THE ONGOING GROWTH OF NEARBY CLUSTERS OF GALAXIES

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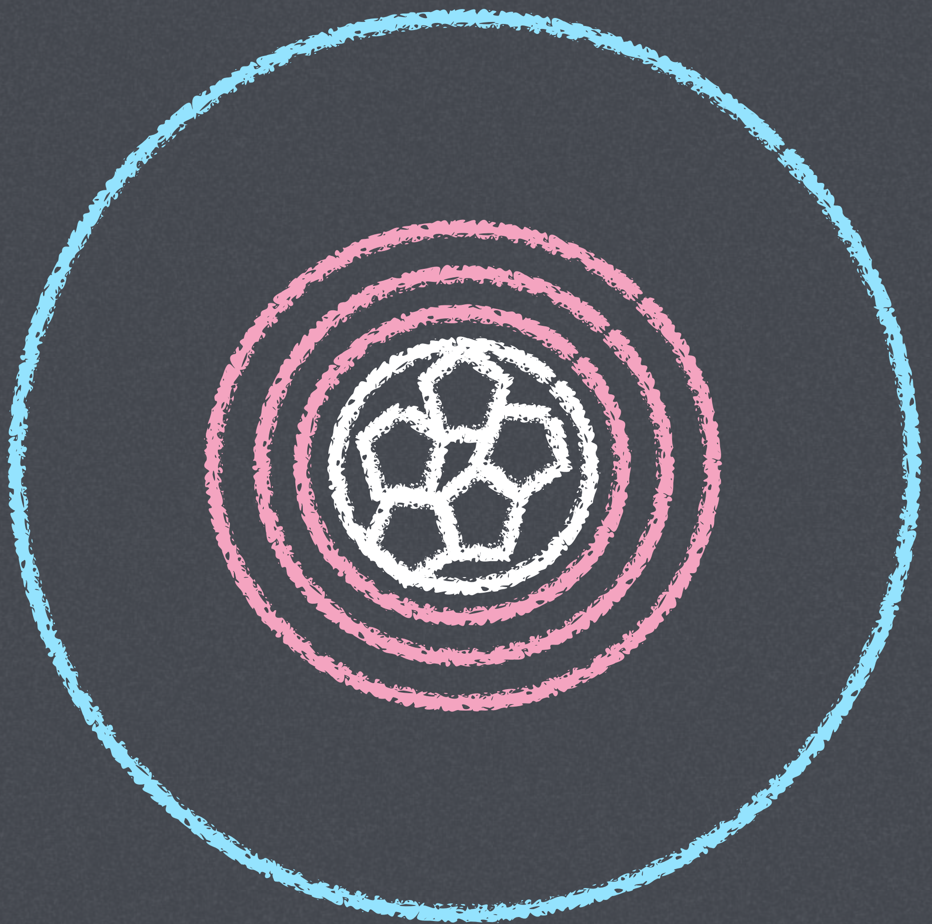
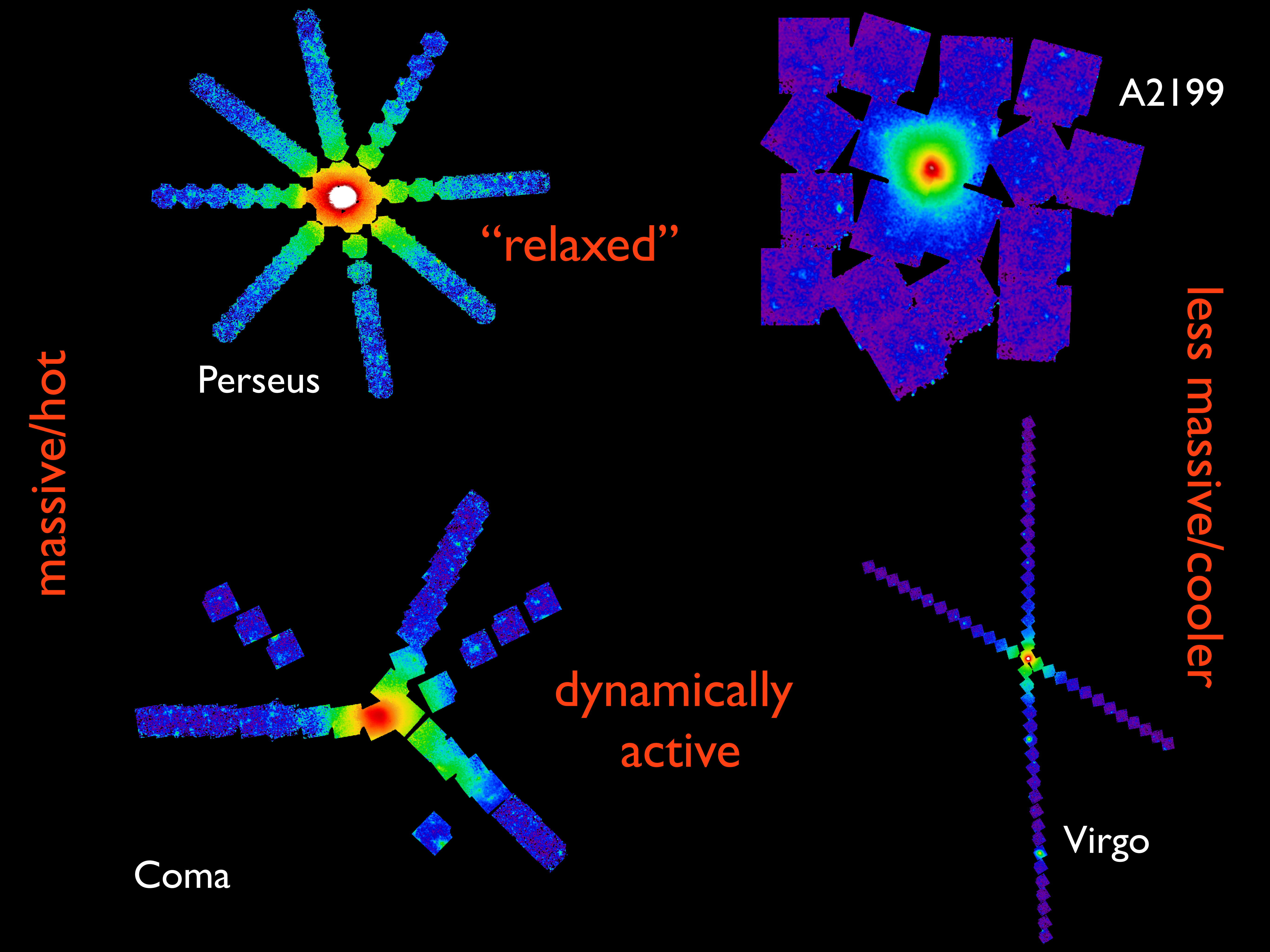
with: Ondrej Urban, N. Werner, S. Allen,
and the Perseus/Virgo Suzaku Key Project collaborations

MY BLACKBOARD VIEW OF GALAXY CLUSTERS (PRE-SUZAKU)

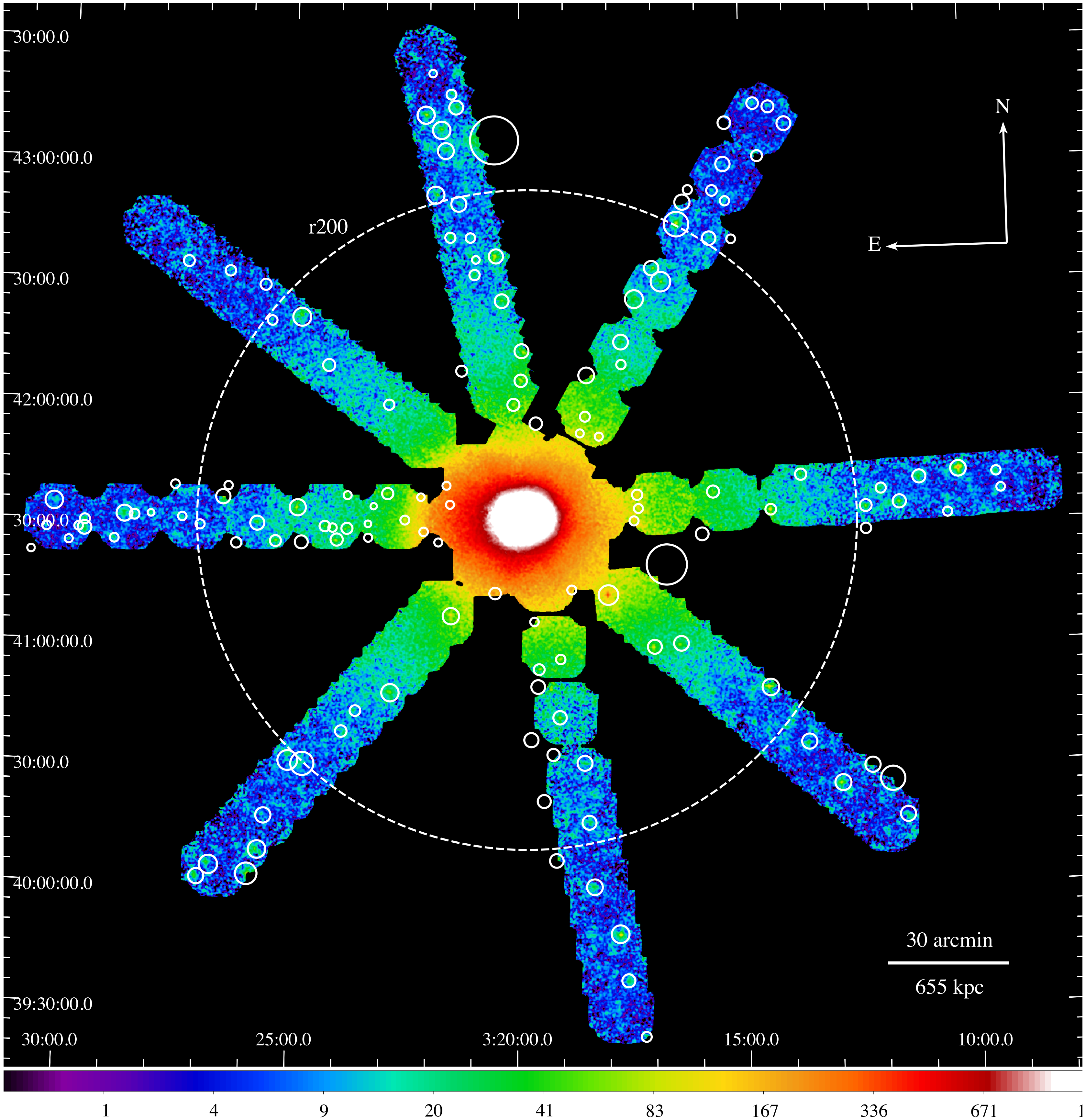


- 2D spectral maps (up to ~r2500)
- thermodynamic profiles (up to ~r500)
- only some information about surface brightness, but no temperature



A2199
"relaxed"
Perseus
massive/hot
less massive/cooler
dynamically
active
Coma
Virgo

