Huntsville, Al Oct 25 2007 **Eight Years of Science with Chandra**

Scaling Relations from Sunyaev-Zel′dovich Effect and Chandra X-ray measurements of high-redshift galaxy clusters

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Motivation of scaling relations

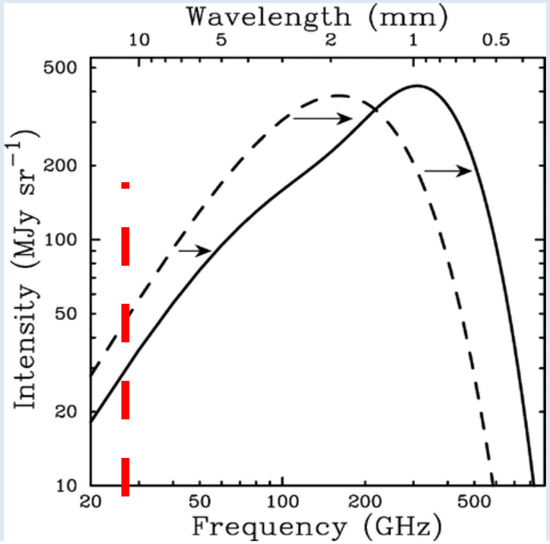
- Obtain *observational* relationships among SZE and X-ray quantities: kT, M_{tot}, M_{gas} and Y

  Establish SZE proxies for mass and temperature that can be used for SZE surveys

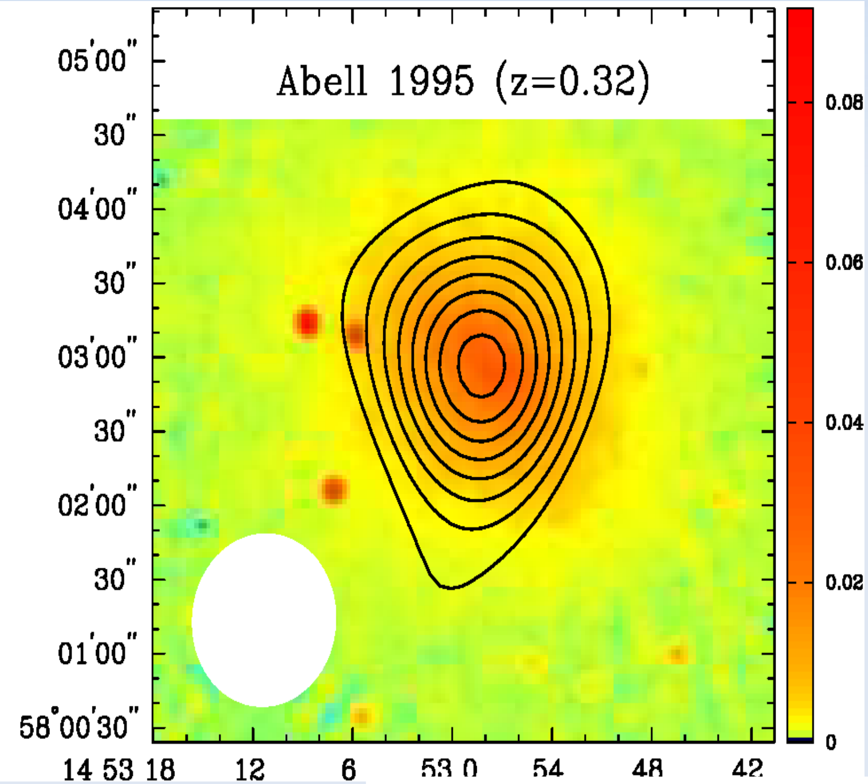
- Compare observed relationships with self-similar scaling relations and numerical simulations

  Understand certain aspects of the physics of galaxy clusters (pre-heating, non-thermal pressure, etc.)

***S**unyaev-**Z**el′dovich **E**ffect and X-ray Observations*



(Credit: Carlstrom et al., ARA&A vol 40, pg 643, 2002)



(Bonamente et al. 2006, ApJ 647, 25)

$$\Delta T_{CMB} = f_{(x,T_e)} T_{CMB} \int \sigma_T n_e \frac{k_B T_e}{m_e c^2} dl$$

$$y = \int \sigma_T n_e \frac{k_B T_e}{m_e c^2} dl$$

$$S_X = \frac{1}{4\pi(1+z)^4} \int n_e^2 \Lambda_{ee} dl$$

SZE / X-ray sample

- Have SZE/X-ray available for 38 clusters, z=0.14-0.89

  (Bonamente et al. 2006; LaRoque et al. 2006)

CLUSTER	Z	CLUSTER	Z
CL 0016+1609	0.541	ABELL 1689	0.183
ABELL 68	0.255	RX J1347.5-1145	0.451
ABELL 267	0.230	MS 1358.4+6245	0.327
ABELL 370	0.375	ABELL 1835	0.252
MS 0451.6-0305	0.550	MACS J1423.8+2404	0.545
MACS J0647.7+7015	0.584	ABELL 1914	0.171
ABELL 586	0.171	ABELL 1995	0.322
MACS J0744.8+3927	0.686	ABELL 2111	0.229
ABELL 611	0.288	ABELL 2163	0.202
ABELL 665	0.182	ABELL 2204	0.152
ABELL 697	0.282	ABELL 2218	0.176
ABELL 773	0.217	RX J1716.4+6708	0.813
ZW 3146	0.291	ABELL 2259	0.164
MS 1054.5-0321	0.826	ABELL 2261	0.224
MS 1137.5+6625	0.784	MS 2053.7-0449	0.583
MACS J1149.5+2223	0.544	MACS J2129.4-0741	0.570
ABELL 1413	0.142	RX J2129.7+0005	0.235
CL J1226.9+3332	0.890	MAC J2214.9-1359	0.450
MACS J1311.0-0310	0.490	MACS J2228.5+2036	0.412

