Suzaku Observations of Clusters

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Other Related Summary Talks

Groups of Galaxies – Loewenstein

Search for Missing Baryons (WHIM) - Ohashi

Hard X-ray Emission from Clusters – Fukazawa

Anything Left?

Observations to the Virial Radius

Bulk Motions

Possible Future Cluster Program

Element Abundances in $kT \geq 3$ keV Clusters

Observations to the Virial Radius

The virial radius (r_{180}) is the "edge" of a cluster.

Chandra and XMM can measure temperatures to ~0.6 r_{180}.

- Thermodynamics of the cluster gas known in only ~20% of total cluster volume.

- Mass of relaxed clusters known only to ~0.6 r_{180}.

Low background of Suzaku enables temperature and mass measurements to r_{180}.

Cold Dark Matter paradigm + simulations make predictions for the mass structure of clusters.

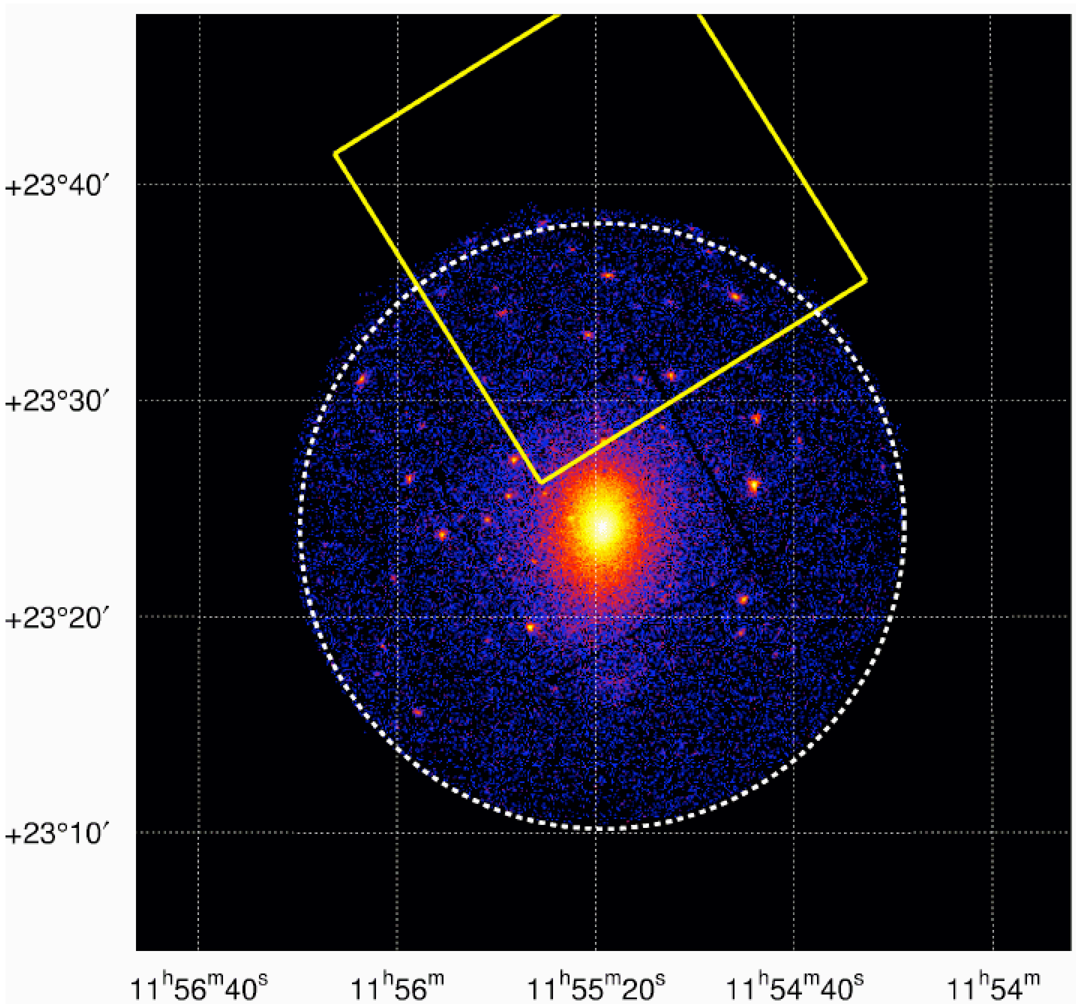
Universal total mass profile.

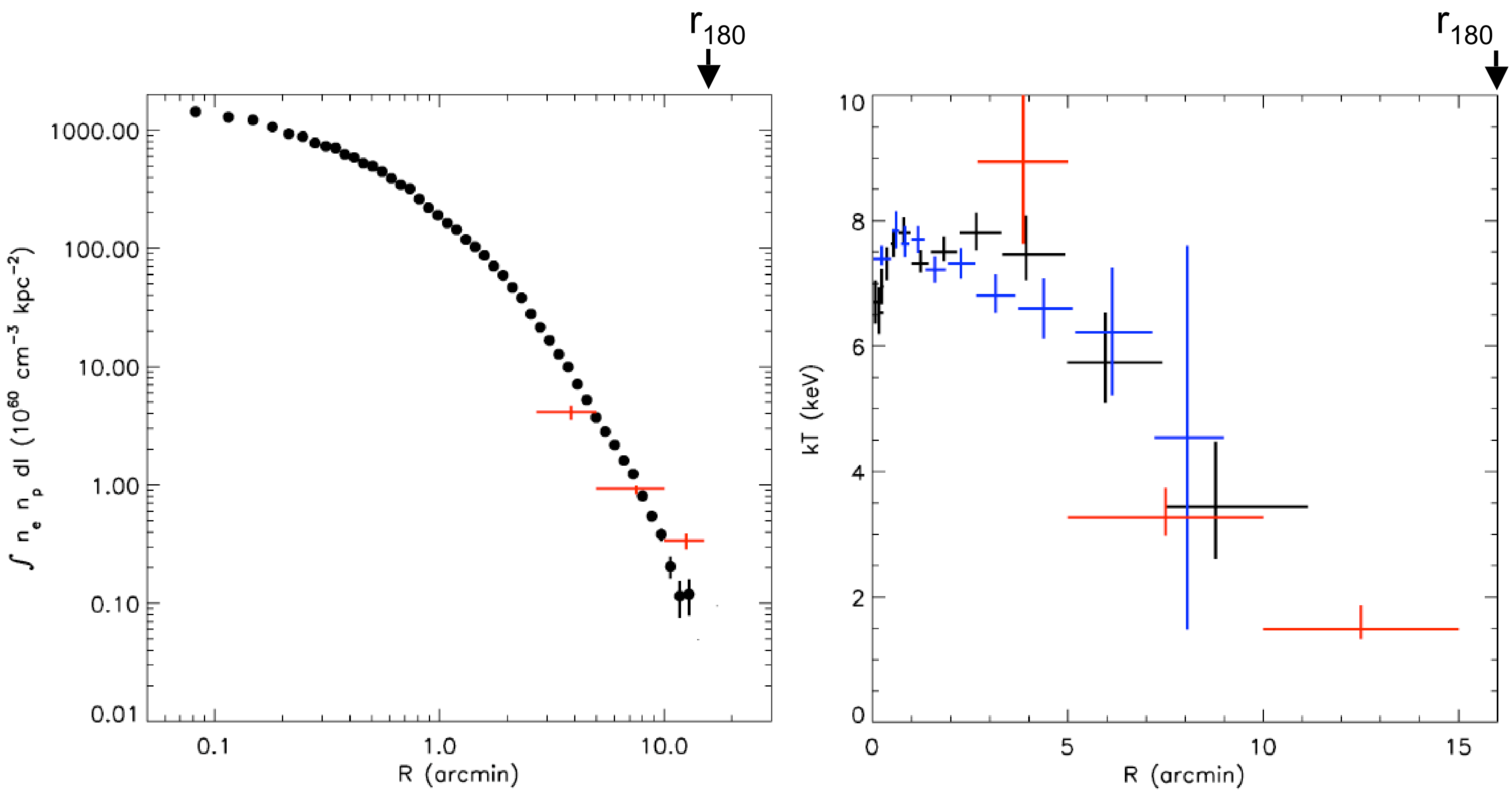
When scaled appropriately with r_{180} and z.

Goal is to measure gas temperature with high accuracy out to r_{180} in relaxed clusters so as to obtain the total mass profile from hydrostatic equilibrium.

Disagreement of these predictions with high-quality data indicates either break down of CDM calculations or hidden biases in the data.