The Perseus Key Project



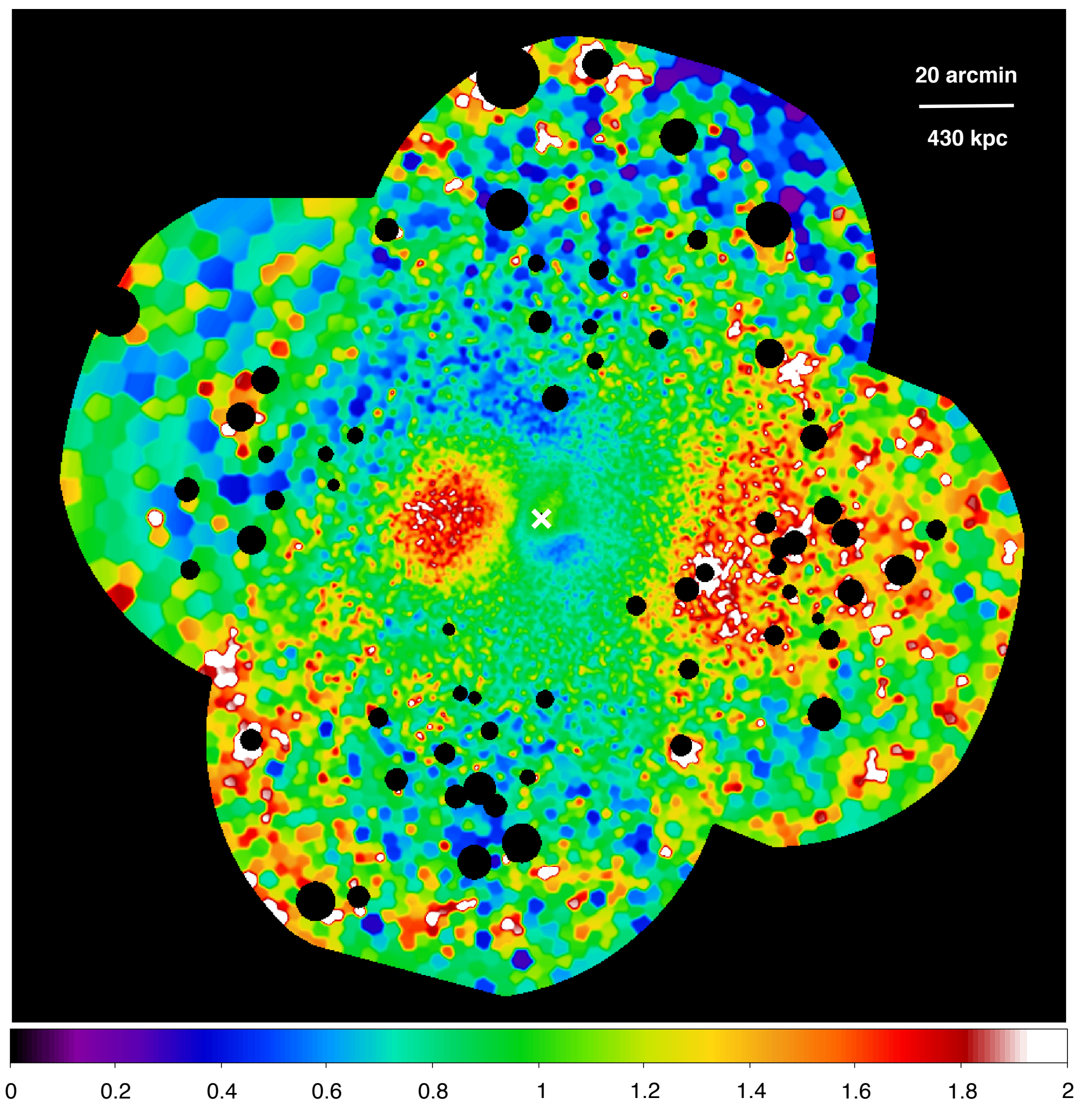
85 Suzaku pointings

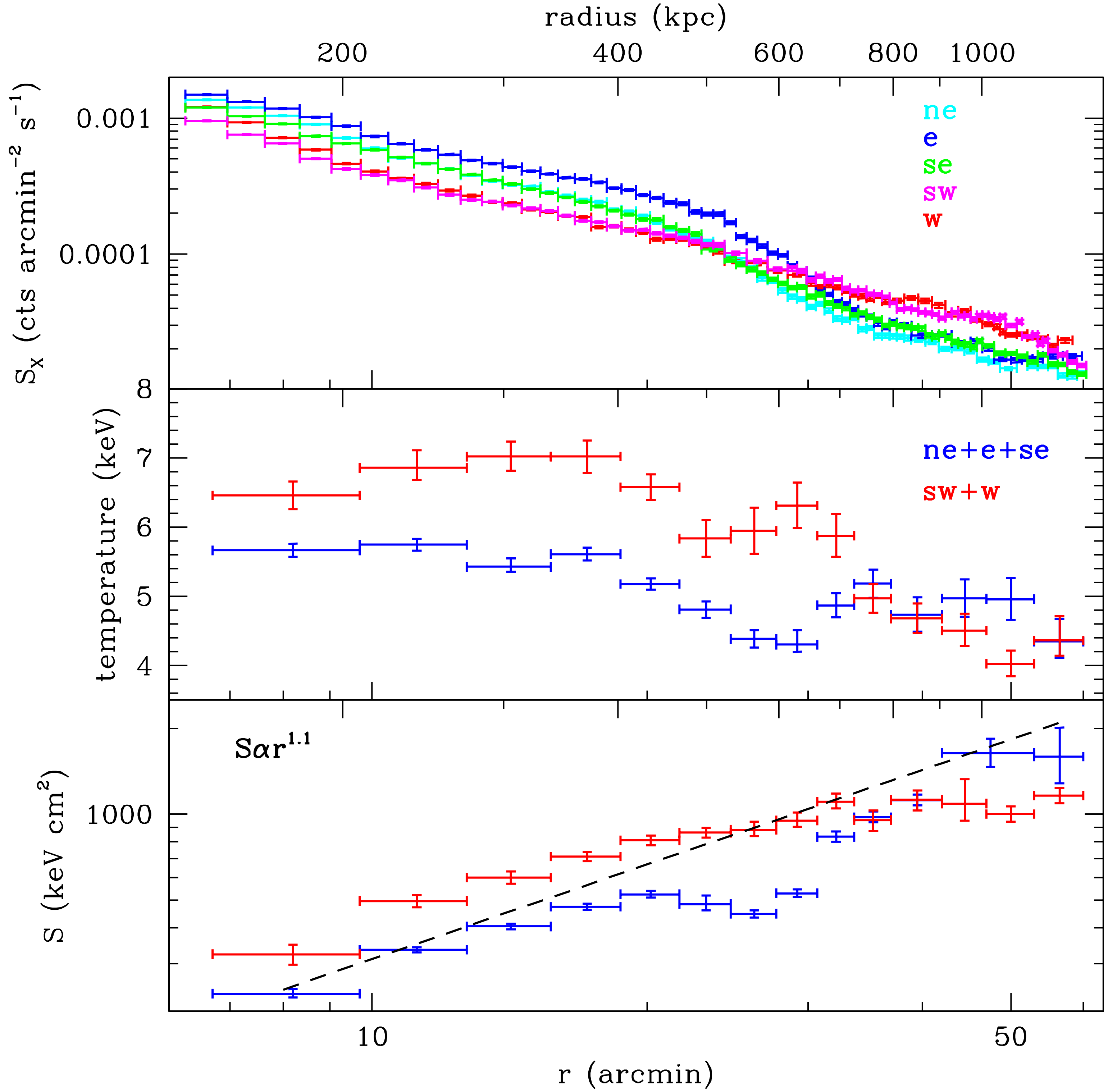
8 different directions

1Ms total exposure

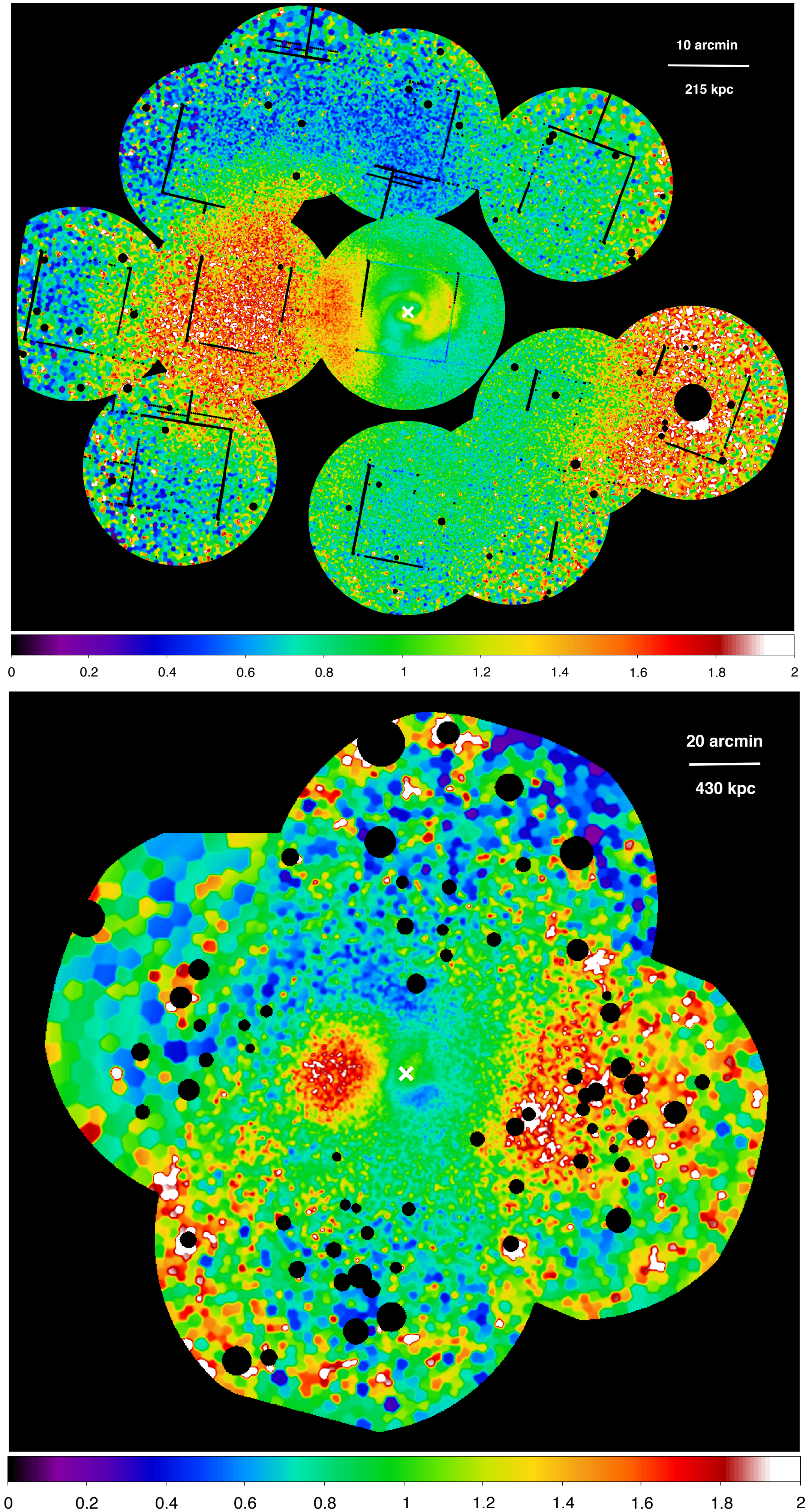
AO 4-6 (July '09 - Sept '11)