SZE/X-ray data modeling

- Isothermal β model, excised 100 kpc from X-ray data to avoid cool core
- Analytical expressions for SZE decrement and X-ray surface brigthness

$$n_e(r) = n_{e0}\left(1+\frac{r^2}{r_c^2}\right)^{-3/2\beta} \Rightarrow \begin{cases} \Delta T = \Delta T_0\left(1+\frac{\theta^2}{\theta_c^2}\right)^{(1-3\beta)/2} \\ S_X = S_{X0}\left(1+\frac{\theta^2}{\theta_c^2}\right)^{(1-6\beta)/2} \end{cases}$$

- Tested versus a non-isothermal, double-β model: same results in measurements of D_A and masses (Bonamente et al. 2006; LaRoque et al. 2006)
- Advantage: single average temperature <T> for scaling relations
- More sophisticated modeling in progress using *Sunyaev-Zeldovich Array* data (see T. Mrokzkowski's poster)

SZE/X-ray Scaling Relations

- Simple self-similar model of collapse of overdense structures (Kaiser 1986; Binney and Tremaine 1987; Bryan and Norman 1997; etc.): Isothermal, late-formation, neglects non-gravitational processes
- Prediction of simple *T – Mass relationship*: $T \propto M_{\Delta}^{2/3} E(z)^{2/3}$
- Use overdensity Δ=2500, reachable for all clusters in sample

- Y is the *integrated Compton-y parameter* $Y \equiv \int y \, d\Omega \propto \frac{1}{D_A^2} \int n \, T \, dV$

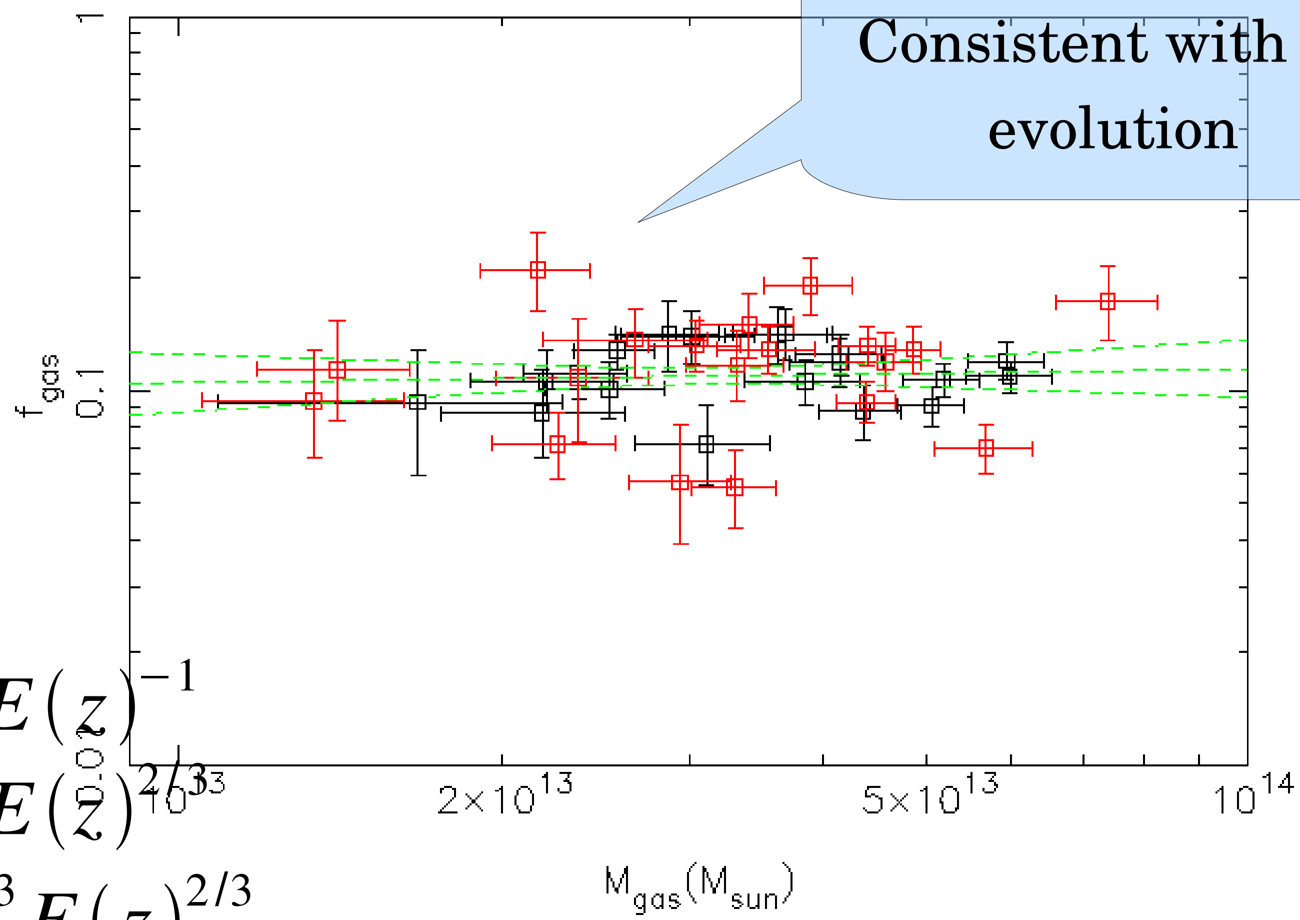
  Use Y D_A^2 as the *intrinsic Y* (as in da Silva et al. 2004, Nagai 2006)
- Apply to the Kaiser (1986) model to obtain SZE scaling relations:

$$\begin{cases} Y D_A^2 \propto f_{gas} T^{5/2} E(z)^{-1} \\ Y D_A^2 \propto f_{gas} M_{tot}^{5/3} E(z)^{2/3} \\ Y D_A^2 \propto f_{gas}^{-2/3} M_{gas}^{5/3} E(z)^{2/3} \end{cases}$$

SZE / X-ray Scaling Relations Results (1) : f_{gas} vs. M_{gas}

f_{gas} - M_{gas}

$\alpha = 0.14 \pm 0.08$



Consistent with no evolution

$$Y D_A^2 \propto f_{gas} T^{5/2} E(z)^{-1}$$

$$Y D_A^2 \propto f_{gas} M_{tot}^{5/3} E(z)^{2/3}$$

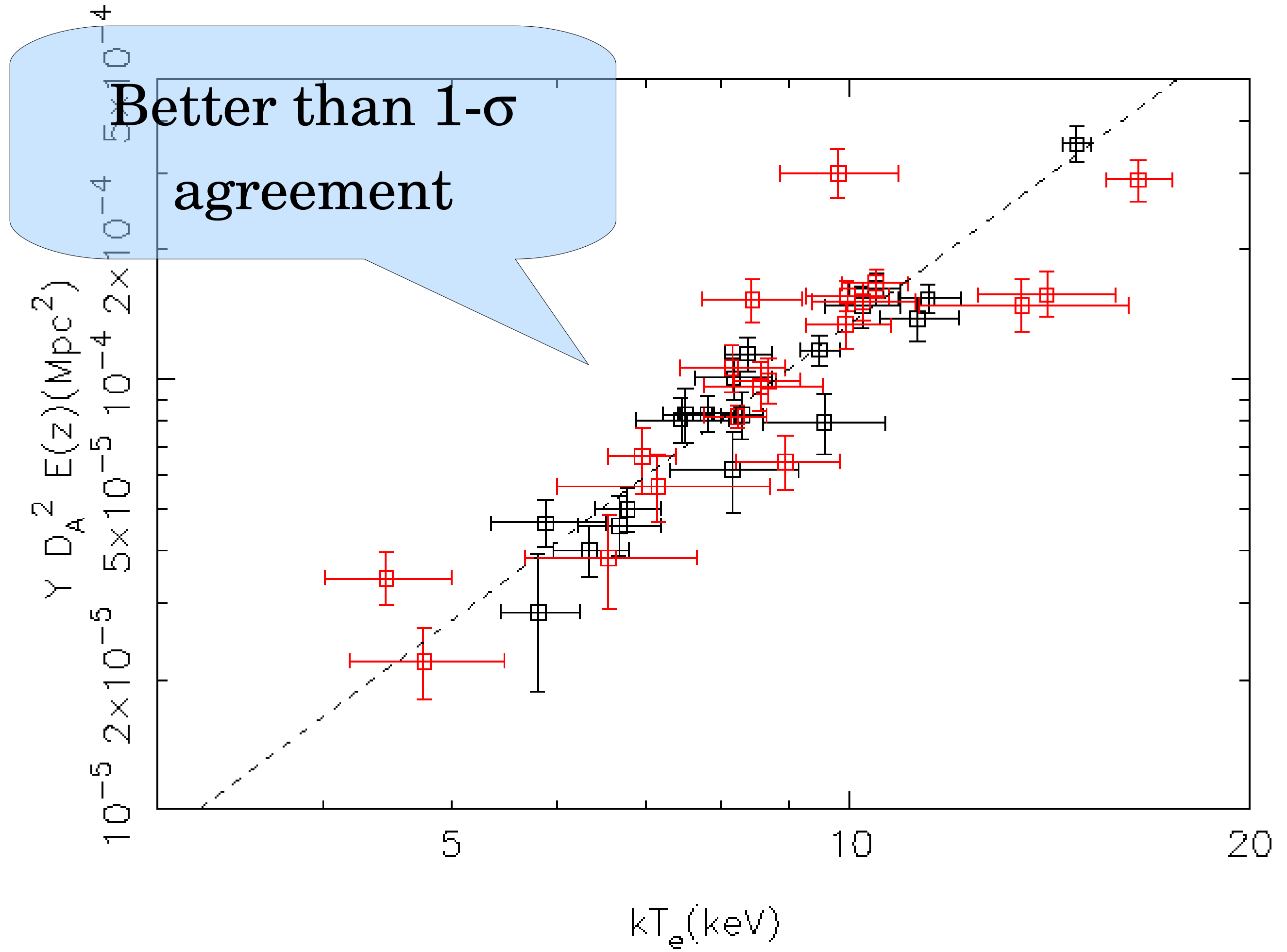
$$Y D_A^2 \propto f_{gas}^{-2/3} M_{gas}^{5/3} E(z)^{2/3}$$

(Bonamente et al. 2008)

