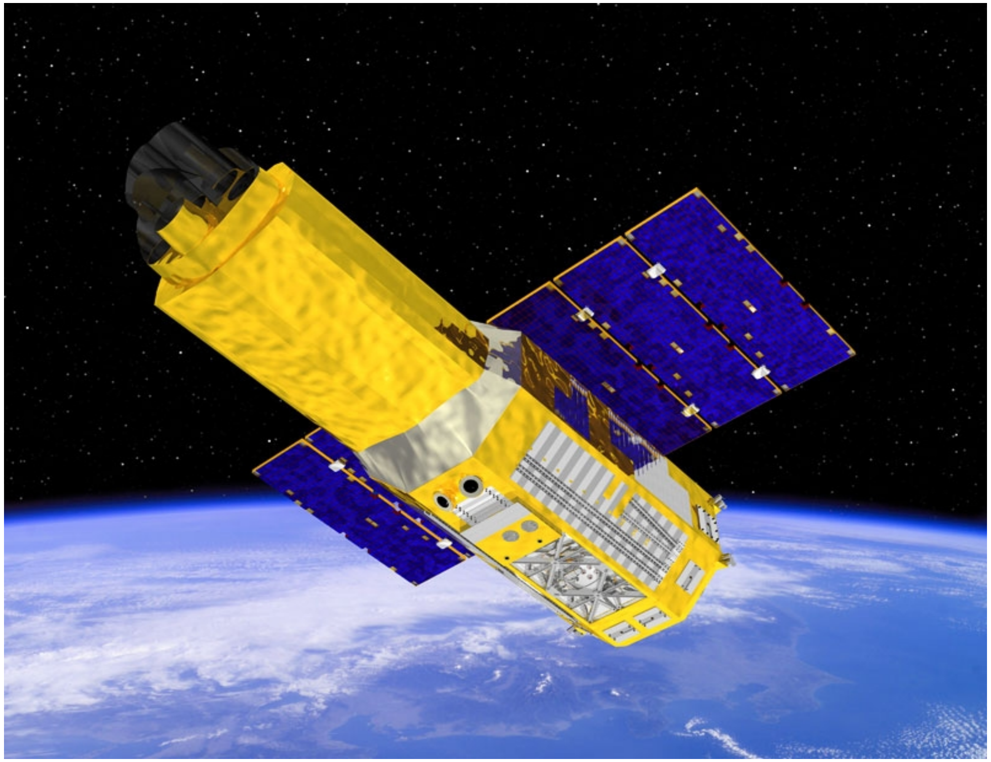
X-ray observations of galaxy cluster outskirts



Stephen Walker

IoA, Cambridge

Andy Fabian
Jeremy Sanders

UNIVERSITY OF CAMBRIDGE
ioa

Talk overview

- The importance of cluster outskirts observations

Talk overview

- The importance of cluster outskirts observations
- The importance of Suzaku for outskirts observations

Talk overview

- The importance of cluster outskirts observations
- The importance of Suzaku for outskirts observations
- General results from Suzaku

Talk overview

- The importance of cluster outskirts observations
- The importance of Suzaku for outskirts observations
- General results from Suzaku
- Large scale gas sloshing

The importance of cluster outskirts

Cluster formation

- Infalling gas is shock heated near the virial radius to high temperatures
- Asymmetric, with accretion along large scale structure filaments.

Burns et al. 2010

The importance of cluster outskirts

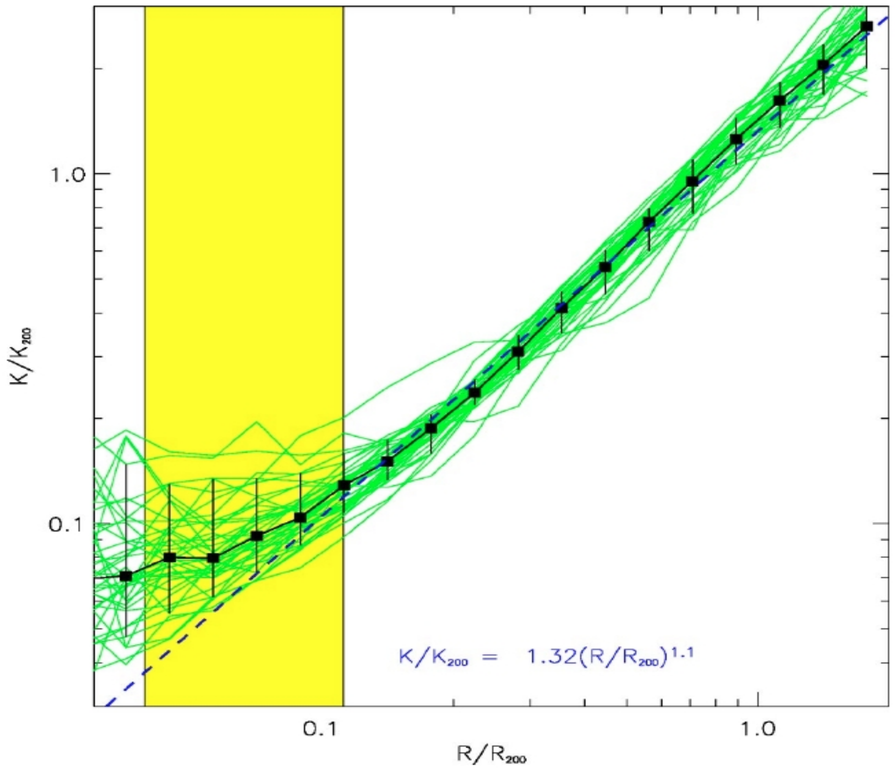
- Study physics of cluster accretion.

The importance of cluster outskirts

- Study physics of cluster accretion.
- Test hydrostatic equilibrium.
- Non-thermal pressure support?

The importance of cluster outskirts: Entropy

- Numerical simulations predict an $r^{1.1}$ relation, excluding non-gravitational processes.
- Can test where this breaks down.



Voit et al. (2005)

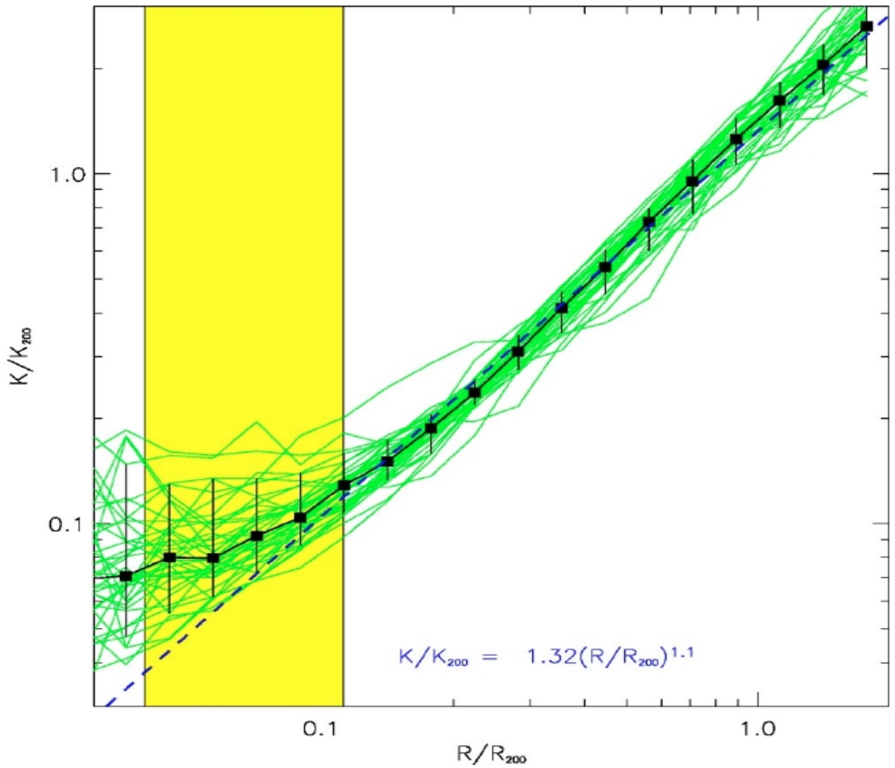
The importance of cluster outskirts: Entropy

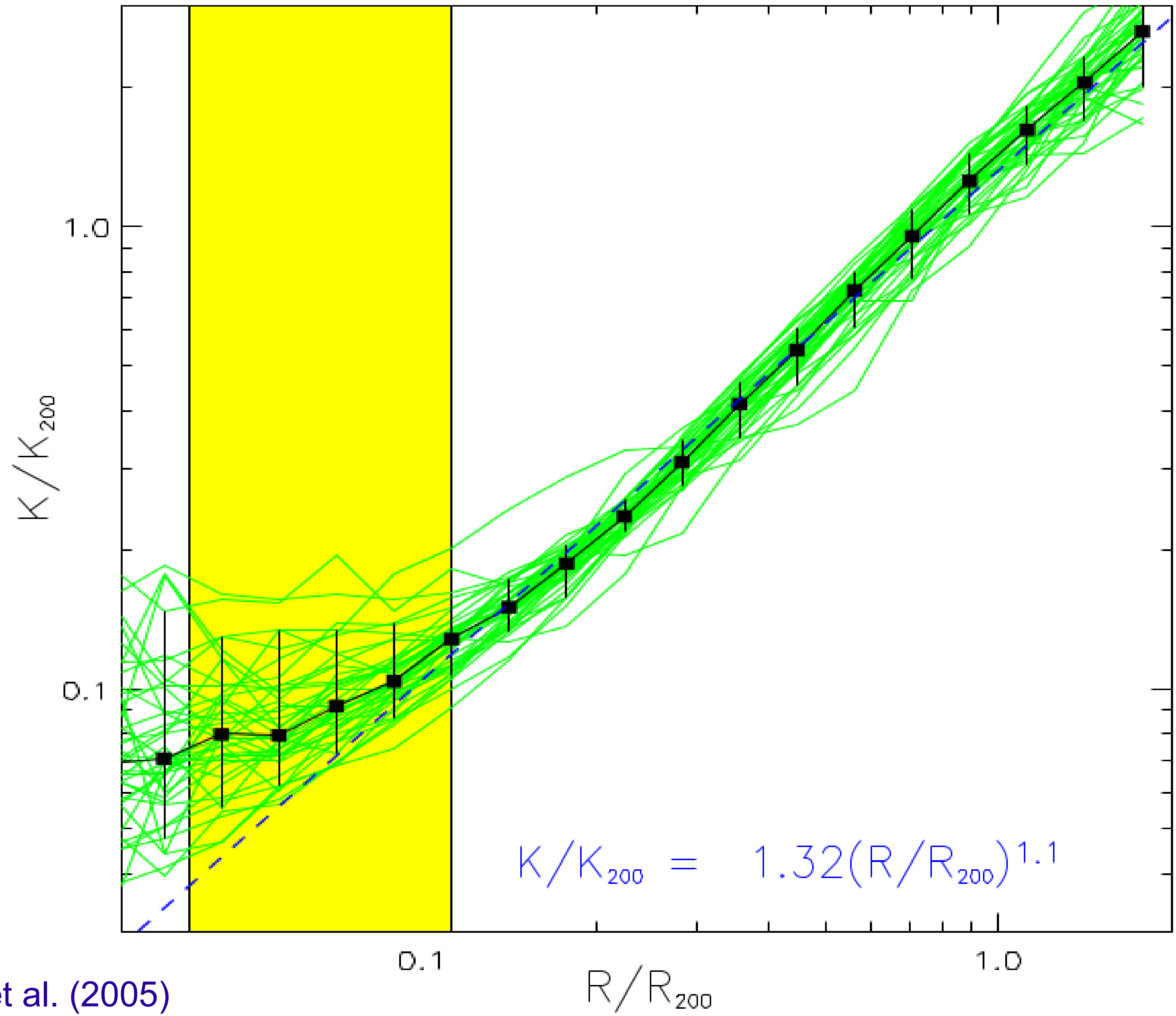
- Numerical simulations predict an $r^{1.1}$ relation, excluding non-gravitational processes.
- Can test where this breaks down.

$$K = k_B T / n_e^{2/3}$$

$$s = k_B \ln(K) + s_0$$

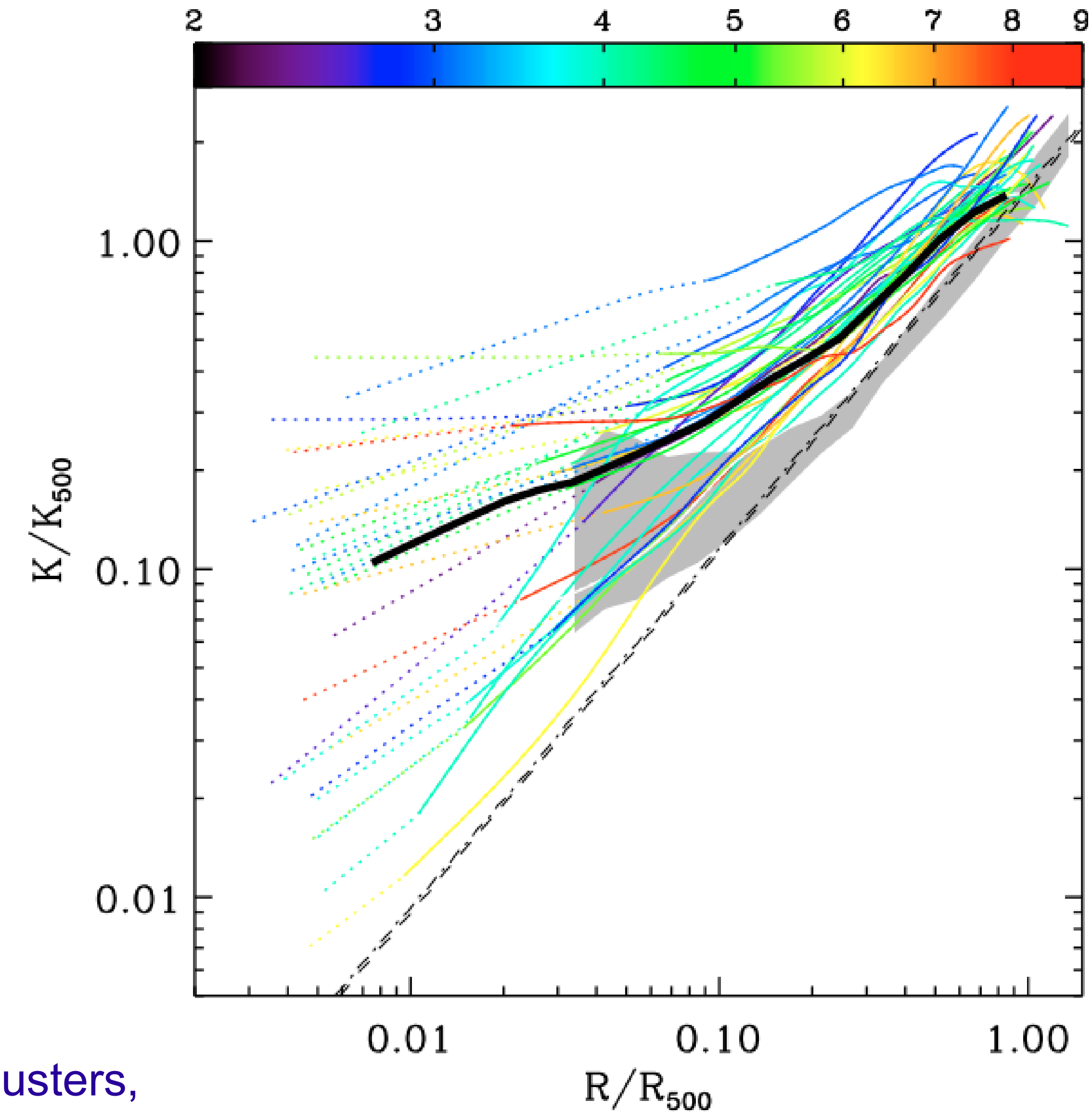
Voit et al. (2005)





Voit et al. (2005)

Central entropy excess

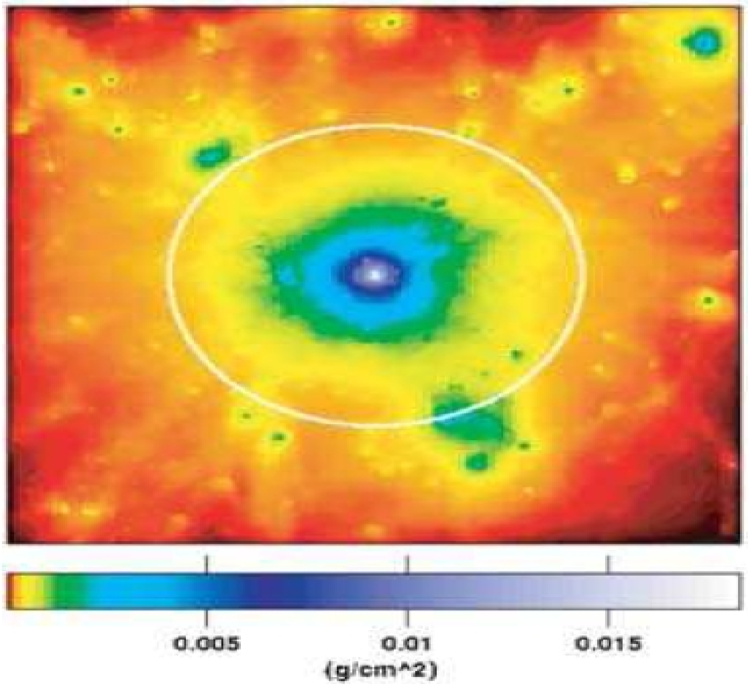


REXCESS clusters,
Pratt et al. (2010)

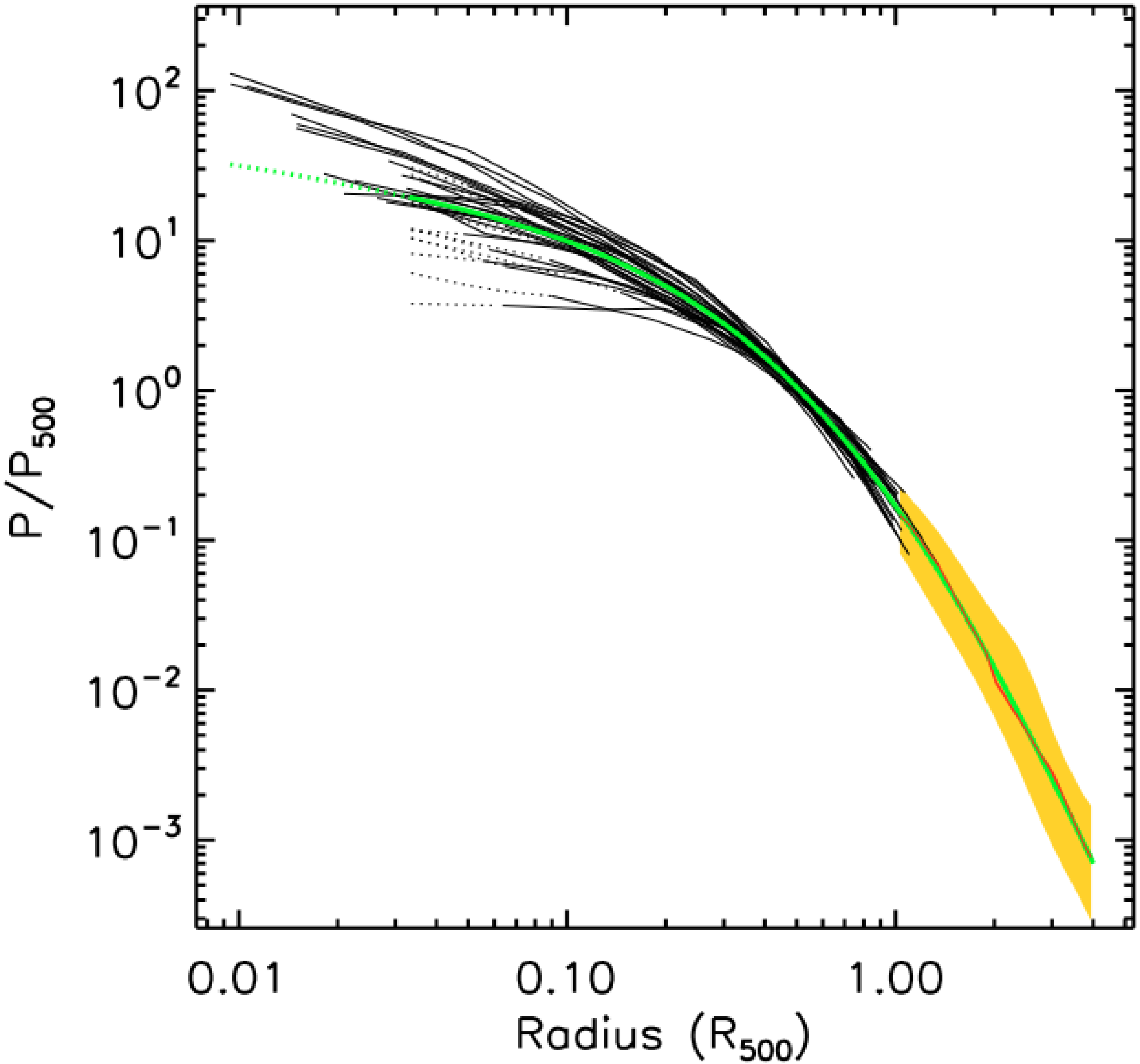
The importance of cluster outskirts: Clumping

- Simulations predict ICM near outskirts is clumped.

Projected gas density, Roncarelli et al. (2006)

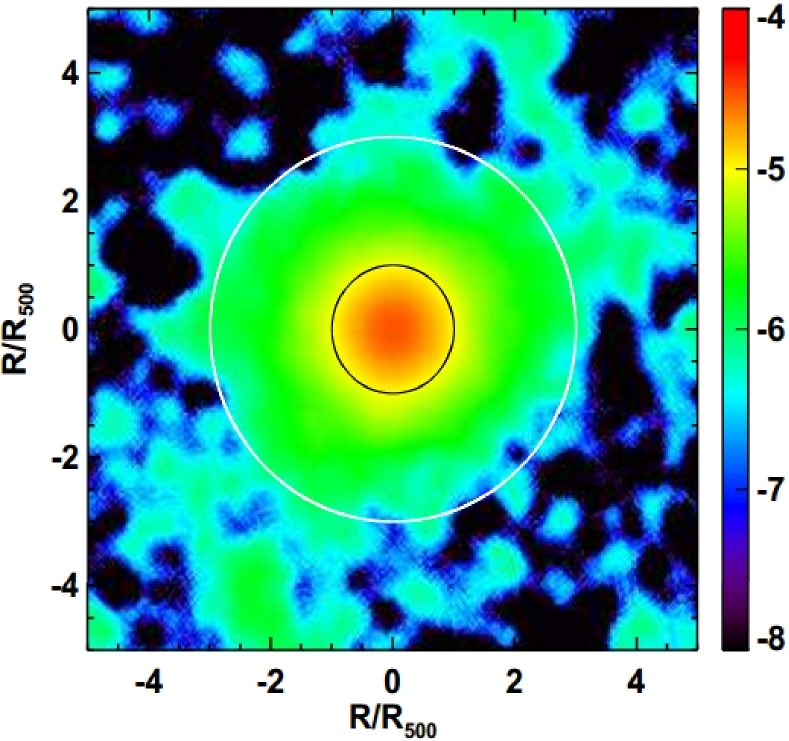


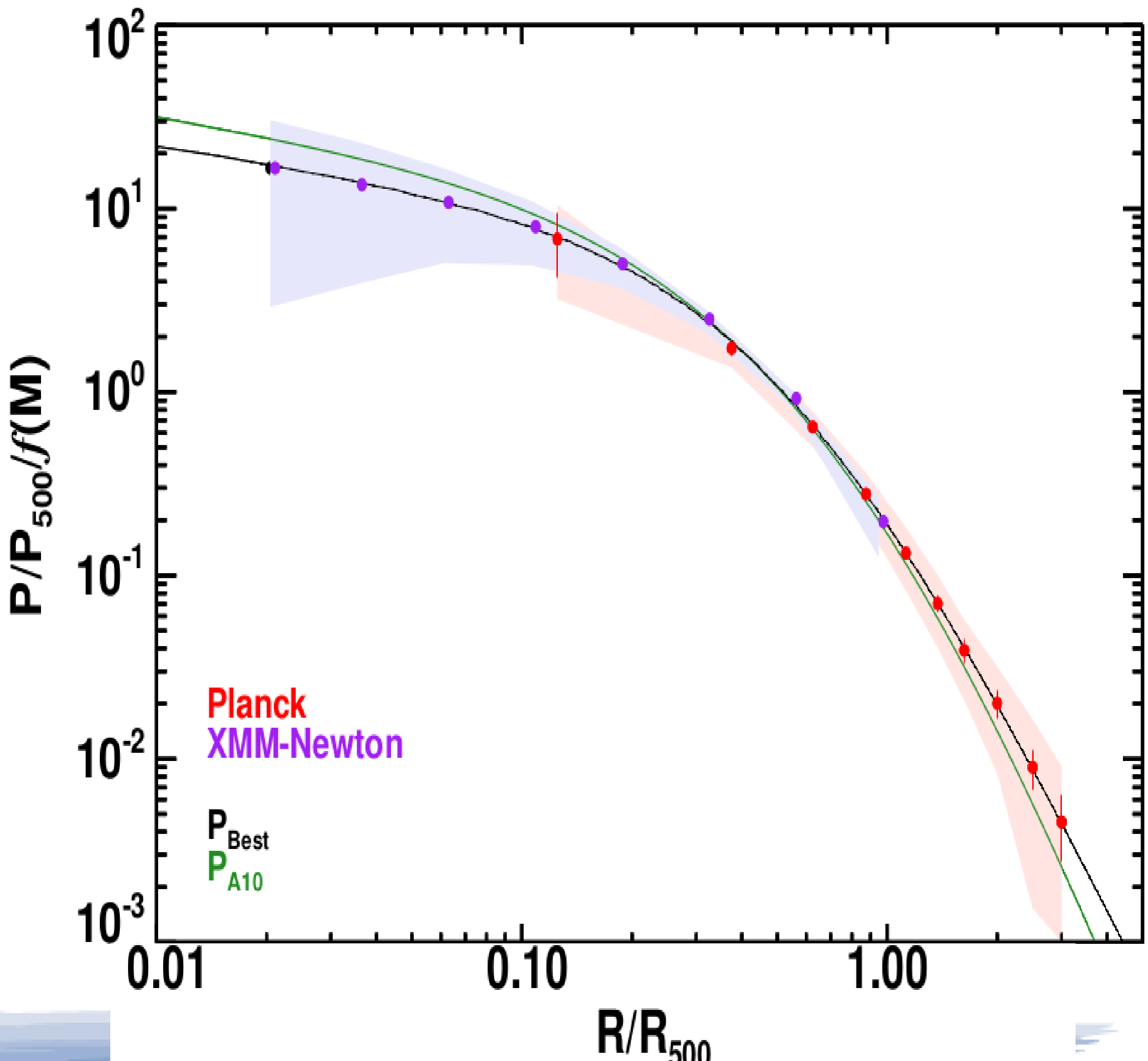
Universal pressure profile



Arnaud et al. (2010)