ALTERNATING BRIGHT, LOW-TEMPERATURE LARGE-SCALE FEATURES



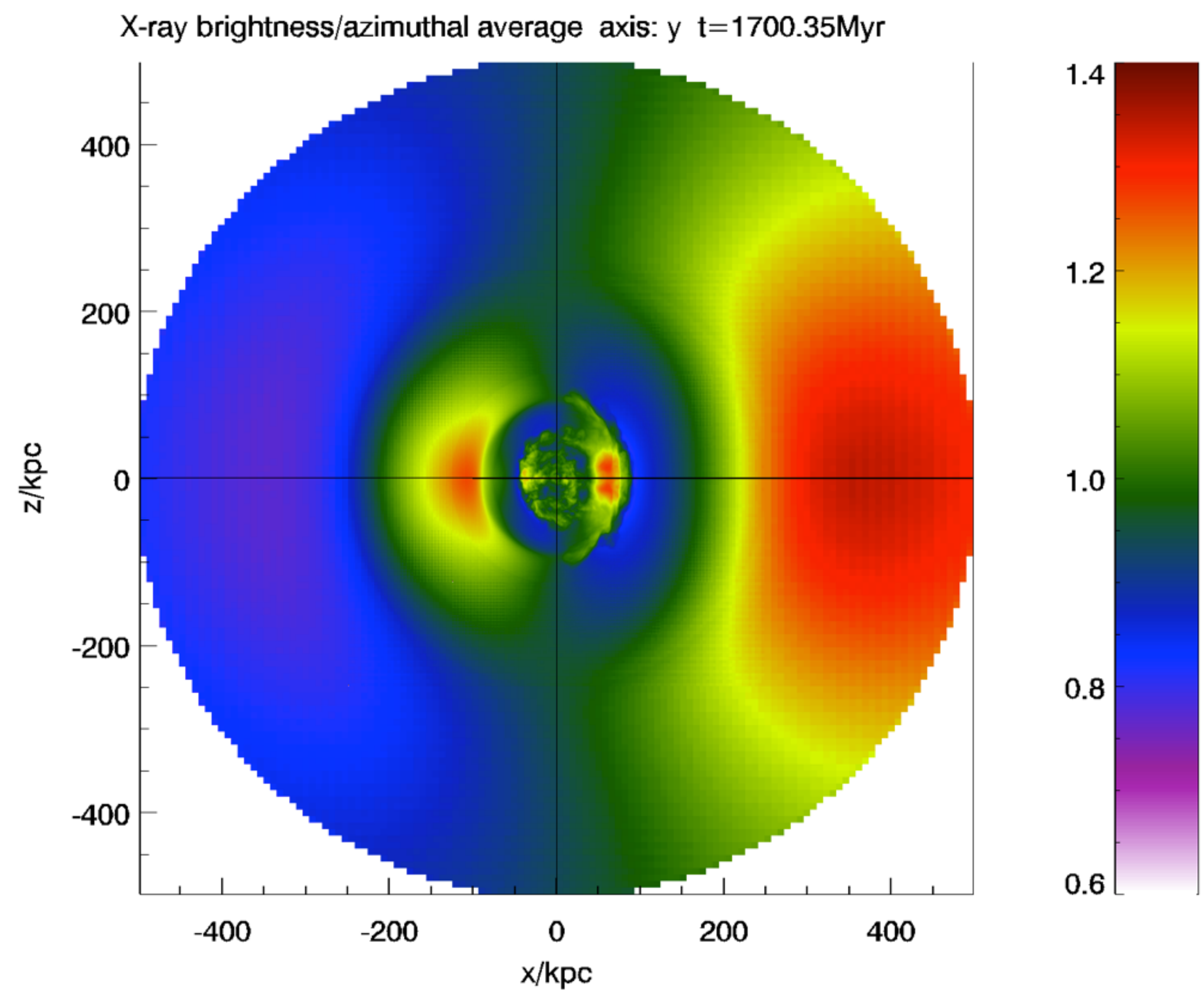


Simionescu et al. 2012



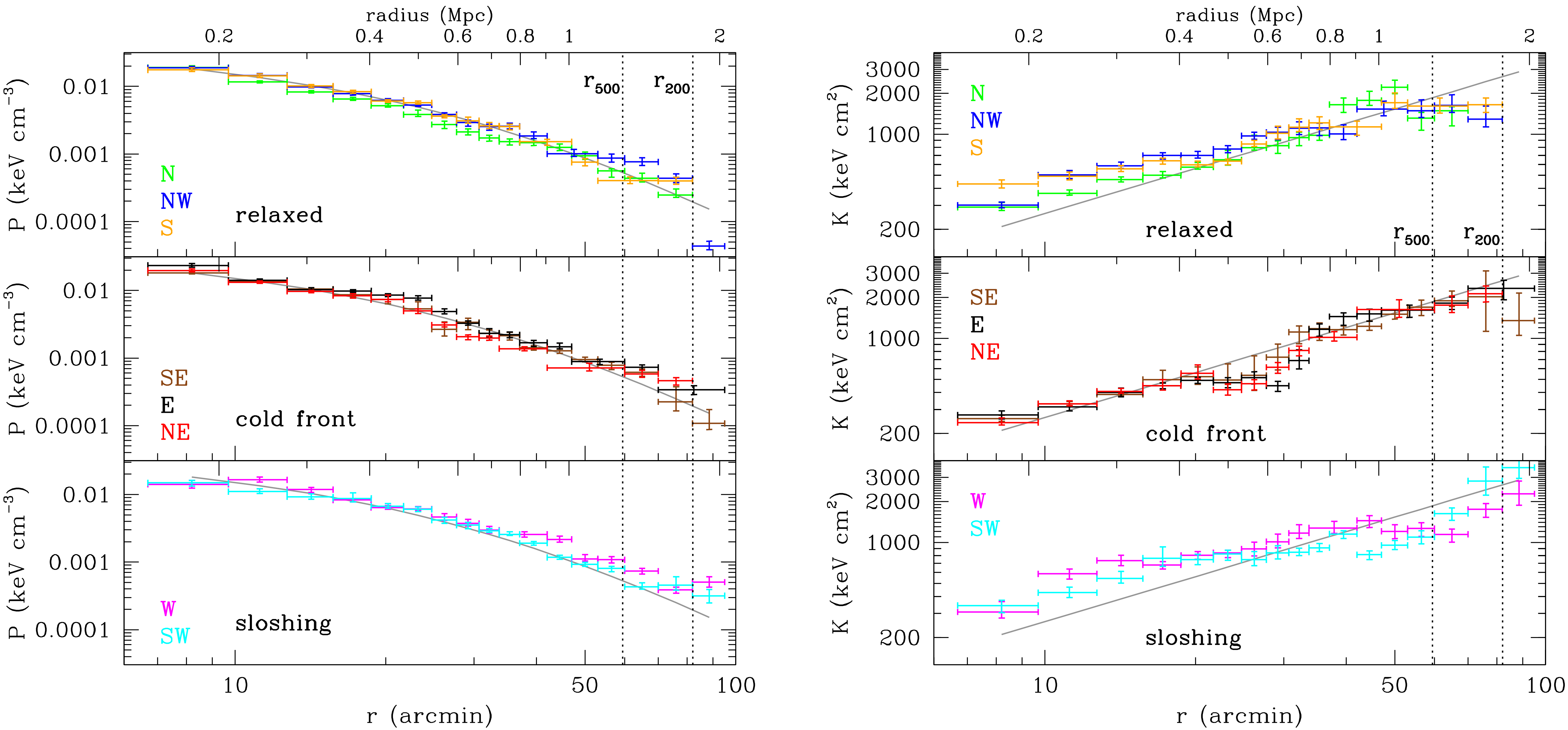
JUST LIKE THE SLOSHING SEEN IN COOL CORES BUT ON MUCH LARGER SCALES!

see also Rossetti et al. 2013 (A2142), Walker et al. 2014 (RXJ2014.8-2430)



Roediger et al. 2011

PRESSURE AND ENTROPY PROFILES IN PERSEUS



Urban et al. 2014

$$\frac{K}{K_{500}} = 1.47\left(\frac{r}{r_{500}}\right)^{1.1}$$

(Voit et al. 2005, Pratt et al. 2010)

$$kT^{\mathrm{expected}}(r) = P(r)^{2/5}K(r)^{3/5}$$

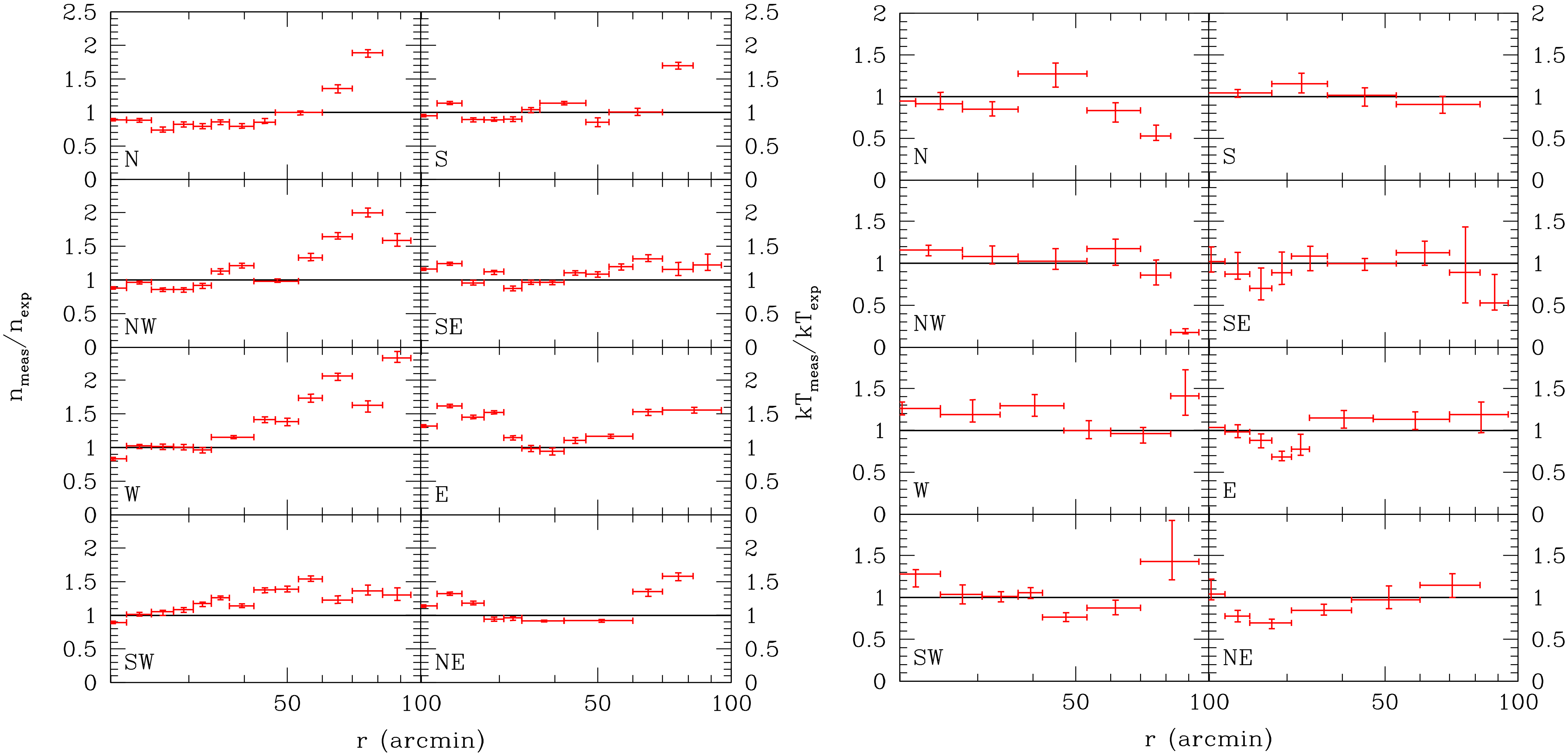
$$n_{\mathrm{e}}^{\mathrm{expected}}(r) = P(r)^{3/5}K(r)^{-3/5}$$

$$\frac{P(r)}{P_{500}} = \frac{P_0}{(c_{500}x)^{\gamma}\left[1 + (c_{500}x)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

(Nagai et al. 2007, Planck Collaboration 2013)

Note 1: be careful about normalisation of entropy power law model!