SZE / X-ray Scaling Relations Results (2) : Y vs. T

Y - T

$\alpha = 2.37 \pm 0.23$ (2.50)

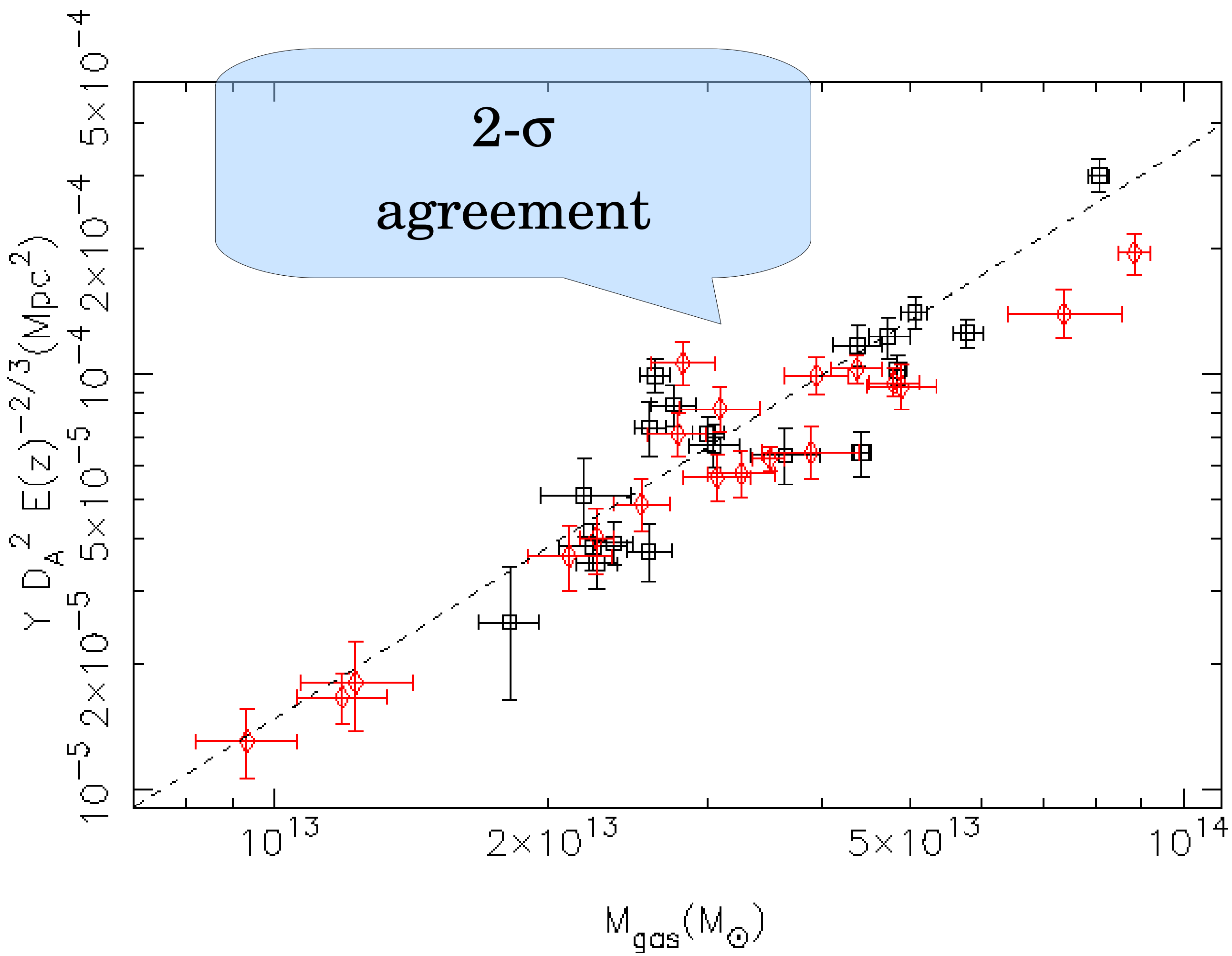


(Bonamente et al. 2008)

SZE / X-ray Scaling Relations Results (3) : Y vs. M_{gas}

Y - M_{gas}

$\alpha = 1.41 \pm 0.13$ (1.67)



