Modelling the Sunyaev Zeldovich Scaling Relations
(Implication for SZ Power Spectrum)

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Outline

- Sunyaev Zeldovich effect and Scaling relations
- Cluster structure modeling
- The ICM pressure profile
- SZ scaling relations : comparison with observations
- SZ power spectrum and CBI excess

CLUSTERS & THE SUNYAEV ZELDOVICH EFFECT

The intracluster medium (ICM) at temperatures of several million Kelvin emits X-Rays mainly through THERMAL BREMSSTRAHLUNG

CMB Photons while passing through the ICM get *UPSCATTERED*

→ *“ SUNYAEV ZELDOVICH EFFECT “*

Spectral distortion in the CMB spectrum i.e. increment if ν > 218 GHz , null at 217 GHz and a decrement at lower ν .

Frequency dependence

Thermal energy

$$S_\nu = \frac{j_\nu(x)}{D_a^2(z)} \frac{\sigma_T}{m_e c^2} \int kT n_e \, dV$$

Redshift independent

SCALING RELATIONS

"Scaling relations" connect the mass and various observables (like T, Szflux etc) to each other.

If *gravity* alone influences cluster properties , scaling relations are SELF SIMILAR (Kaiser 1986) .

X-ray M-T relation ⟵

$$M_{\Delta_c} \propto T^{3/2} E^{-1}(z)$$

Ysz – T relation ⟵

$$\Delta S \propto \int y(\theta) \mathrm{d}\Omega \propto d_A^{-2} \int T n_e \mathrm{d}^3 r \propto d_A^{-2} T^{5/2} E^{-1}(z)$$

Nongravitational heating due to supernovae, AGN, star formation , galactic winds, cooling cause etc ---> DEVIATIONS FROM SELF-SIMILARITY.

Observed deviations from self similarity :

- Lower normalisation of observed M-T relation
- Steeper slope of M-T relation and L-T relation
- Entropy floor

Deviations more prevalent in clusters with smaller mass and groups

Cluster structure modeling : 1 . The dark matter halo

The Dark matter halo , the primary component of a cluster is seen to follow the NFW profile from simulations :

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

→ Scale radius

This scale is encoded in the Concentration of the halo .

What is the cluster extent ?

The Virial radius (Spherical collapse model)

Overdensity Δ is 2500,500 for XRay;
200, 180Ω_m for N-body sims
~100 for the virial radius .

Critical density   overdensity

$$r_{vir} = \left[\frac{M_{vir}}{\frac{4\pi}{3}\rho_{crit}(z)\Delta_c(z)}\right]^{1/3}$$

A good cluster boundary is the shock radius that is typically 2-3 times the virial radius.

Cluster structure modeling : 2 . The baryonic component

The **β model** ,first proposed by Cavaliere and Fusco-Femiano in 1976 ,is the most commonly used model and is based on early observations .

$$S_X = S_{X0}\left(1+\frac{\theta^2}{\theta_c^2}\right)^{(1-6\beta)/2}$$

$$n_e(r) = n_{e0}\left(1+\frac{r^2}{r_c^2}\right)^{-3\beta/2}$$

X-ray surface brightness

Gas density

Typically values of β range from .5 to 1.

Recent model proposed by **Komatsu and Seljak** in 2002 is the most favoured one. This does not have any free parameters.

Even the K-S model faces tension

- It fails to reproduce the **scaling relations** at low masses.
- It is used in SZ-templates ; can't resolve the CMB arc-min scale **excess anamoly**

Cluster structure modeling : 3 . The gas dynamical equation

$$\frac{d\phi(x)}{dx} = \frac{1}{\rho(x)}\frac{dP(x)}{dx} + \frac{1}{\rho(x)}\frac{d[\rho(x)\sigma_r^2(x)]}{dx} + 2\beta(x)\frac{\sigma_r^2(x)}{x}$$

Gas pressure   Gas density   Radial velocity dispersion   Velocity anisotropy parameter