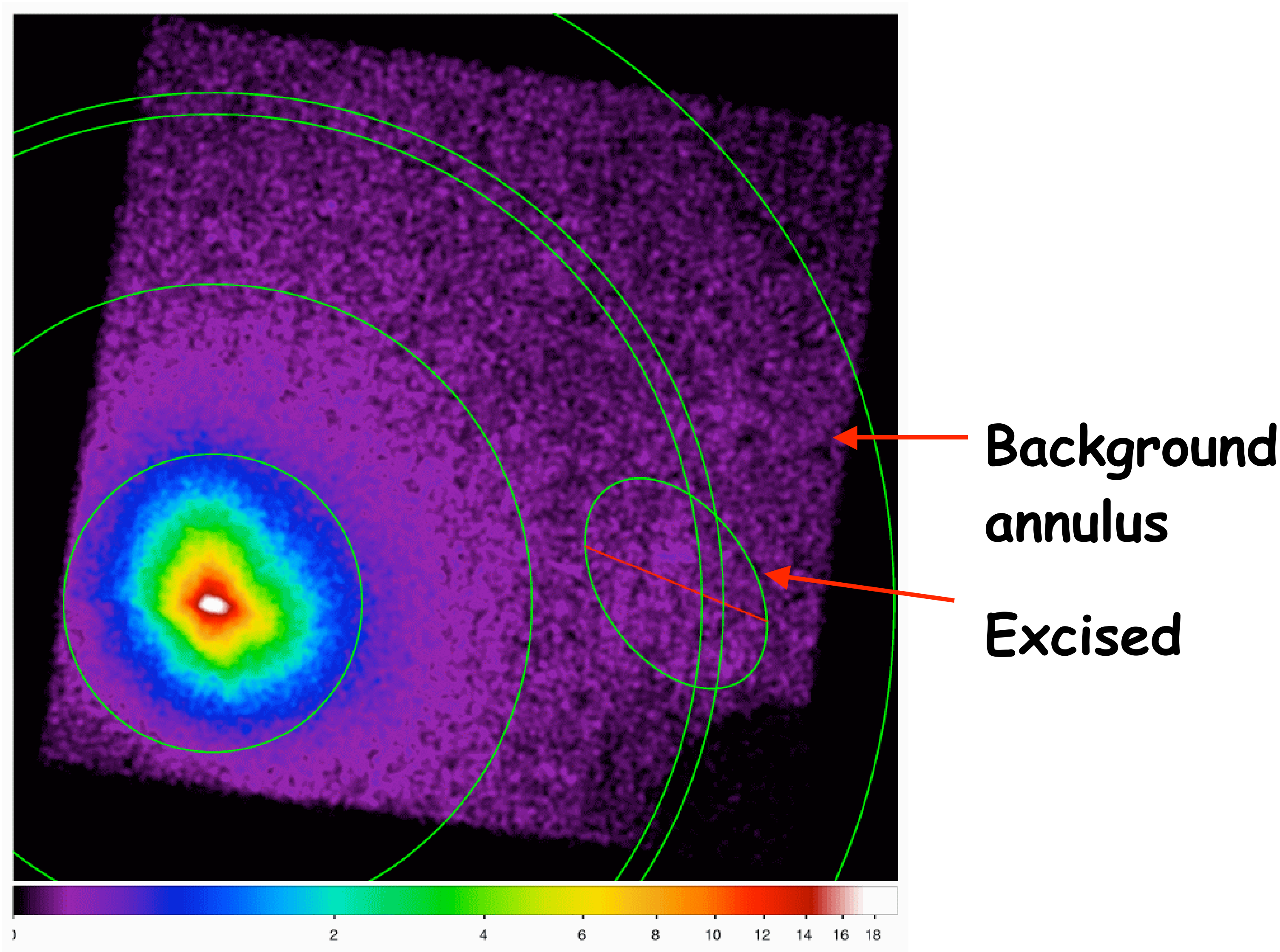
A1413 Hoshino et al. in preparation

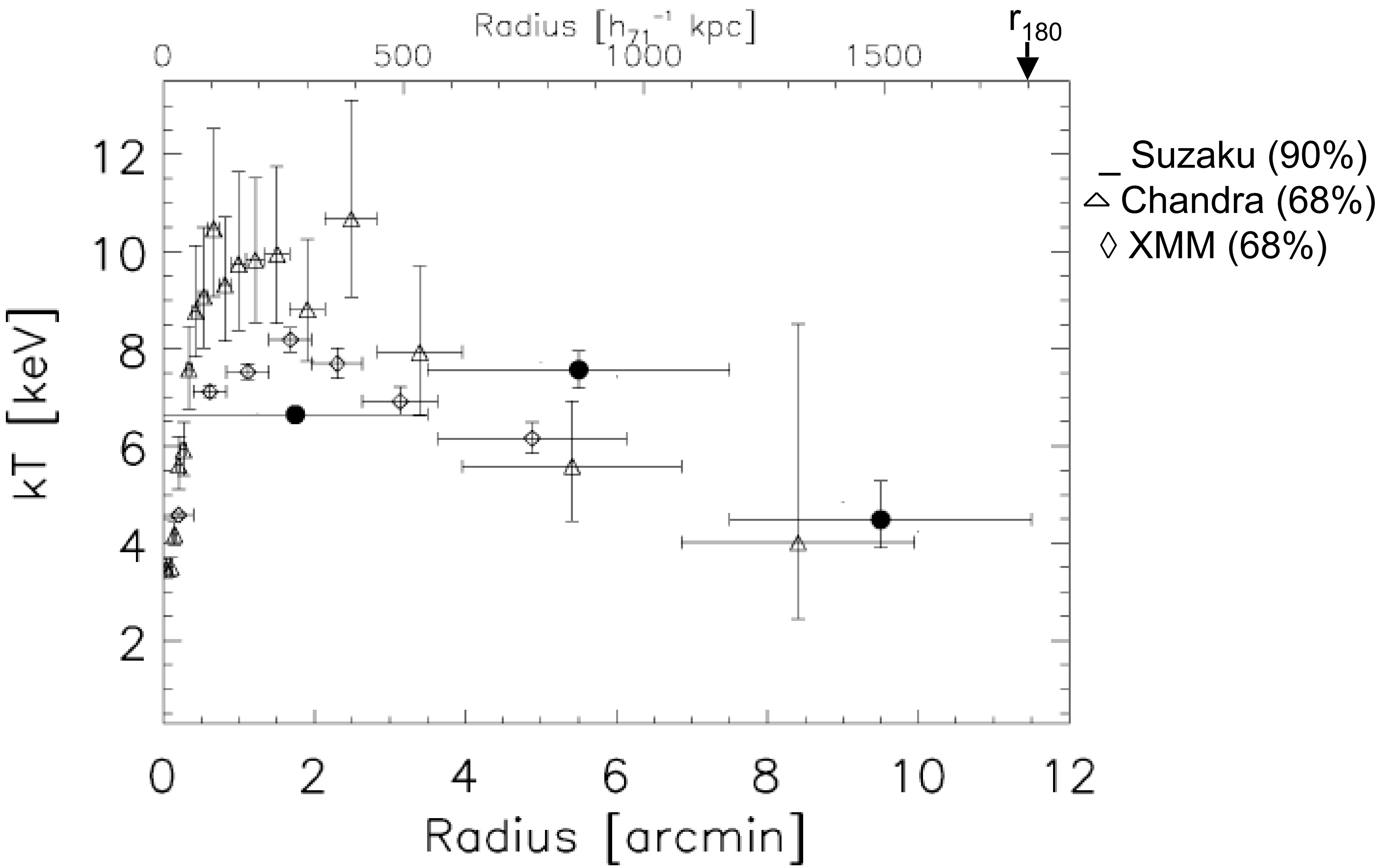




Suzaku **Chandra** **XMM** **68% errors**

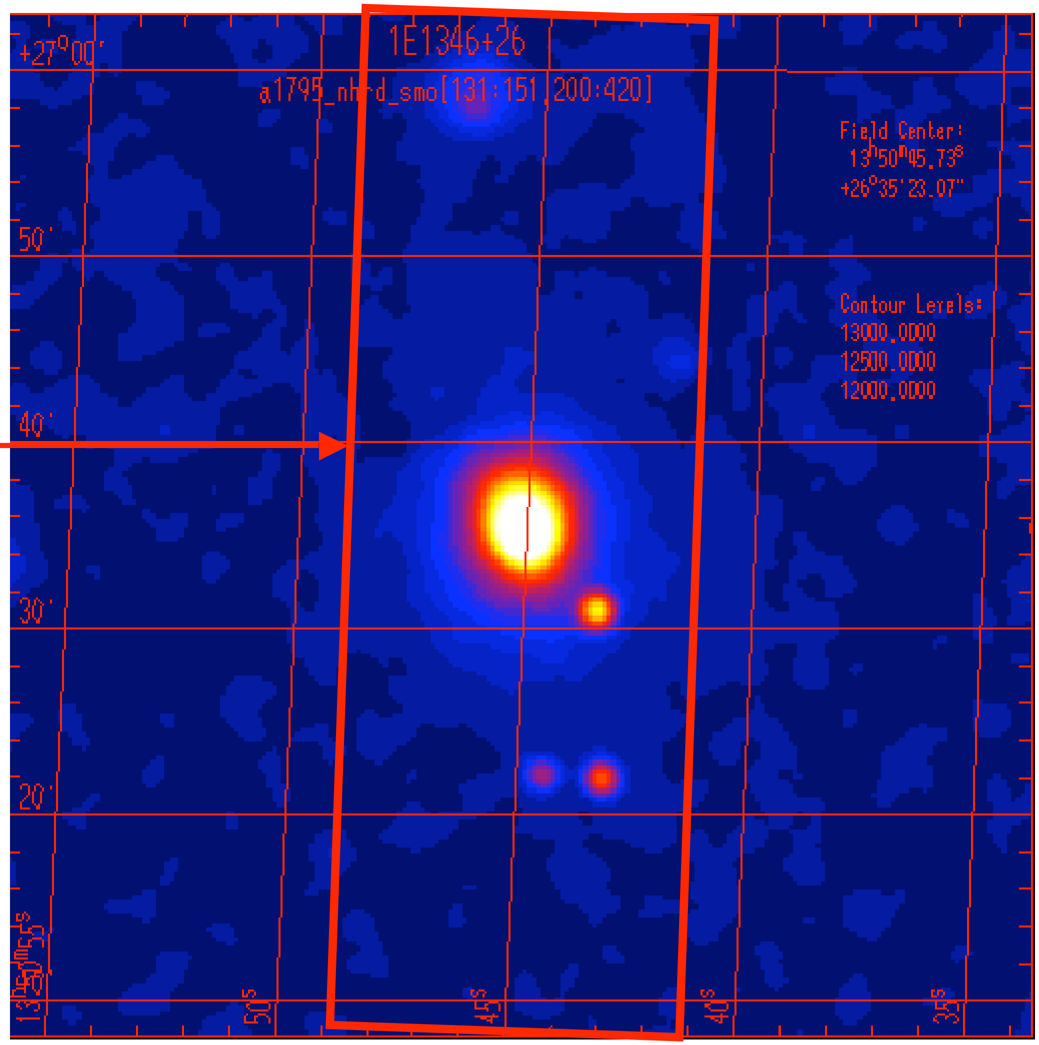
A2204 Reiprich et al. in preparation





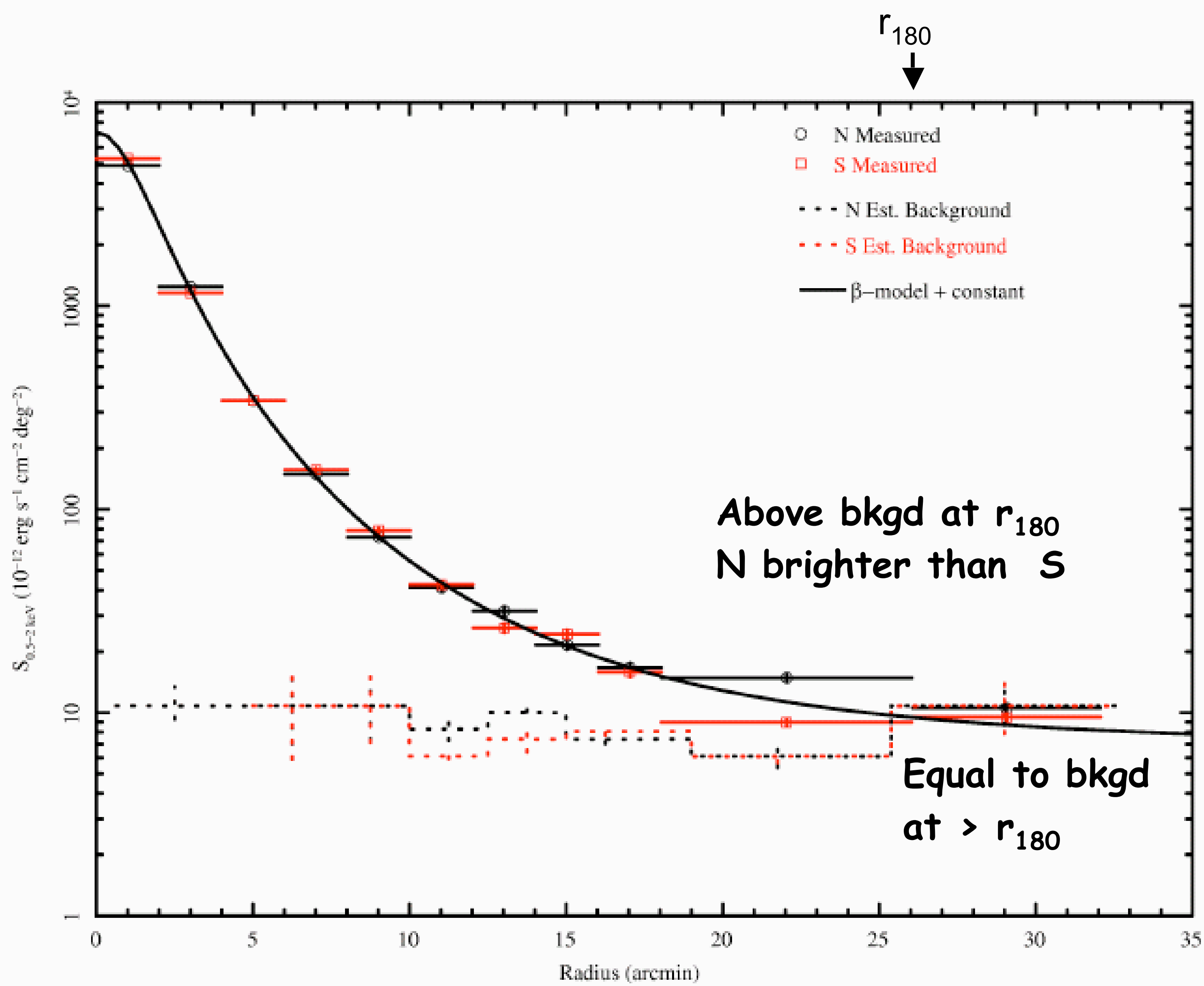
Radius [h_{71}^{-1} kpc]
0
500
1000
1500
r_{180}
12
10
8
6
4
2
kT [keV]
0
2
4
6
8
10
12
Radius [arcmin]
_ Suzaku (90%)
Chandra (68%)
XMM (68%)

A1795 Bautz et al. in preparation

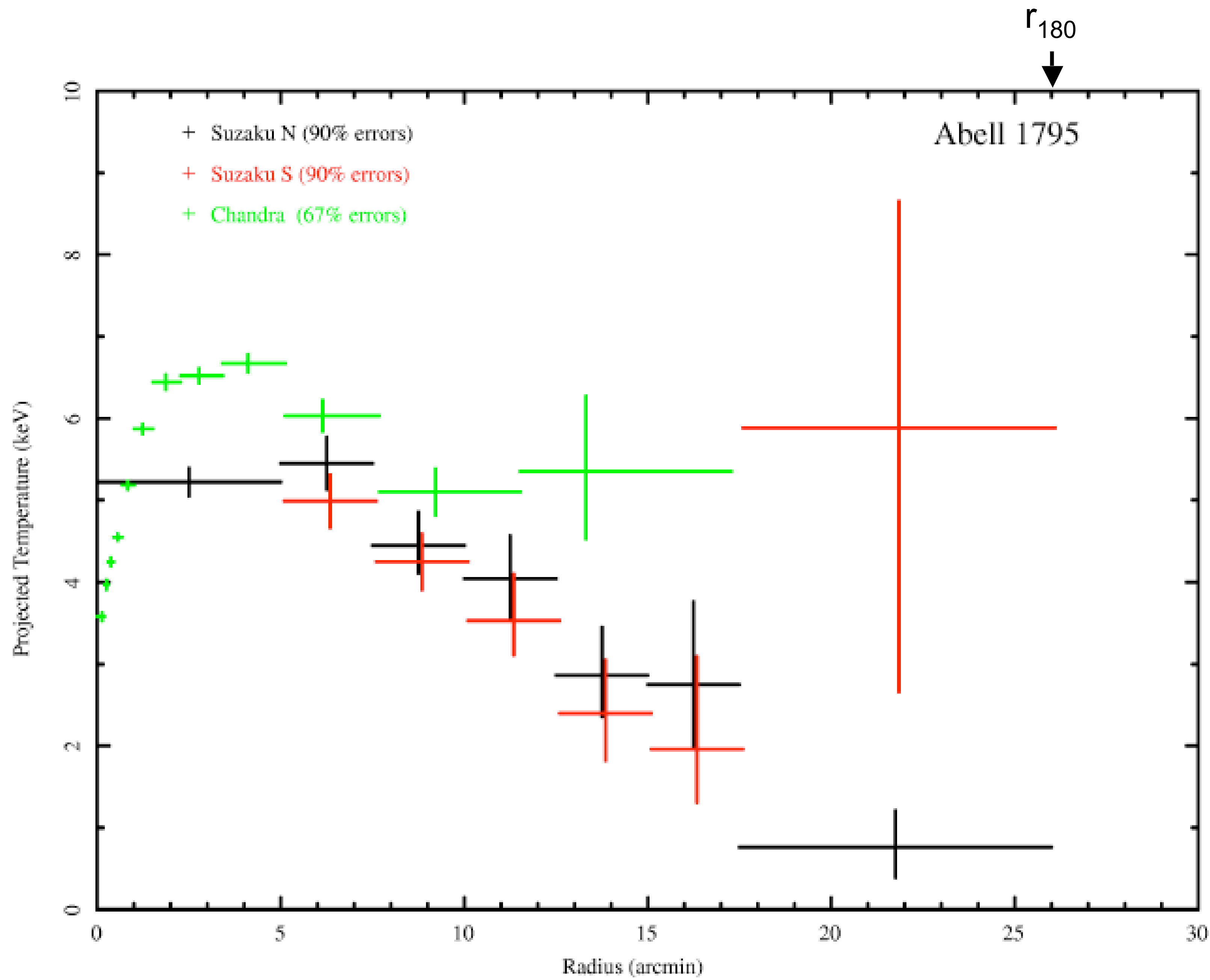


Multiple pointings on N-S axis

0.5 – 2.0 keV ROSAT PSPC image from Dan Davis



r180
N Measured
S Measured
N Est. Background
S Est. Background
β–model + constant
Above bkgd at r180
N brighter than S
Equal to bkgd
at > r180
Radius (arcmin)
S0.5-2 keV (10^-12 erg s^-1 cm^-2 deg^-2)



r_{180}
Abell 1795
Suzaku N (90% errors)