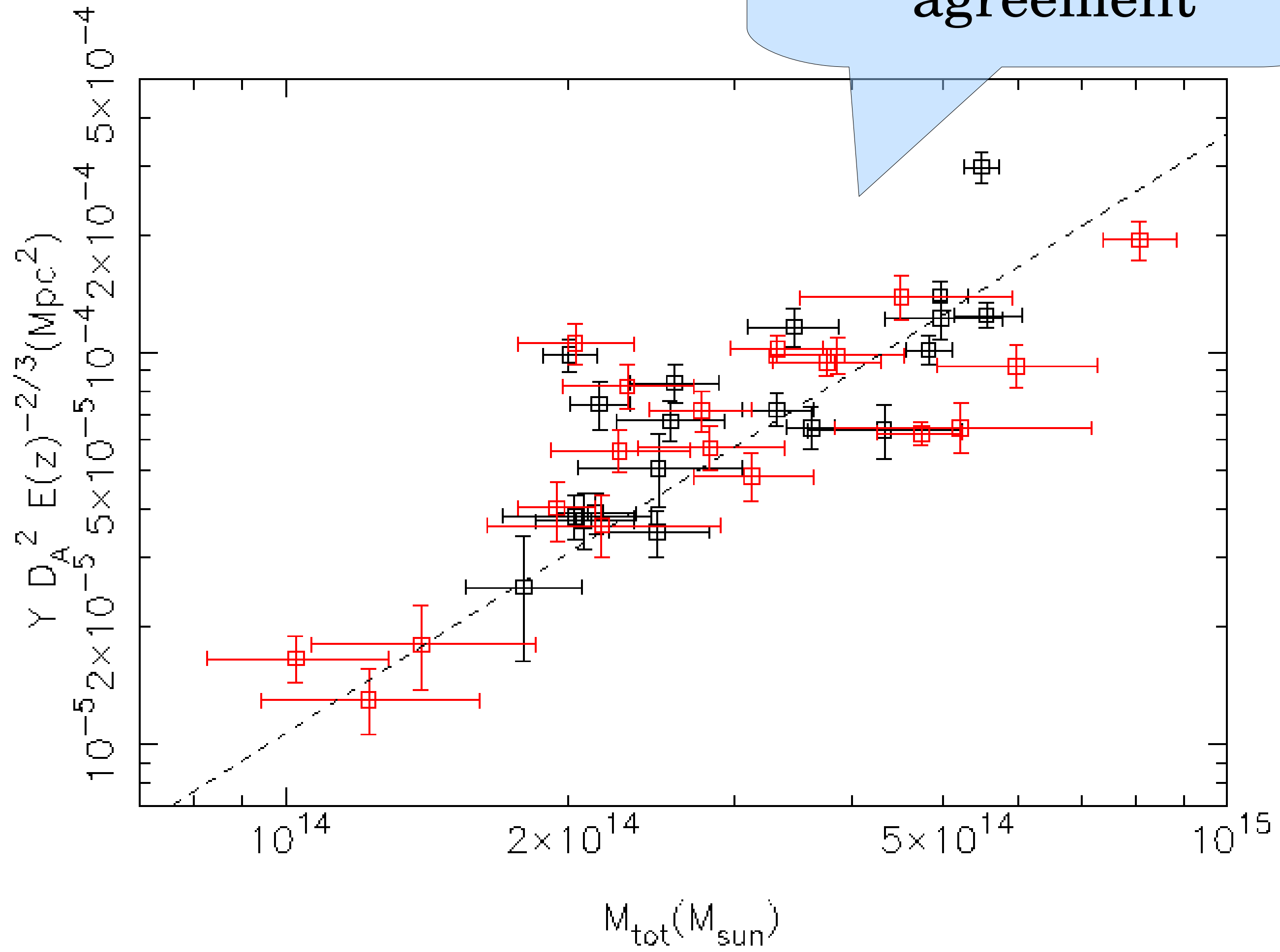
(Bonamente et al. 2008)

SZE / X-ray Scaling Relations Results (4) : Y vs. M_{tot}

Y - M_{tot}

$\alpha = 1.66 \pm 0.20$ (1.67)

Better than 1-σ agreement



(Bonamente et al. 2008)

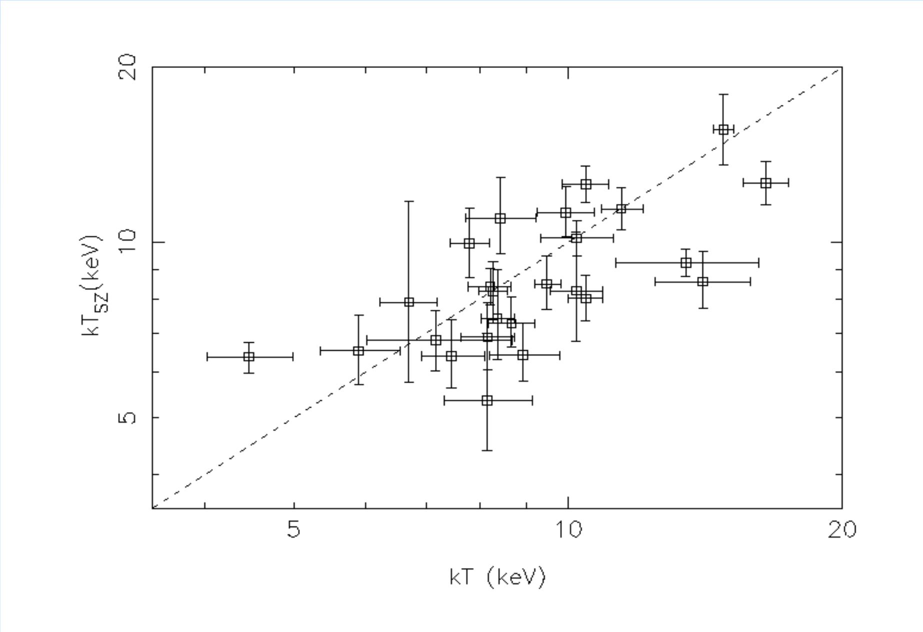
Comparison of joint analysis with SZ-only analysis

