Exploring the Outskirts of Galaxy Clusters

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Clusters as Tools

- cosmology
  - formation of structure is governed by gravity; measuring mass distribution of clusters is a direct test of cosmology
- astrophysics
  - non-gravitational processes (AGN and SN heating, radiative cooling) change the thermodynamics
- chemical evolution
  - “beacons” that can trace production and distribution of elements

A Word About "Entropy"

Fundamental Relation of Thermodynamics

$$dU = \delta Q - \delta W$$

internal energy — dU

heat — δQ

work — δW

$$dU = T\,dS - P\,dV$$

entropy — dS

A Word About "Entropy"

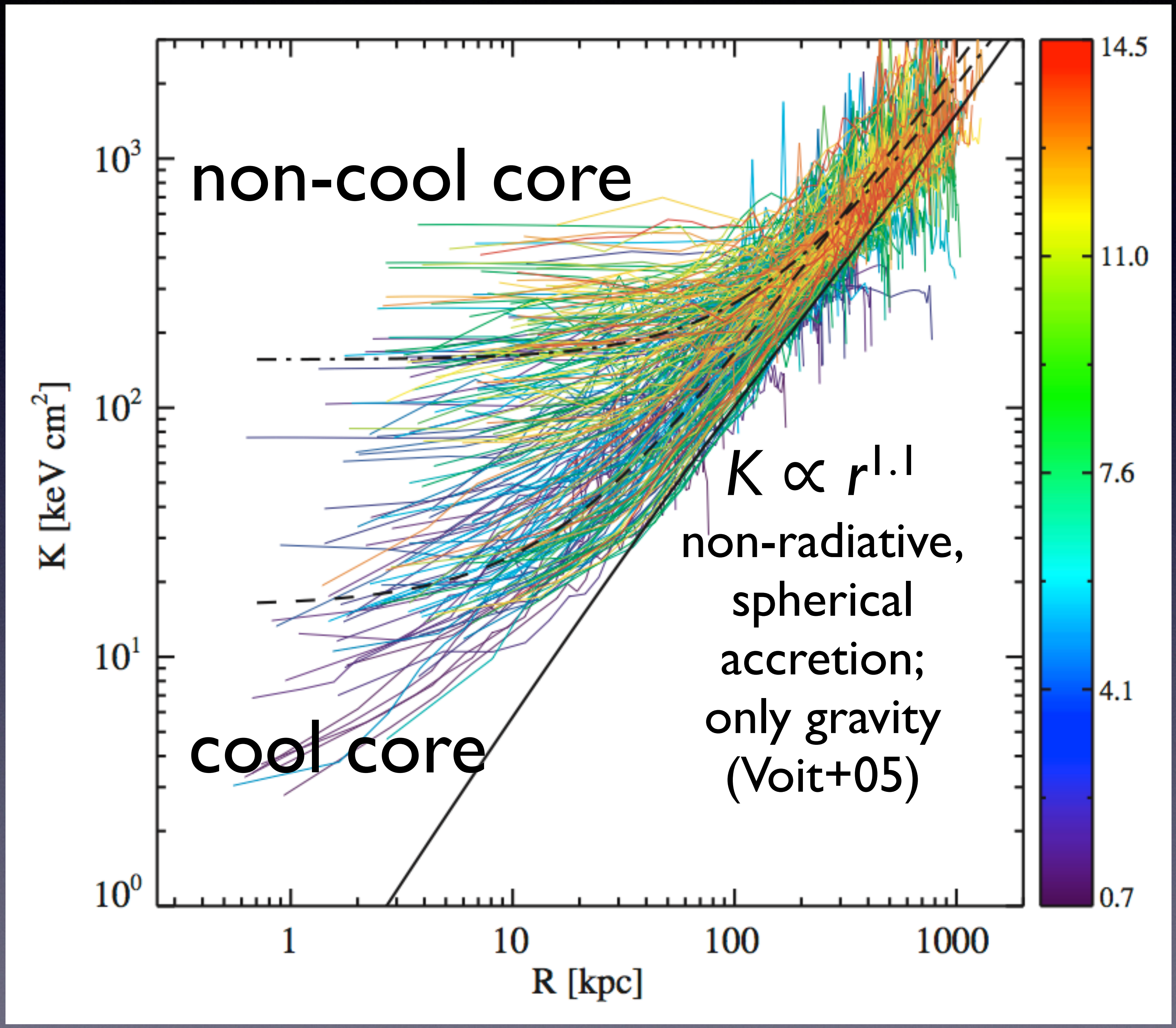
$$dU = TdS - PdV$$

- entropy encodes the thermal history of the gas; only heat energy transferred in or out of the system can change the entropy
  - shock heating, AGN heating, radiative cooling

From Cavagnolo+09:

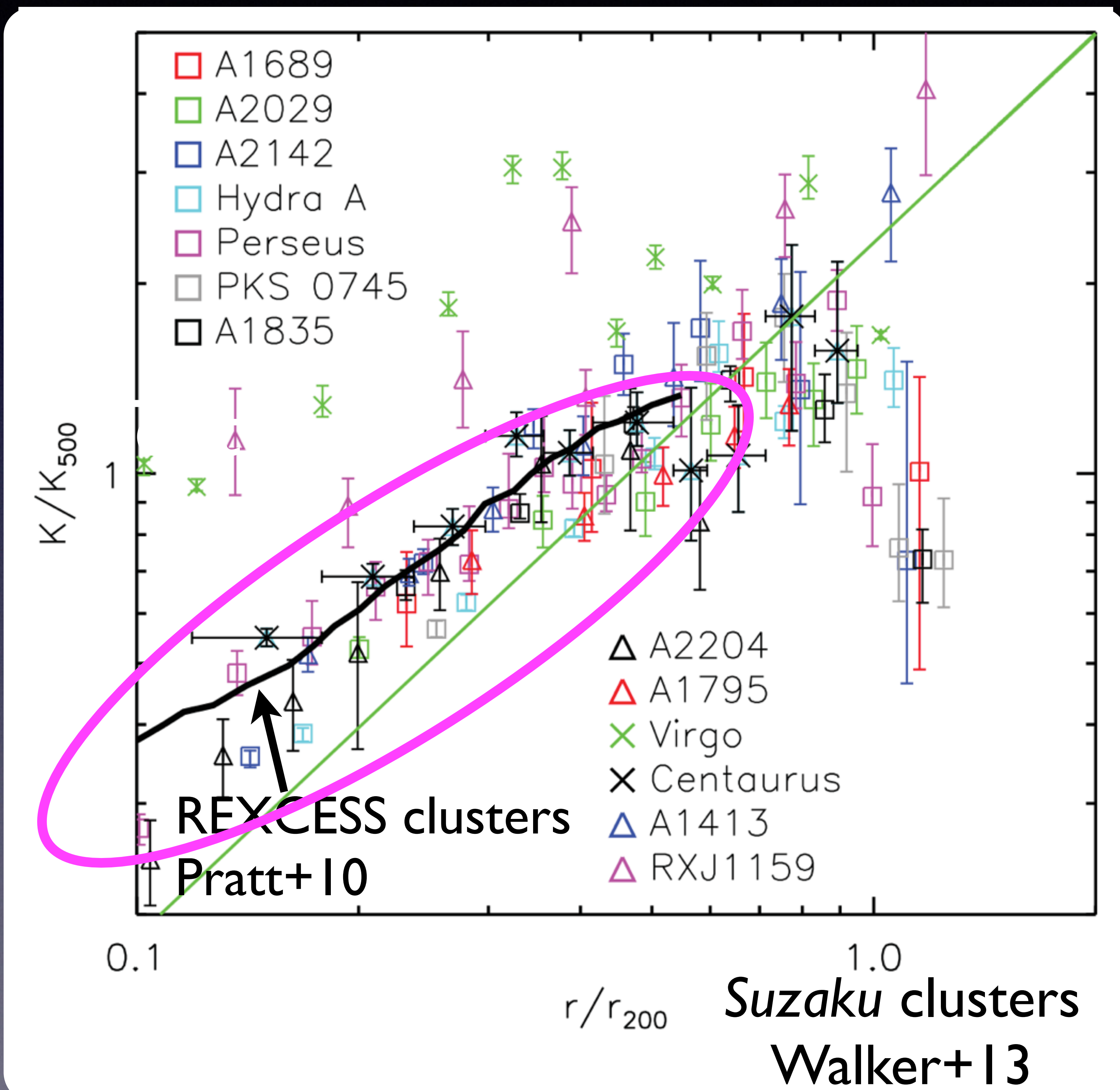
"Thus, gravitational potential wells are giant entropy sorting devices: low entropy gas sinks to the bottom of the potential well, while high entropy gas buoyantly rises to a radius at which the ambient gas has equal entropy."

The Power of Entropy



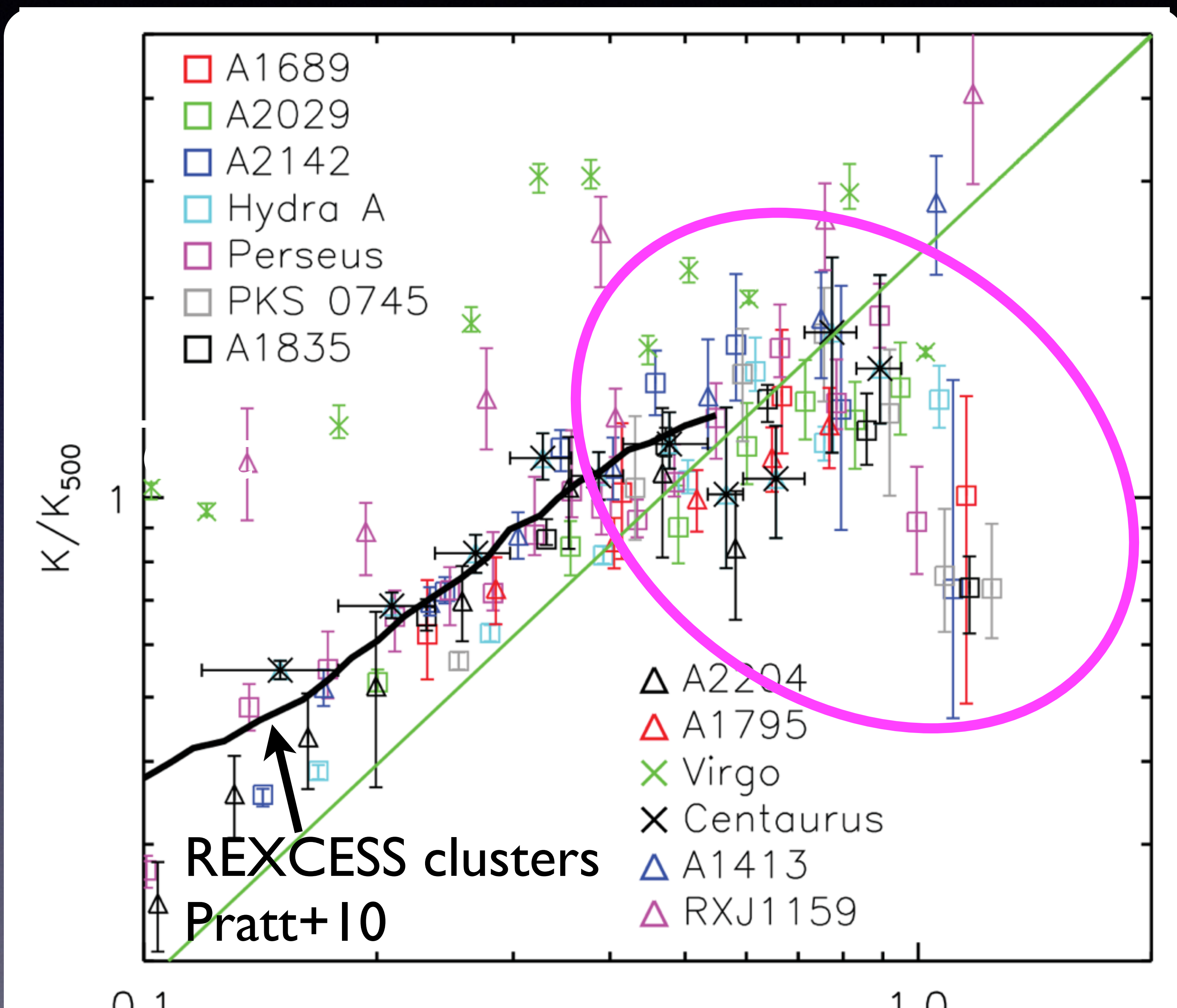
Cavagnolo+09 (ACCEPT)

