# Two Topics in Cluster Cosmology: Studying Dark Energy and $\sigma_8$

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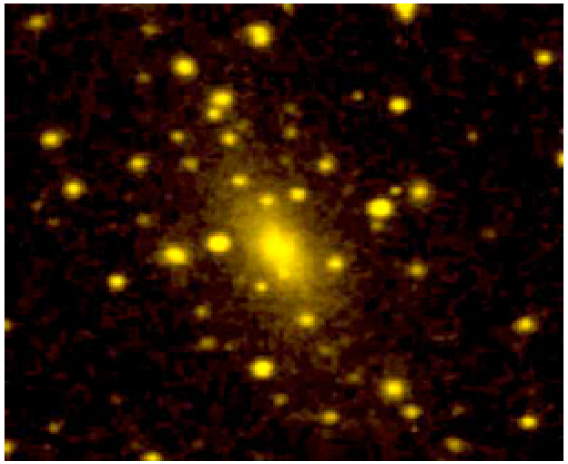
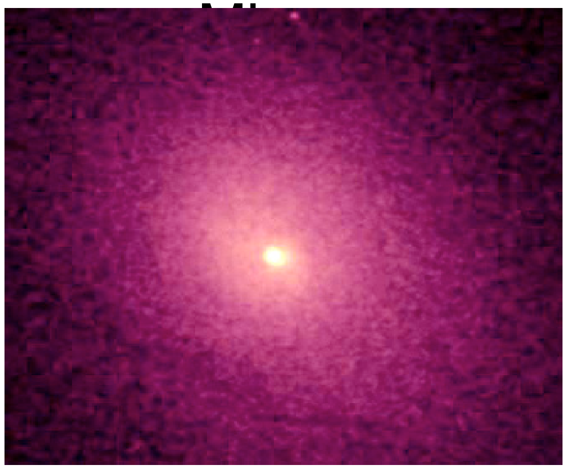
# What are galaxy clusters ?

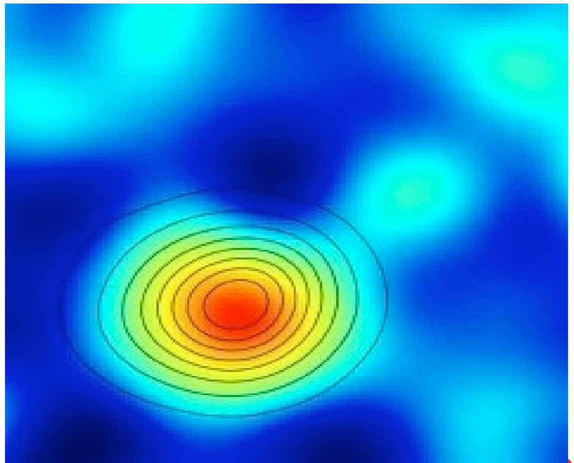
- Clusters of galaxies -> Most massive objects ($M > 10^{14}$ $M_{Solar}$), **large and easy to detect**
- They typically contain ~ $10^2$ - $10^3$ galaxies. --> Optical
- Size ~ few Mpc
- Hot Gas in ICM @ $10^{7\text{-}8}$ K --> Xray, SZ
- Dark Matter ~ 85-87% --> Lensing

Optical





X-Rays



# Surveys dealing with clusters

Many many Surveys (**ongoing/finished**, **approved**, **proposed**) for potential cluster studies:

*** Red Sequence Cluster Survey**
*** Spitzer adaptaion of the RCS**
*** South Pole Telescope**
**APEX-SZ**
**Atacama Cosmology Telescope**
*** Blanco Cosmology Survey**
**Sunyaev-Zeldovich Array**
**XMM-LSS Serendipitous Survey**
**XMM-Cluster Survey**

**Pan-Starrs**
**Dark Energy Survey**
**Large Synoptic Survey Telescope**
*** eROSITA, Planck**

**Dark Universe Exporer, * Spitzer Legacy Extremeley Wide Survey**
**Cluster Imaging Experiment, Cluster Cosmology Atacama Telescope**
**Constellation-X, XRay Evolving Universe Spectroscopy**

ON SCALING RELATIONS AND SELF-SIMILARITY -

Assumption: Gravity ONLY decides the thermodynamic state of the ICM. No preferred scale→ hence self-similar (first proposed by Kaiser)_

Mass $M_{\Delta c}$ is enclosed in radius $R_\Delta \rightarrow$ $M_\Delta \sim \rho_c(z)\Delta_c R^3_\Delta$

$\rho_c(z) \sim E^2(z)$_

$R \sim M^{1/3} E^{-2/3}(z)$_

**1) M-T reln:**

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

**2) $L_X$-T reln:**

$$L_X = \int_V \left(\frac{\rho_{\rm gas}}{\mu m_p}\right)^2 \Lambda(T)\, dV$$

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

**3) SZ relns:**

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

$$y_0 \propto T^{3/2} E(z) \propto L_X^{3/4} E^{1/4}(z)$$

## SCALING RELATIONS and CLUSTER COSMOLOGY -

The relations between the different integrated properties of a cluster and with its mass are known as scaling relations.

Ex – Xray Flux – Mass / SZ-flux – Mass / GasTemp – Mass/ Xray Flux – Temp etc

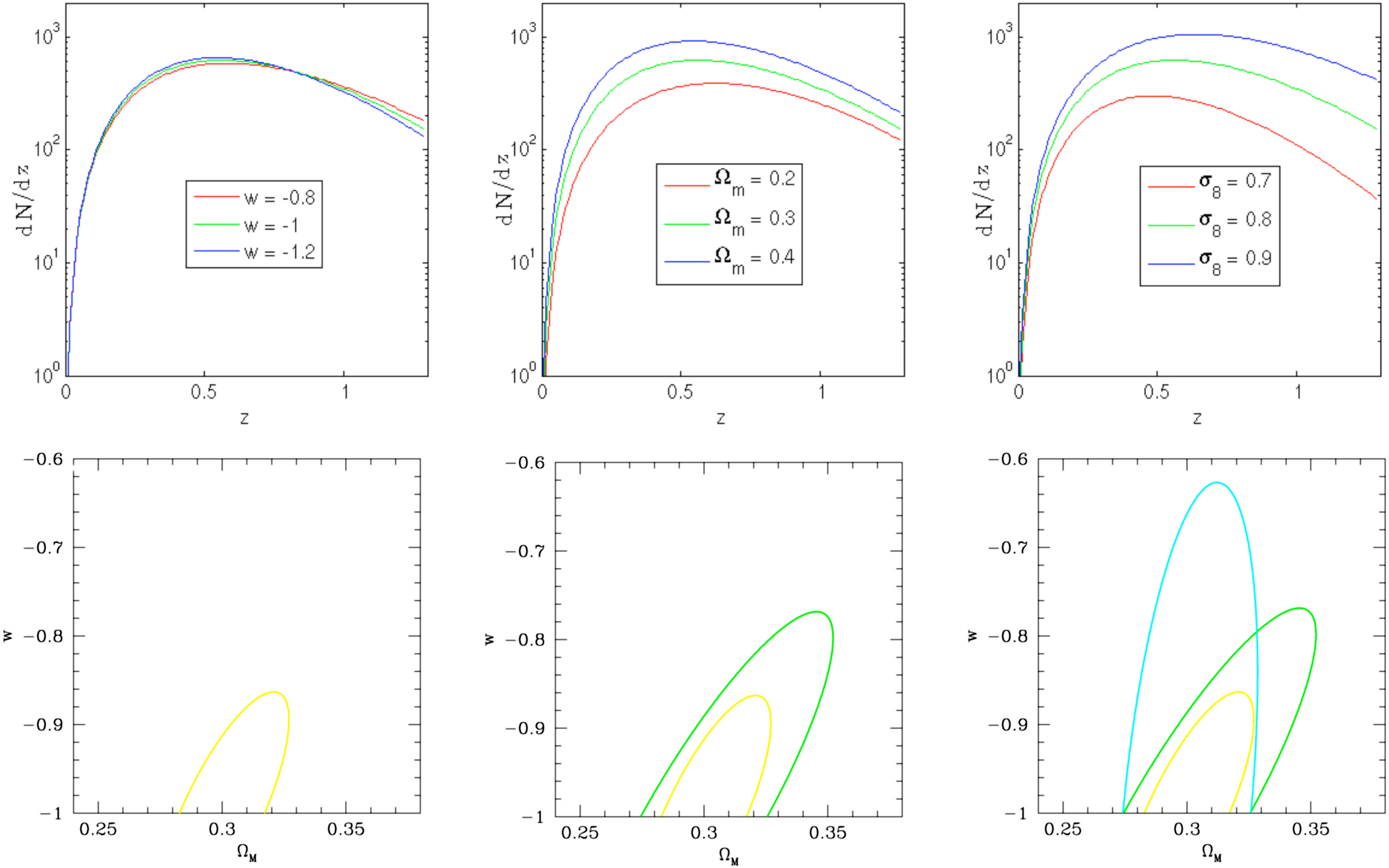
A) Cosmology – cluster connection is mainly through mass. For example, the mass function of
- haloes (i.e clusters) depends sensitively on cosmology (like sigma8, DE etc).
- Many cluster surveys are planned/ongoing use clusters as cosmological probes.
- Similarly, new CMB anisotropies due to clusters depend on how these clusters of diff masses
- are distributed in the sky.

- B) Unfortunately, for most of these surveys/CMB anisotropies clusters masses are not directly
- measured. They have to inferred from cluster obervables (like flux).

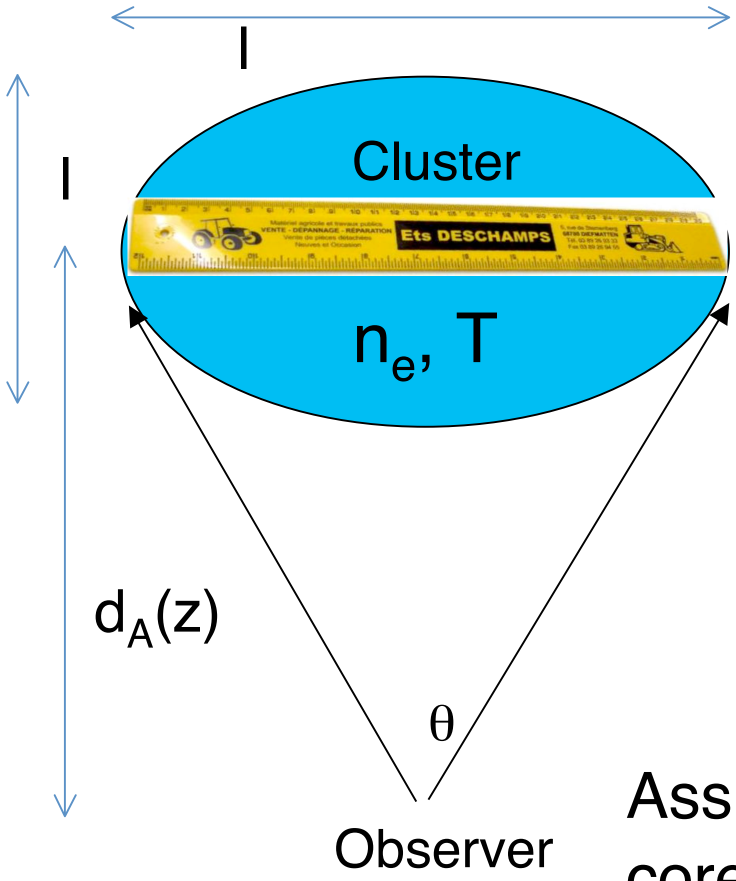
- So, KNOWLEDGE OF SCALING RELATION IS CRUCIAL FOR USING CLUSTERS IN
- COSMOLOGY.
- **INCORRECT SCALINGS ----> INCORRECT COSMOLOGY.**

- C) Theoretical understanding needed because observationally one cannot go to large cluster
- radii to cover the entire mass of the cluster.

