

Joint X-ray/SZE analysis of the intra-cluster medium

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with

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& the APEX-SZ
collaboration



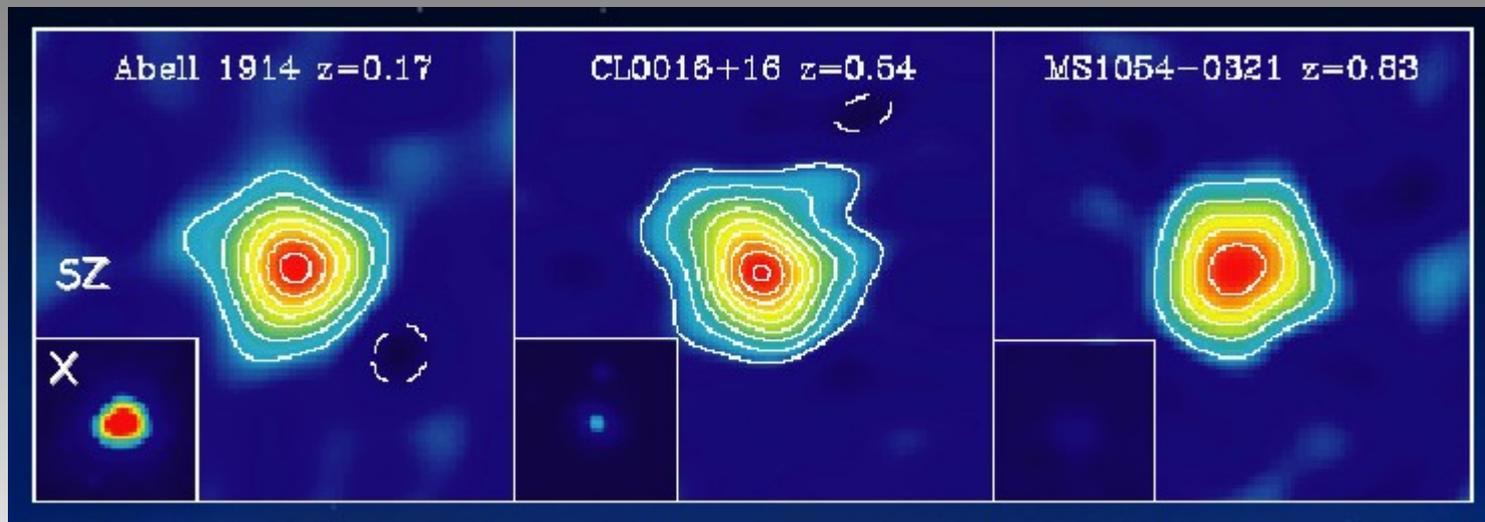
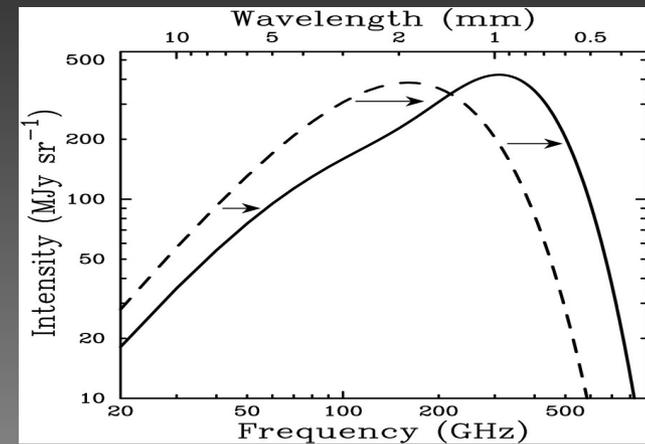
The Sunyaev-Zel'dovich (SZ) Effect

Thermal SZE is a small (<1 mK) distortion in the CMB caused by inverse Compton scattering of the CMB photons

$$\frac{\Delta T}{T_{\text{CMB}}} = g(x) \int n_e(l) \frac{k_B T_e(l)}{m_e c^2} dl$$

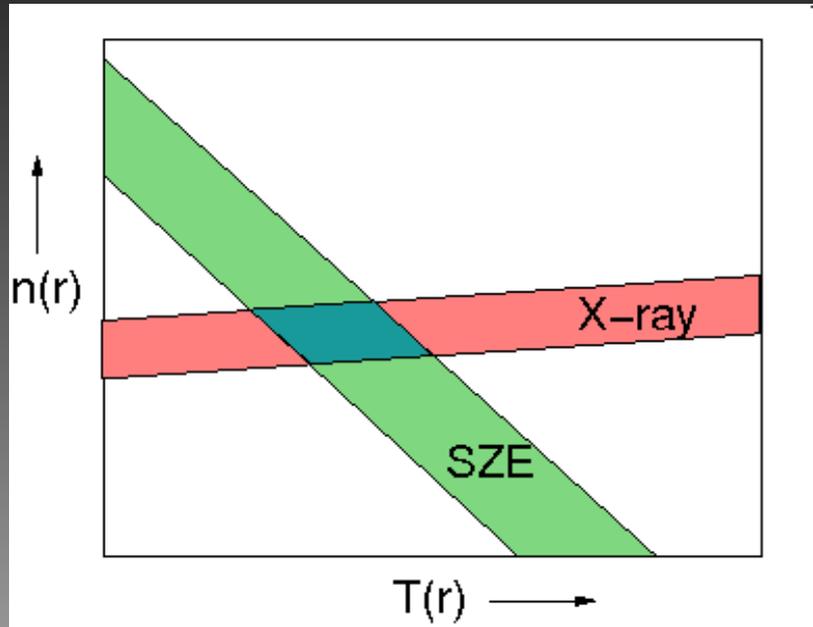
Total cluster flux density is independent of redshift!

$$\Delta S_\nu = \int \Delta I_\nu d\Omega \propto \frac{\int n_e T_e dV}{D_A^2} \propto \frac{f_{\text{gas}} M_{\text{tot}} T_e}{D_A^2}$$



Carlstrom et al.

ICM temperature de-projection



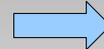
$$\text{X-ray} \sim n_e^2 \Lambda(T_e)$$

$$\text{SZE} \sim n_e T_e$$

Abel's integral inversion
to de-project density
& temperature

(SZE) observed $\Delta T(\theta)$ (SZE) $n_e(r) T_e(r)$

$$f(\theta) = \int_{-\infty}^{\infty} g(r) dl = 2 \int_{d_A \theta}^{\infty} g(r) \frac{r dr}{\sqrt{r^2 - d_A^2 \theta^2}},$$



$$g(r) = \frac{1}{\pi d_A} \int_{\infty}^{r/d_A} \frac{df(\theta)}{d\theta} \frac{d\theta}{\sqrt{\theta^2 - r^2/d_A^2}}.$$

