Title: From RCS & SPT to eROSITA - Cosmology with Galaxy Clusters

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Abstract:

From CBI & RCS to SPT & eROSITA
Cosmology with Clusters

Subba Majumdar
Tata Institute of Fundamental Research
Mumbai

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Cosmology with Clusters

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... and this story is not about how large the goose is?...but, how many can we get and what to do with them?

The telescopes ...

RCS-2 : 1000 sq deg using Megacam in CFHT (close to 800 deg done),
Optical clusters, g'~25.3 mag, r' ~ 24.8 mag, z' ~ 22.5 mag
RCS1 ~ 90 sq deg
detection of clusters through red-sequence in color-magnitude space

SPT - 10 m telescope at South Pole, deployed last summer (2007-20011)
mm-wave, SZ clusters, 4000 sq-deg
6 X 160 detectors,
1 arcmin resolution at 2mm
(similar to ACT, almost identical science goals)

eROSITA - to be launched from Russia on Spectrum-RG mission in 2010-11
Xray, whole sky (41000 sq deg), FOF ~ 7 X 41 sq arcmin
25 arc sec resolution, sensitivity at 0.5 - 10 KeV (0.5-2 kev for clusters)
4e-14 ergs/cm2/s

CBI - 13 element interferrometer at 10 freq band (26-36 GHz)
Cl measured from l = 300 - 3000
FOV ~ 44 arc min, resolution 4.5 -10 arc min
Mosaic obs ~ 4 sq deg with rms of 2.4 mJ/beam
SZ fluctuations

How do we make use of clusters?

Counting clusters or looking at the 3D/2D distribution of clusters
(Optical, SZ, Xray surveys)

Studying the secondary CMB fluctuations due to clusters.
(Only SZ surveys) -- Mark's 'ACT' talk

The two crucial ingredients:

Theory/simulations tell you the distribution of halos as a function of mass.

One can connect cluster observables (say xray luminosity, optical richness) to cluster mass.

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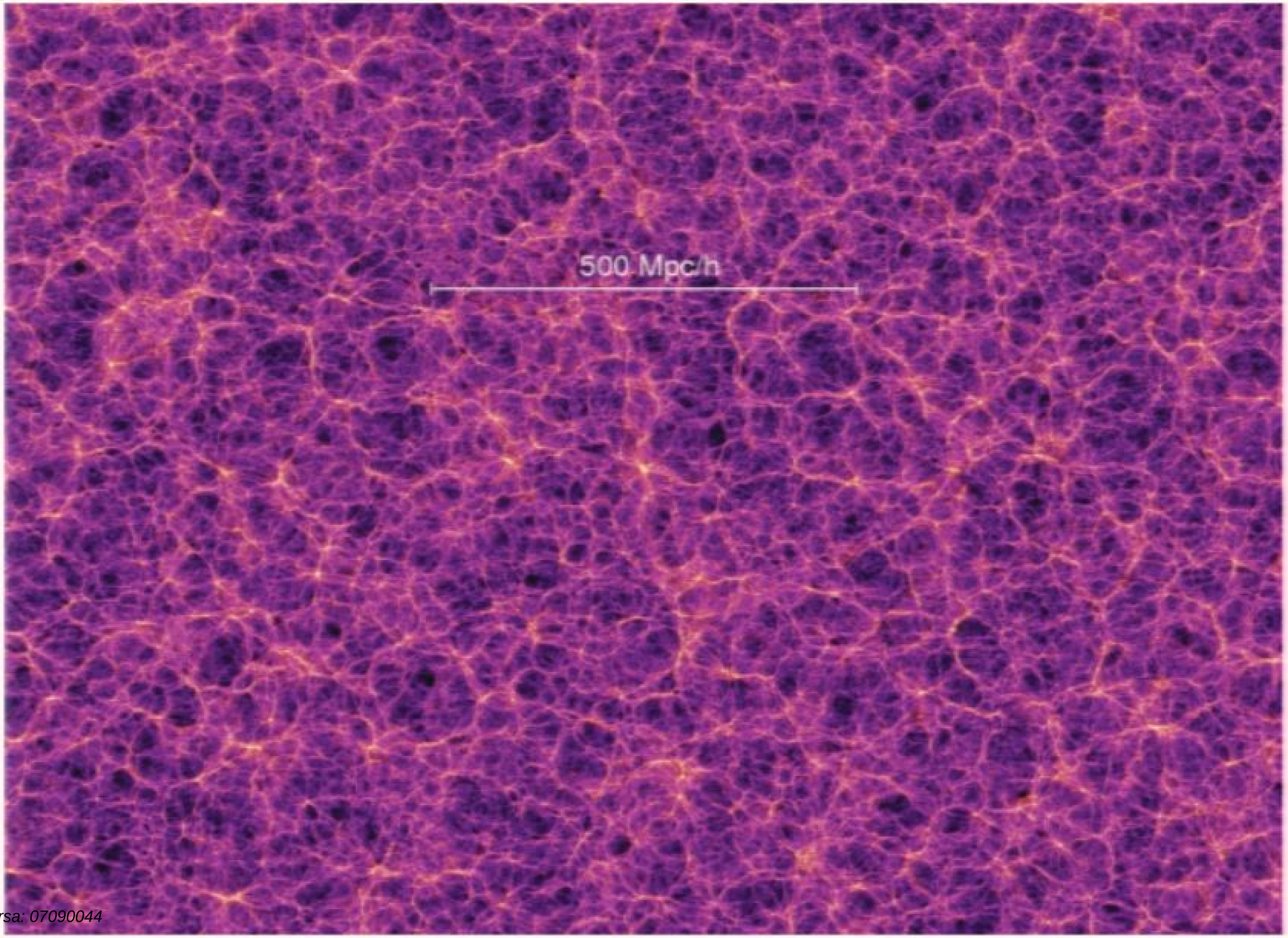
There are four parts to my talk on cluster cosmology