Note 2: be careful about inferring r_{500} from scaling relations! (e.g. Y_X-r_{500} relation has less scatter than kT-r_{500}) Ideally, use exact same method as Planck Collaboration 2013 if using their model.

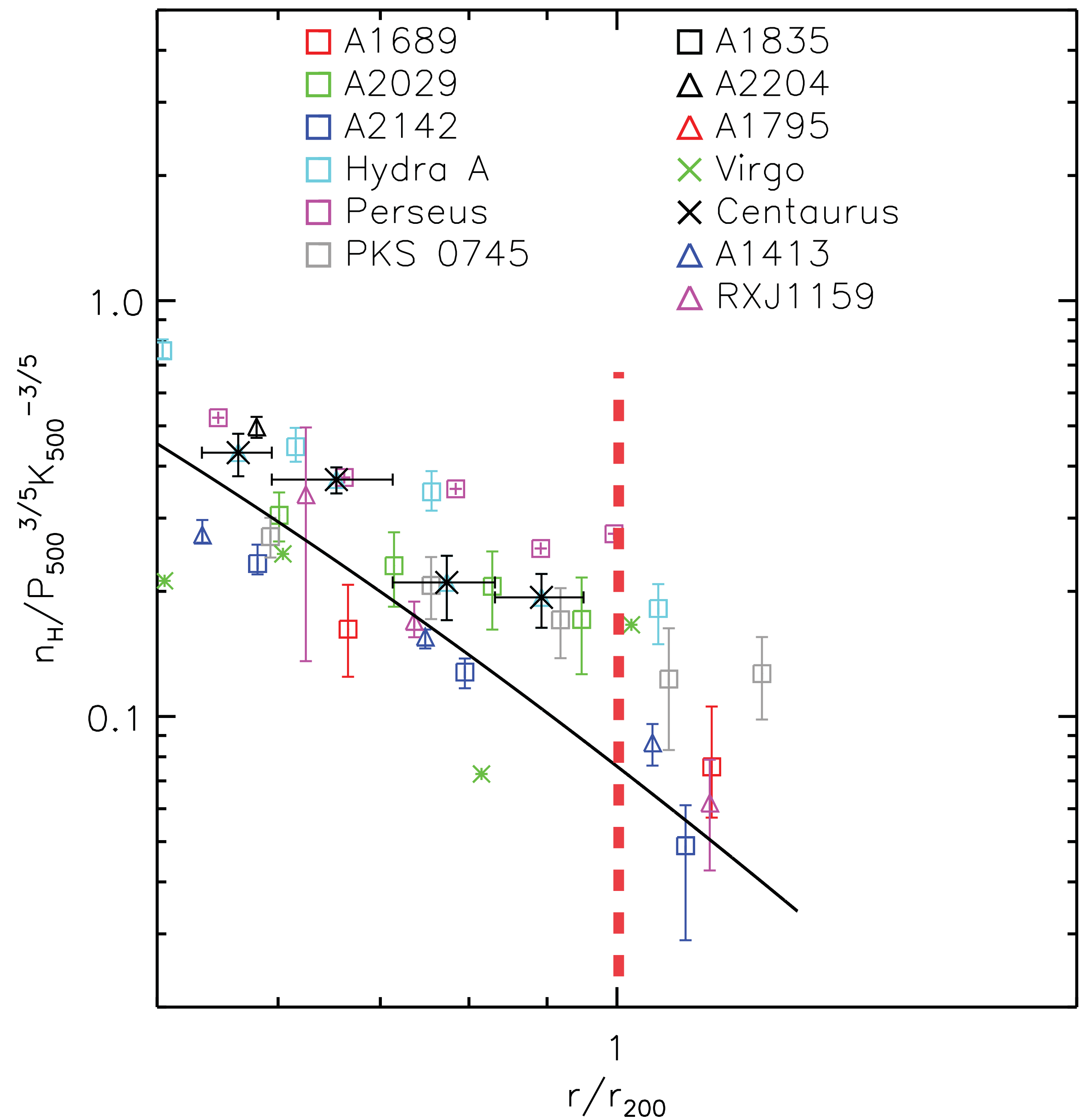


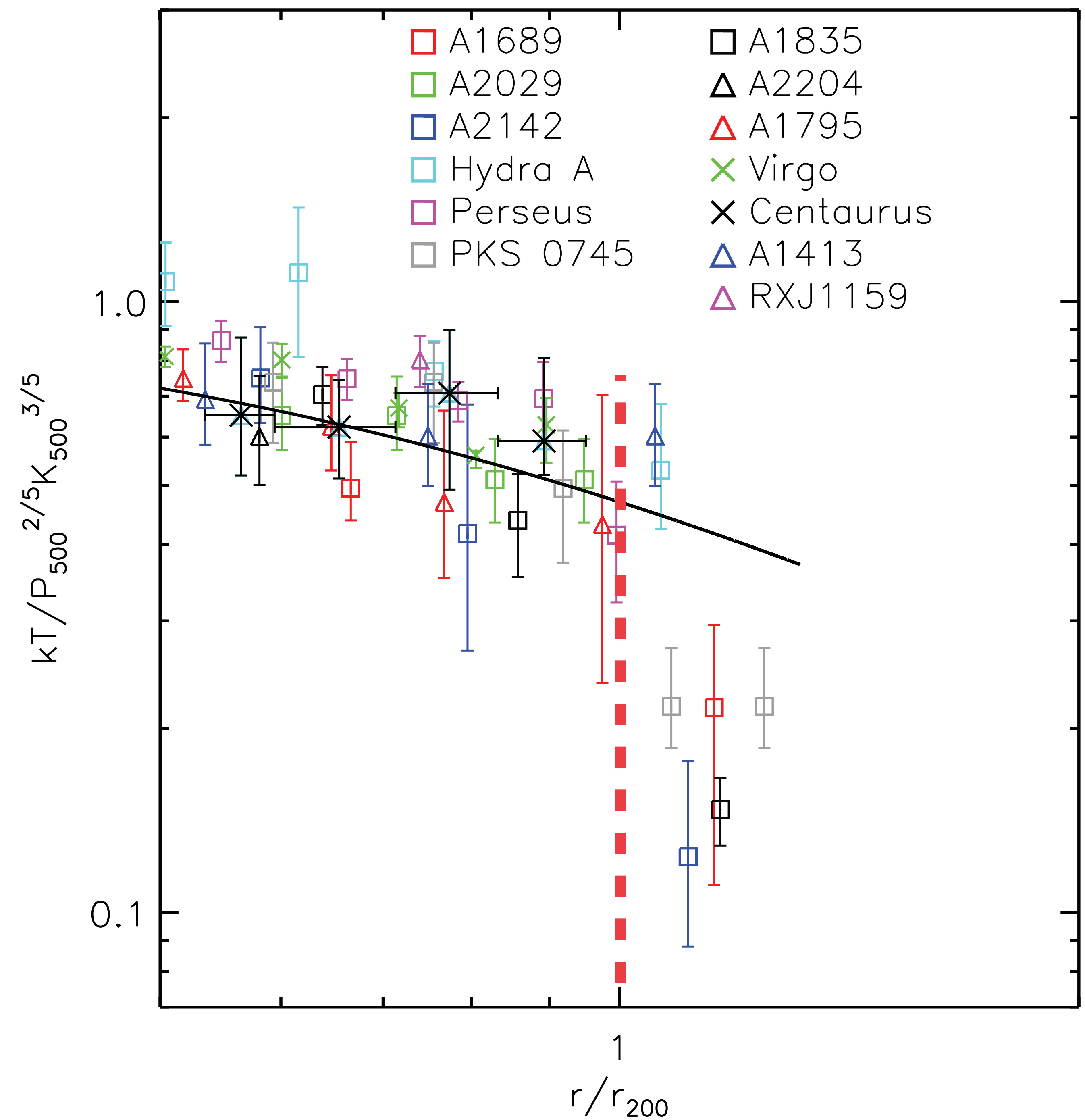
In Perseus, *within* r_{200} along all arms, correcting n_e is SUFFICIENT to bring BOTH entropy and pressure in agreement with expected profiles.

Both "macroscopic clumping" (due to E-W large-scale sloshing asymmetries) and "microscopic clumping" (along relaxed N-S axis) must be present.

Urban et al. 2014

IS THIS DENSITY BIAS COMMON?



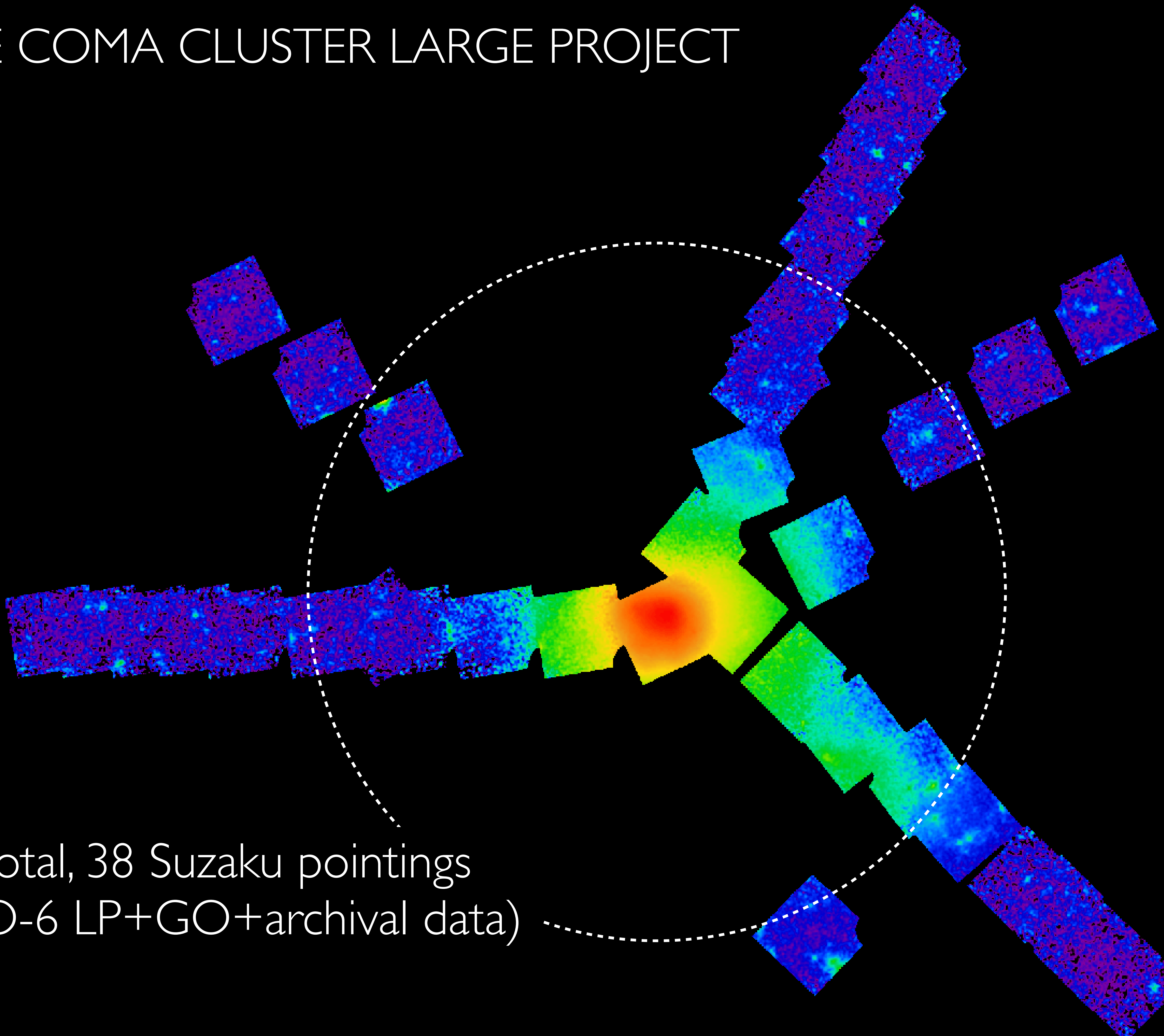


NO temperature biases within r200; some interesting effects start to be seen beyond (does electron-ion non equilibrium set in as well??)