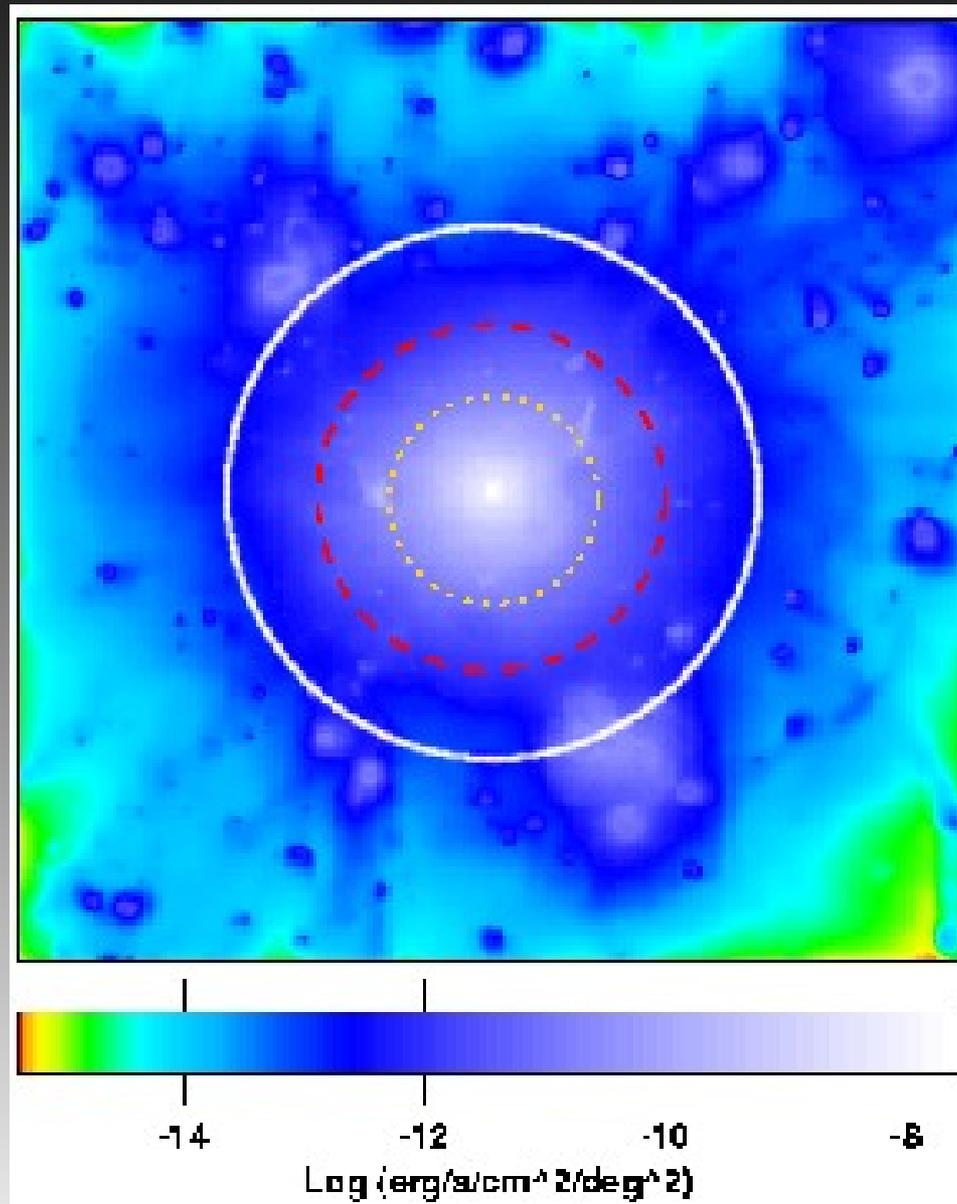
Cluster ICM

R_{2500} ($\sim 0.3 R_{200}$)
 ~ 0.5 Mpc

X-Ray
Strong Lensing

R_{500} ($\sim 0.7 R_{200}$)
 ~ 1.0 Mpc

X-Ray
SZ Effect
Weak Lensing

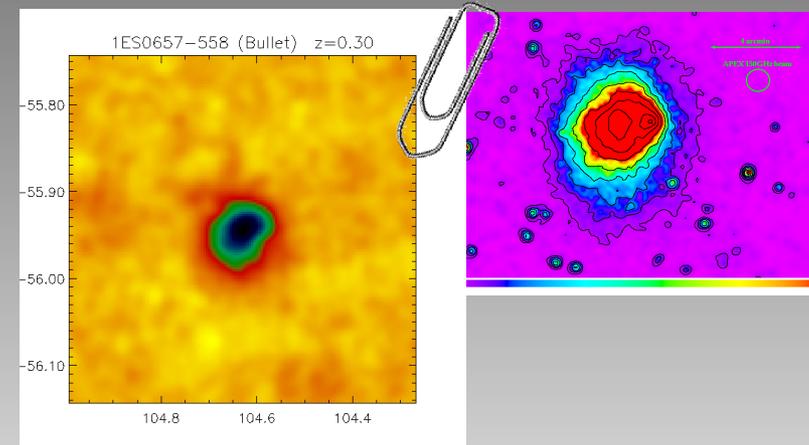
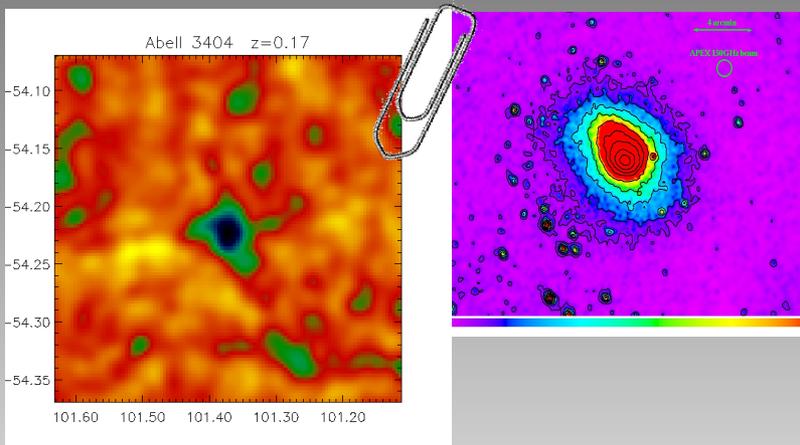
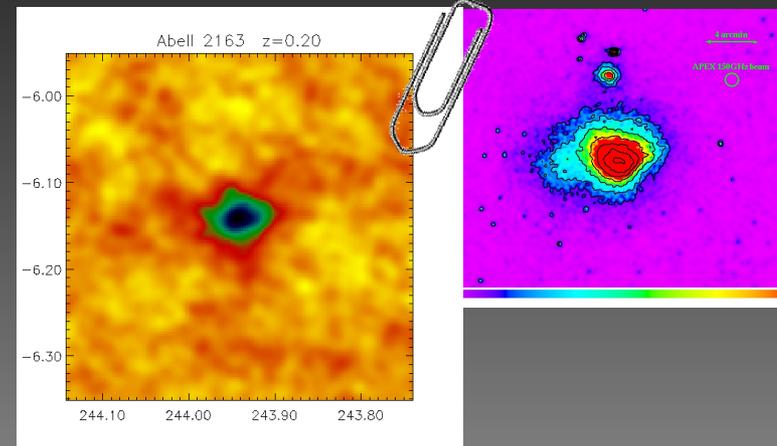
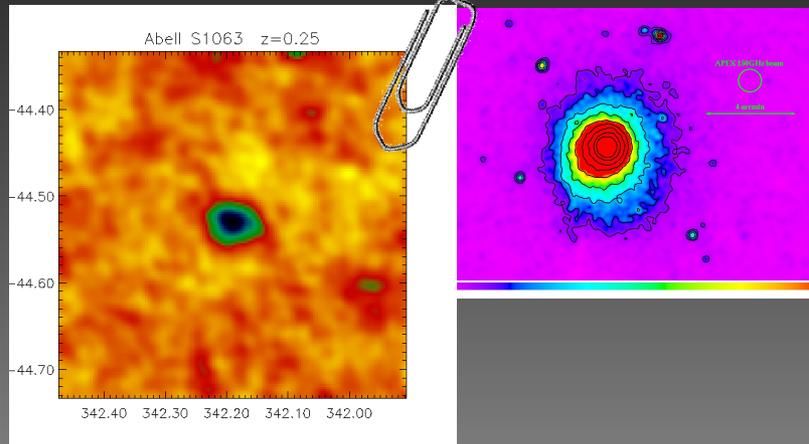