Part One: Clusters as a one parameter family of masses



M I L L E N I U M S I M U L A T I O N

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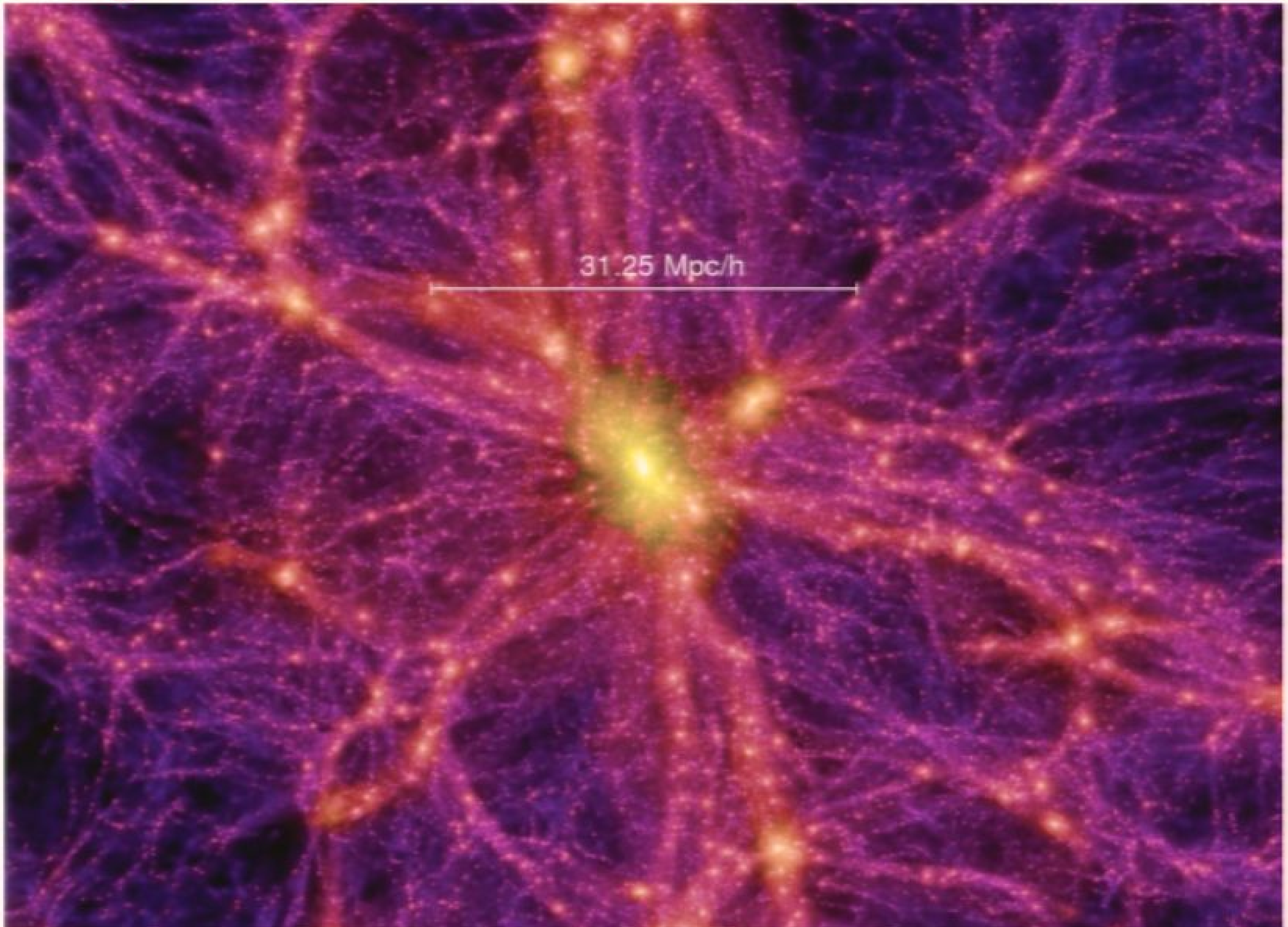


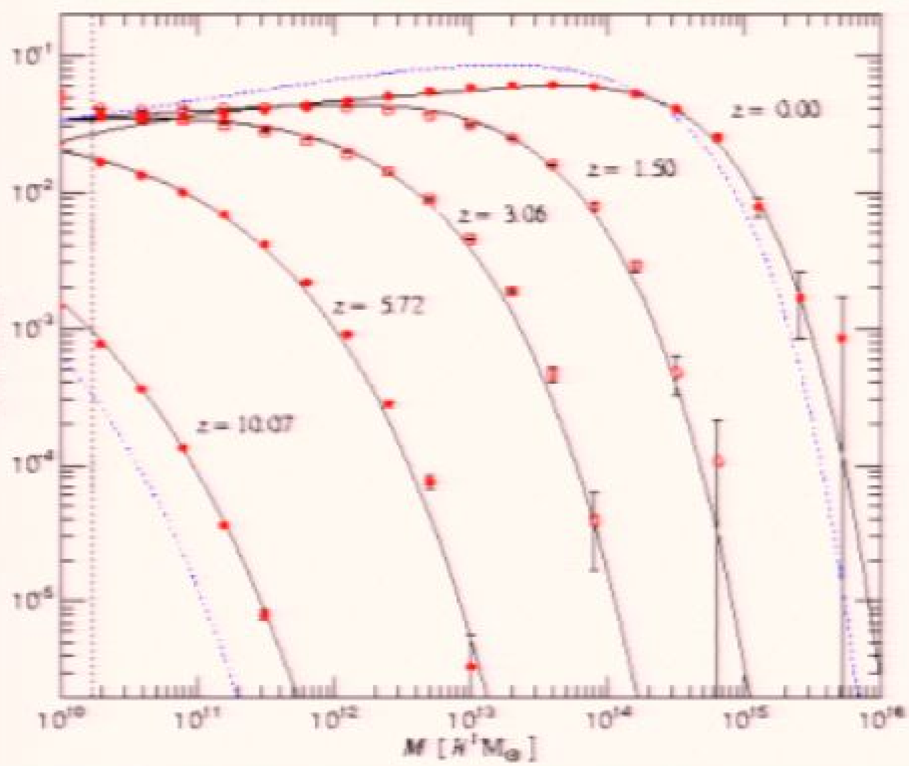
M I L L E N I U M S I M U L A T I O N

Counting clusters: mass function, growth fn & σ_8…

To start: filter the mass distribution with mass dependent scale & get the variance

$$\sigma_R^2 = \sigma_M^2 = \langle \delta_R^2 \rangle = \frac{1}{2\pi^2} \int dk\, k^2 P(k)\, \tilde{W}_R^2(k)$$

$\sigma_8 = \sigma_M(R=8h^{-1}\ \mathrm{Mpc})$



Universality when written in terms σ_M

Analytical - Press & Schecter 1976,
Simulations - Seth & Tormen, Jenkins etal,
Warren etal , Lukic etal 2006

$$f(\sigma_M, z) = 0.315 \exp(-|\ln \sigma_M^{-1} + 0.61|^{3.8})$$

Growth function : $\dfrac{\partial^2 \delta}{\partial t^2} + 2H(t)\dfrac{\partial \delta}{\partial t} - 4\pi G \bar{\rho} \delta = 0$

Finally: Number counts & SZ fluctuations…

For some area in the sky and some redshift range, i.e for some volume

$$\frac{dn}{dz d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_{M_{\lim}}^{\infty} dM \frac{dn(M,z)}{dM}$$

Number counts

Volume **Mass function**

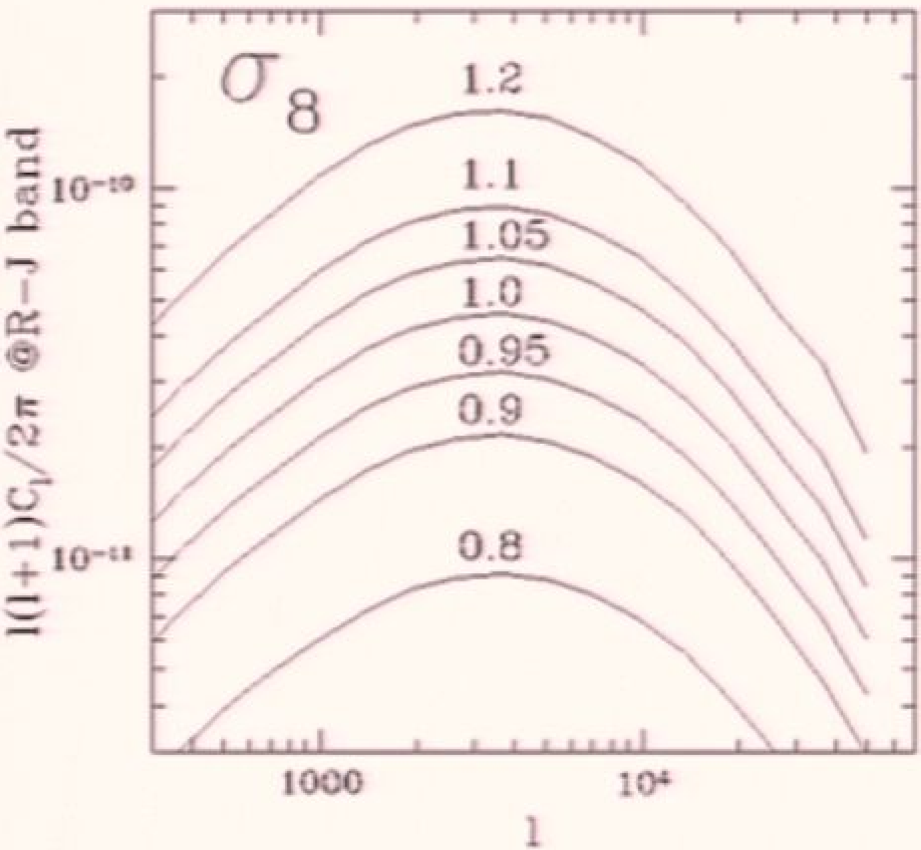
$$C_l = g_\nu^2 \int_{z_{\min}}^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |y_l(M,z)|^2$$

