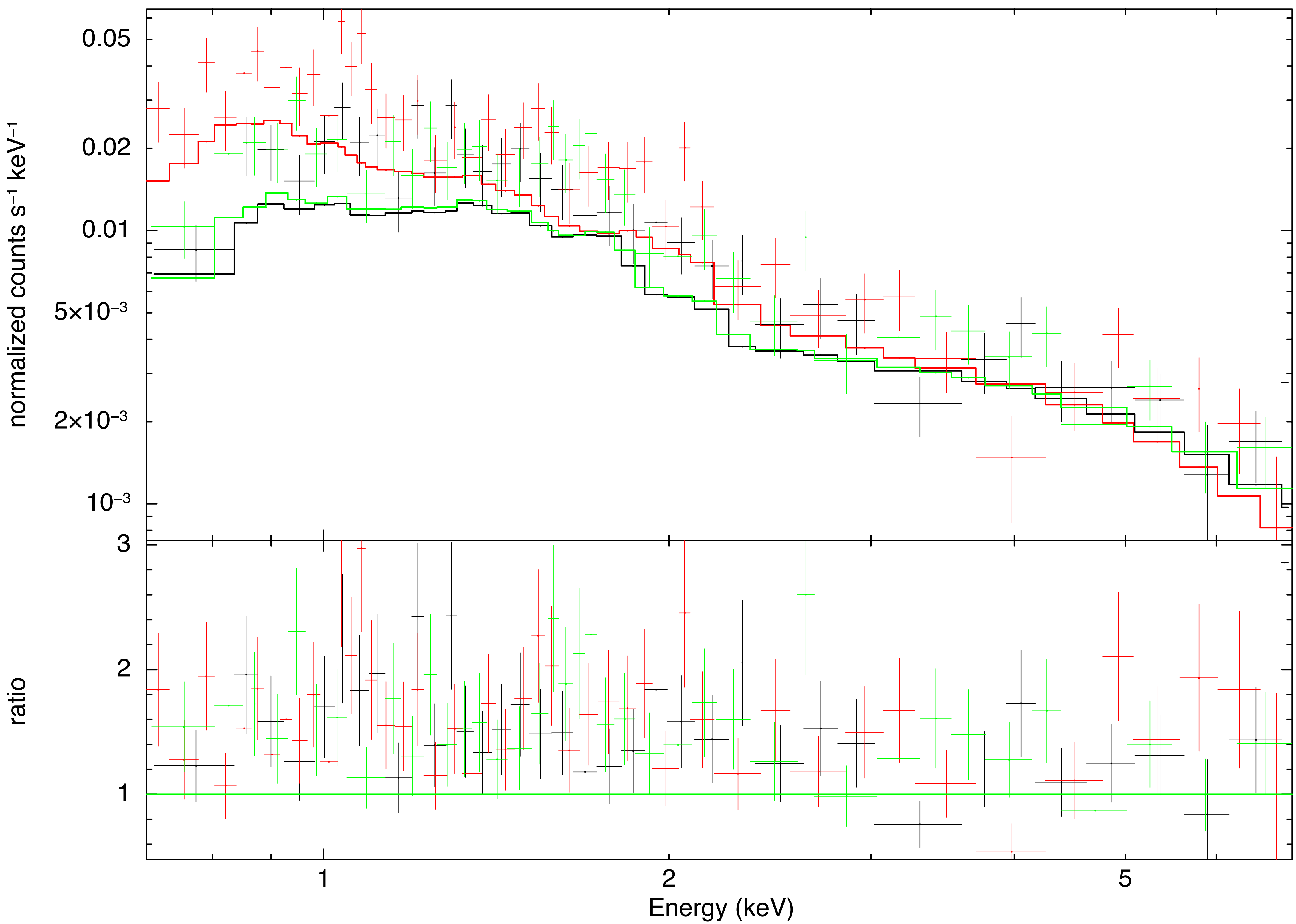
- We have obtained the first observational proofs for gas clumping in cluster outskirts.

- 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}



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