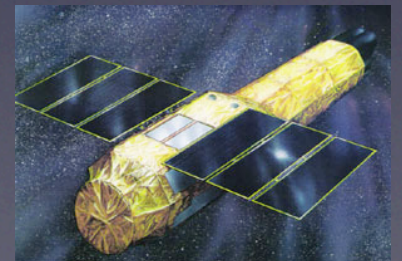


The Outer Limits of Galaxy Clusters: Observations to the Virial Radius with *Suzaku*

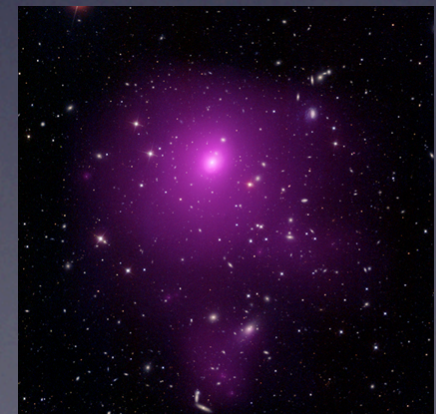
Eric Miller
MIT Kavli Institute

Mark Bautz, Richard Mushotzky, Dave Davis,
Jithin George, Patrick Henry,
Madoka Kawaharada



Why Study Cluster Outskirts?

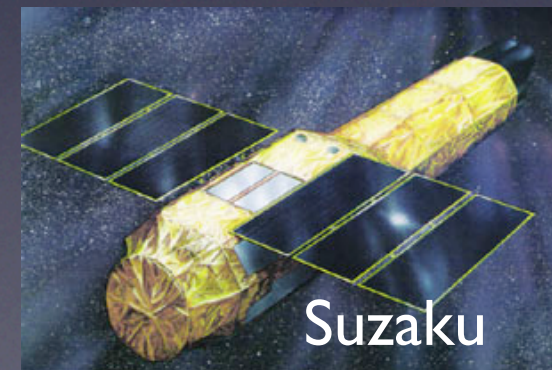
- majority of dark matter, baryons, metals in cluster
- clusters are still accreting at $R_{\text{vir}} \sim R_{200}$
 - constrain cluster formation models, assembly history
 - clumping, turbulence, electron-ion non-equilibrium
 - universal temperature, pressure profiles?
- clusters as cosmological tools via mass, baryon fraction
 - helpful to understand cluster physics to use them as cosmological probes



Abell 85: X-ray (NASA/CXC/SAO/A.Vikhlinin et al.); Optical (SDSS)

Observational Challenges

- hot ICM in X-rays; very faint in outskirts, less than 30% of BG at R_{vir}
- large coverage area needed
- *Chandra* - high spatial resolution
- *XMM* - high throughput
- *Suzaku* - low instrumental background
 - but poor spatial resolution



Clusters to R_{200} with *Suzaku*

PKS 0745-191

George+2009

Abell 2204

Reiprich+2009

Abell 1795

Bautz+2009

Abell 1413

Hoshino+2010

Abell 1689

Kawaharada+2010

Perseus

Simionescu+2010

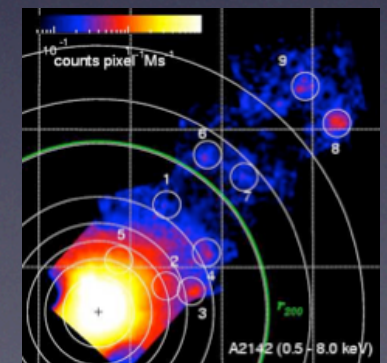
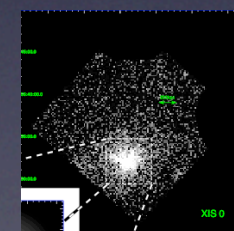
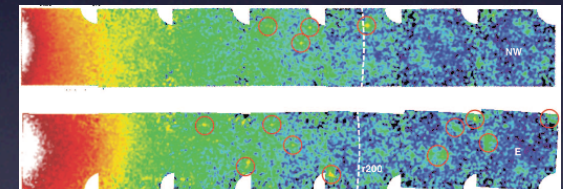
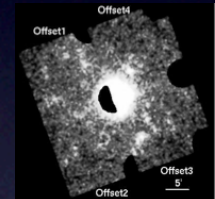
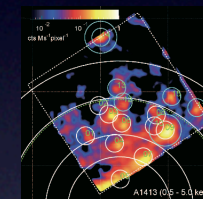
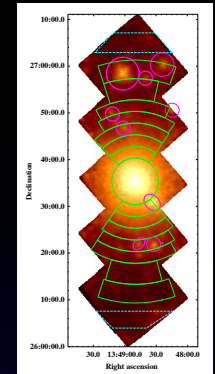
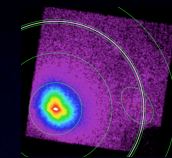
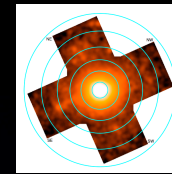
RXJ 1159+5531

Humphrey+2011

Abell 2142

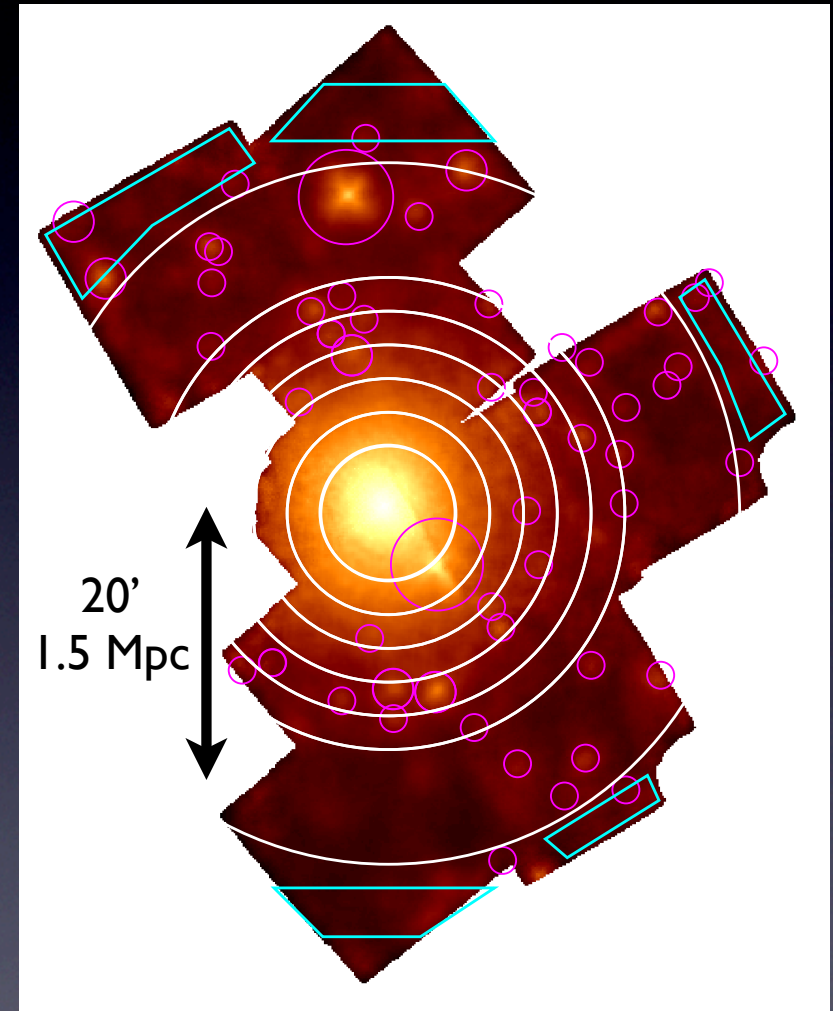
Akamatsu+2011

....and more!



Abell 1795 with *Suzaku*

- 9 *Suzaku* pointings, 250 ksec out to $25' = 2 \text{ Mpc} \sim R_{200}$
- *Suzaku* HPD $\sim 2' \sim 150 \text{ kpc}$
- spectral extraction regions
point sources (excluded)
background regions
- density & temperature profiles
→ entropy, f_{gas} , pressure profile
(assuming hydrostatic equilibrium, spherical symmetry)