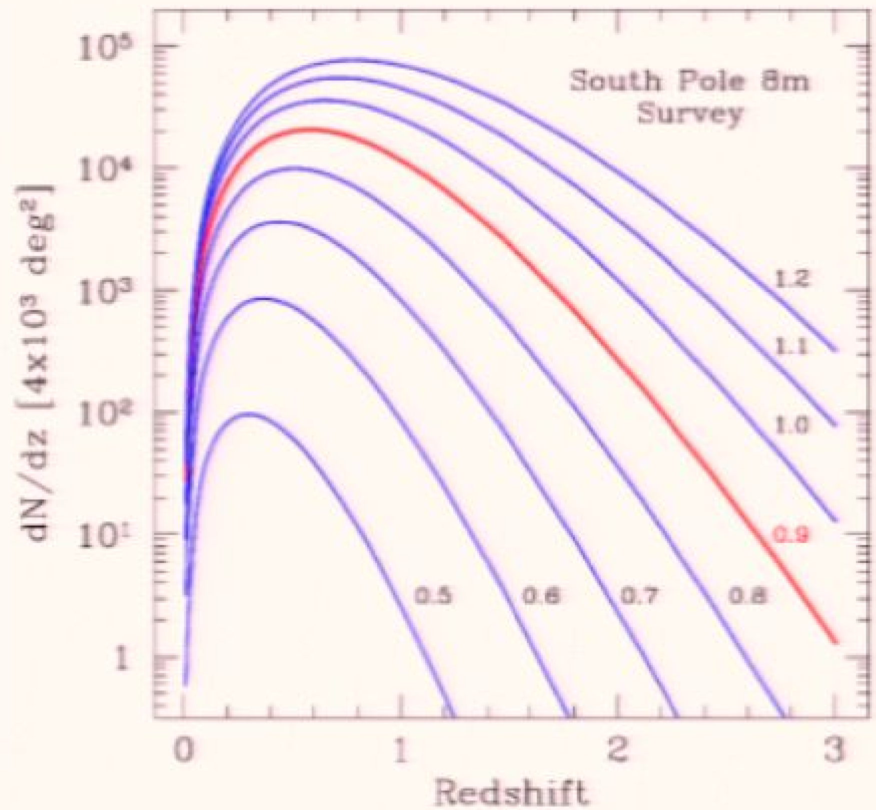
SZ - fluctuations

The cool freq dependence

The FT of the form-factor (pressure profile) of the clusters

The σ_8 influence on clusters...





Seljak etal 2000 , Majumdar 2001, Komatsu & Seljak 2002,others

More cosmology dependence..

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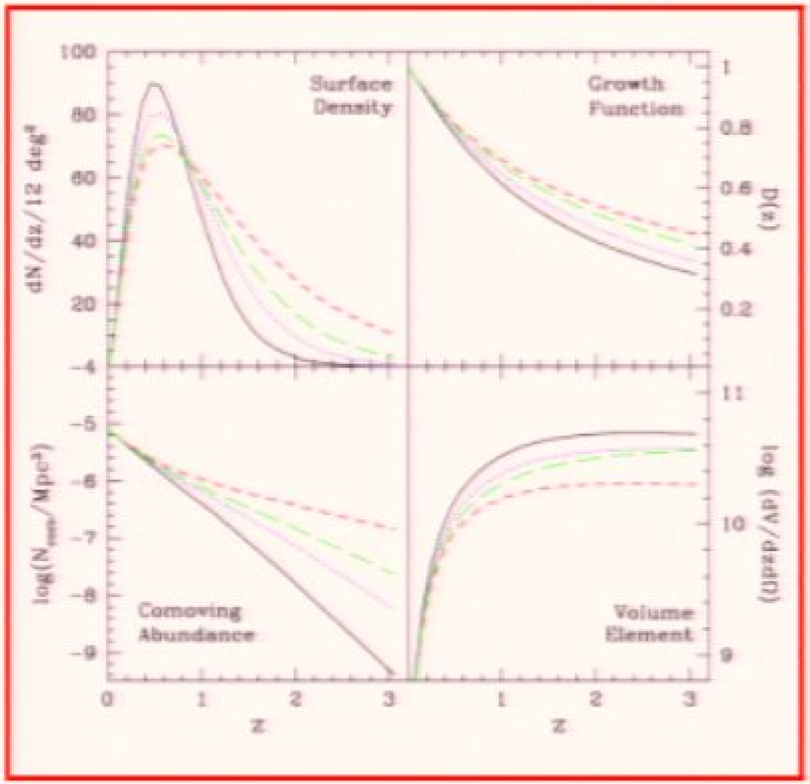
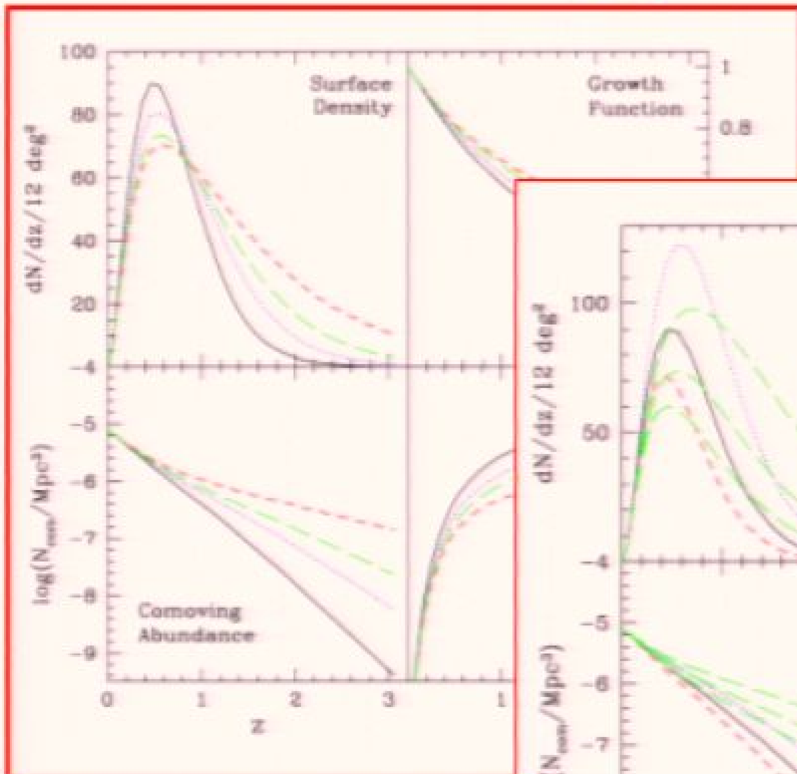


With '*w*'

More cosmology dependence..