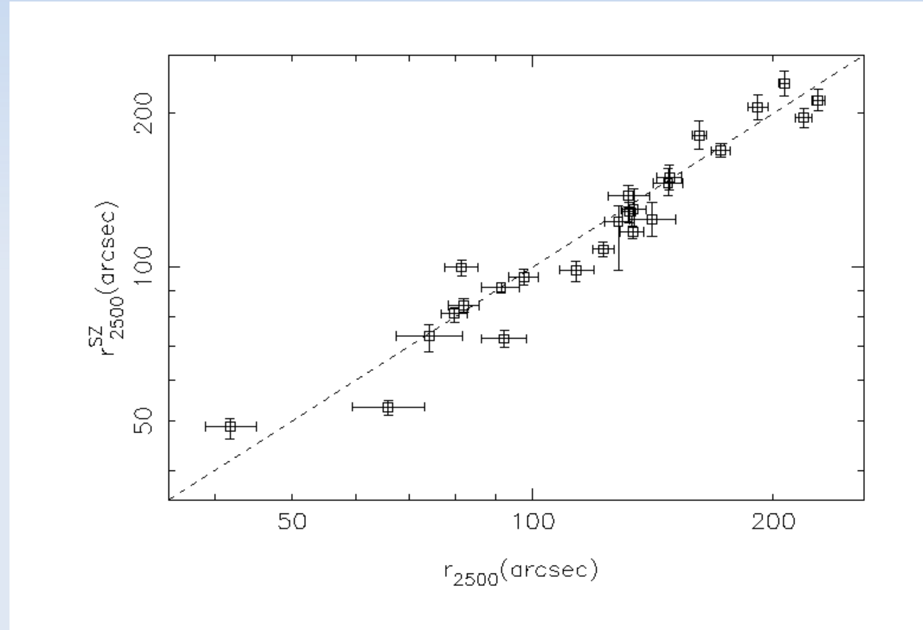
- Motivation: upcoming SZE surveys (e.g., South Pole Telescope) will not have full benefit of X-ray observations
- Analyze a sub-sample of 25 clusters using only the SZ data, analysis is fully independent of X-ray data:
- Estimate the plasma temperature and r_{2500} using the assumption of constant f_{gas} and solving iteratively the equation

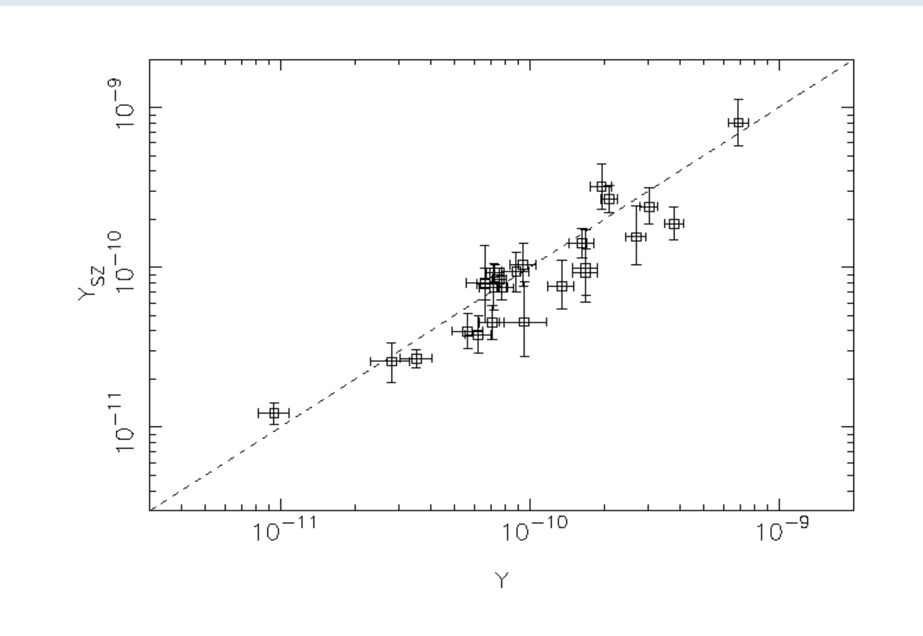
$$M_{gas}(r_{2500}) = f_{gas} M_{tot}(r_{2500})$$

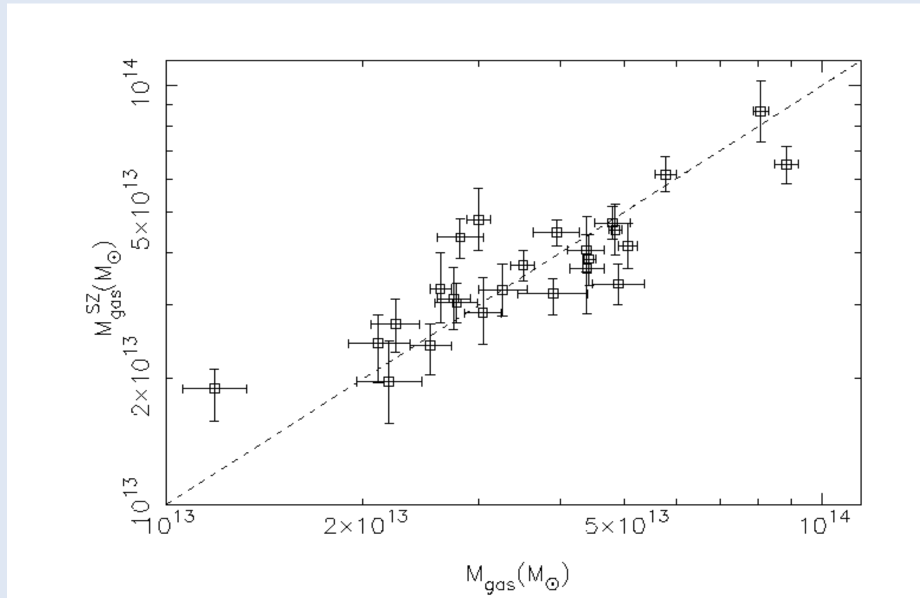
  in order to find consistent estimates of T and r_{2500} (Joy et al. 2001)
- Fix β=0.7 due to limited spatial resolution of SZE data
- Obtain masses, T and Y and compare with joint X-ray/SZE measurements