Suzaku S (90% errors)
Chandra (67% errors)
Projected Temperature (keV)
Radius (arcmin)
0
2
4
6
8
10
0
5
10
15
20
25
30

Observations to the Virial Radius: Summmary

Suzaku can detect clusters to r_{180}

Preliminary warnings from Kyoto 2006 removed

±10% changes in non X-ray background propagate to systematic kT errors < statistical

Scattered light not a big effect: ~50% @ 5_ from cool core A2204; 20% 4_ from non cool core A1413

Agreement with other data not perfect, but comparison hampered by different spatial coverage and spatial resolution

Bulk Motions

Virial motions of galaxies are ~1000 km s^{-1}

Hydrodynamic simulations indicate that gas motions can be 200 km s^{-1} in relaxed clusters and 1000 km s^{-1} in merging clusters

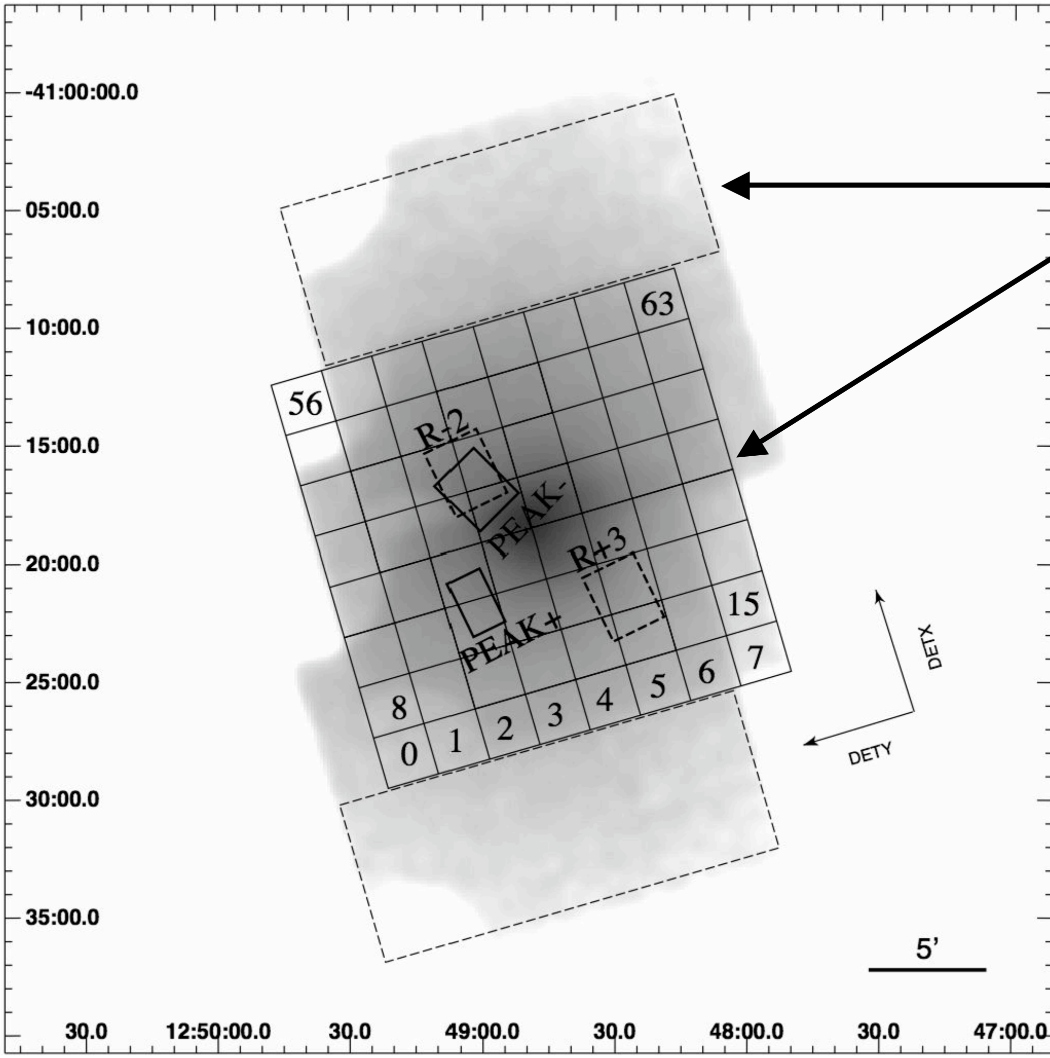
Some reports in literature that gas is moving at ~1000 km s^{-1}