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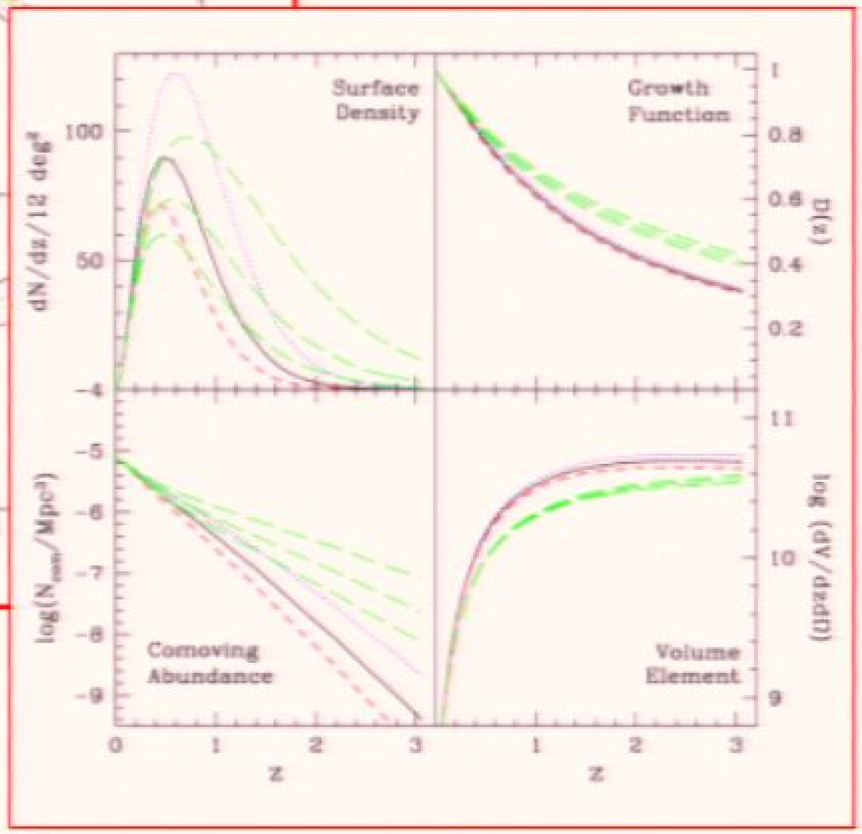
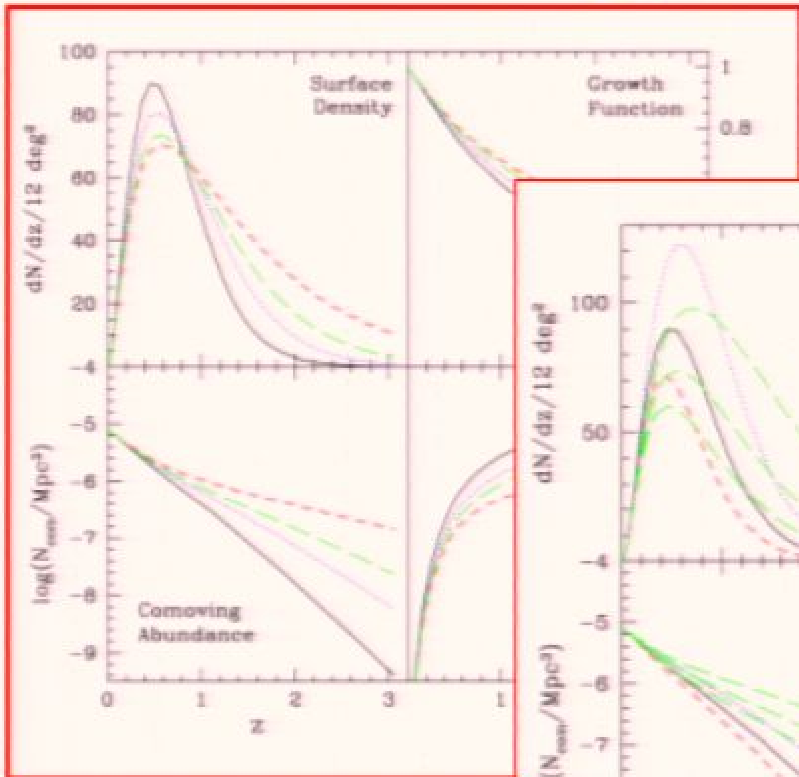
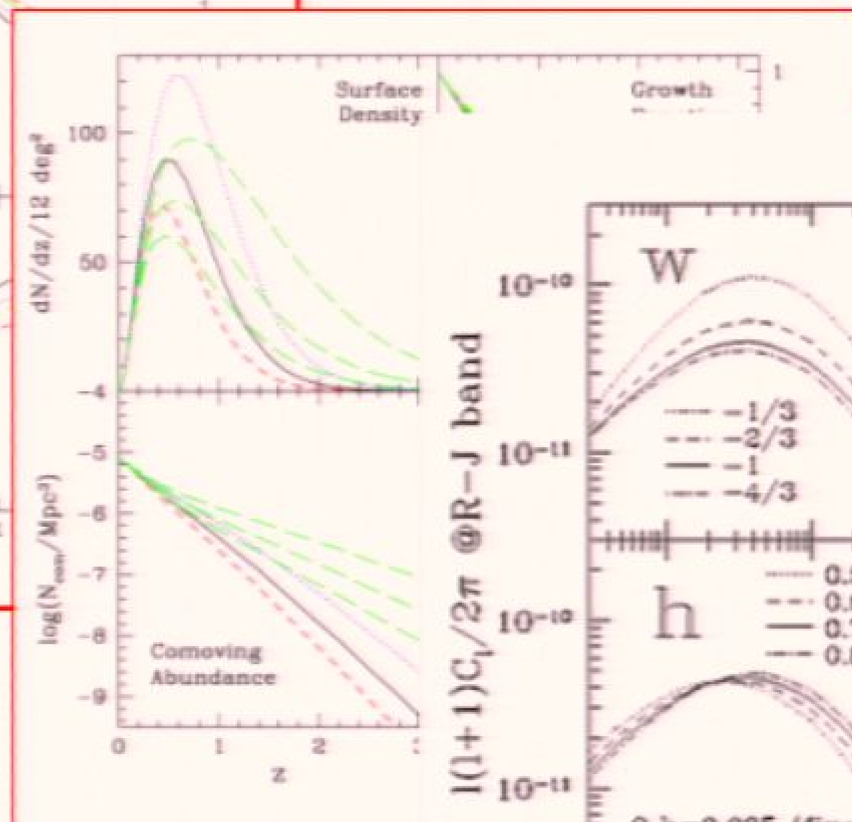