Comparison of joint analysis with SZ-only analysis





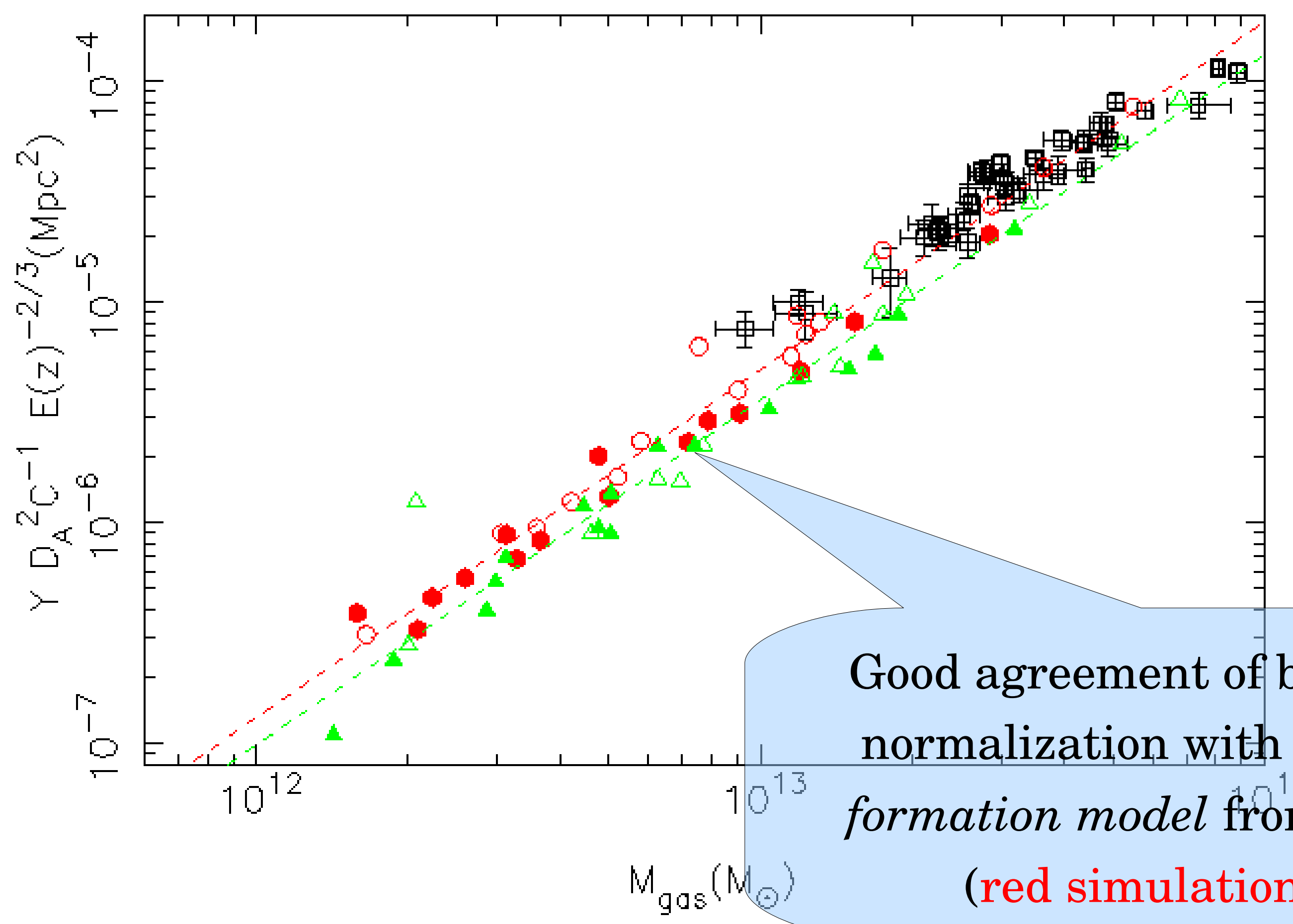




(Bonamente et al. 2008)

SZE/X-ray Scaling Relations: preliminary comparison with simulations

- Test the effect of cooling and star formation by comparison with the simulations of *Nagai (2006), ApJ 538, 549*



Good agreement of both slope and normalization with *cooling--star formation model* from simulations (red simulation points)

(Bonamente et al. 2008)

Conclusions

- Established observationally SZE scaling relations at $z<1$ for $Y - M_{tot}$, $Y - M_{gas}$, $Y - T$: can obtain T and M from Y.
- Successful comparison with numerical simulations
- SZE surveys upcoming (e.g., **SZA, APEX, SPT, ACT, AMI**) to detect clusters at all z, can implement cosmological tests (e.g., $d\mathcal{N}(>\mathcal{M})/dz$)