R_{200}
 ~ 1.5 Mpc

SZ Effect
Weak Lensing

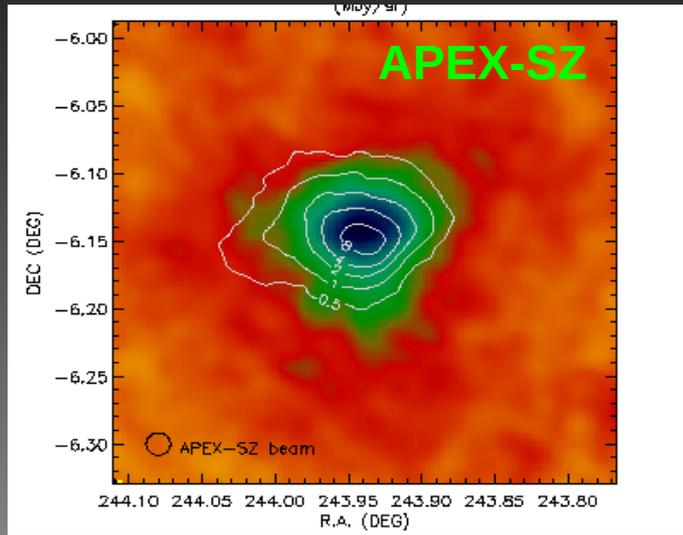
Roncarelli, Ettori et al. 2006

The APEX-SZ Clusters (and their *XMM-Newton* counterparts)

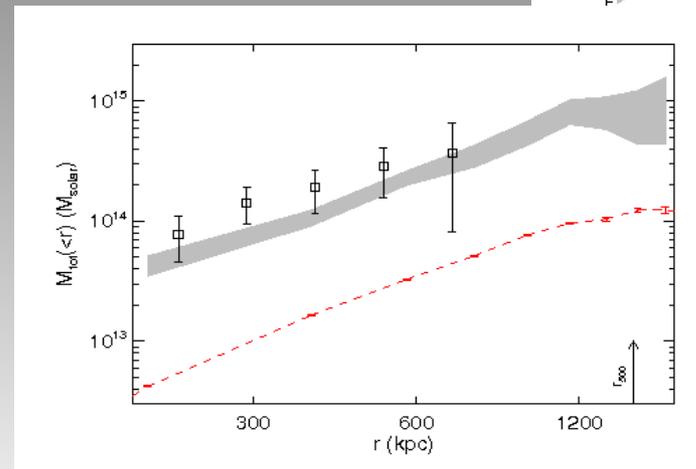
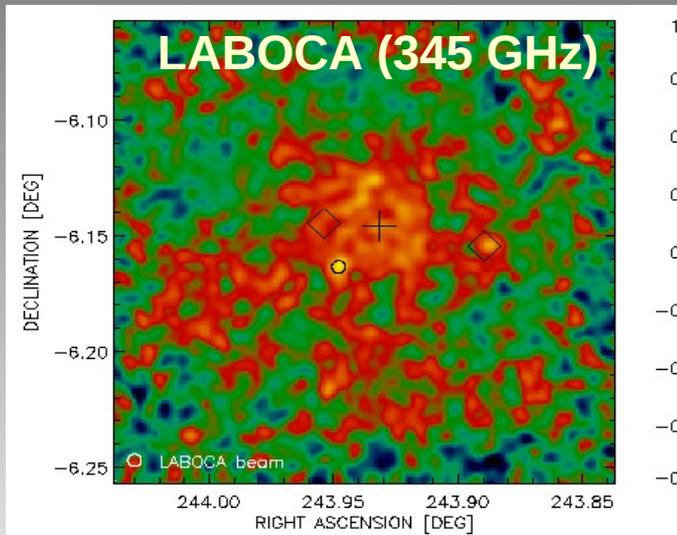
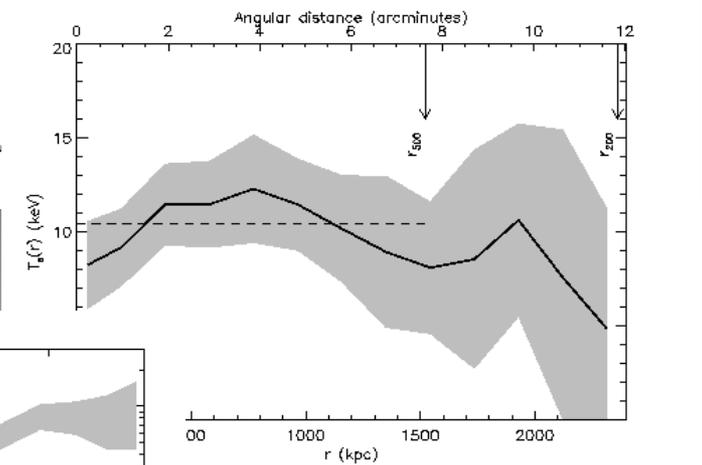
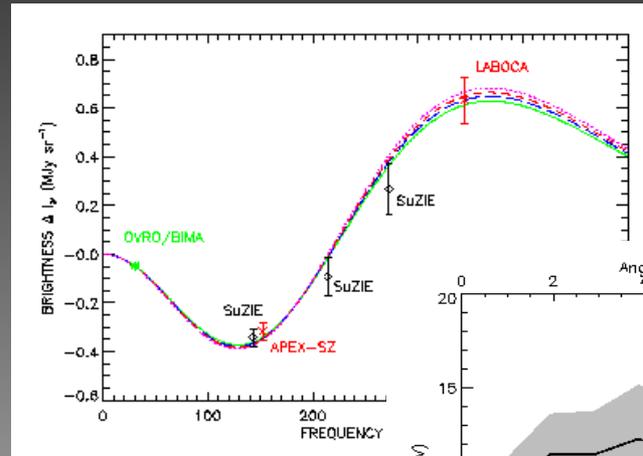


+ about two dozen more!