Entropy in the Outskirts



- AGN feedback
- merging mixing
- cool core vs. non-cool core

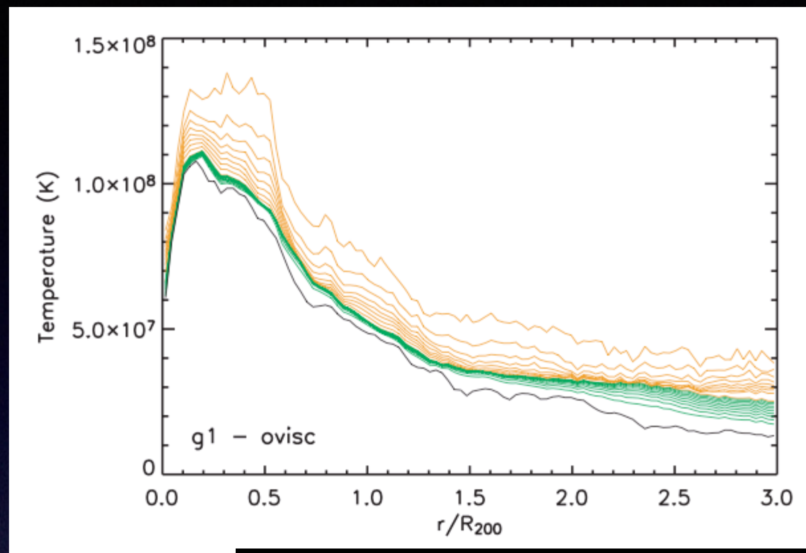
Entropy in the Outskirts

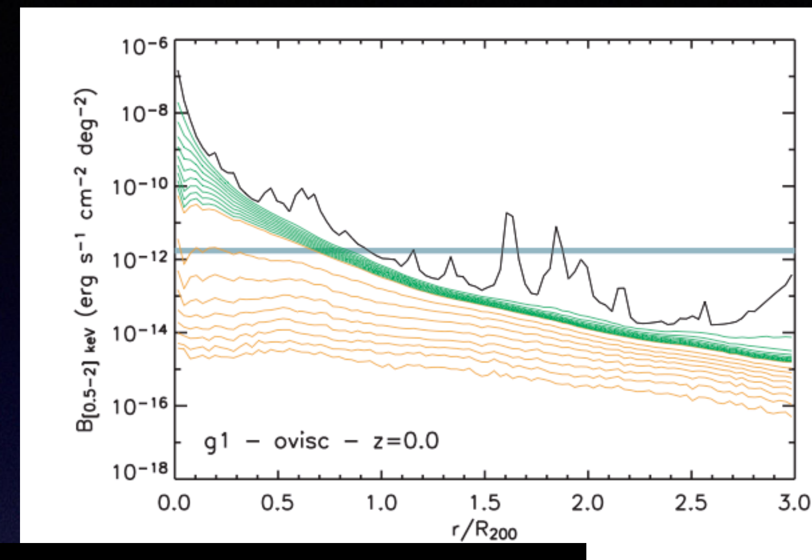


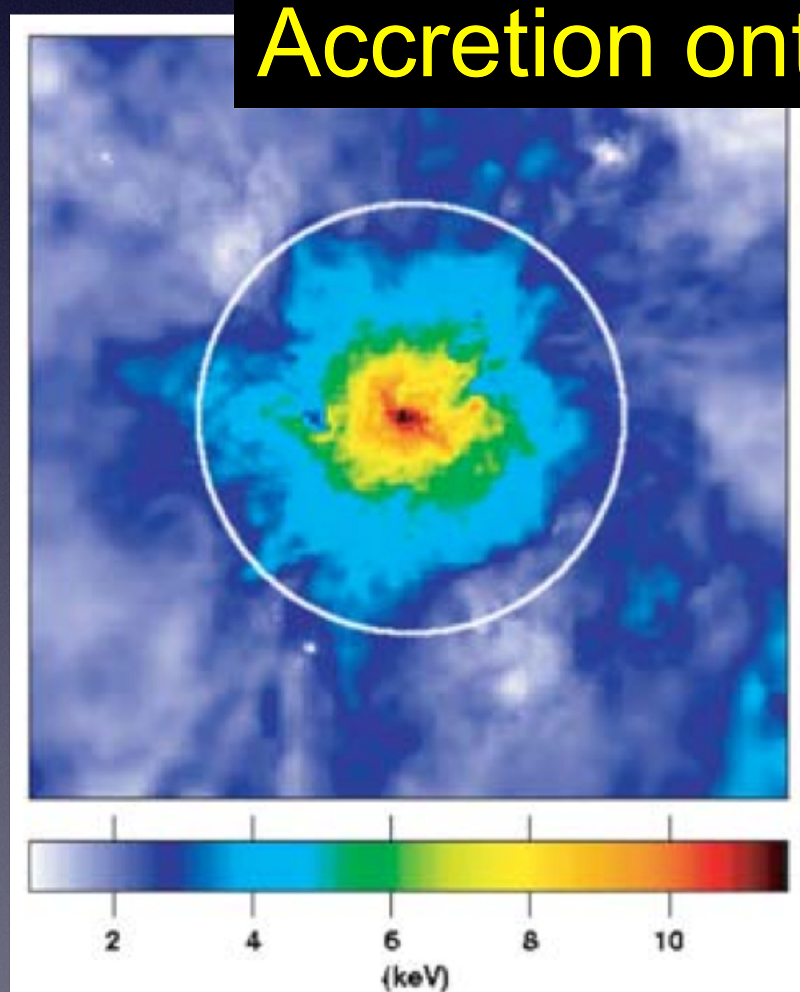
Suzaku clusters
Walker+13

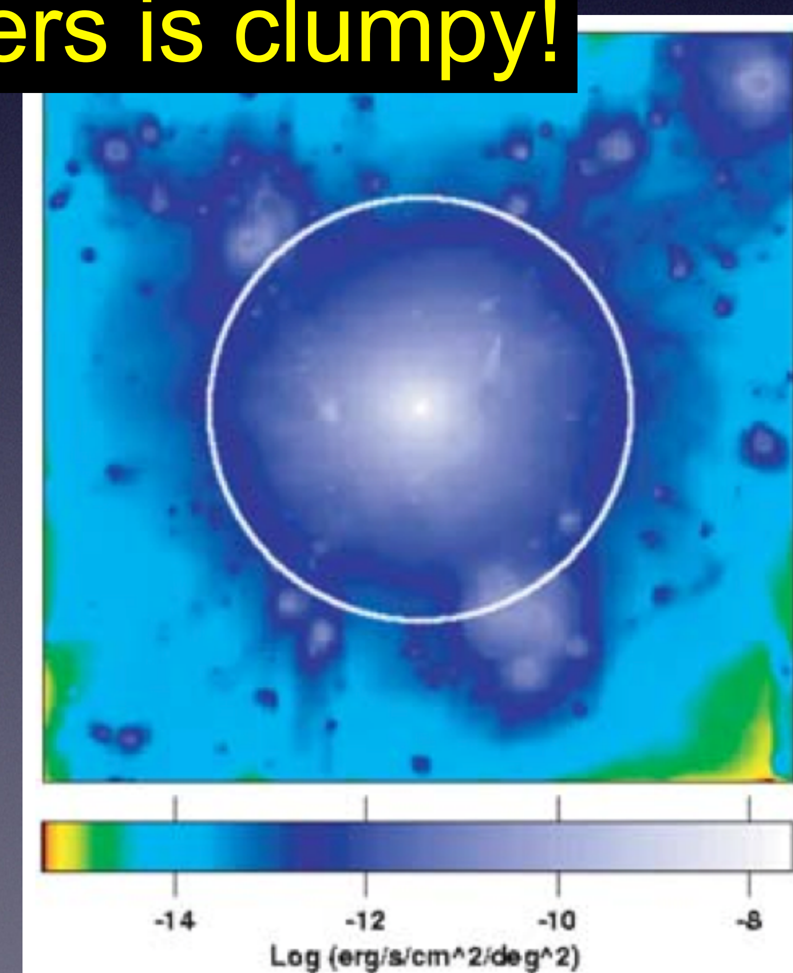
- hydrostatic equilibrium?
- low-entropy accreting halos?
- EM ∝ n_e^2
  → inferred density may be enhanced by "clumping"
  → lower $K = kT\, n_e^{-2/3}$

Comparison with Simulations







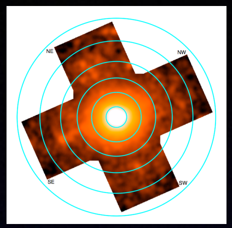


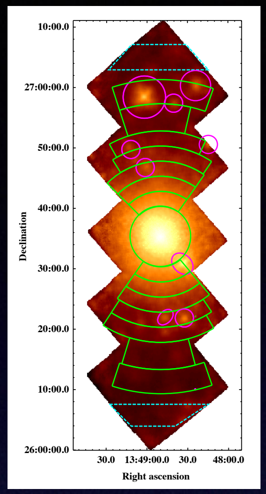
Accretion onto clusters is clumpy!