# Cosmology with cluster numbers ?



# Estimating the size of the cluster using bith SZ + Xray …




$$\Delta T_{CMB} \propto \int n_e T_e dl \quad \& \quad S_X \propto \int n_e^2 T_e^{1/2} dl$$

Estimate: $l \sim \dfrac{(y_{SZ})^2}{S_X T^{3/2}}$

Compare with observed θ to get $d_A$

$$d_A = l/\theta$$

Assume a cluster model, say β-model (estimate th
core radius as the standard ruler) and do the mat

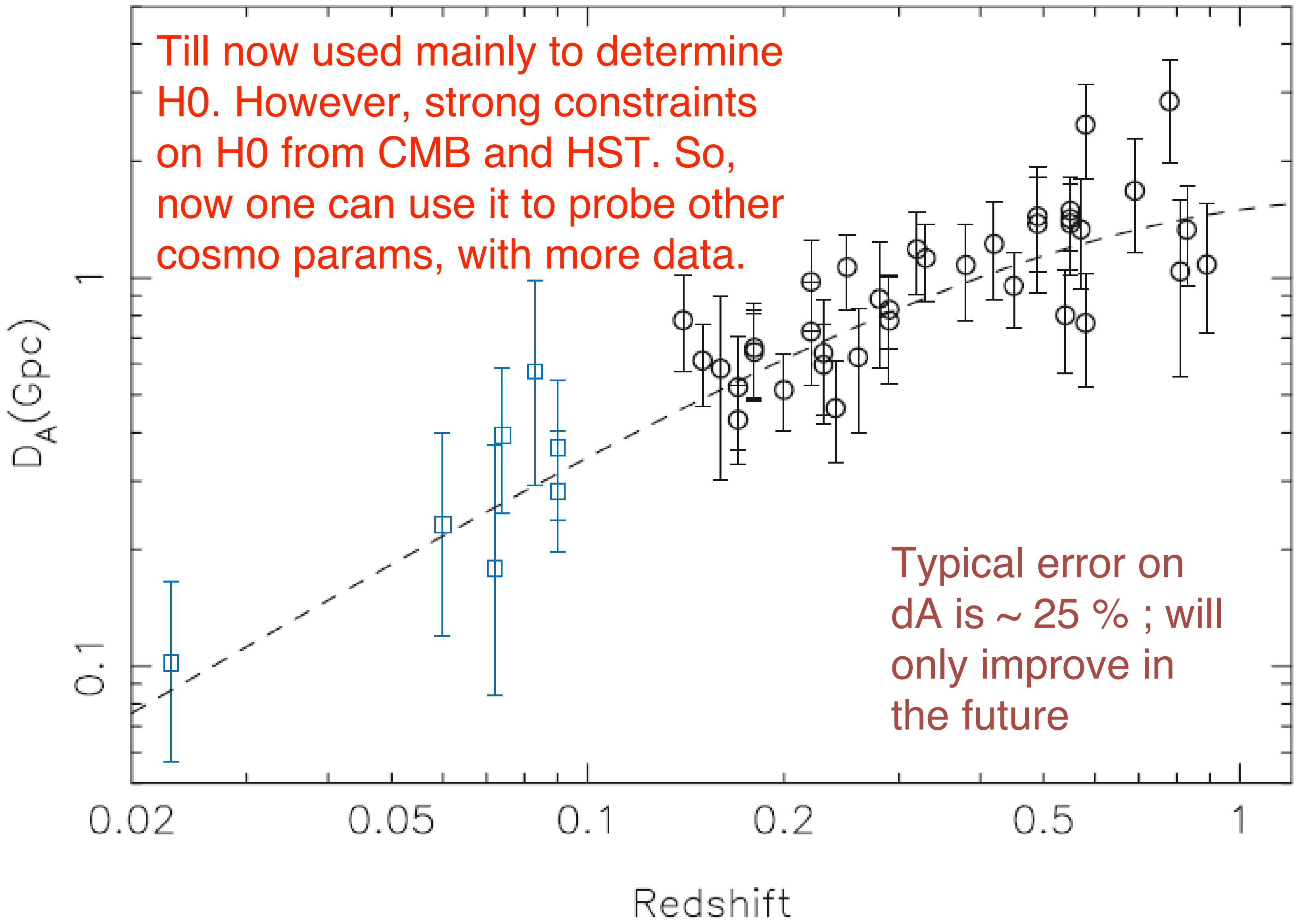
$$n_e(r) = n_{e0}\left(1+\frac{r^2}{r_c^2}\right)^{-\frac{3\beta}{2}}$$

… Isothermal $\beta$ model

$$r_{c,est} = \frac{\left[\frac{\Delta T(\theta)}{T}\right]^2_{obs}}{S_X(\theta)_{obs}} \frac{\Gamma(3\beta-1/2)\Gamma(3\beta/2)^2}{\Gamma(3\beta/2-1/2)^2\Gamma(3\beta)} \frac{m_e^2 c^4 \alpha}{16\pi^{3/2}(1+z)^4 \sigma_T k_B T_{e,fit}^2}\left[1+\left(\frac{\theta}{\theta_{X,core}}\right)^2\right]^{-1/2}$$

# Getting dA(z) with clusters …

Bonamente et. al. '06

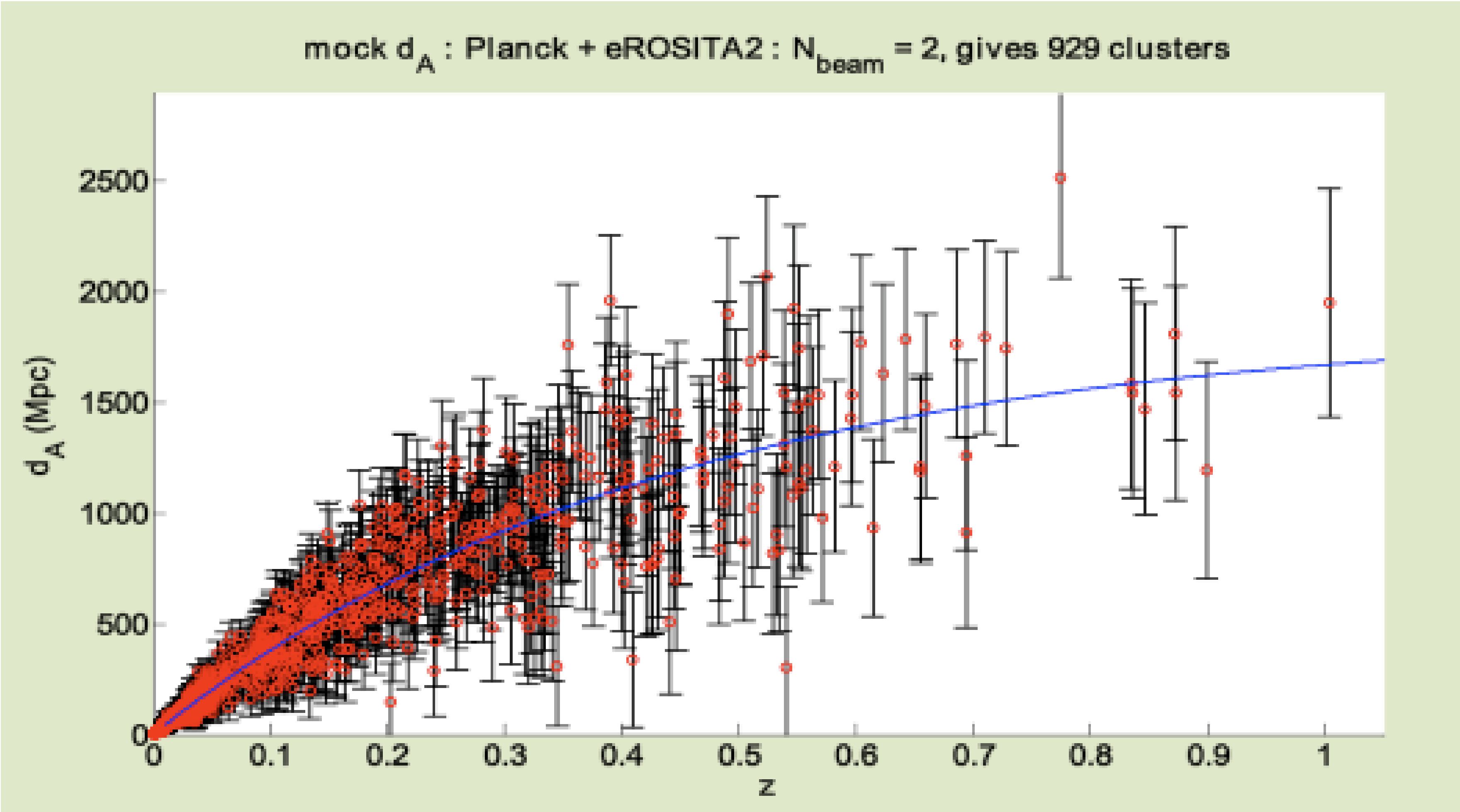



Till now used mainly to determine H0. However, strong constraints on H0 from CMB and HST. So, now one can use it to probe other cosmo params, with more data.

Typical error on dA is ~ 25 % ; will only improve in the future

38 clusters
:
Chandra
+ OVRO
+ BIMA

# From current to (mock) future data -



# So where do we get the clusters fom ?

- We consider the following 3 surveys –

SZ

a) South Pole Telescope: 4000 deg$^2$ @ 8 mJy

b) Planck : 30000 deg$^2$ @ 100 mJy (353 Ghz)

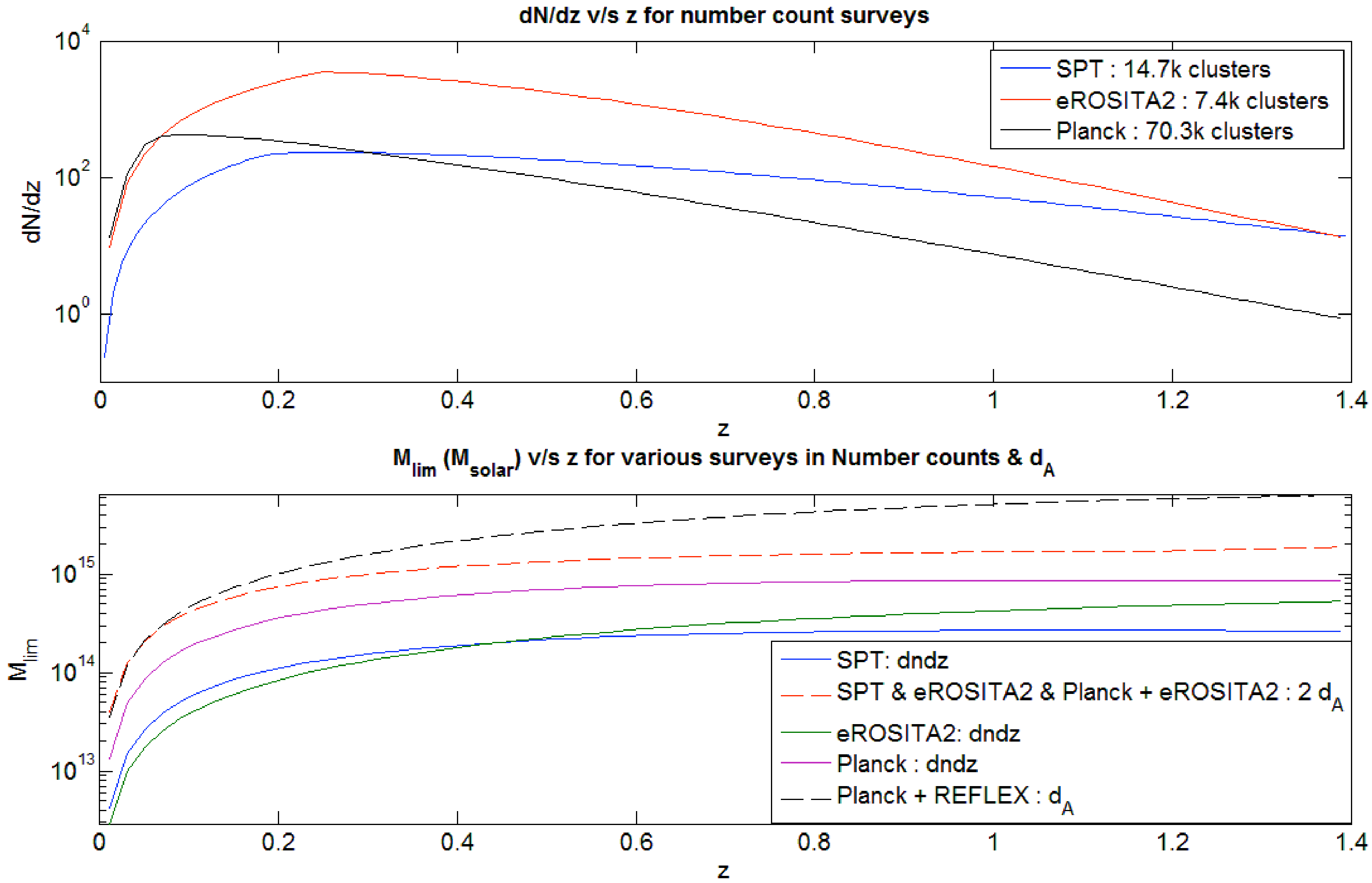
XR

c) eROSITA2 : 20000 @ 8.25 x $10^{-14}$ erg/cm$^2$/s

Various overlaps of these surveys are considered to obtain mock distributions of clusters at various redshifts.