Suzaku can measure the larger of these velocities: 1σ systematic energy error is 10 eV or ~450 km s^{-1}

Goal is to determine how much gas pressure support is provided by bulk vs. random motions

X-ray mass measurements are wrong to the extent

Centaurus Cluster Ota et al. PASJ 59, S351, 2007



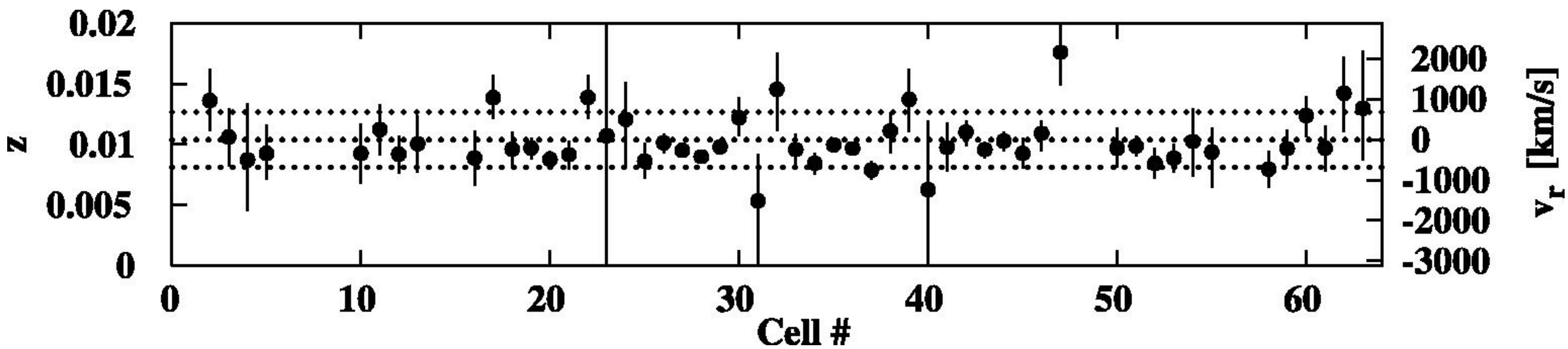
Δv < 1400 km s^{-1} (90% confidence) on scales of 135 h_{70}^{-1} kpc

Does not confirm Chandra

Region	Suzaku/XIS	Chandra/ACIS
	Δv (km s^{-1}) *	Δv (km s^{-1}) †
PEAK−, PEAK+	-660 ± 390 (± 660)	2900 ± 700
R−2, R+3	-540 ± 360 (± 660)	2400 ± 1000

*The velocity difference derived from the XIS spectra. The 68% statistical errors and (the 68% systematic errors) are quoted.
†The velocity difference and the 1 σ error derived from the Chandra ACIS spectra (Dupke, Bregman 2006).

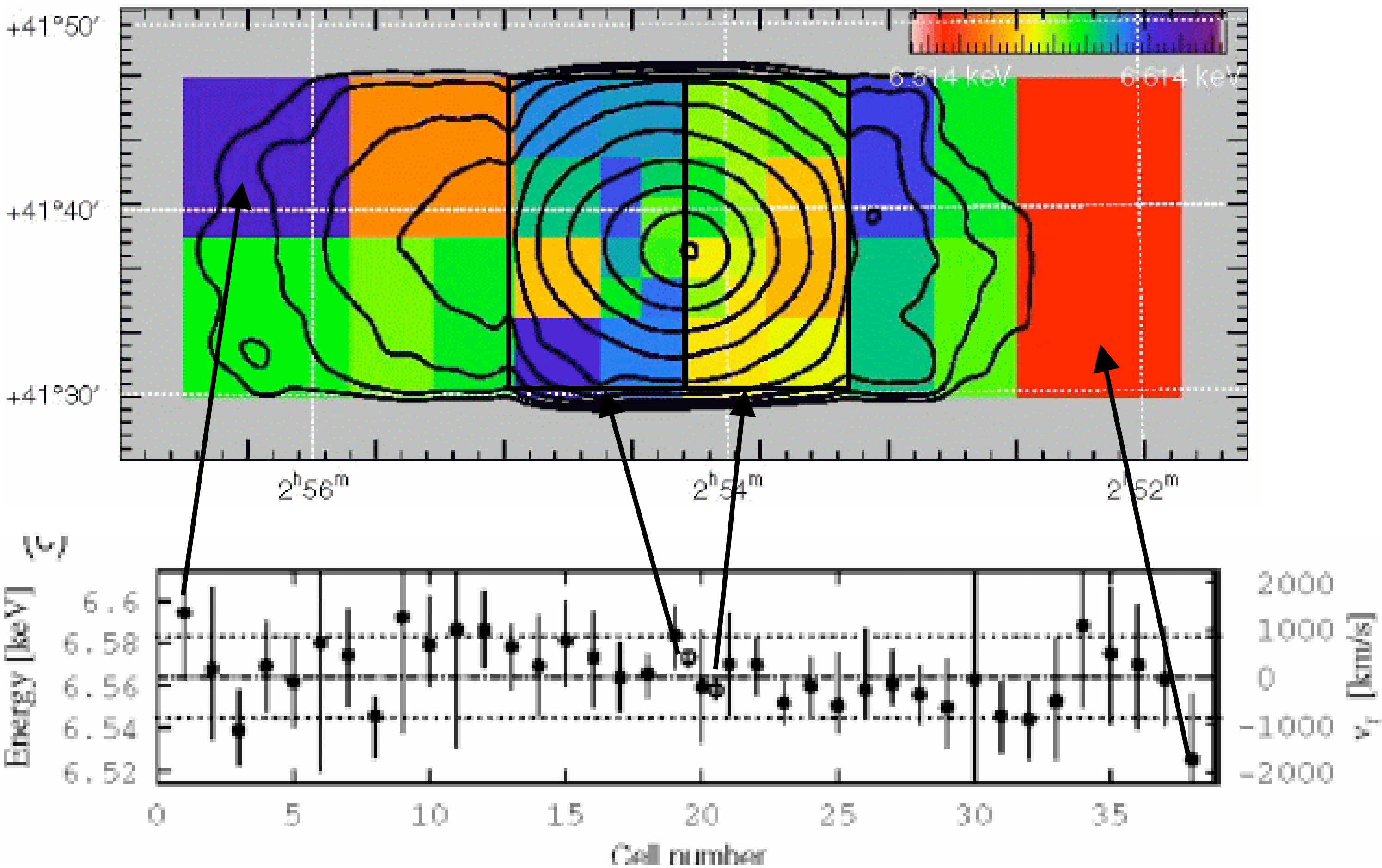
Centaurus Cluster Limit on Small Scale Velocities



64 (28.4 h_{70}^{-1} kpc)^2 cells (1σ errors)

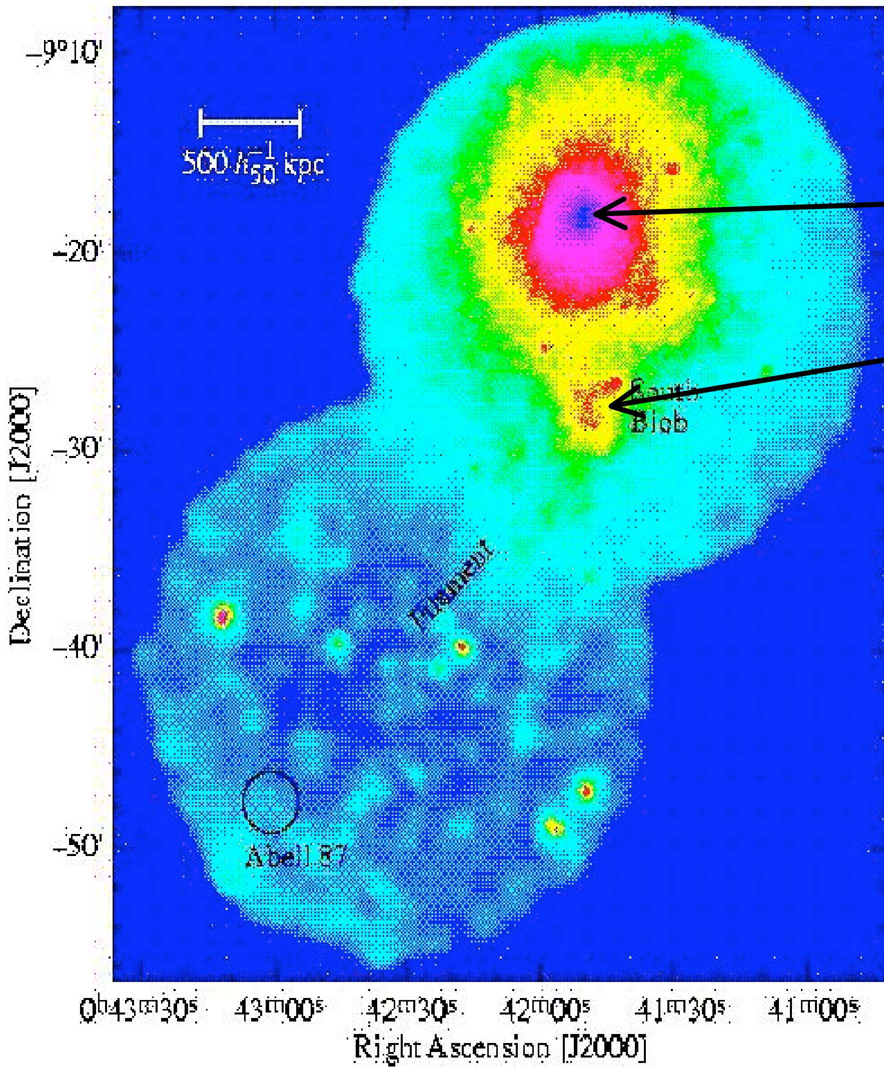
Velocity difference <720 km s^{-1} (90% confidence)

AWM 7 Cluster Sato et al. 0707.4342



4σ significant, but systematics yield Δv < 2000 km s^{-1} (90% confidence) on scales of 200 h_{70}^{-1} kpc