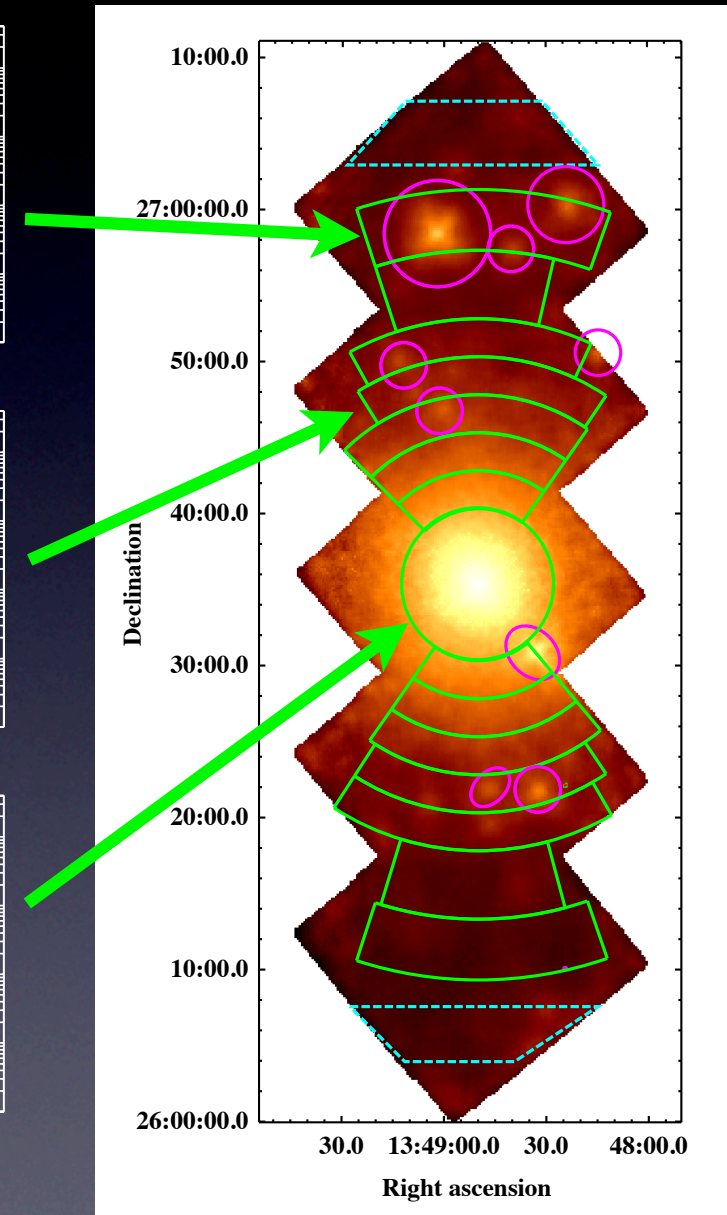


Bautz+2009, Miller+in prep

Abell 1795

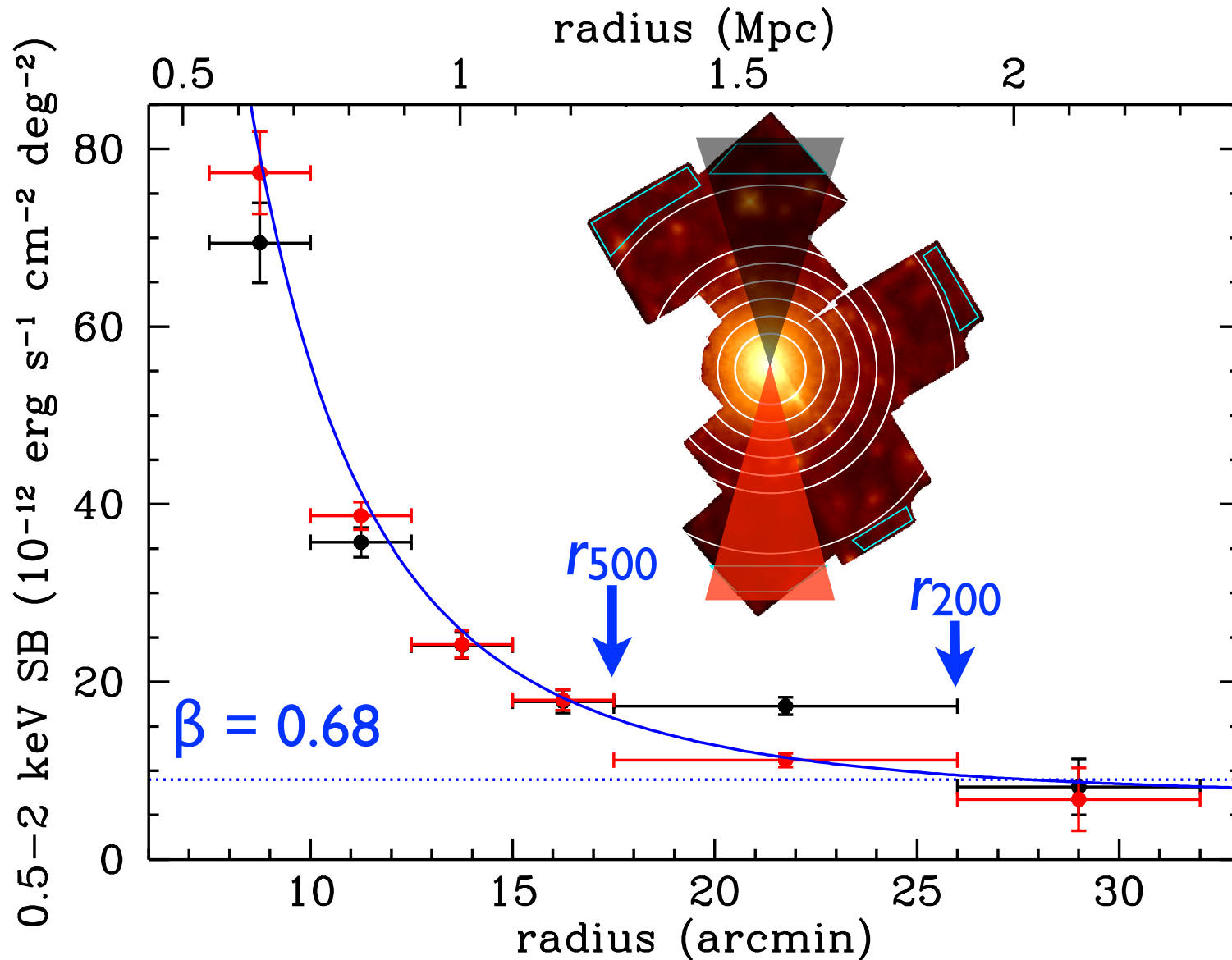
counts $\text{s}^{-1} \text{keV}^{-1}$

cluster
Galactic
thermal
foreground
extragalactic
background

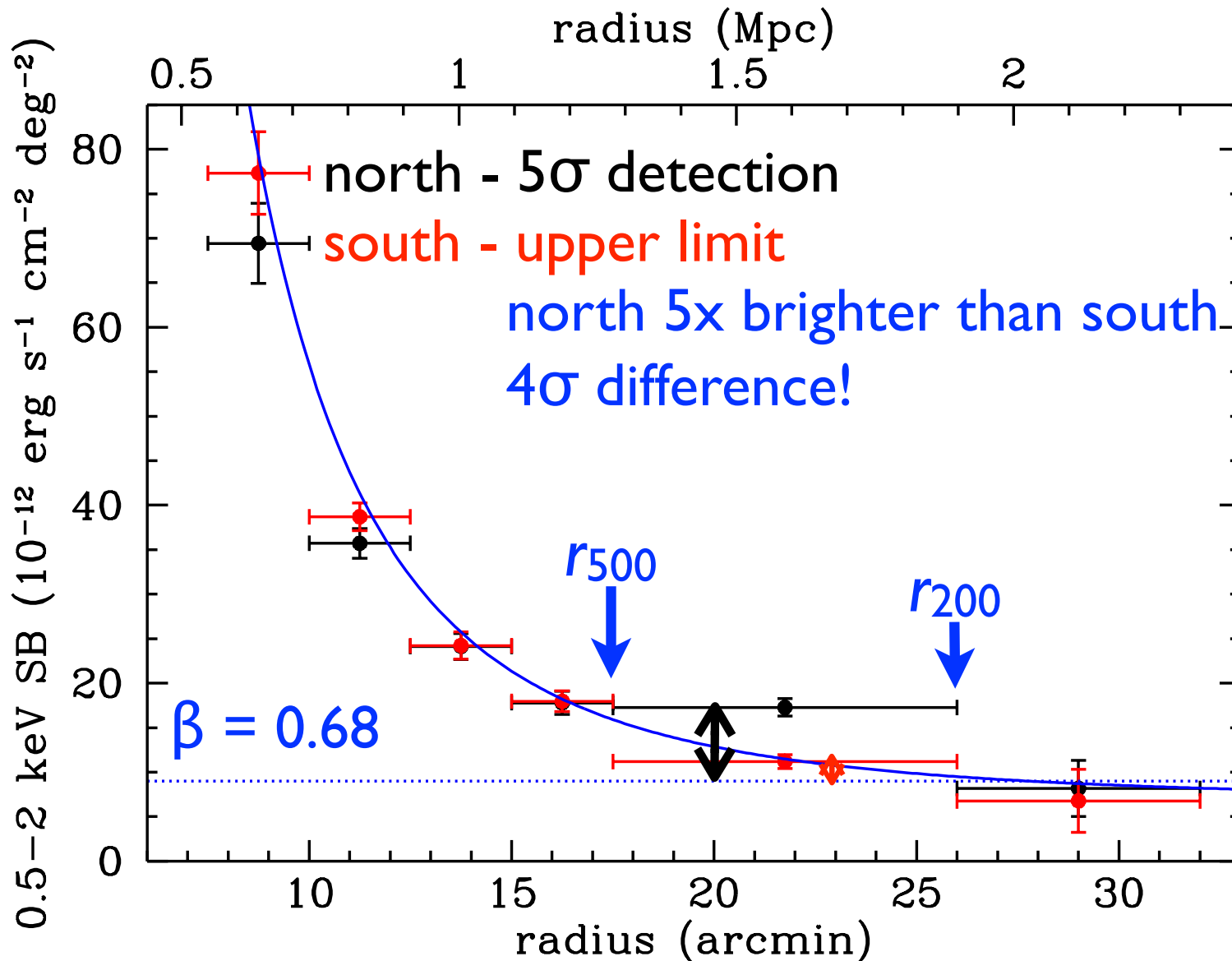


Bautz+2009

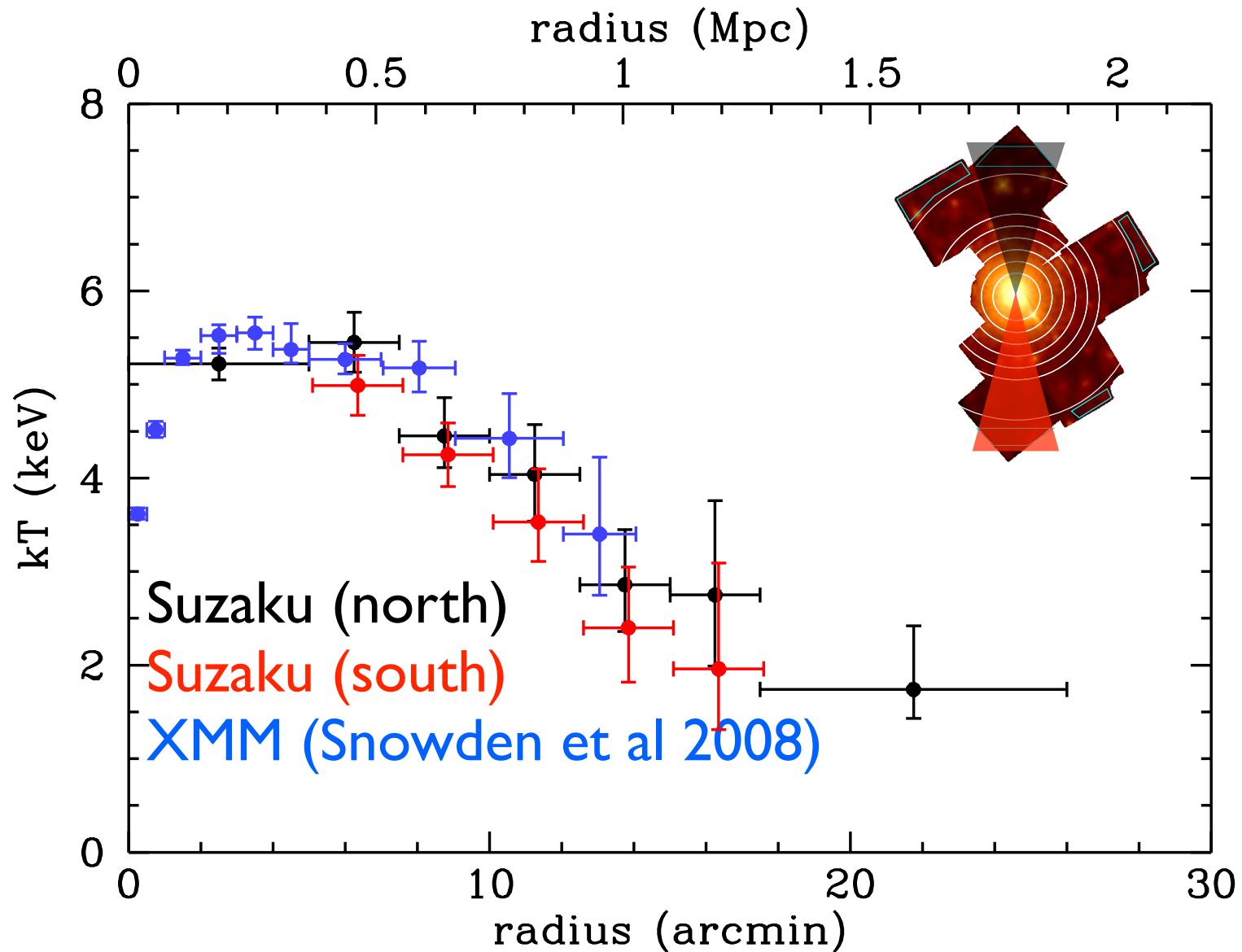
A1795 Surface Brightness



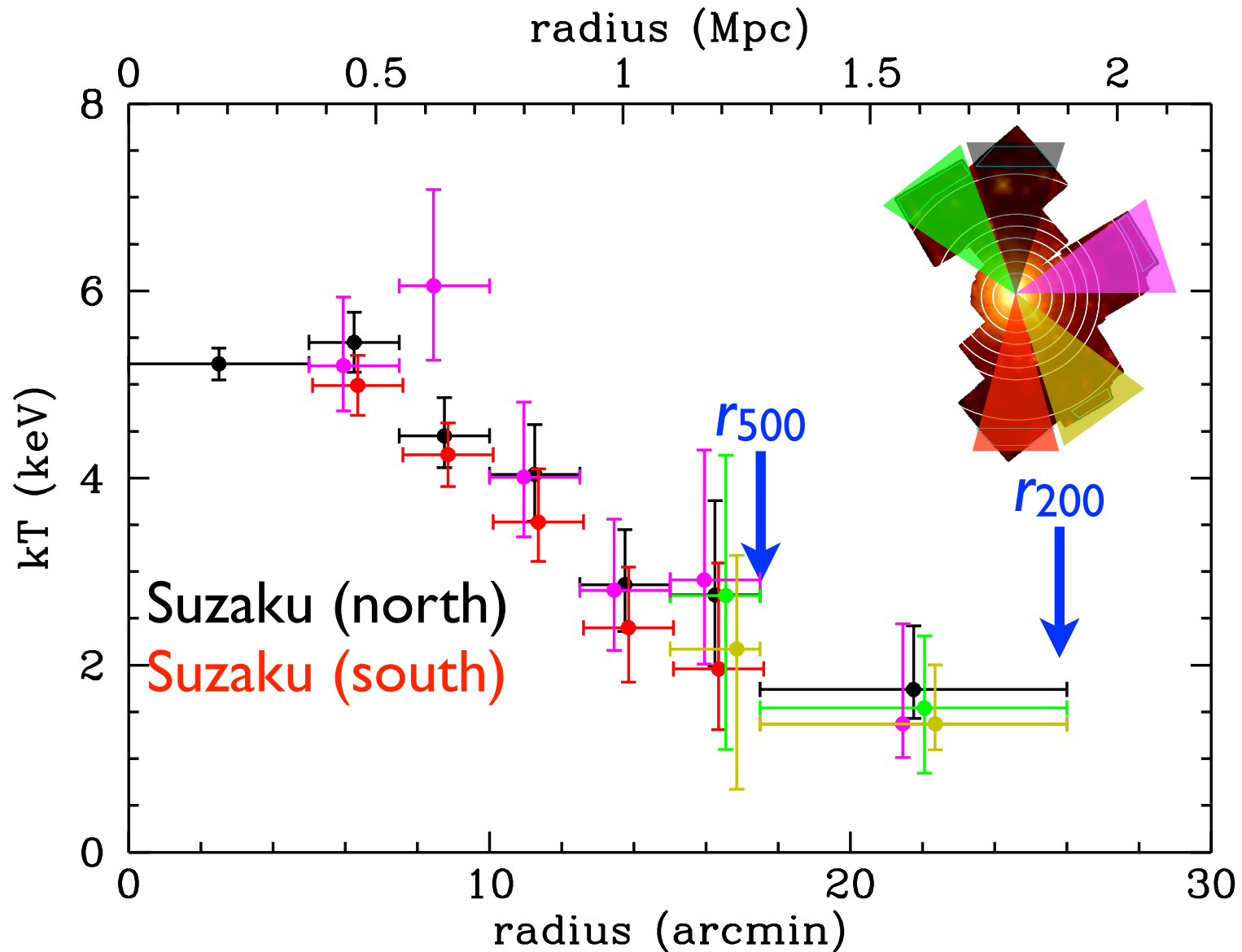
A1795 Surface Brightness



A1795 Temperature Profile



A1795 Temperature Profile



$z = 0.000$

Comparison with Simulations

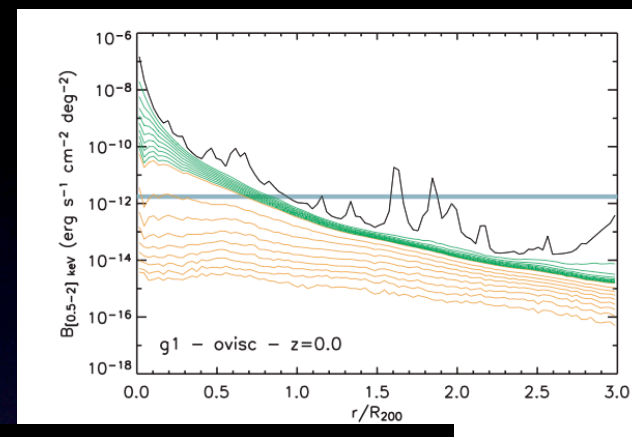
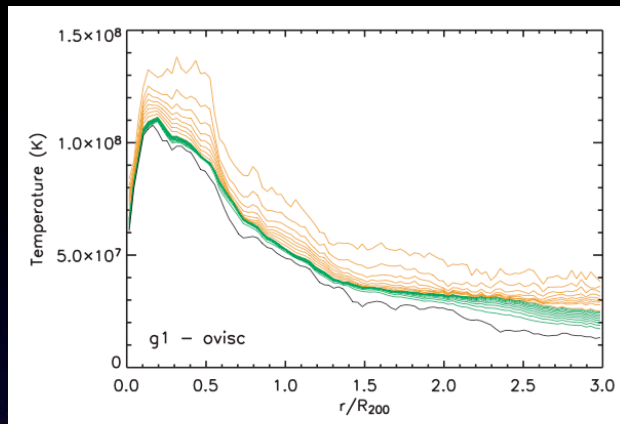
Temperature Isocontours