Last two terms vanish under Hydrostatic equilibrium

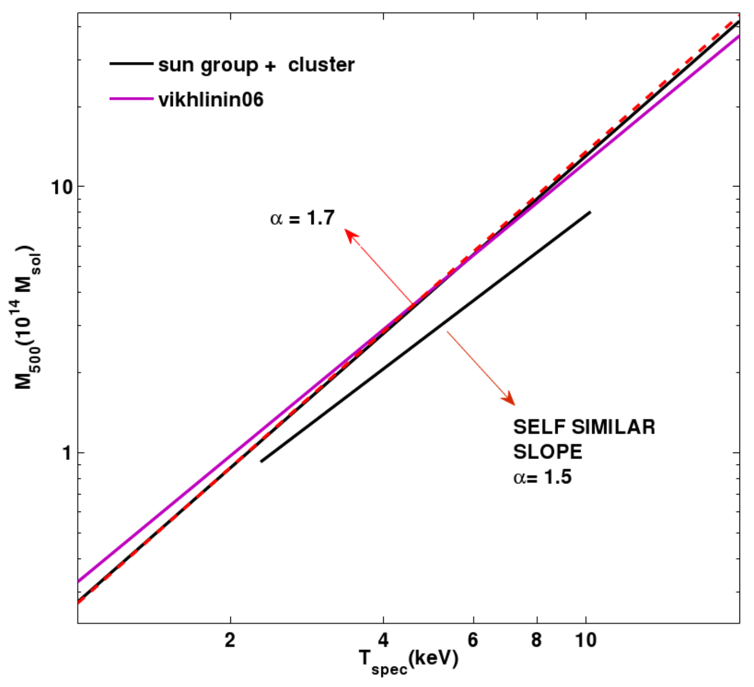
Masses underestimated by 10 % at R_{500} due to assumption of **H.E.**

For cc (cool core clusters) ,inside the core $T(r) \propto r^{.4}$

Outside the core for both cc and ncc clusters (Arnaud et al 2005,2007 ; Vikhlinin et al 2006) $T(r) \propto \rho(r)^{\gamma-1}$

Resulting temperature decline match well with observations .

Cluster Structure modeling 4. Normalising the profiles



$$M_\delta E(z) = A \left[\frac{T}{5keV}\right]^\alpha$$

Temperature normalisation

We normalize the temperature to the M-T relation from Sun et al 2008.

Density normalisation

Baryon fraction expected to be close to **universal baryon fraction** from simulations : (Kravtsov et al 2005 , Dolag et al 2006)

Observationally 10-15 % baryons are in stellar form : Overcooling observed in simulations.

Gas fraction is normalised at "cluster boundary", i.e atleast Rvir or beyond

At a glance

- Start with an initial temperature normalisation and find the density and temperature profiles.
- Average spectroscopic temperature is calculated between .1 R_{500} and R_{500}
- This is normalised to the temperature from the observed M-T relation.
- The equation for the gas profile is solved . i.e. Modified form of equation of Hydrostatic equilibrium . (Accounting for various forms of non-thermal pressure)
- Density profile is normalised by gas mass fraction
- Procedure is carried out iteratively since the average temperature depends on the density
- Self – Consistent gas density and temperature profiles are calculated

Gas profiles :