Some clusters show no density bias, e.g. A2142 or the group RXJ1159

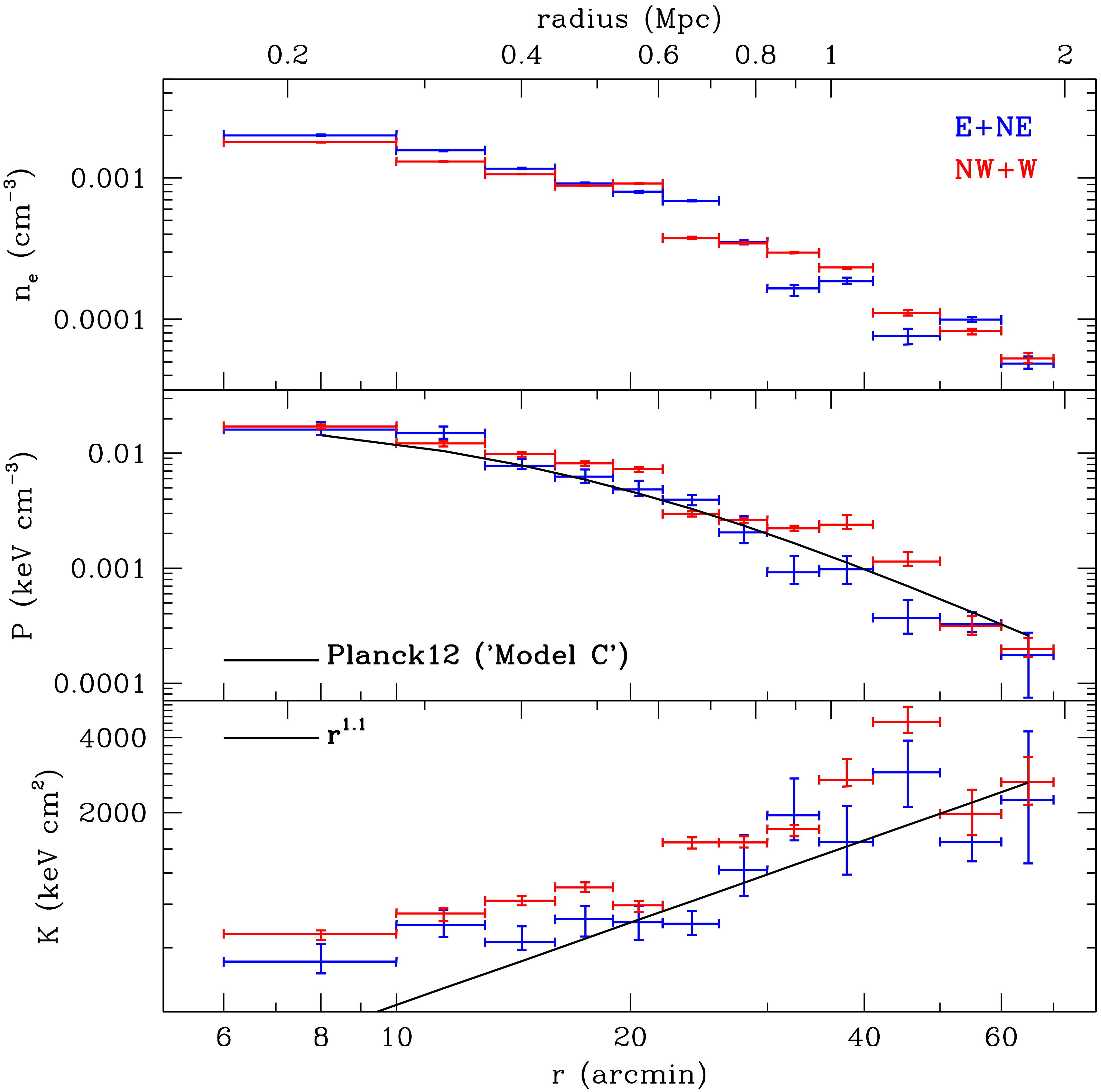
Walker et al. 2013

THE COMA CLUSTER LARGE PROJECT



In total, 38 Suzaku pointings
(AO-6 LP+GO+archival data)

Clumping in the Coma Cluster?



Coma: entropy and pressure agree with expectations beyond r_{500}

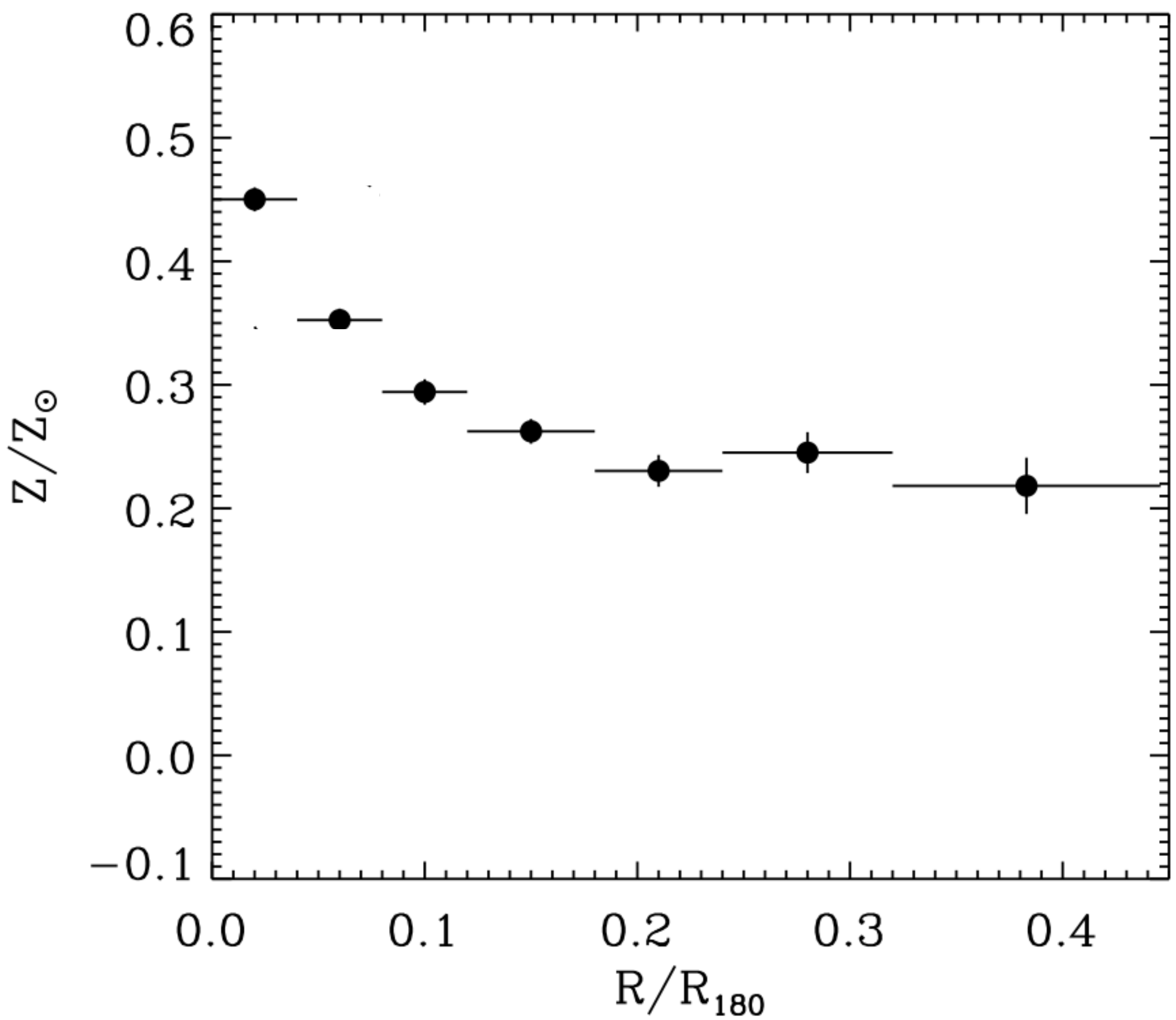
Are the clumps destroyed in more dynamically active regions?

Can we use the morphology of the central parts to infer the dynamical state of the outskirts?