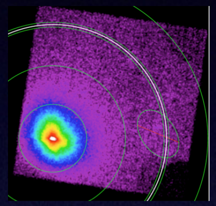
Roncarelli+2006 (also Burns+2010, Nagai+2011)

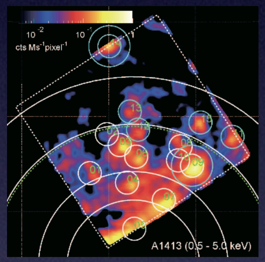
Clusters to R_{200} with *Suzaku*

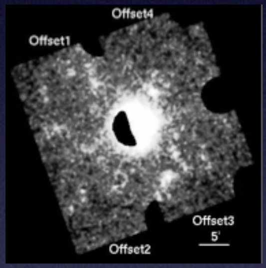
PKS 0745-191	George+2009 Walker+2012
Abell 2204	Reiprich+2009
Abell 1795	Bautz+2009
Abell 1413	Hoshino+2010
Abell 1689	Kawaharada+2010
Perseus	Simionescu+2011 Urban+2013
Abell 2142	Akamatsu+2011
RXJ 1159+5531	Humphrey+2012
Centaurus	Walker+2013
ESO 3060170	Su+2013

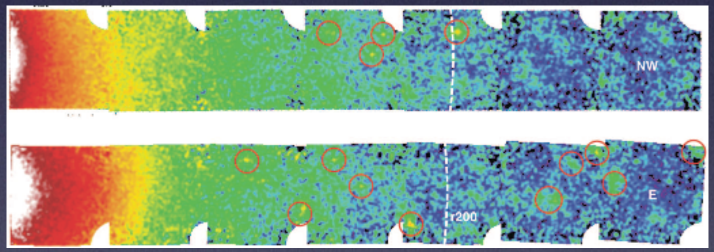


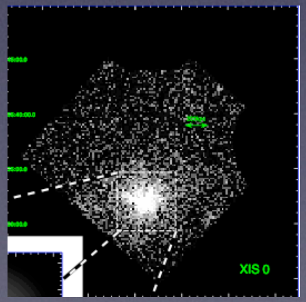


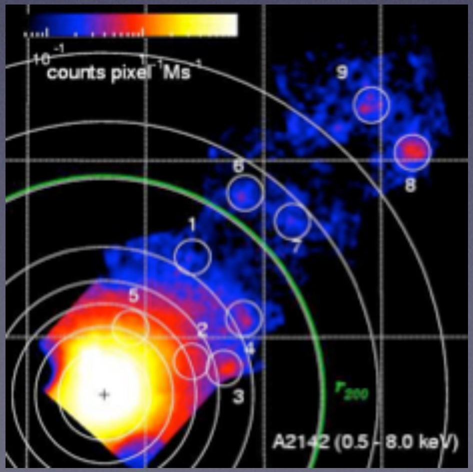








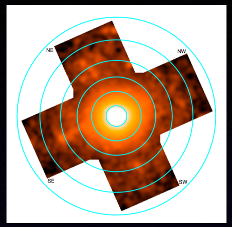


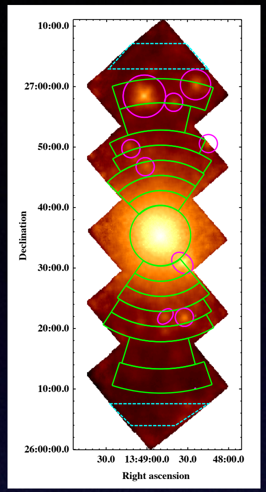


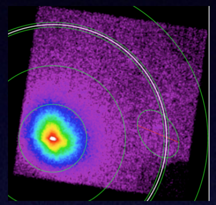
….and more!

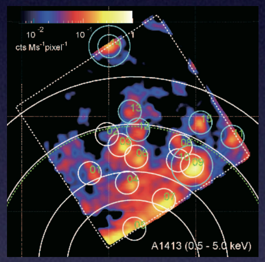
Clusters to *R_{200}* with *Suzaku*

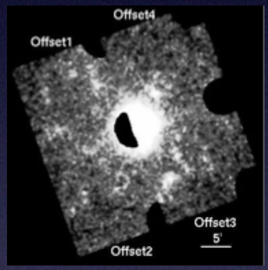
- differing azimuthal coverage
- heterogeneous analysis methods
- plan: systematic observations of well-defined sample

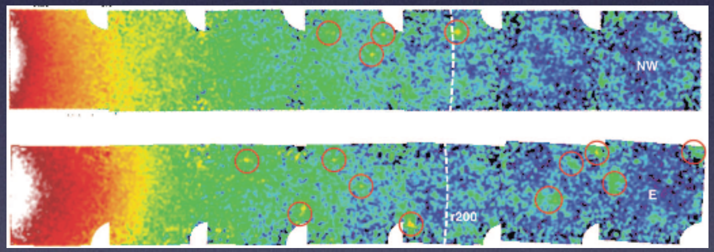


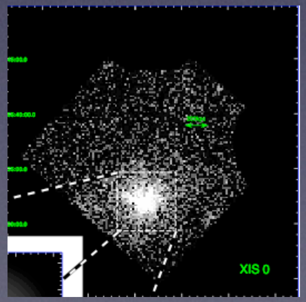


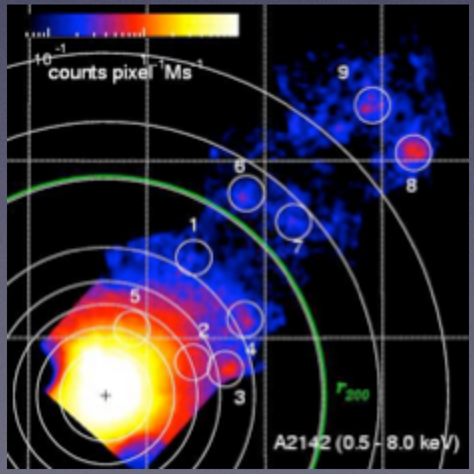








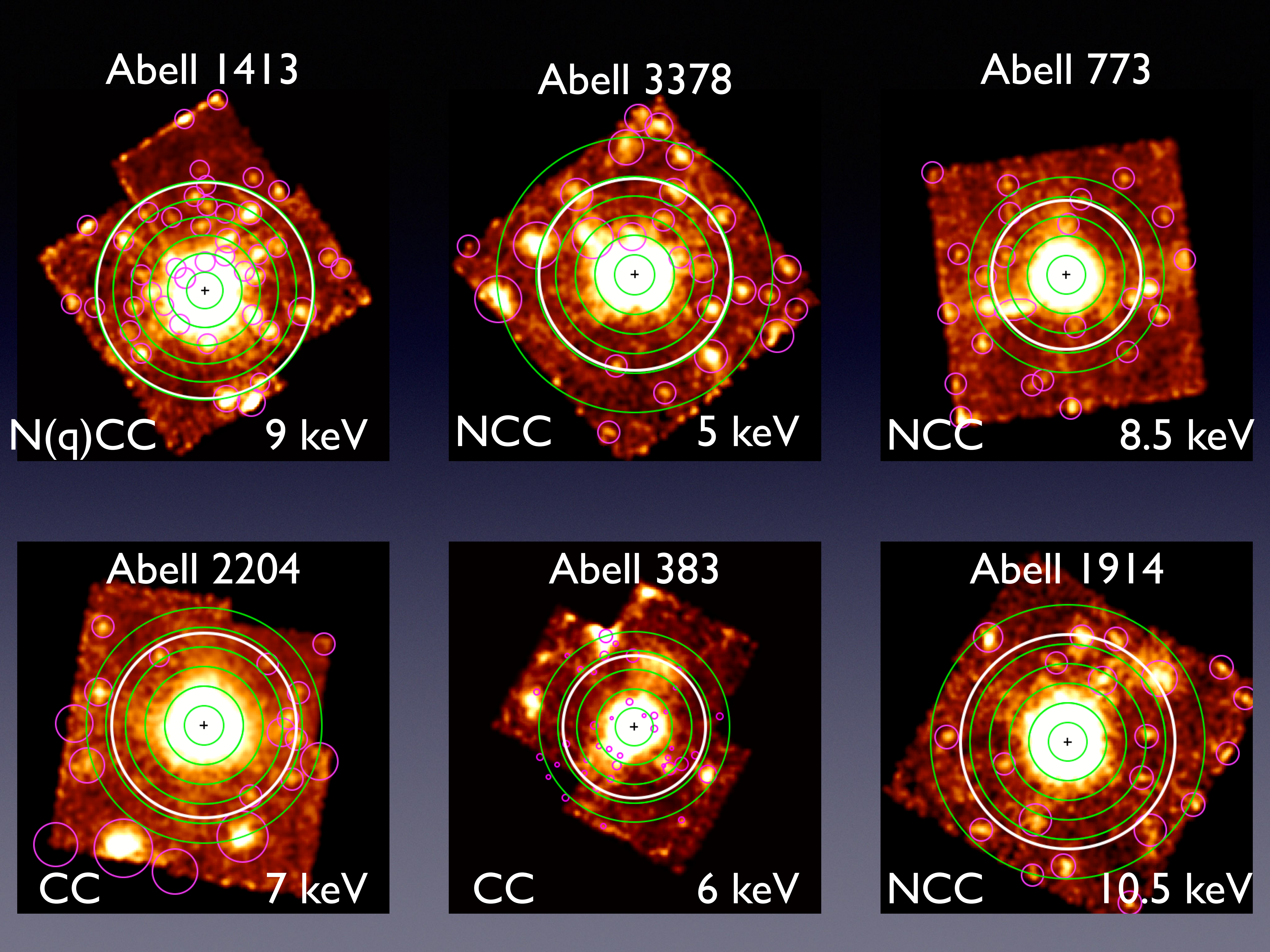




Suzaku Cluster Outskirts Project

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
A3378	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
A665	0.179	11.7	200	April 2012
A2597	0.080	15.0	200	Dec 2012

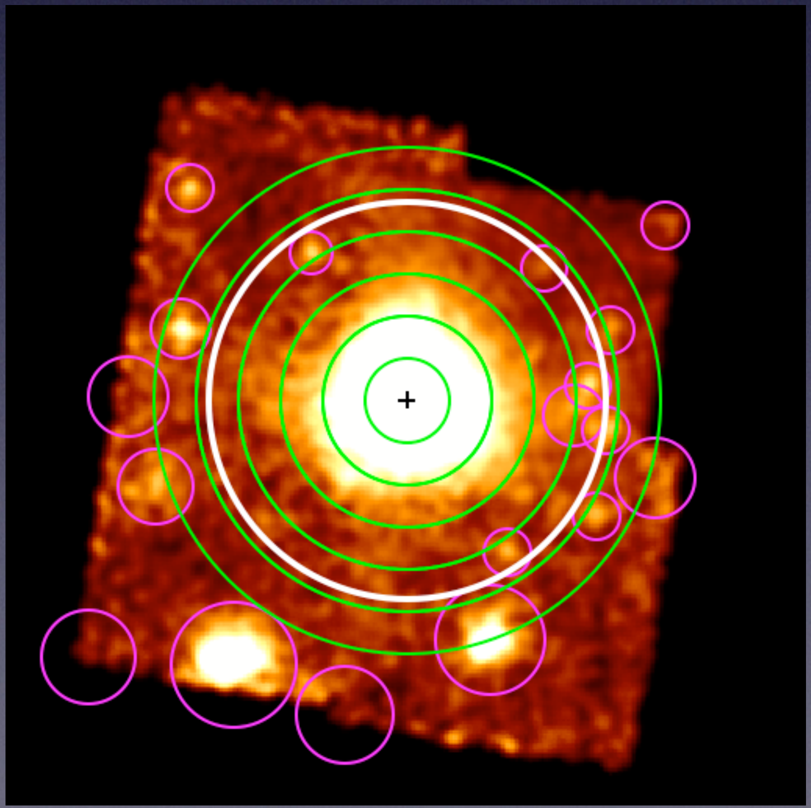
- selected from Snowden et al. 2008 XMM cluster catalog
- "relaxed", no substructure
- falling, flat, and rising kT profiles
- full azimuthal coverage out to R_{200}