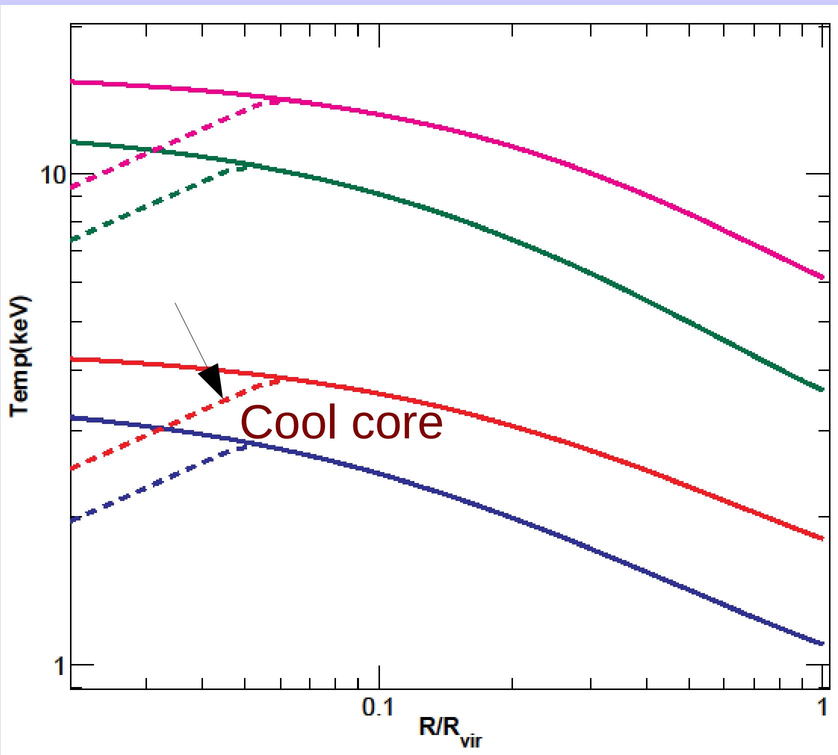
$M_{vir} = 10^{14}\ h^{-1}$, $z = 0$

$M_{vir} = 10^{14}\ h^{-1}$, $z = 1$

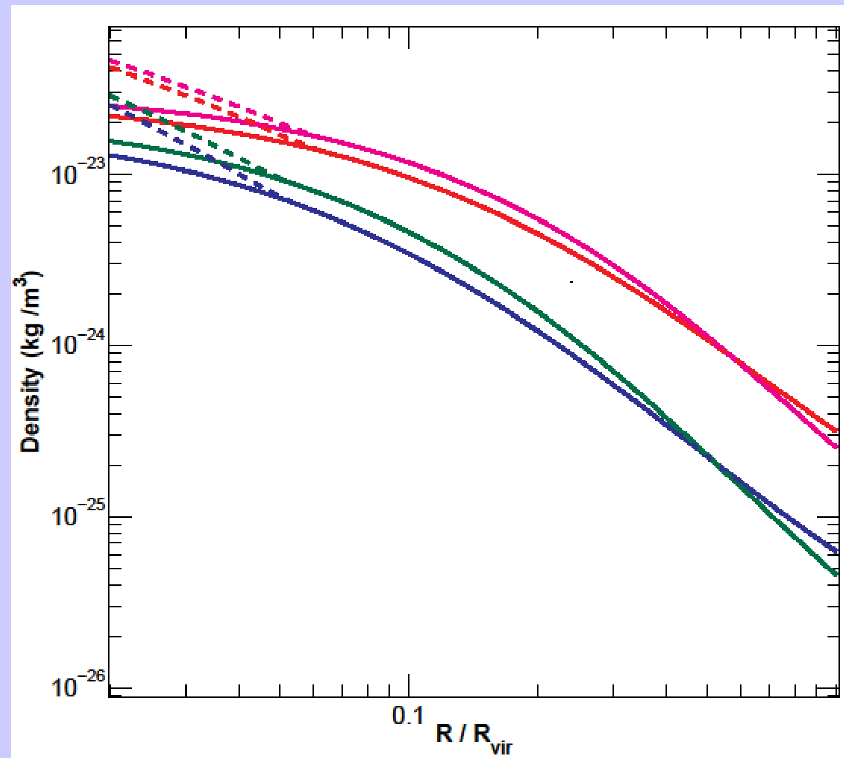
$M_{vir} = 10^{15}\ h^{-1}$, $z = 0$

$M_{vir} = 10^{15}\ h^{-1}$, $z = 1$