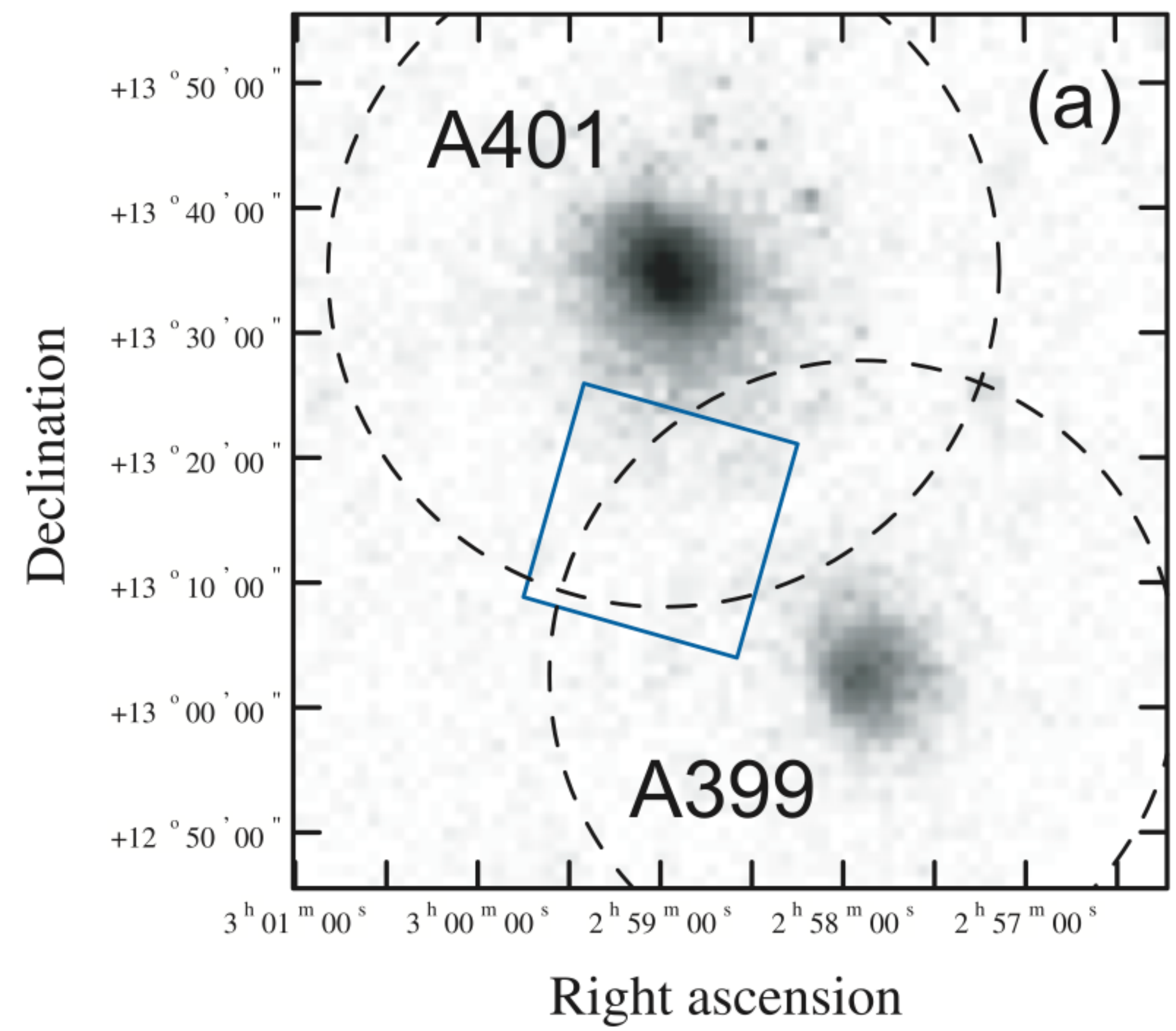
Simionescu et al. 2013

Beyond thermodynamics:
Chemical enrichment history of the ICM

Previous Evidence Suggesting Metal Enrichment in Cluster Outskirts

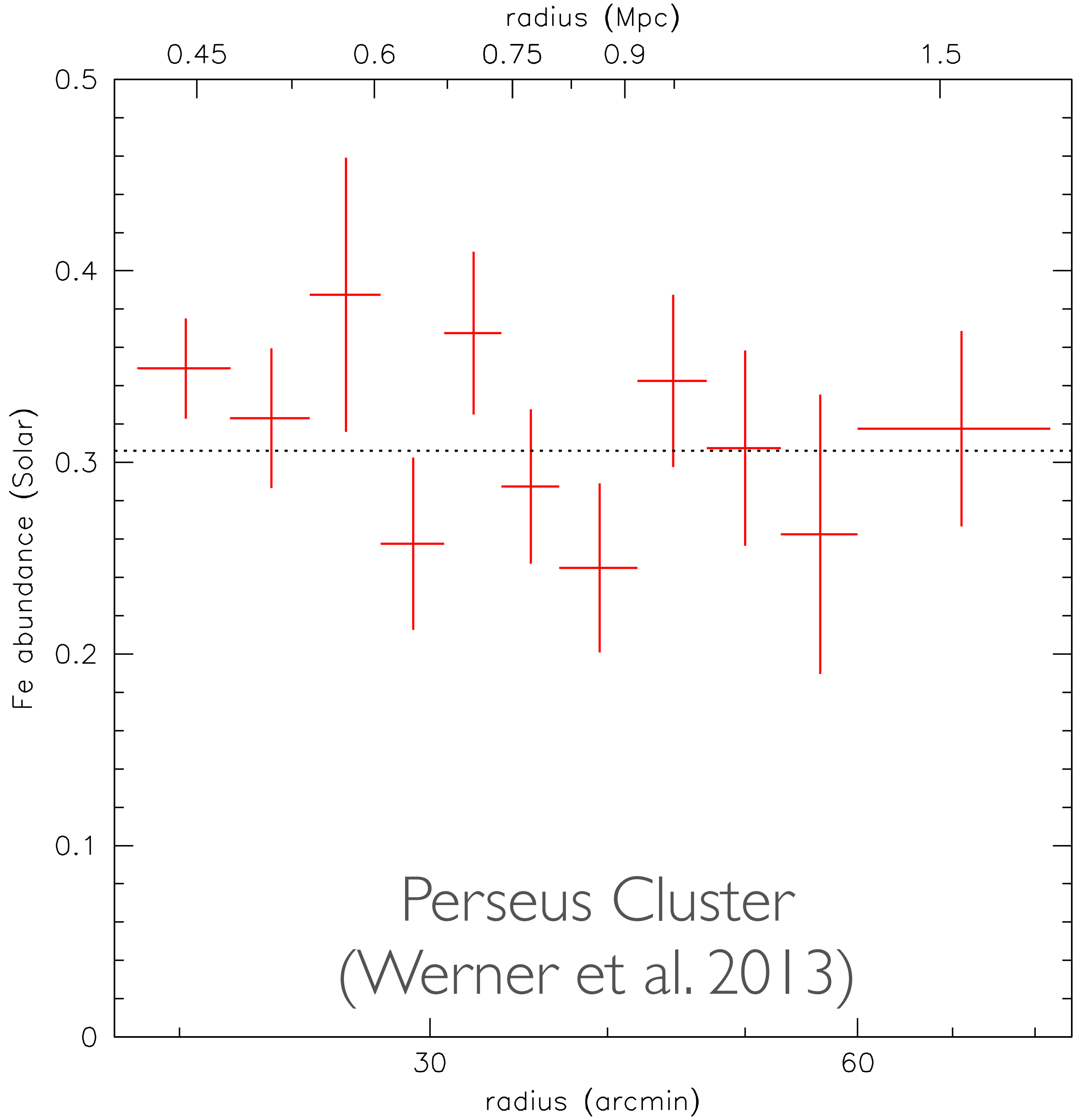


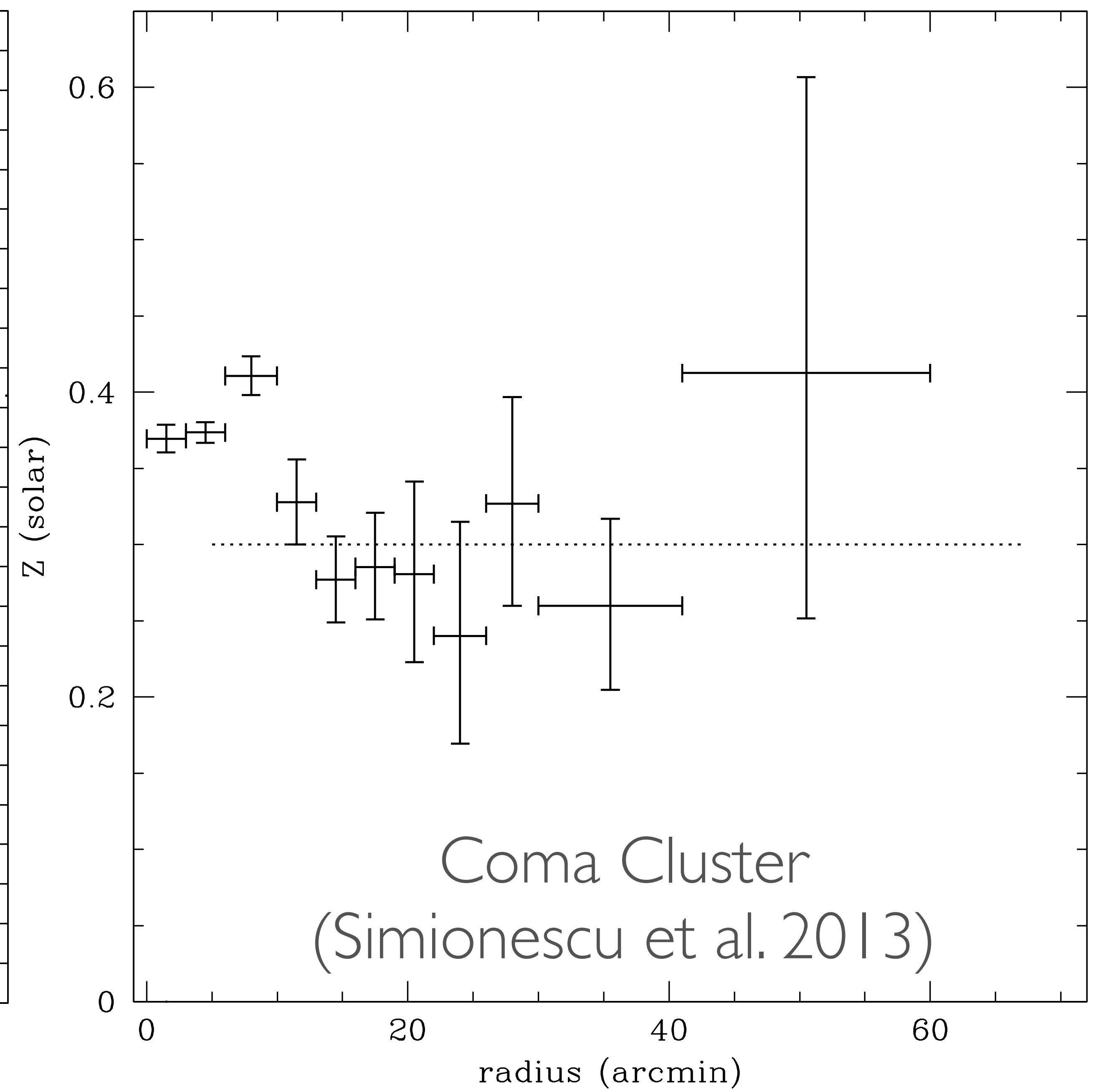
Leccardi et al. 2008
average metallicity profile of a sample of clusters with XMM



Fujita et al. 2008
abundance in the compressed region between two merging clusters with Suzaku