With Ω_M

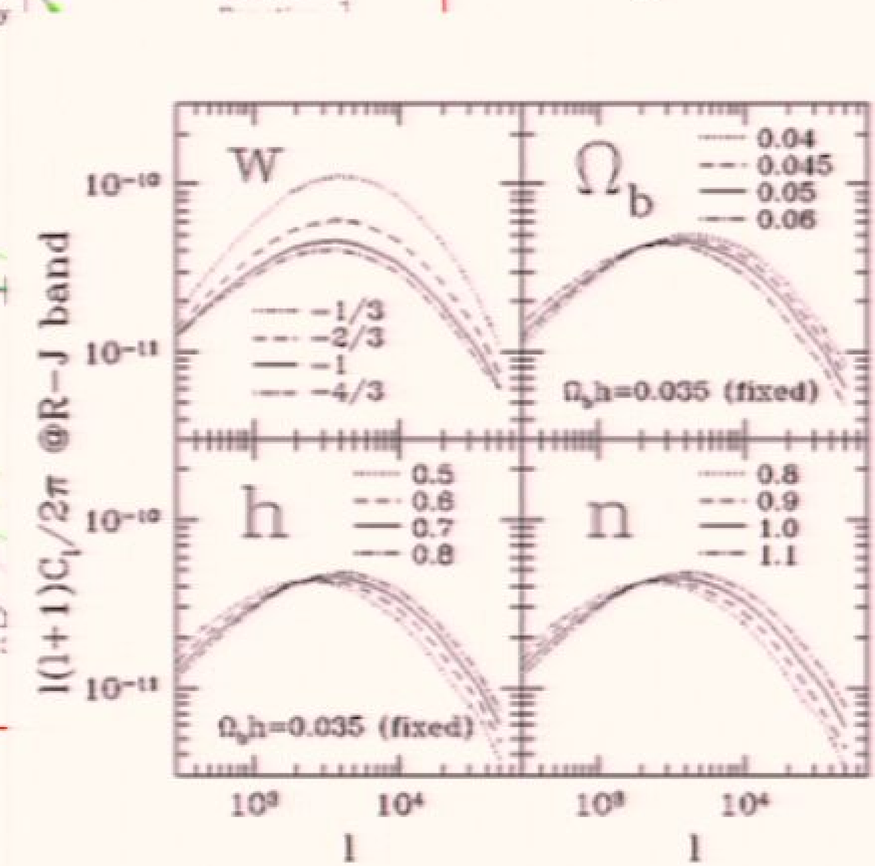
More cosmology dependence..



With '*w*'



With Ω_M



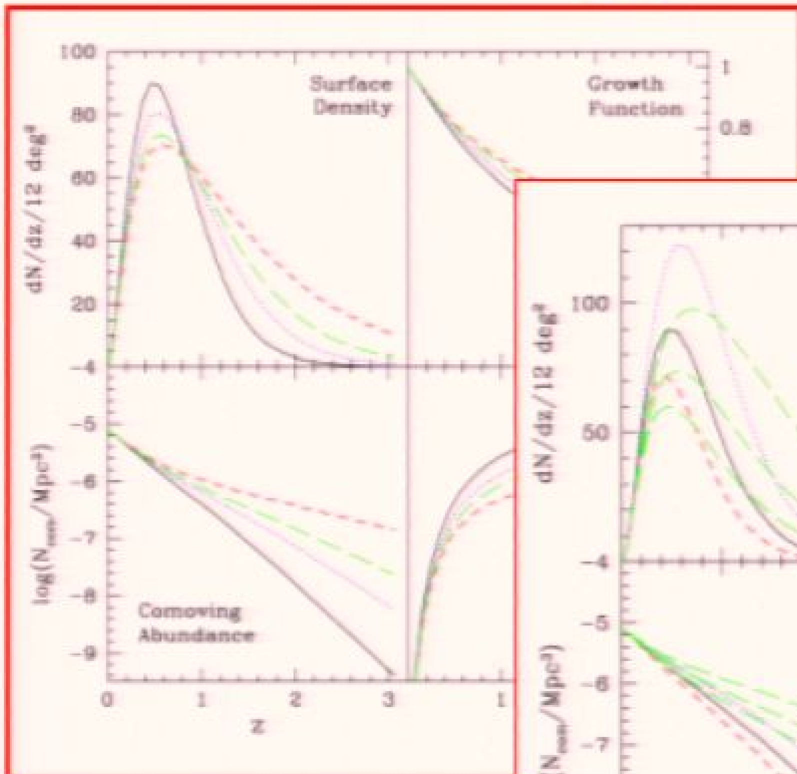
Part two : Connecting cluster masses to the observables

Examples of Observables :

Xray Luminosity, Tempertaure (e-ROSITA)
SZ-flux (SPT, CBI)
Galaxy overdensities (RCS)

Turns out there are 'scaling relations', .e
Observable ⟷ Mass

More cosmology dependence..



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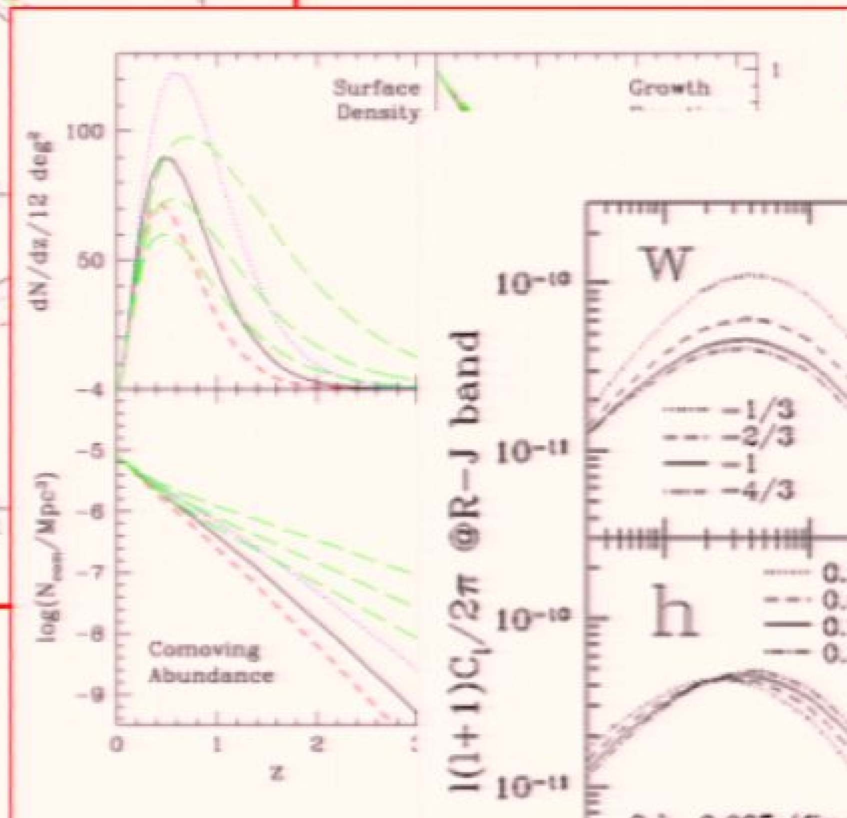
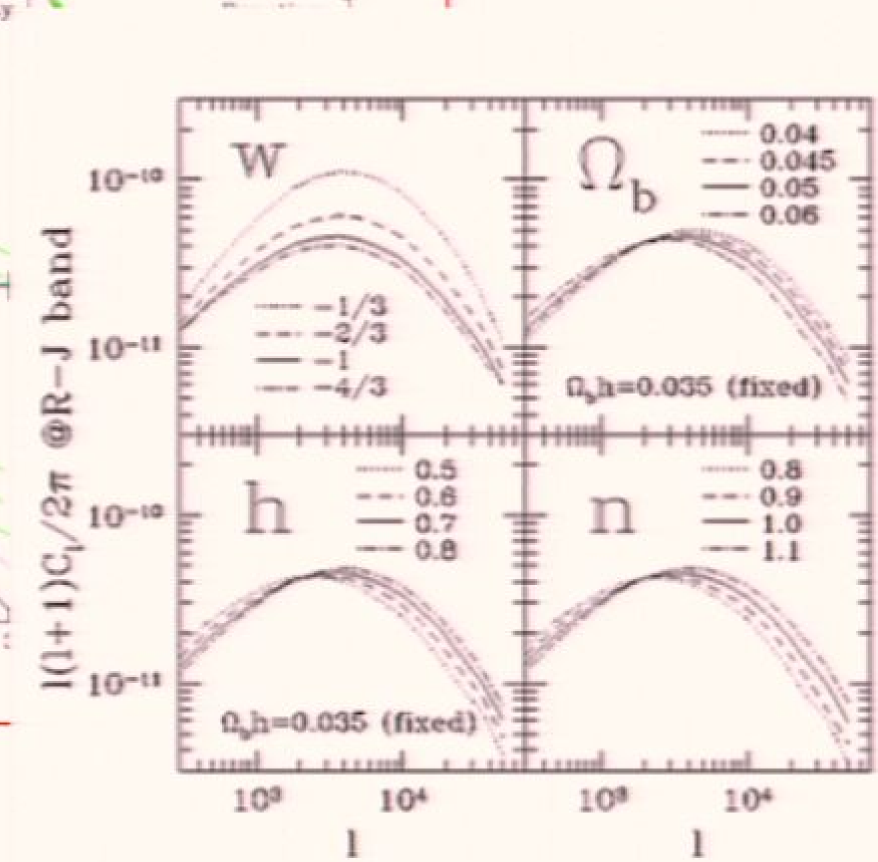