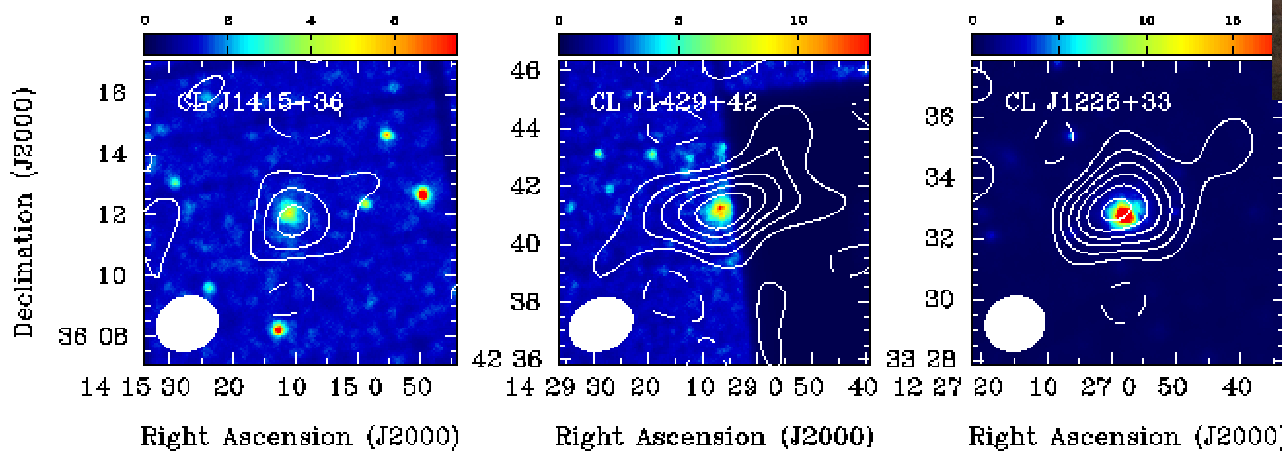
FUTURE WORK:

- The *Sunyaev Zeldovich Array* (SZA) has just started operations: Larger FOV (12') than OVRO/BIMA, two bands (~30 and ~90 Ghz), 8 GHz bandwidth

Conclusions

- *What the Sunyaev Zeldovich Array can do for scaling relations*:

* High redshift clusters (Muchovej et al. 2007)

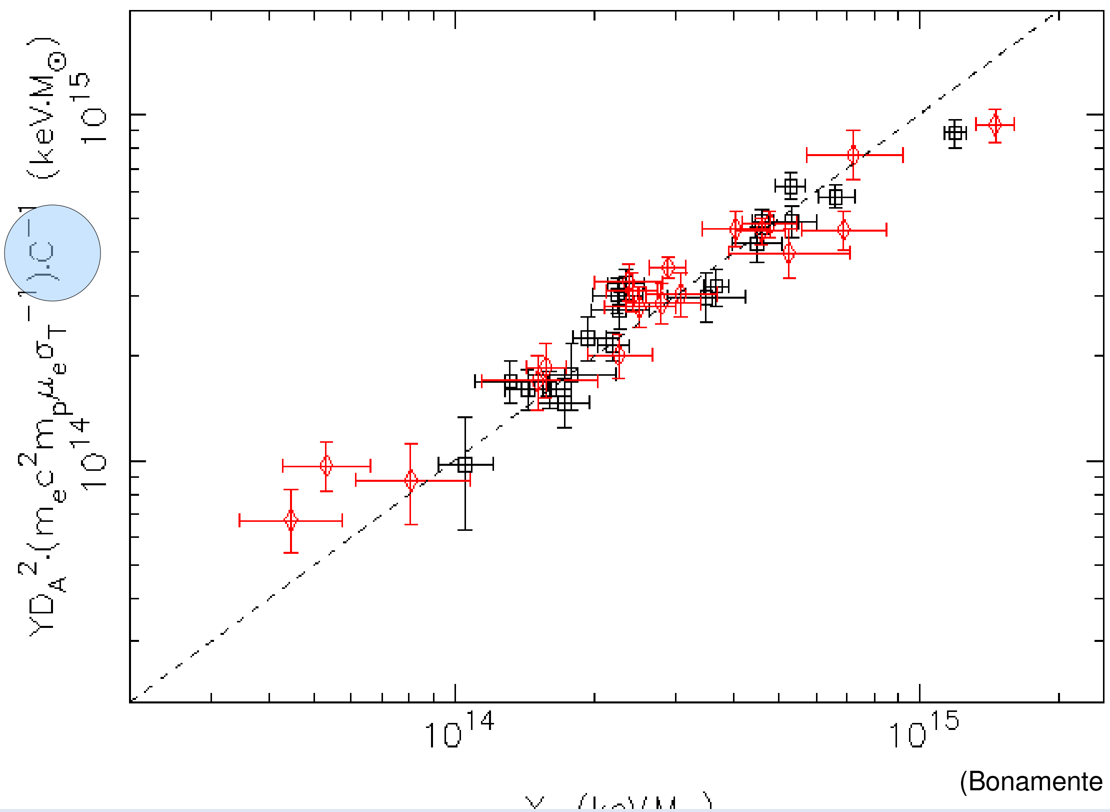


Muchovej et al. (2007)

* Extend to lower mass clusters
* Data for complete sample of 35 BCS clusters at z~0.25
* More accurate modeling of the intra-cluster medium (T. Mroczkowski)

Comparison of Y with Y_X

- The X-ray observable $Y_X = M_{gas}(r_{2500})\,kT$ proposed as low-scatter proxy of total mass (Kravtsov et al. 2006)
- Can directly establish equivalence between Y and Y_X using our data



(Bonamente et al. 2008)

SZE/X-ray Scaling Relations: Comparison with simulations

- Test the level of pre-heating (entropy floor) by comparison with the simulations of *McCarthy et al. 2003, ApJ 591 526*