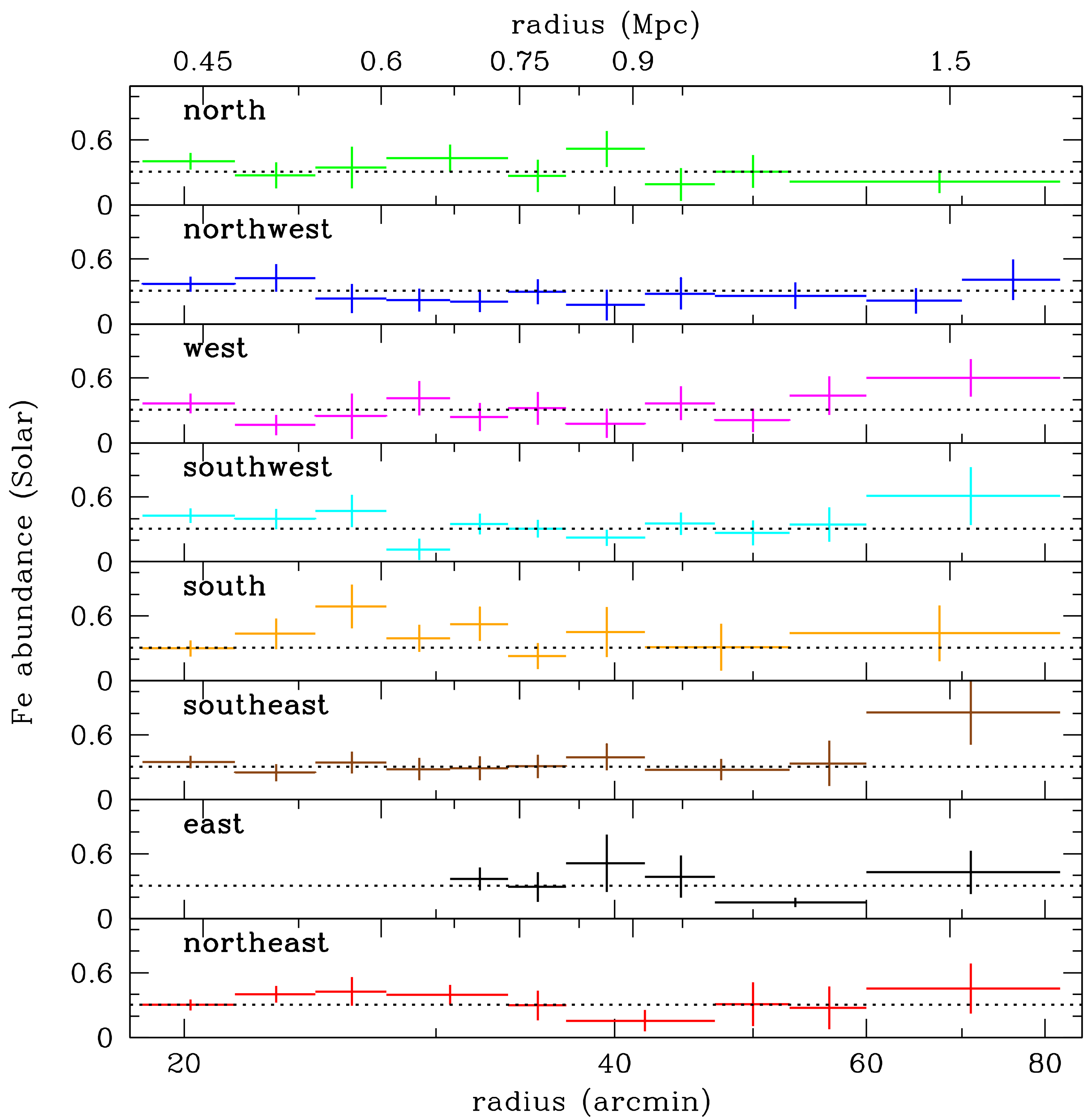
Metallicity Profiles with SUZAKU





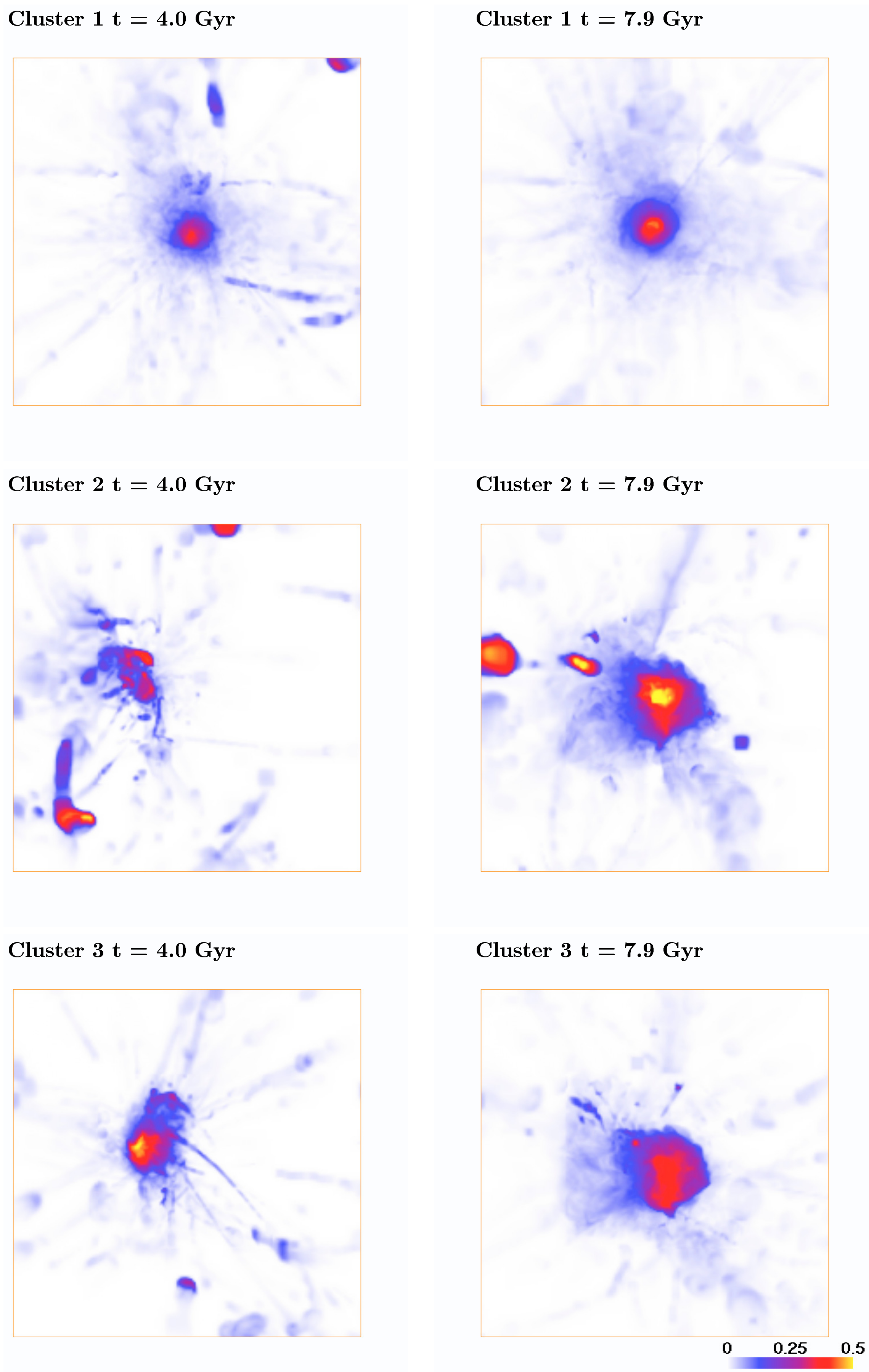
Flat metallicity profile with Z~0.3 Solar out to r200 exquisitely measured in the Perseus Cluster. The metallicity profile in Coma also shows the same trend (albeit with much larger error bars).

Iron spread smoothly throughout the Perseus cluster



78 Fe abundance measurements across the cluster at different radii *and azimuths* show strikingly uniform distribution

Werner et al. 2013, *Nature*



Domainko et al. 2006

Ram-pressure stripping of member galaxies should produce a central peak and a patchy metallicity distribution.

The uniform iron distribution suggests that galactic winds at z~2 were mainly responsible for getting the metals out of the galaxies and into the IGM/ICM.

Metals escaped from the galaxies and got mixed into the intergalactic gas before the entropy profile became very steep, preventing efficient mixing.

Implications of Early Metal Enrichment

- all massive clusters should show a similar, uniform level of enrichment at 1/3 of the Solar metallicity.

- galactic winds during the period of peak star formation and AGN activity probably played an important role in getting the metals out of the galaxies early on (z~2)

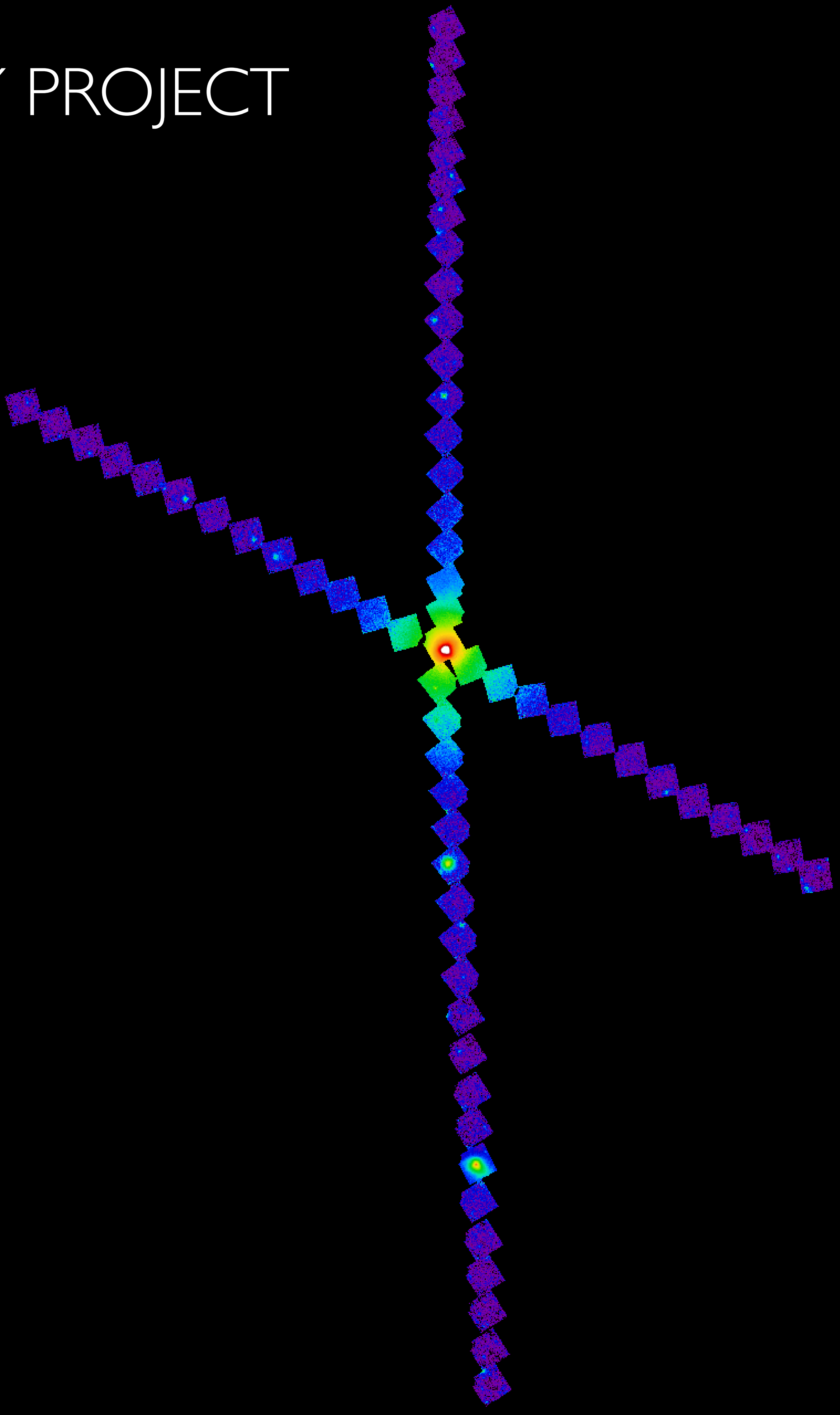
- many type Ia supernovae (SNIa), which are the main sources of Fe, must have exploded shortly after the epoch of peak star-formation. This is consistent with recent findings based on SNIa delay time distributions (Maoz et al. 2012).

- this scenario predicts that the warm-hot intergalactic medium in large-scale structure filaments connecting to massive clusters is also metal-rich, and can be detected in line-emission with future high-grasp, high-spectral resolution missions.

- if the material currently falling into massive clusters is iron-rich, iron nuclei are likely to be accelerated as they pass through the accretion shocks, providing an important source of the highest energy cosmic rays.

…OR CAN WE ACHIEVE SUCH A UNIFORM MIXING OF THE METALS EVEN AT LATER TIMES??