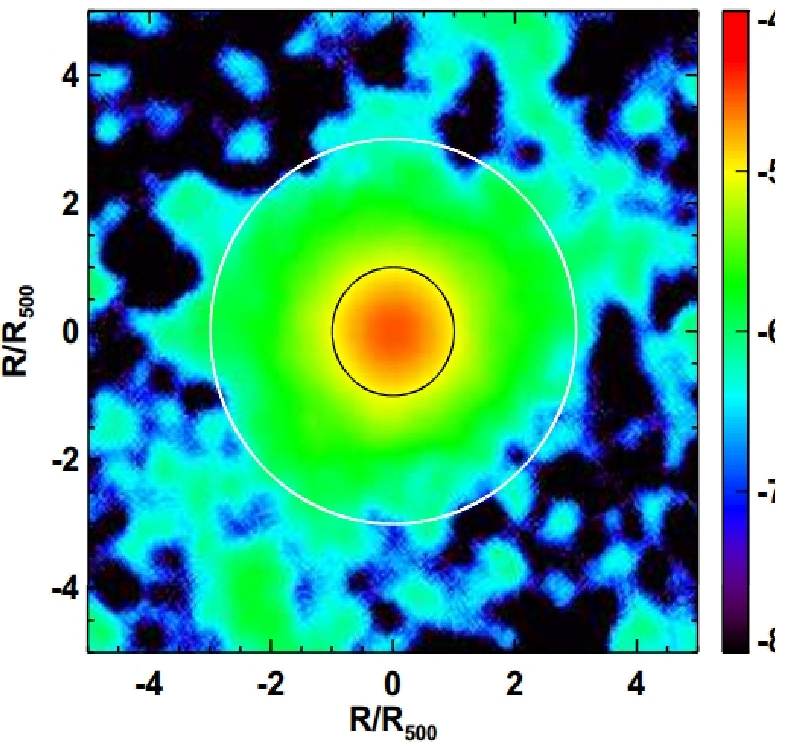
Planck

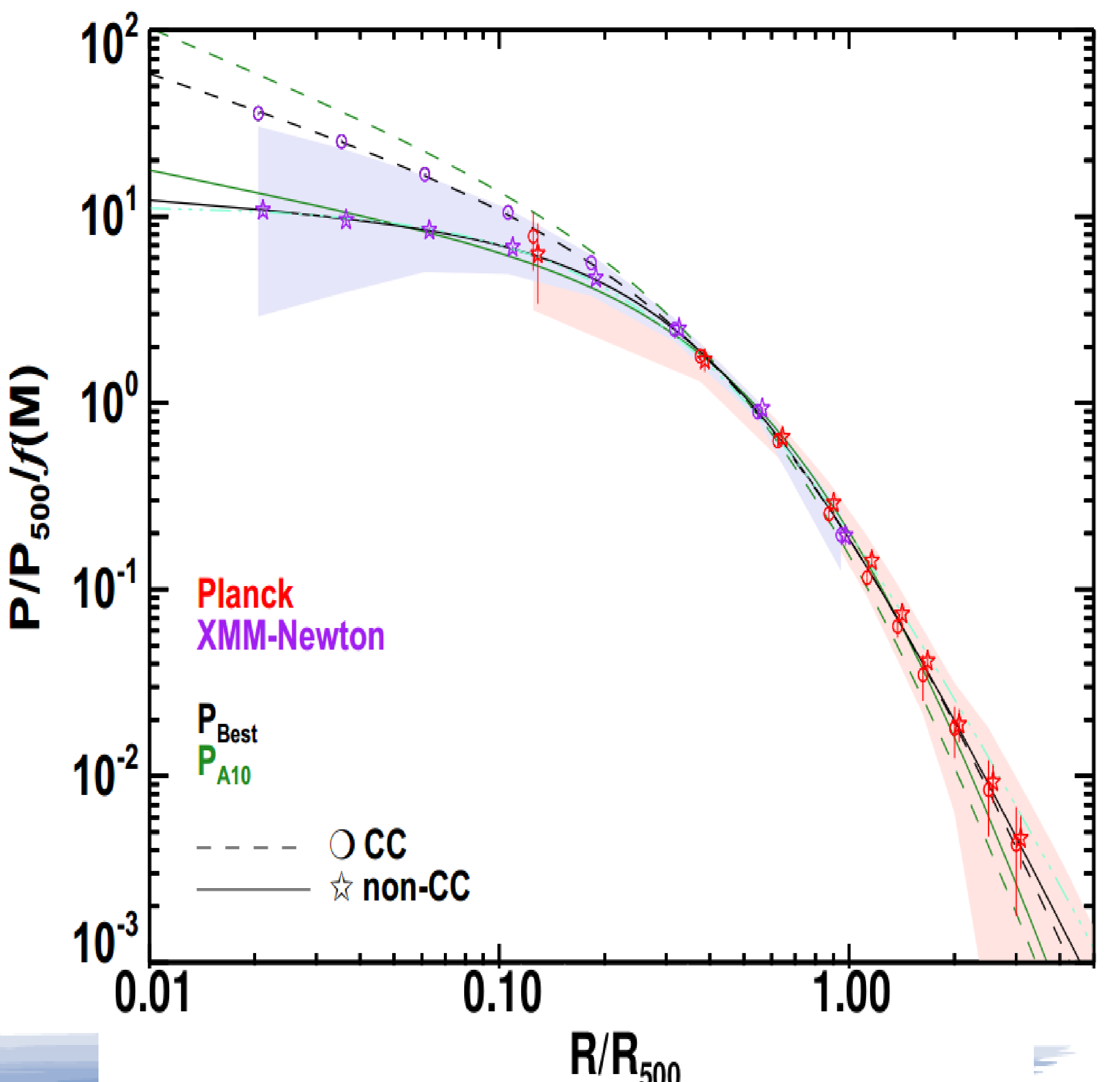




Planck pressure profile, ⟶
Planck Intermediate
Results. V. (2012)

Planck

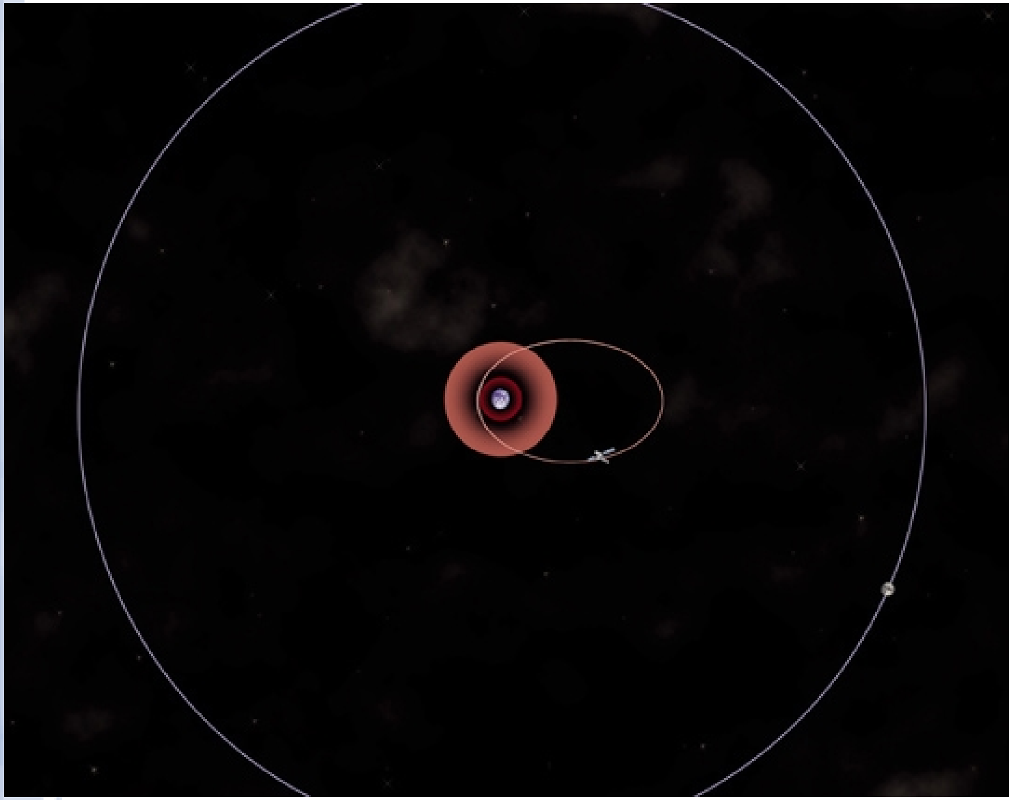


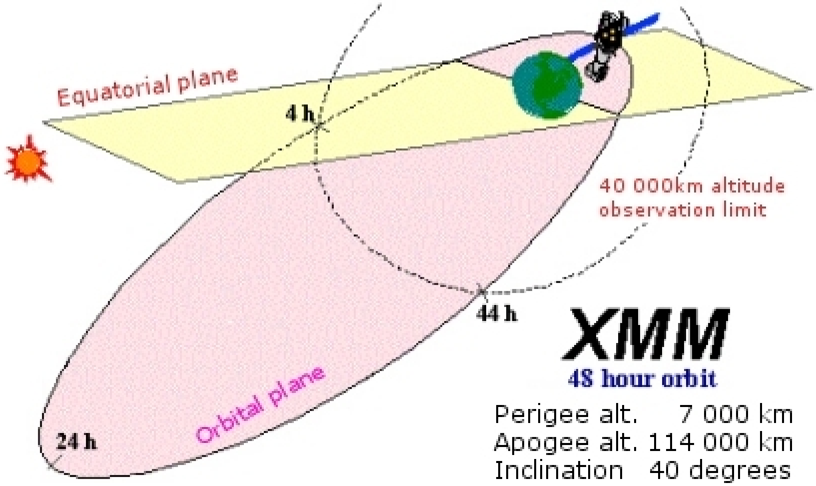


Planck pressure profile, →
Planck Intermediate
Results. V. (2012)

The importance of Suzaku for cluster outskirts observations

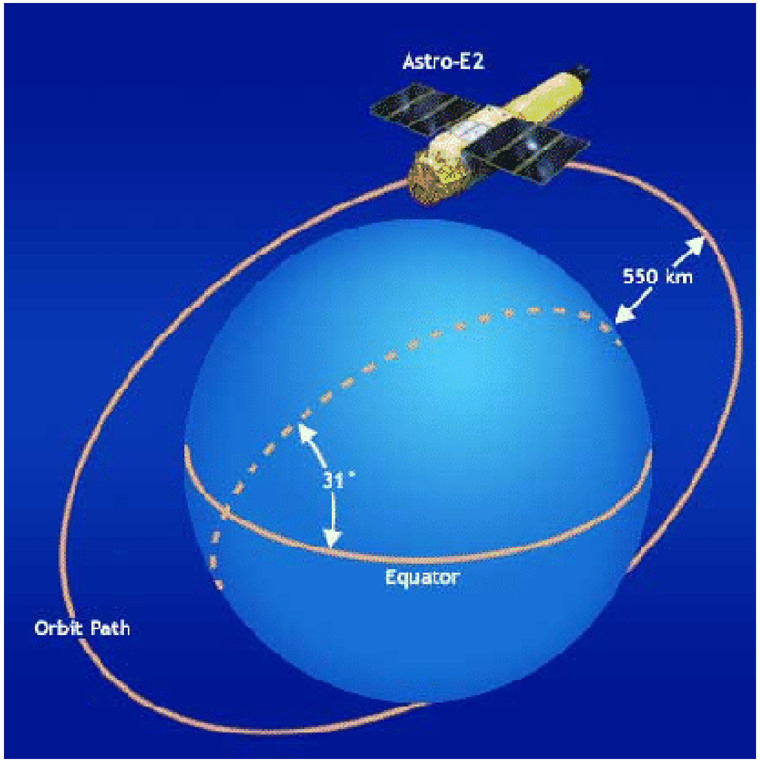
Orbits

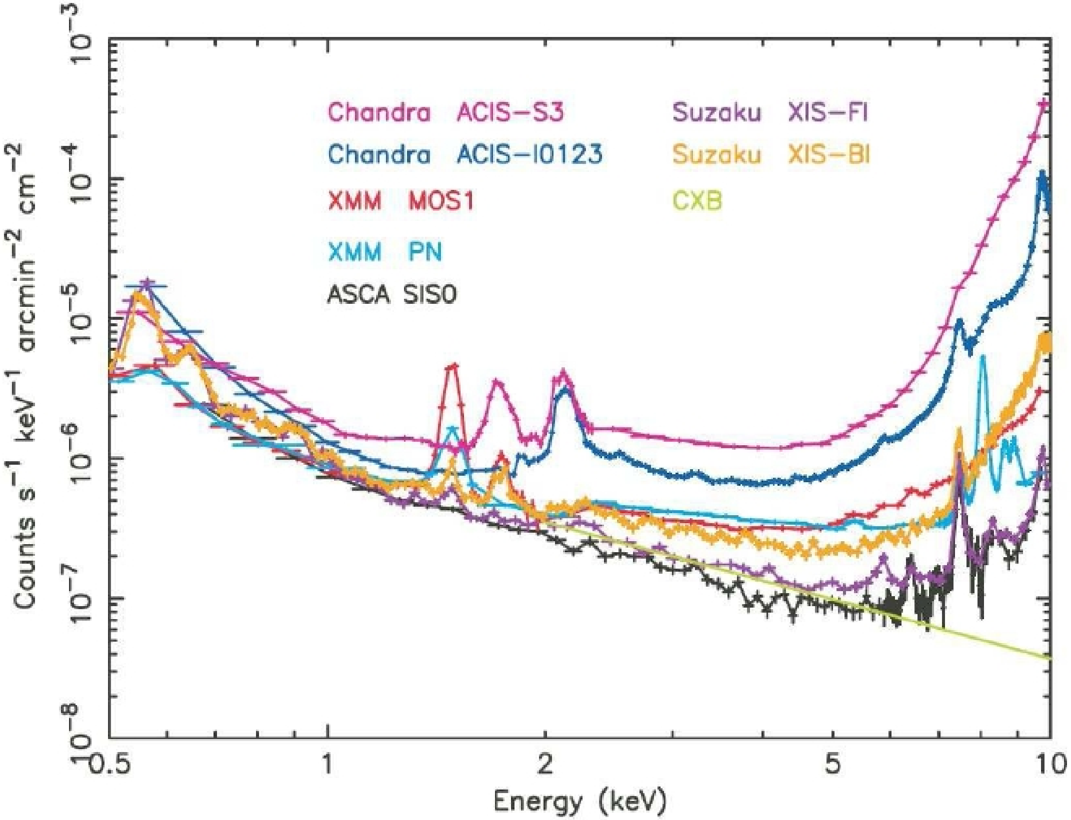



Equatorial plane
4 h
40 000km altitude
observation limit
44 h
XMM
48 hour orbit
Perigee alt. 7 000 km
Apogee alt. 114 000 km
Inclination 40 degrees
24 h
Orbital plane

Suzaku's background

- Low orbit gives low and stable particle background.





Suzaku's background

- NXB is low, stable, and reproducible using night Earth data.

Suzaku's background

- NXB is low, stable, and reproducible using night Earth data.

Table 7. Reproducibilities of the NXB models.*

Energy range (keV)	Sensor	Statistical error† (%)	Reproducibility† *COR2* (%)	PIN-UD (%)
1–7	XIS 0	2.29 ± 0.54	1.89 ± 0.84	2.02 ± 0.90
	XIS 1	1.72 ± 0.39	2.61 ± 0.80	2.70 ± 0.81
	XIS 2	2.37 ± 0.56	1.73 ± 0.84	0.31 ± 0.79
	XIS 3	2.50 ± 0.59	2.08 ± 0.92	1.20 ± 0.88
5–12	XIS 0	1.96 ± 0.46	1.03 ± 0.66	1.89 ± 0.79
	XIS 1	0.85 ± 0.19	2.98 ± 0.72	2.36 ± 0.59
	XIS 2	1.98 ± 0.47	1.87 ± 0.75	1.20 ± 0.72
	XIS 3	2.14 ± 0.50	1.51 ± 0.75	0.40 ± 0.72

Tawa et al. (2008)

What are the best targets?

What are the best targets?

- Modest PSF (HPD, 2 arcmins)
- Need to minimise systematics and maximise signal to noise
- Want good azimuthal coverage

What are the best targets?

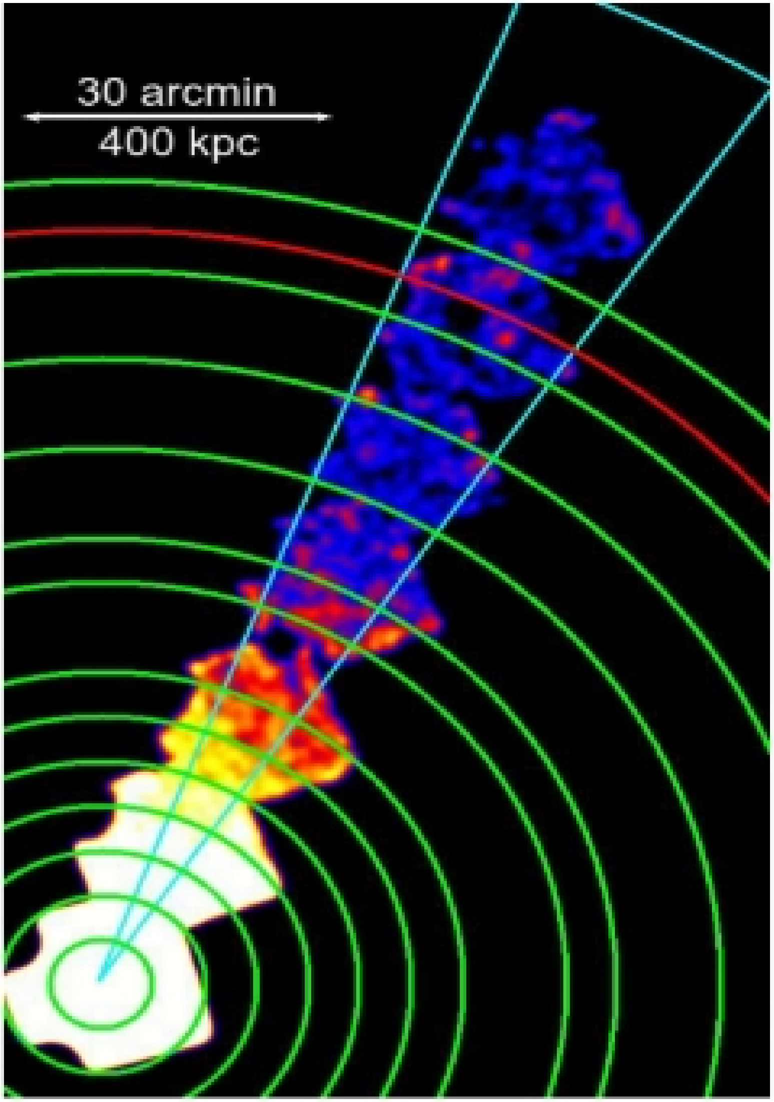
- Observe nearby bright clusters for high spatial resolution profiles with low azimuthal coverage

What are the best targets?

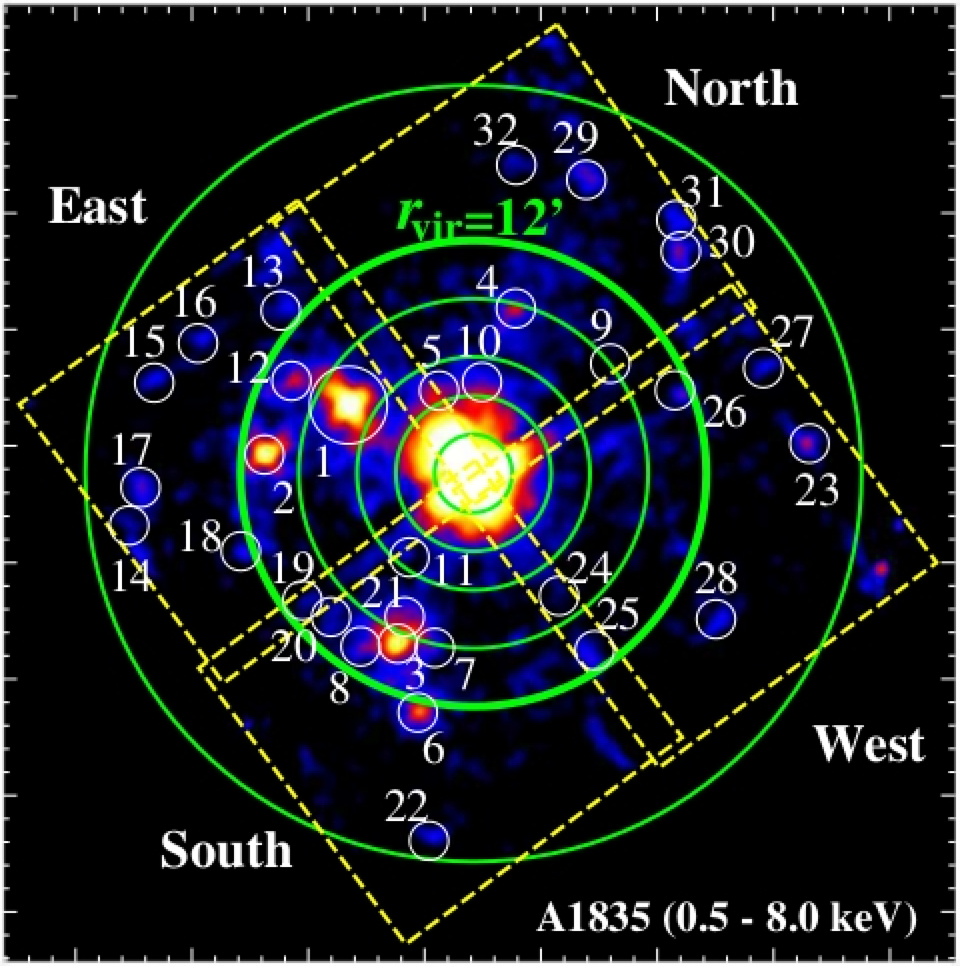
- Observe nearby bright clusters for high spatial resolution profiles with low azimuthal coverage

  OR

- Observe more distant clusters for better azimuthal coverage (but lower spatial resolution).

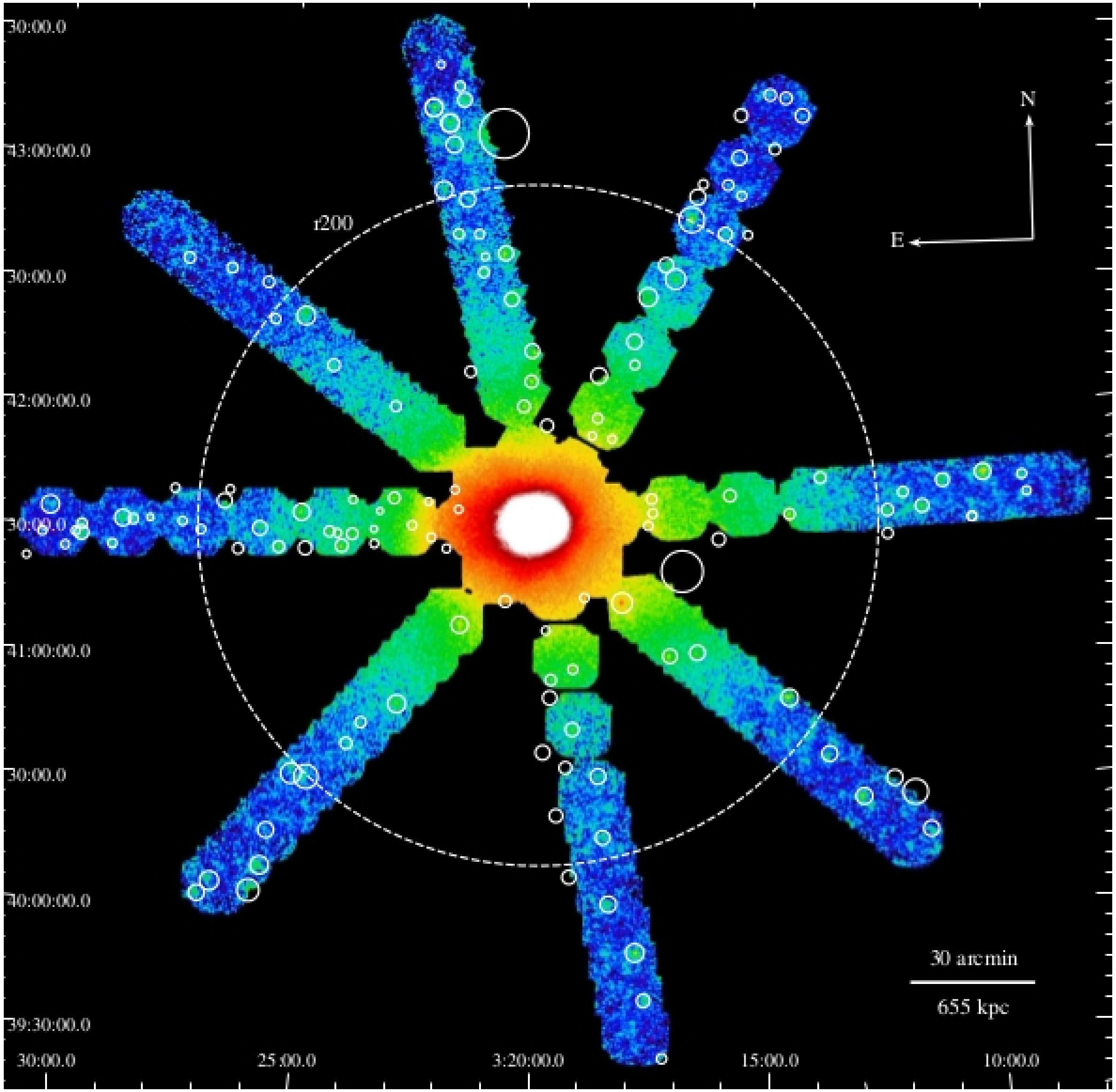


Centaurus –
Walker et al. (2013a)



Abell 1835 -
Ichikawa et al. (2013)

Perseus



Urban et al. 2014

What are the best targets?