A85 Tanaka et al. in preparation



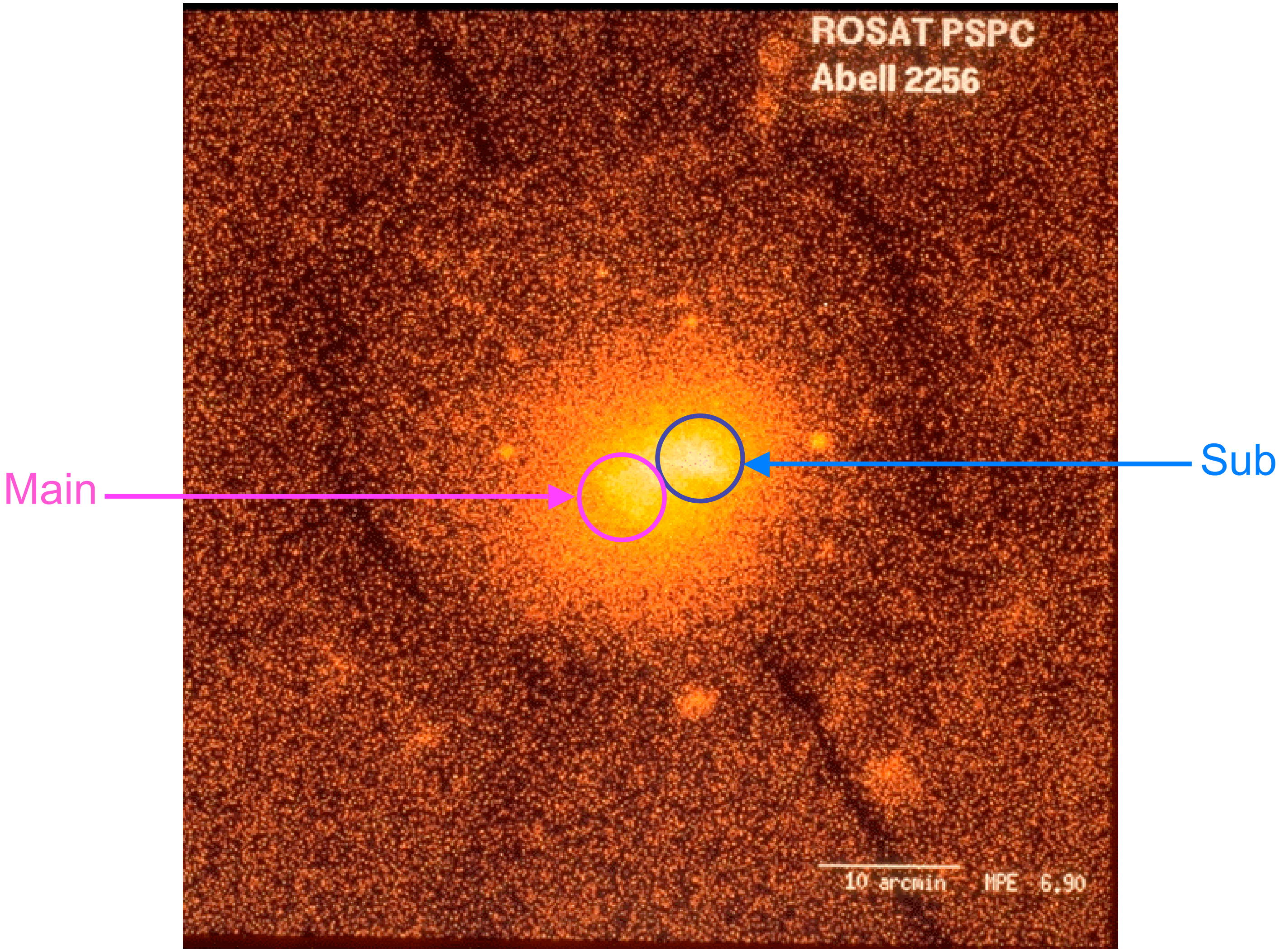
Main

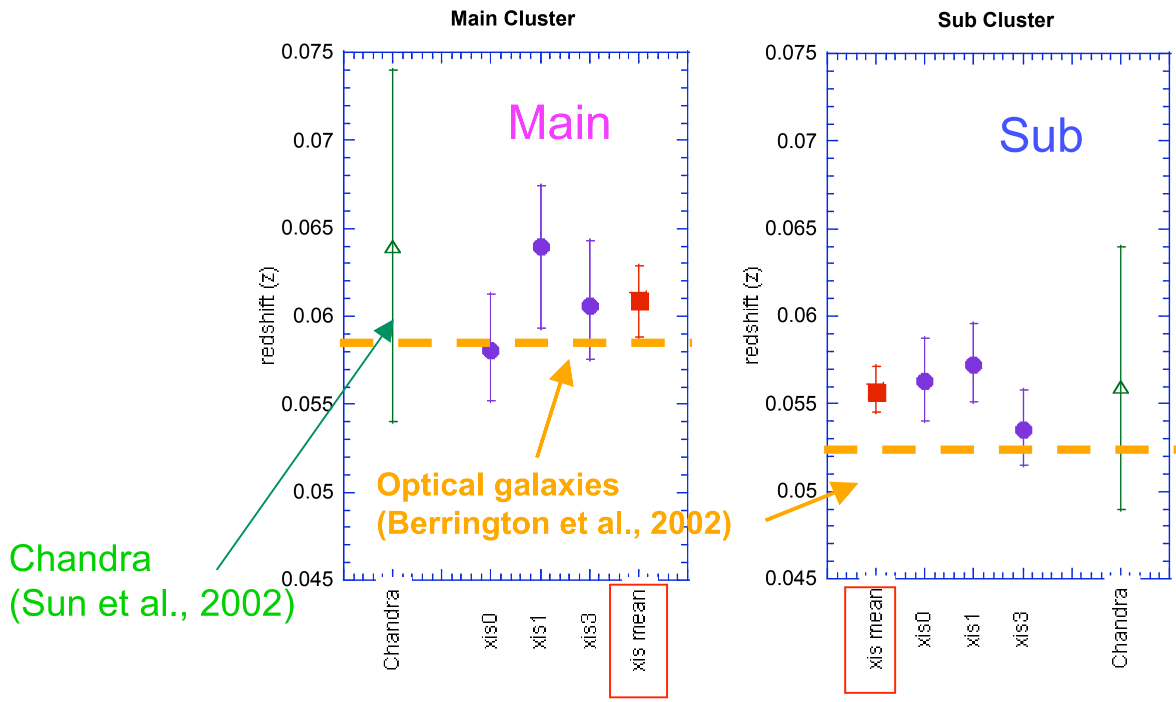
Sub

XMM Image from F. Durret

Sub - Main 2.1σ significant, but systematics yield Δv < 2700 km s^{-1} (90% confidence) on scales of 700 h_{70}^{-1} kpc

A2256 Hayashida et al. in preparation





90% errors

Velocity Difference = 1590^{+700}_{-750} km s^{-1} (90% confidence)

Main-Sub 3.4σ significant, but systematics yield Δv < 2700 km s^{-1} (90% confidence) on scales of 250 h_{70}^{-1} kpc

Likely real X-ray detection since galaxies increase confidence

Bulk Motions: Summary

Velocity statistical uncertainity usually $<$ systematic uncertainity of energy scale over the face of the detector

With present calibration, only the very highest velocity bulk motions will be detectable

Example: A2256 galaxies have a non Gaussian velocity distribution. Decomposing into three Gaussians yields Δv = 1963 km s^{-1}

Possible (Very?) Large Cluster Cosmology Program

Goal is to answer "What is the dark energy?"
That means, what is its equation of state:
P = w _c^2. If dark energy is cosmological constant
then w =0. If it is a scalar field ϕ then

$$w = \frac{0.5\,\dot{\phi}^2 - V(\phi)}{0.5\,\dot{\phi}^2 + V(\phi)}$$

Program will measures the temperatures for the 500 brightest clusters from the ROSAT All-Sky Survey

Will derive the number density and spatial power spectrum: N(z) + P(k)

Need at least two things to use clusters for cosmology

Low scatter mass – X-ray observable relation whose form is understood

Temperature YES

Cluster population is regular in that observable
Regular means all look the same when use properly scaled quantities.

Temperature YES

Mass - Observable Relation

Observable	Scatter	Self Sim Shape?	Observable Cosmo Depend?
Richness	70%	?	N
Luminosity	40%	N	Y
Temp.	20%	Y	N
Gas mass	10%	N	Y
Y_x	10%	Y	Y