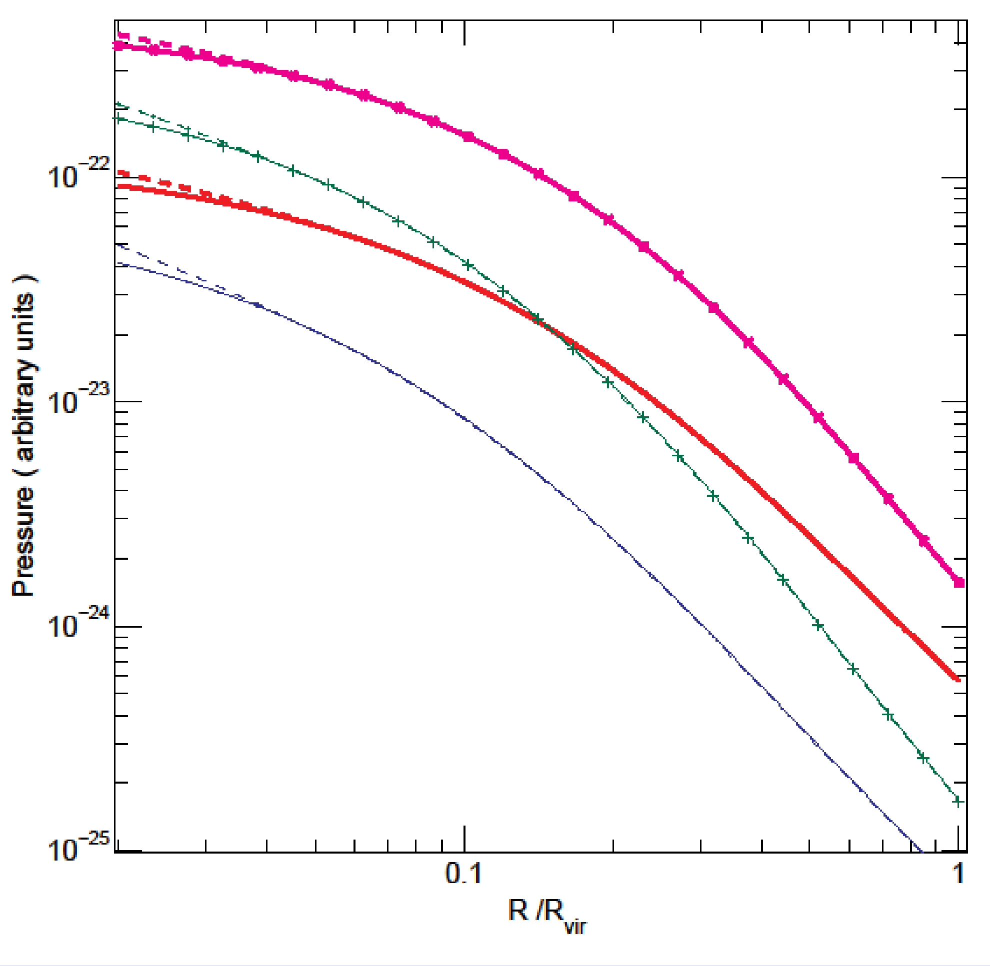
Temperature



Density



Pressure



$M_{vir} = 10^{14}\ h^{-1}$, z = 0

$M_{vir} = 10^{14}\ h^{-1}$, z = 1

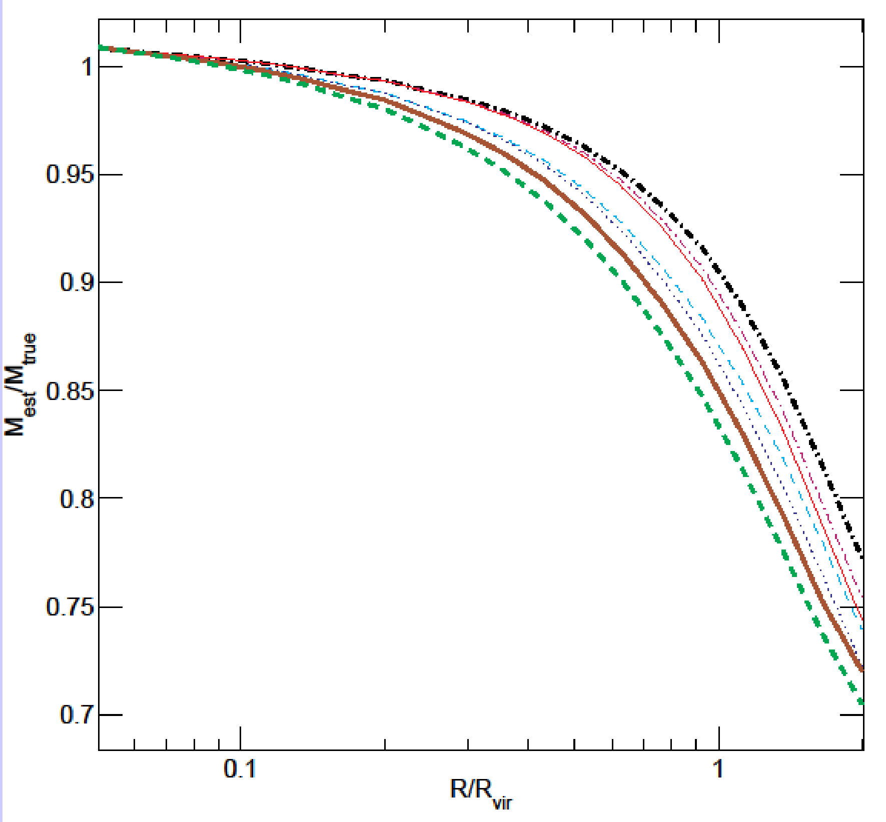
$M_{vir} = 10^{15}\ h^{-1}$, z = 0

$M_{vir} = 10^{15}\ h^{-1}$, z = 1

Cool core clusters and non cool core clusters have almost identical pressure profile

NON-THERMAL PRESSURE : ACTUAL CLUSTER MASS VS RECOVERED MASS :

Non –thermal pressure is mainly due to turbulent motions .