- Observe the brightest, nearest clusters
- Need to observe over a range of masses
- And over a range of dynamic states

What are the best targets?

Cluster	Redshift	2-10 keV Flux (10^{-11} erg cm^{-2} s^{-1})		2-10 keV Luminosity (h_{50}^{-2} erg s^{-1})	Temperature (keV)
A426*	0.0183	75.0	[1]	1.10×10^{45}	5.5 ± 0.5
Ophiuchus*	0.028	44.5	[1]	1.52×10^{45}	9.0 ± 0.8
Virgo	18 Mpc	30.0	[1]	1.16×10^{43}	2.4 ± 0.3
Coma	0.0232	25.4	[1]	5.95×10^{44}	8.0 ± 0.3
A2319*	0.0564	12.1	[2]	1.70×10^{45}	$9.2^{+1.8}_{-1.7}$
A3571	0.0391	11.5	[1]	7.67×10^{44}	$7.6^{+1.2}_{-0.9}$
Centaurus	0.0109	11.2	[1]	5.75×10^{43}	3.6 ± 0.4
Triang. Aust.*	0.051	11.0	[1]	1.26×10^{45}	8.0 ± 1.4
3C129*	0.022	9.59	[1]	2.02×10^{44}	$5.6^{+0.7}_{-0.6}$
AWM7*	0.0172	9.14	[1]	1.17×10^{44}	3.6 ± 0.2
A754	0.0528	8.53	[1]	1.05×10^{45}	$8.7^{+1.8}_{-1.6}$
A2029	0.0767	7.52	[2]	1.97×10^{45}	$7.1^{+2.0}_{-1.4}$
A2142	0.0899	7.50	[1]	2.72×10^{45}	$11.0^{+2.0}_{-1.7}$
A2199	0.0309	7.12	[1]	2.97×10^{44}	4.7 ± 0.4
A3667	0.0530	6.68	[2]	8.28×10^{44}	$6.5^{+1.5}_{-1.6}$
A478	0.09	6.63	[1]	2.41×10^{45}	6.8 ± 1.0
A85	0.0518	6.37	[2]	7.54×10^{44}	$6.6^{+1.8}_{-1.4}$
A3266	0.0594	5.90	[2]	9.21×10^{44}	$7.4^{+1.6}_{-1.2}$
A401	0.0748	5.88	[2]	1.47×10^{45}	$8.6^{+1.4}_{-1.6}$
0745-19*	0.1028	5.87	[1]	2.80×10^{45}	$8.5^{+1.9}_{-1.4}$
A496	0.0320	5.67	[1]	2.54×10^{44}	$4.8^{+0.9}_{-0.8}$
A1795	0.0616	5.30	[1]	8.91×10^{44}	$5.1^{+0.4}_{-0.5}$
A2256	0.0601	5.20	[2]	8.32×10^{44}	$7.4^{+1.8}_{-1.5}$

Edge et al. (1990)

What are the best targets?

	Cluster	Redshift	2-10 keV Flux (10^{-11} erg cm^{-2} s^{-1})		2-10 keV Luminosity (h_{50}^{-2} erg s^{-1})	Temperature (keV)
Simionescu et al,. 2011, 2012	A426*	0.0183	75.0	[1]	1.10×10^{45}	5.5 ± 0.5
	Ophiuchus*	0.028	44.5	[1]	1.52×10^{45}	9.0 ± 0.8
Urban et al. (2011)	Virgo	18 Mpc	30.0	[1]	1.16×10^{43}	2.4 ± 0.3
Simionescu et al. 2013	Coma	0.0232	25.4	[1]	5.95×10^{44}	8.0 ± 0.3
	A2319*	0.0564	12.1	[2]	1.70×10^{45}	$9.2^{+1.8}_{-1.7}$
	A3571	0.0391	11.5	[1]	7.67×10^{44}	$7.6^{+1.2}_{-0.9}$
Walker et al. 2013a	Centaurus	0.0109	11.2	[1]	5.75×10^{43}	3.6 ± 0.4
	Triang. Aust.*	0.051	11.0	[1]	1.26×10^{45}	8.0 ± 1.4
	3C129*	0.022	9.59	[1]	2.02×10^{44}	$5.6^{+0.7}_{-0.6}$
	AWM7*	0.0172	9.14	[1]	1.17×10^{44}	3.6 ± 0.2
	A754	0.0528	8.53	[1]	1.05×10^{45}	$8.7^{+1.8}_{-1.6}$
Walker et al. (2012a)	A2029	0.0767	7.52	[2]	1.97×10^{45}	$7.1^{+2.0}_{-1.4}$
Akamatsu et al. (2011)	A2142	0.0899	7.50	[1]	2.72×10^{45}	$11.0^{+2.0}_{-1.7}$
Sato et al. in prep	A2199	0.0309	7.12	[1]	2.97×10^{44}	4.7 ± 0.4
Akamatsu et al. (2011)	A3667	0.0530	6.68	[2]	8.28×10^{44}	$6.5^{+1.5}_{-1.6}$
	A478	0.09	6.63	[1]	2.41×10^{45}	6.8 ± 1.0
Ichinohe et al. 2014	A85	0.0518	6.37	[2]	7.54×10^{44}	$6.6^{+1.8}_{-1.4}$
	A3266	0.0594	5.90	[2]	9.21×10^{44}	$7.4^{+1.6}_{-1.2}$
	A401	0.0748	5.88	[2]	1.47×10^{45}	$8.6^{+1.4}_{-1.6}$
Walker et al. (2012b)	0745-19*	0.1028	5.87	[1]	2.80×10^{45}	$8.5^{+1.9}_{-1.4}$
	A496	0.0320	5.67	[1]	2.54×10^{44}	$4.8^{+0.9}_{-0.8}$
Bautz et al. (2009)	A1795	0.0616	5.30	[1]	8.91×10^{44}	$5.1^{+0.4}_{-0.5}$
	A2256	0.0601	5.20	[2]	8.32×10^{44}	$7.4^{+1.8}_{-1.5}$

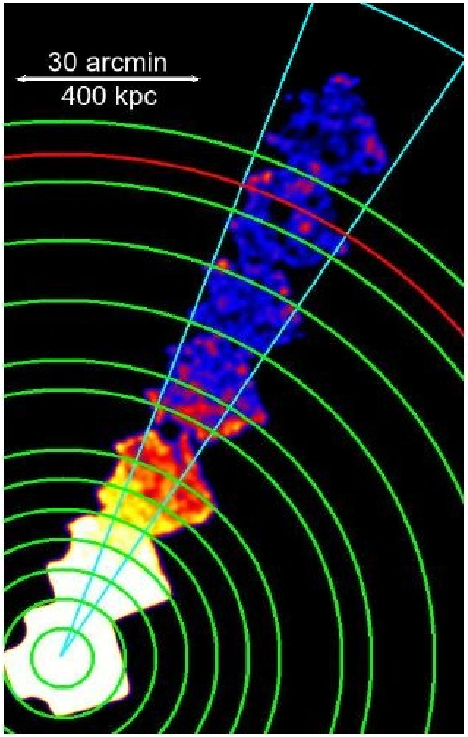
General cluster properties
and
Entropy profiles

Walker et al. 2012c, MNRAS, 427, L45-L49 (arXiv:1208.5950)

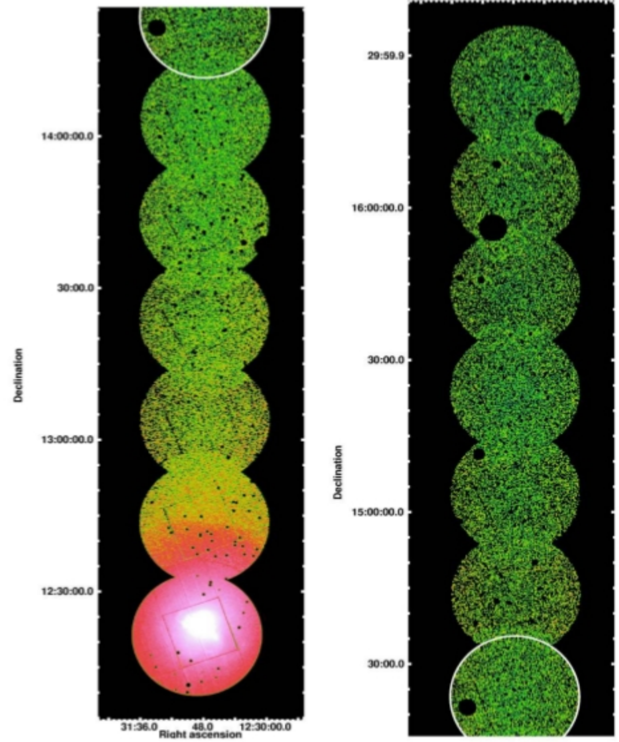
Walker et al. 2013a, MNRAS, 432, 554 (arXiv:1303.4240)

Cluster outskirts observations

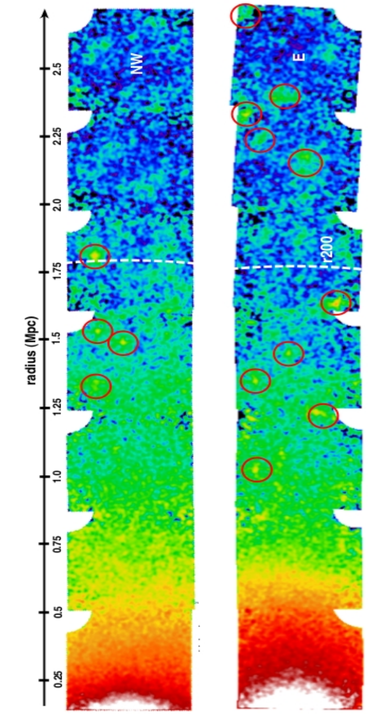
Cluster	z	Reference	Plot symbol	$M_{500}/10^{14}\ M_{\odot}$
Abell 1689	0.183	Kawaharada et al. (2010)	Red square	11.4
Abell 2029	0.0767	Walker et al. (2012)	Red square	7.2
Abell 2142	0.0899	Akamatsu et al. (2011)	Blue square	8.0
Hydra A	0.0539	Sato et al. (2012)	Cyan square	1.5
Perseus	0.0183	Simionescu et al. (2011)	Pink square	4.8
PKS 0745-191	0.1028	Walker et al. (2012a)	Grey square	7.3
Abell 1835	0.253	Bonamente et al. (2013)	Black square	7.8
Abell 2204	0.152	Sanders et al. (2009)	Black triangle	$8.39^{\dagger}$
Abell 1795	0.063	Bautz et al. (2009)	Red triangle	4.1
Virgo	16.1 Mpc	Urban et al. (2011)	Green crosses	1.02*
Abell 1413	0.143	Hoshino et al. (2010)	Blue triangle	$4.8^{\dagger}$
Centaurus	0.0109	This work	Black crosses	1.2
RX J1159+5531	0.081	Humphrey et al. (2012)	Pink triangles	0.63



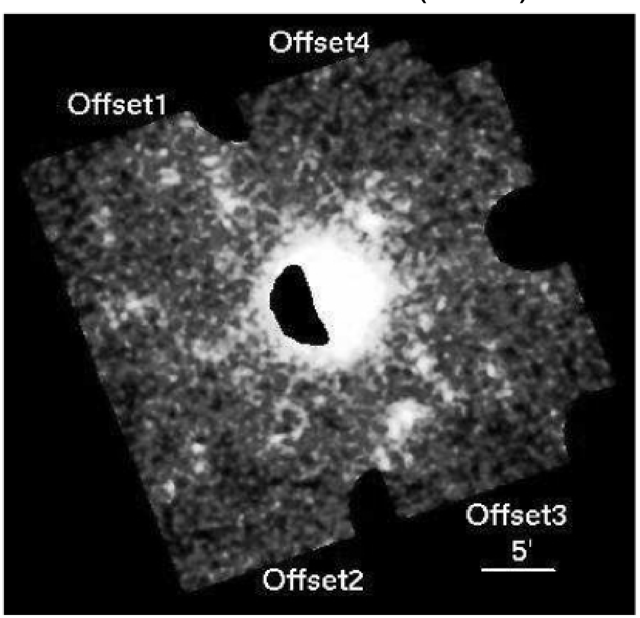
Centaurus
Walker et al. (2013)



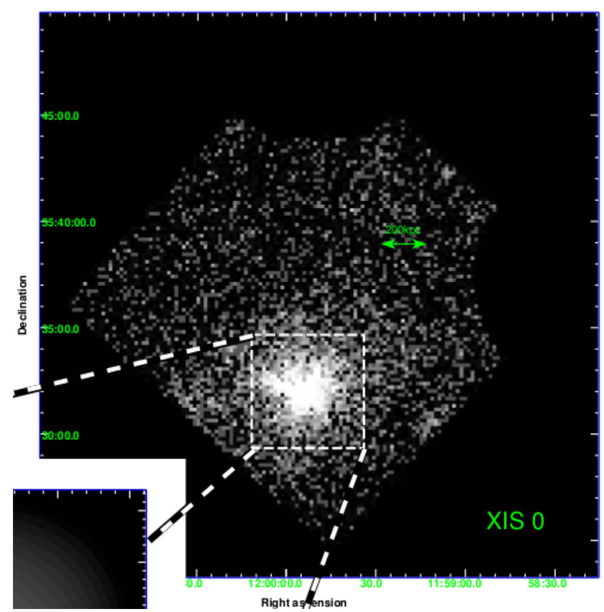
Virgo
Urban et al. (2011)



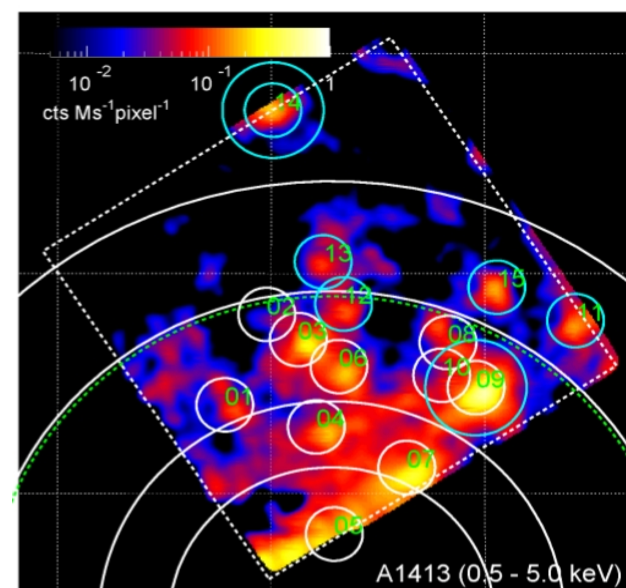
Perseus
Simionescu et al. (2011)



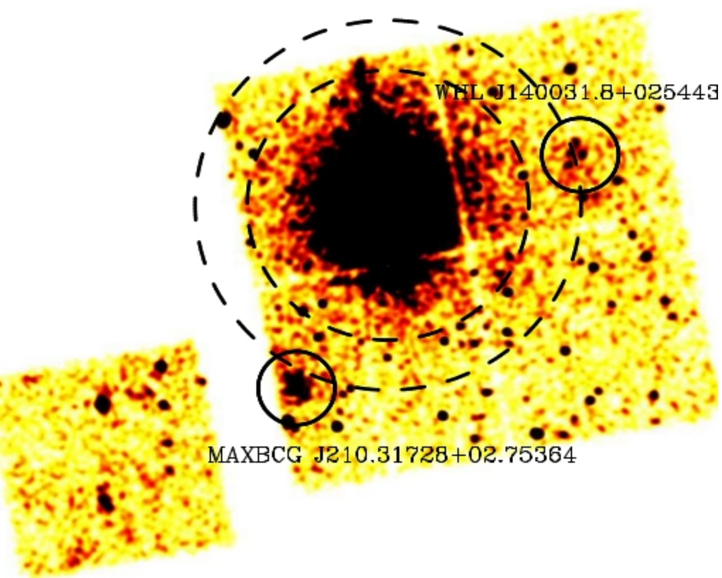
Abell 1689
Kawaharada et al. (2010)



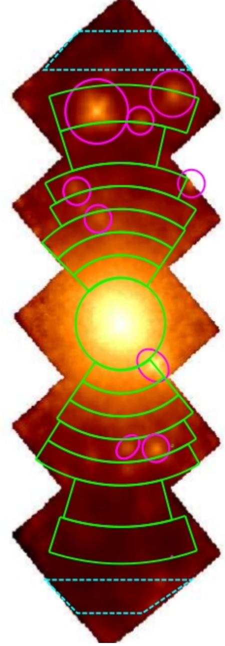
RX J1159+5531
Humphrey et al. (2012)



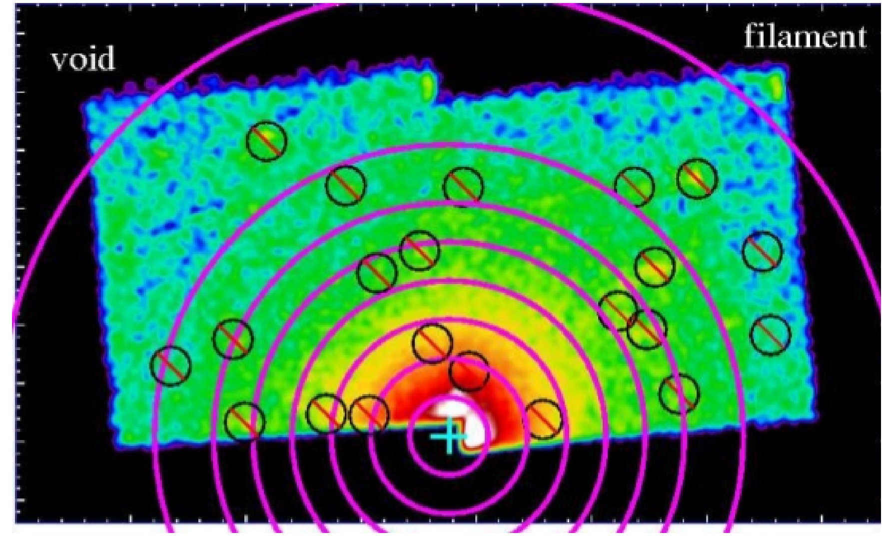
Abell 1413
Hoshino et al. (2010)



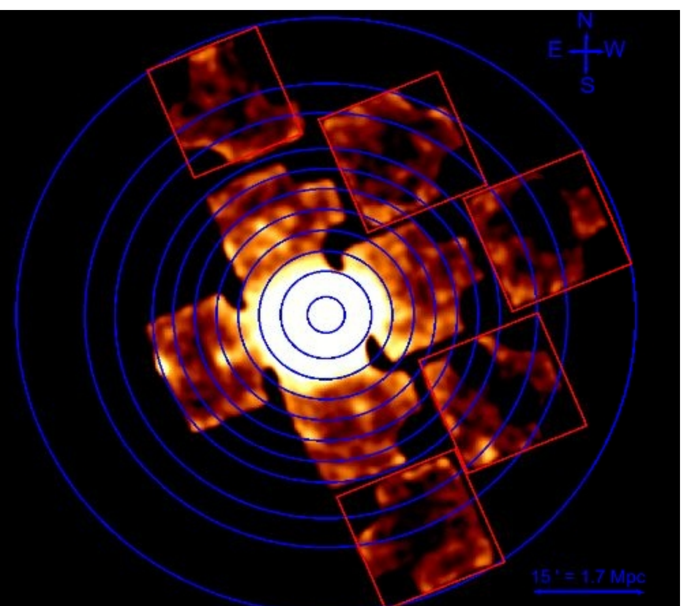
Abell 1835
Bonamente et al. (2013)



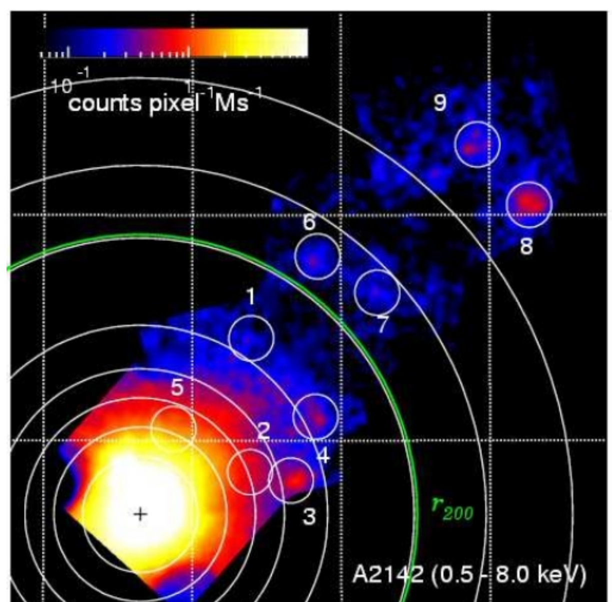
Abell 1795
Bautz et al. (2009)



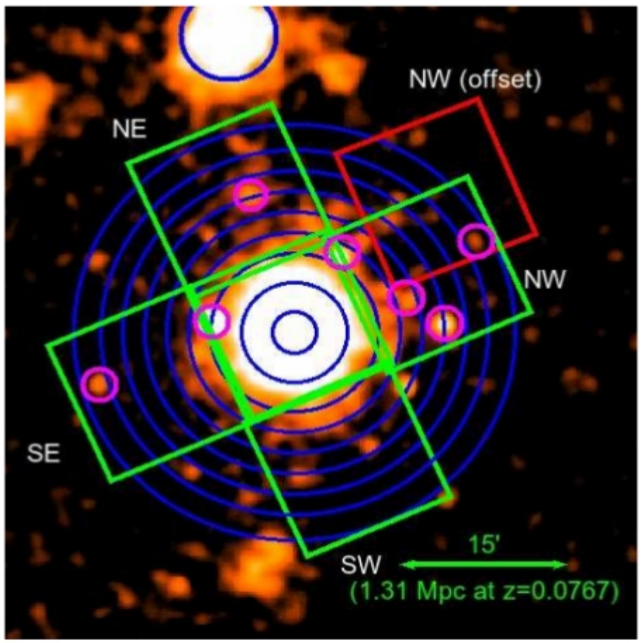
Hydra A
Sato et al. (2012)



PKS 0745-191
Walker et al. (2012b)

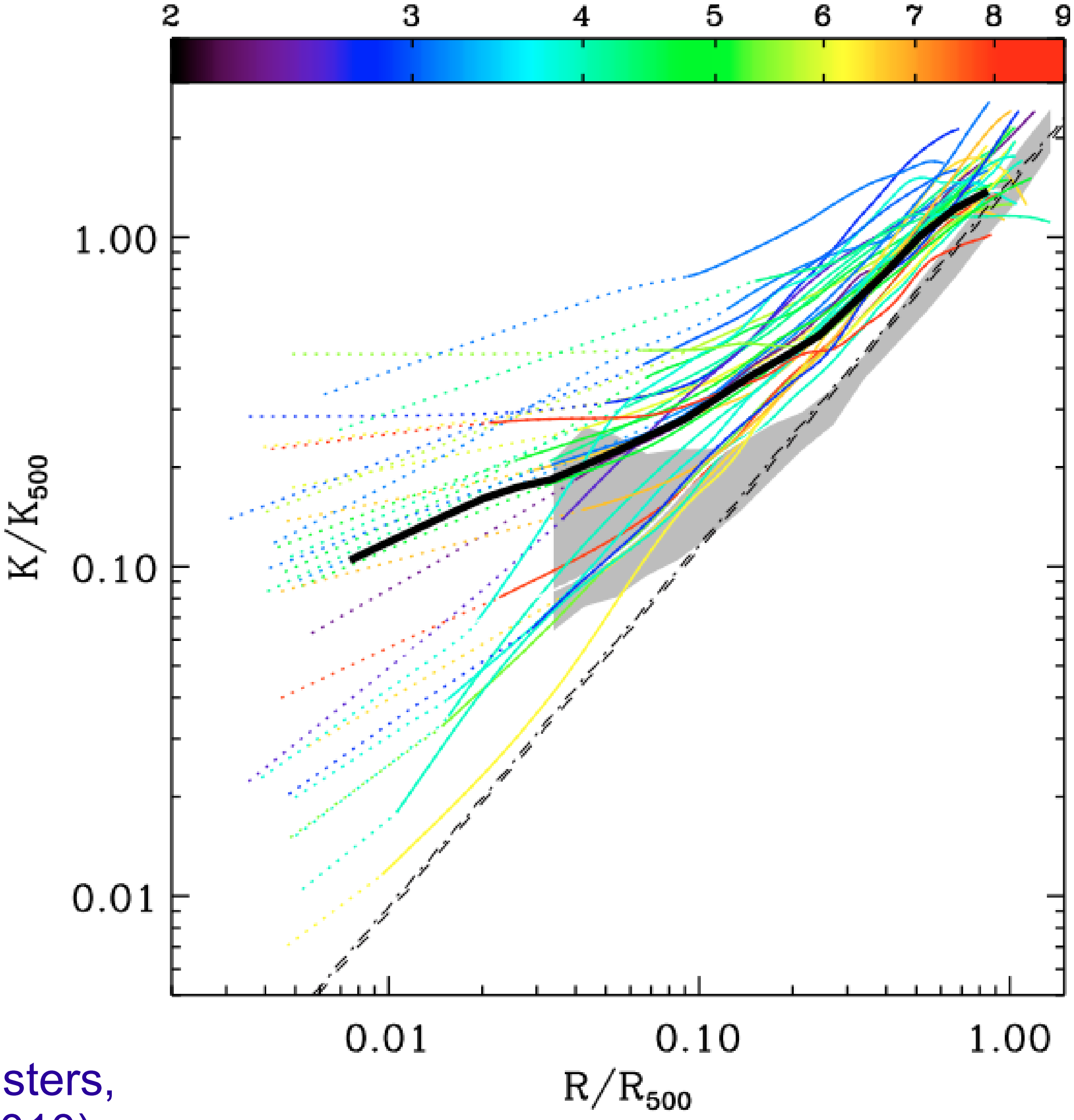


Abell 2142
Akamatsu et al. (2011)