- Blue = 10^6 K (WHIM)
- Green = 5×10^6 K
- Purple = 10^7 K
- Red = 5×10^7 K

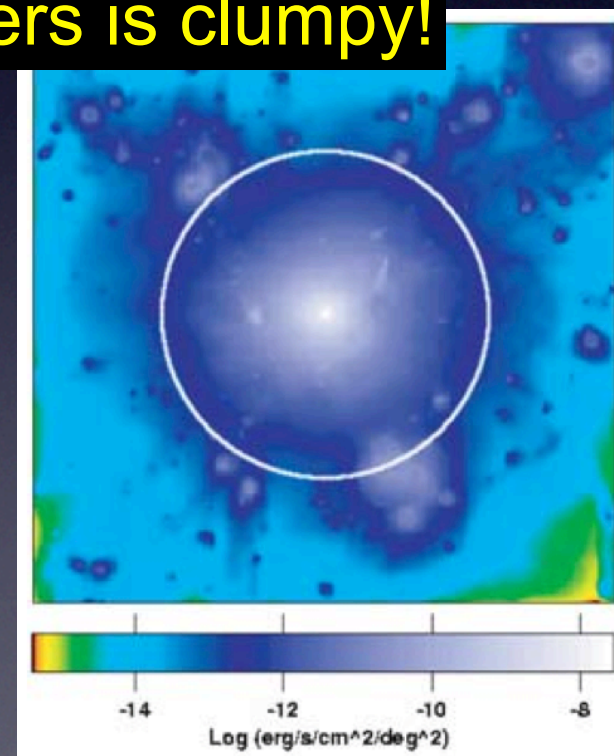
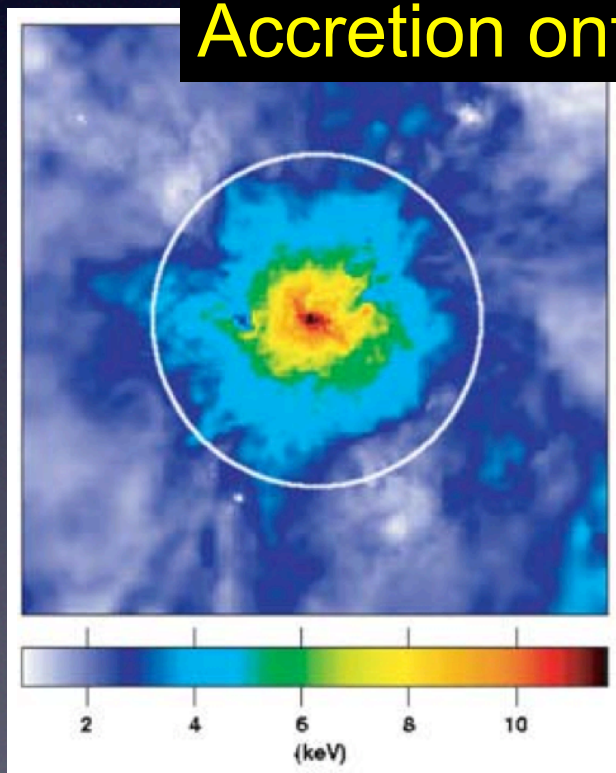
Accretion onto clusters is not spherical!

Burns+2010

Comparison with Simulations

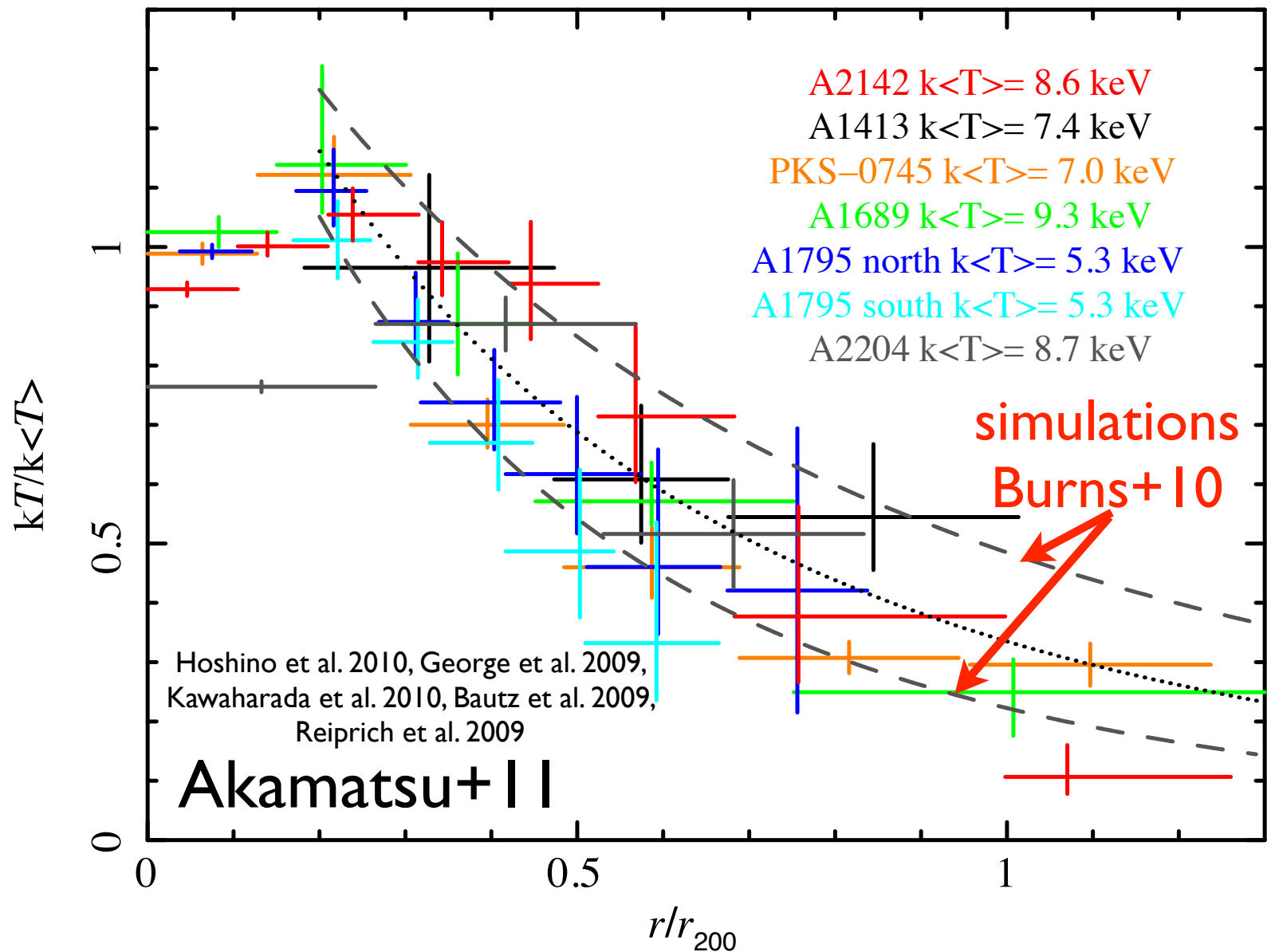


Accretion onto clusters is clumpy!



Roncarelli+2006 (also Burns+2010, Nagai+2011)

Clusters to R_{200} with *Suzaku*



declining kT to R_{200}
 “universal” temperature profile
 (Burns+10)

A2142 $k\langle T \rangle = 8.6$ keV
 A1413 $k\langle T \rangle = 7.4$ keV
 PKS-0745 $k\langle T \rangle = 7.0$ keV

Hoshino et al. 2010, George et al. 2009,
 Kawaharada et al. 2010, Bautz et al. 2009,
 Reiprich et al. 2009

Akamatsu+11

Suzaku Cluster Outskirts Project

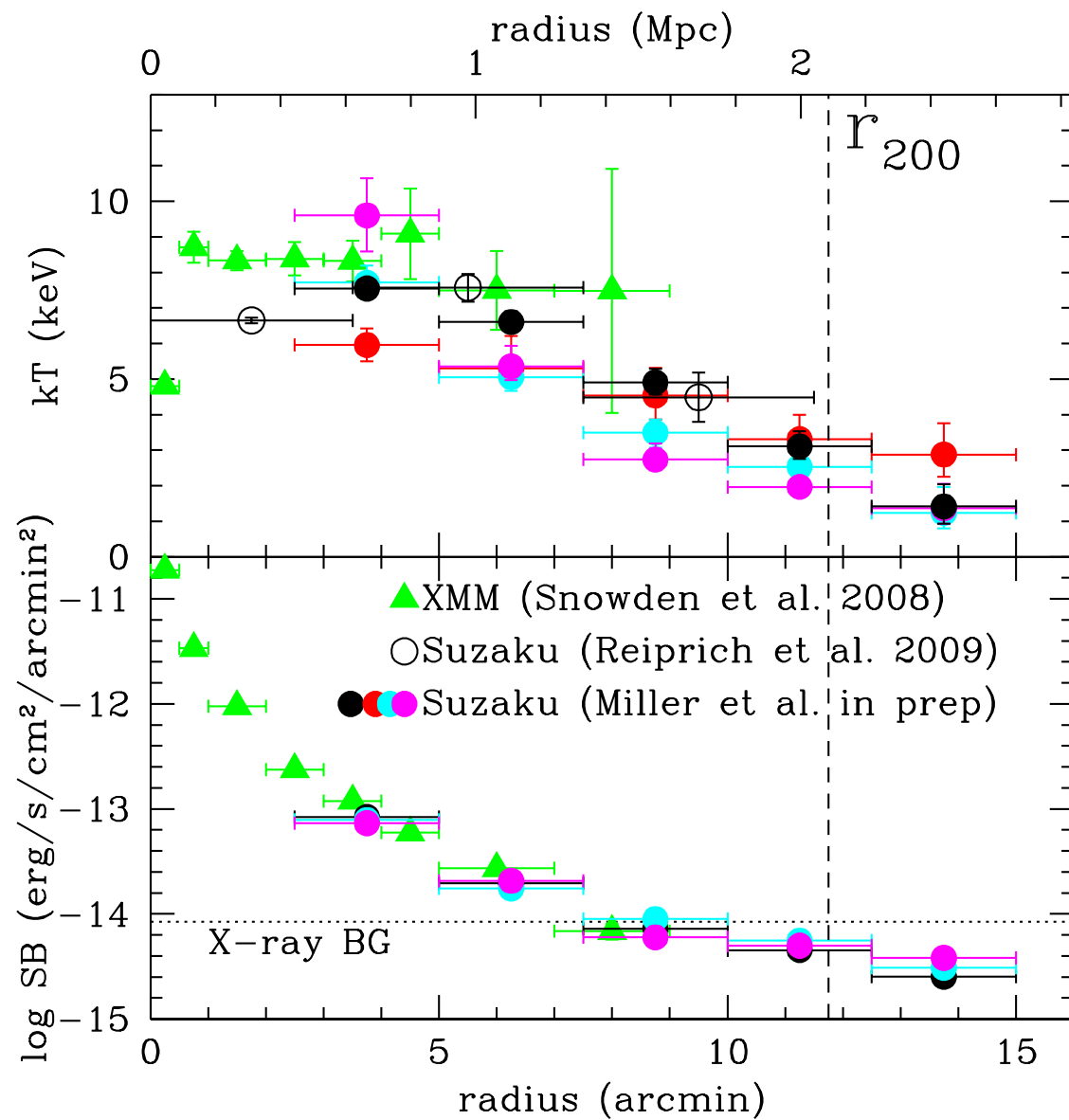
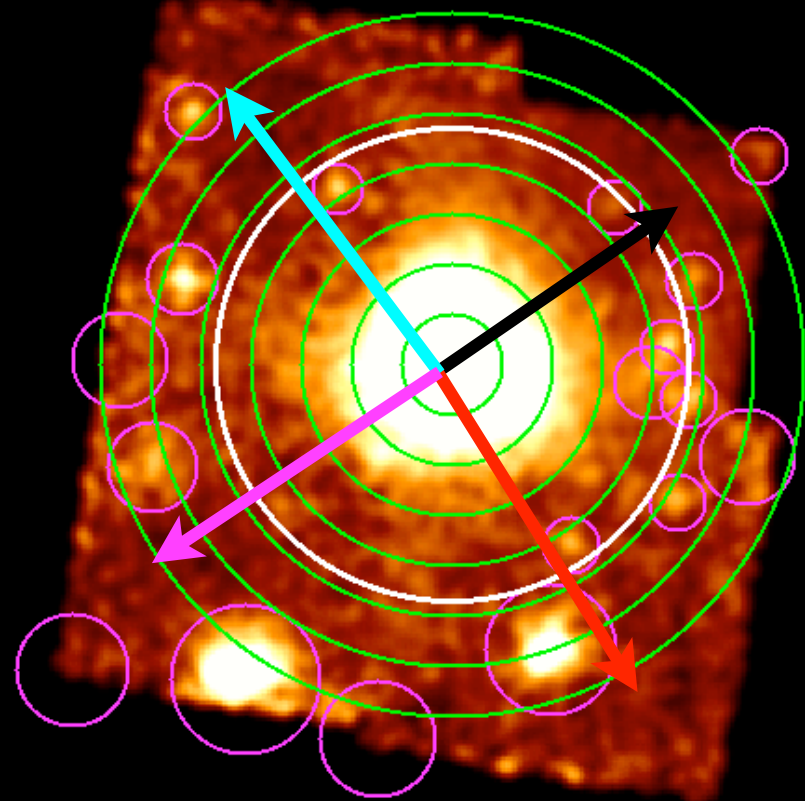
Cluster	z	R_{200}	ksec	date obs.
A383	0.187	9.3	110	July 2010
A1413	0.135	14.8	170	May 2010 + archive
A1795	0.063	26.0	260	June 2009 + archive
A1914	0.174	14.5	160	June 2010
A2204	0.151	11.8	140	Sep 2010 + archive
RXCJ0605	0.137	12.2	150	May 2010
A773	0.216	9.5	200	May 2011
A2667	0.221	10.0	200	July 2011
A1068	0.147	10.8	200	Oct 2011