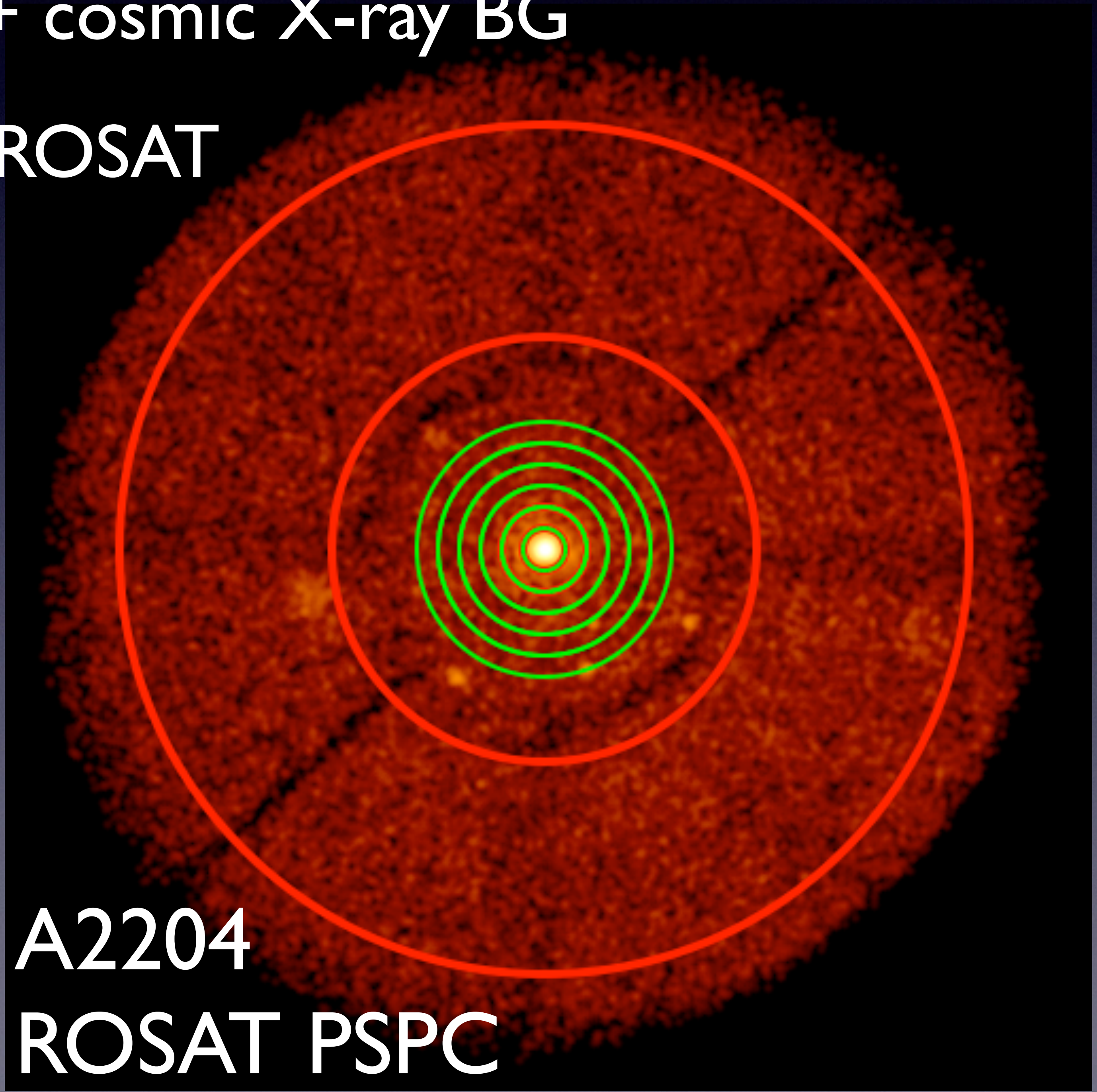

Abell 1413
N(q)CC
9 keV
Abell 3378
NCC
5 keV
Abell 773
NCC
8.5 keV
Abell 2204
CC
7 keV
Abell 383
CC
6 keV
Abell 1914
NCC
10.5 keV