Number counts constraints from the same SZ/XRay survey, added to those from $d_{A.}$ (common to SZ+Xray)

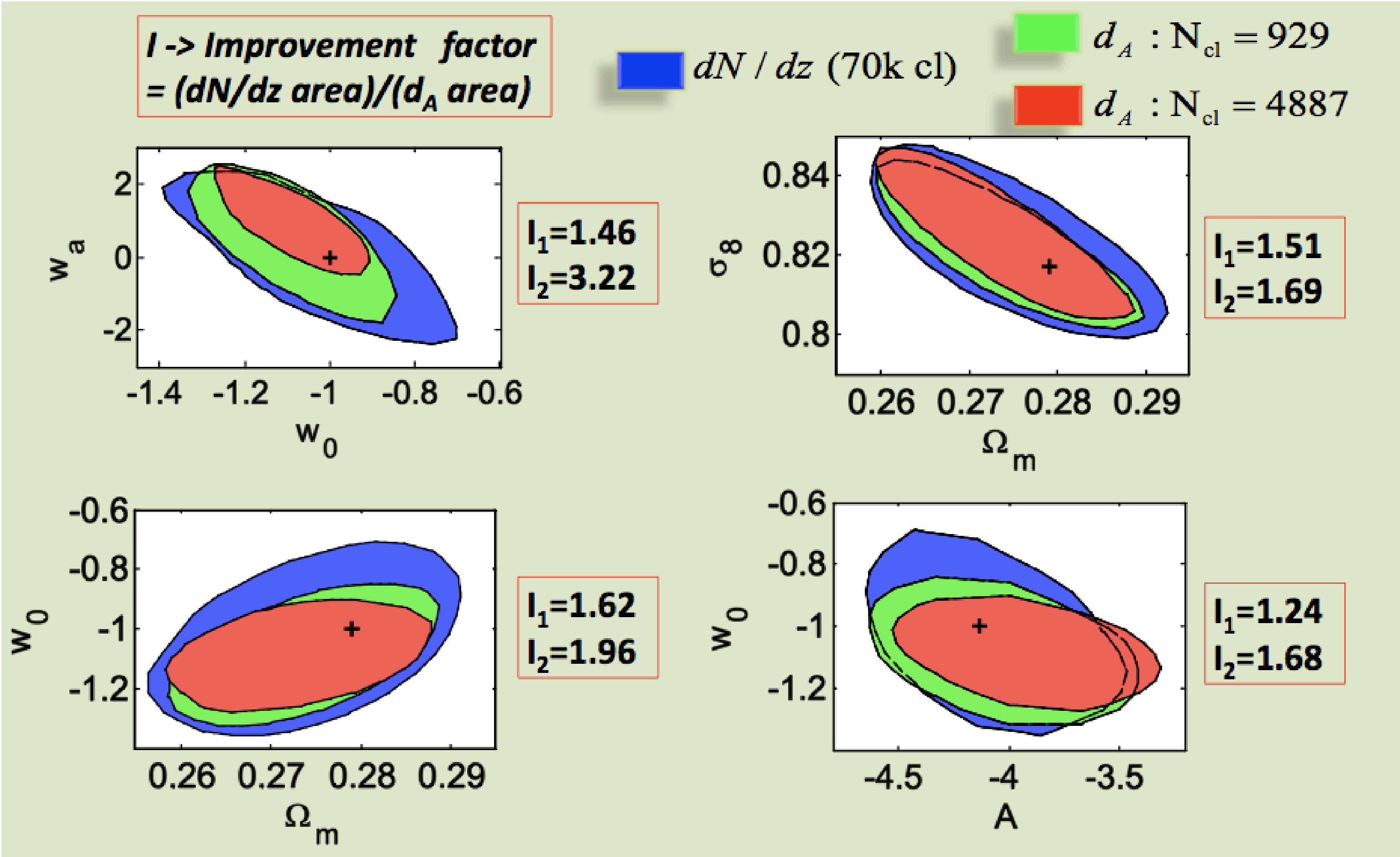
# Gathering the cluster rulers from overlapping surveys -



# The dA error budget -

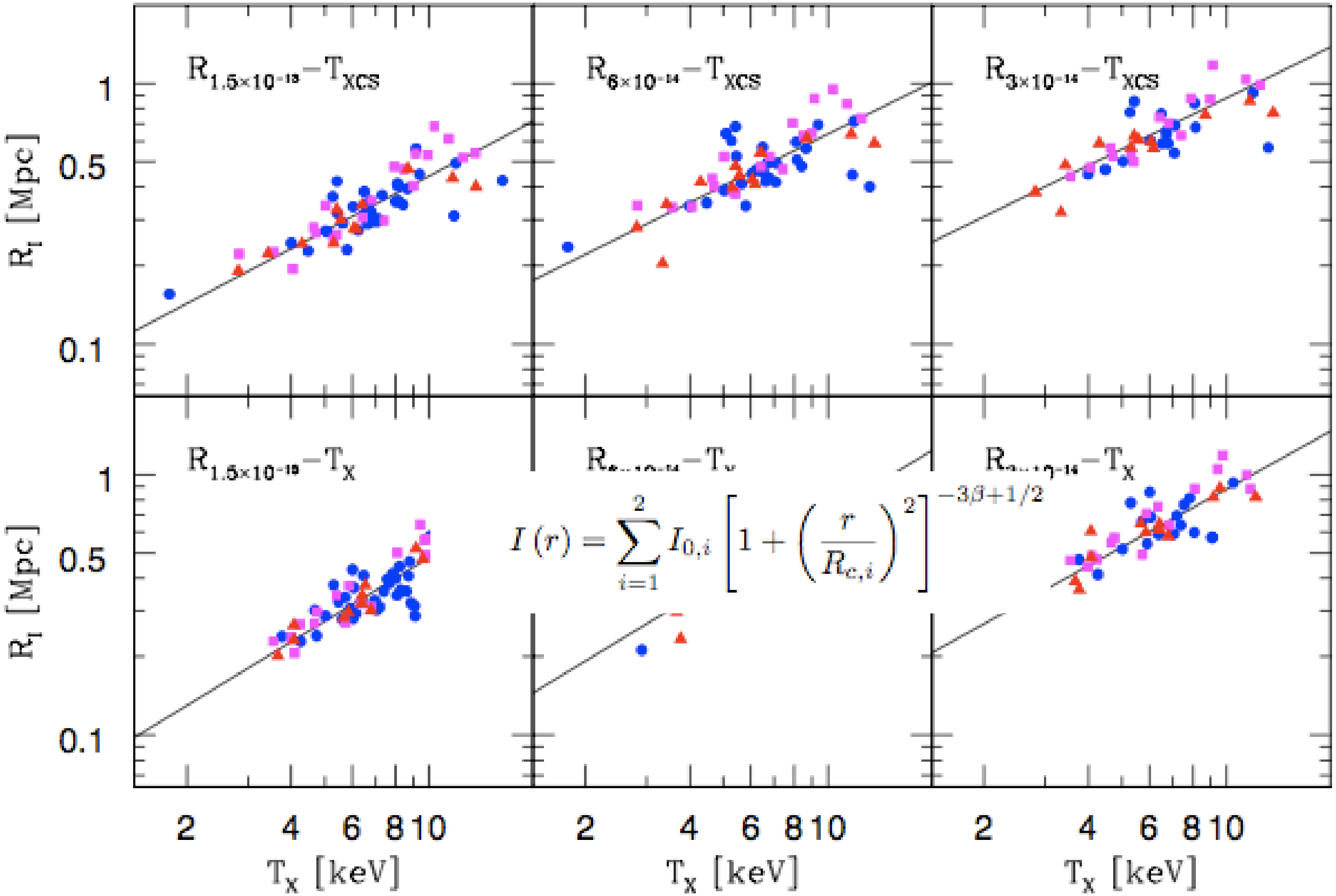
| Source | Effect on $D_A$ (%) |
|---|---|
| Statistical Contributions | |
| Galactic $N_{\mathrm{H}}$ | $\leq \pm 1$ |
| Cluster asphericity | $\pm 15$ |
| SZE point sources | $\pm 8$ |
| Kinetic SZE effect | $\pm 8$ |
| CMB anisotropy | $\leq \pm 2$ |
| X-ray background | $\pm 2$ |
| Systematic Contributions | |
| Presence of radio halos | $+3$ |
| X-ray absolute flux calibration ($S_{\mathrm{X}}$) | $\pm 5$ |
| X-ray temperature calibration ($T_e$) | $\pm 7.5$ |
| SZE calibration | $\pm 8$ |

… Bonamente et. al. (2006)



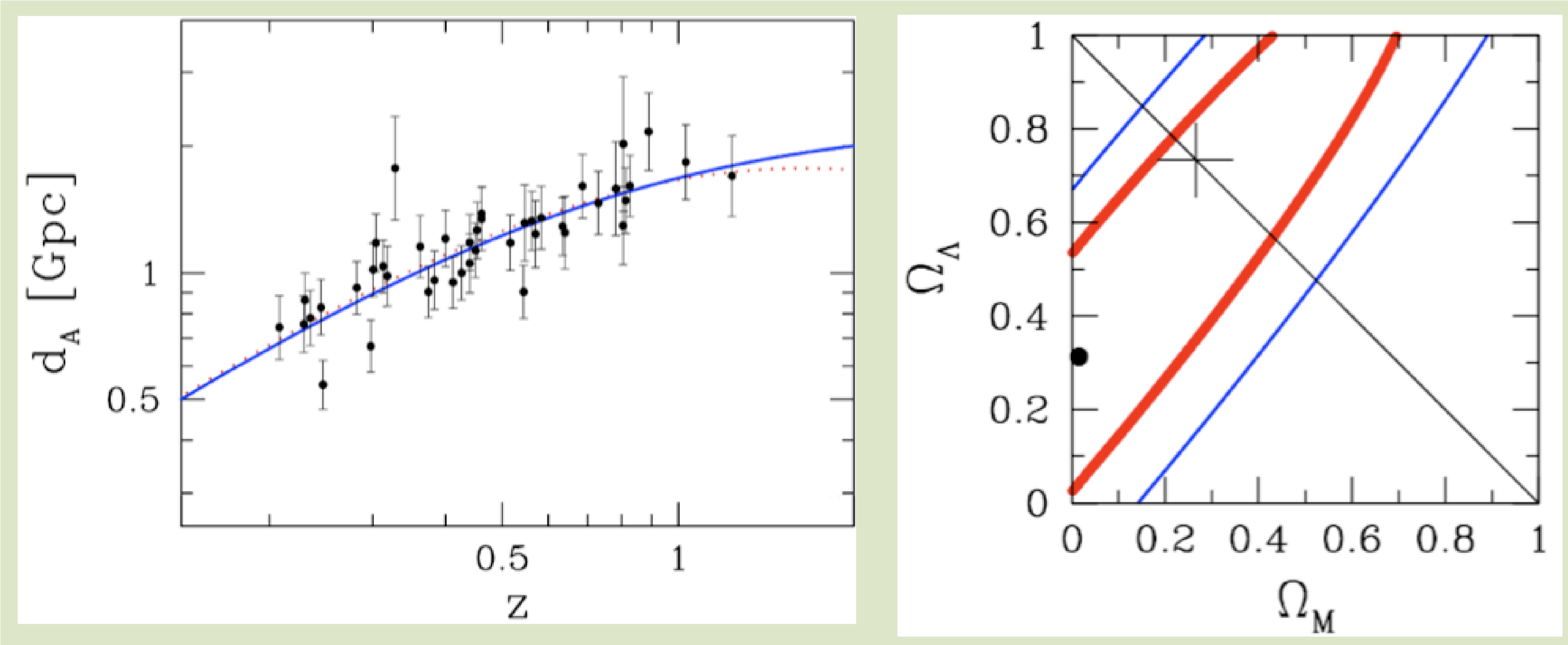
I -> Improvement factor
= (dN/dz area)/(d_A area)
dN / dz (70k cl)
d_A : N_cl = 929
d_A : N_cl = 4887
I1=1.46
I2=3.22
I1=1.51
I2=1.69
I1=1.62
I2=1.96
I1=1.24
I2=1.68
w_a
w_0
σ_8
Ω_m
A

# Isophotal Size and Cosmology -




For simple (say double-β model) $$I(r)=\sum_{i=1}^{2} I_{0,i}\left[1+\left(\frac{r}{R_{c,i}}\right)^2\right]^{-3\beta+1/2}$$