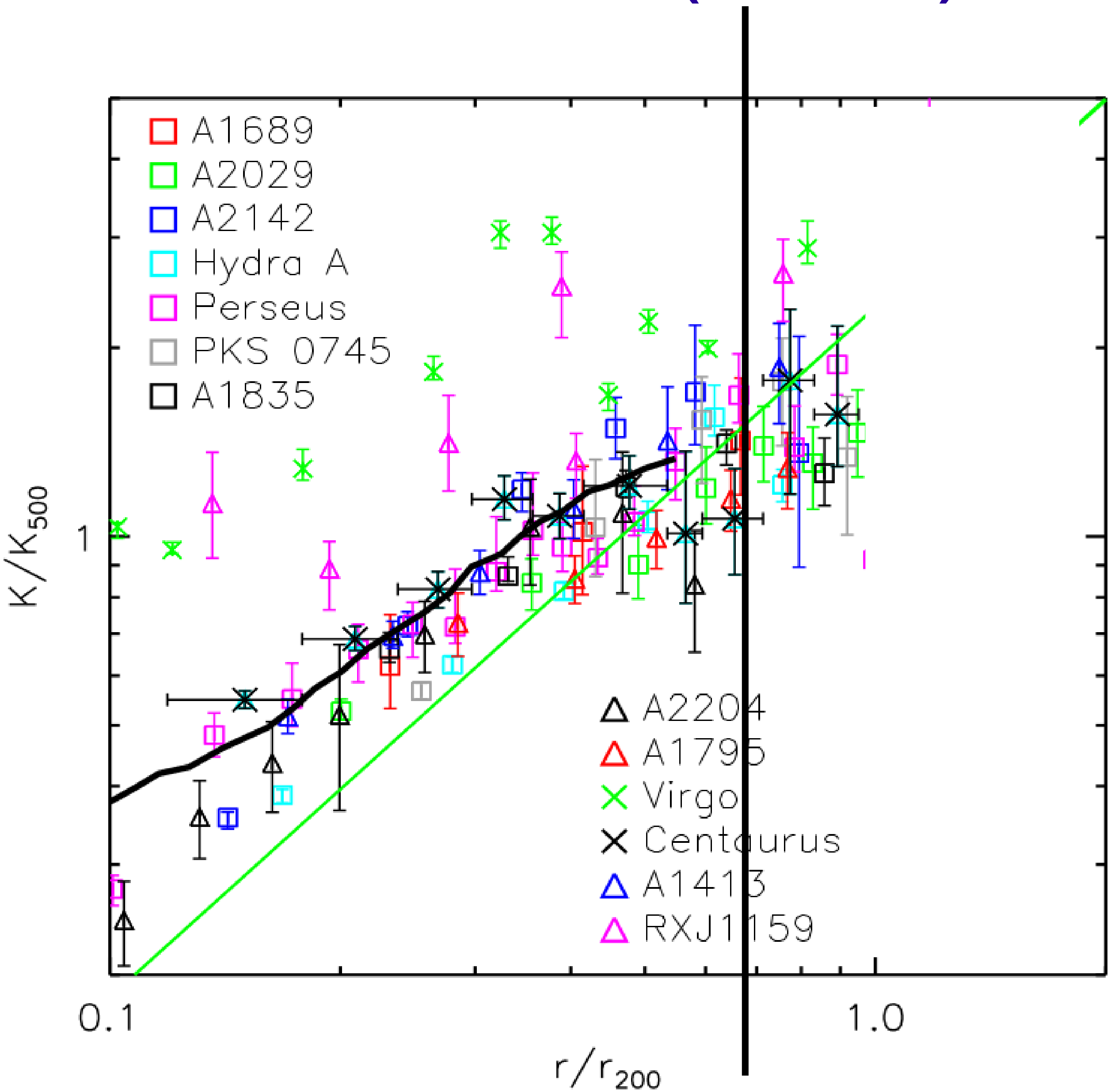
Abell 2029
Walker et al. (2012a)

Central entropy excess

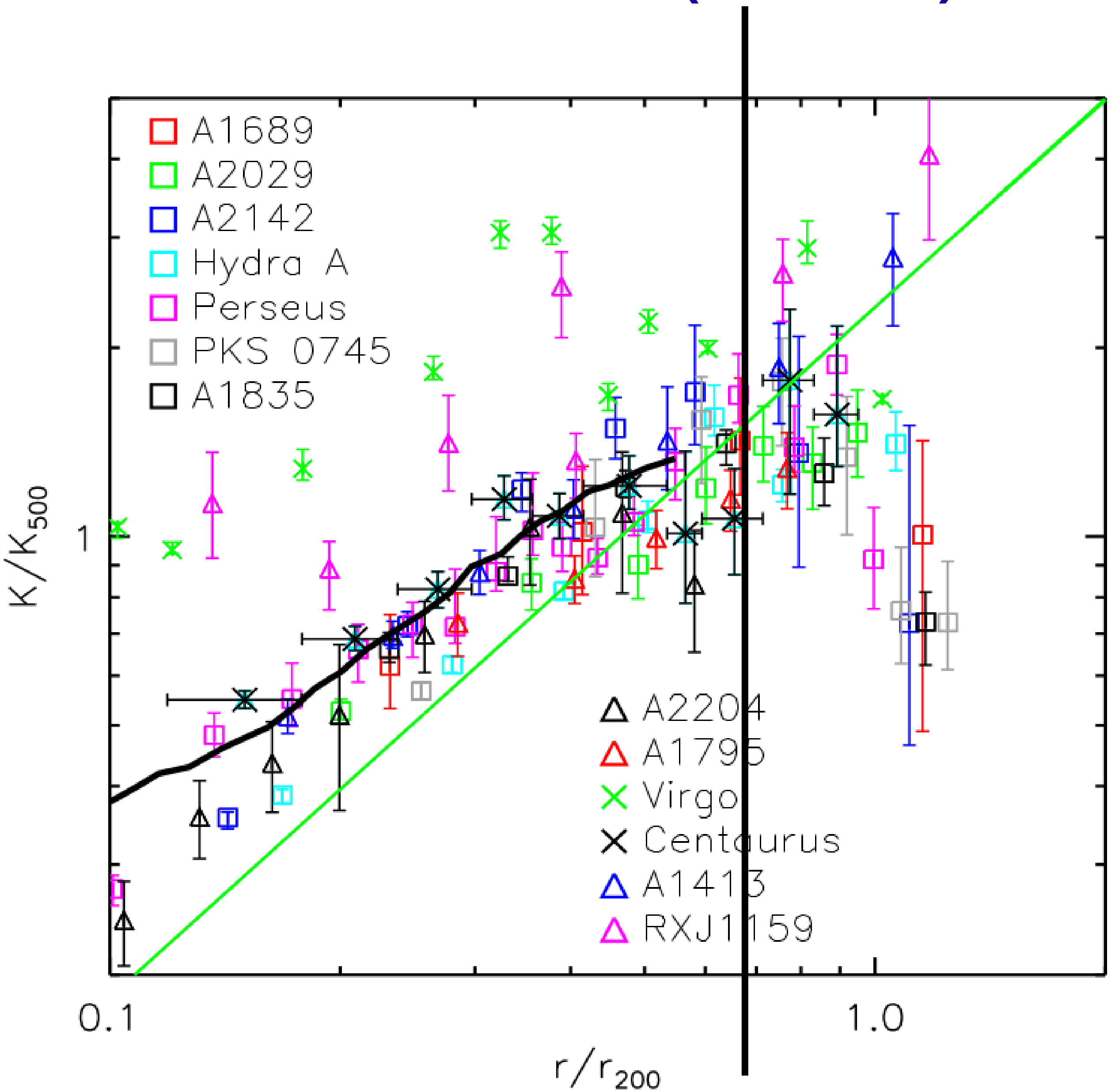


REXCESS clusters,
Pratt et al. (2010)

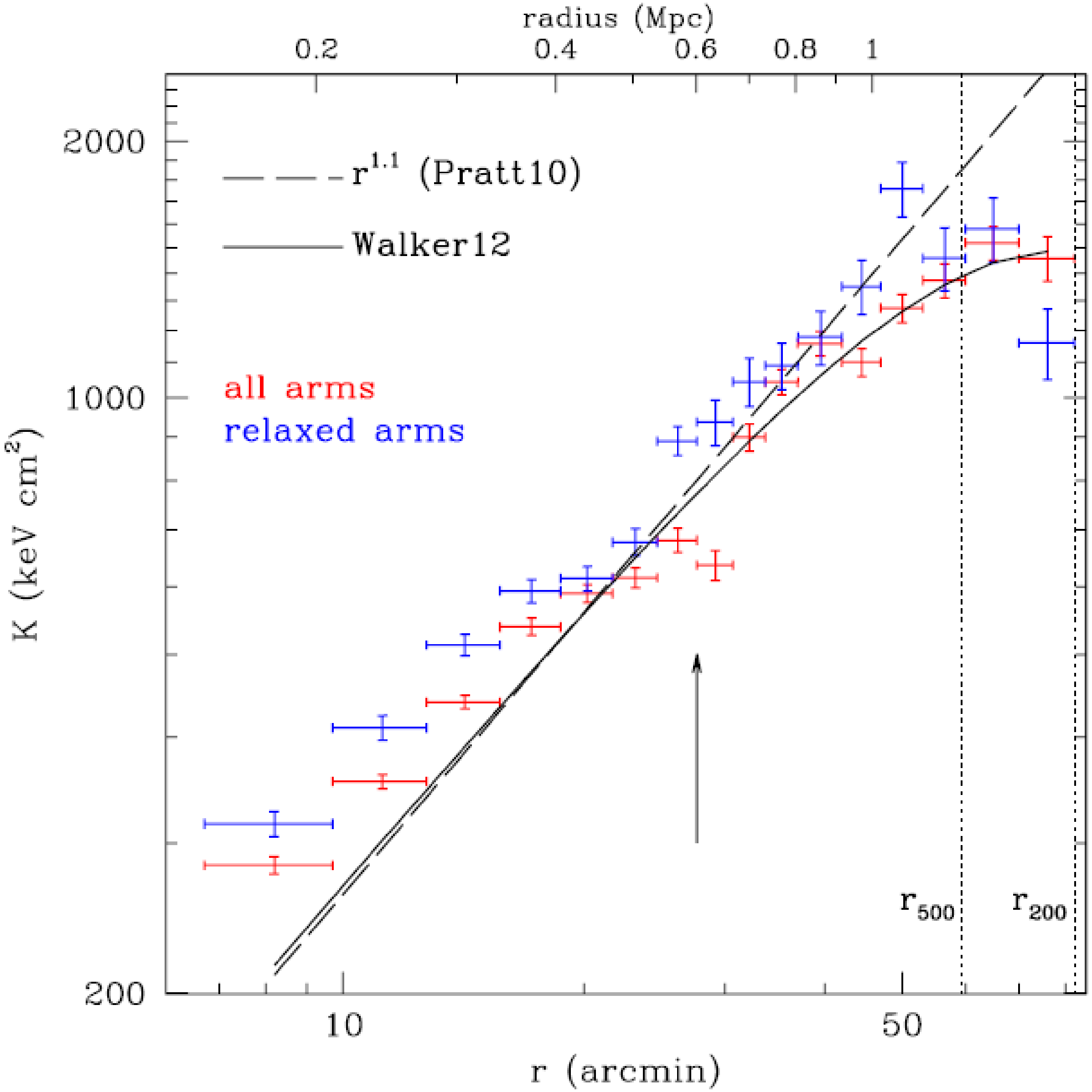
Walker et al. (2013)a

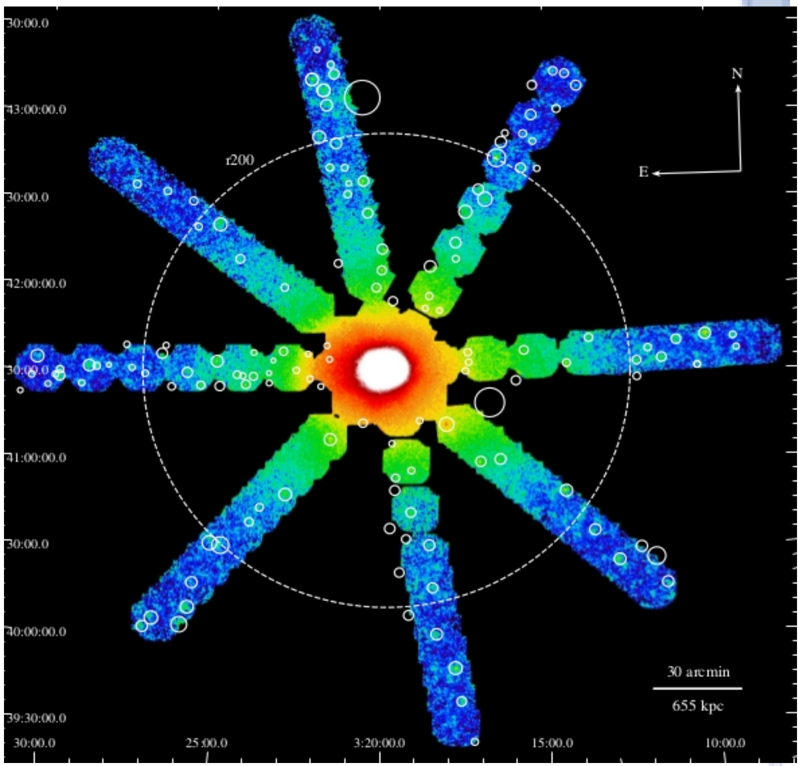


Walker et al. (2013)a



Perseus (all 8 arms)

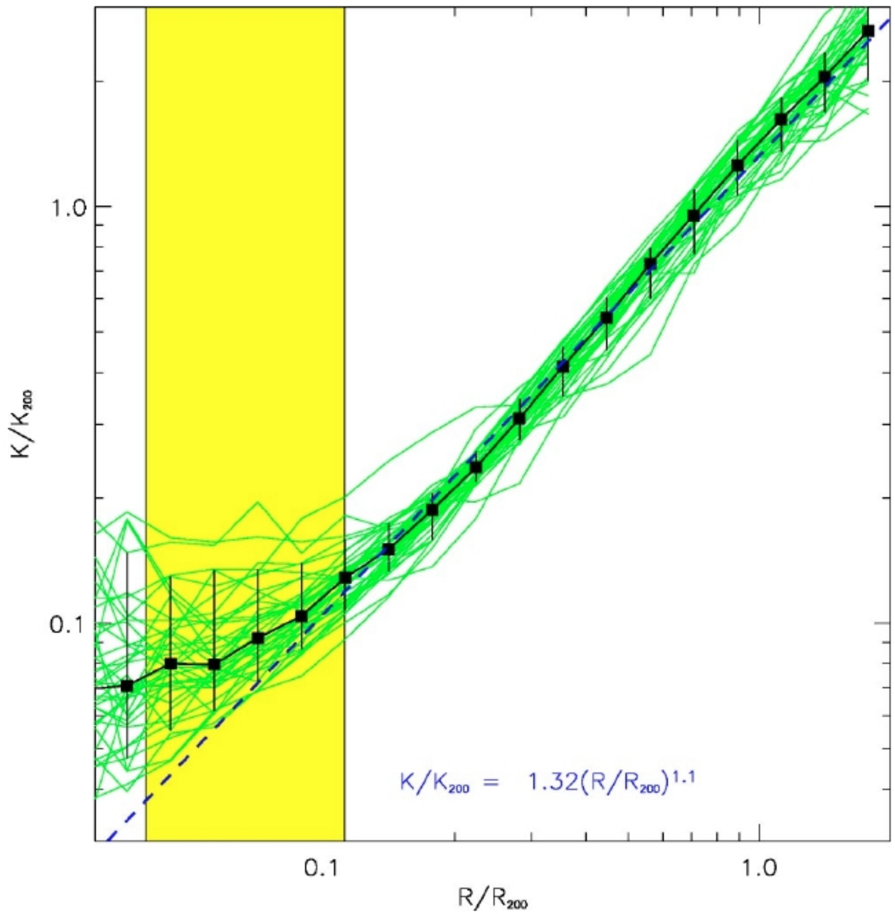




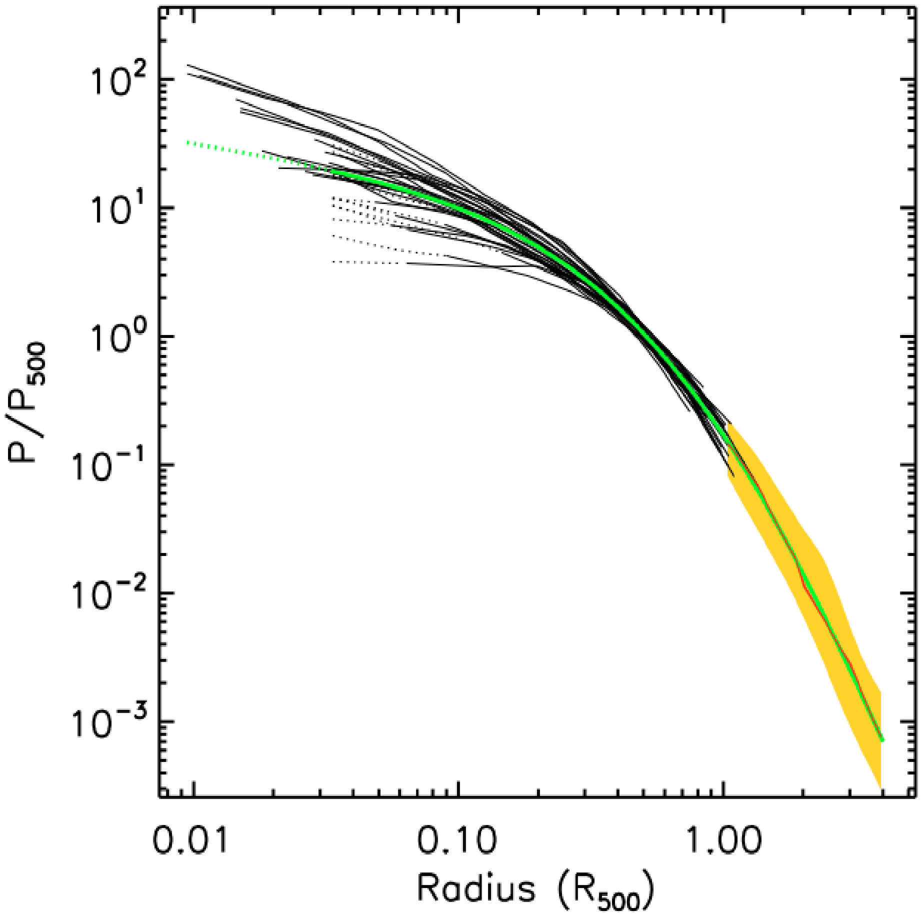
Urban et al. (2014)

Entropy flattening

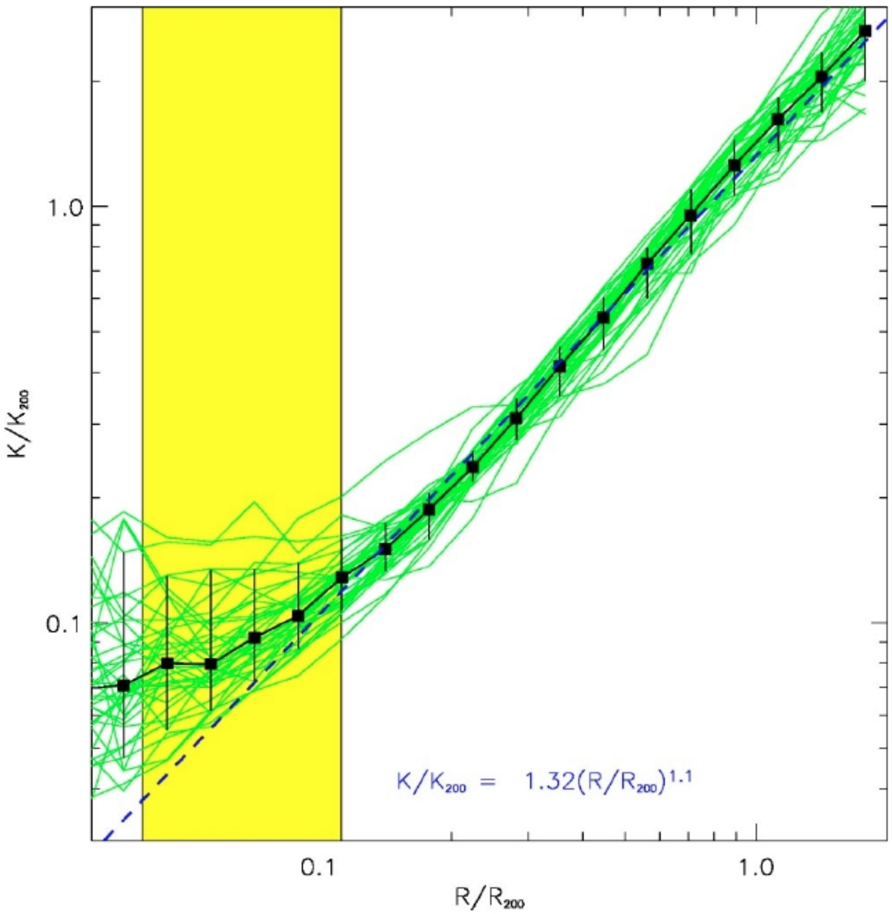
- Is this being caused by the temperature differing from expectations?
- Or is it the density?
- Or both?