Background Systematics

$S_{cluster}(R_{200})$ < 30% of X-ray background

- Galactic thermal BG + cosmic X-ray BG
  - use outer regions, ROSAT

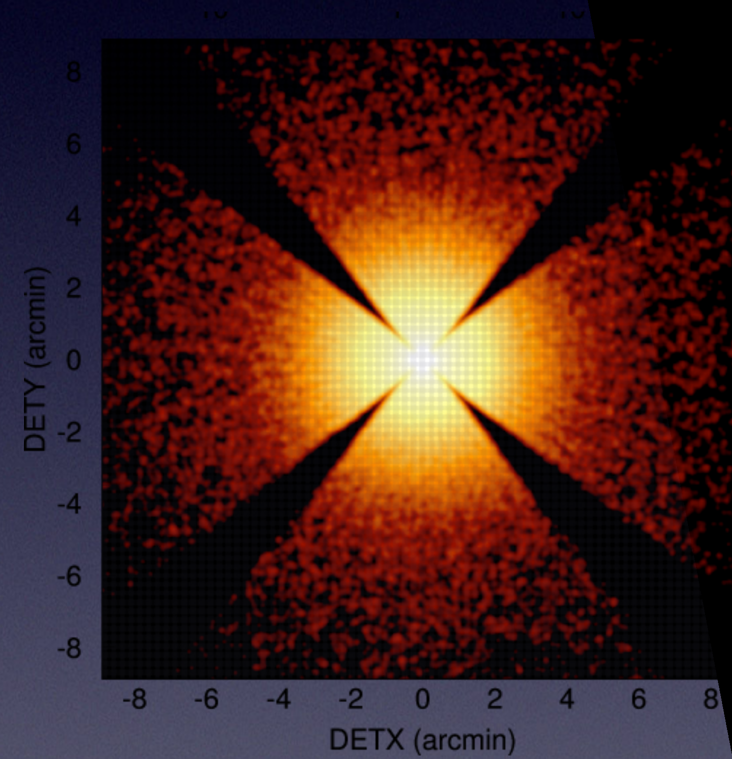


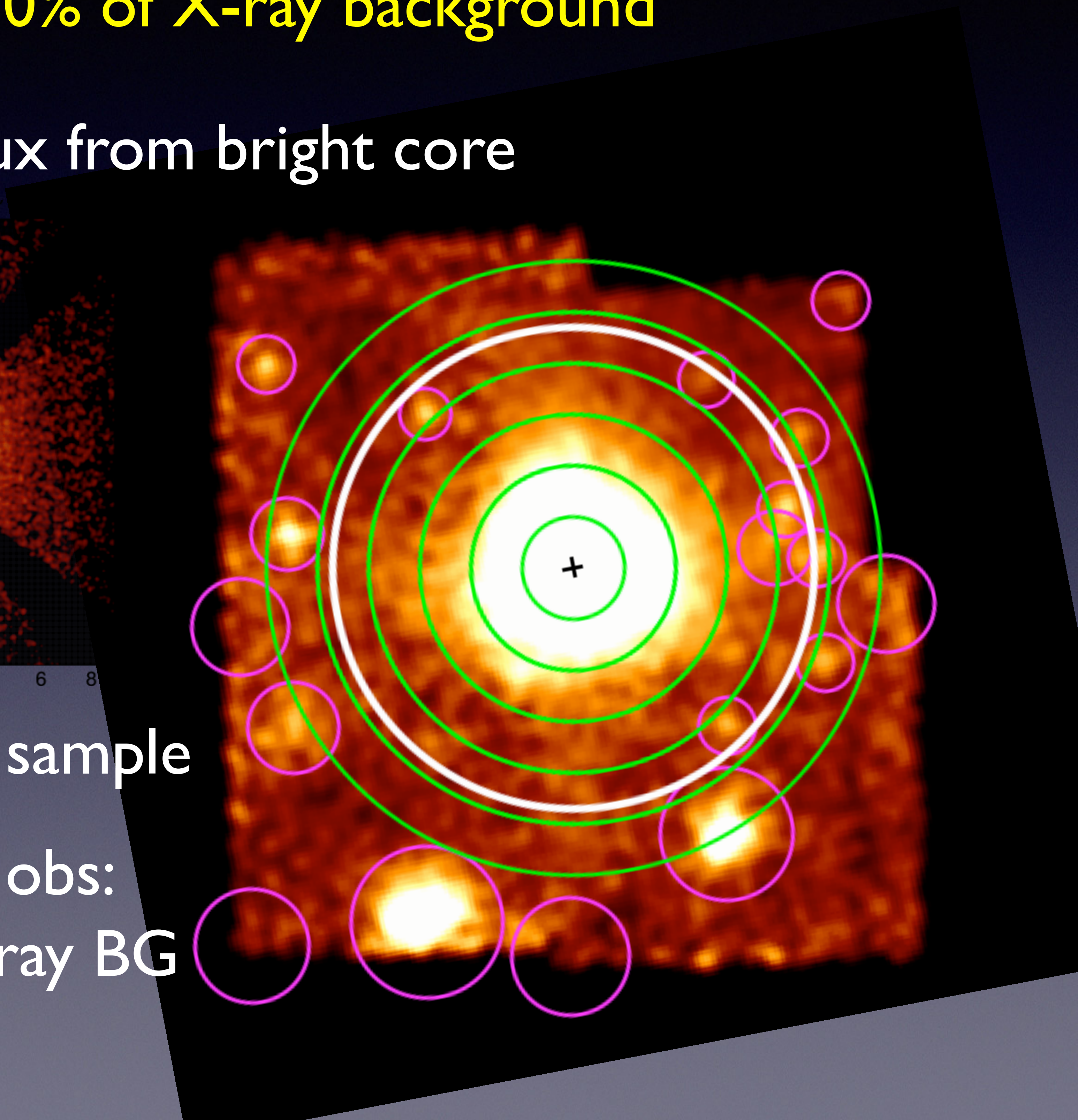


Background Systematics

$S_{cluster}(R_{200})$ < 30% of X-ray background

- scattered X-ray flux from bright core



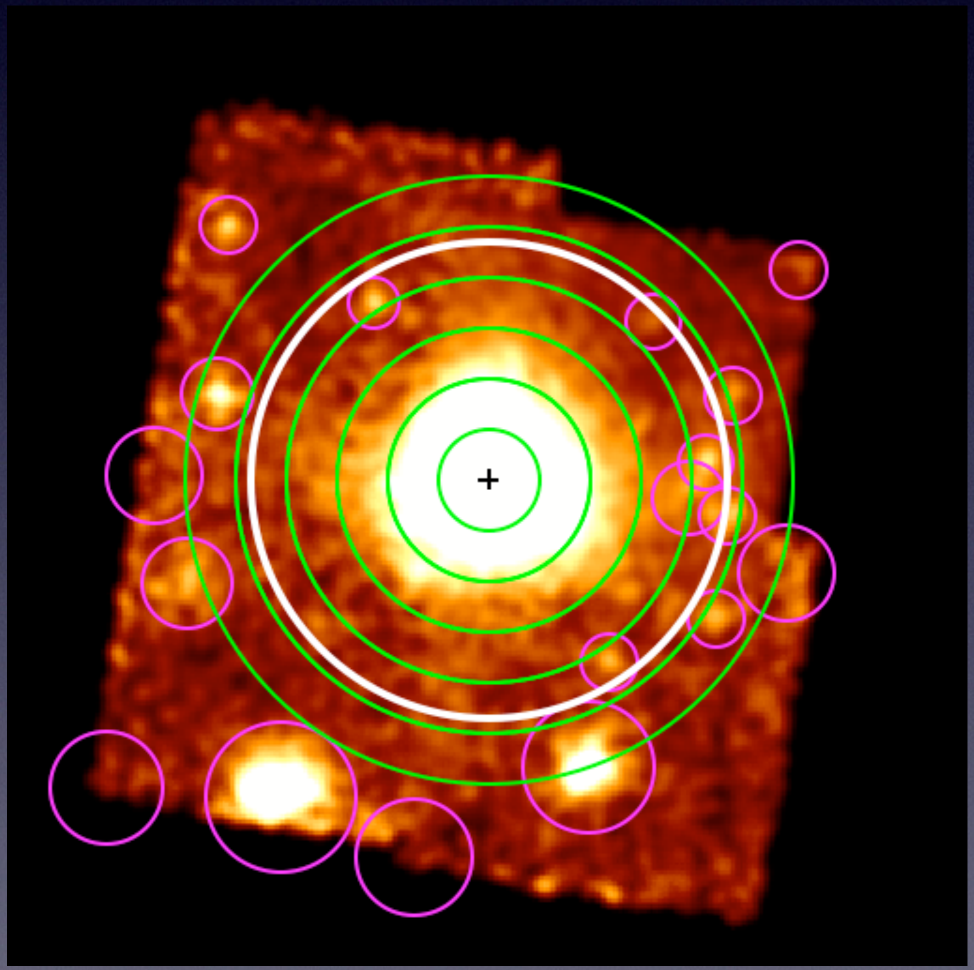