THE VIRGO CLUSTER KEY PROJECT



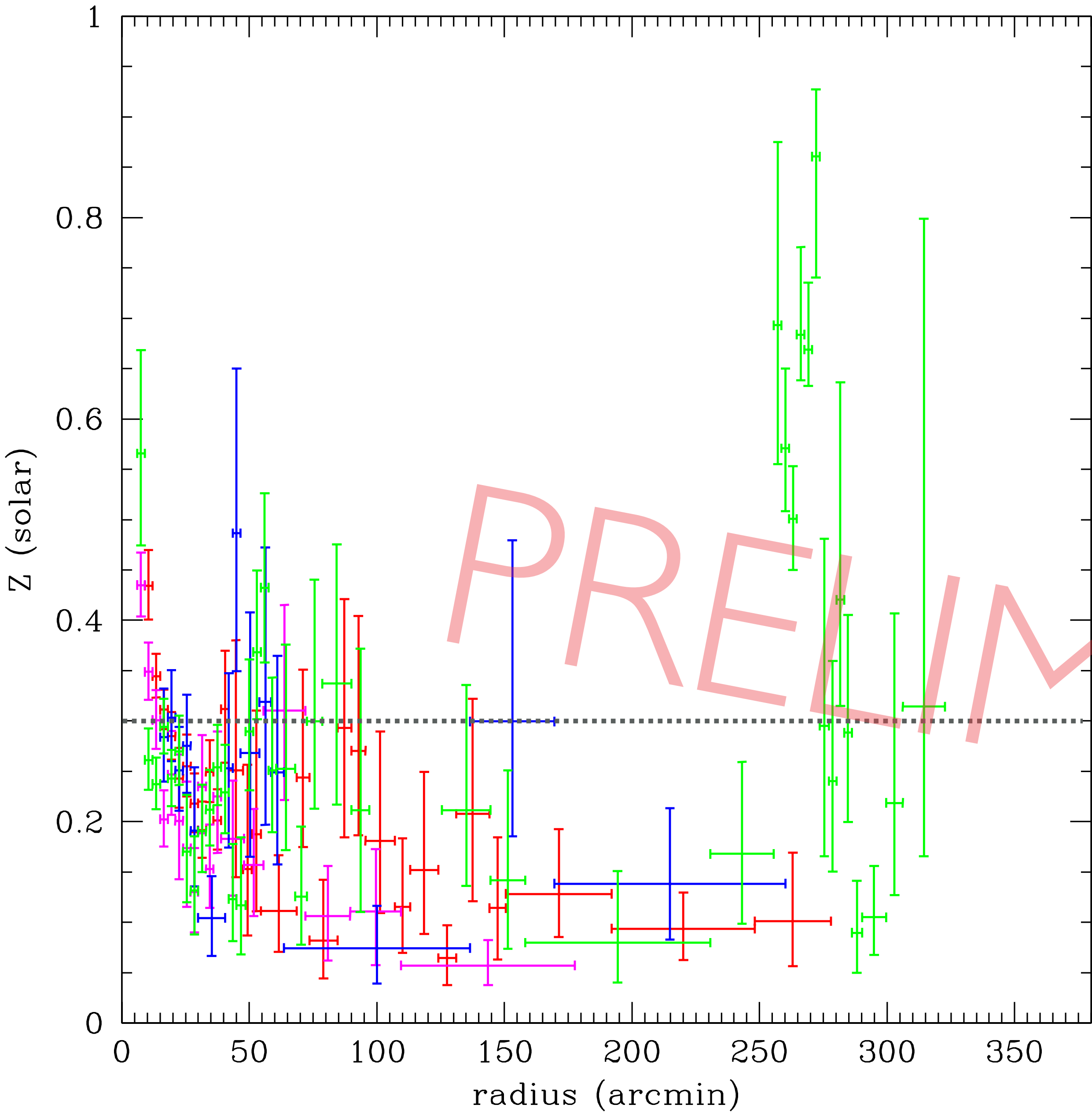
60 Suzaku pointings

4 different directions

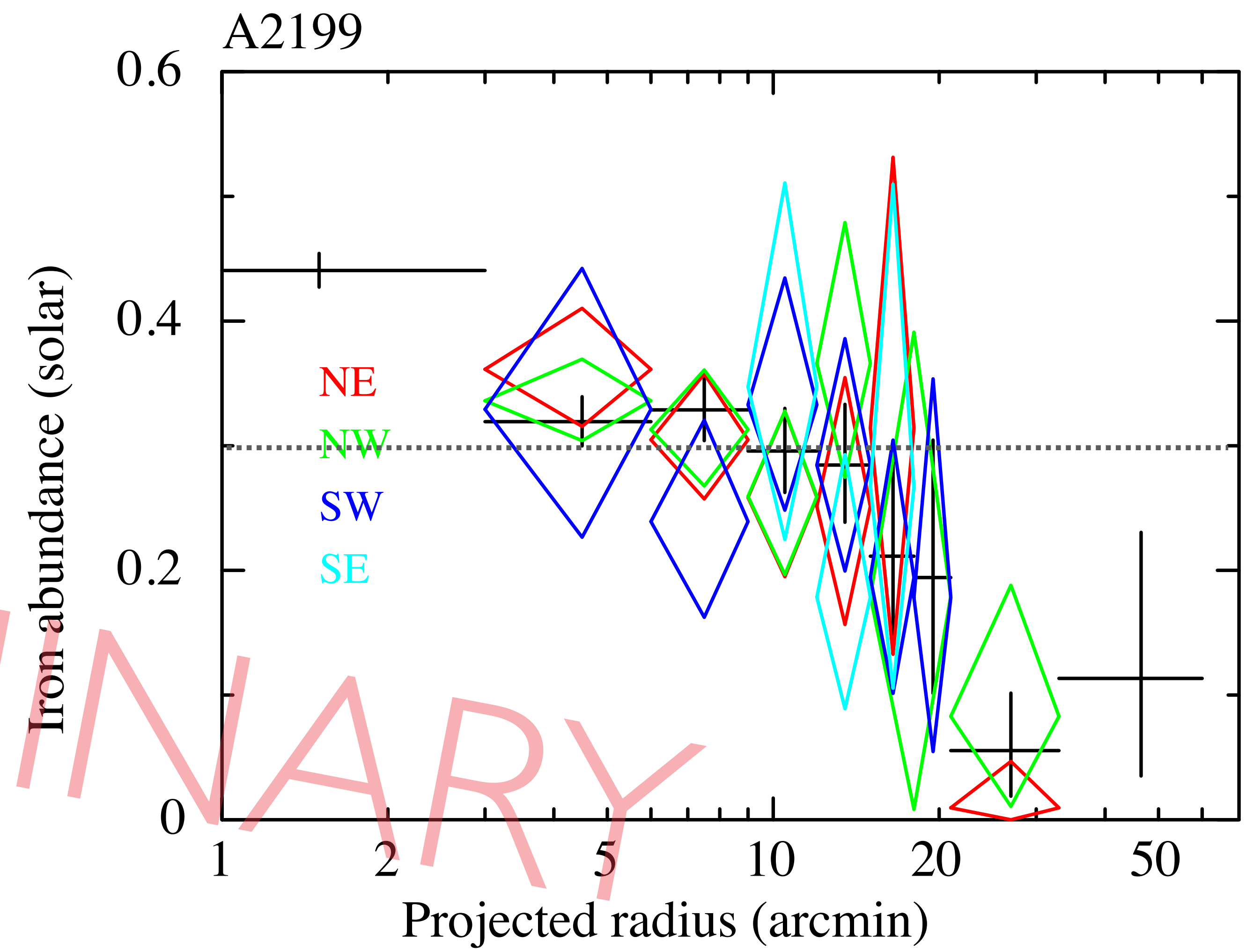
over 1Ms total
exposure

AO 7-8

Lower Metallicity in the Outskirts of Lower Mass Clusters?



Simionescu et al., in prep



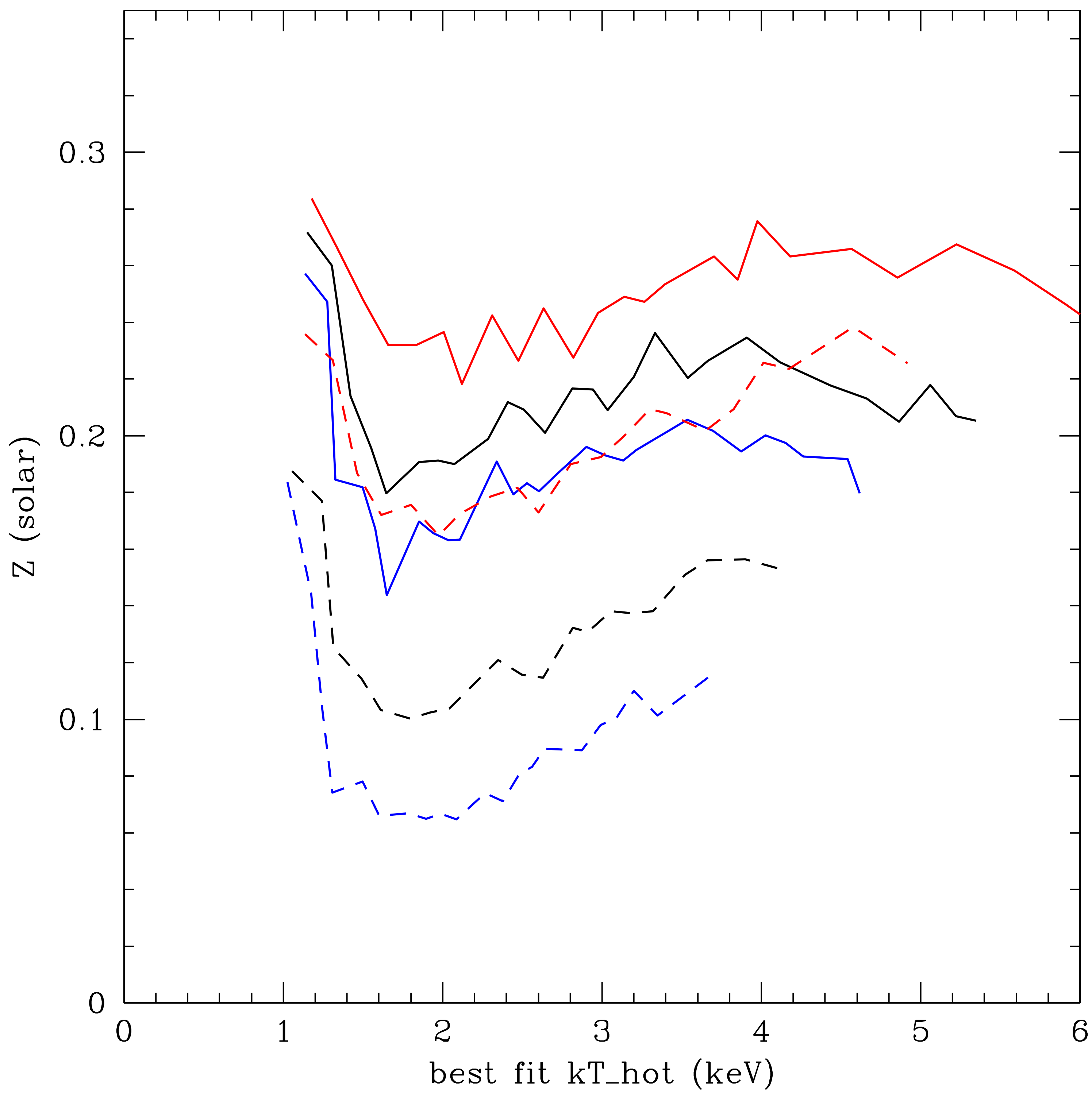
Sato et al., in prep

Metallicity lower than 1/3 Solar in the outskirts of lower-mass clusters.

Virgo shows a larger dispersion, rather than uniform distribution!

Real effect or onset of Fe-L bias??

Is it possible to bias the metallicity from 0.3 down to 0.1 solar due to multiphase gas?



Simulate mixture of two temperatures, each with 0.3 solar metallicity

Solid lines: T_{cool}=1 keV
Dashed: T_{cool}=0.7 keV

Red: Y_{cool}=0.1 Y_{hot}
Black: Y_{cool}=0.2 Y_{hot}
Blue: Y_{cool}=0.3 Y_{hot}

TAKE HOME MESSAGES

- The gas density in cluster outskirts becomes nonuniform between r500 and r200. Not all clusters show the same clumping level; some may show none. No other non equilibrium effects *required* to explain gas entropy and pressure within r200, *but* these additional non equilibrium effects might set in beyond r200.

- Perseus Key Project results show that the metallicity is constant at 0.3 solar both as a function of radius *and azimuth* out to the edge of the cluster. Early enrichment or more efficient mixing than previously thought? Lower-mass clusters tend to have lower metallicity in the outskirts (or is this a multi-phase bias?)