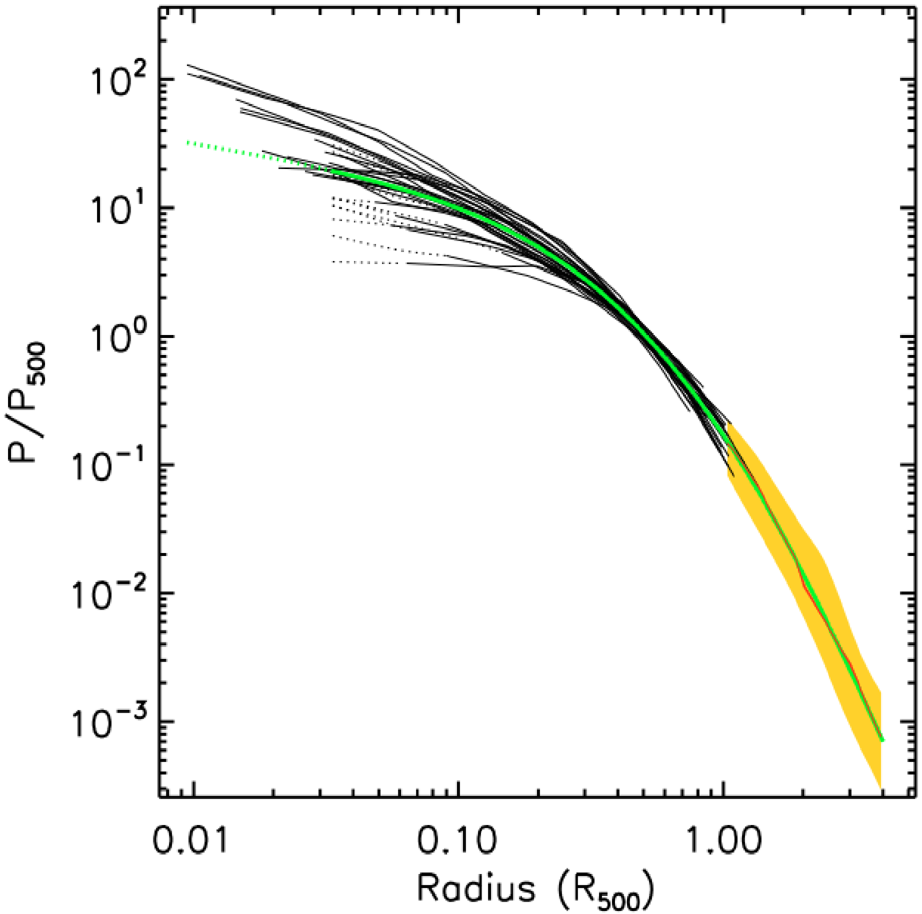


$$K = kT/n_e^{2/3}$$



$$P = n_e kT$$



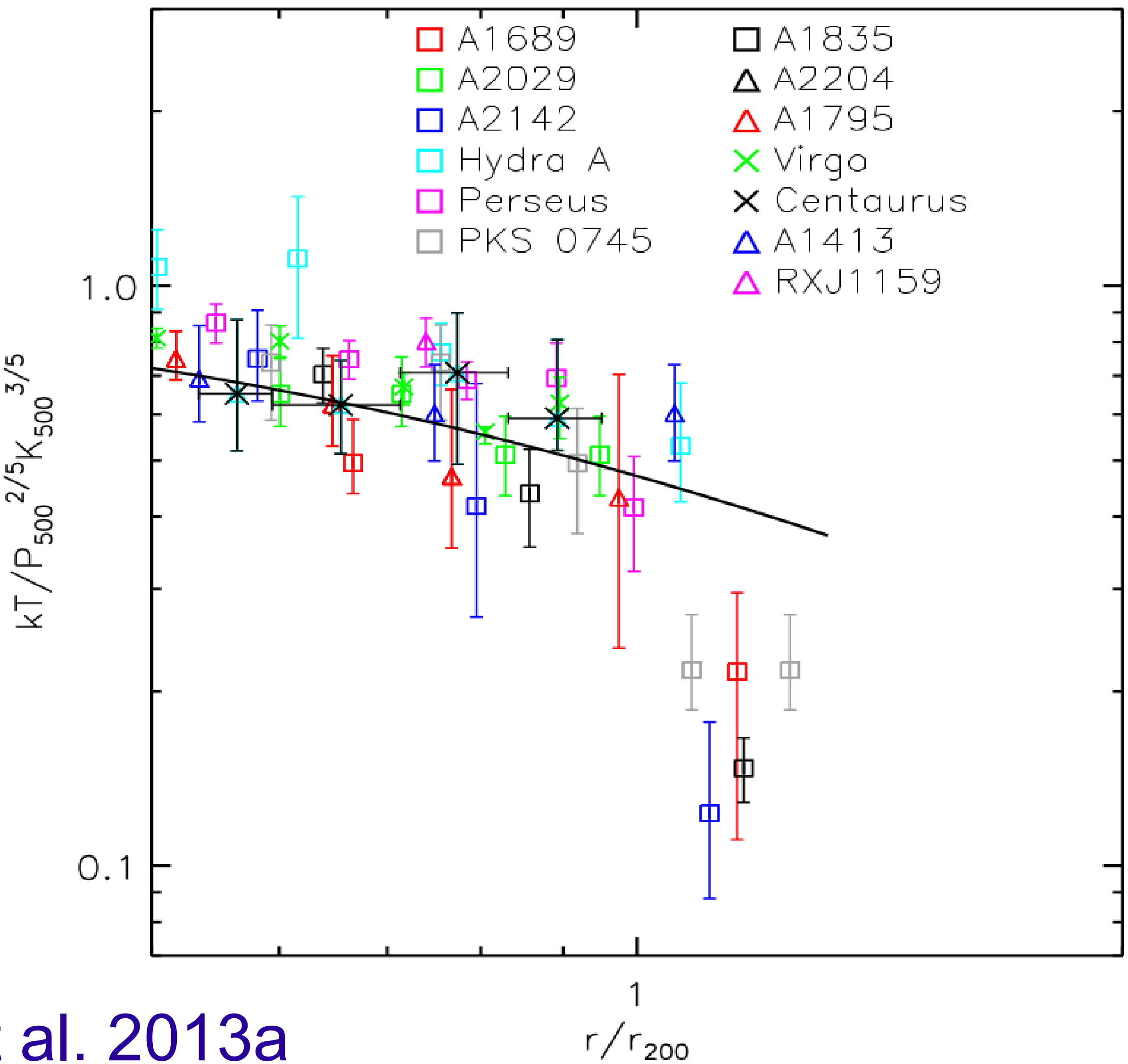


$$K = kT/n_e^{2/3} \qquad P = n_e kT$$

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

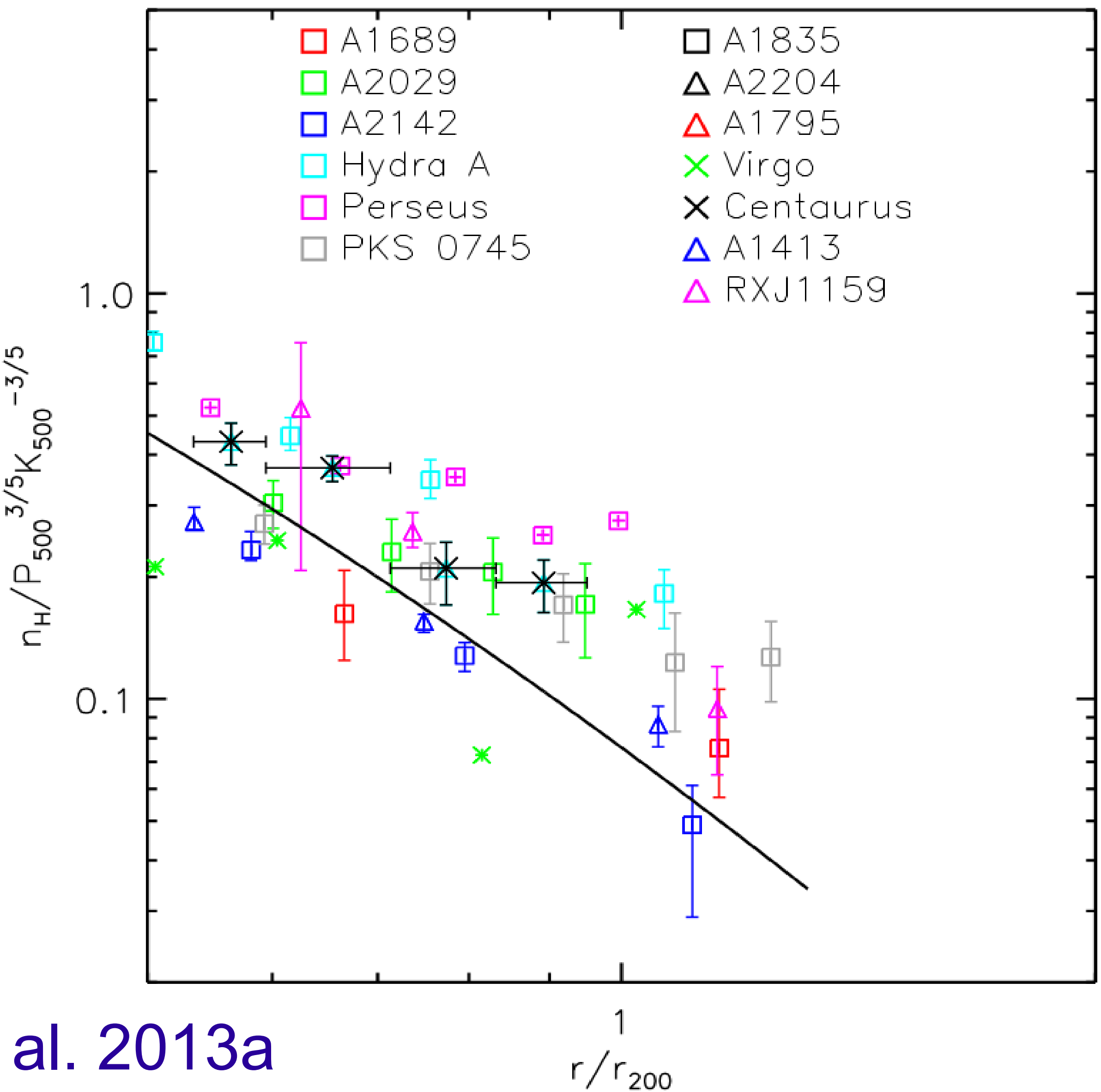
$$n_H(r) = (1/1.2)P(r)^{3/5}K(r)^{-3/5}$$

Scaled Temperatures



Walker et al. 2013a

Densities

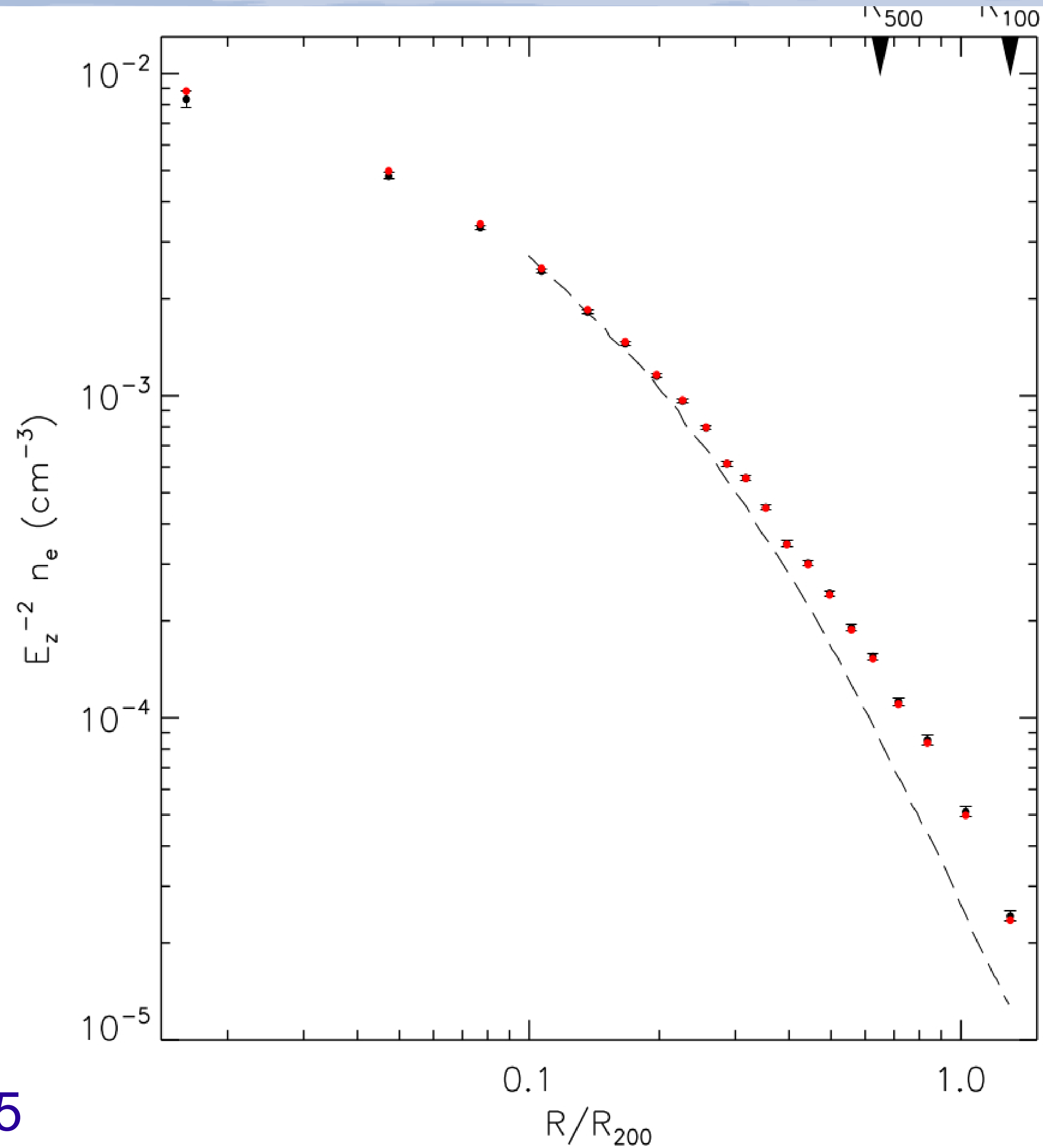


Walker et al. 2013a

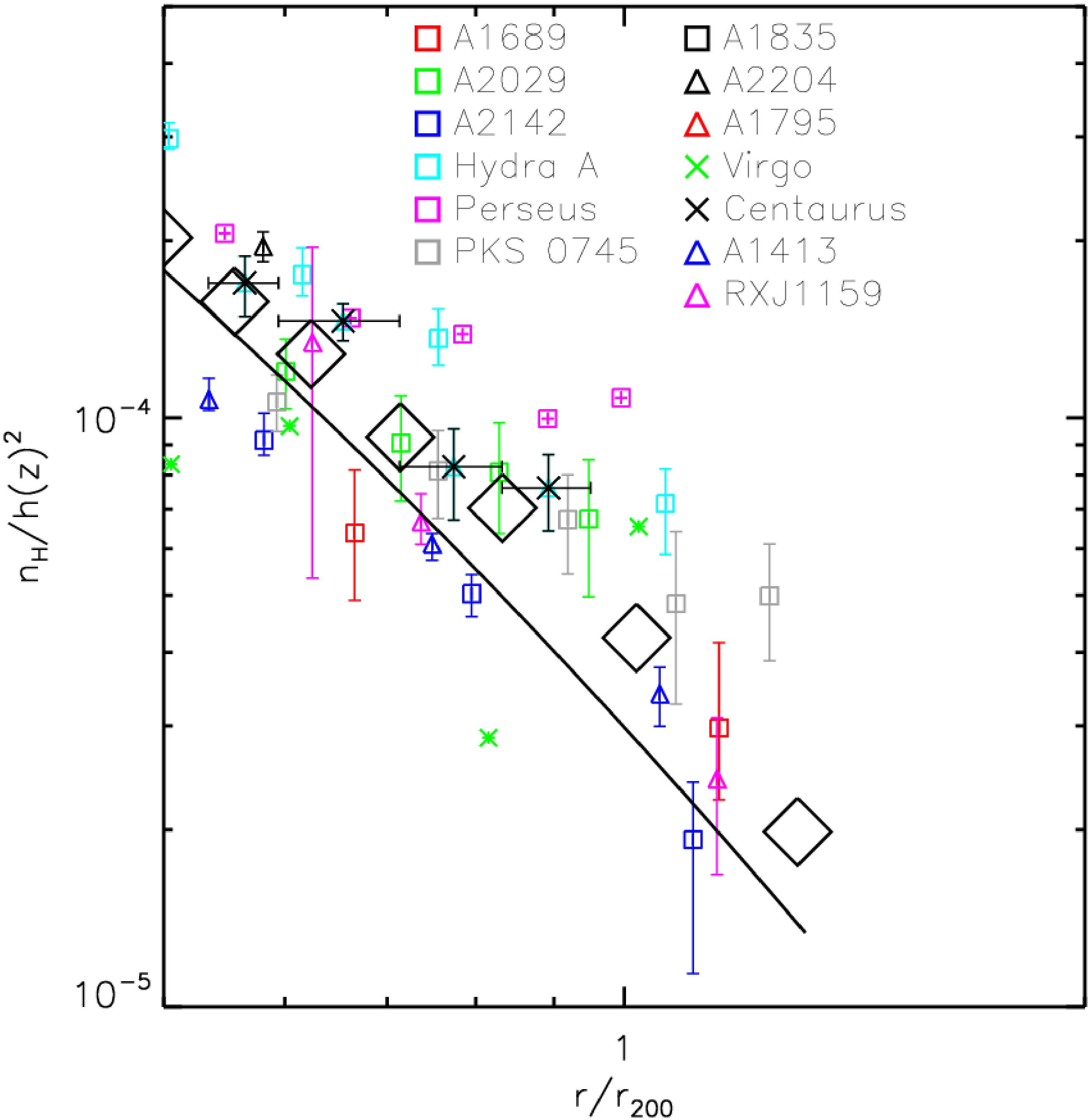
Clumping biases:

- average temperature low
- average density high

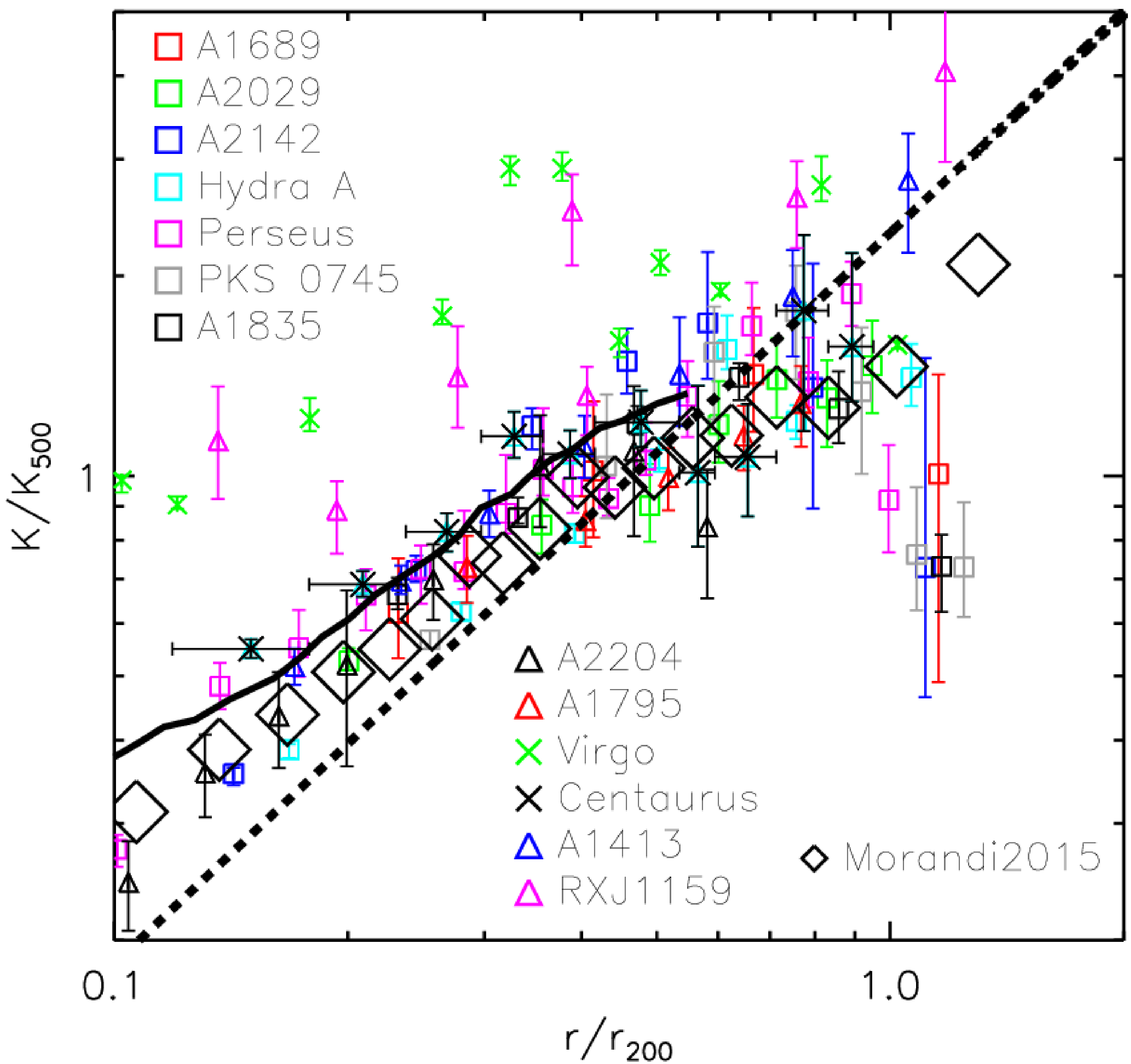
- Qualitatively similar to what we observe



Morandi et al. 2015

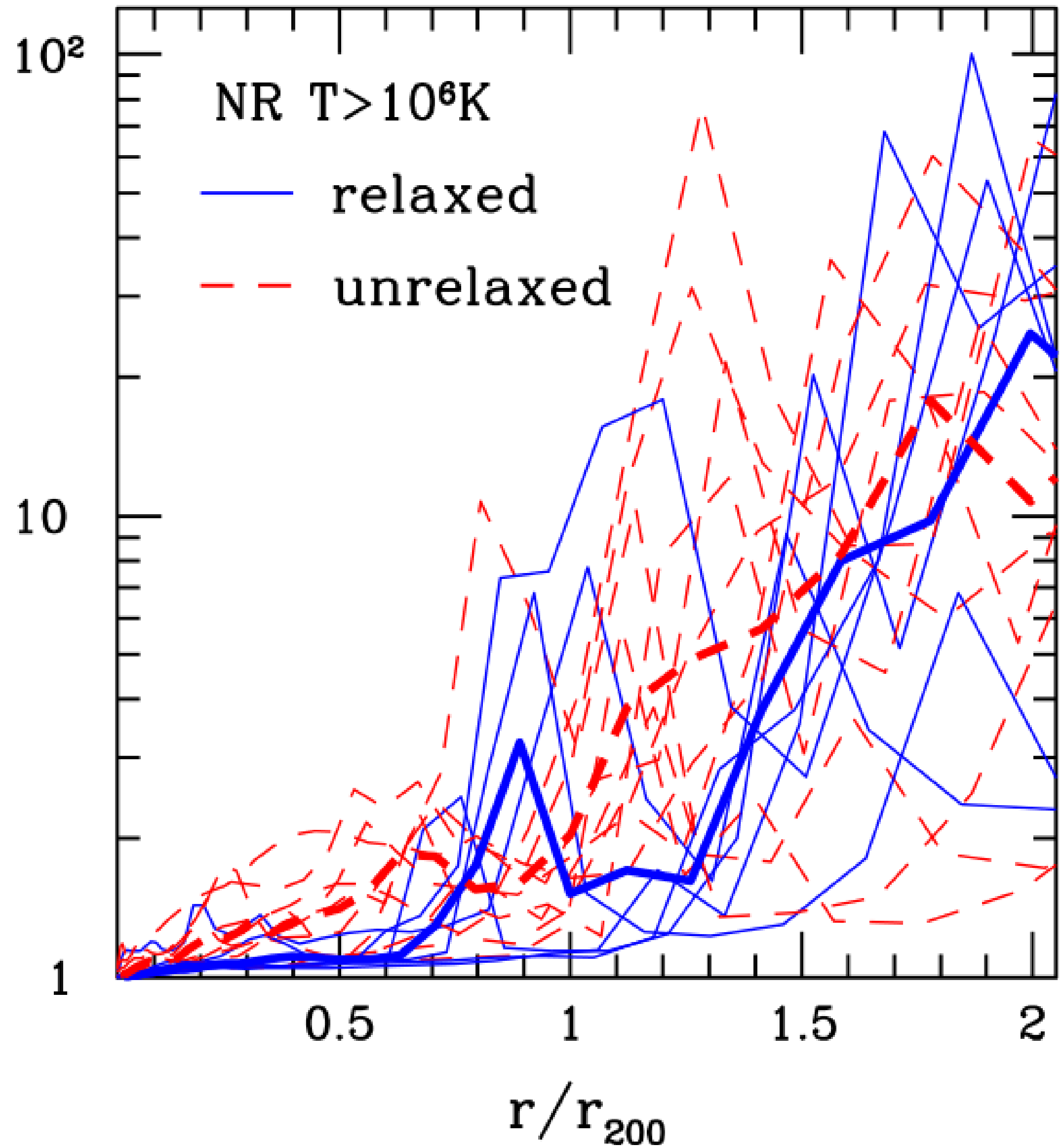


A1689
A2029
A2142
Hydra A
Perseus
PKS 0745
A1835
A2204
A1795
Virgo
Centaurus
A1413
RXJ1159
10^{-4}
10^{-5}
$n_H/h(z)^2$
1
r/r_{200}



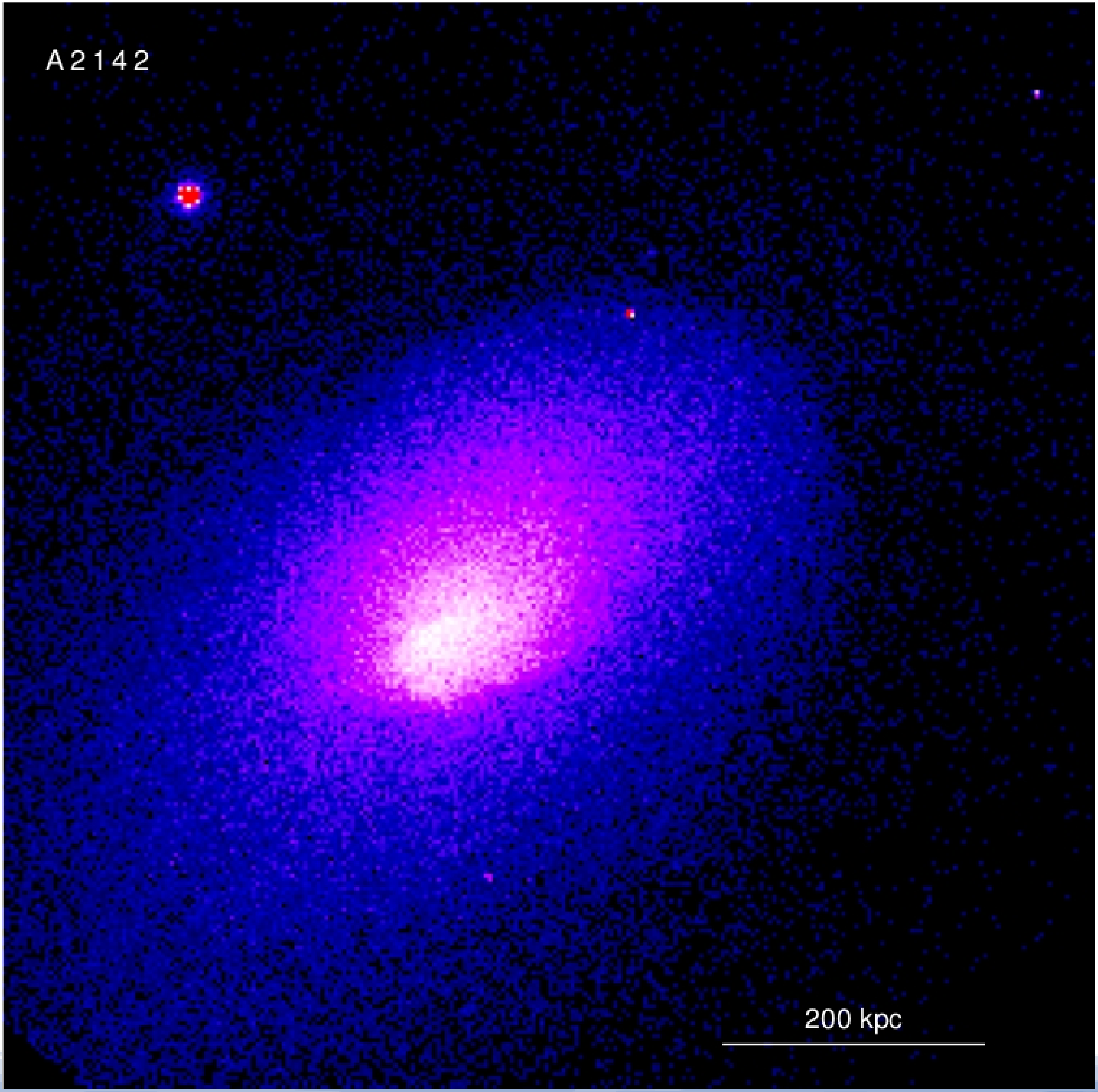
A1689
A2029
A2142
Hydra A
Perseus
PKS 0745
A1835
A2204
A1795
Virgo
Centaurus
A1413
RXJ1159
Morandi2015
K/K500
1
0.1
1.0
r/r200

Nagai et al. (2011)

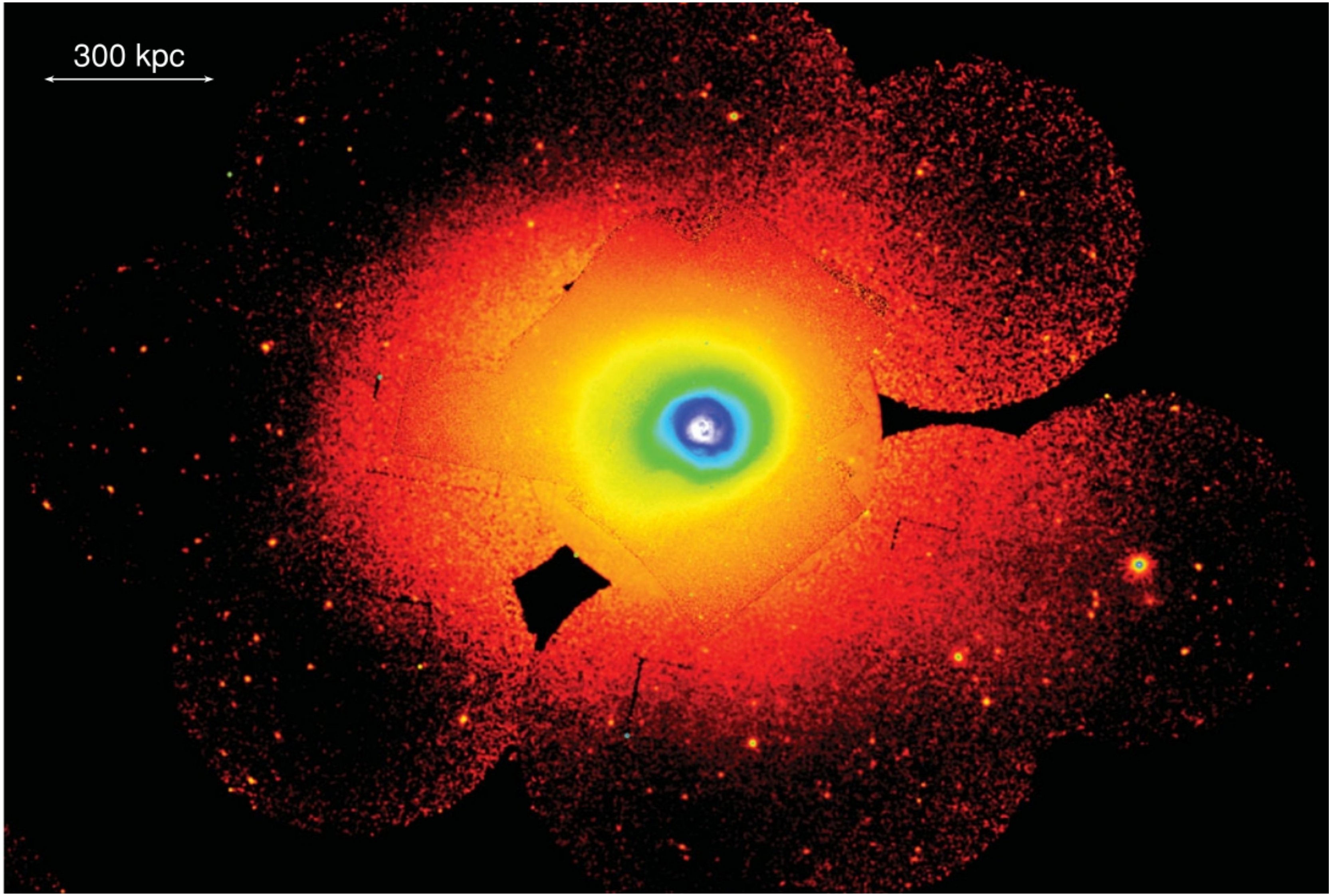


Large scale gas sloshing in galaxy clusters

A2142 – Markevitch et al. (2000)