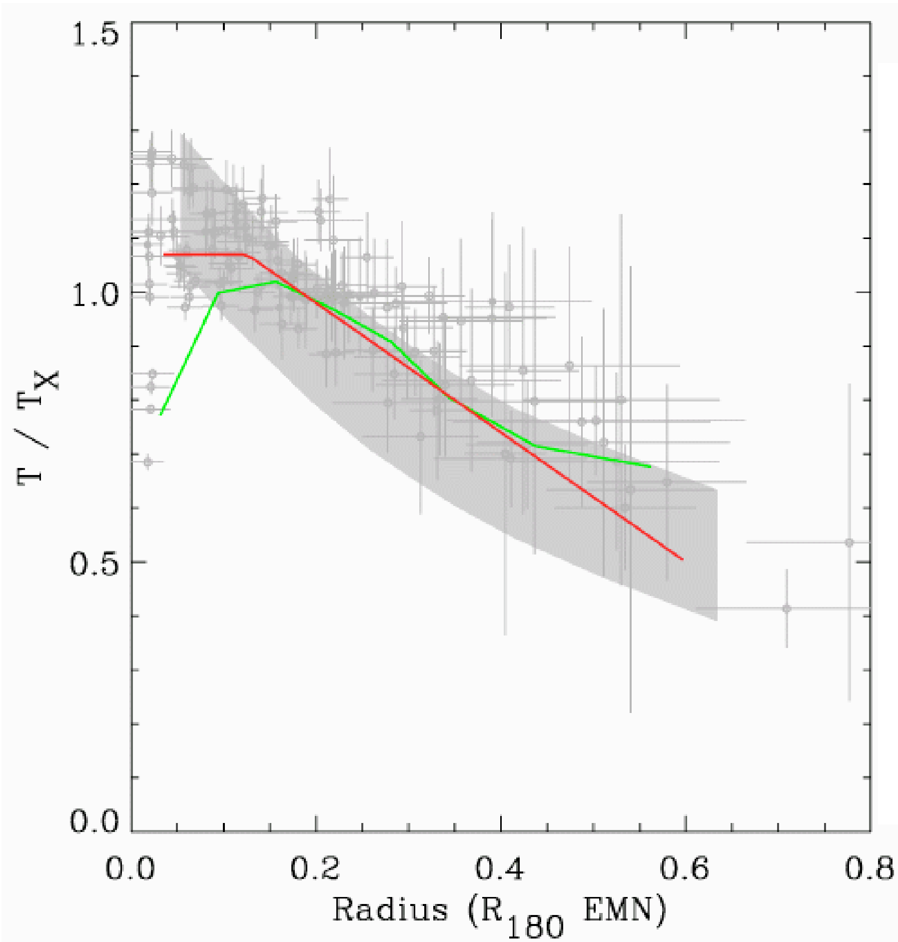
Choose Temperature

- Low scatter
- Self similar shape so simple physics
- Independent of cosmology

Suzaku can not measure Y_x due to spatial resolution

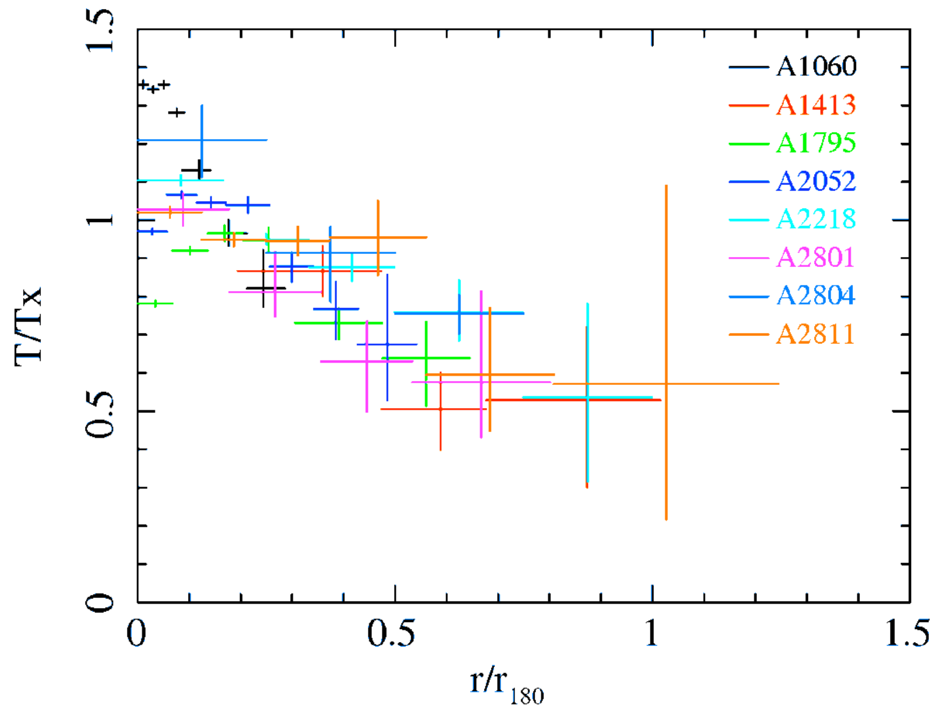
Temperature Profiles Very Regular

Pratt et al. 2007



Agreement among 4 missions

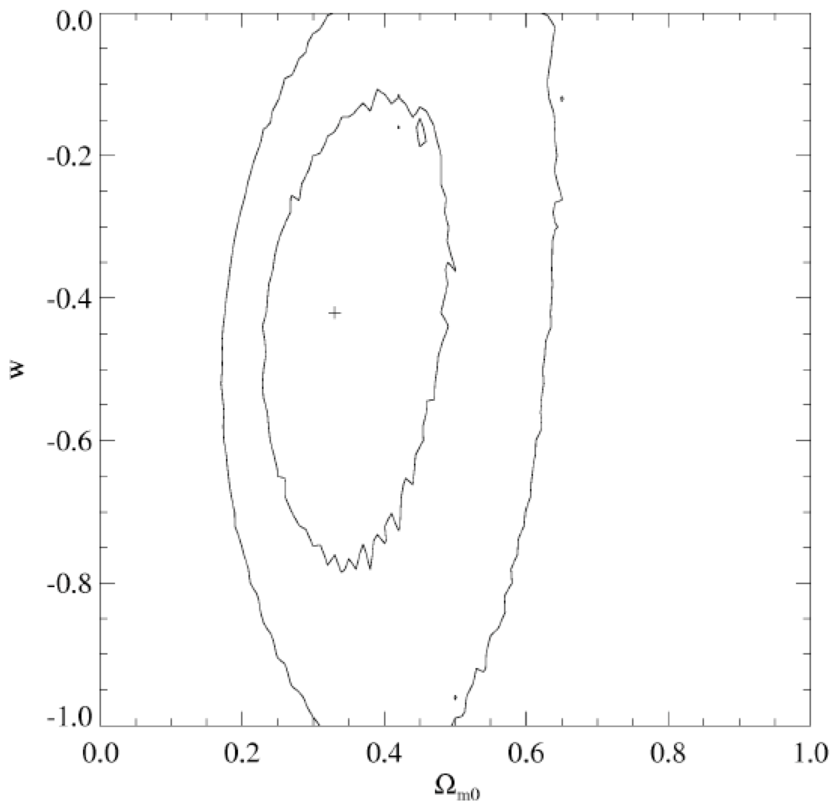
Tawa et al. in prep.

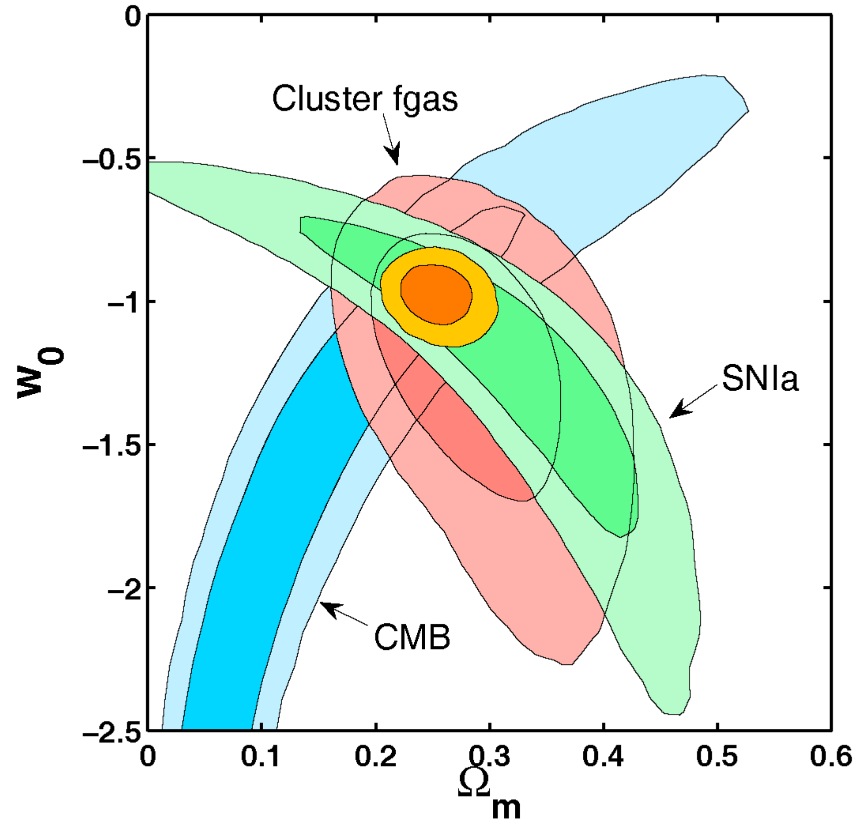


Agreement with Suzaku

Extend to larger radius

Some Current Cluster Constraints
(1σ, 2σ 2 parameters)