# Using Xray Isophotal size -
# Estimating dA with on only Xray clusters




**O'Hara, Mohr & Sanderson (2007)**

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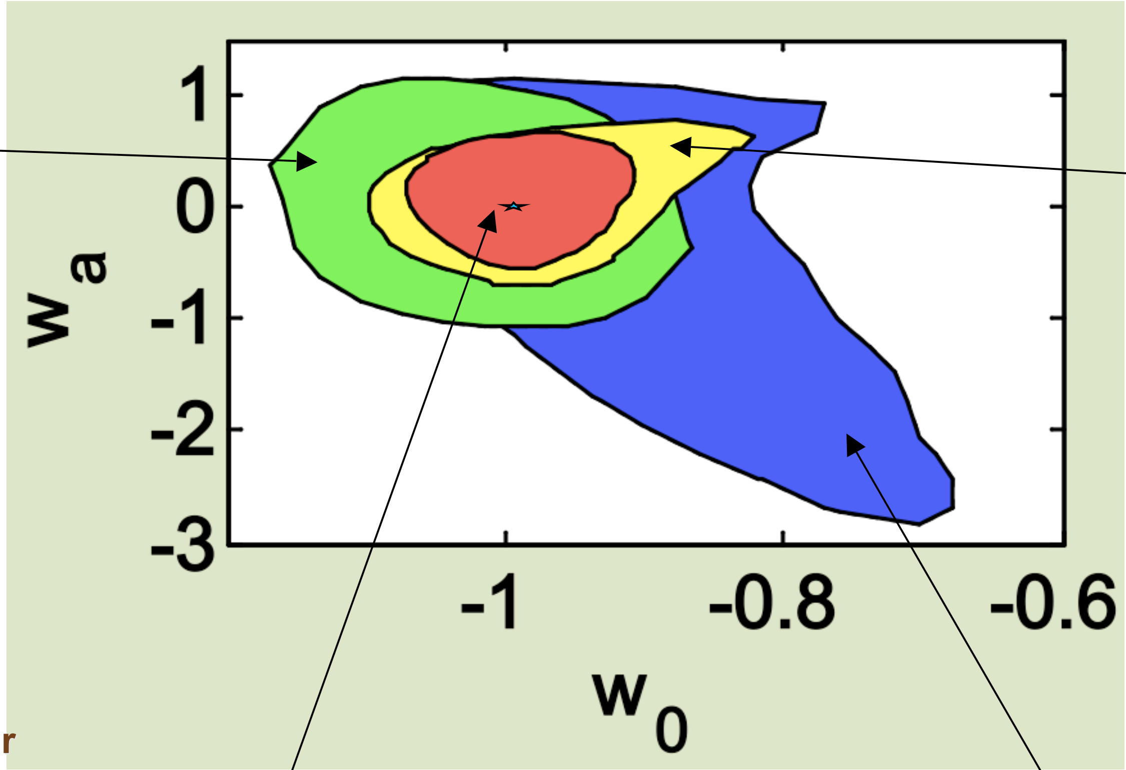
$$R_I = A_2 L^{\alpha_2} (1+z)^{\gamma_2}$$

$$\theta_I = \frac{R_I}{d_A} = A_2 \frac{L^{\alpha_2} (1+z)^{\gamma_2}}{d_A} = A_2 \frac{(4\pi \mathrm{d}_L^2 \times \mathrm{flux})^{\alpha_2} (1+z)^{\gamma_2}}{d_A}$$

# Result from Isophotal Sizes ..

Only dndz

dA+CMB




Khedekar, SM and Mohr (in prep)

dndz + dA
(no CMB prior)

Only dA

| Params | dn/dz | $d_A$ catalog 1 | $d_A$ catalog 2 | RI catalog |
|---|---|---|---|---|
| $\Omega_m$ | 0.011 | 0.0098 | 0.0092 | 0.008 |
| $w_0$ | 0.22 | 0.15 | 0.12 | 0.052 |
| $w_a$ | 1.5 | 1.2 | 1.0 | 0.38 |

# So what is *great* about this method if it succeeds in practice?

1. Bypasses mass measurement and hence mass uncertainties !!
   Makes full use of self-calibration without the ‘ifs and buts’ associated with
   Self calibration in number counts.

2. Orthogonal to dndz measurements and hence effectively break DE degeneracy.

3. Competetive in strength.

4. Can be use in conjunction with dndz to test gravity theories

5. No new observations needed. Isophotal size is very easy to do relative to other Measurements.

# Short Summary for Part One -

Using clusters are an ensemble of rulers can give additional handle on DE.

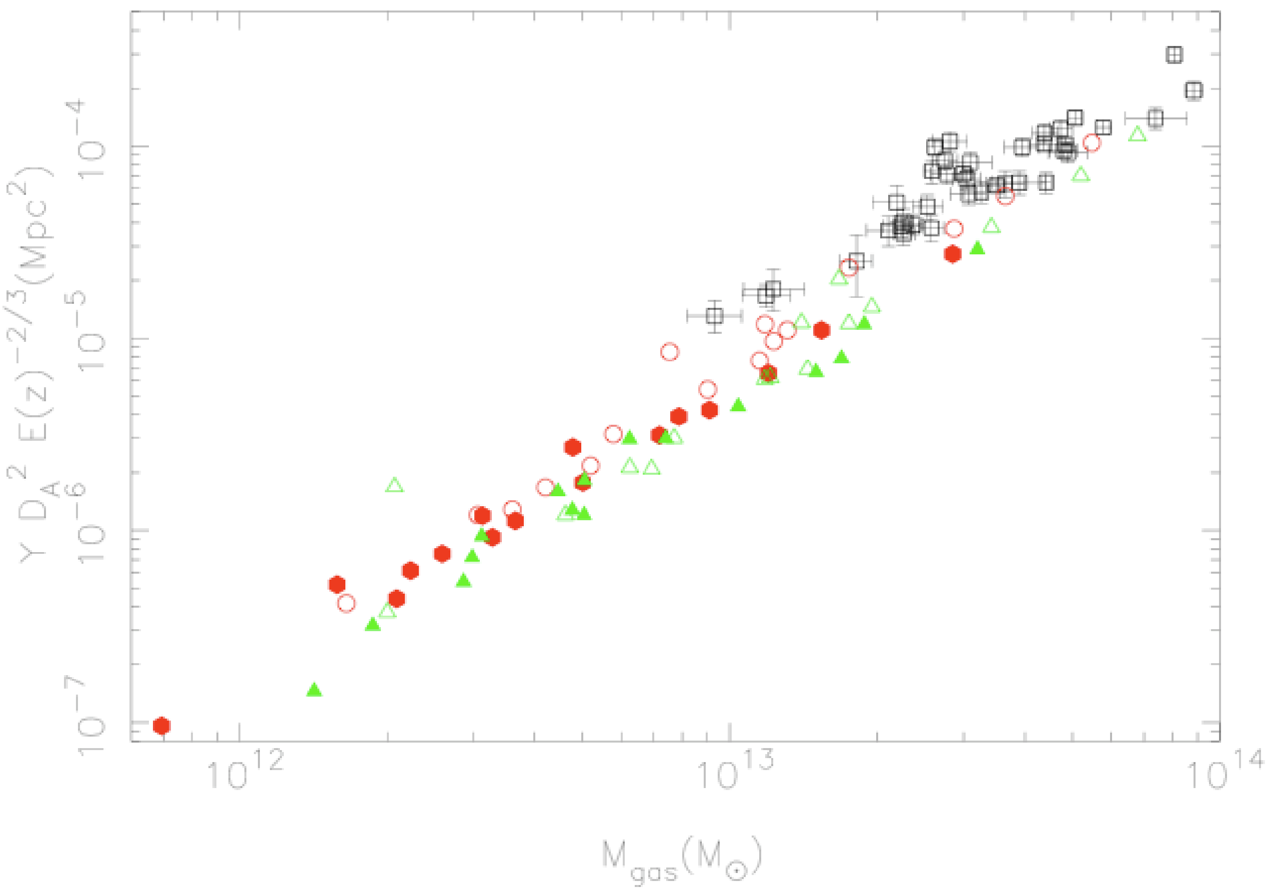
For clusters found in SZ & Xray surveys in common patch,  a typical cluster Scale radius cane be computed and hence dA at cluster redshift.

Using Isophotal sizes in Xray cluster surveys for cosmology can be a new and very powerful probe of DE.

This does not suffer from the problems of mass uncertainties.

It can give us % level constraints on DE.

# Cluster Scalings: Sims vs Theory --




**Observations:**
**Bonamente etal 2007**
**With SZA**

**Simulations:**
**Nagai & Kravtsov 2006**

# A bit of motivation -

Most analytical or simulation models are **'bottom-up'** models.
Simulations have similar problems to KS model. Both have many similarities.

Present cluster models faces tension :

1. It fails to reproduce scaling relations at low masses (Xrays)
2. Used as SZ cluster templates -vs- "CBI-excess" .

Ideally, one should just use 'observed scaling relns'.

Caveats – 1) Need good observations at higher redshifts also
2) There are no observations at virial radius.
3) SZ surveys have started but only two SZ observational scaling papers.
4) SZ flux is still measured at smaller radius.

Thus we need cluster model that will give SZ scaling relations that agree with observations at smaller radius, across a large mass range and which can then be used to predict scaling relations for the whole clusters.

**We build a very simple 'top-down' cluster model that fulfils these requirements.**
**Easier to run MCMC with analytic models**

ANALYTIC MODELLING OF GALAXY CLUSTER - THE DARK MATTER

1. The primary component of a cluster is the dark matter halo (NFW).

2. The size / mass of a halo - depends on our definition.
   a) They are connected by a constant over-density

   b) Choice of overdensity - i) xray observations typically go upto $\Delta$ = 2500, 500
   ii) Nbody sims use $\Delta$ = 200, $180\Omega_M$
   iii) Virial radius is $\Delta$ = 170 (for sCDM), ~ 100 (LCDM)

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

   c) Given NFW profile, one can covert between definitions.

   d) Clusters do not have a well-defined outer boundary. A `good' boundary is the shock radius _ typically 2-3 virial radius.
   Will be important later for normalization

The underlying variation is in halo concentration with cluster mass and redshift.
We use observed c-M relation from Comerford & Natarajan (2008)

# ANALYTIC MODELLING OF GALAXY CLUSTER - THE BARYONIC MATTER

1. Baryonic matter is dominated by Intra-cluster gas.

2. Following early X-ray observations, the most common and still used by many observers is the so called β-model, first proposed by Cavaliere & Fusco-Femiano (1976)_

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

$$M_{\rm tot}(r) = \frac{3\beta k T_X}{G\mu m_p}\frac{r^3}{r_c^2 + r^2}$$

_

Recent observations and simulations for long time shows model to be incorrect at small and large radii. Especially, gas profiles tend to be steeper at outer region
**--> model underestimates total mass.**

3. Later improvement is incorporating non-isothermality and analytically solving for gas in equilibrium in NFW haloes (spherical/triaxial) by Makino & Suto. But has free parameters.

4. Komatsu & Seljak (2001) has proposed a 'Universal model for cluster gas' based on simple assumptions (with no free params). This is the favoured model at present.

# THE TEMPERATURE PROFILE -

## Cool Core Clusters -

Due to increased density at cluster cores, cooling time is less than hubble time _ gas can cool easily and forms cool core. Gas flows in to form 'cooling-flows'.

We motivate our temp profiles from Xray observation :

1) within the cool cores (Sanderson etal 2007)

$$T(r) \propto r^{.4}$$

2) Outside the cool cores, we take the temp profile to be 'polytropic' (Vikhlinin etal 06, Sanderson 07, Arnaud etal 07, Sun etal 08)

$$T(r) \propto \rho(r)^{\gamma-1}$$

## Non Cool-core Clusters -

The temperature profile is taken to be polytropic through out. It is almost flat in the inner radii.
(Sanderson etal 2007, O'Hara etal 2007)

Our final temp profiles matches very well the trend and extent seen in observations of falling temperatures at large cluster radii.

# GAS DYNAMICAL EQUATION AND THE DENSITY PROFILE -

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

**THERMAL PRESSURE** **DISPERSION PRESSURE** **ANISOTROPIC PRESSURE**

$x = r/r_c$

We neglect the anisotropic term (typically small)

In general, most analytic models neglect non-thermal terms and only use term 1 (example, Komatsu-Seljak)

$$\frac{d\phi(x)}{dx} = \frac{1}{\rho(x)}\frac{dP(x)}{dx}$$

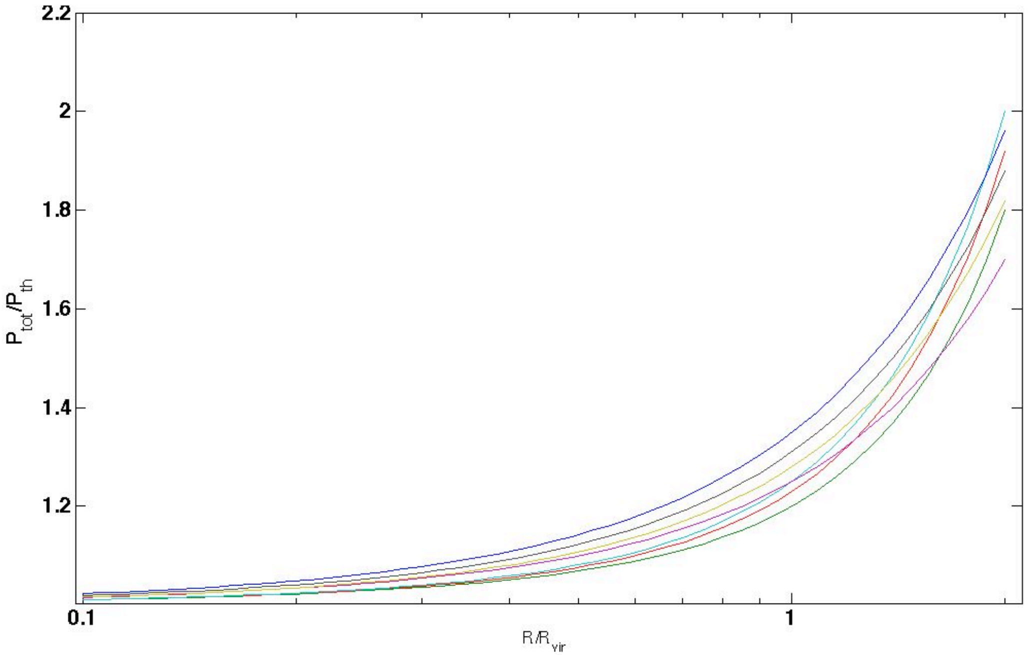
We know that neglecting non-thermal pressure biases mass-estimate
--> and hence scaling relations.
Bias is as bad as working with a beta-model mass estimate.