With Ω_M



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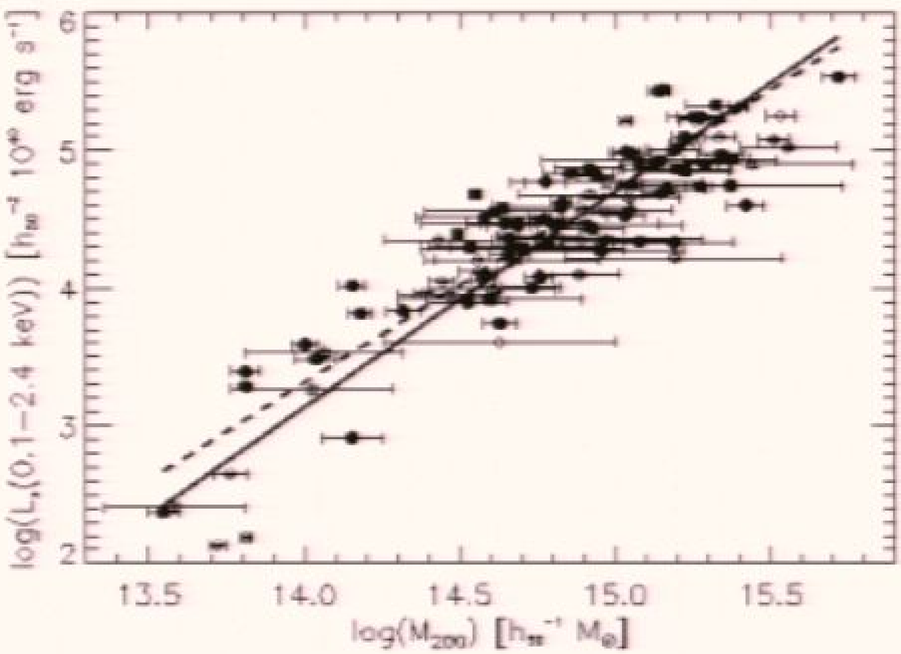

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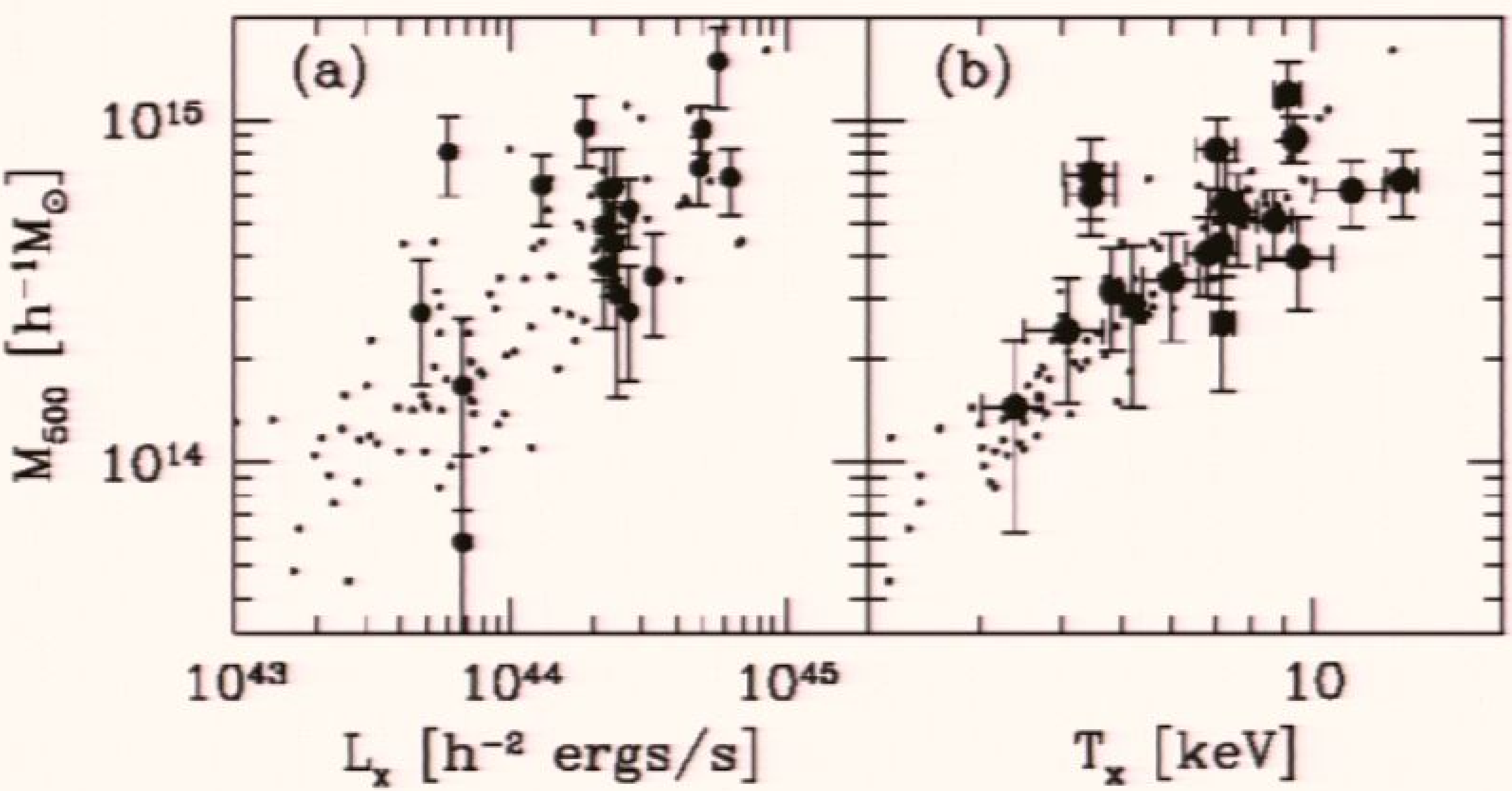