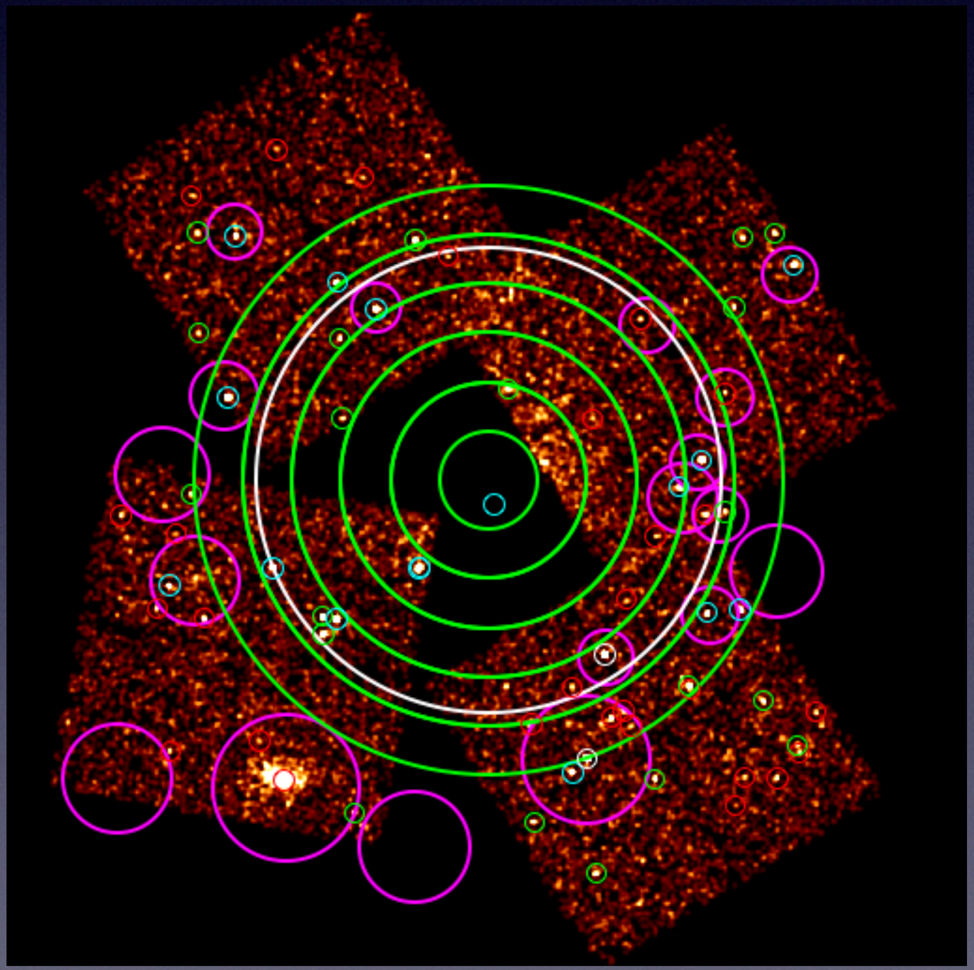
- restrict cluster sample
- simulations, cal obs: σ_{SB} < 3% of X-ray BG

Background Systematics

$S_{\mathrm{cluster}}(R_{200})$ < 30% of X-ray background

- point source Poisson noise

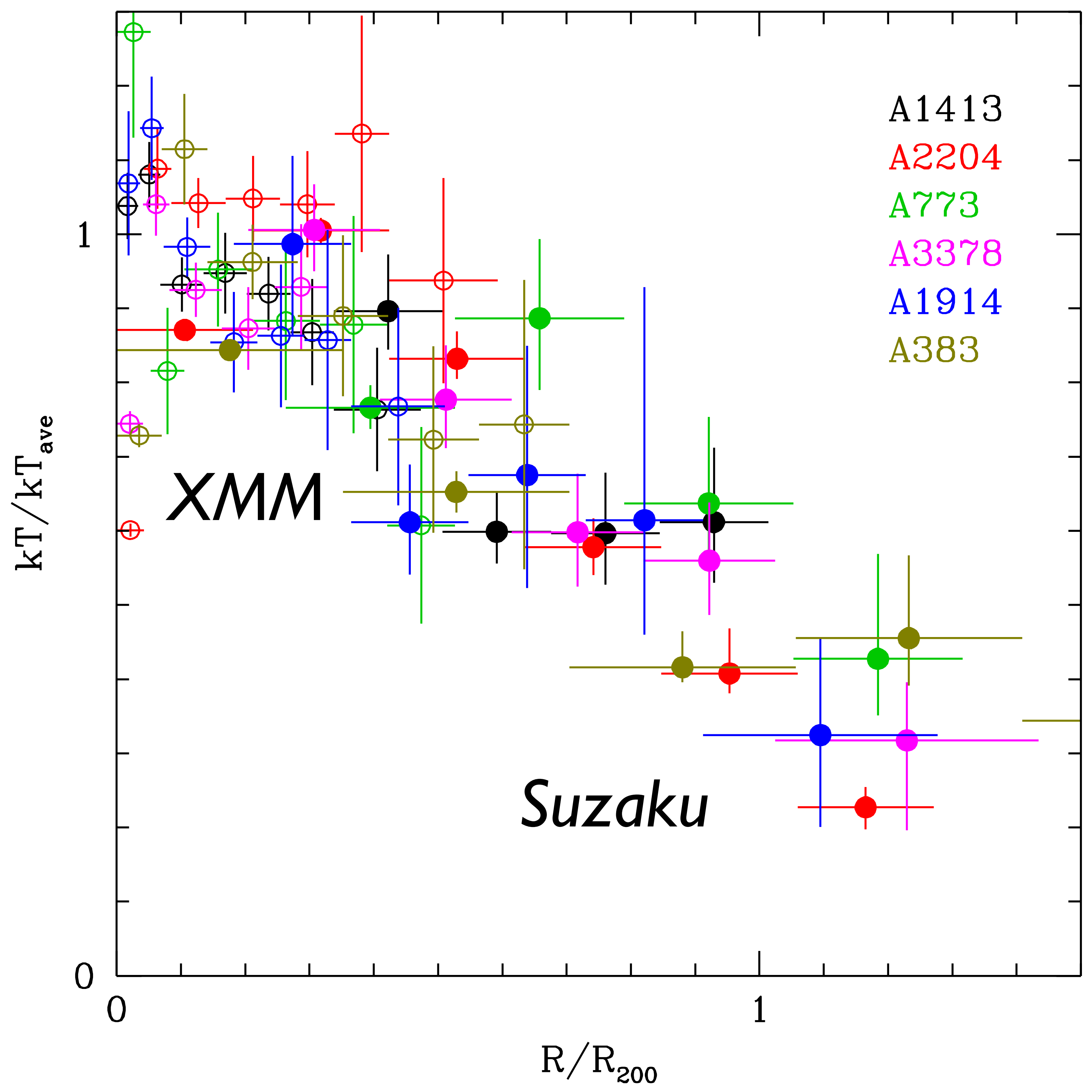




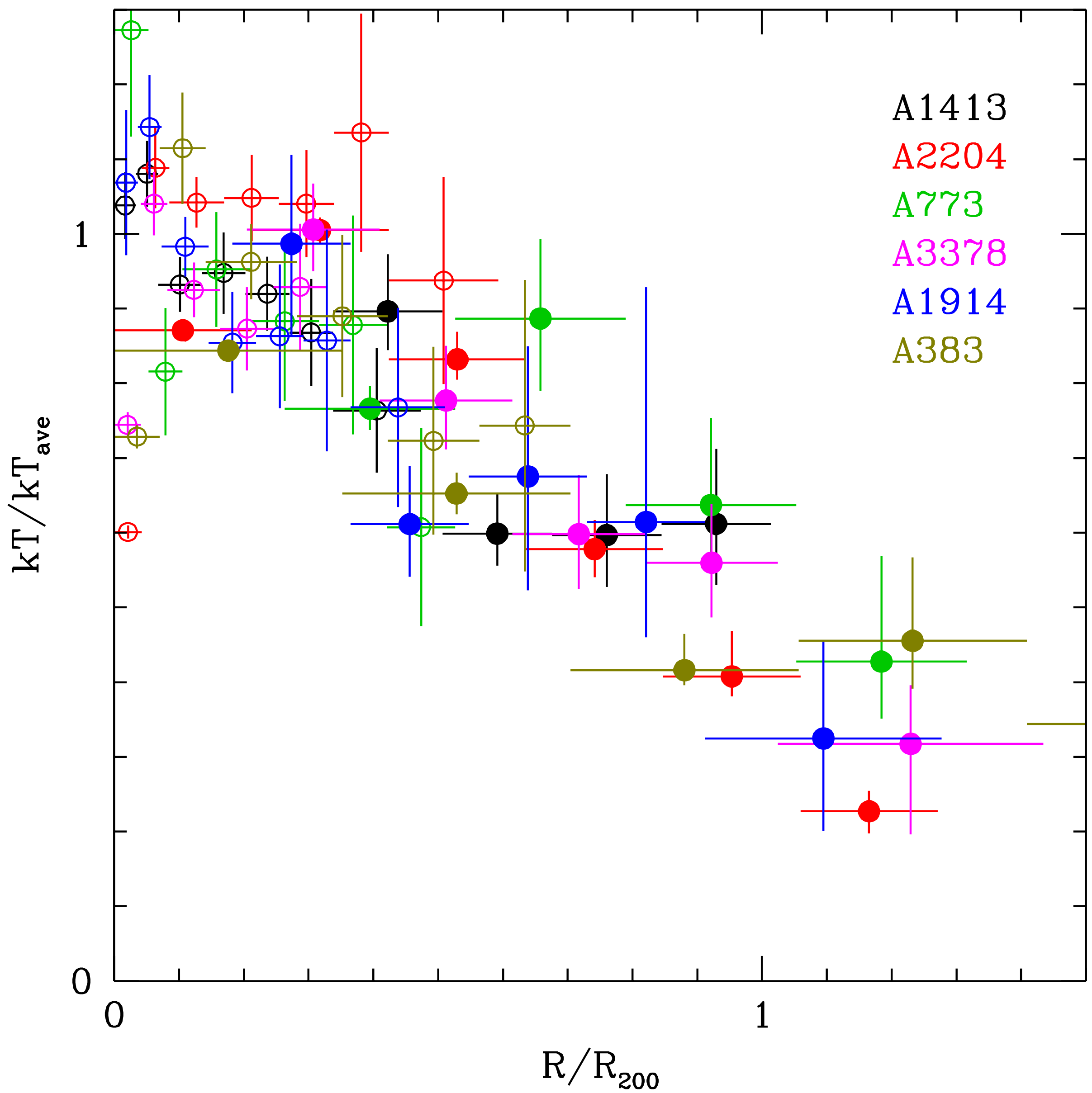
- with *Chandra* snapshots:
  σ_{SB} < 5% of X-ray BG (full annulus)