NON THERMAL PRESSURE CONTRIBUTION -

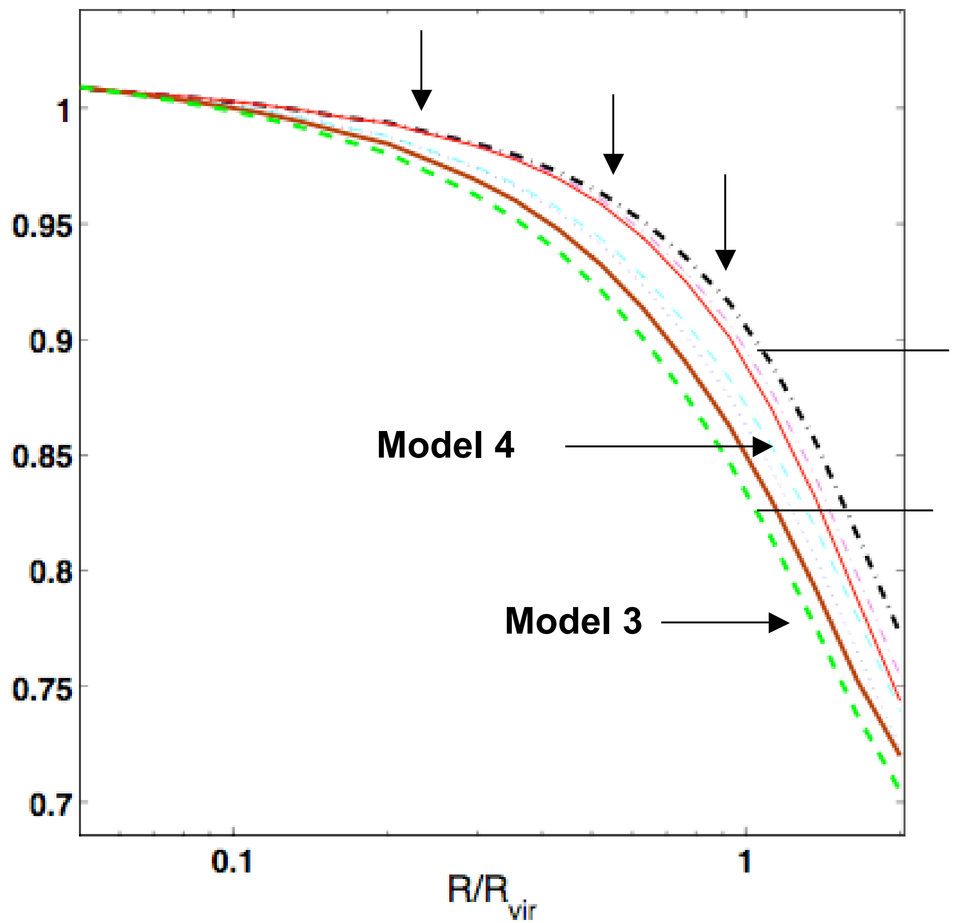
Xray observations do not give us any direct inputs into the non-thermal pressure support.

Simulations give a handle on non-thermal pressure. However, instead of adopting any particular simulation results, we only adopt the *relative thermal/non-thermal pressure*. This quantity is more 'robust' across different simulations

Rasia, Pfrommer pvt communication

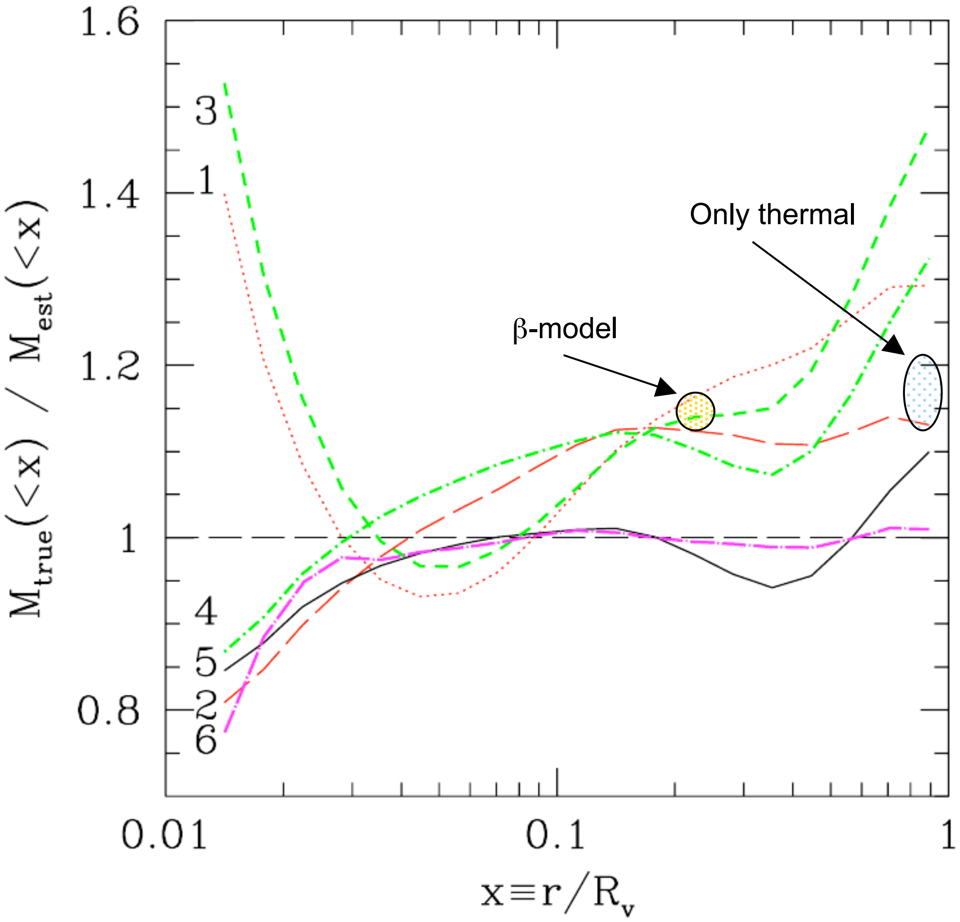



$$P_{NT}/P_T = \frac{\rho(x)\sigma_r^2(x)}{P(x)}$$

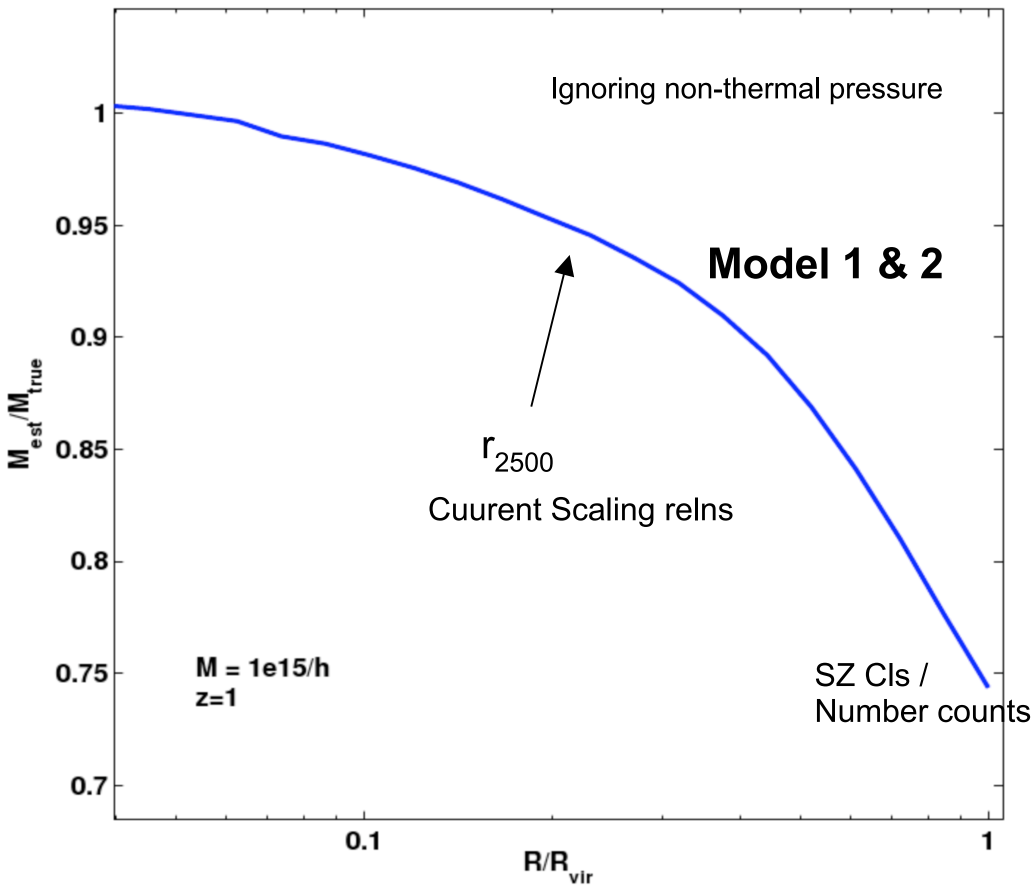


ACTUAL CLUSTER MASS – VS – RECOVERED MASS -

Simple hydrostatic eqlm or ignoring non-thermal pressure, assumption of isothermality as well as commonly used beta model biases recovered cluster mass.




Simulations (Rasia et al 2004)



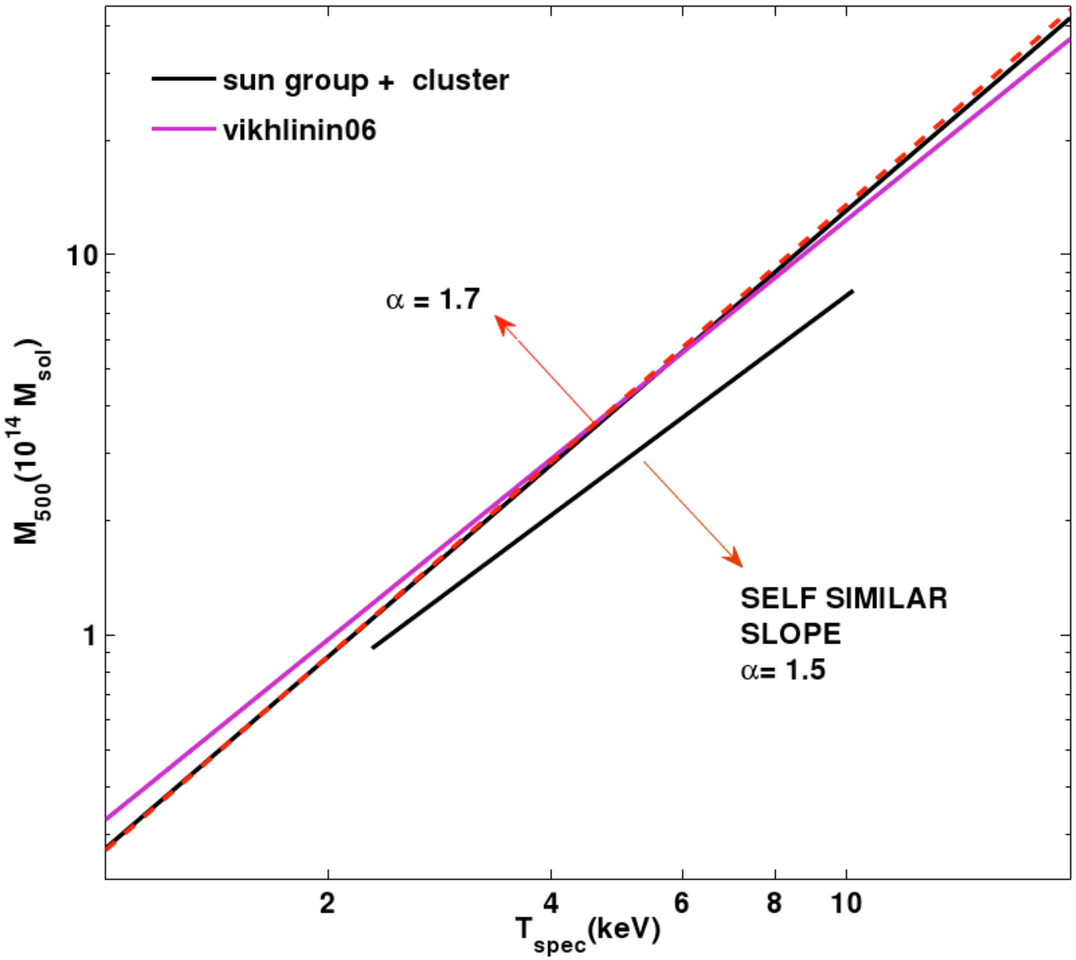

Model 1 non-thermal component

## NORMALIZING TEMPERATURE -

We hide our lack of knowledge of cluster gas physics by --> forcing the temperature to follow Xray observations 'exactly'.