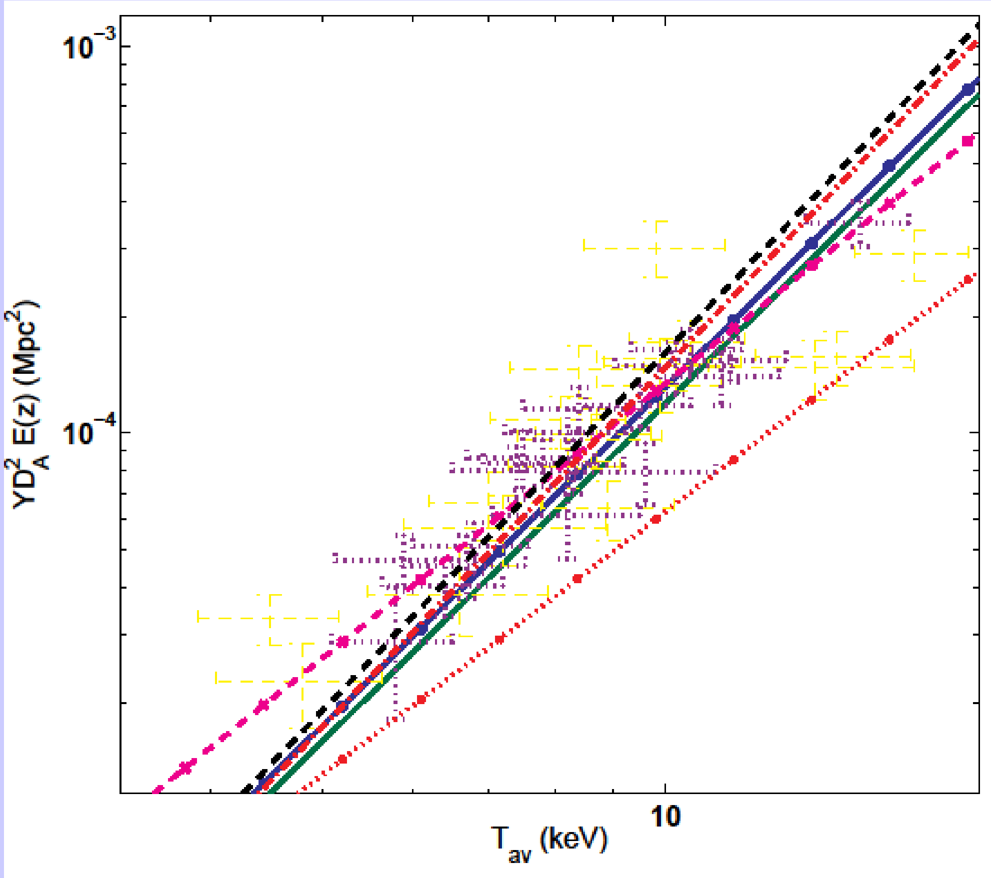


P_{nt}/P_{th} is taken from simulations (Rasia et al 2004) for the fiducial model.

Other reasonable amounts of non-thermal pressure are taken for other models.

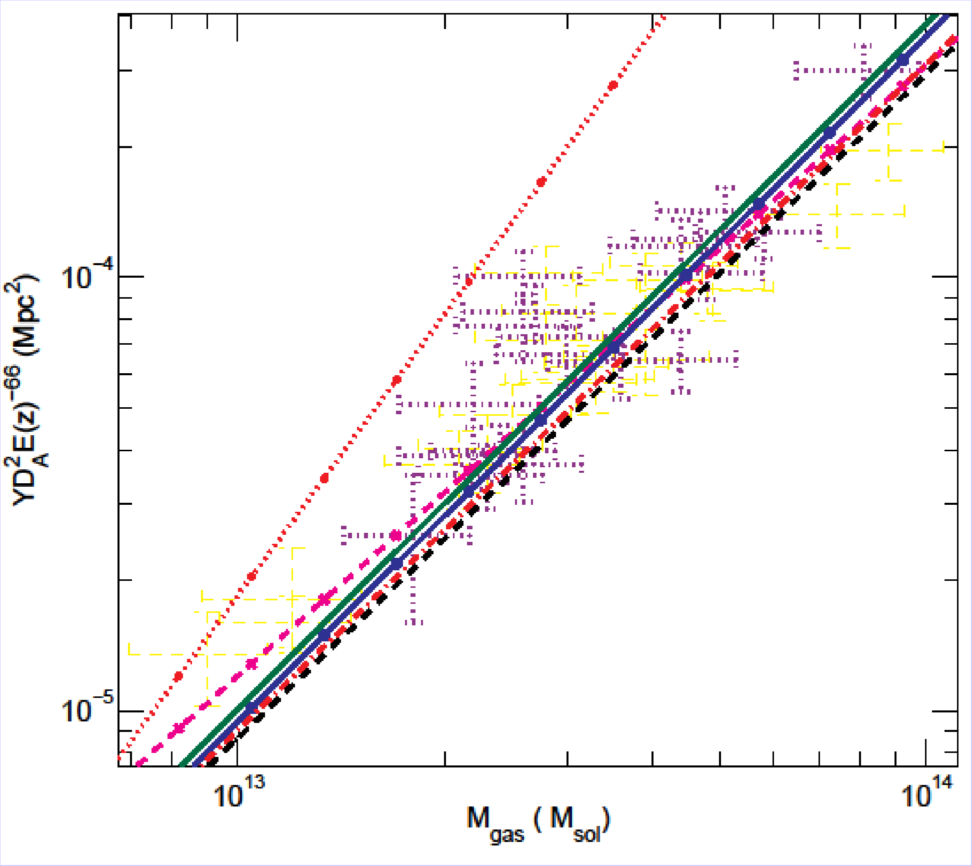
The S-Z scaling relations : comparison with observations