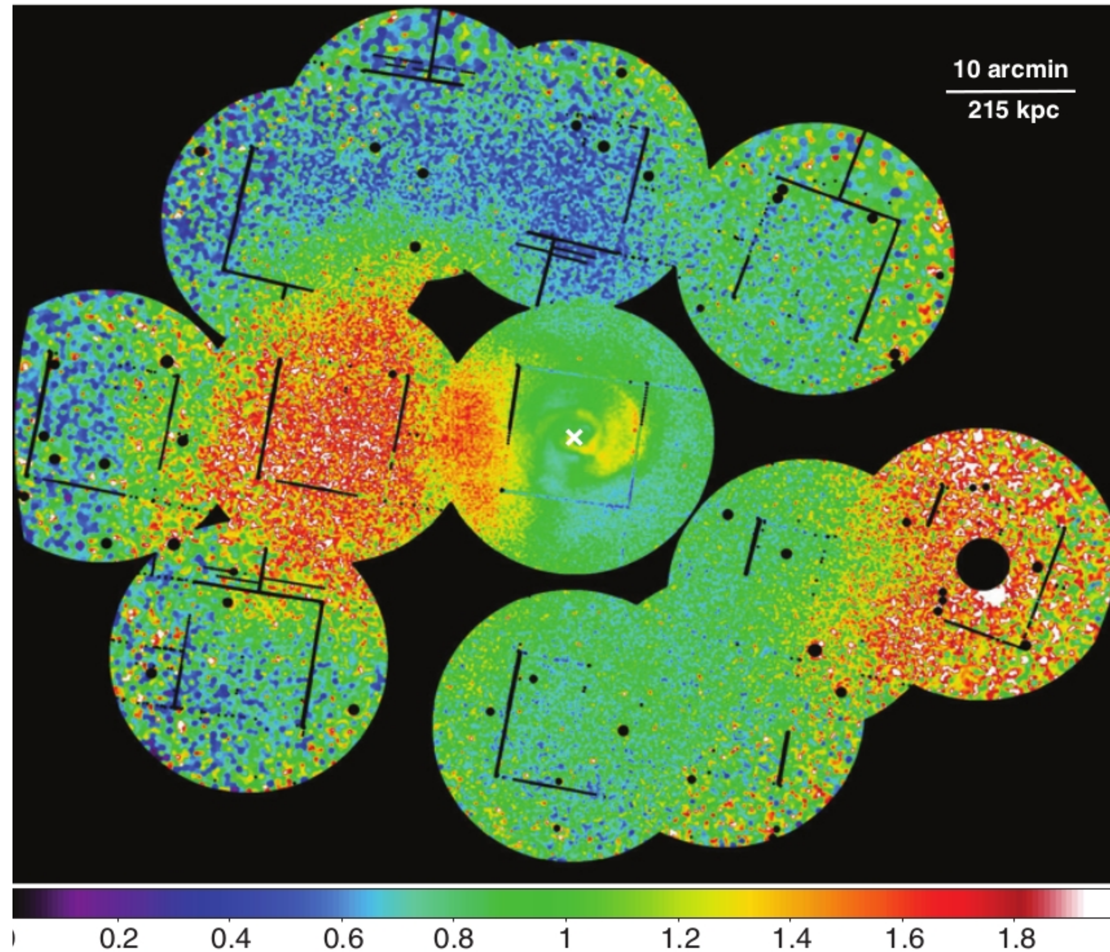


Perseus



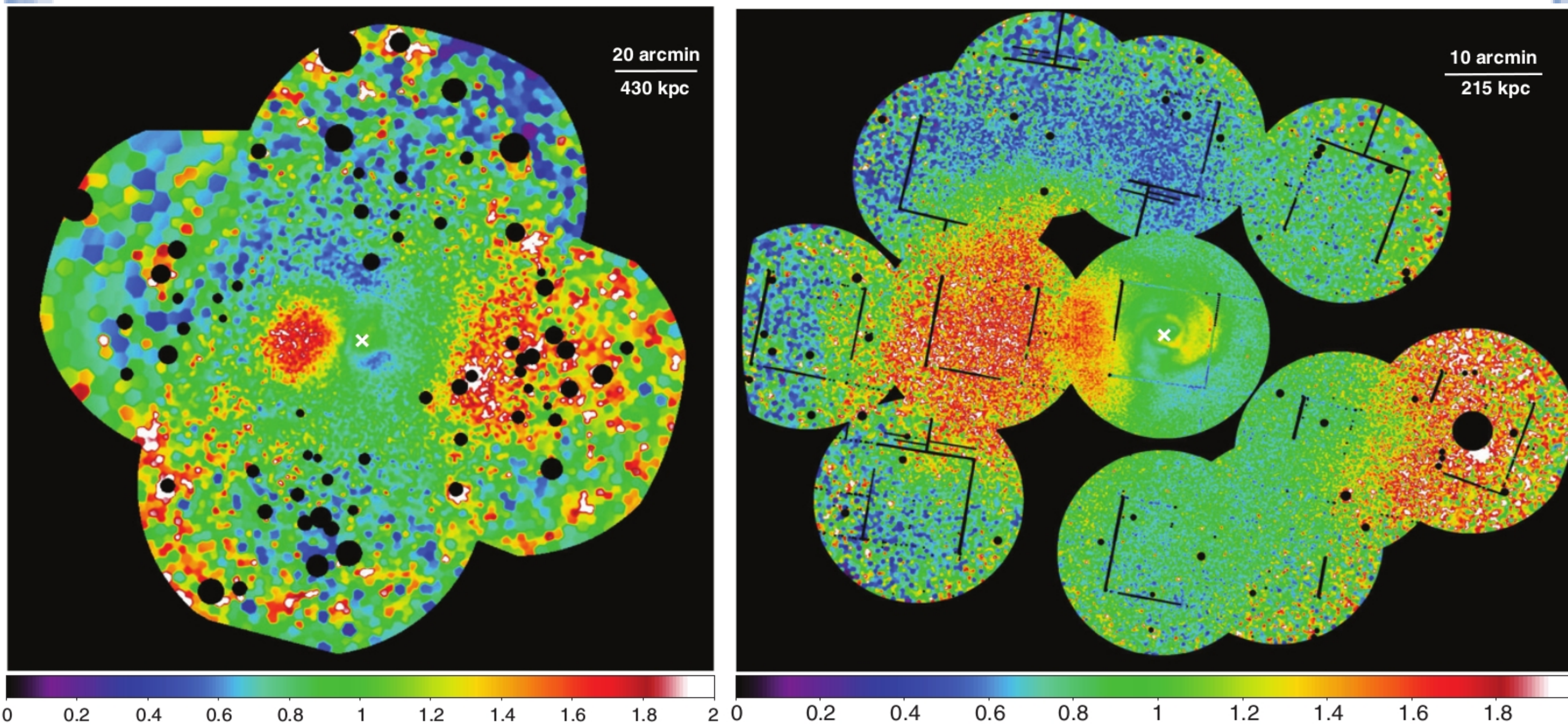
Fabian et al. (2011)