OBSERVED M-T RELATIONS

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




We use M-T relation from Sun etal 2008 (more like a superset of previous data, like Vikhlinin)

$\alpha$ = 1.68 +/- 04 A = (2.85 +/- 0.18) $h^{-1}$e14 $M_0$

## NORMALIZING GAS DENSITY -

Cooling/heating influences gas fraction as a function of radius.
However, at sufficiently large scale (virial radius and beyond), the integrated gas mass fraction attains Universal value.

$$M_{gas}\,(r > R_{vir}) \;=\; O(1)\,\Omega_b/\Omega_m\;\; M_{halo}\,(r > R_{vir})$$

Different cases:

Model 1 - Universal at $R_{vir}$ ; $P_{tot}/P_{thermal}$ from Rasia etal (2004).
Model 2 - 0.9 * Universal and $R_{vir}$ ; $P_{tot}/P_{thermal}$ from Rasia etal (2004).

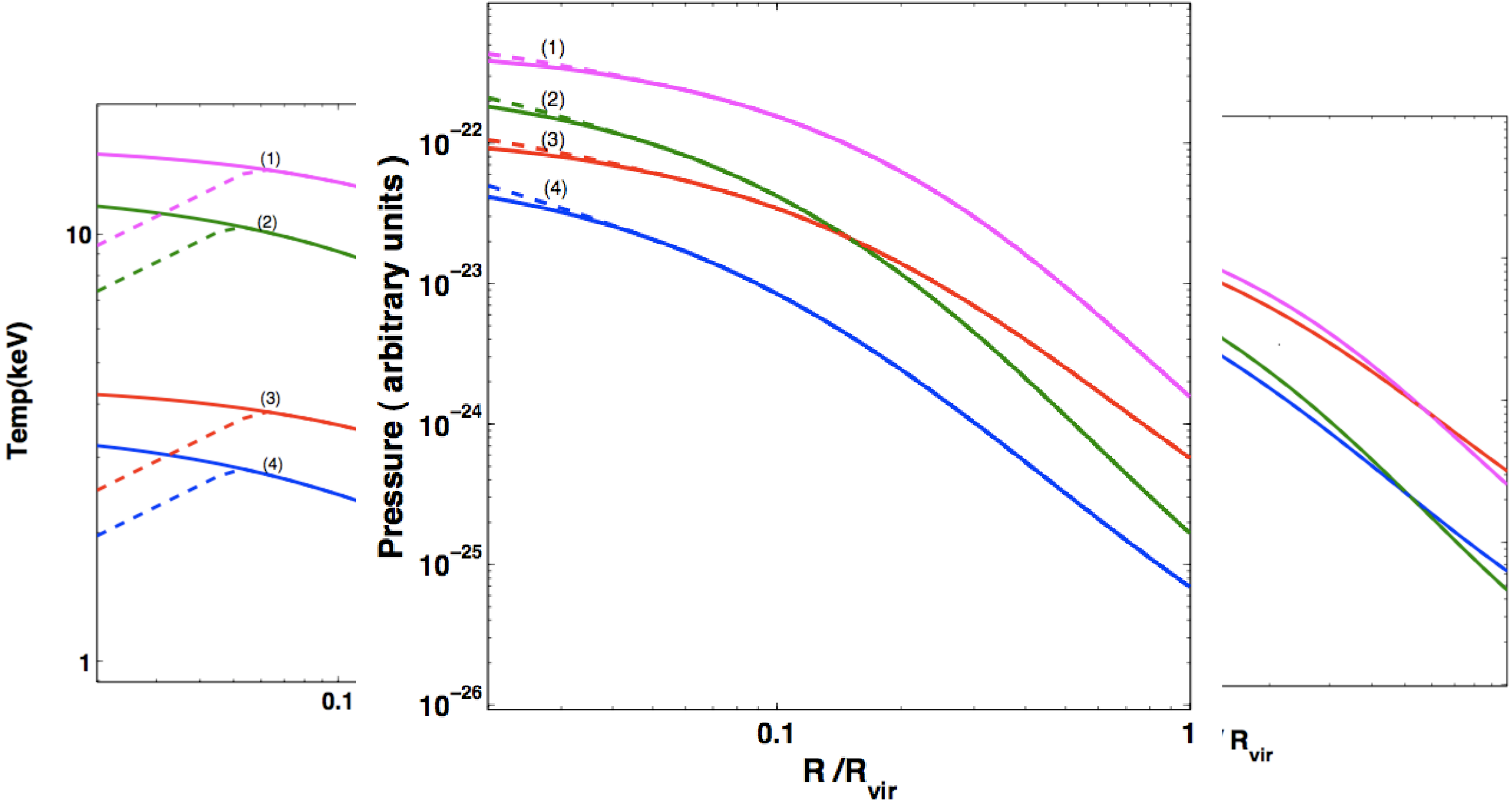
Model 3 - Universal at $2R_{200}$ ; $P_{tot}/P_{thermal}$ for highest non-therm press
Model 4 - Universal at $2R_{200}$ ; $P_{tot}/P_{thermal}$ for intermediate non-therm press

Model 5 - Universal at $2R_{200}$ ; only thermal pressure
Model 6 - Universal at $R_{vir}$ ; only thermal pressure

Temperature influences density through dynamical equation. Once mass normalised, the density influences calculation of average temperature, needed for normalization.

$$T_{sl} = \frac{\int n^2 T^{.75}/T^{1/2} dV}{\int n^2 T^{.75}/T^{3/2} dV}$$

Thus the set of equations need to be solved iteratively, for each model.




Cases: M ~ $10^{14}$/h $M_0$ , $10^{15}$/h $M_0$ , **z= 0.01, 1**

Recap -
Till now, our entire modelling of cluster gas density and temperature is based upon
1. Recent high resolution xray observations for temp
2. universality of baryon fraction at largest radii
3. non-thermal component from simulations.

With these, we construct SZ properties of clusters, i.e

1a) SZ cluster scaling relations (and compare with recent Bonamente etal 2008 obs)

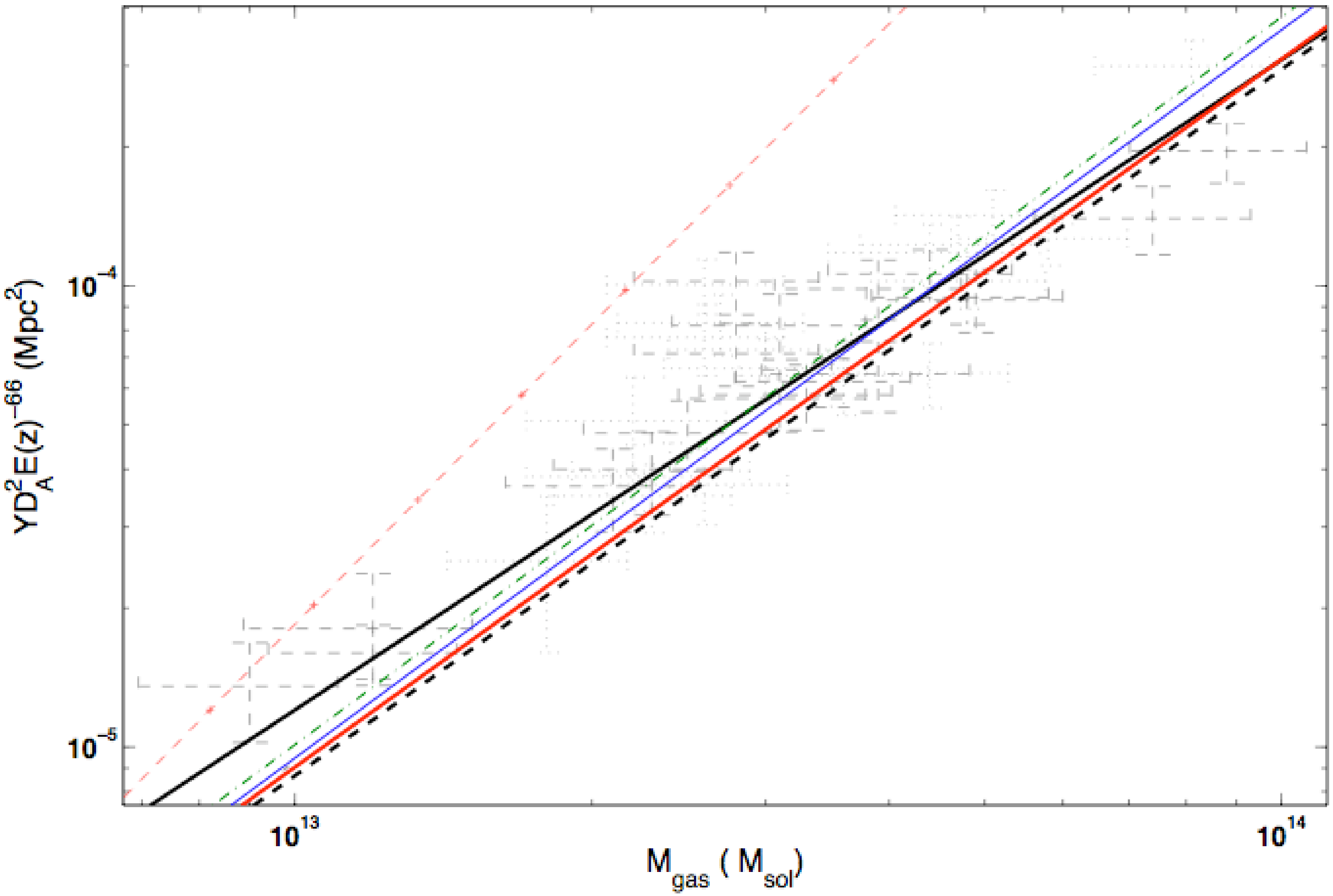
$$\log Y = A + B \log X$$

Y = SZ Flux

X = Gas Mass, Total Mass, Temperature

1b) SZ $M_{200}$ scaling reln needed for dndz

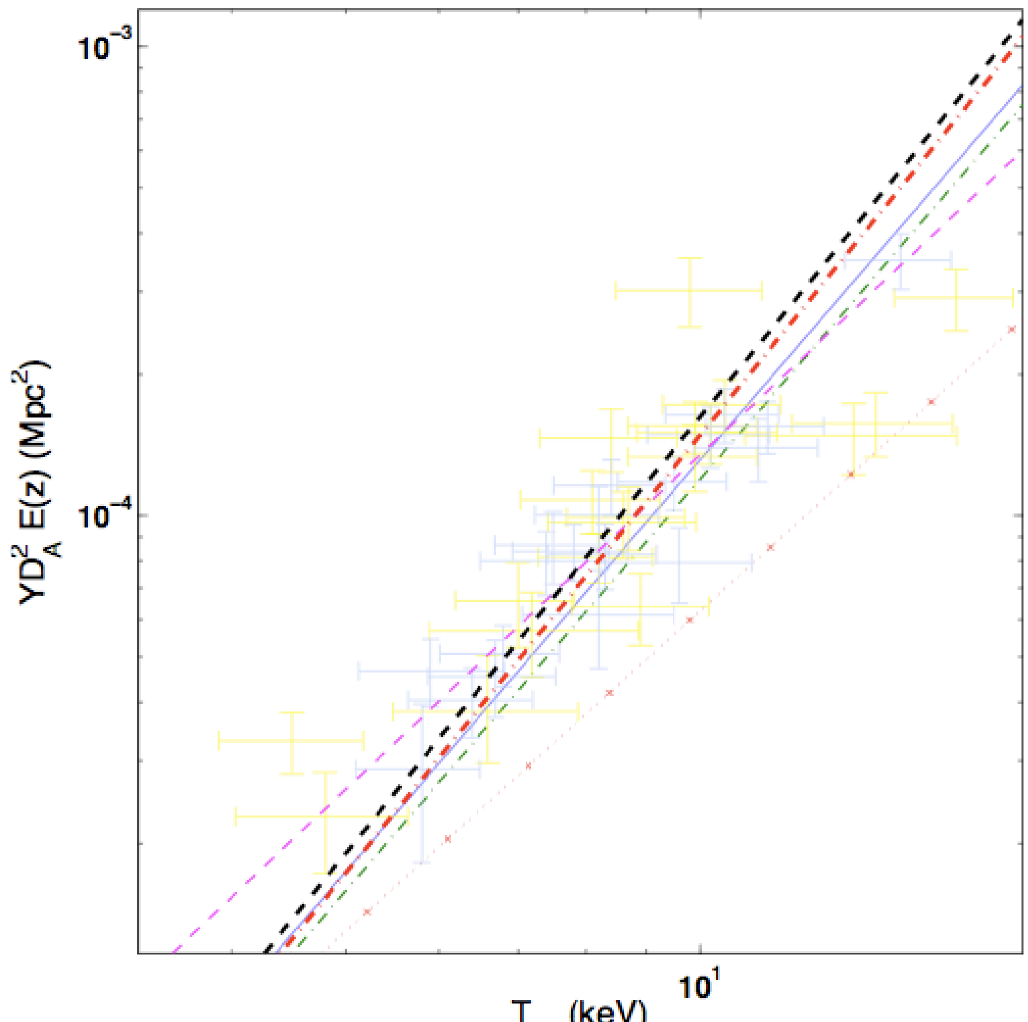
2) SZ power spectrum and compare with CBI+ observations