First APEX-SZ + XMM modeling: A2163



APEX-SZ + LABOCA imaging of Abell 2163
 Nord, Basu, Pacaud et al., *A&A in press*
 (arXiv: 0902.2131)



Non-parametric
 Temperature
 modeling

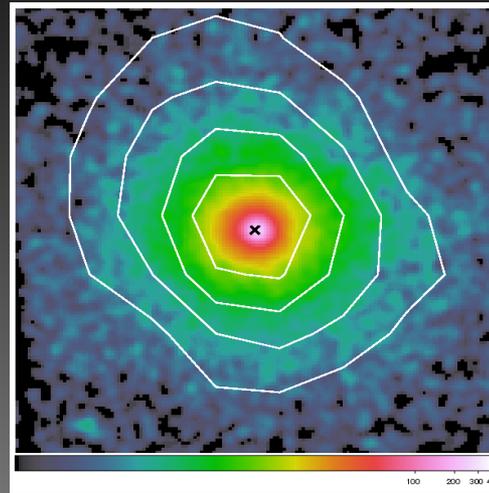
ICM temperature de-projection

Abell 2204:

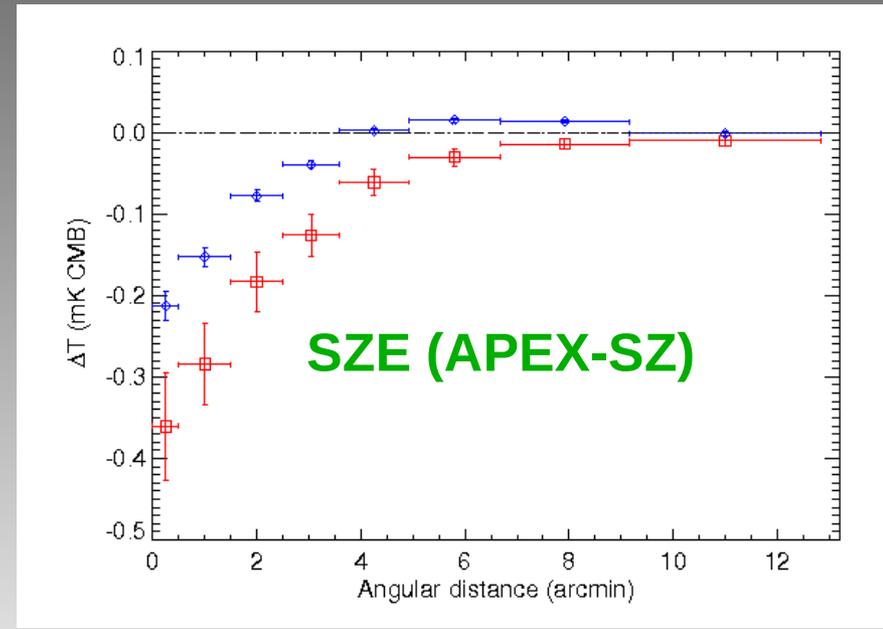
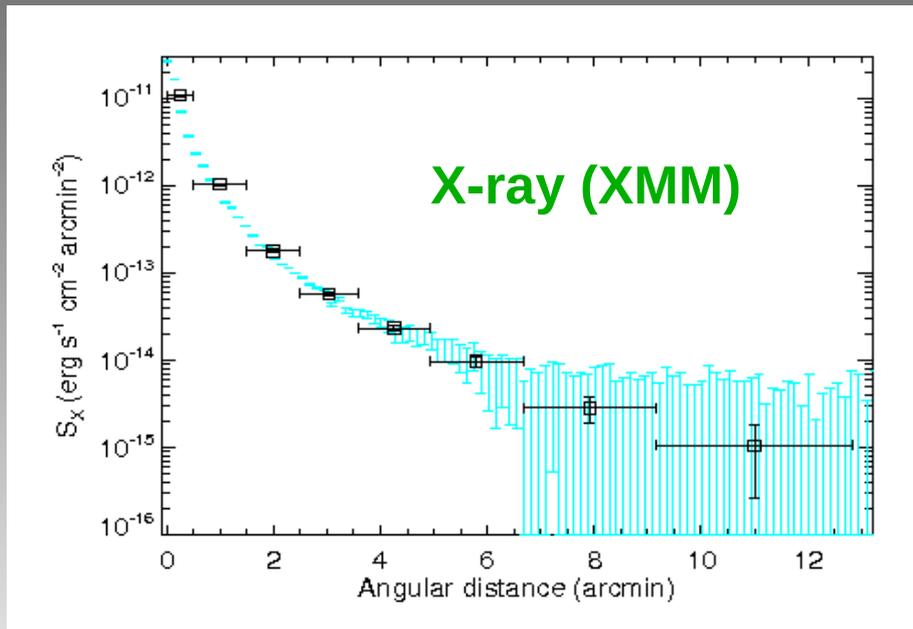
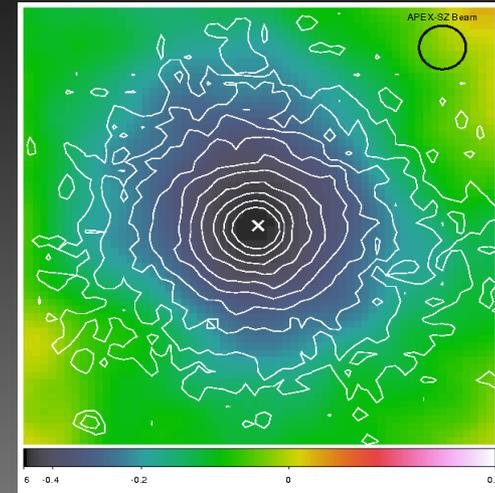
Prototypical
Relaxed cluster

Basu, Zhang, Nord
et al. (*submitted*)

X-ray image with
SZ contours



SZ image with
X-ray contours



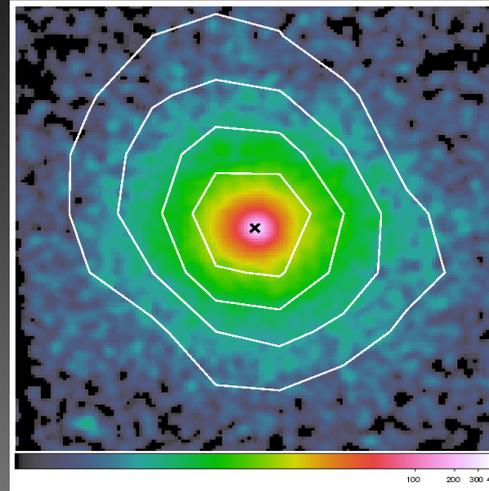
ICM temperature de-projection

Abell 2204:

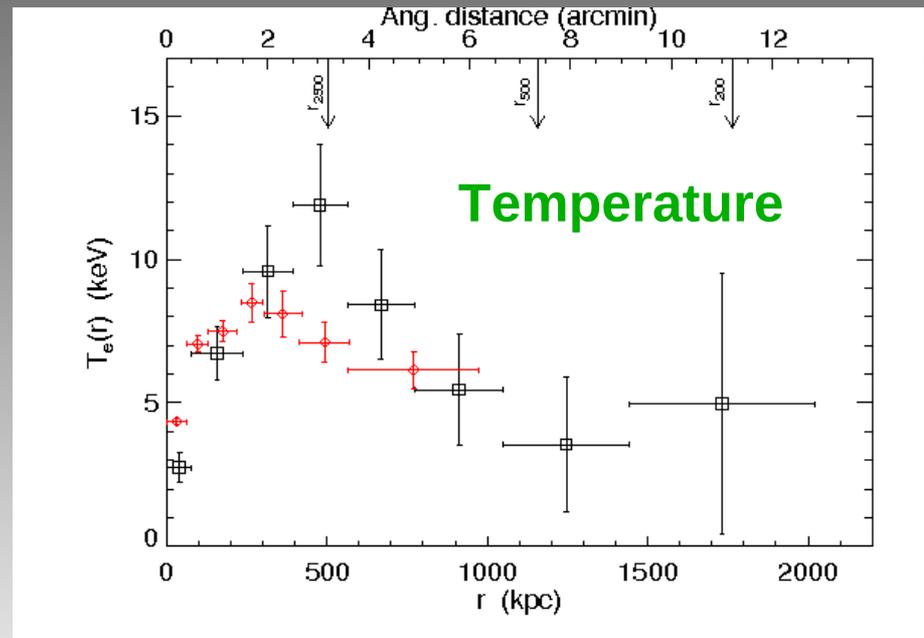
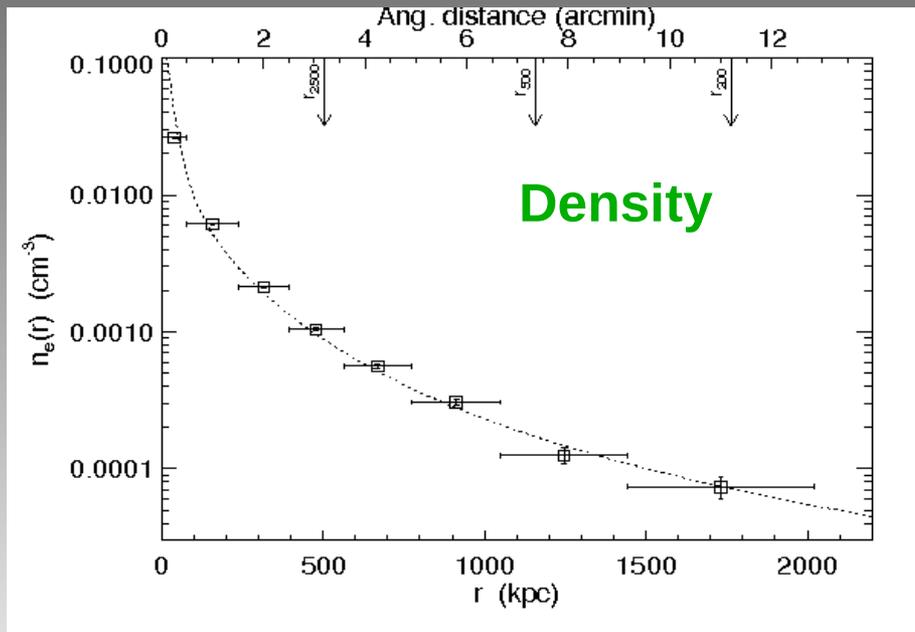
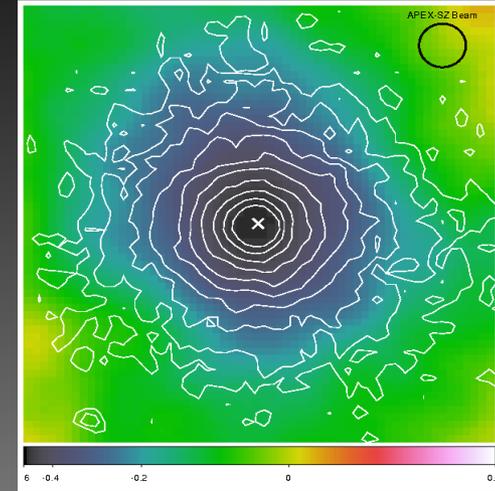
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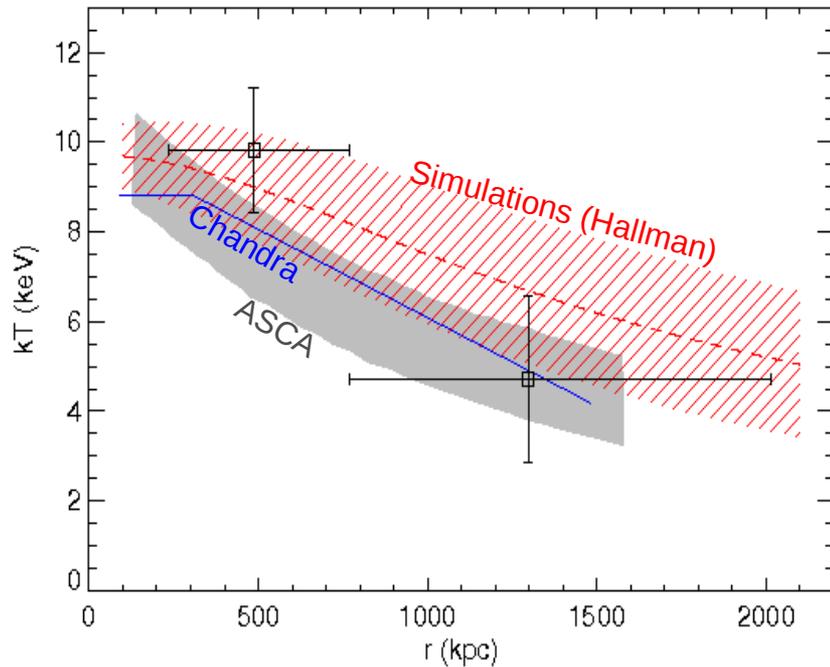
X-ray image with
SZ contours