1. The Y – T_{av} relation



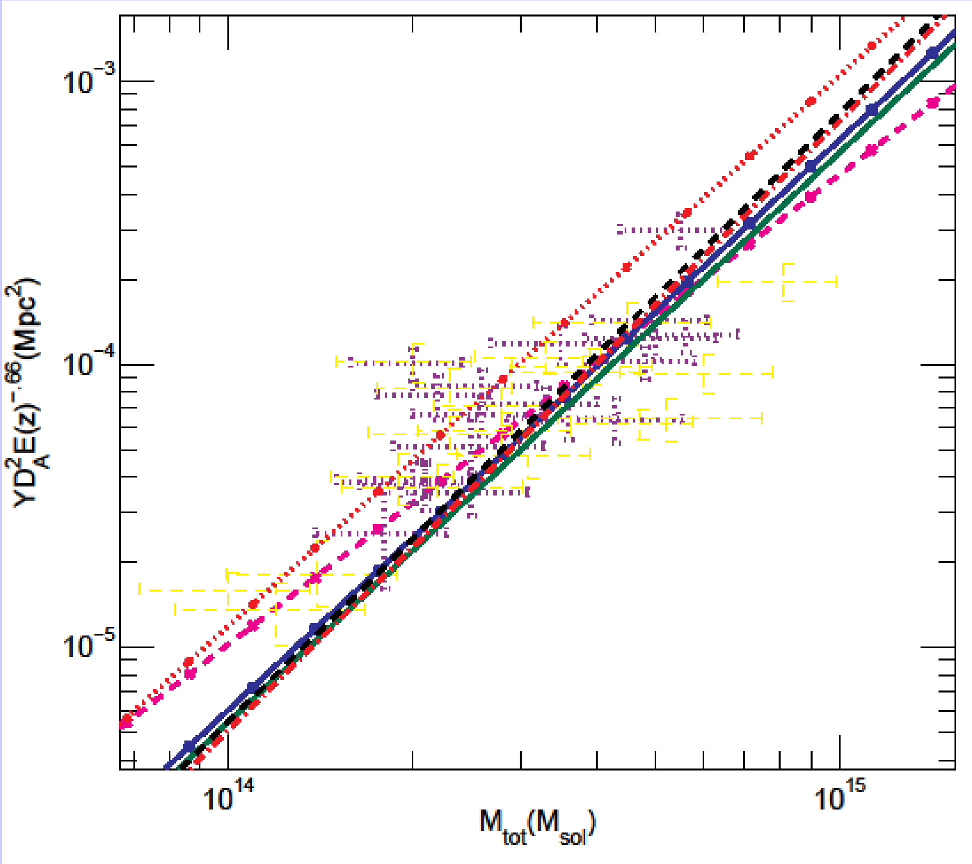
Y-T_X		
Model	A (norm)	B (slope)
Bonamente	-6.33±.32	2.46 ± .34
model 1	-6.80	2.92
model 2	-6.84	2.91
model 3	-6.93	3.10
model 4	-6.88	3.09
thermal 1	-6.77	3.07
thermal 2	-6.70	2.95
K-S	-6.47	2.28

2. The Y – M_{gas} relation



Y-M_{gas}		
Model	A (norm)	B (slope)
Bonamente	-25.86 ± 3.45	1.60 ± .25
model 1	-25.55	1.58
model 2	-25.51	1.58
model 3	-25.01	1.54
model 4	-24.98	1.53
thermal 1	-25.16	1.54
thermal 2	-25.58	1.57
K-S	-33.01	2.18

3. The Y – M_{tot} relation



Y-M_{tot}		
Model	A (norm)	B (slope)
Bonamente	-31.20 $\pm$5.35	1.87 $\pm$ .35
model 1	-33.43	2.015
model 2	-33.45	2.01
model 3	-35.46	2.15
model 4	-35.37	2.15
thermal 1	-35.19	2.14
thermal 2	-34.05	2.06
K-S	-32.28	1.95

Y200 Scaling relation:

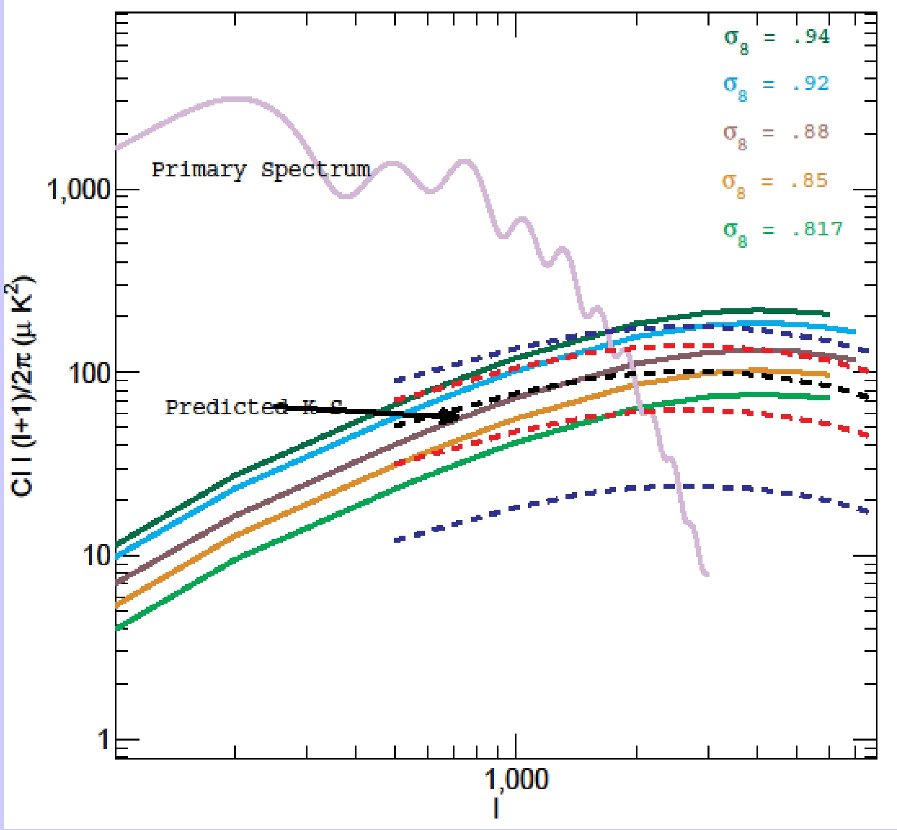
Model	A_{te}	B_{te}	A_{mg}	B_{mg}	A_{mt}	B_{mt}
fiducial	-6.26	2.78	-25.57	1.53	-28.06	1.61
$\gamma = 1.12$	-6.22	2.77	-25.62	1.54	-27.93	1.61
c0 = 9, c_{exp}=.17	-6.25	2.82	-25.40	1.52	-27.97	1.61

- SZ flux increases as the non-thermal pressure is decreased.
- The flux decreases with an increase in the polytropic index .
- There is a slight increase when the concentration is decreased .

This is the first prediction of SZ scaling relations at r200 that is consistent with both X-ray and SZ observations

The S-Z power spectrum : comparison with observations

$$C_l = f_\nu^2 \int_0^{z_{max}} \frac{dV}{dz} dz \int_{M_{min}}^{M_{max}} \frac{dn}{dM} dM y_l^2$$



$$C_l \propto \sigma_8^{6\text{-}8} (\Omega_b h)^2$$

Weak dependence on other cosmological parameters

Excess power seen at l >1800

CBI excess

Using the K-S model,Sievers et al 2009 find the best fit :

$\sigma_8 = .922$;

We get the best fit $\sigma_8 = .84$

CONCLUSIONS :

- We have built a simple phenomological model for galaxy clusters based on x-ray observations and simulations.

- This model predicts SZ scaling relations at R2500 that are in very close agreement with observations.

- The scaling relations at r_{200} have been predicted .This is important for cluster surveys

- The SZ power spectrum is compatible with the excess power observed at high l values (CBI excess)