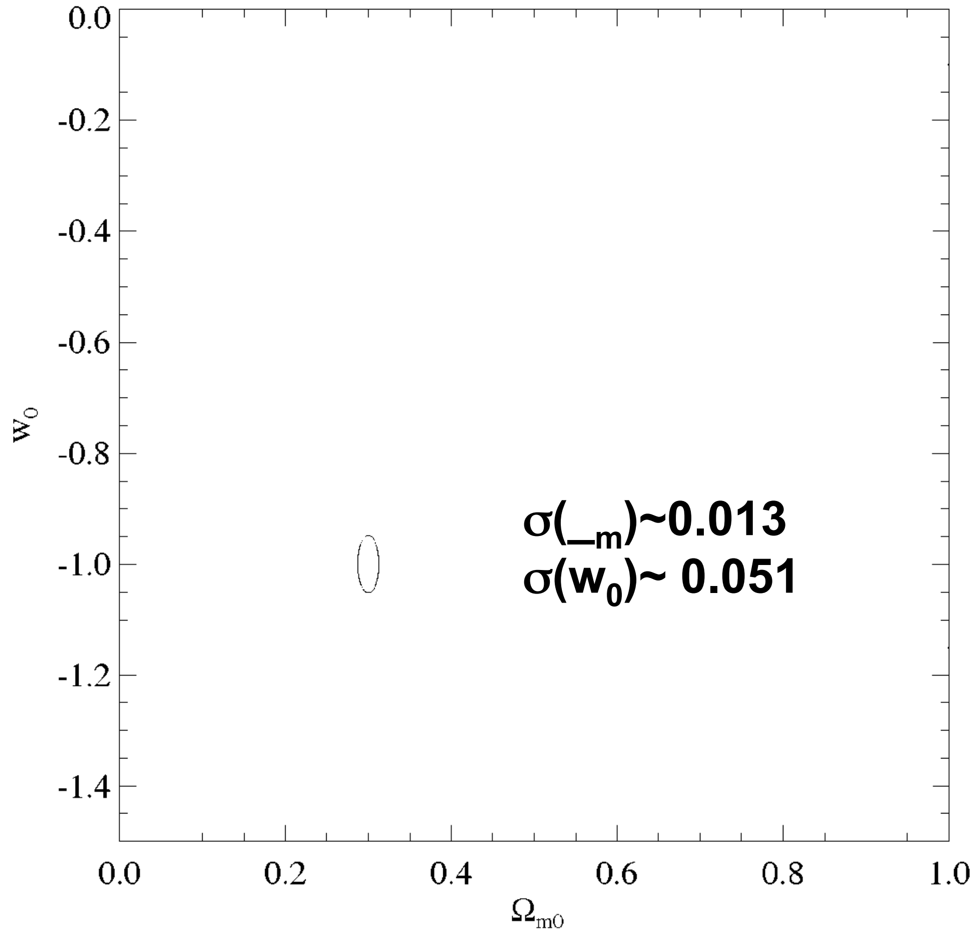




Henry ApJ 609, 603, 2004
43 kTs (N(z), no P(k))
σ(_m)~0.15 σ(w_0)~0.3

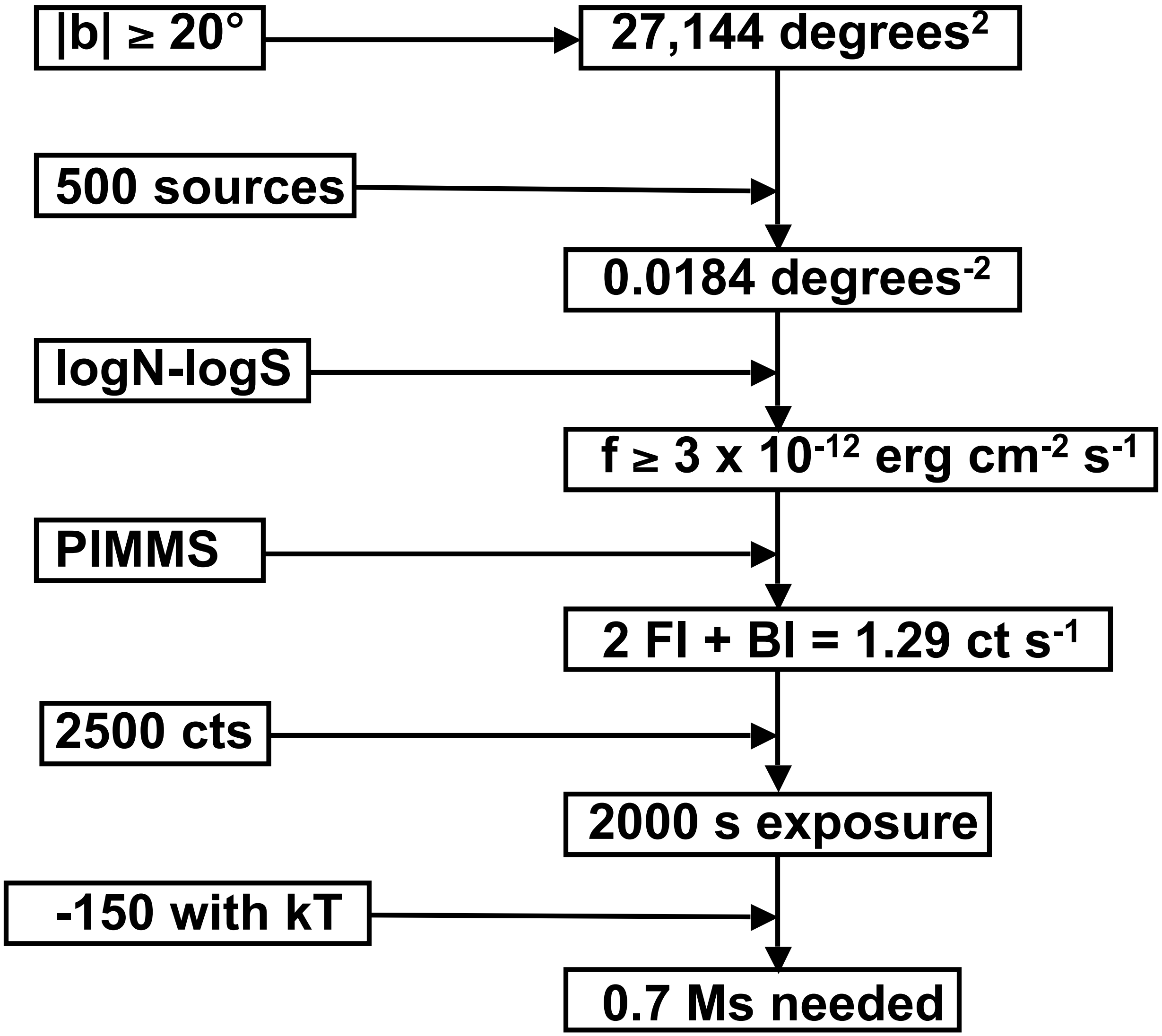
Allen et al., 0706.0033
42 gas fractions
σ(_m)~0.10 σ(w_0)~0.4

Projected Constraints (Back of Envelope!)

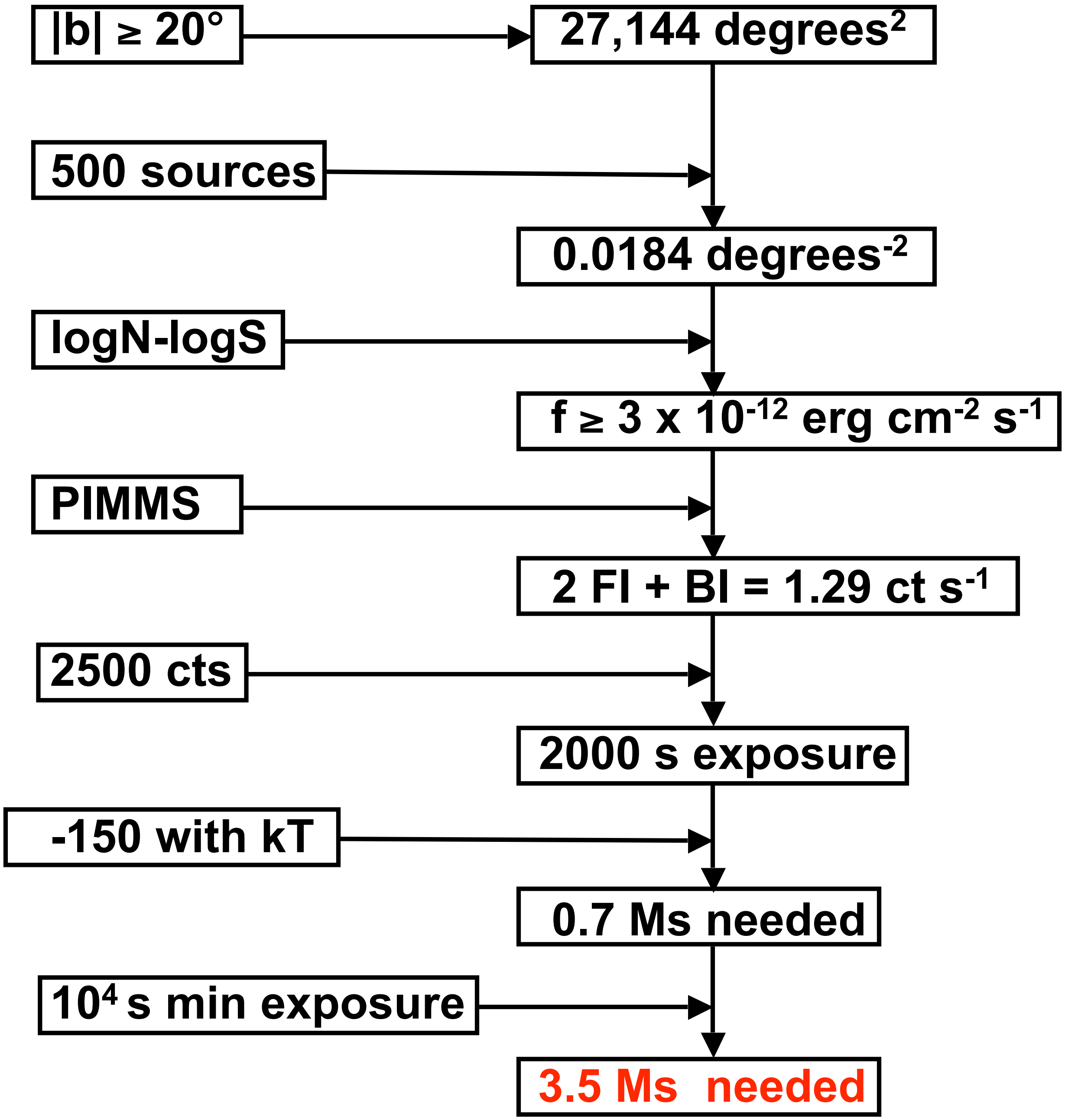


Scale Henry (2004) by square root of sample size

Scale from Majumbar & Mohr (2004) adding P(k) to N(z)



|b| ≥ 20°
27,144 degrees^2
500 sources
0.0184 degrees^{-2}
logN-logS
f ≥ 3 x 10^{-12} erg cm^{-2} s^{-1}
PIMMS
2 FI + BI = 1.29 ct s^{-1}
2500 cts
2000 s exposure
-150 with kT
0.7 Ms needed


|b| ≥ 20°
27,144 degrees^2
500 sources
0.0184 degrees^{-2}
logN-logS
f ≥ 3 x 10^{-12} erg cm^{-2} s^{-1}
PIMMS
2 FI + BI = 1.29 ct s^{-1}
2500 cts
2000 s exposure
-150 with kT
0.7 Ms needed
10^4 s min exposure
3.5 Ms needed

Possible Future Cluster Program: Summary

Substantially improve errors on existing cluster work.

Minimum exposure time requires 92 elapsed days!

Clusters separated by 7.5° on average.
Can that be used to improve efficiency?

Element Abundances in kT ≥ 3 keV Clusters

Origin of metals in cluster gas is a long-standing problem.

Clusters are so massive that they trap nearly all metals expelled from galaxies, thus providing a measure of

- Initial mass function
- Star formation rate
- Supernova rate of Ia vs II

Goal is to measure Fe vs _(O, Ne, Mg,…) abundances

Suzaku has good sensitivity to lines <1 keV from O

Sato et al. (ApJ 667, L41, 2007) analyze two clusters and two groups. Take A1060 as an example.