**SZFlux - $M_{gas}$**

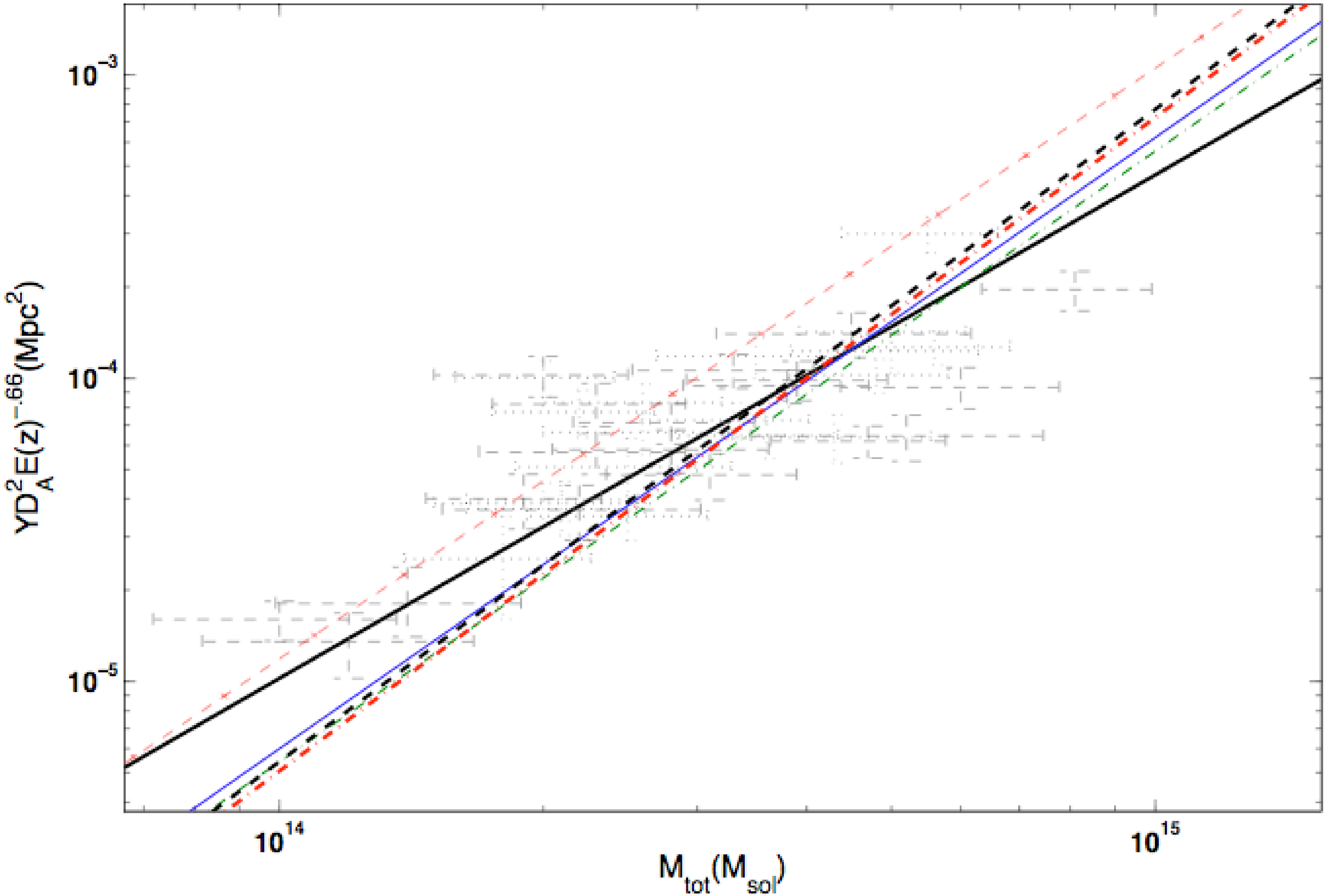
New comparison
In a later
Slide !

| | | | | |
|---|---|---|---|---|
| model 1 | -25.55 | 1.5794 | 1.0343 | .5754 |
| model 2 | -25.51 | 1.5781 | .9274 | .4987 |
| model 3 | -25.0082 | 1.5357 | 1.3435 | .7916 |
| model 4 | -24.98 | 1.5321 | 1.5741 | .9812 |
| thermal 1 | -25.1567 | 1.5405 | 2.53 | 1.48 |
| thermal 2 | -25.577 | 1.5725 | 2.28 | 1.31 |
| K-S | -33.0122 | 2.1758 | 10.50 | 5.2296 |




## SZFlux - Temp

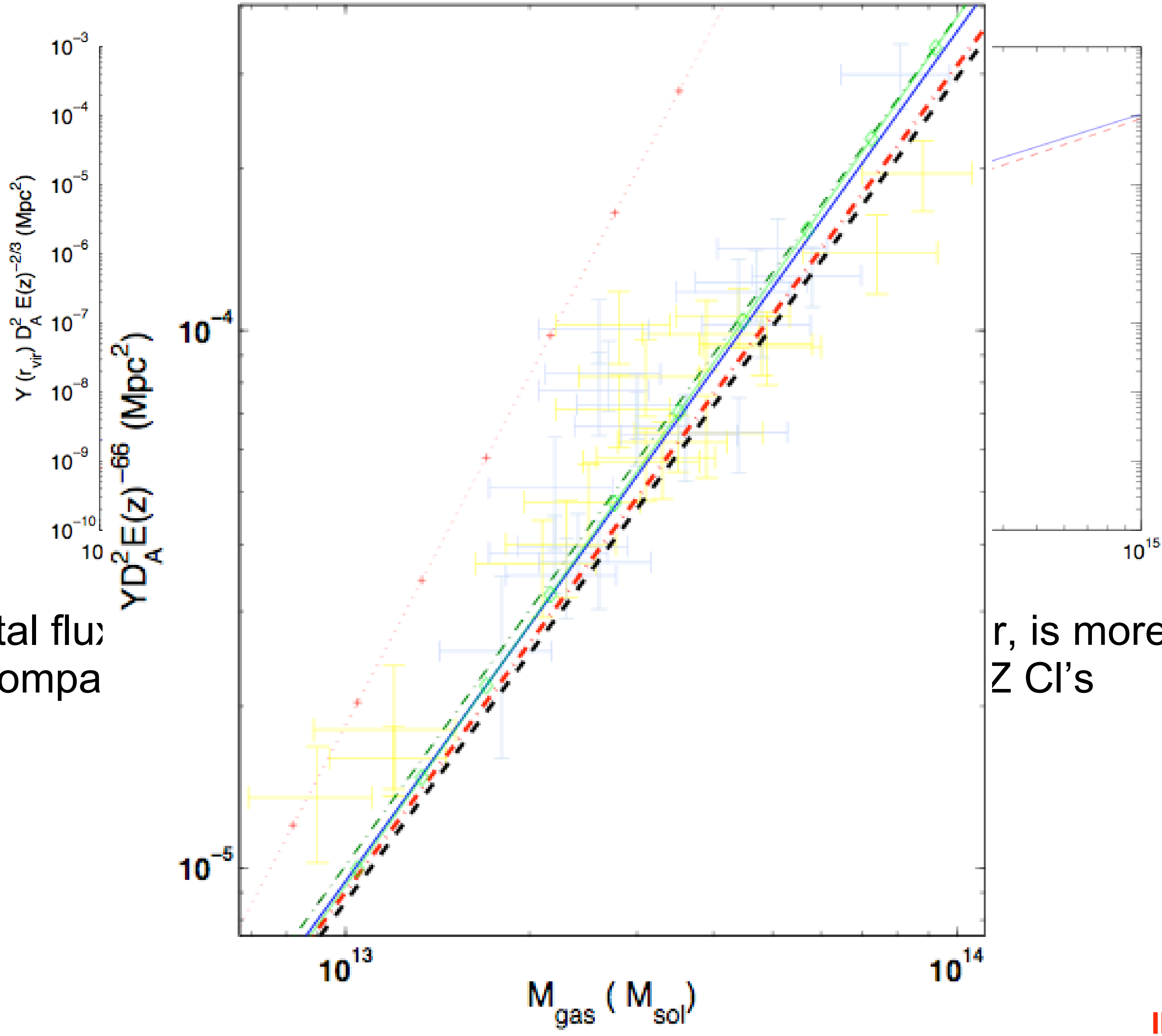
| | | | | |
|---|---|---|---|---|
| Bonamente | | | [illegible] | [illegible] |
| model 1 | -6.7967 | 2.9158 | 1.0769 | .2969 |
| model 2 | -6.8358 | 2.9134 | 1.3164 | .4582 |
| model 3 | -6.9282 | 3.0997 | 1.0768 | .2903 |
| model 4 | -6.8790 | 3.0895 | 1.1217 | .3172 |
| thermal 1 | -6.7716 | 3.0696 | 1.68 | .64 |
| thermal 2 | -6.702 | 2.954 | 1.31 | .4420 |
| K-S | -6.47 | 2.28 | 7.47 | 3.7399 |




## SZFlux - $M_{tot}$

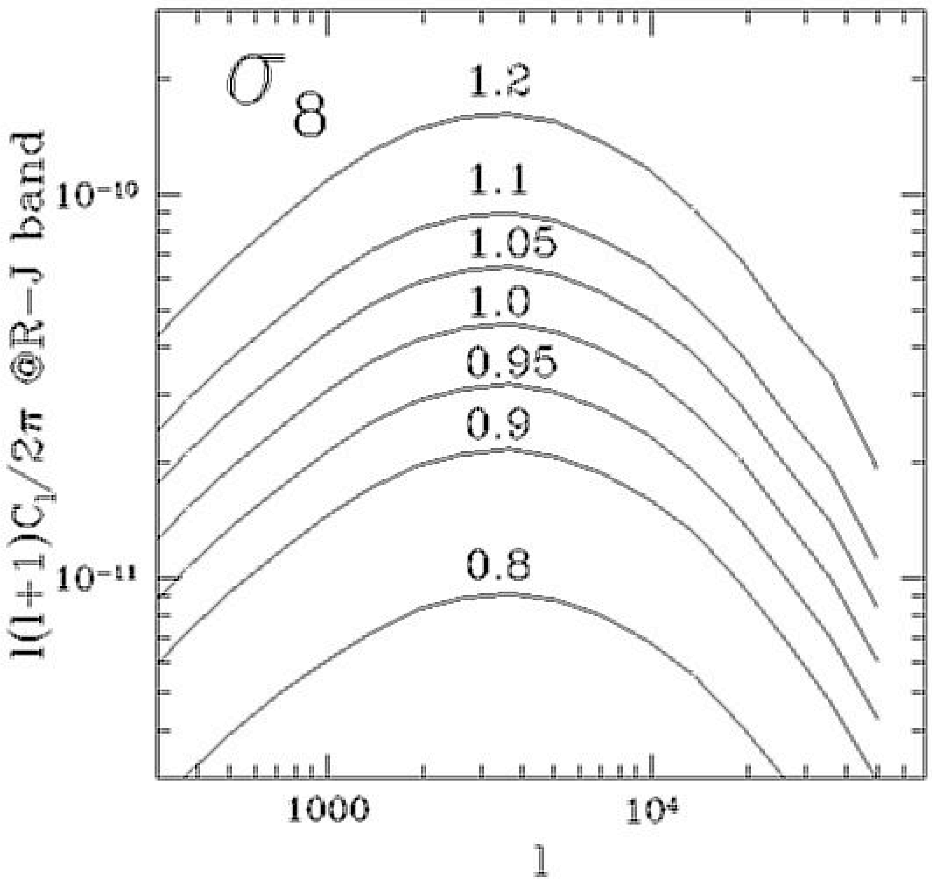
| | | | | |
|---|---|---|---|---|
| Bonamente | | | 1.5714 | .7214 |
| model 1 | -33.43 | 2.015 | 1.8299 | .8878 |
| model 2 | -33.45 | 2.013 | 2.0959 | 1.0584 |
| model 3 | -35.46 | 2.1546 | 1.8868 | .8945 |
| model 4 | -35.37 | 2.1504 | 1.7617 | .8255 |
| thermal 1 | -35.1914 | 2.1431 | 1.66 | .7303 |
| thermal 2 | -34.05 | 2.0626 | 1.64 | .74 |
| K-S | -32.2853 | 1.9549 | 2.5651 | 1.1946 |