- selected from Snowden et al. 2008 XMM cluster catalog
- “relaxed”, no substructure
- falling, flat, and rising kT profiles
- full azimuthal coverage out to R_{200}

Abell 2204

$z = 0.151$

$12' \sim 2 \text{ Mpc}$

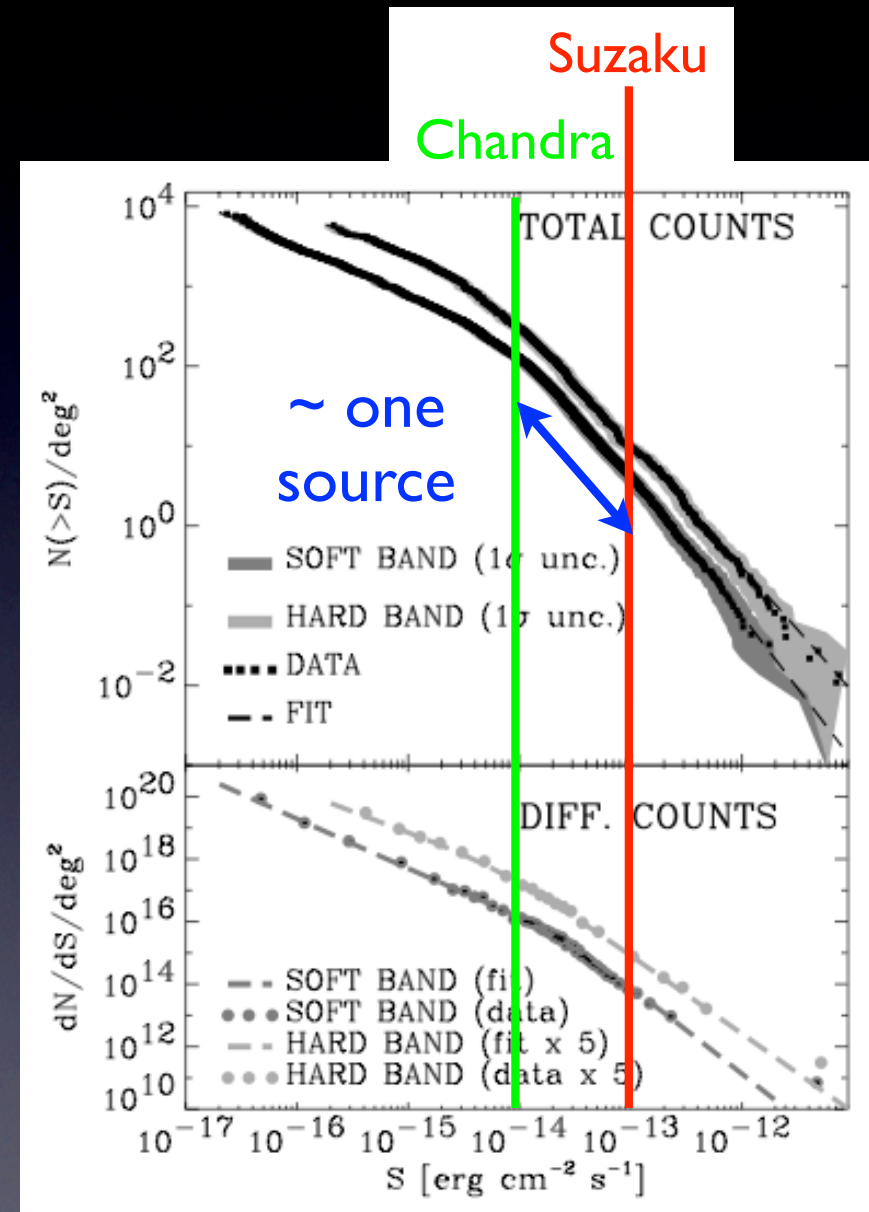


Systematics

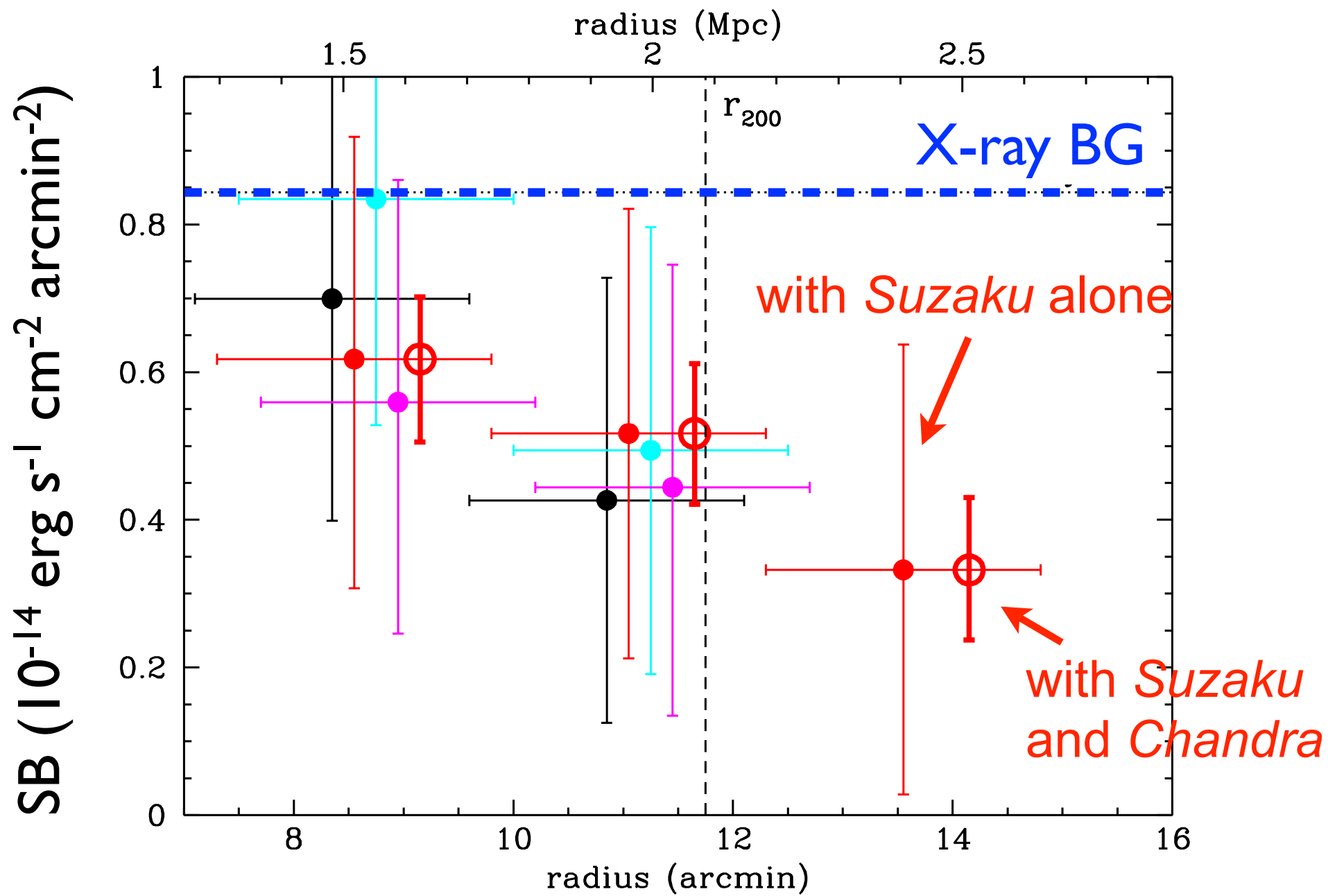
- at r_{vir} , cluster flux $< 30\%$ of background
- **constraining the background is vital**
- particle BG, Galactic thermal BG, cosmic X-ray BG
 - constrained by outer regions, ROSAT
- sources of background uncertainty
 - scattered X-ray flux from bright core ($< 5\%$ of BG; simulations underway)
 - **cosmic background variations (up to 40% of BG)**
for small extraction regions ($\leq 0.01 \text{ deg}^2$), background accuracy limited by Poisson statistics of point sources (AGN) just below threshold

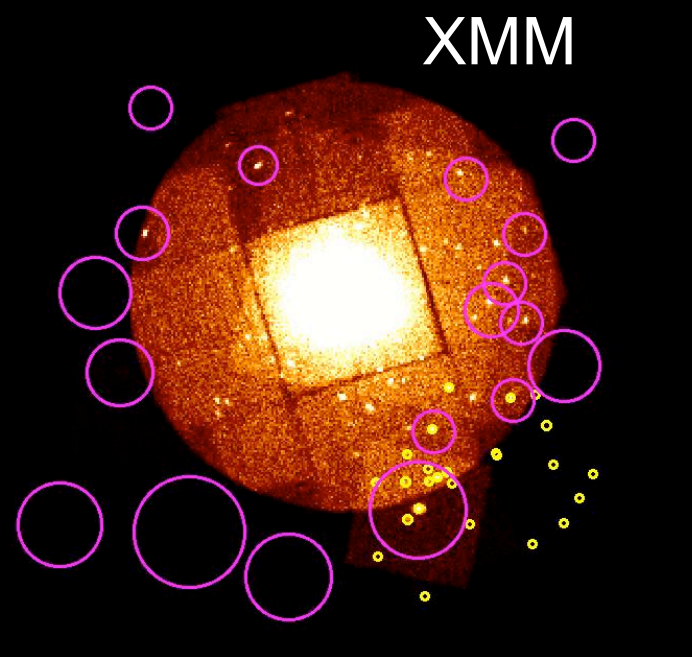
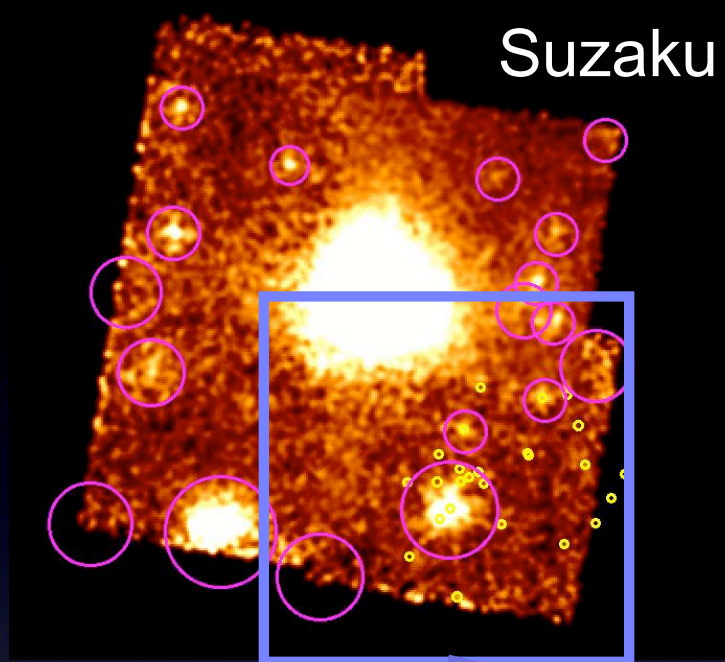
Cosmic Background Variations