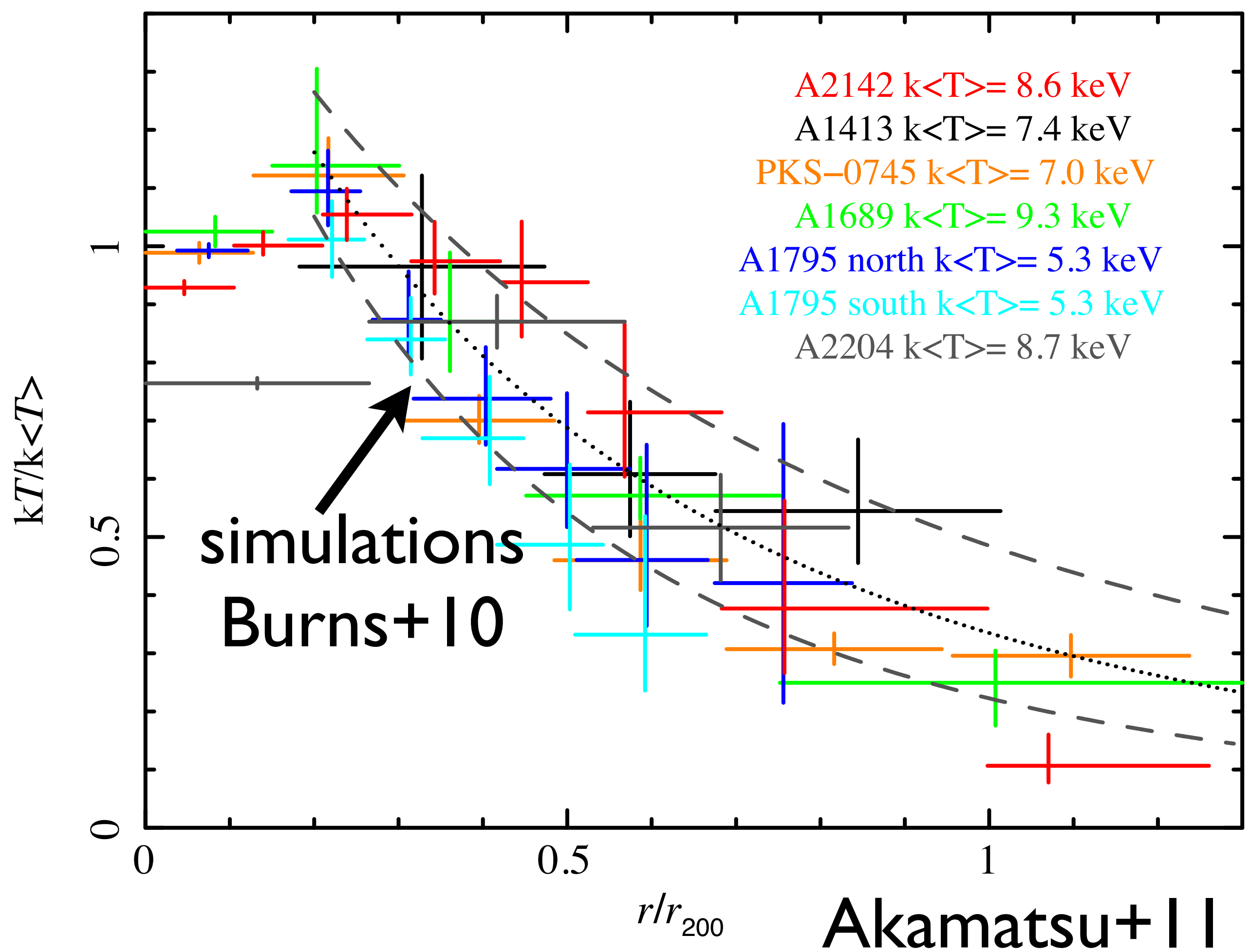
Results

Temperature



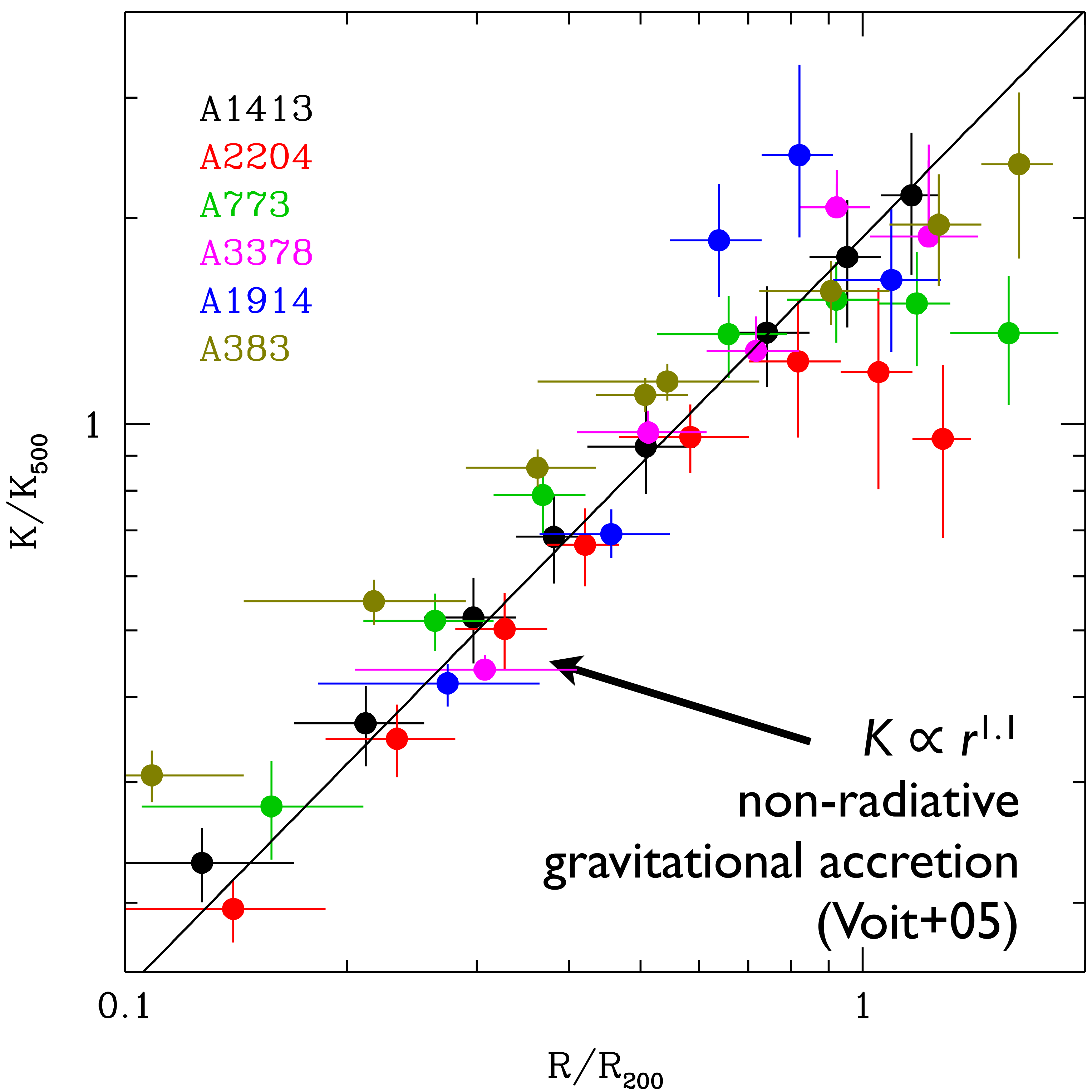
Temperature



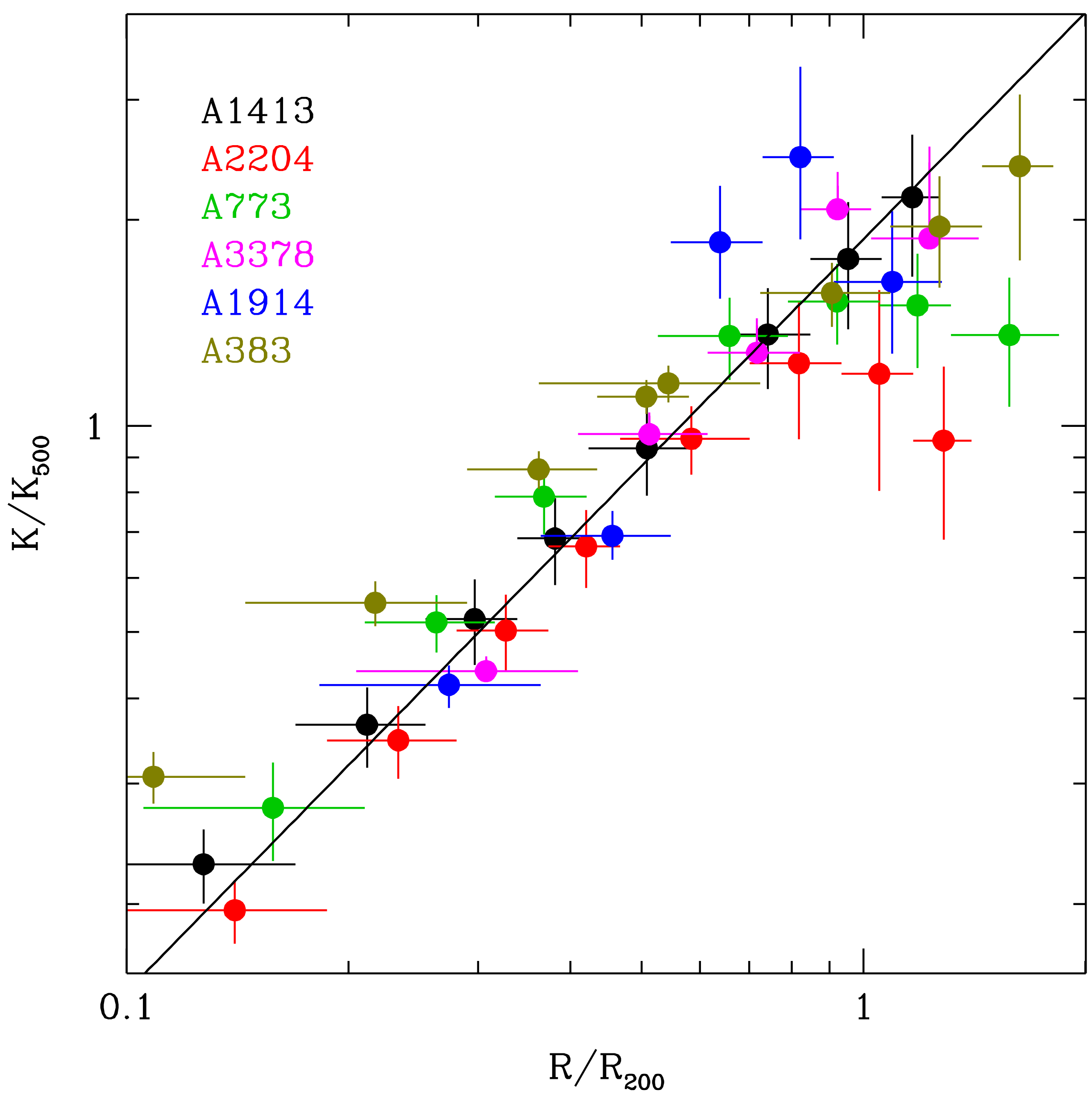


Akamatsu+11

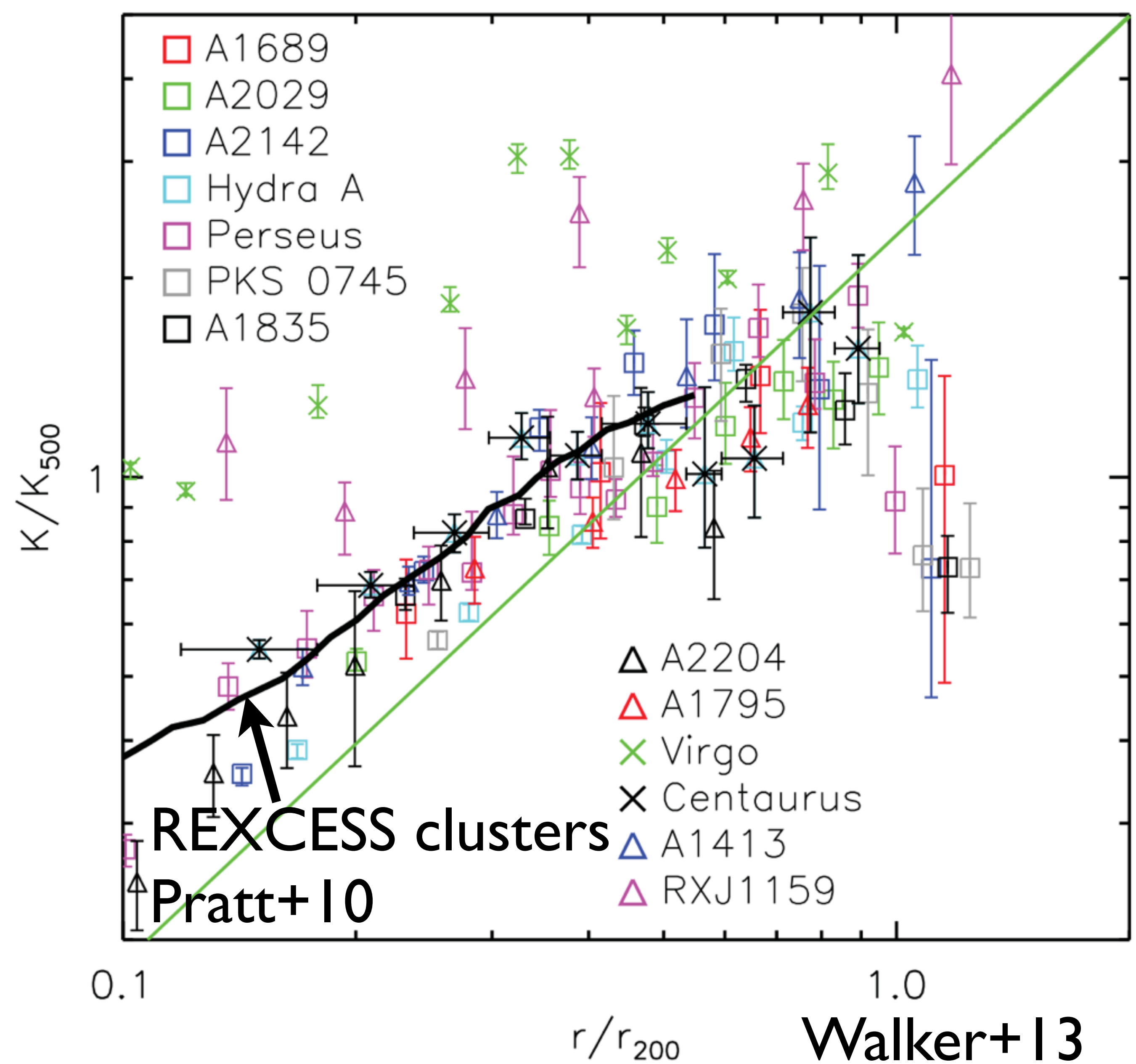
Entropy


A1413
A2204
A773
A3378
A1914
A383
1
K/K500
0.1
1
R/R200
K ∝ r^1.1
non-radiative
gravitational accretion
(Voit+05)