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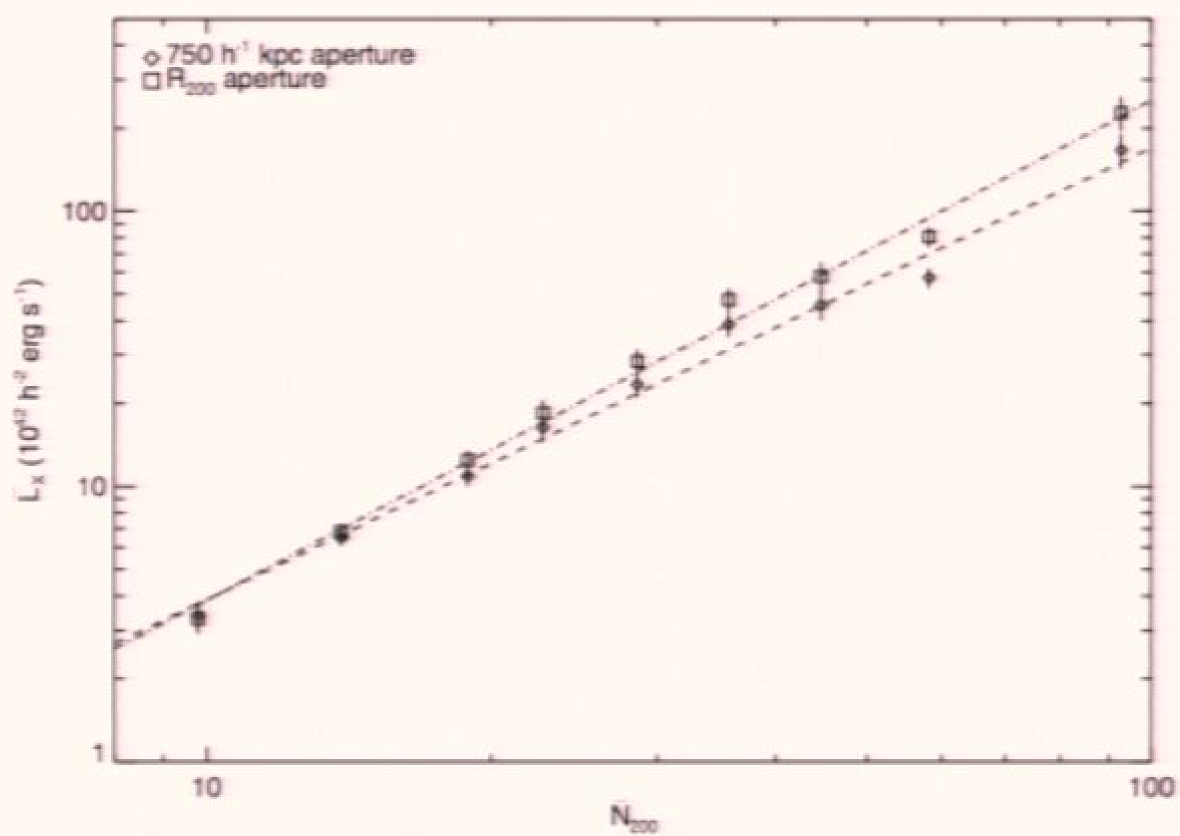
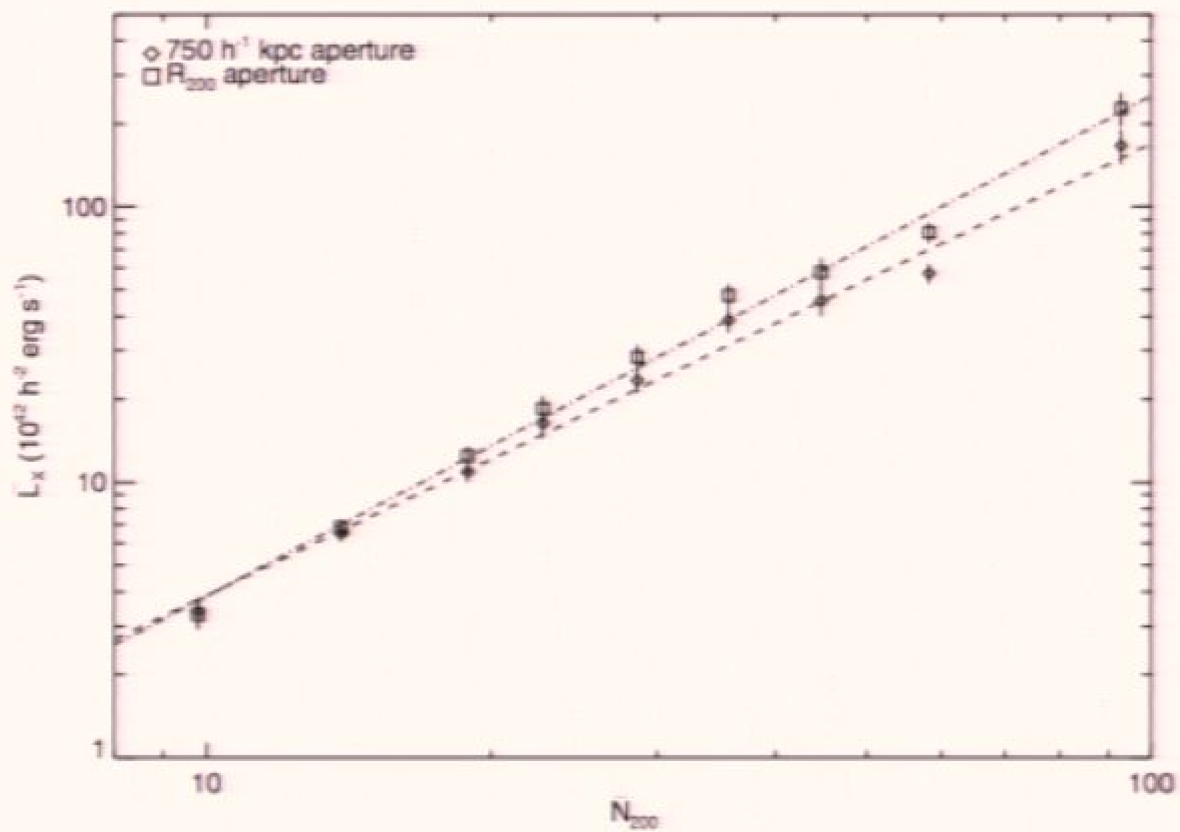
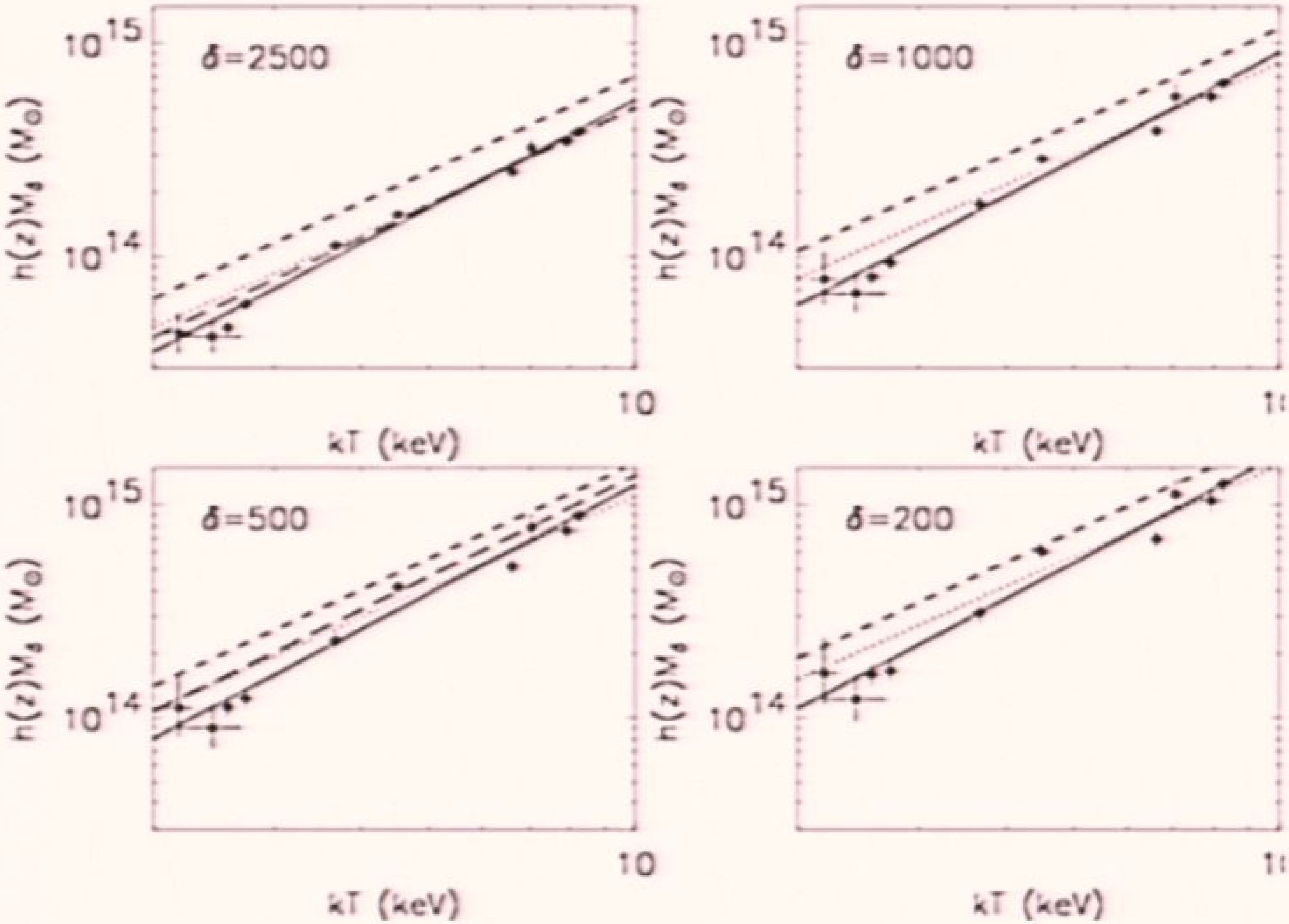