- **Suzaku** detection limit
 $\sim 10^{-13} \text{ erg/s/cm}^2$
- **Chandra** detection limit
 $\sim 10^{-14} \text{ erg/s/cm}^2$
- expect ~ 1 source per region
 between *Suzaku*, *Chandra* limits
- **Suzaku** surf. brightness limit
 $\sigma_B \sim 4 \times 10^{-12} \text{ erg/s/cm}^2/\text{deg}^2$
 $\sim 40\% \text{ of soft BG!}$
- **Chandra** surf. brightness limit
 $\sigma_B \sim 1 \times 10^{-12} \text{ erg/s/cm}^2/\text{deg}^2$
 $\sim 10\% \text{ of soft BG!}$

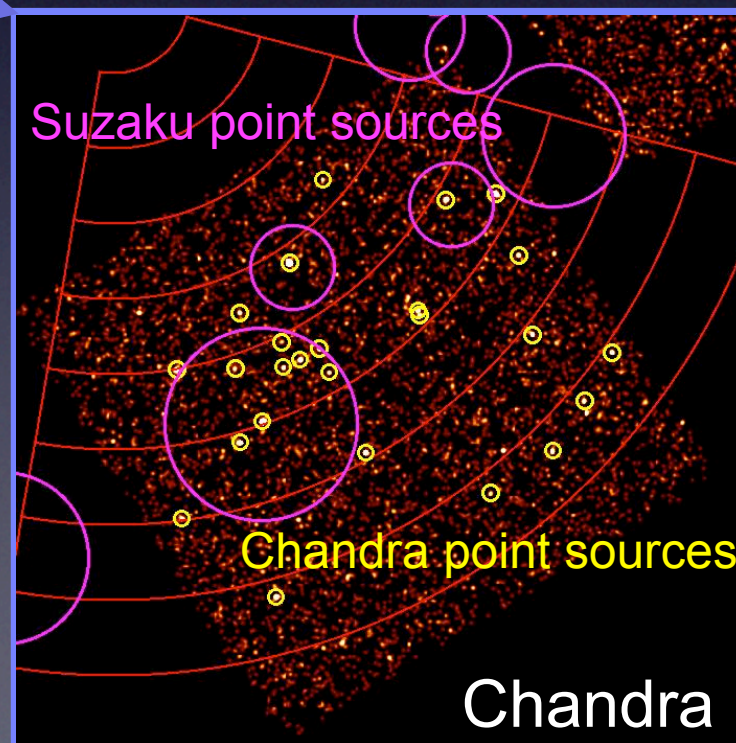
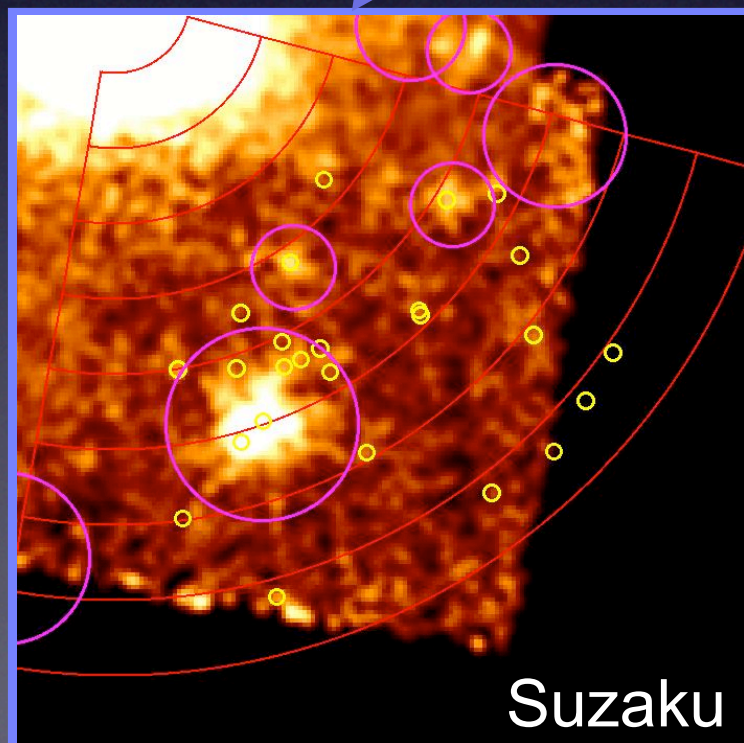


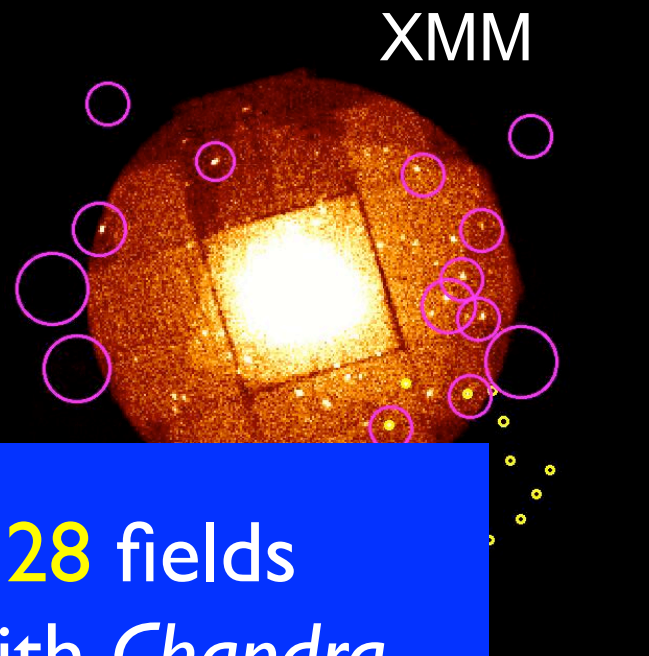
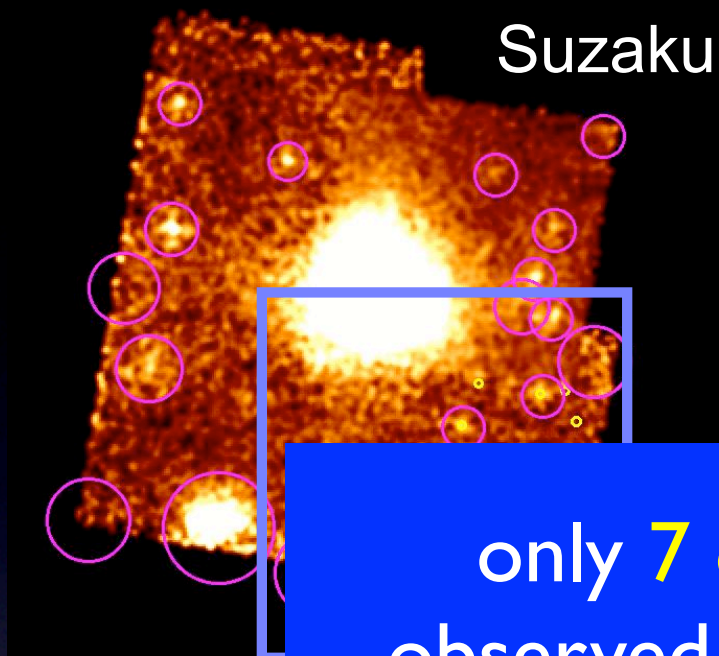
cumulative flux dist. [Moretti et al. 2003](#)





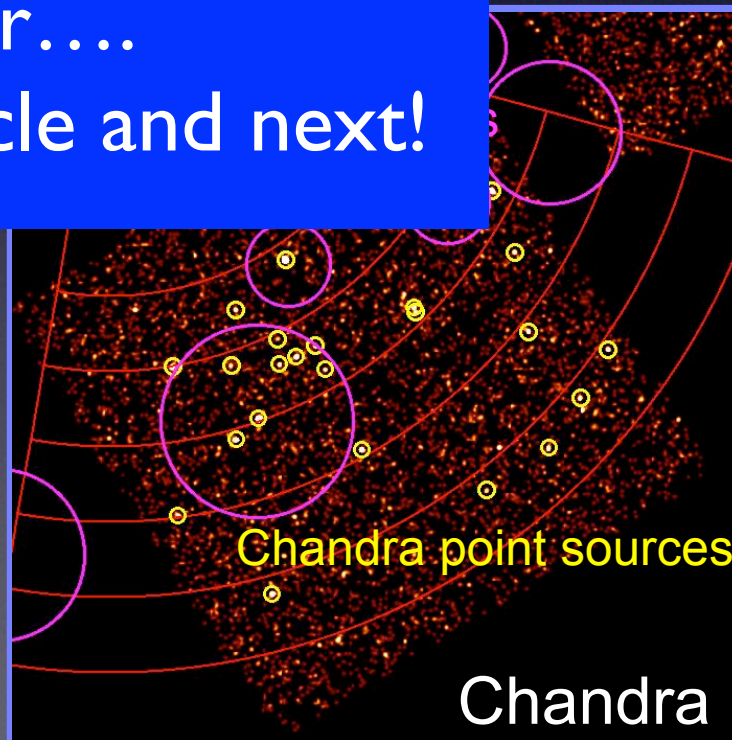
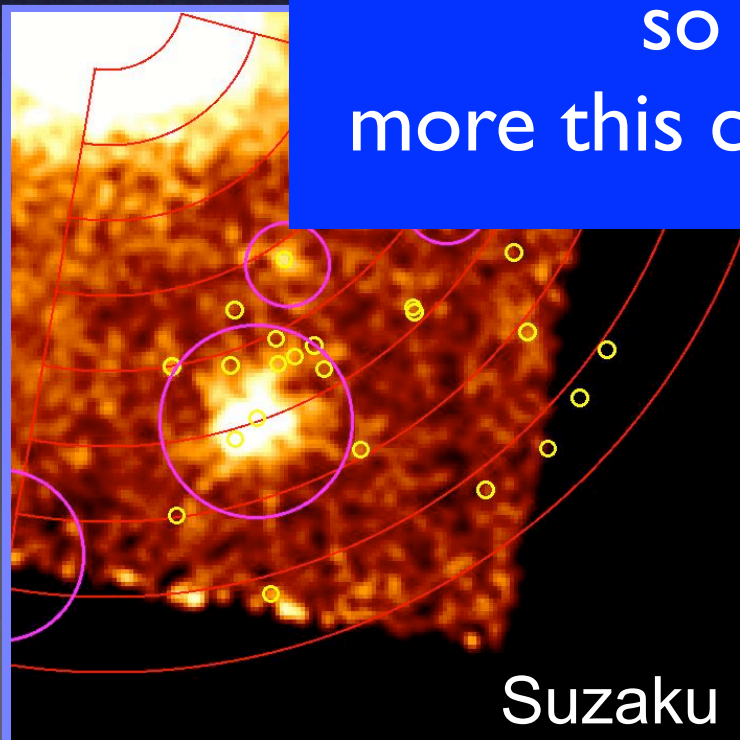
A2204