Entropy

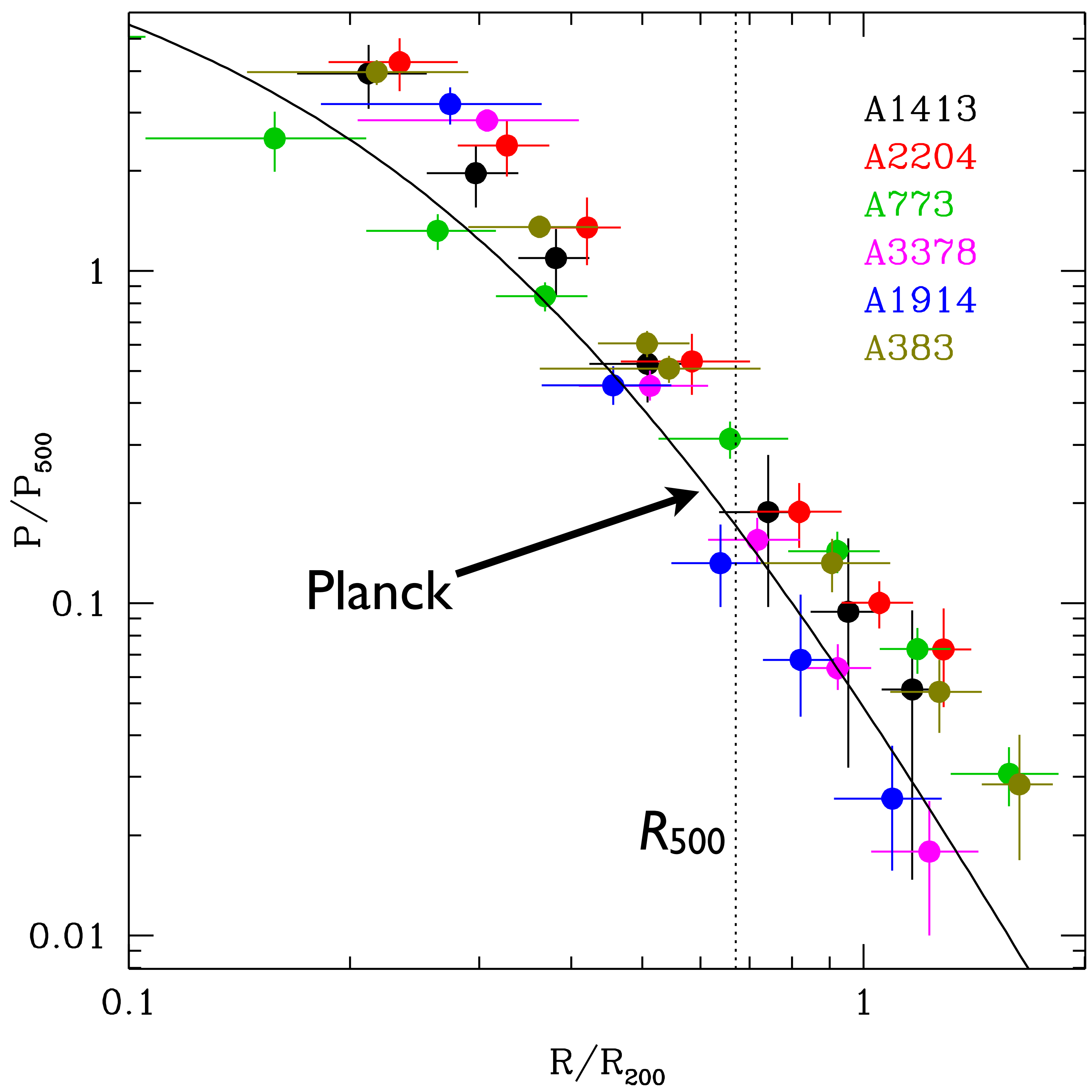


A1413
A2204
A773
A3378
A1914
A383
K/K500
R/R200
0.1
1



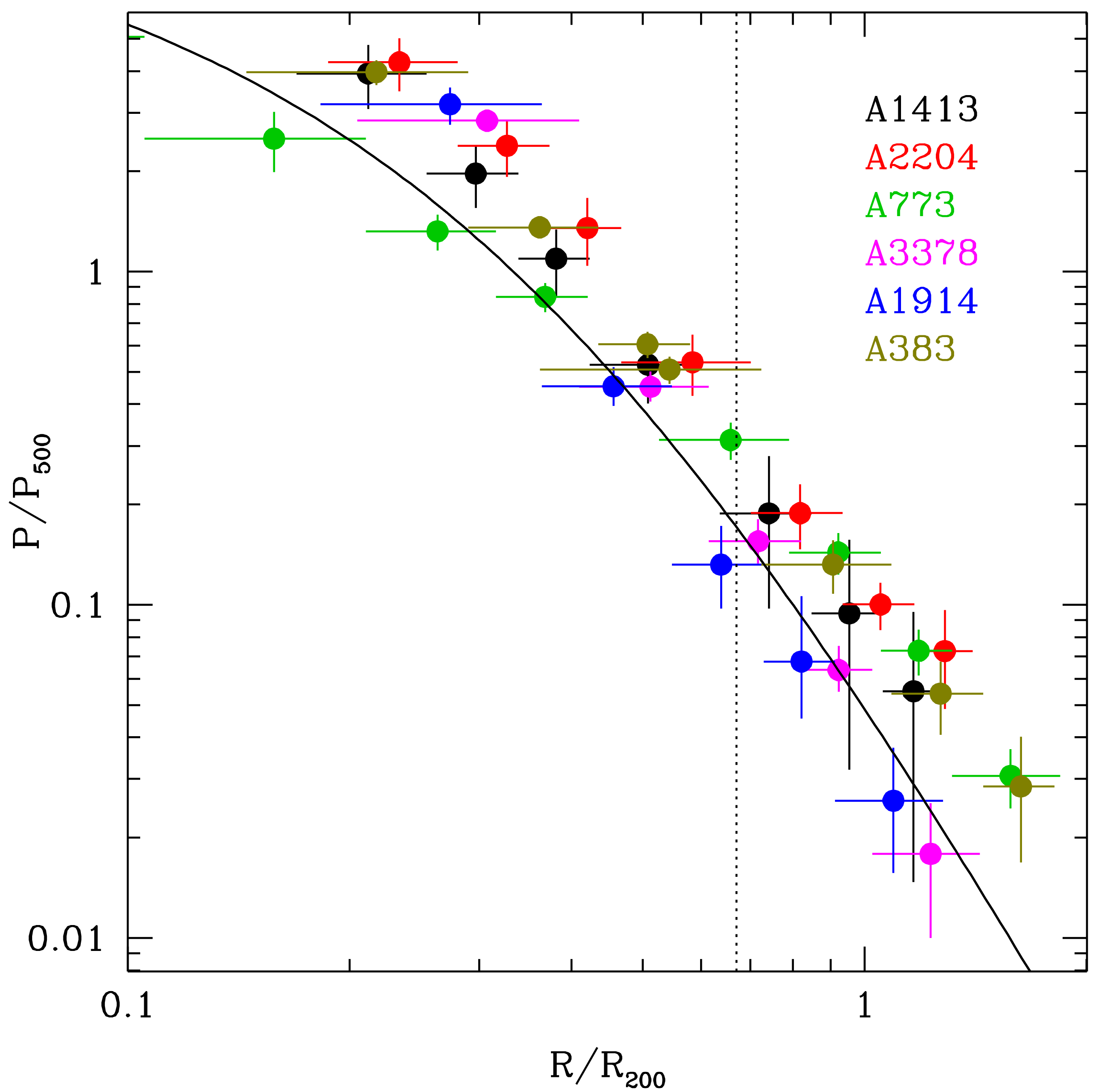
A1689
A2029
A2142
Hydra A
Perseus
PKS 0745
A1835
A2204
A1795
Virgo
Centaurus
A1413
RXJ1159
REXCESS clusters
Pratt+10
K/K500
r/r200
0.1
1.0
Walker+13

Pressure

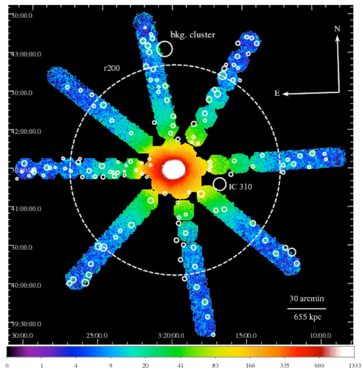


A1413
A2204
A773
A3378
A1914
A383
Planck
R_{500}
P/P_{500}
1
0.1
0.01
0.1
1
R/R_{200}

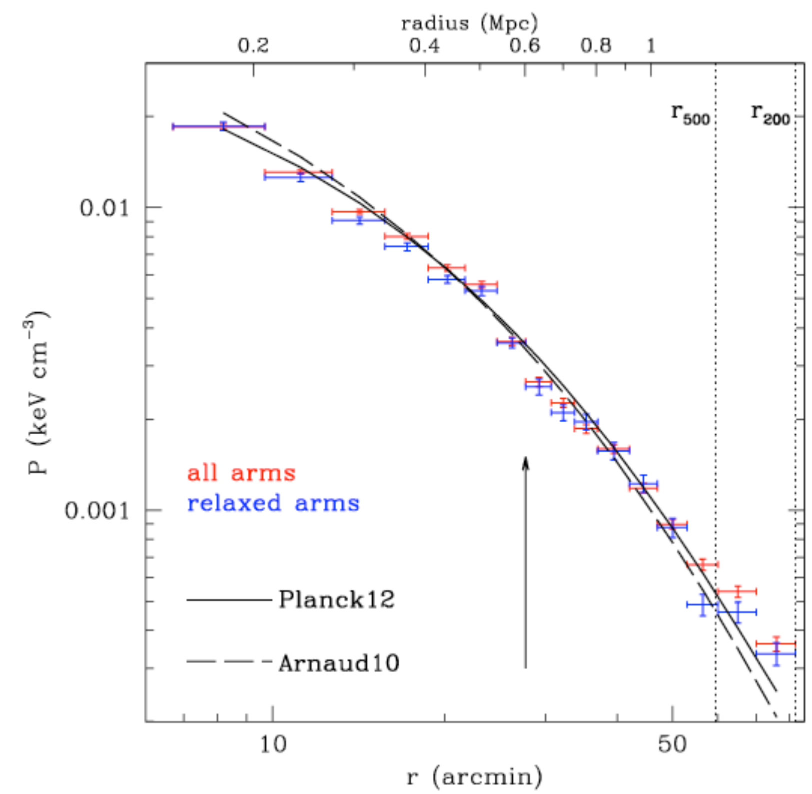
Pressure



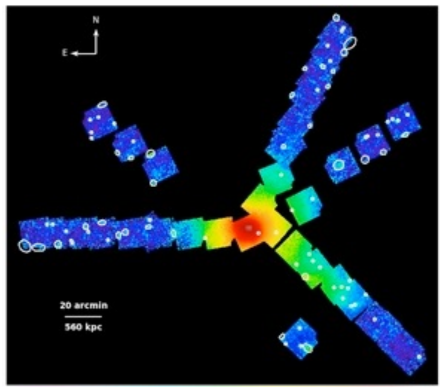
Perseus



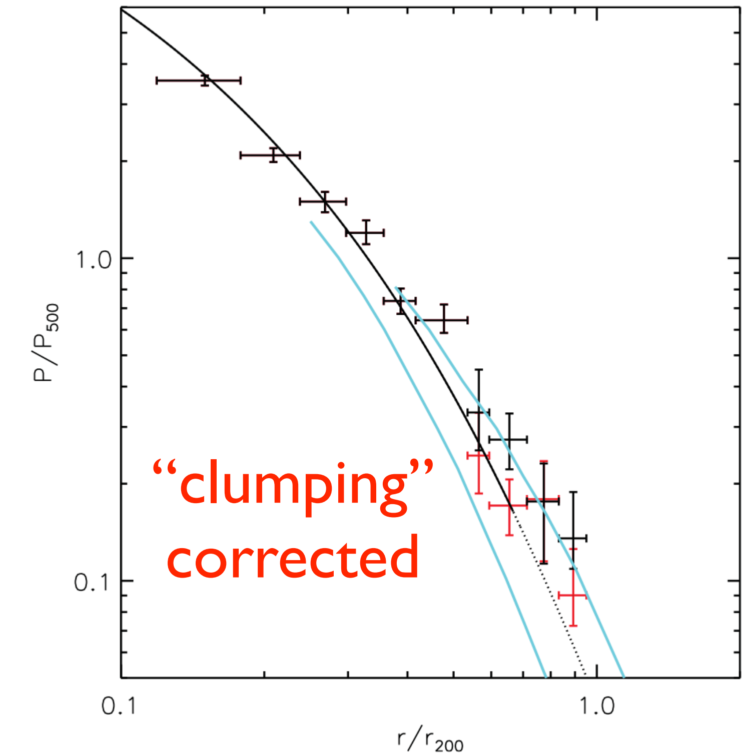
Urban+13



Centaurus

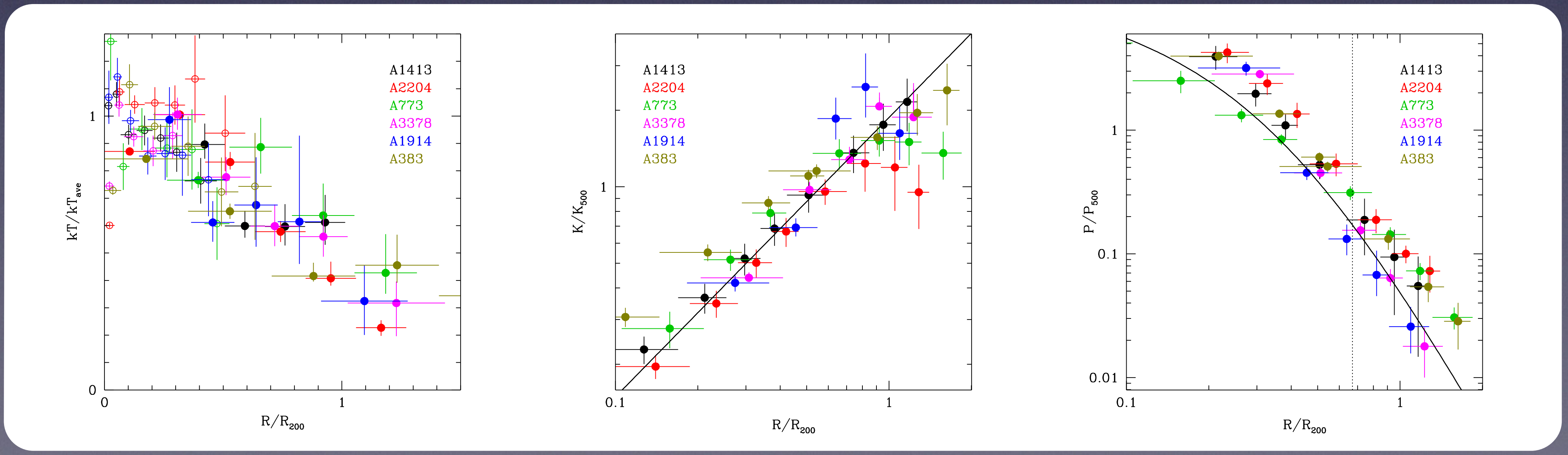


Walker+13



Summary (1/2)

- 20+ clusters observed to R_{200} with *Suzaku*
- our study: 6 of 11 clusters, full azimuthal coverage
    - support "universal" temperature, entropy, pressure profiles
    - *Suzaku* background systematics addressed (PSF, stray light, point sources)



Summary (2/2)

- entropy encodes thermal history of gas
- *most* clusters have entropy decrement beyond R_{500}
    - low-entropy, clumpy (group- and galaxy-scale) infalling halos
    - radius of turn-over varies greatly
        - mass?
          variations predicted in simulations (Nagai+11)
          but not yet constrained in observations
        - environment?
          two isolated fossil groups have no entropy decrement (Humphrey+12, Su+13)