Perseus

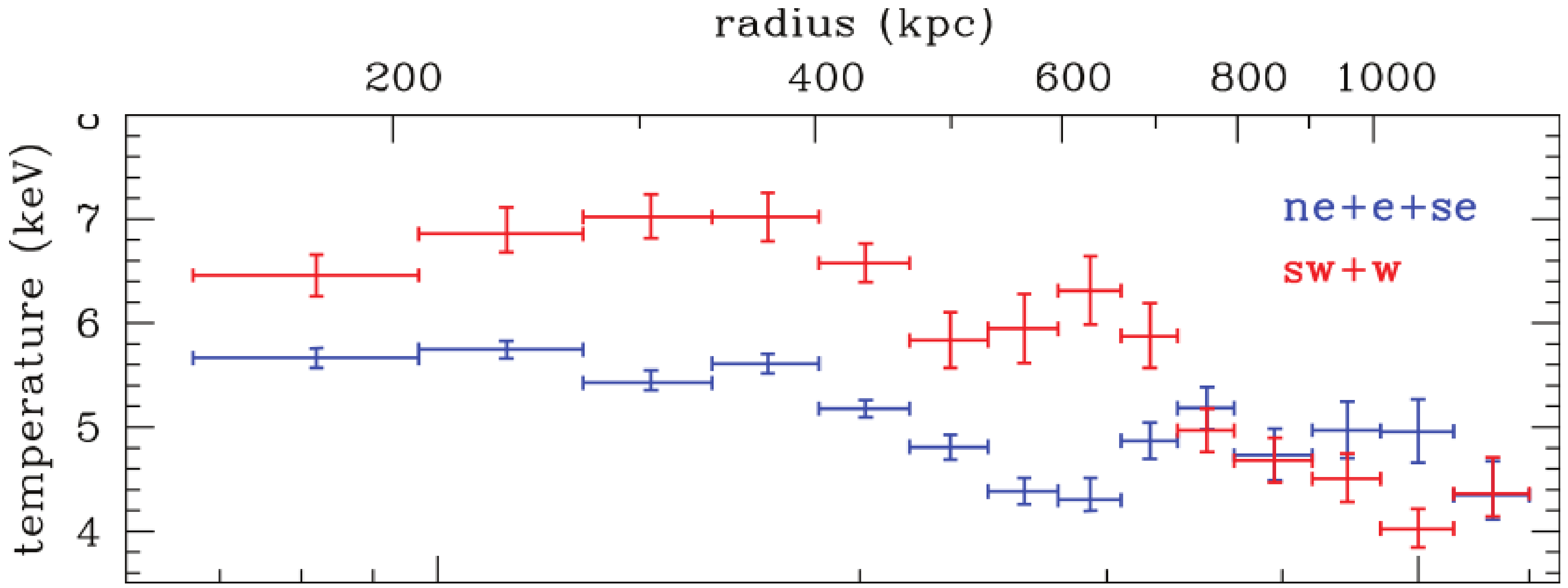


Simionescu et al. 2012

Perseus

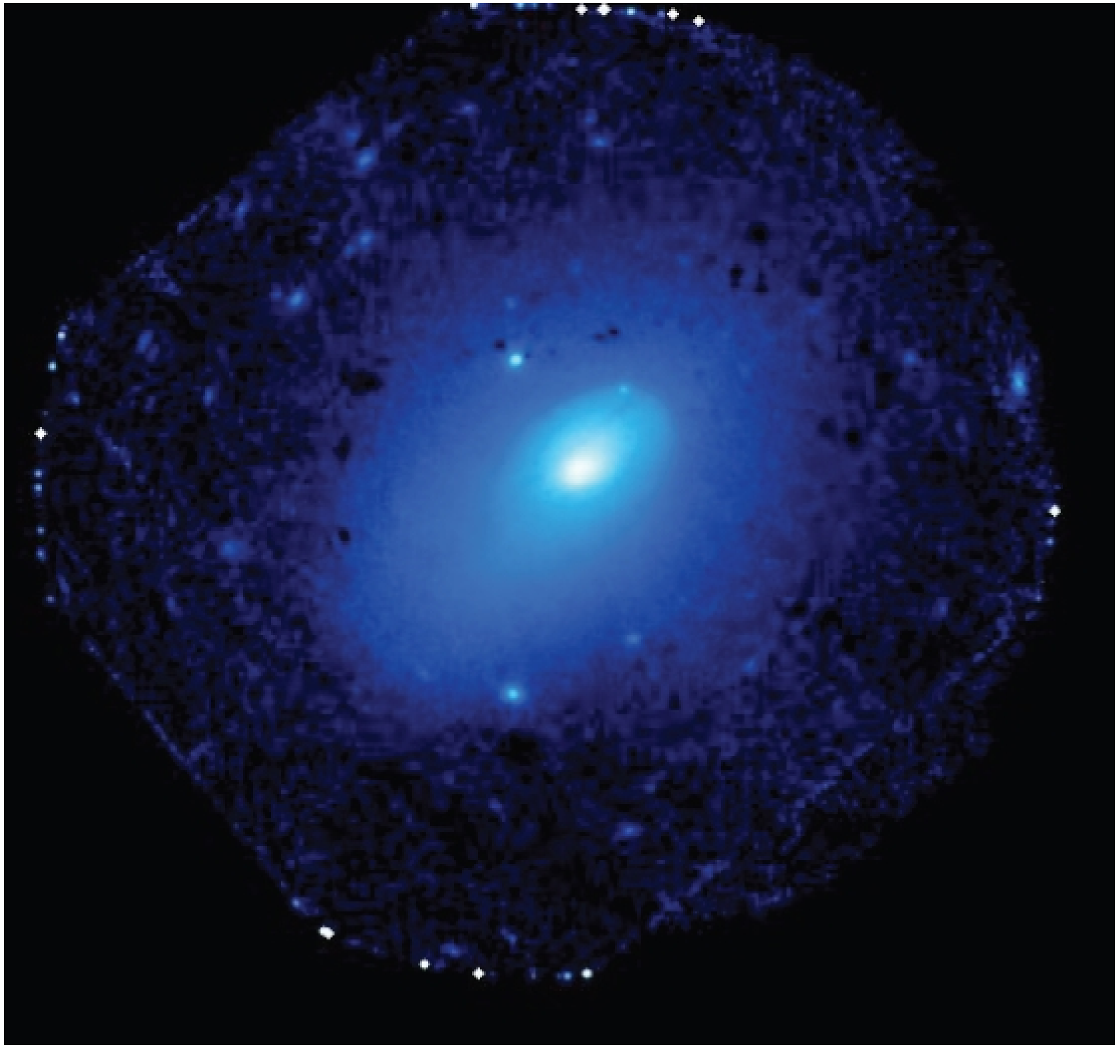


Simionescu et al. 2012



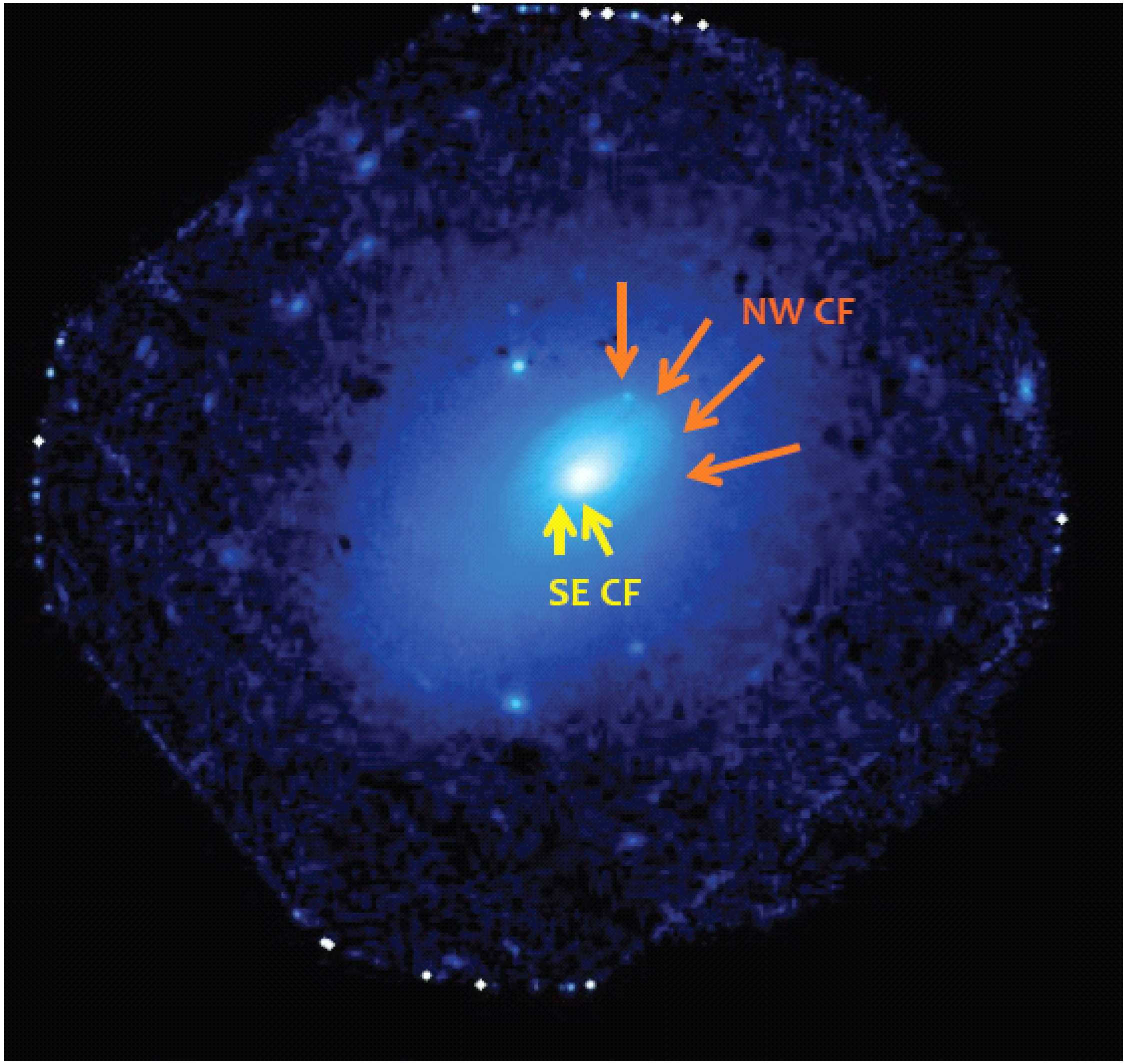
Simionescu et al. 2012

Abell 2142



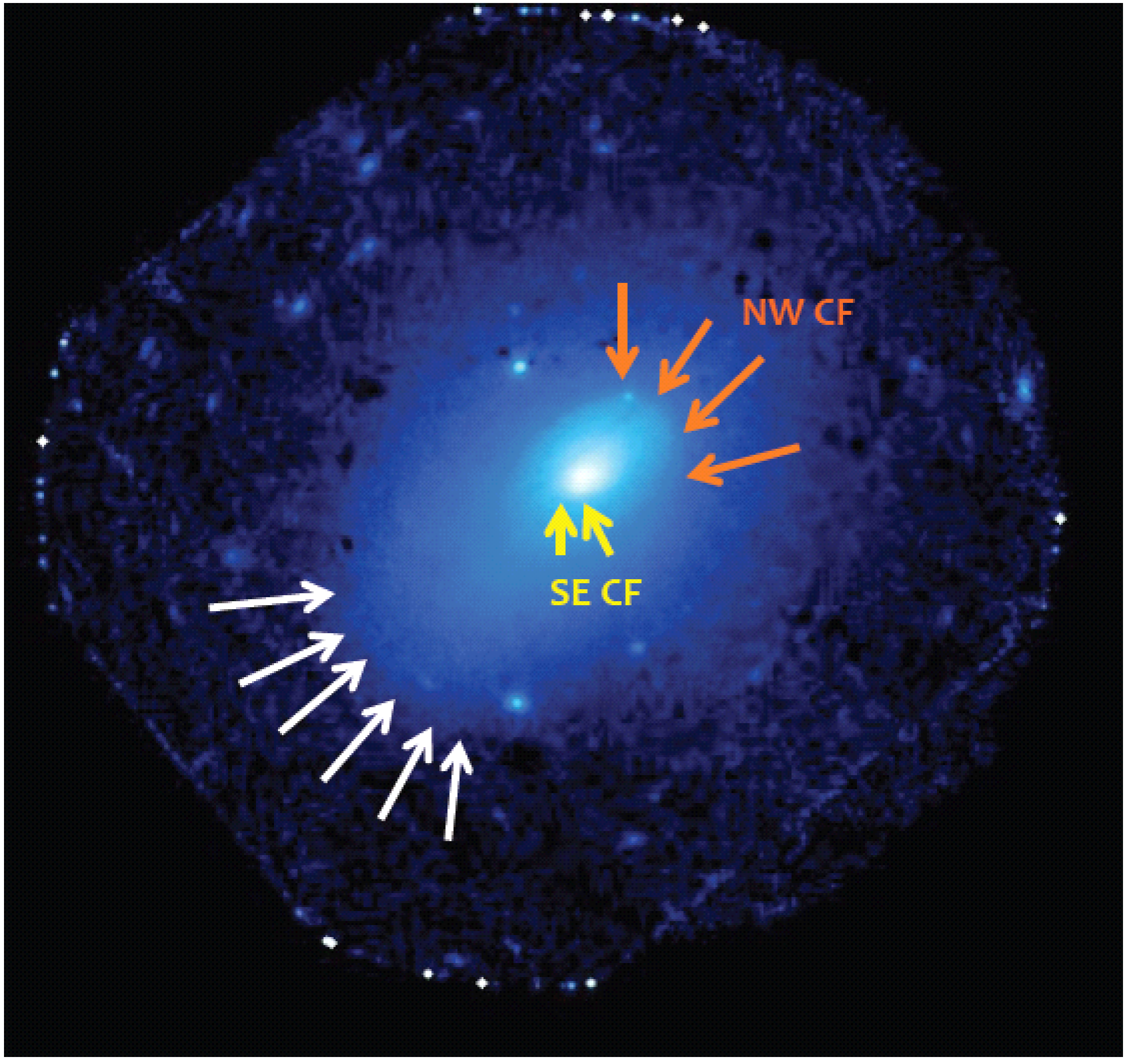
Rossetti et al. 2013

Abell 2142



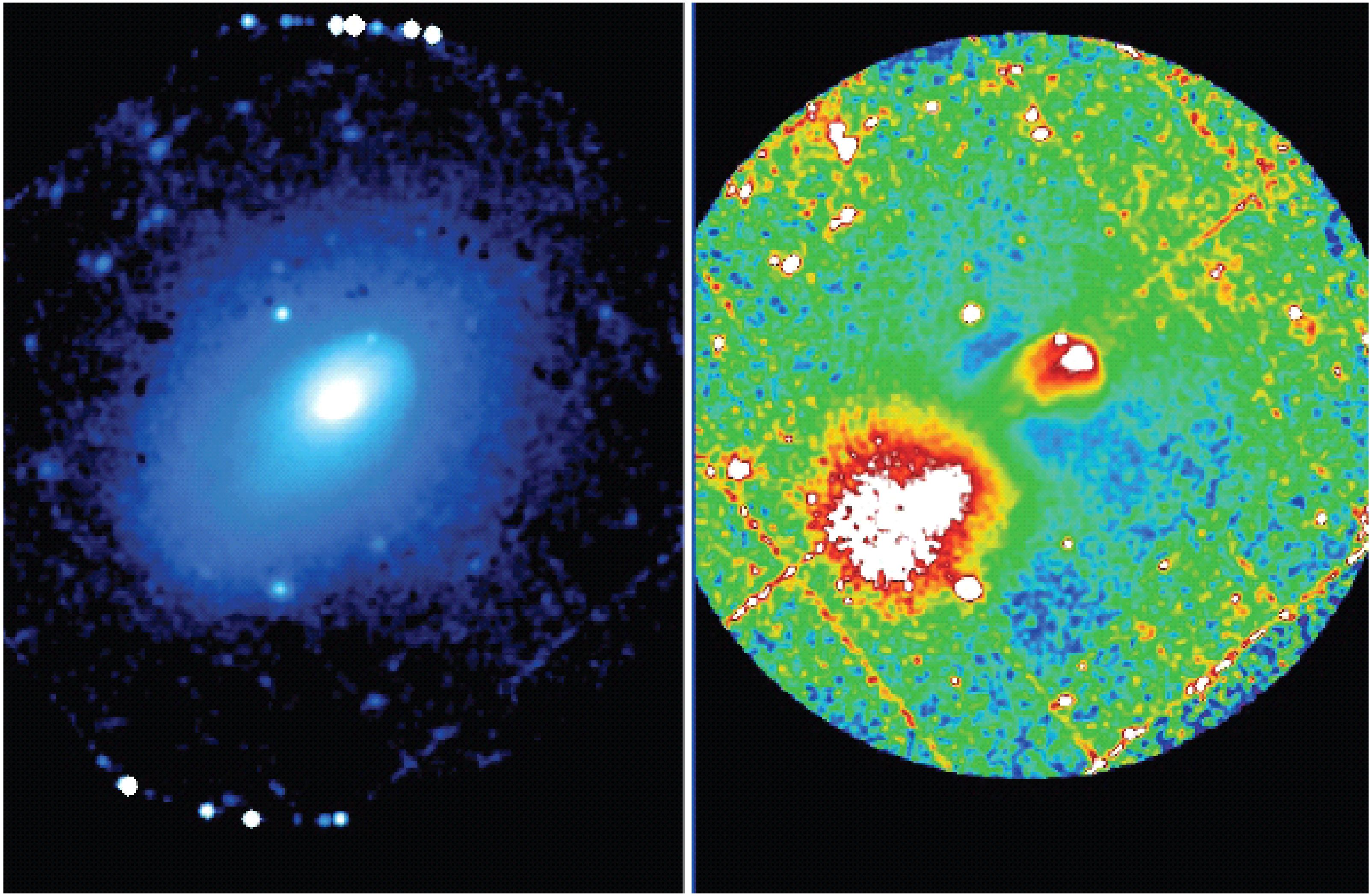
Rossetti et al. 2013

Abell 2142



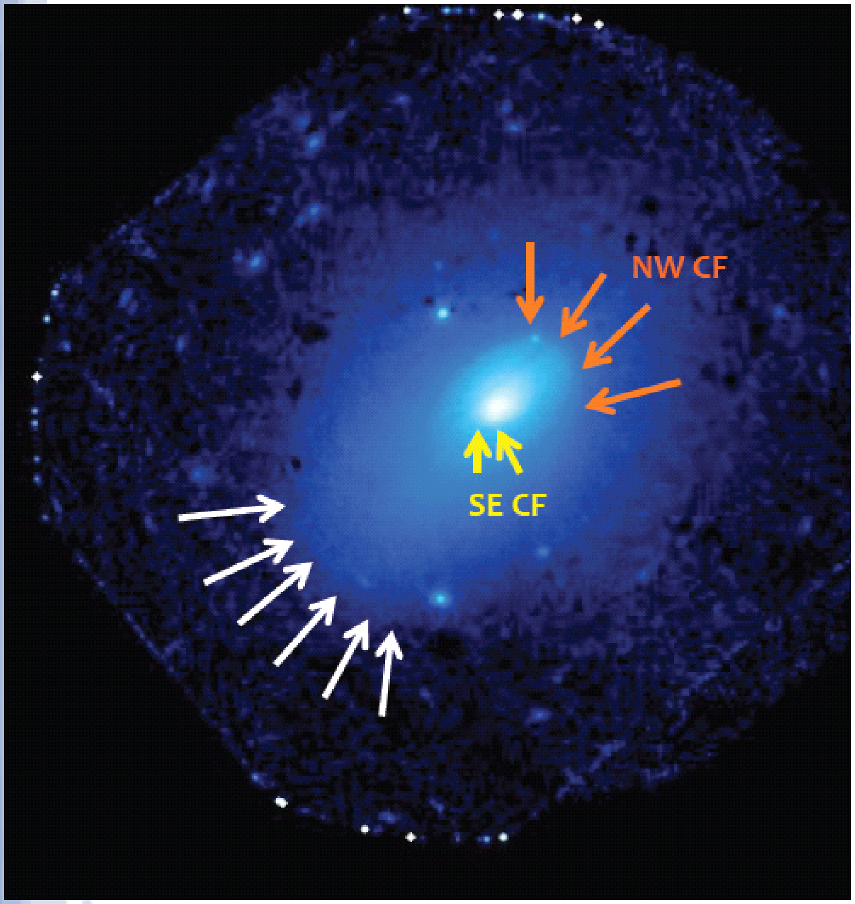
Rossetti et al. 2013

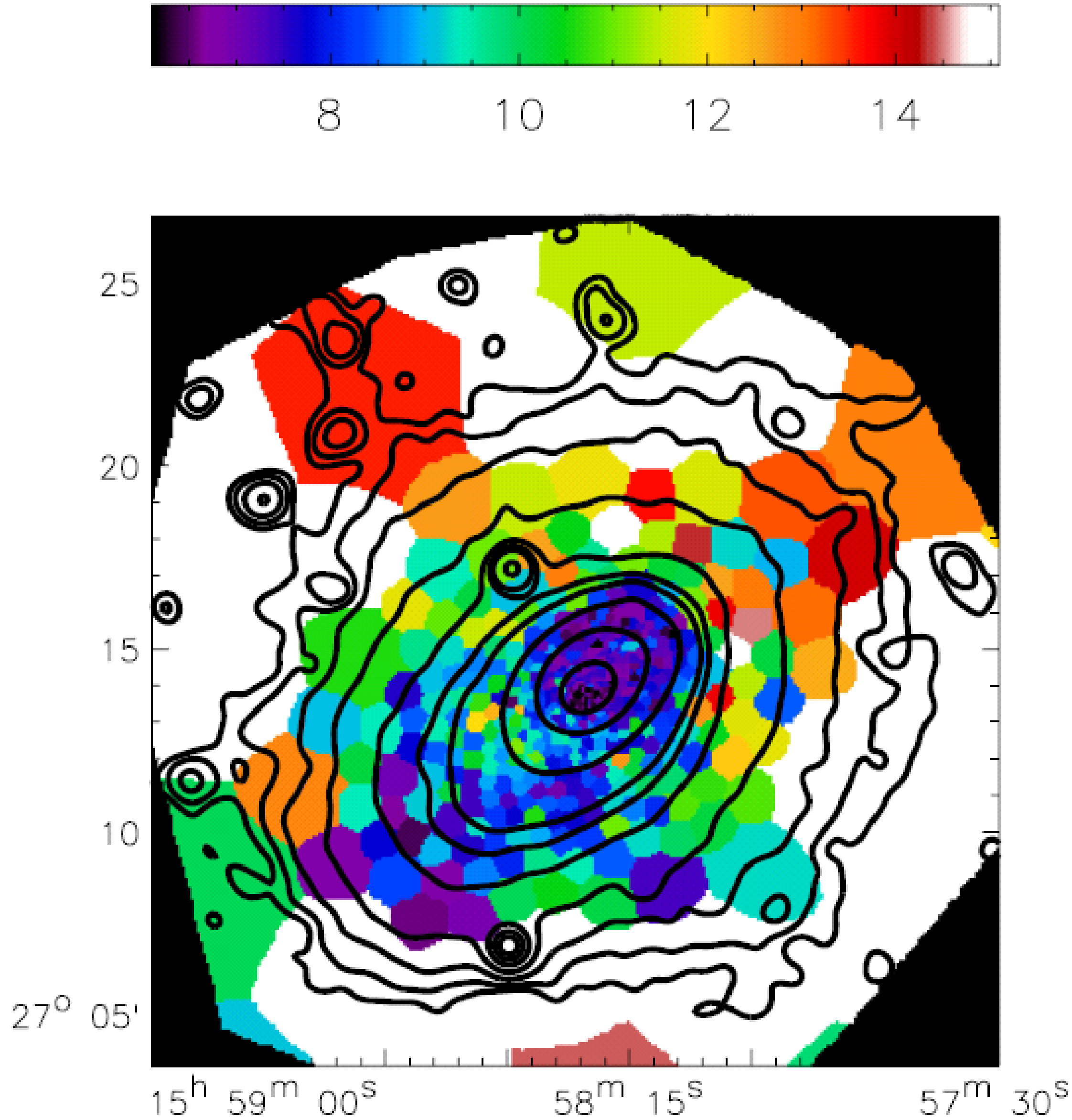
Abell 2142



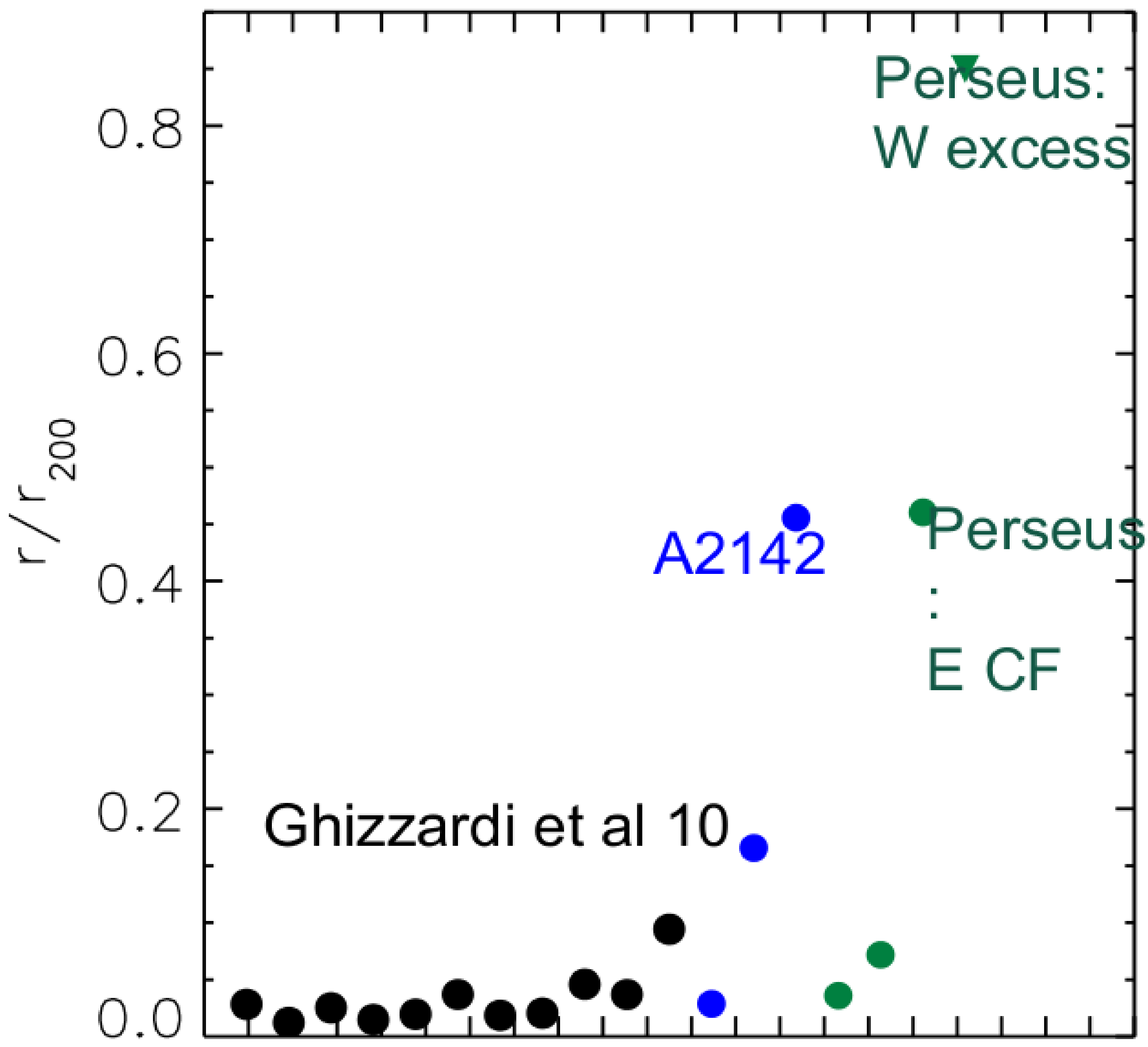
Rossetti et al. 2013

Abell 2142





Rossetti et al. 2013

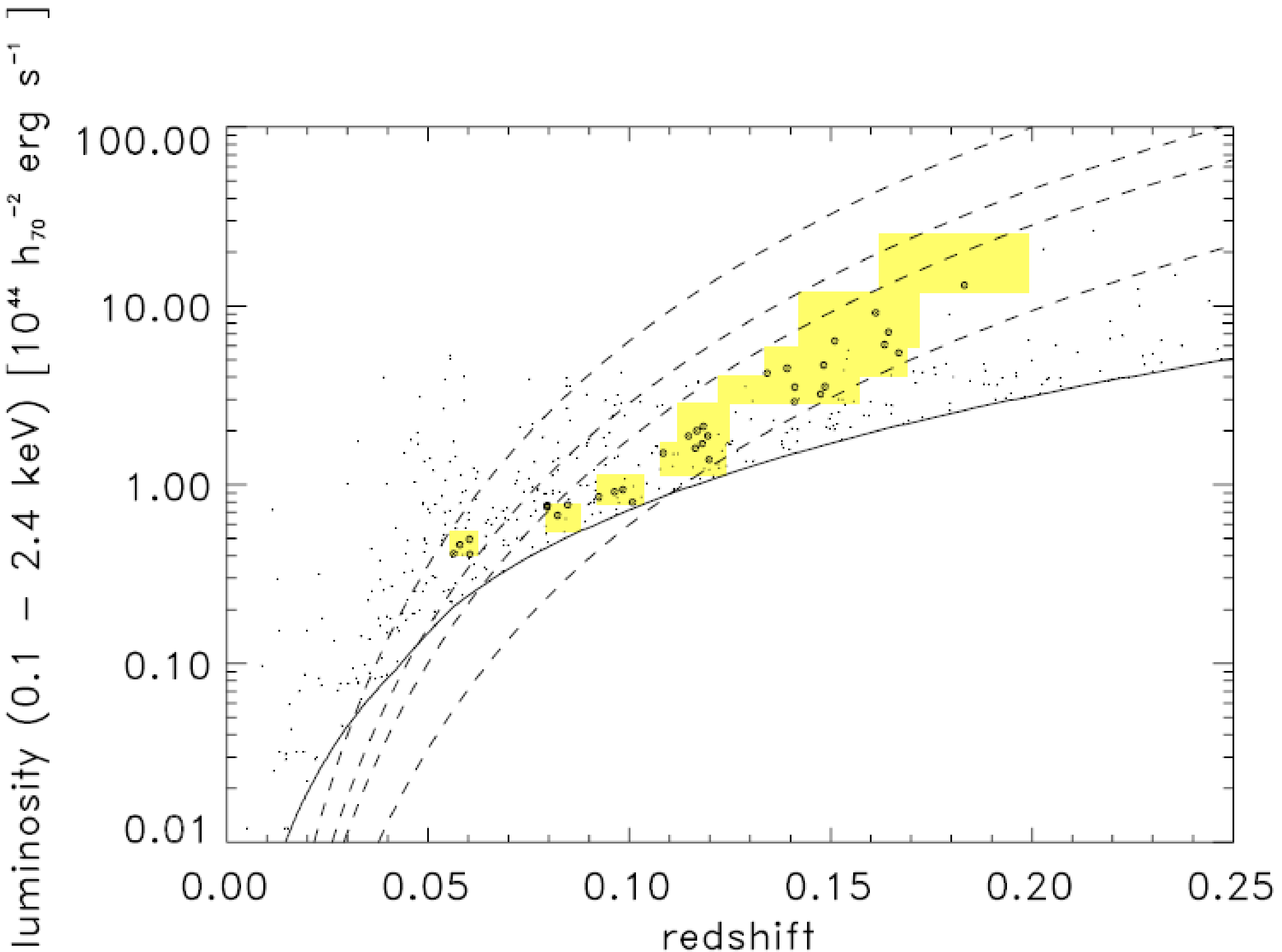


Perseus:
W excess
A2142
Perseus
:
E CF
Ghizzardi et al 10
0.0
0.2
0.4
0.6
0.8
r / r200

Large scale gas sloshing out to half the virial radius in RXJ2014.8-2430

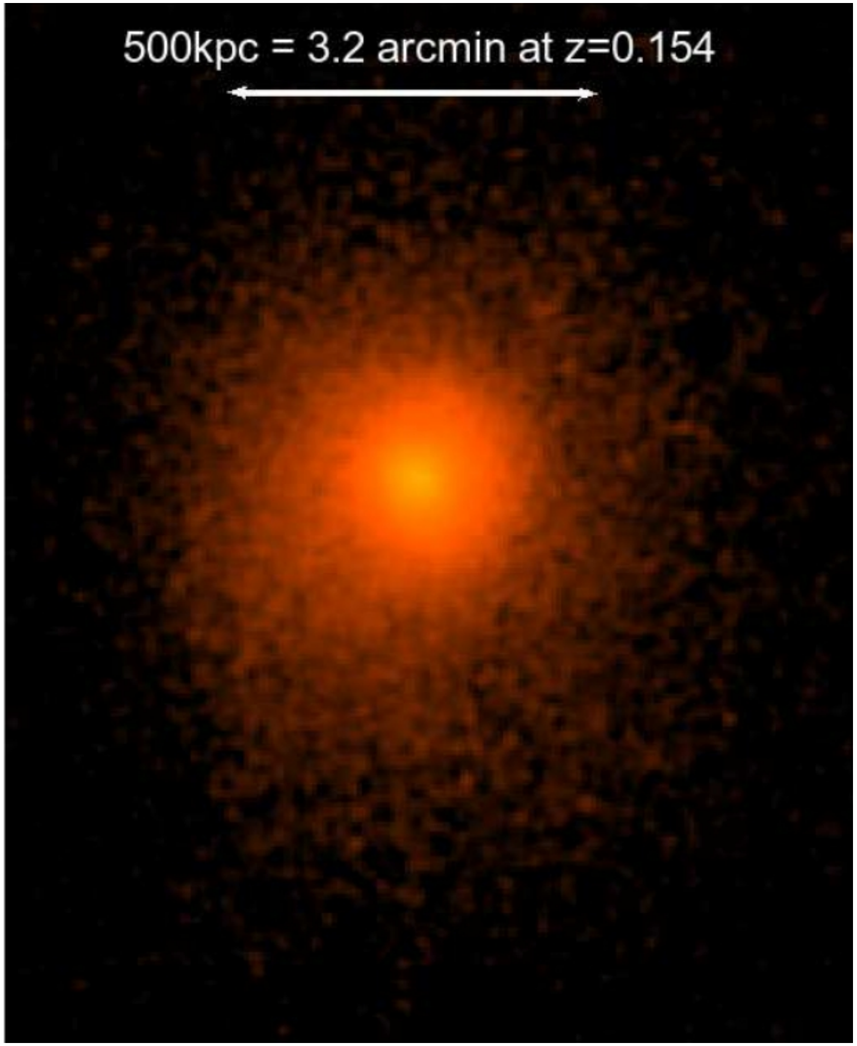
Walker et al. (2014a), MNRAS, 441, L31
ArXiv:**1402.6894**