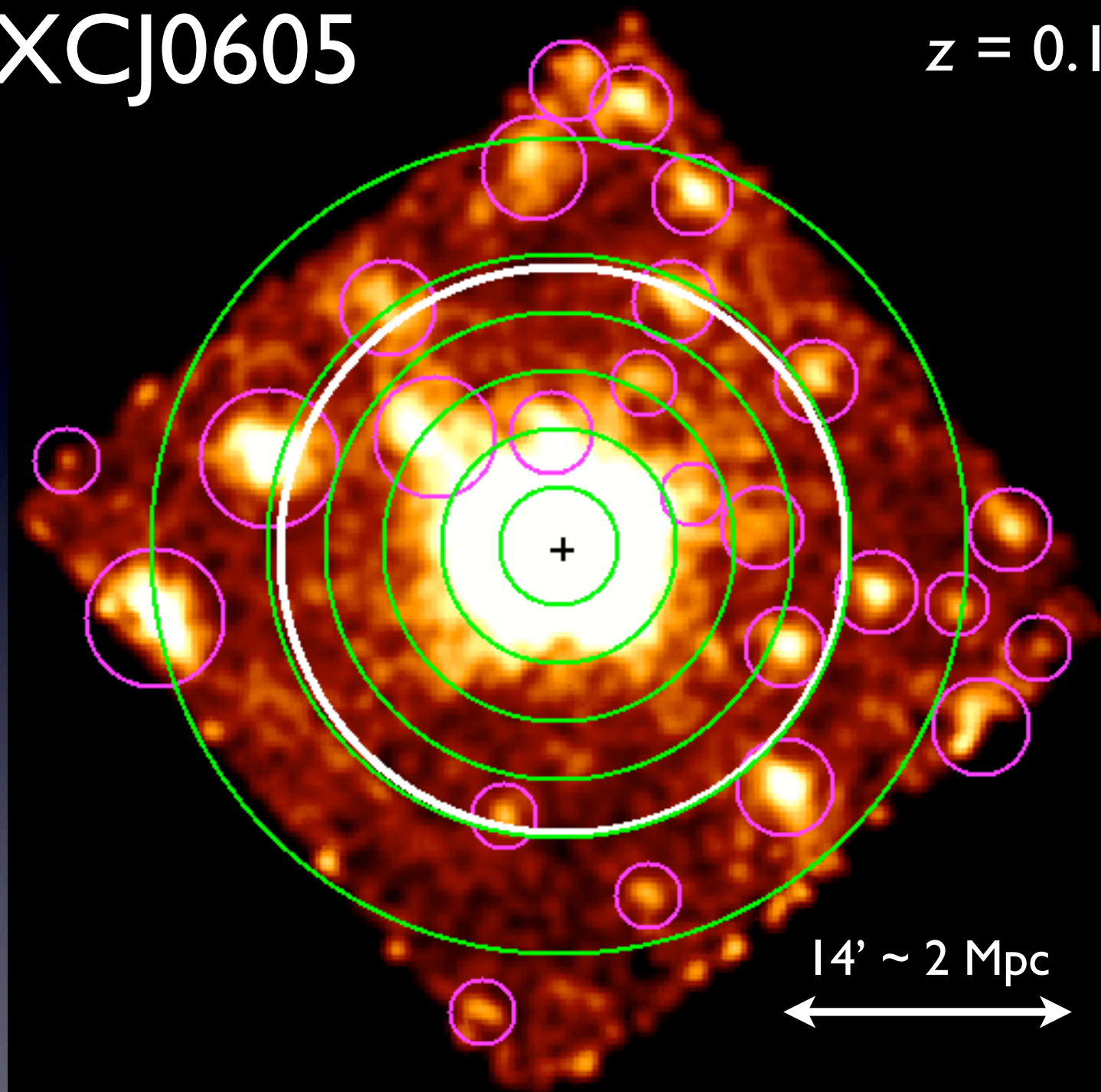
A2204

only 7 of 28 fields
observed with *Chandra*
so far....
more this cycle and next!

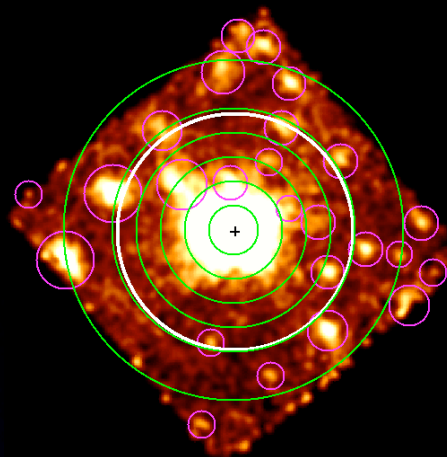


RXCJ0605

$z = 0.137$

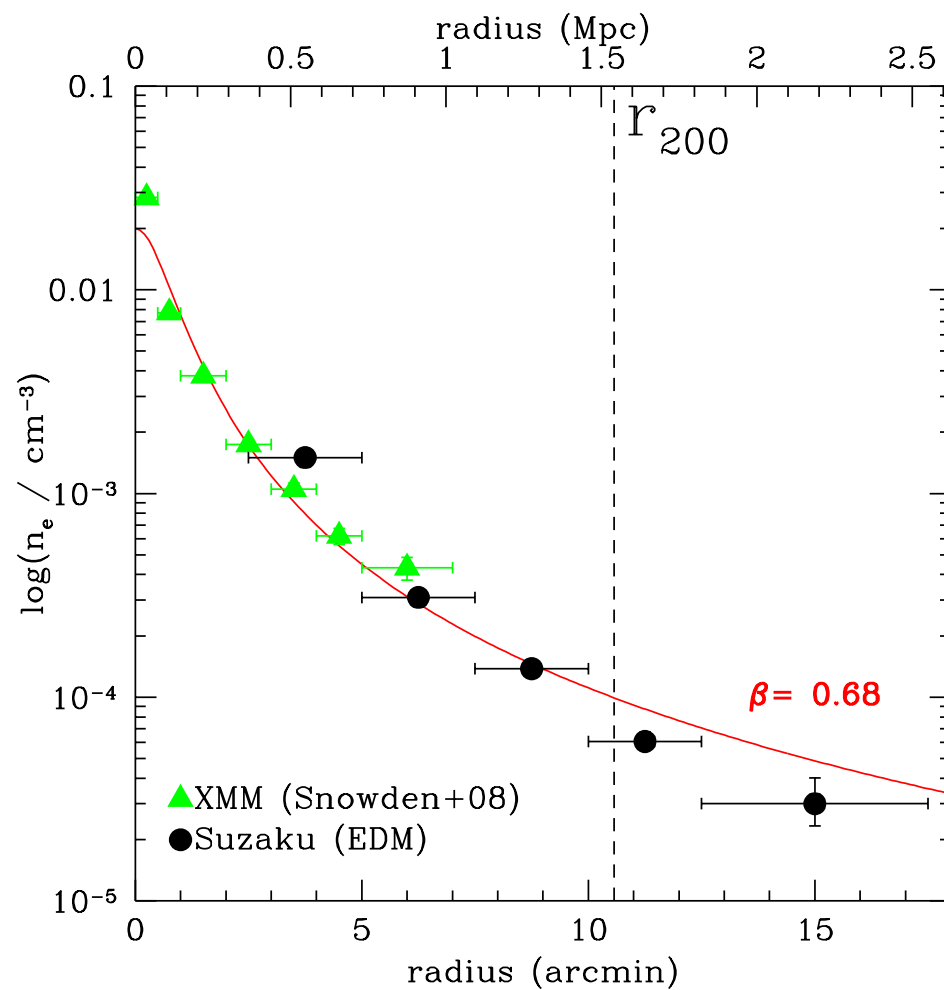
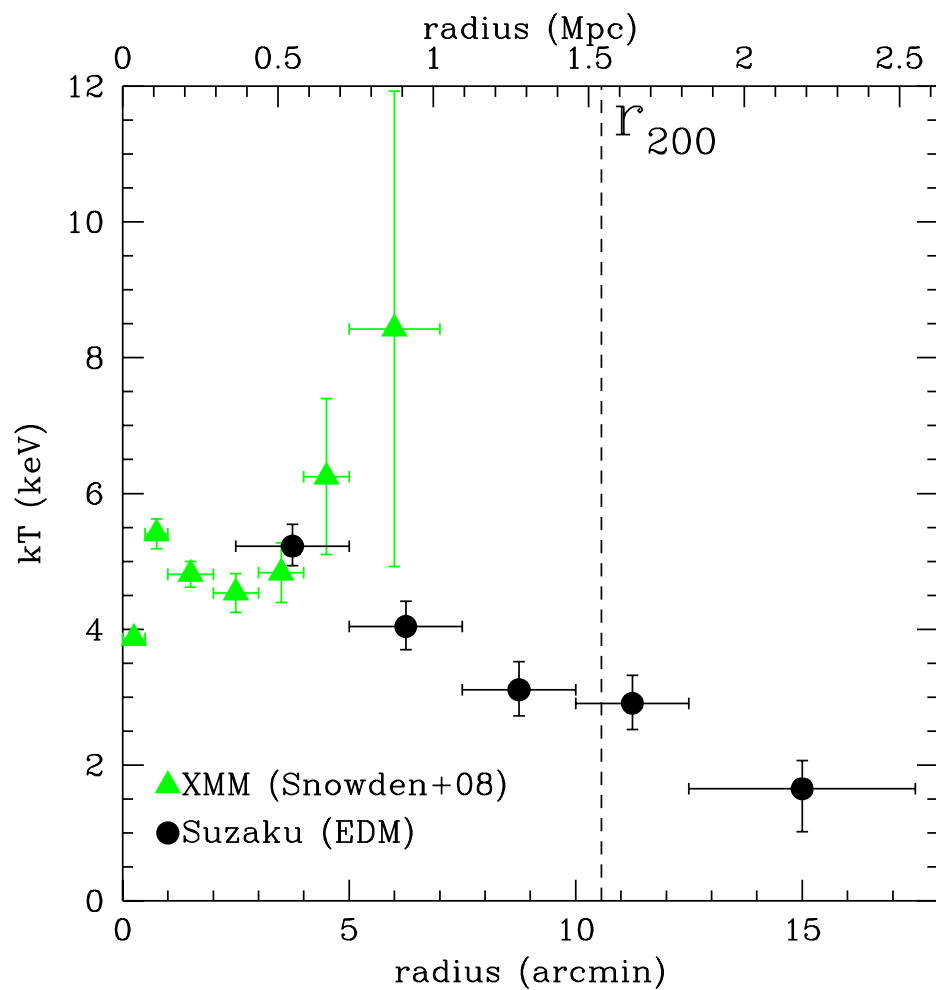


RXCJ0605

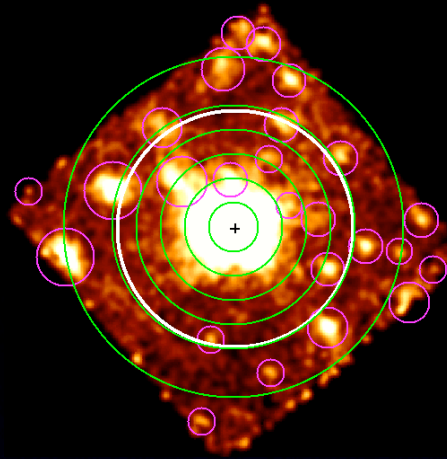


temperature

electron density



RXCJ0605

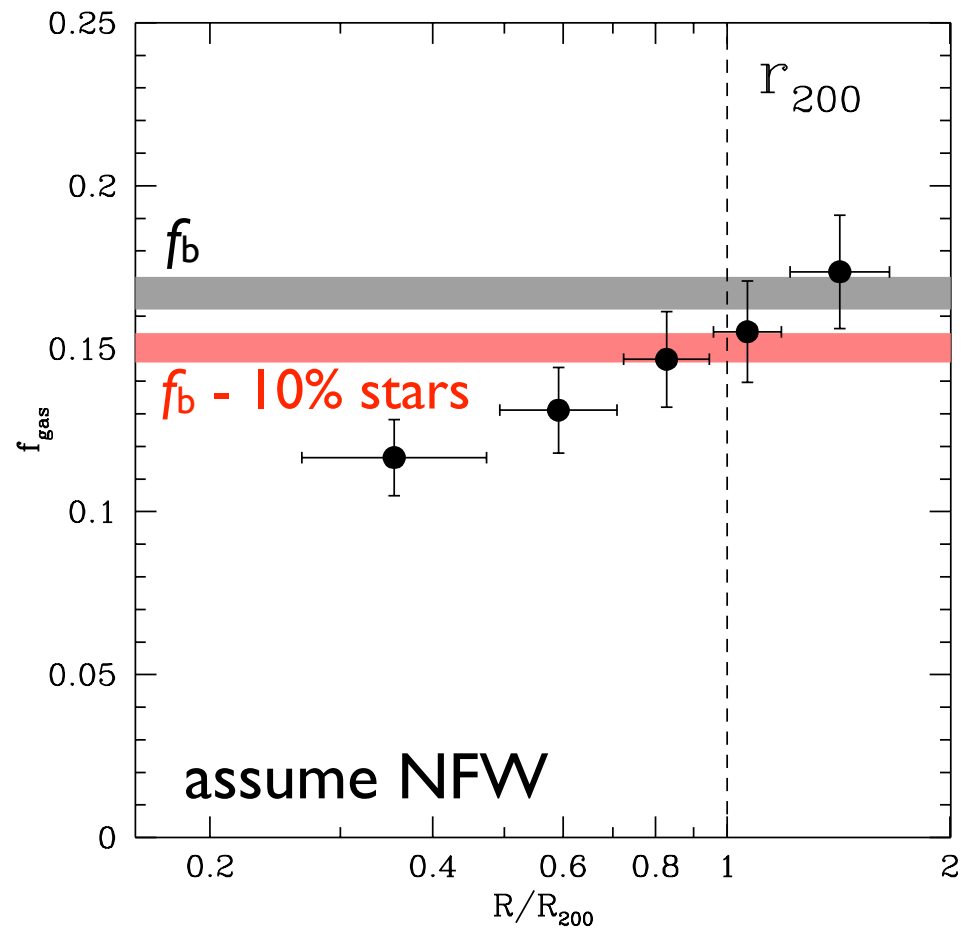
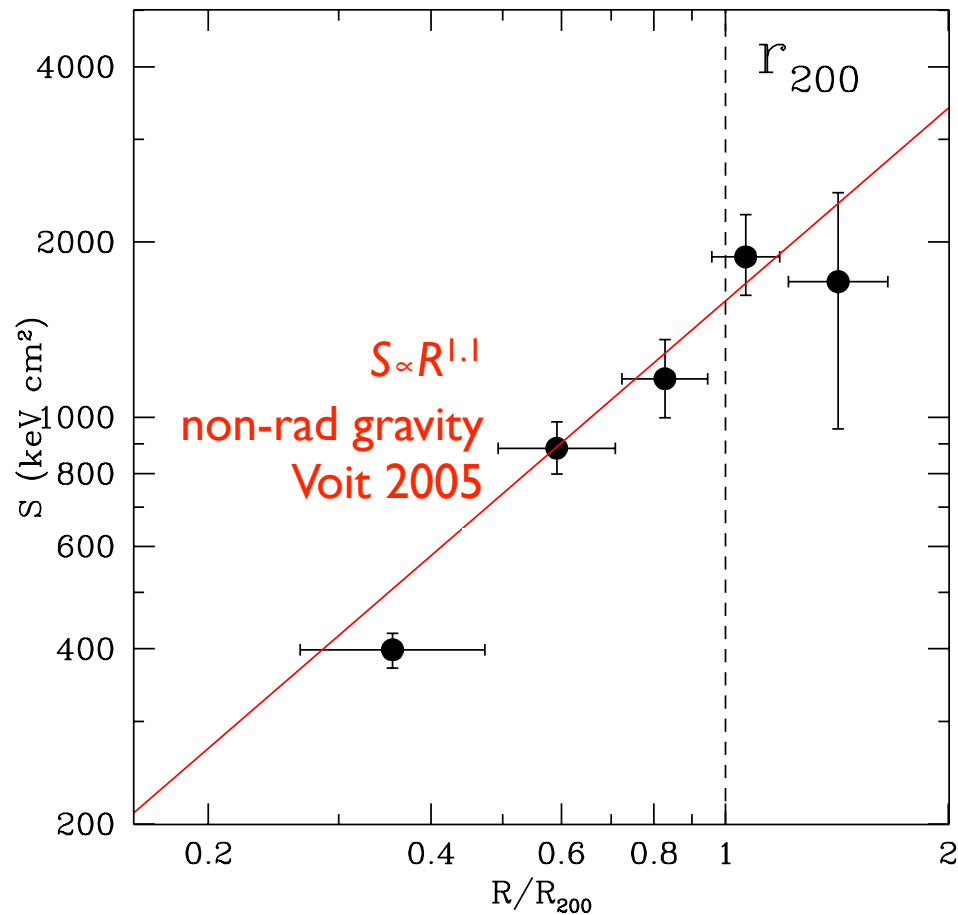