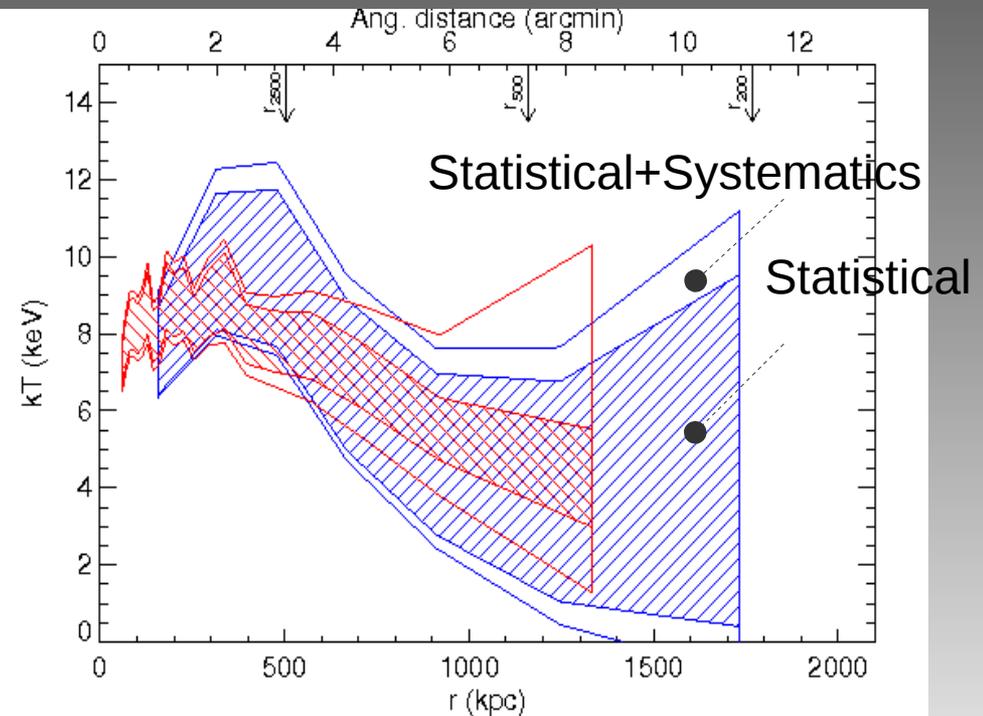
SZ image with
X-ray contours



SZE-derived temperature profile



SZE-demonstration of falling temperature in the cluster outskirts

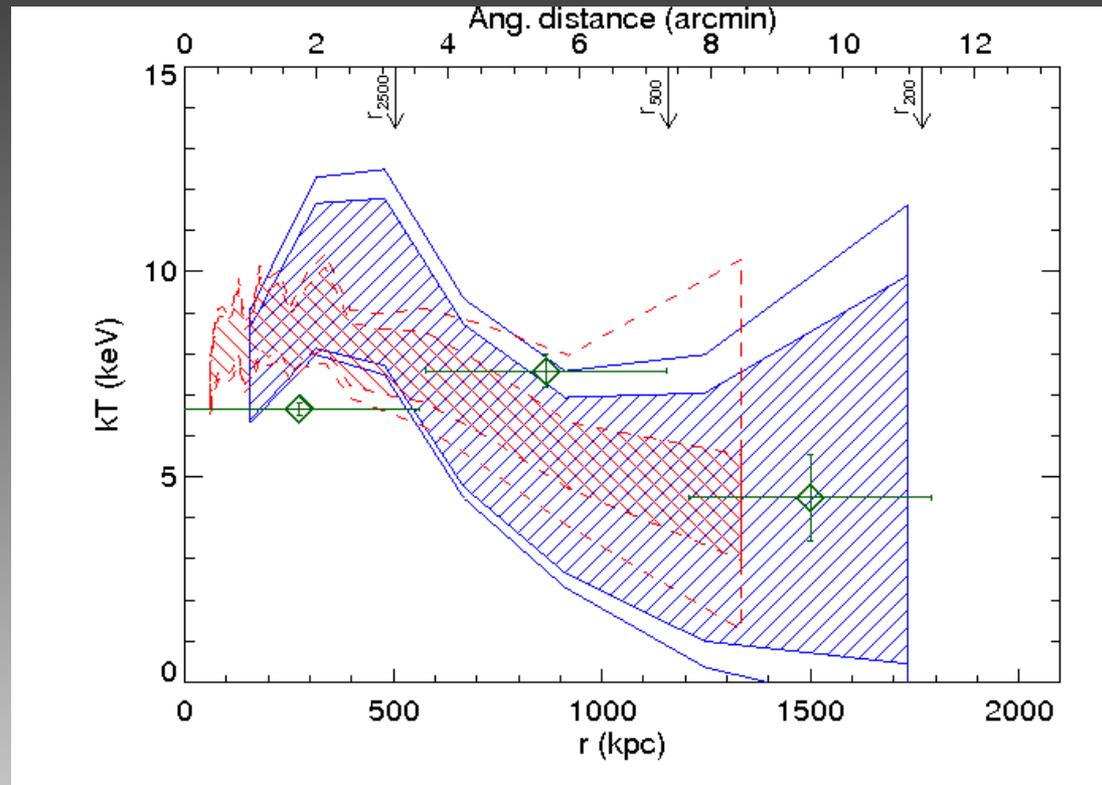


Projected ("spectroscopic-like") temp profile
with re-calibrated Chandra (88 ks) results
(Jaritz, Eckmiller, Reiprich)

Suzaku-derived temperature profile

Suzaku – very low & stable particle background, 😊 but very large PSF 😞

A399/A401 (Fujita et al. 2008), **PKS 0745-191** (George et al. 2009), **A2204** (Reiprich et al. 2009),
A1795 (Bautz et al. 2009)



Projected (“spectroscopic-like”) temp profile
Re-calibrated *Chandra* (88 ks) results
(Jaritz, Eckmiller, Reiprich)

Suzaku measurement of the outer
temperature profile in A2204
(Reiprich, Hudson et al. 2009)

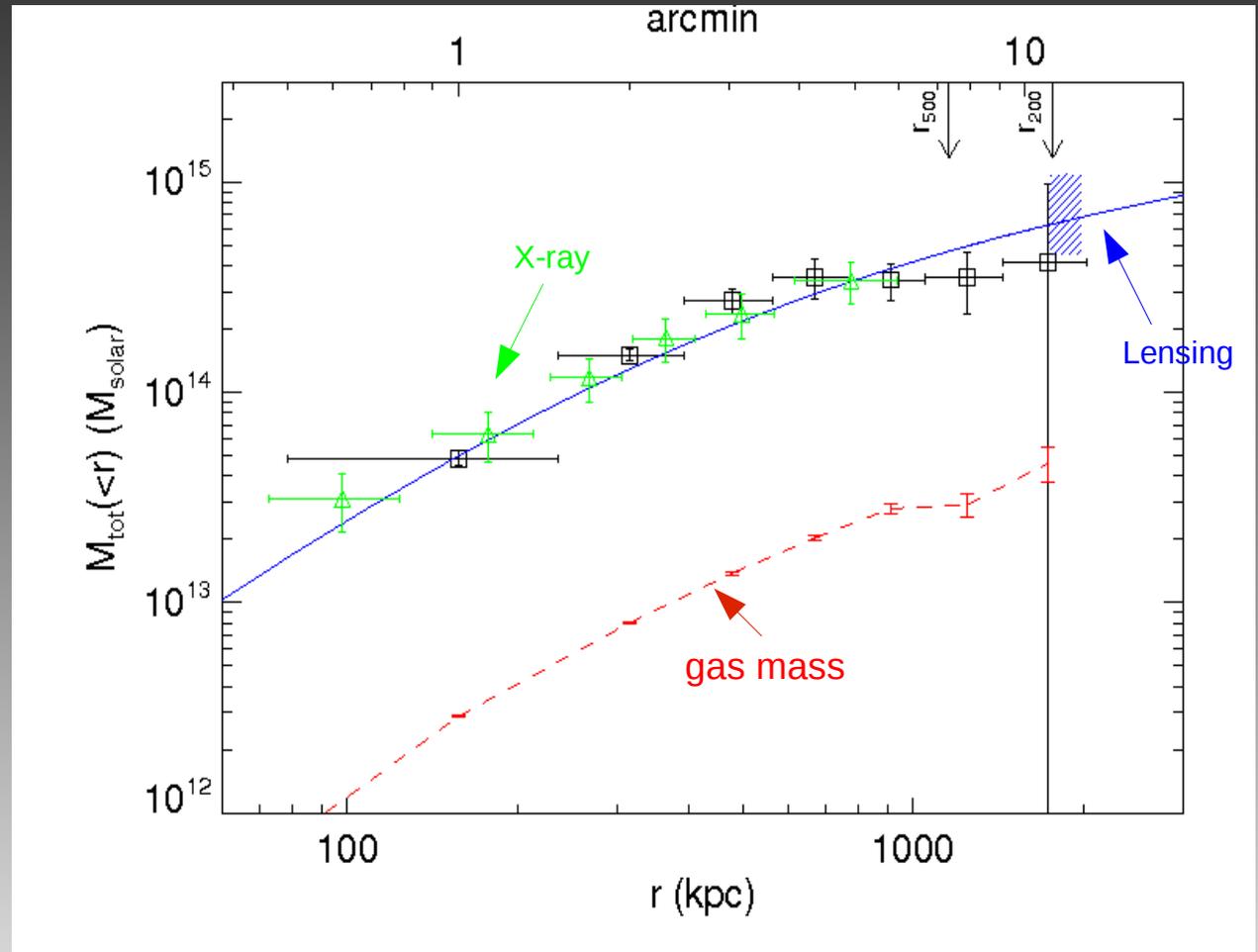
Mass and baryon fraction

Gas in hydrostatic equilibrium inside the dark matter potential well

$$\frac{1}{\rho_g} \frac{dP}{dr} = -\frac{d\phi}{dr} = -\frac{GM(<r)}{r^2}$$

$$M_{\text{tot}}(<r) \propto -T_e(r) \left[\frac{d \ln n_e(r)}{d \ln r} + \frac{d \ln T_e(r)}{d \ln r} \right]$$