# More comparison SZ scaling

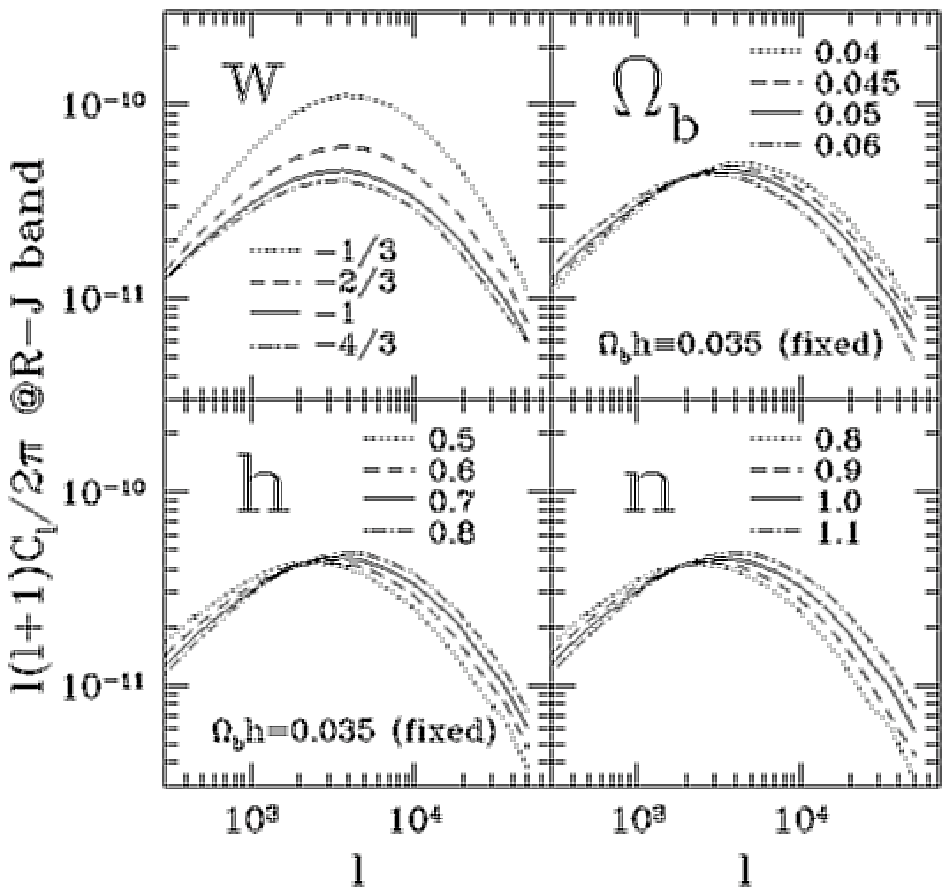



The total flu… r, is more for this
work compa… Z Cl's

# On To SZ Power Spectrum -



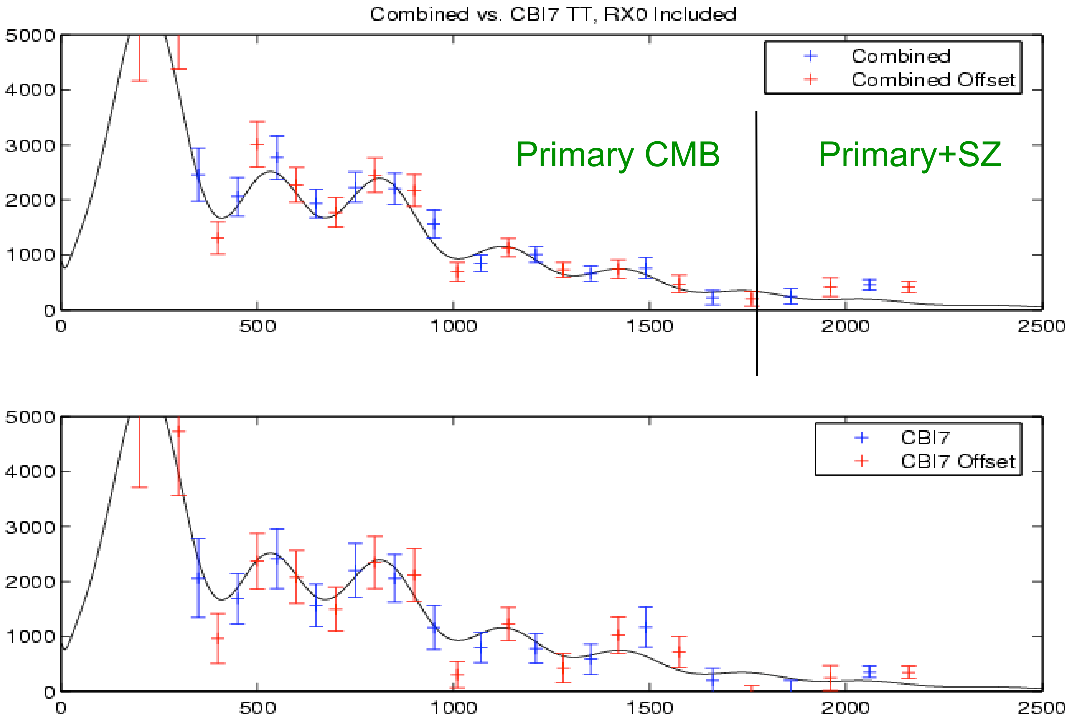

$C_l \sim \sigma_8^{6\text{-}7}$

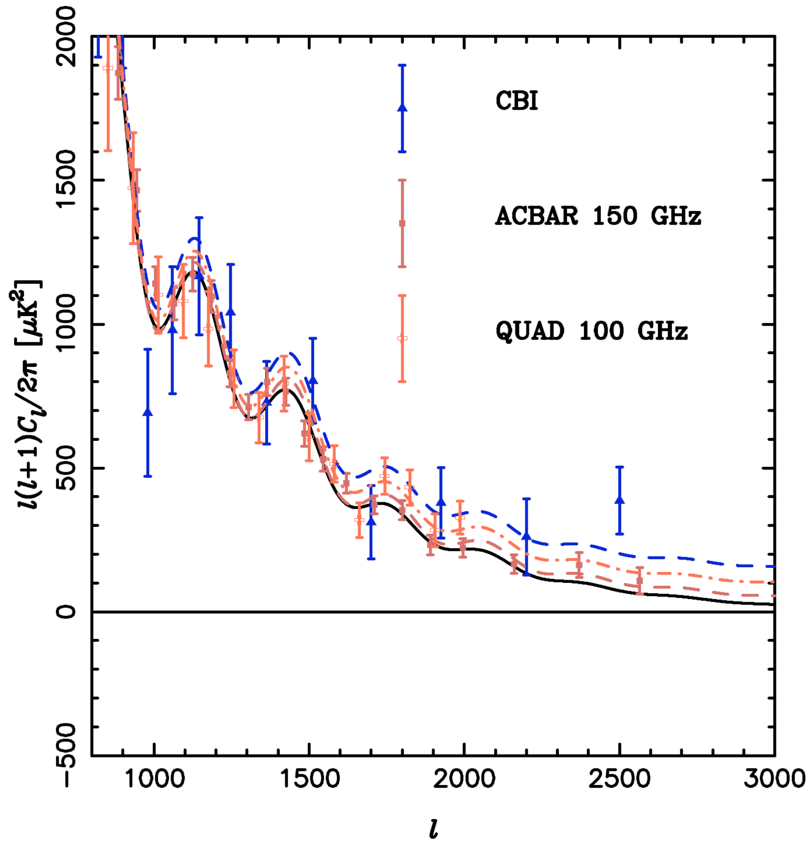



Effect of other parameters are subdued under the effect of $\sigma_8$.

Komatsu & Seljak 2002

# EXCESS OF CMB ANISOTROPY OBSERVED AT SMALL ANGULAR SCALES -



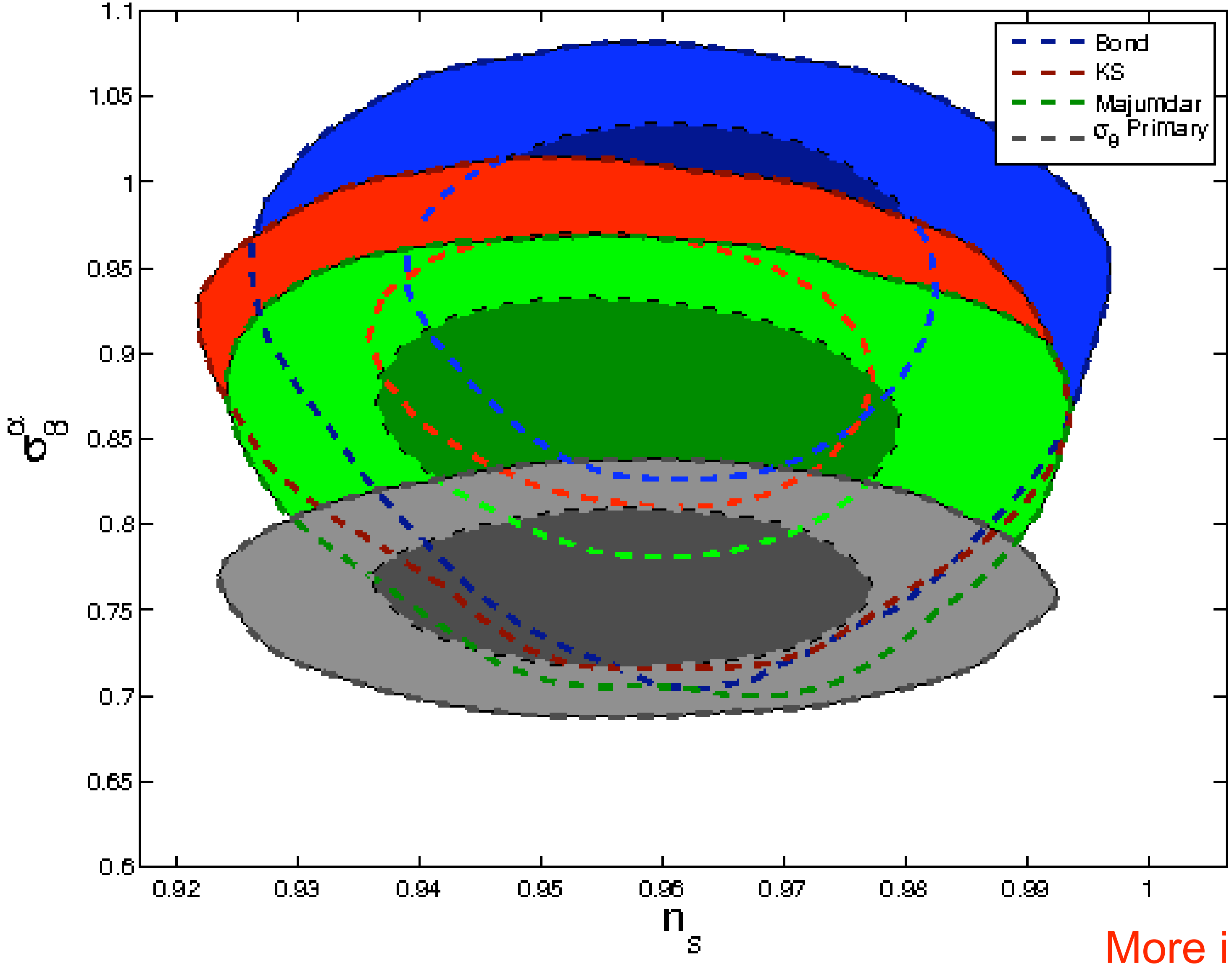




Sievers etal (2009) [and previously Bond etal (2006)] analyized CBI data + radio sources at 30 GHz and found “excess” CMB anisotropy at l > 1500. Moreover, ACBAR & BIMA data also agree with CBI excess, if excess has SZ freq dependence.

They use two different SZ cluster templates: 1) Analytic Komatsu Seljak and 2) SPH simulation They find $\sigma_8$ =0.922±.047 and $\sigma_8$ =0.988±.049. Previous result was $\sigma_8$ = 1.0 - 1.05

# SZ Cl WITH NEW SZ TEMPLATE AND $\sigma_8$ -

$\sigma_8$ = 0.851+/.055 w/out BIMA (including quad 2yr,acbar,cbi,sza,wmap5)




More in Jon Siever's talk

## SUMMARY for PART TWO -

**We have build a 'bottom-up' model of cluster gas density and temperature profiles, normalized so as to give observed Xray mass-temp scaling relation.**

The non self-similar Xray scaling results in non self-similar SZ scaling relations. **We compare our results with the recently observed SZ scaling relations (Y-T, Y-Mgas, Y-Mtot) by Bonamente et al and find excellent agreement.**

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There are two imp implications of this result -

1) We can say that we are observing the same 'family' of clusters in XRay and SZ, thus making modeling of SZ selection of cluster for surveys easier.

2) We can more confidently predict Y-M200 scaling reln used for cluster surveys. This Is important if we want to do so called ‘precision cosmology’

**We use the SZ templates to calculate the expected SZ power spectrum** as arc-min scales. We compare our results to CBI observed anisotropy to constrain $\cup_8$.

**Our best fit _$_8$ ~ 0.84. This is within the 1-sigma error bar of the best fit _$_8$ ~ 0.817** from WMAP. In contrast, previous and recent studies, using other cluster templates have got sigma8 ~ 0.93 – 1.0 (i.e 4-7 sigma away from WMAP value)_

# THANK YOU