$$M_{200} = 4.2 \times 10^{14} M_{\odot}$$

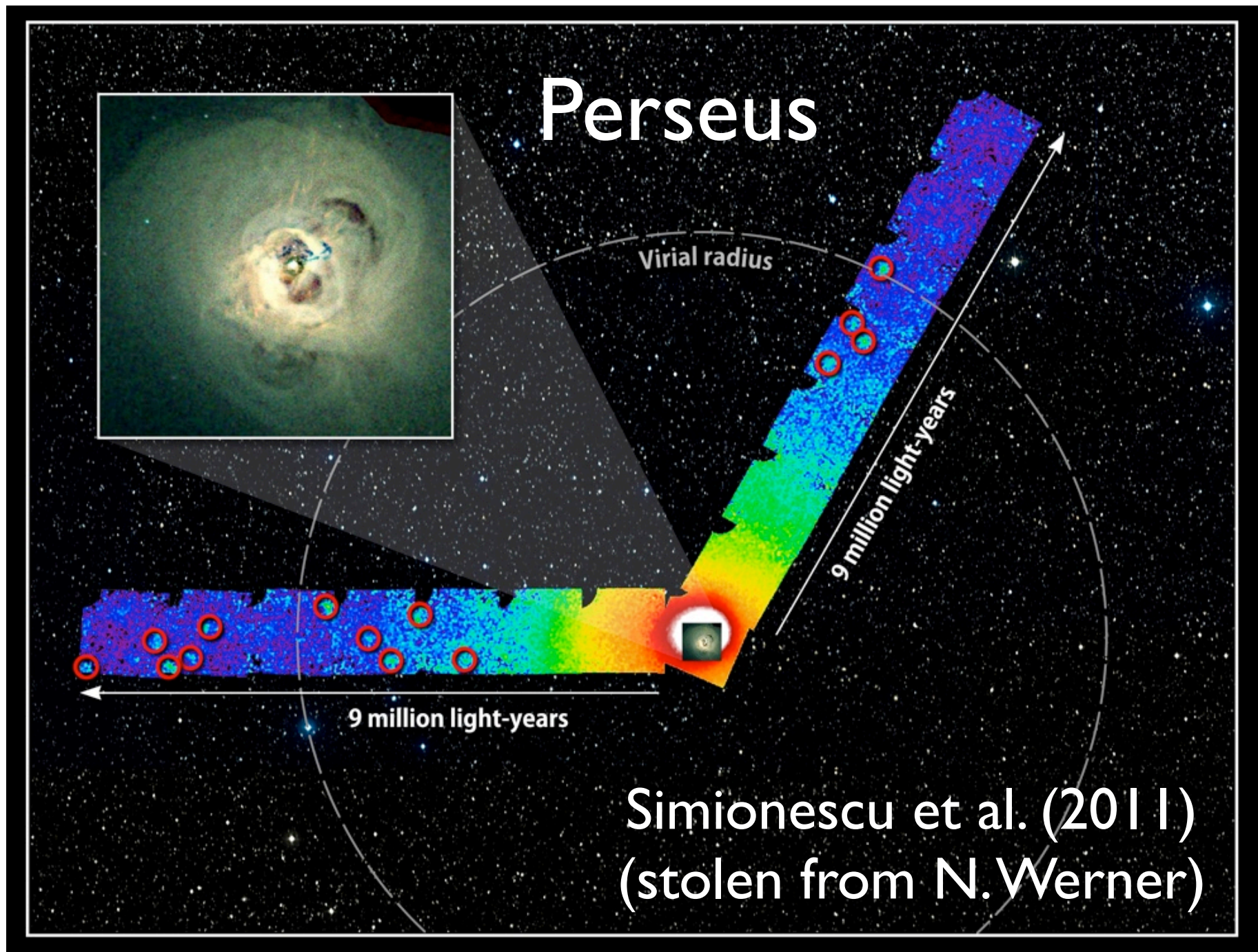
$$c_{200} = 12$$

entropy

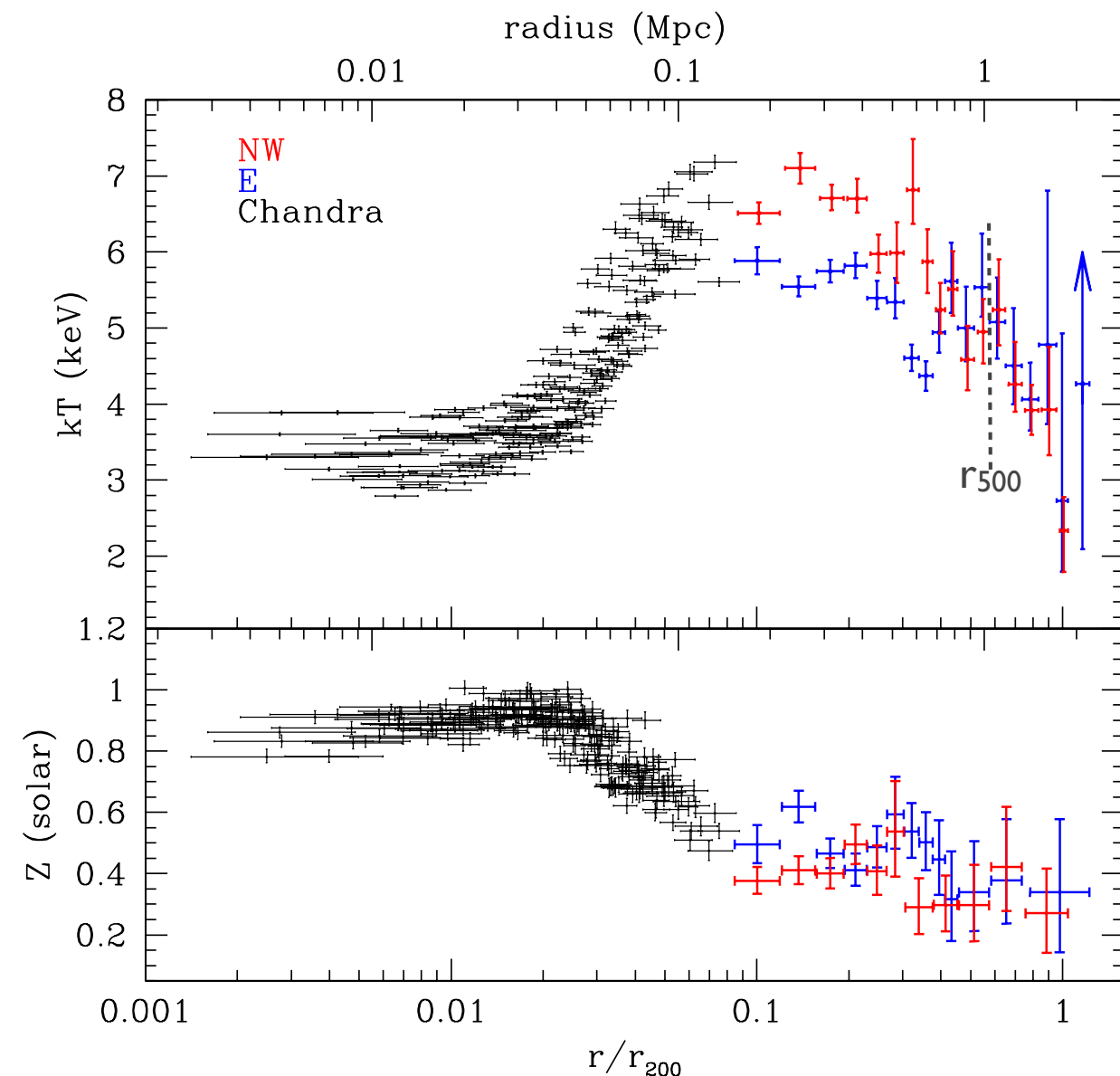
gas fraction



Surface brightness images of the NW and E arms:



Projected temperature and metallicity profiles:



excellent agreement with Chandra data

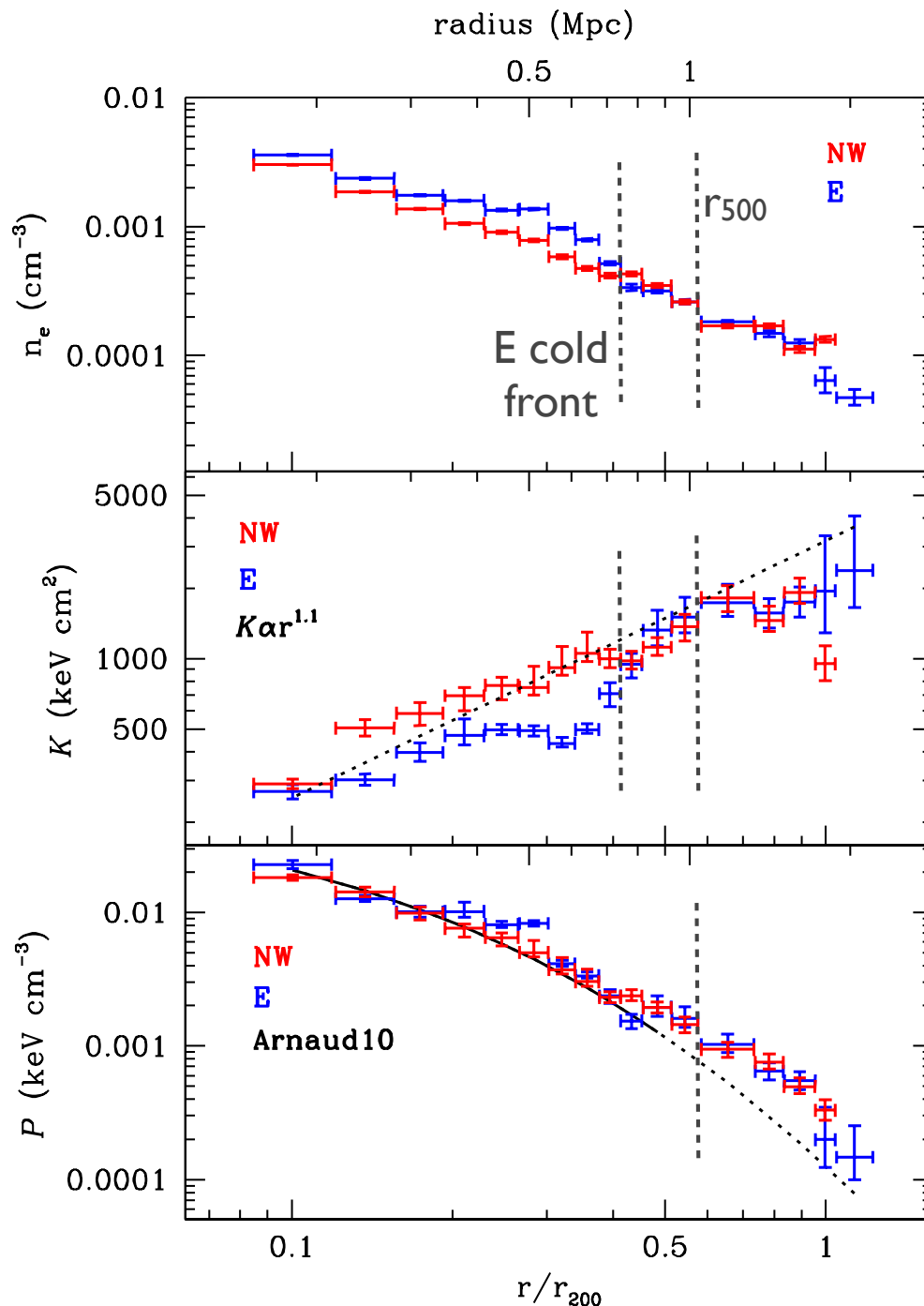
detailed profiles spanning 3 decades in radius