**Spherical symmetry +
Hydrostatic Equilibrium**

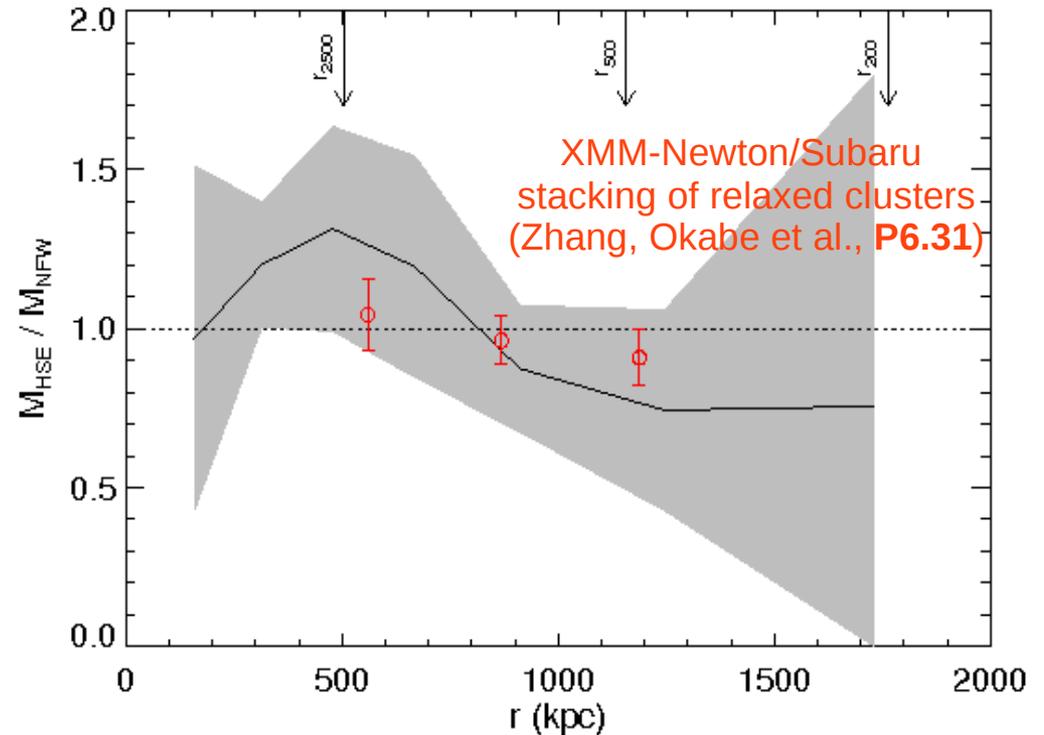
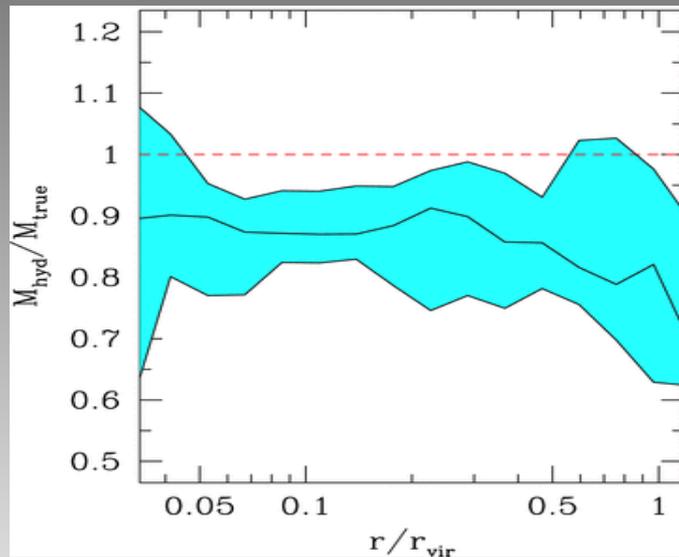


Abell 2204: Basu, Zhang, Nord et al. (submitted)

Mass and baryon fraction

Gas accretion and non-thermal pressure at r_{200} and beyond

HSE at r_{vir}
(Ameglio, Borgani et al. 2009)



Abell 2204: Basu, Zhang, Nord et al.
(submitted)

ICM Entropy profiles

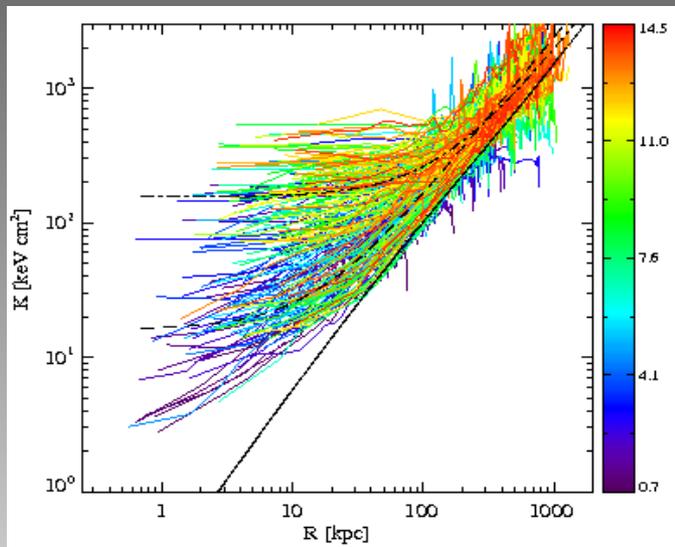
Entropy is a fundamental property of the ICM, describing its history of heating and cooling

Slope of the entropy profile near the cluster center determines the extent of non-gravitational heating

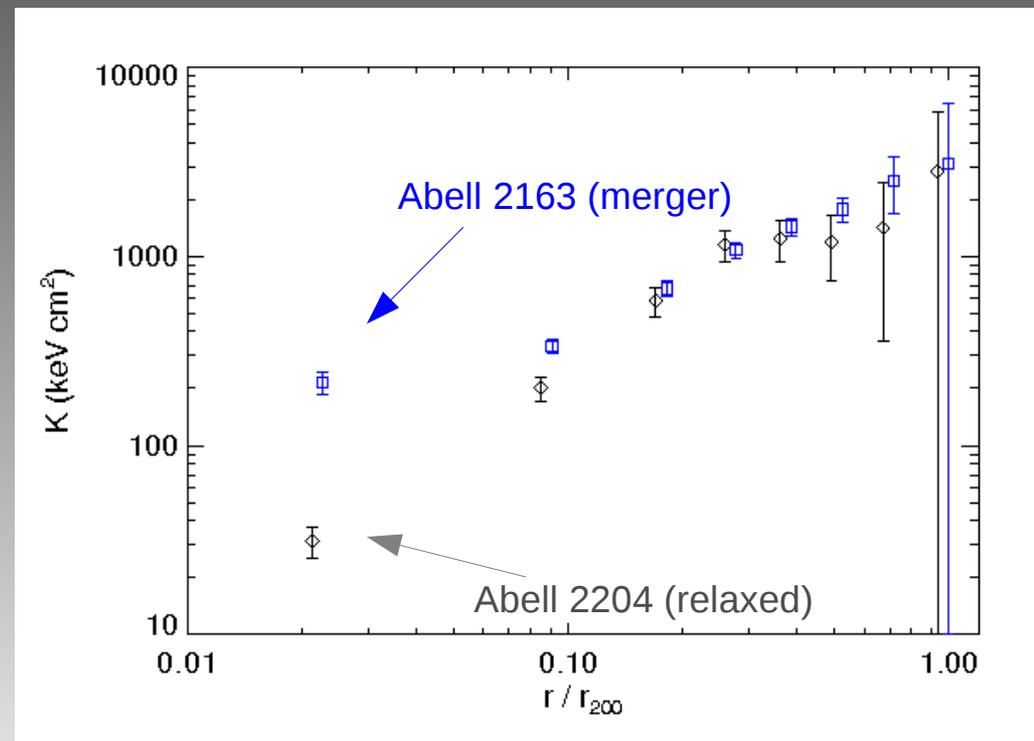
Low entropy near the virial radius indicates infall, shock heating/cooling.. again non-gravitational processes