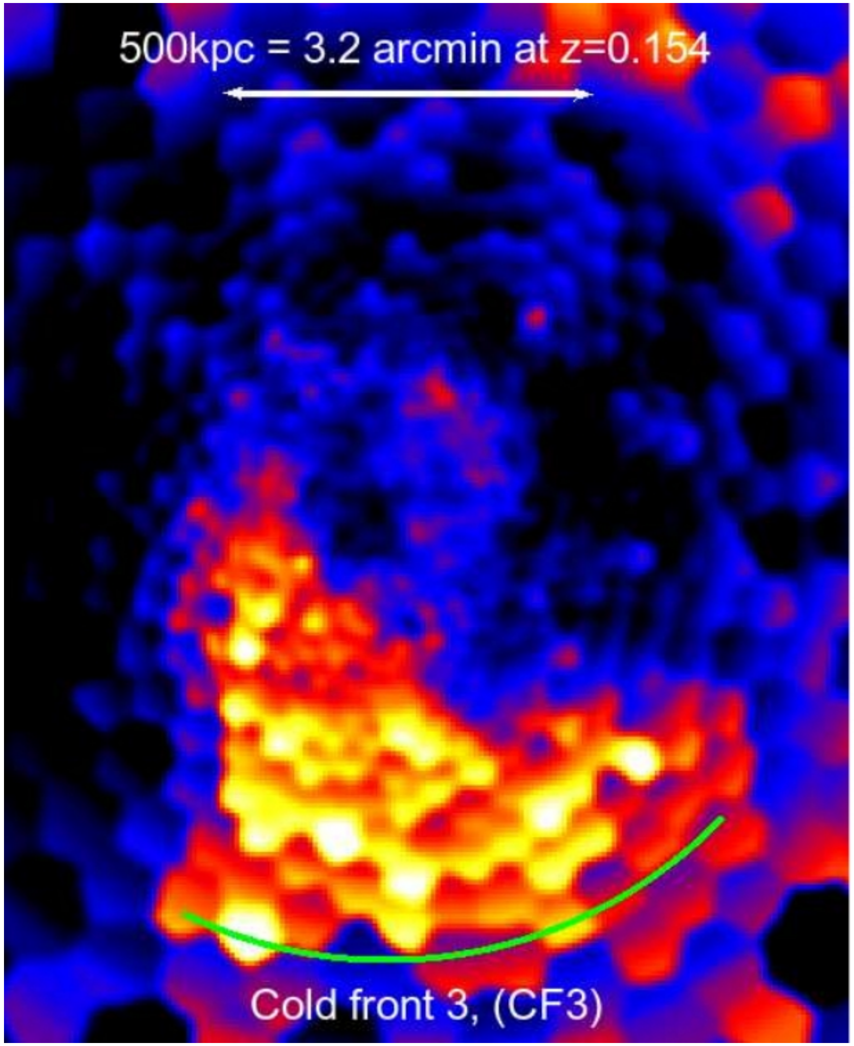
REXCESS clusters



Boehringer et al. 2007

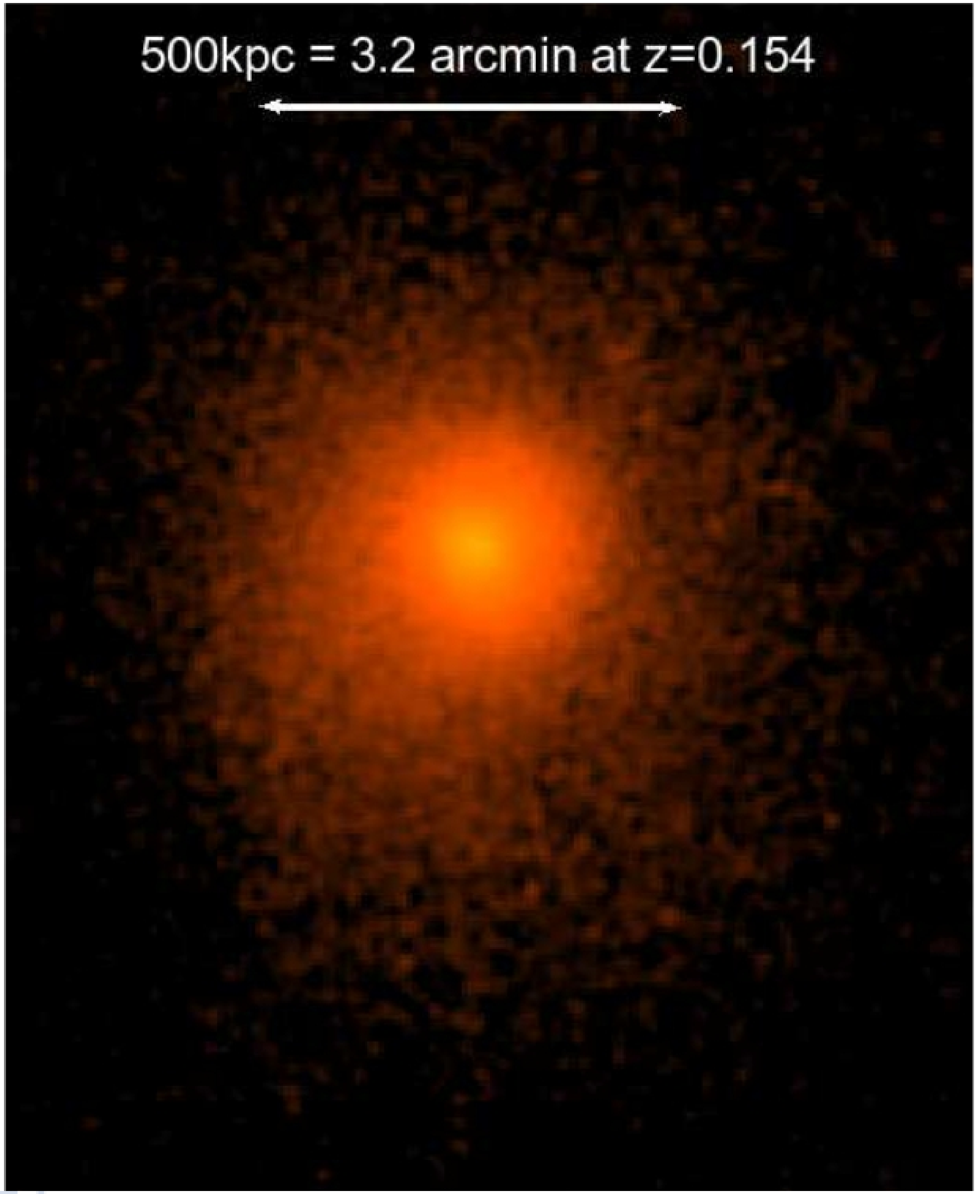
RXJ 2014.8-2430

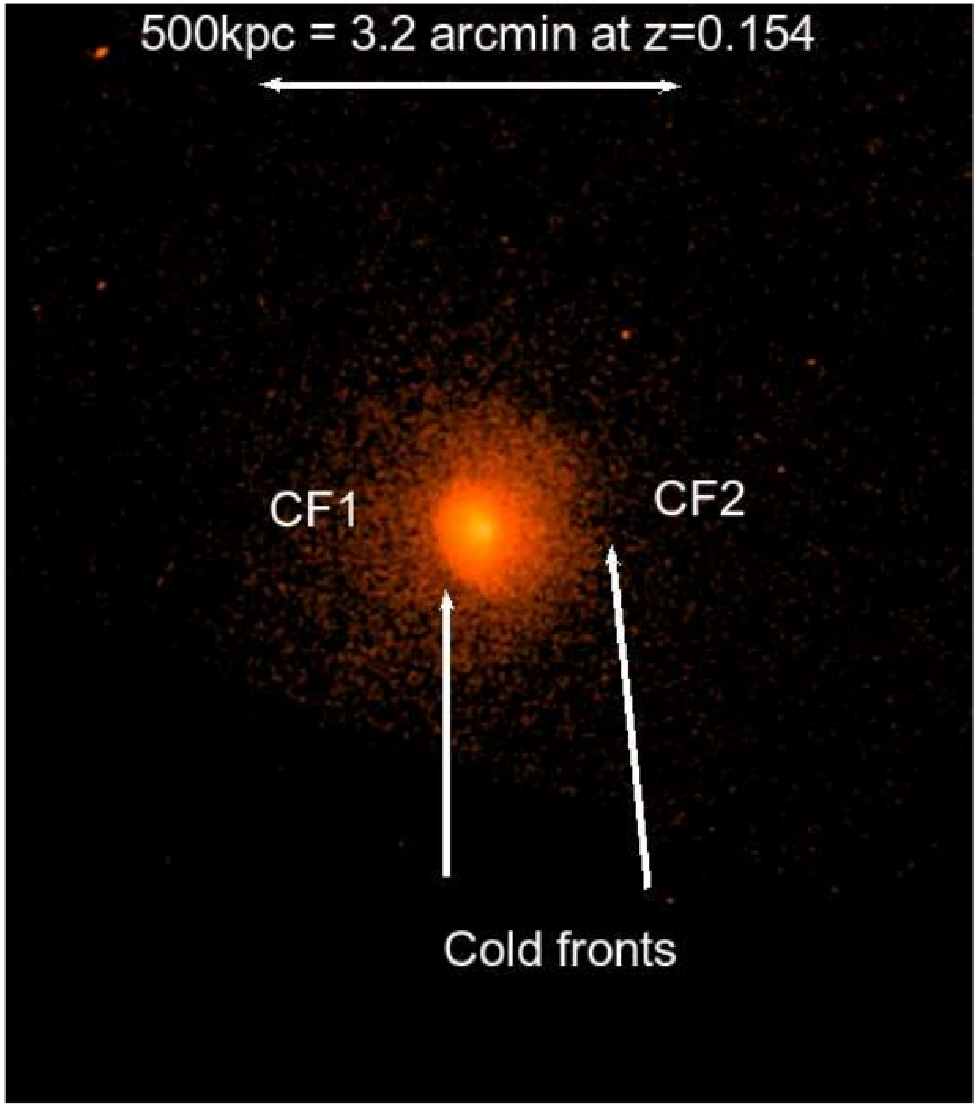




Walker et al. 2014a

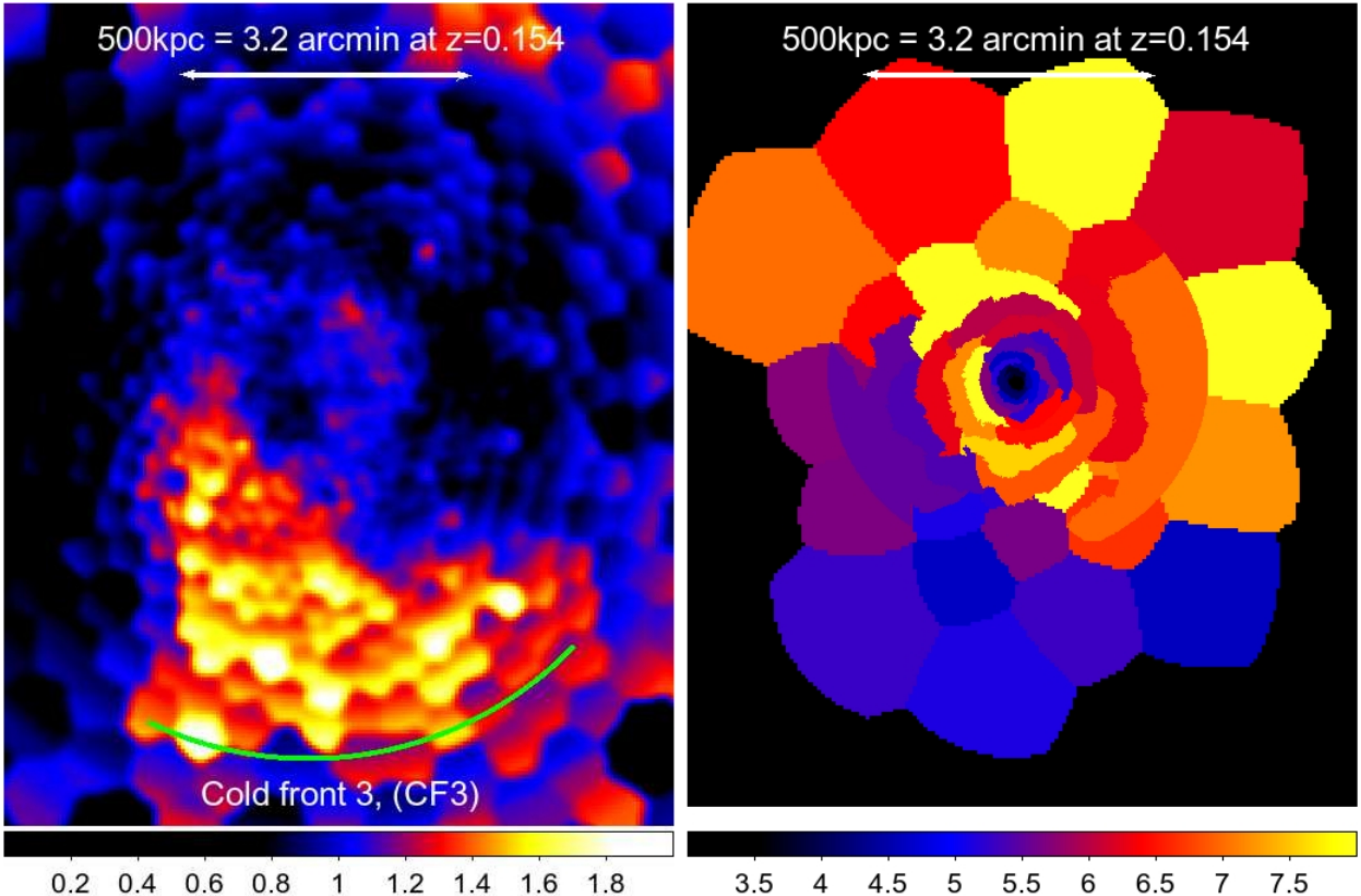
RXJ 2014.8-2430





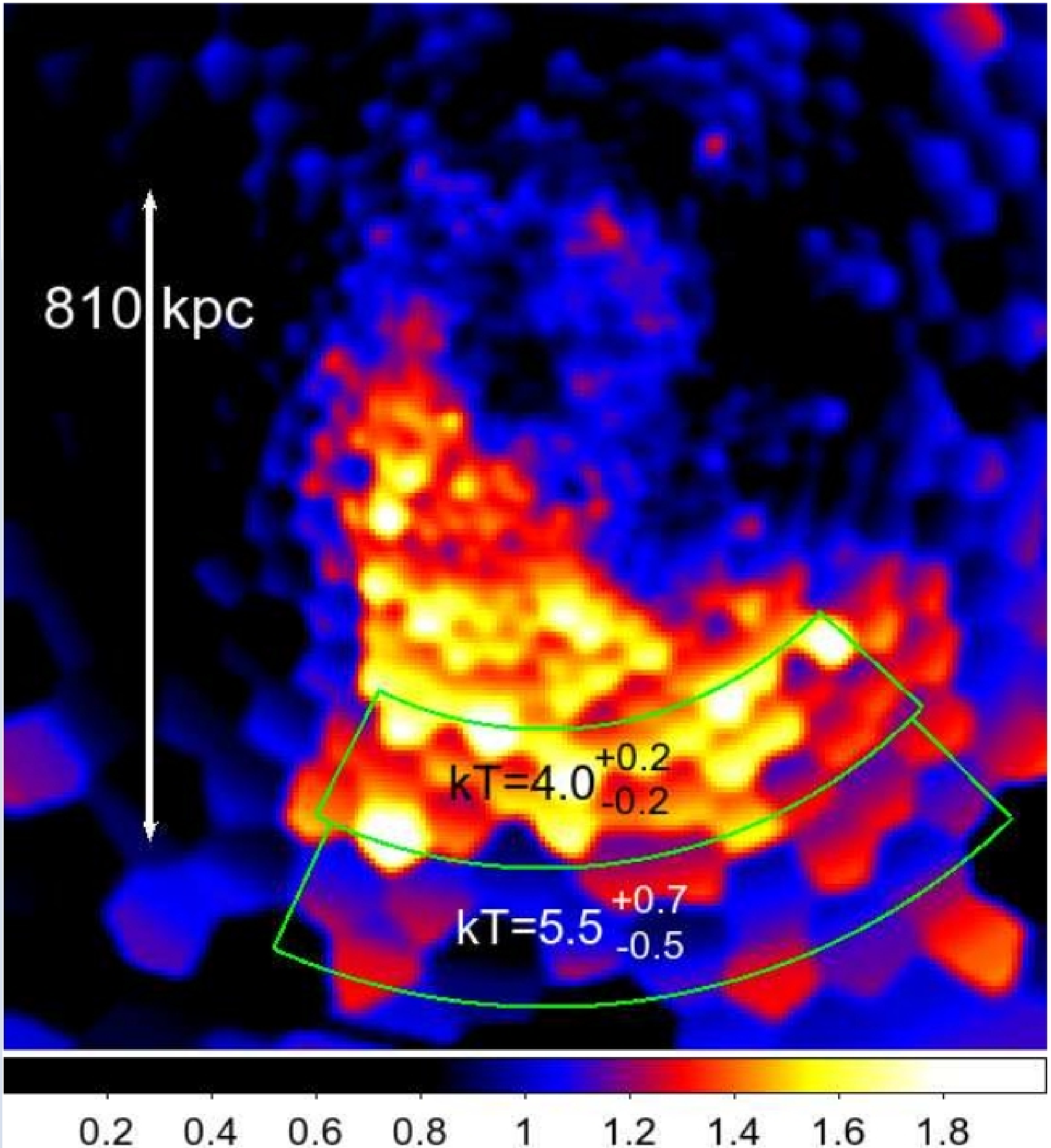
Walker et al. 2014a

RXJ 2014.8-2430

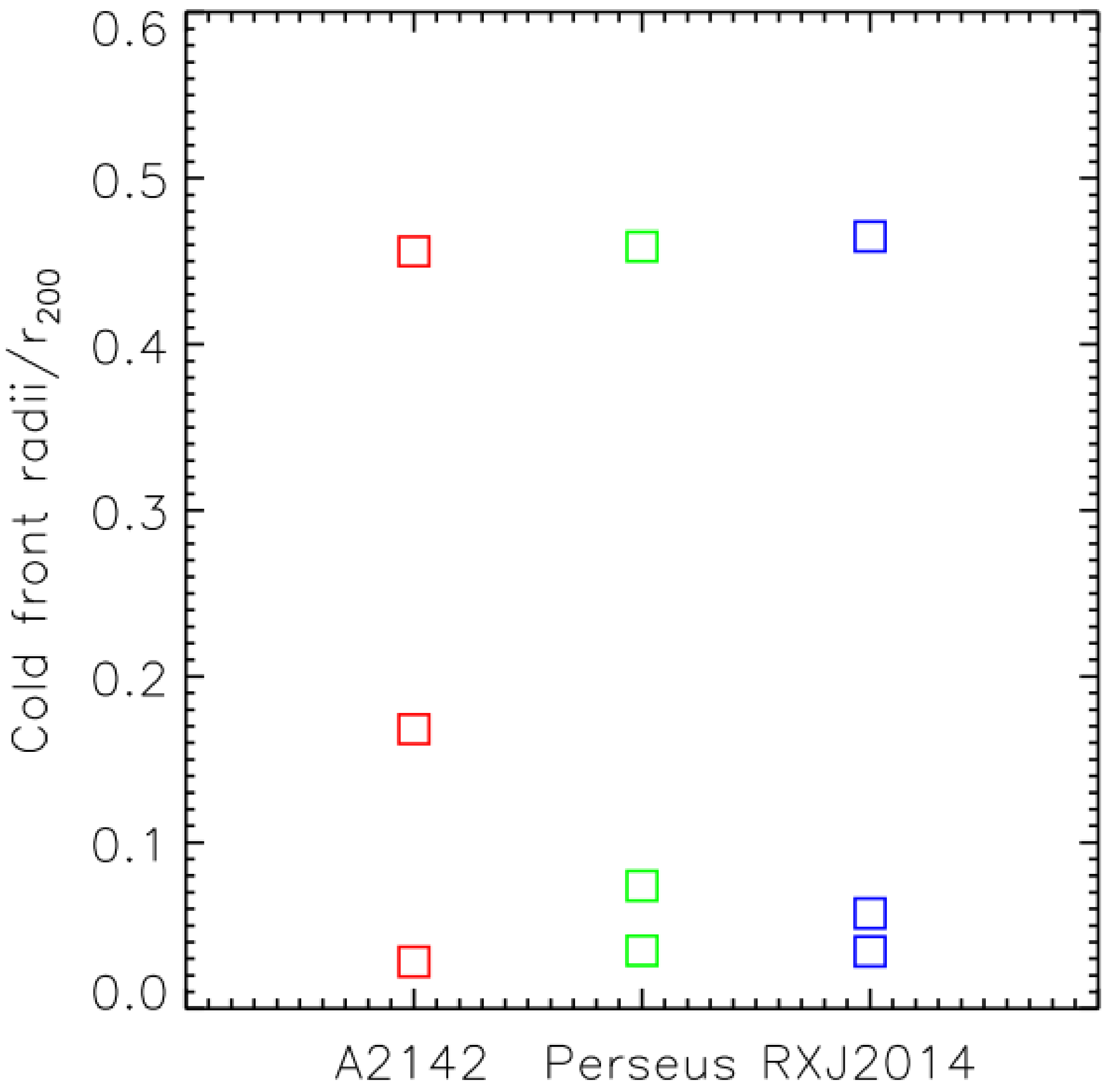


Walker et al. 2014a

RXJ 2014.8-2430



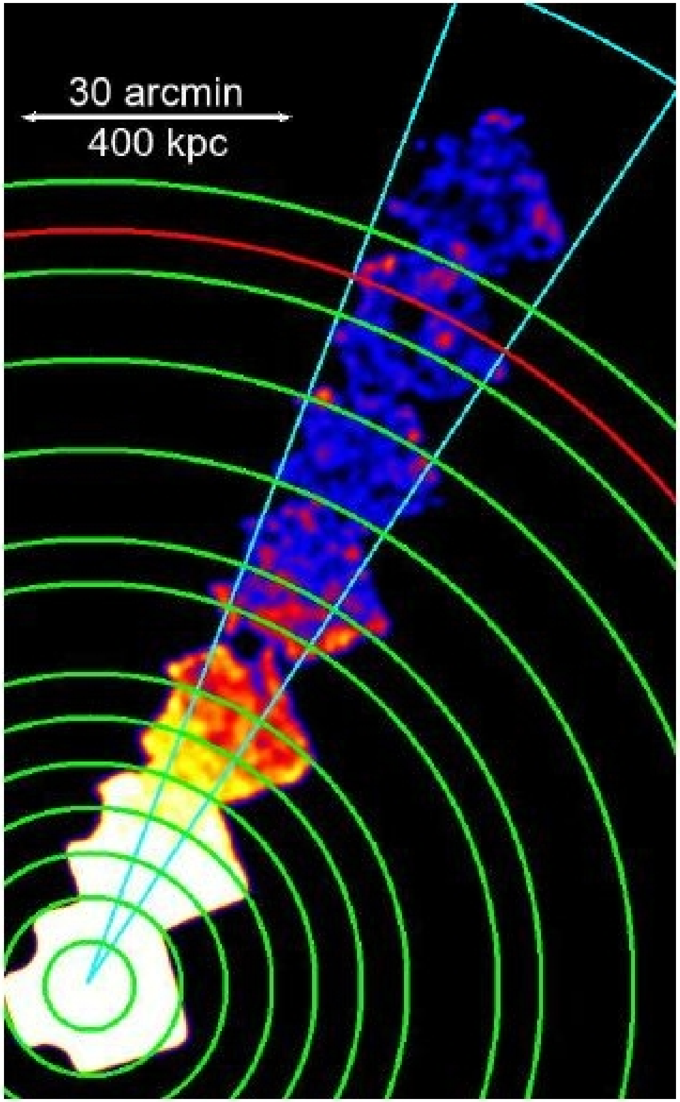
Walker et al. 2014a

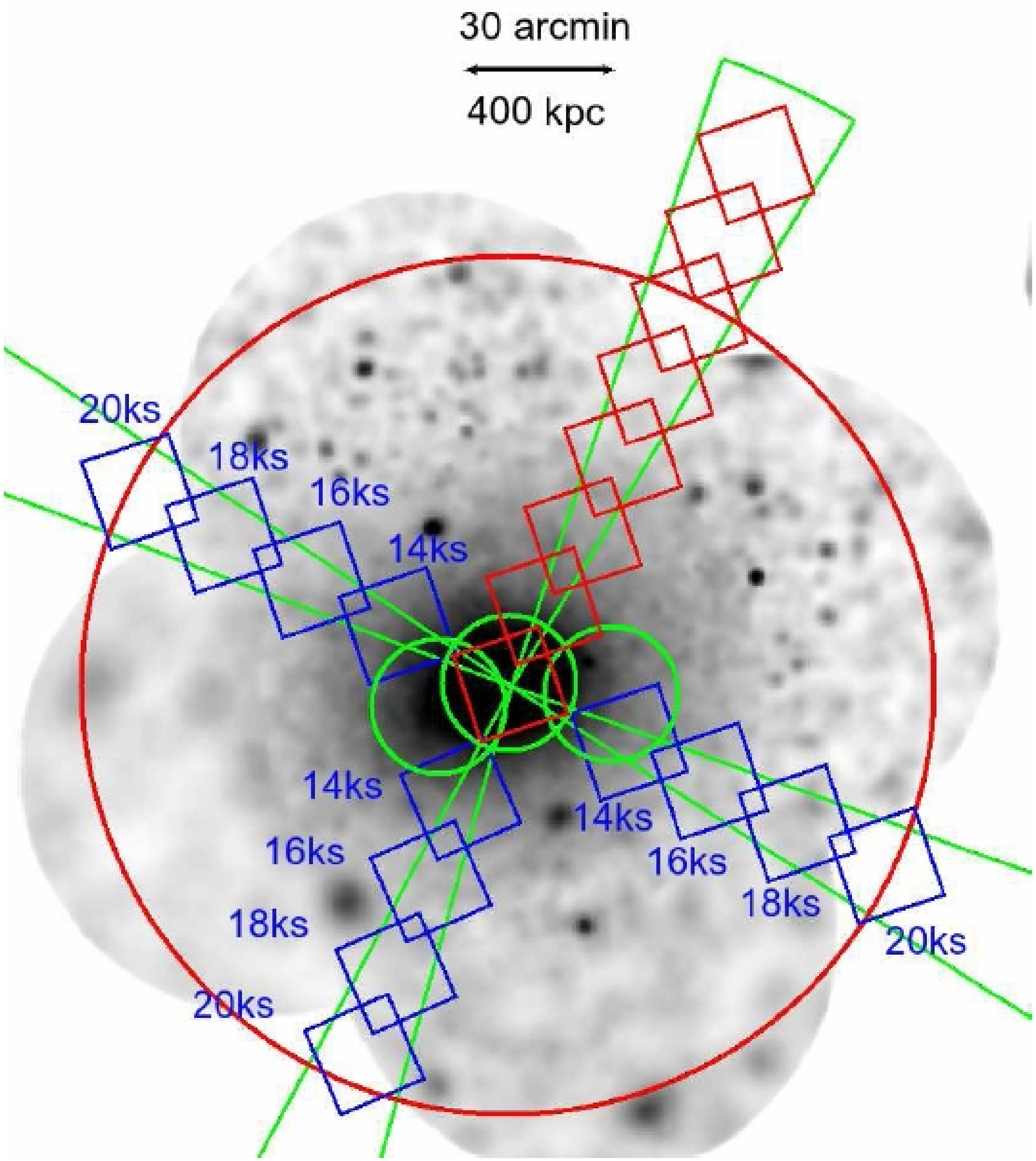


Walker et al. 2014a

Accepted Suzaku Proposals

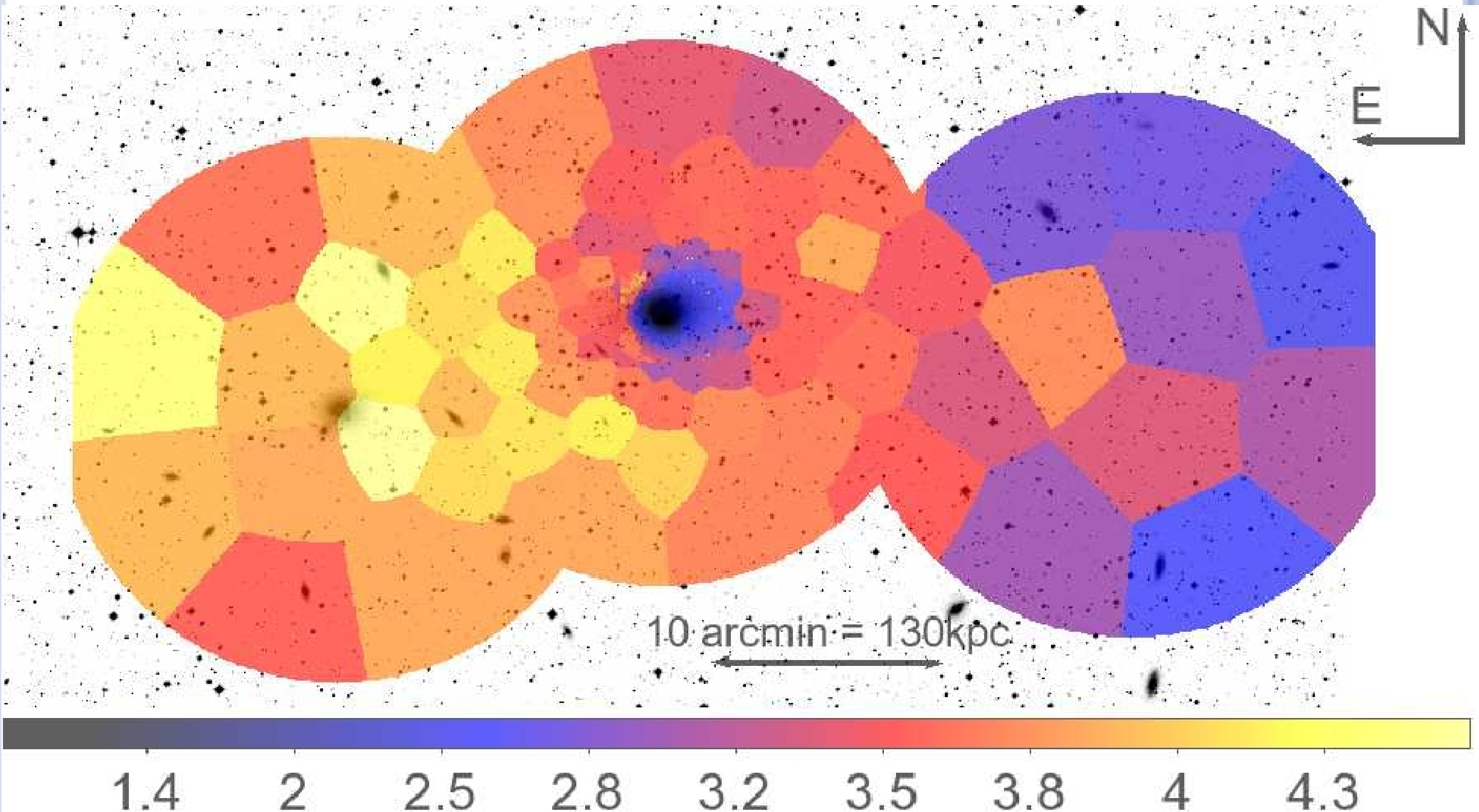
Centaurus cluster





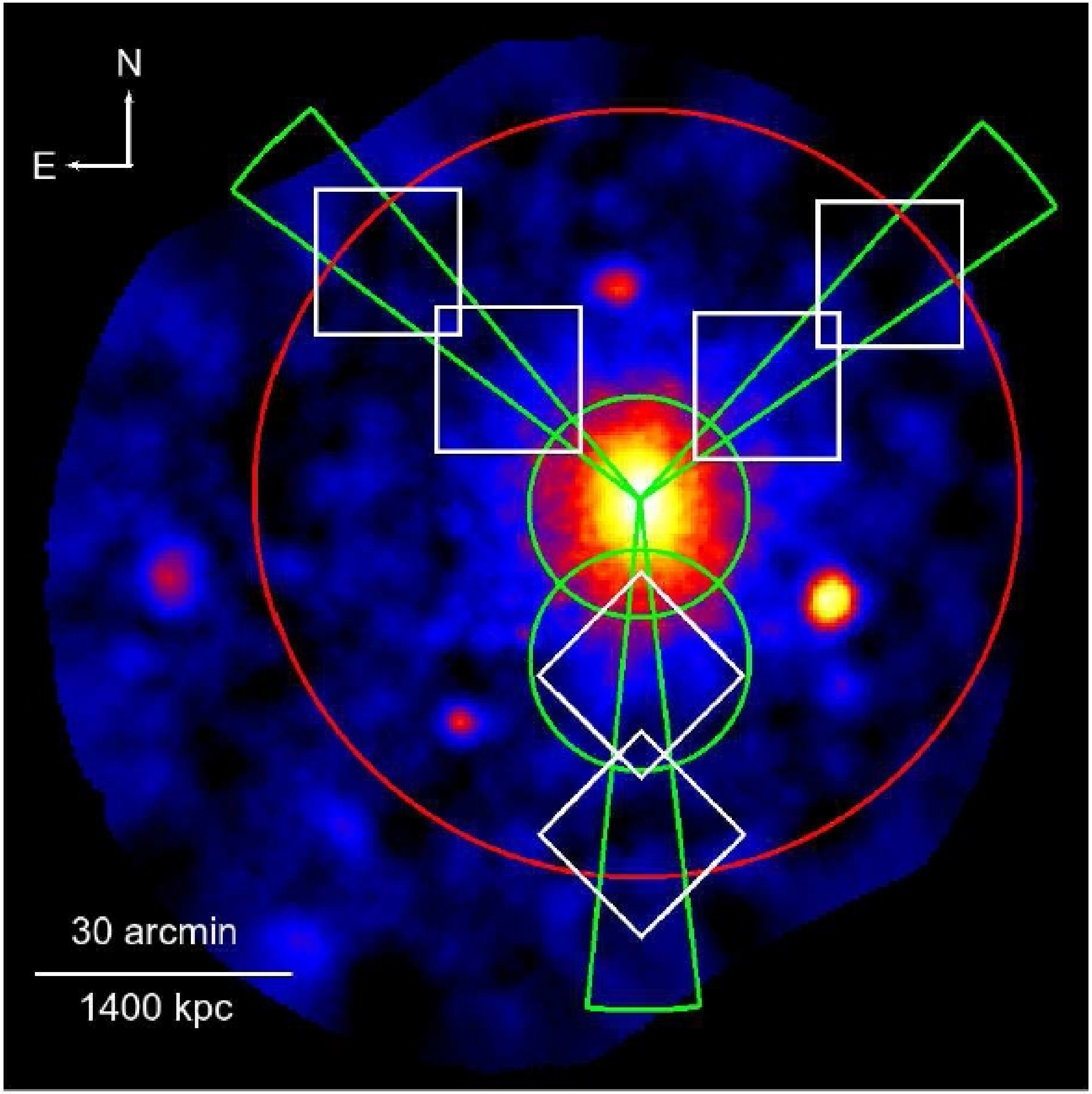
Walker et al. 2013a

Temperature map



Walker et al. 2013b

A3571



Summary

- Suzaku's low background provides unique observations of cluster outskirts.
- Can easily measure T at r_{200}
- Provides insights to process in the ICM around r_{200}
- Clumping can qualitatively explain the observations.


Thank you