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

metallicity profile measured for the first time until the virial radius

Simionescu et al. (2011)
(stolen from N. Werner)

Deprojected thermodynamic profiles:



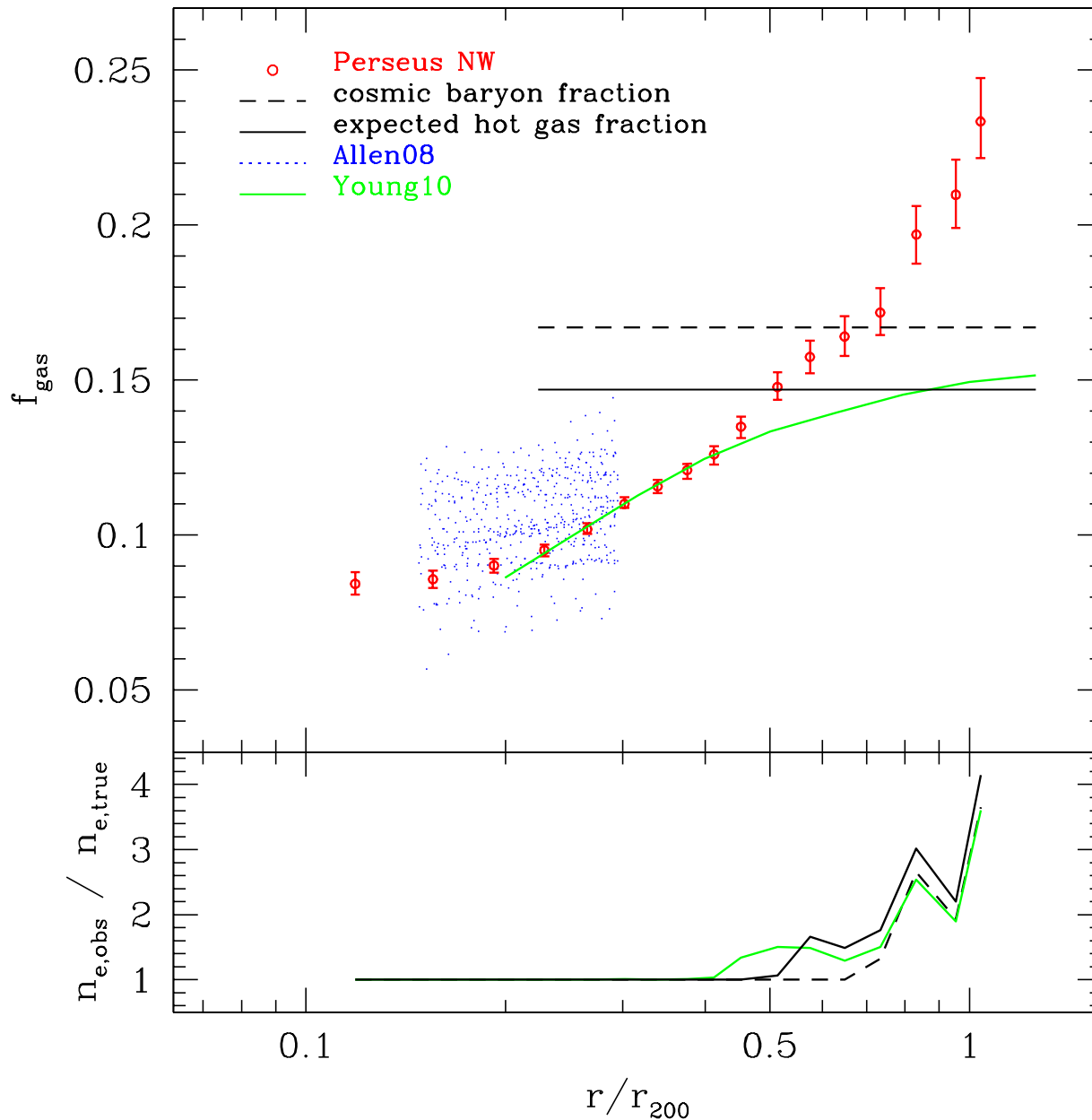
shallow decline of electron density at large radii

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)

Simionescu et al. (2011)
(stolen from N. Werner)

Gas mass fraction profile towards the NW:



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

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

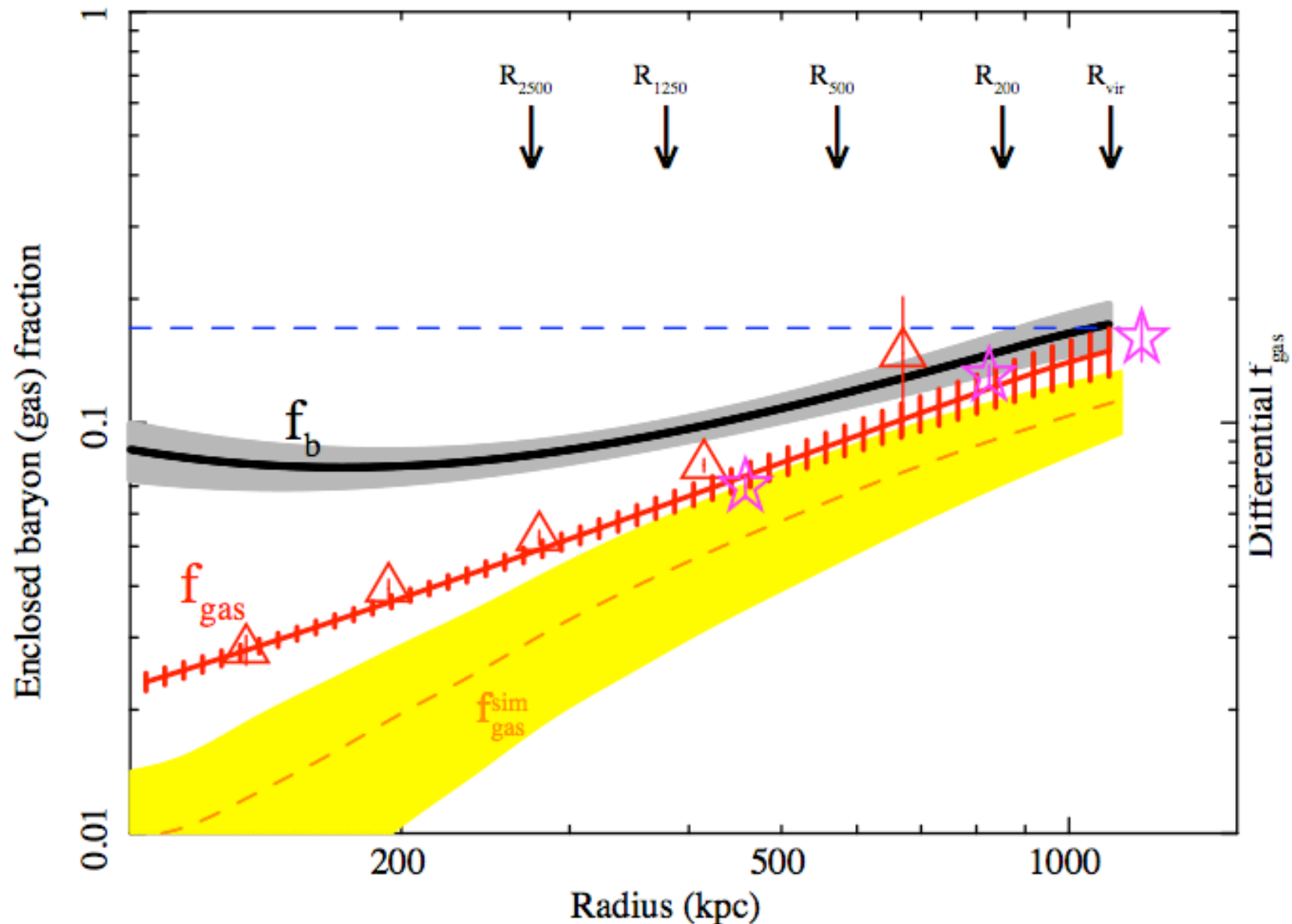
bottom panel shows the first measurements of the gas clumping factor

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

Simionescu et al. (2011)
(stolen from N. Werner)

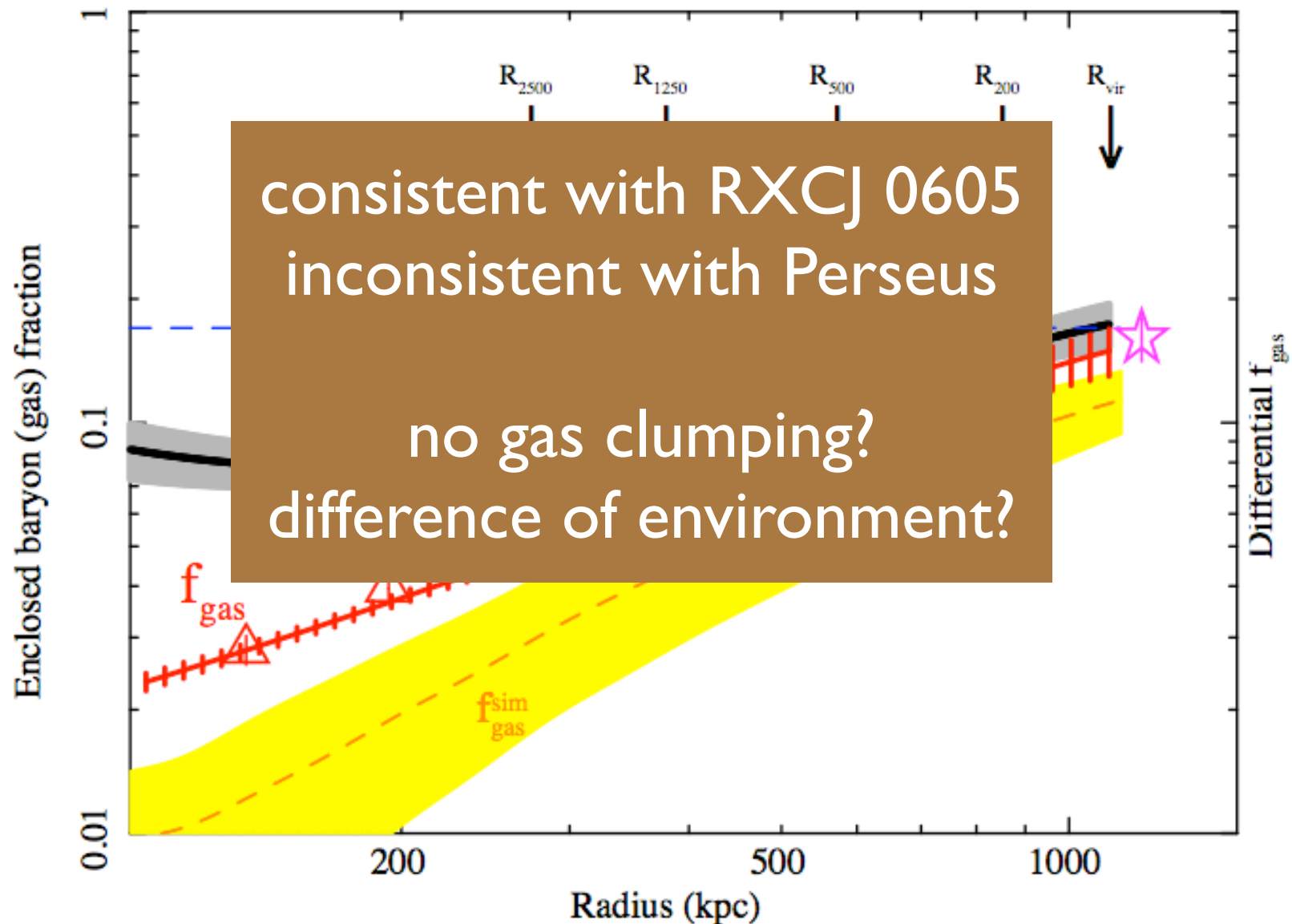
Fossil Group RXJ 1159+5531

Humphrey+2011



Fossil Group RXJ 1159+553 I

Humphrey+2011



Summary

- 9 clusters selected from Snowden *XMM* catalog
- multiple directions probed to R_{200}
 - but need *Chandra* point source data
- average profiles to $R_{100} \sim R_{\text{vir}}$
- confirm falling kT profiles
- so far consistent with cosmic baryon fraction at R_{200}
 - lack of clumping, environmental factors?
 - stay tuned....