$$K = T_e n_e^{-2/3}$$

Abell 2204, Basu, Zhang, Nord et al.

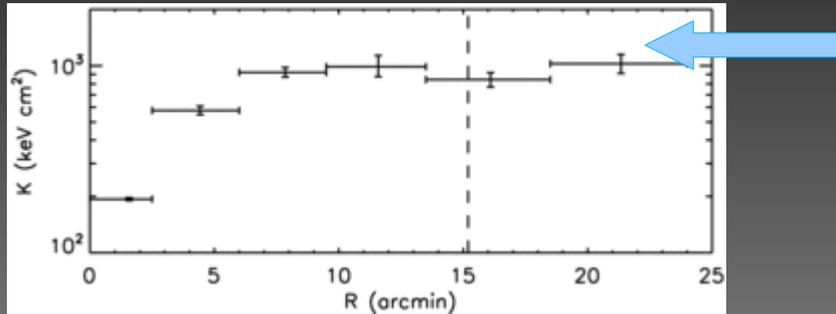


Cavagnolo et al. 09



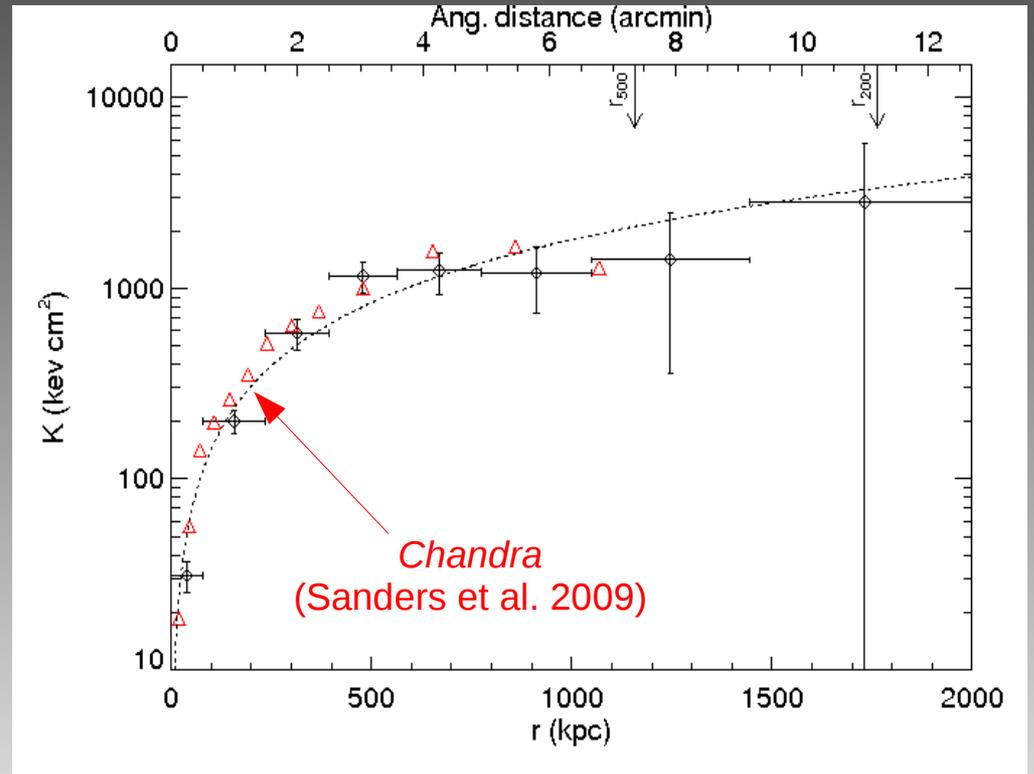
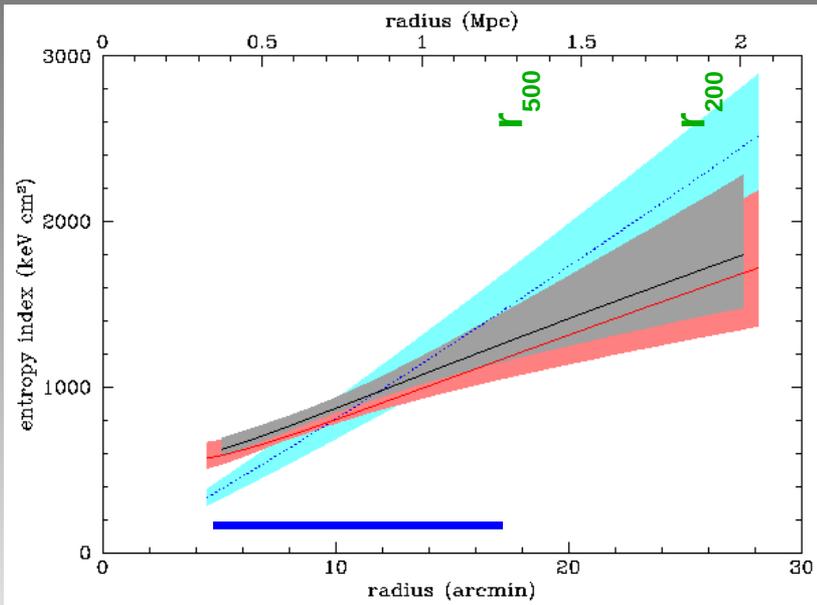
ICM Entropy profiles

PKS 0745-191 with *Suzaku*: George et al. 2009



ICM entropy in the cluster outskirts not rising as expected!

Abell 1795 with *Suzaku*: Bautz et al. 2009



Abell 2204, Basu, Zhang, Nord et al. (submitted)

To summarize..

Analysis of the intra-cluster medium (ICM) with resolved SZE maps have become a reality (long way to catch up with the sophistication and depth of the X-ray spectral analysis).

We have performed the first non-parametric joint X-ray/SZE modeling of ICM properties (A2163, A2204: Nord, Basu, Zhang et al.) out to r_{200}
Stacking analysis in progress, also with *Suzaku* data.

Multi-pixel bolometer imaging data is now able to verify ICM entropy the features at the cluster core, and also the dropping gas temperature at large radii, independent of X-ray spectroscopy.

With better control of SZE statistical and X-ray background uncertainties, we can go beyond r_{200} with available instruments.