kT = 3.0 keV, $r_{180} = 1.53\ h_{70}^{-1}$ Mpc

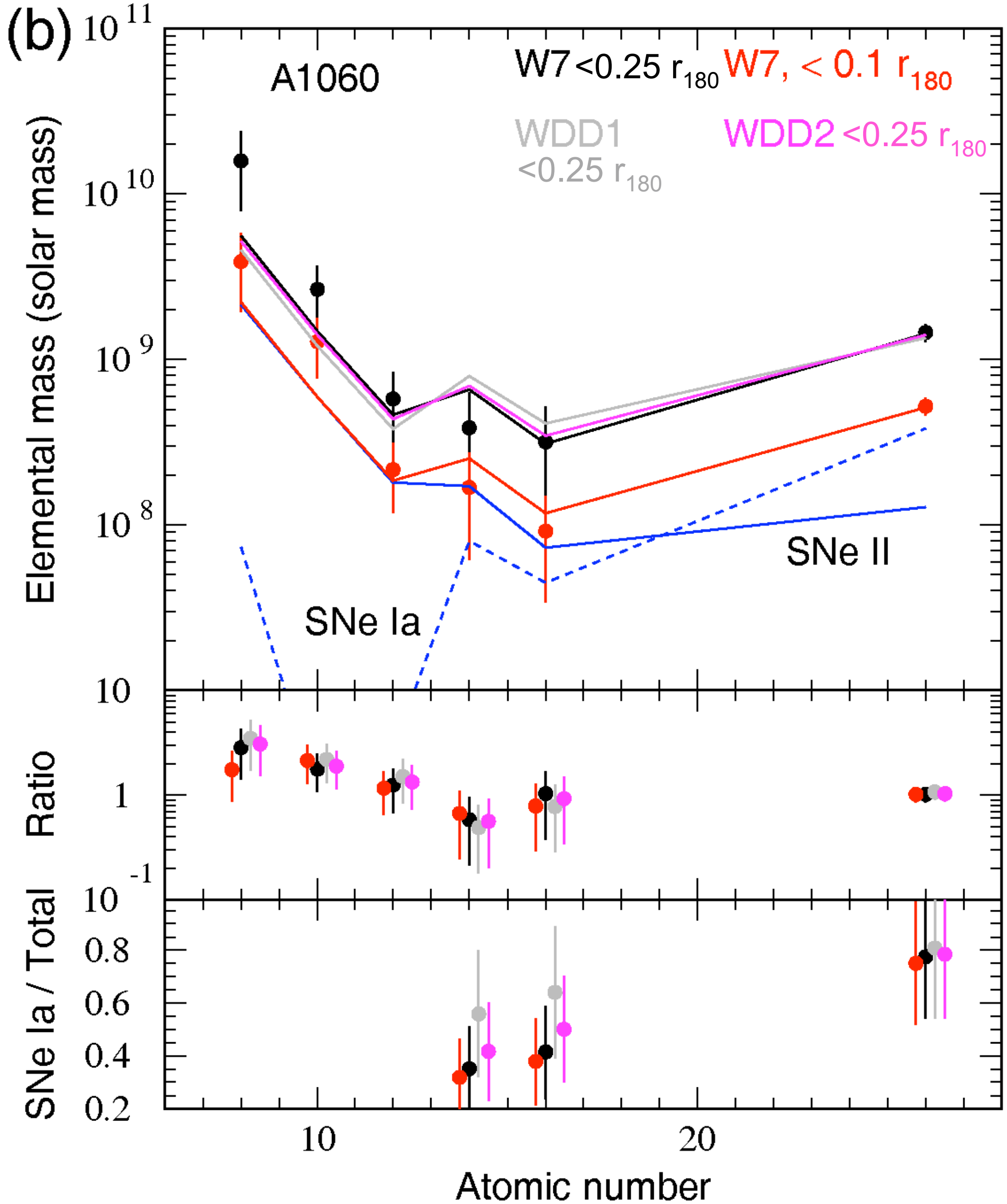
With Salpeter initial mass function

SN II/SN Ia ~ 3

~75% of Fe and ~35% Si synthesized in SN Ia

Cluster SN II/K-band galaxy luminosity = 1.6×10^{-3},

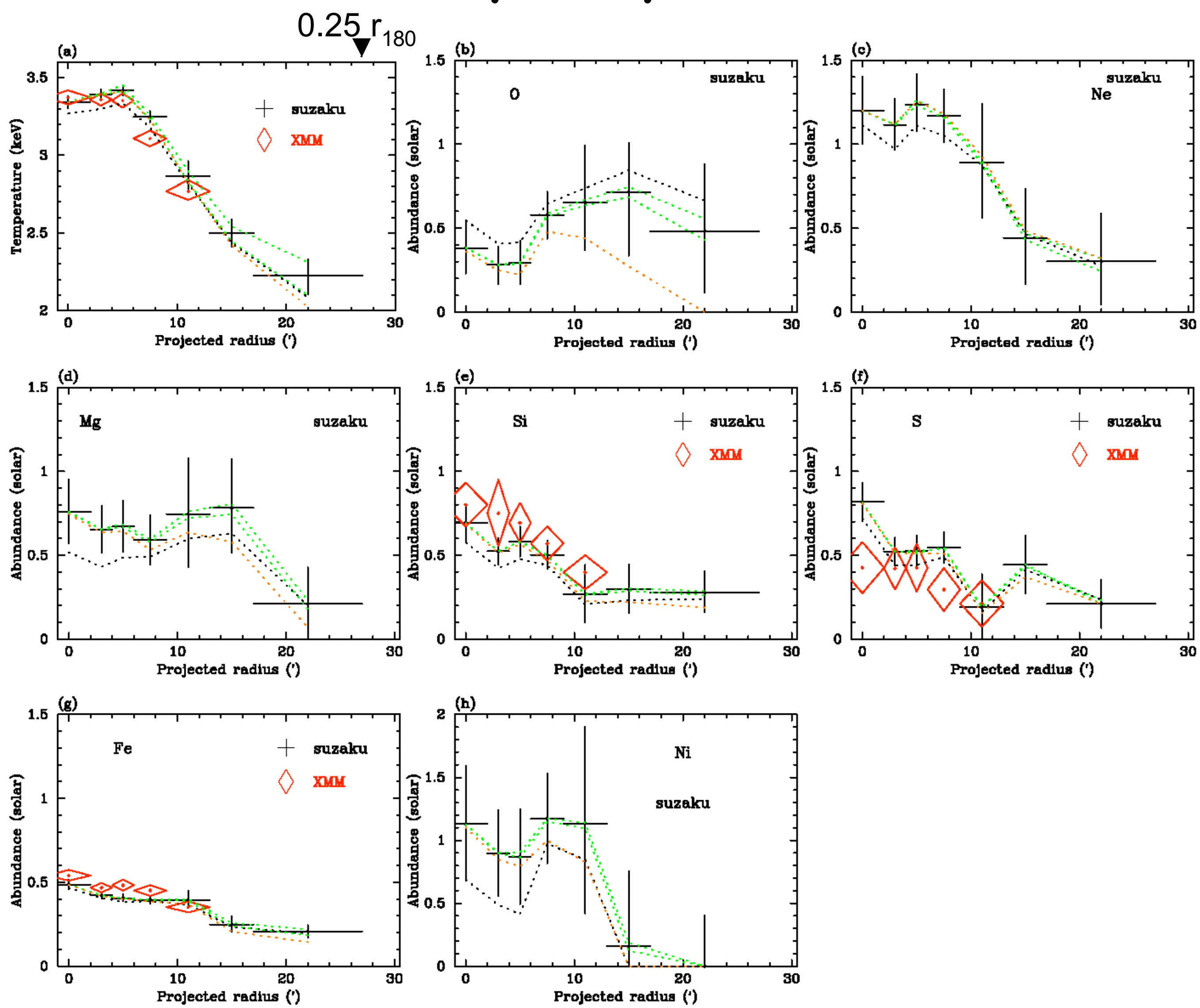
similar to field value of 2.5×10^{-3}. Not included



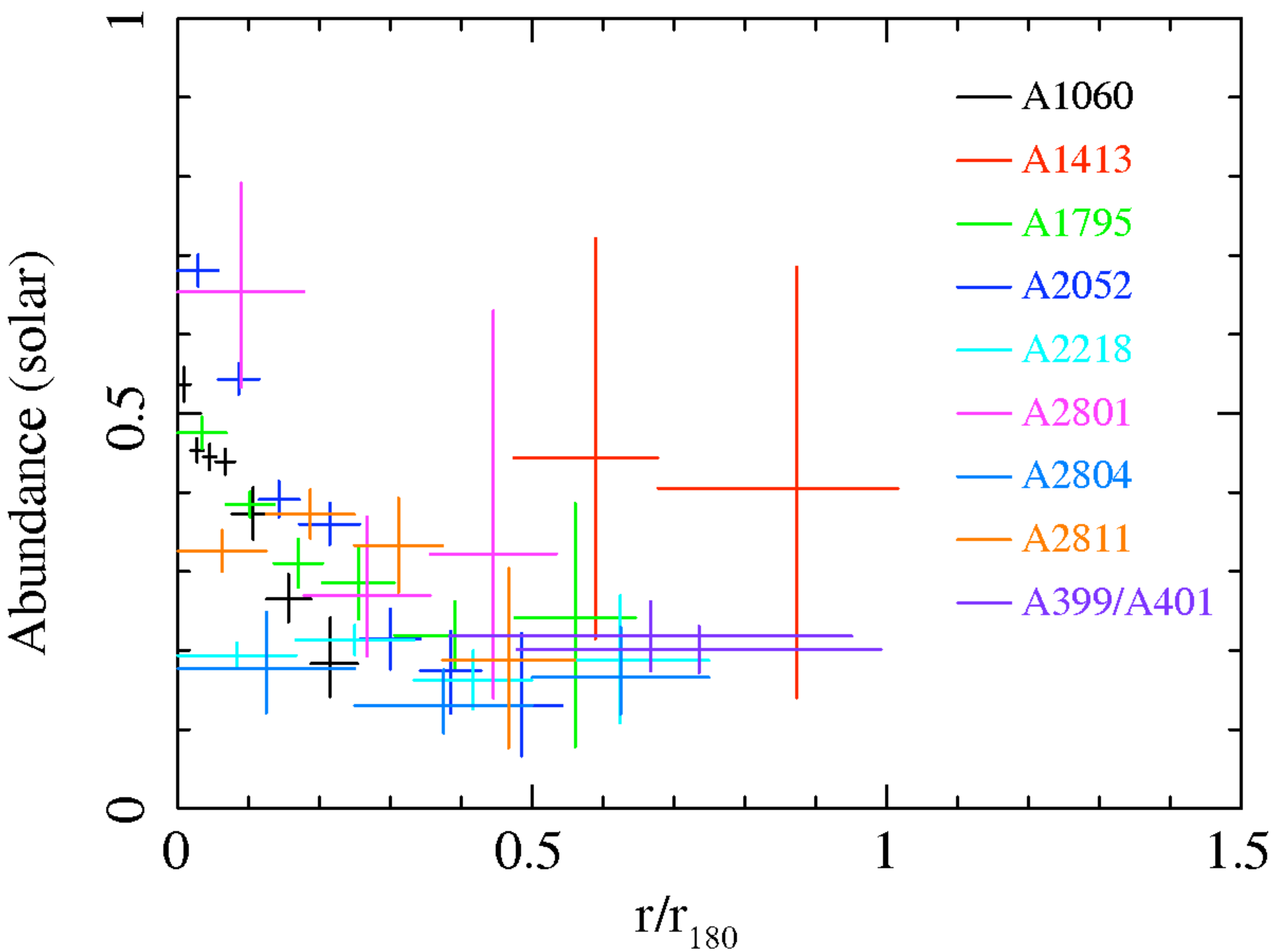
(b)
A1060
W7 <0.25 r_{180}
W7, < 0.1 r_{180}
WDD1 <0.25 r_{180}
WDD2 <0.25 r_{180}
SNe Ia
SNe II
Elemental mass (solar mass)
Ratio
SNe Ia / Total
Atomic number

Suzaku Extends Radial Abundance Profiles

Sato et al. PASJ 59, 299, 2007   A1060



Tawa et al. in prep.
Fe abundances approaching r_{180}



Elemental Abundances in kT ≥ 3 keV Clusters: Summary

Suzaku improves on previous work by:

- Better measurements of O and Mg lines at low energy
- Extending radial profiles beyond centers

See Mike Loewenstein!