Part two : Connecting cluster masses to the observables

Therefore, all relations have 1)amplitude (normalization)
2) slope
3) redshift dependence, manly due to H(z)

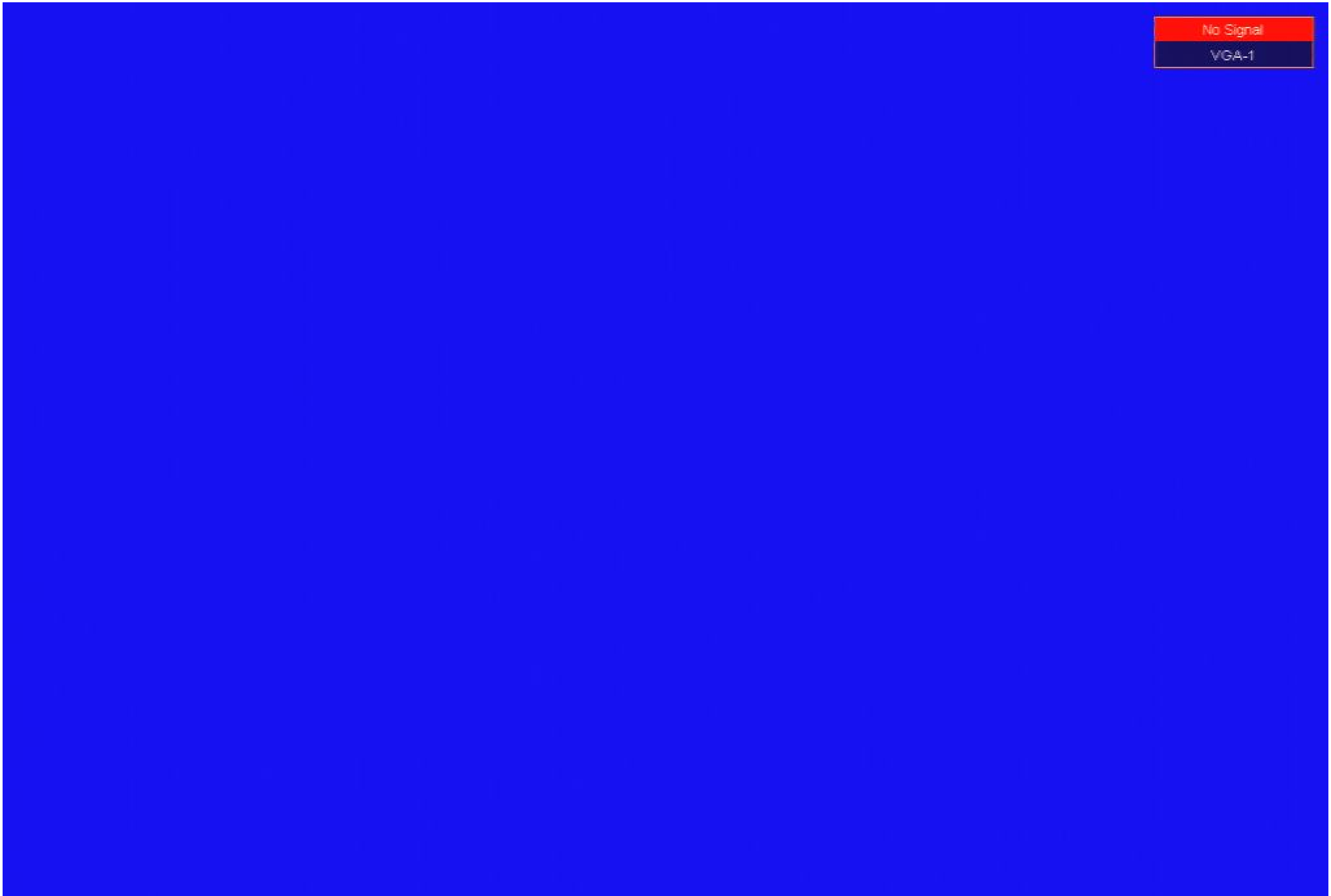


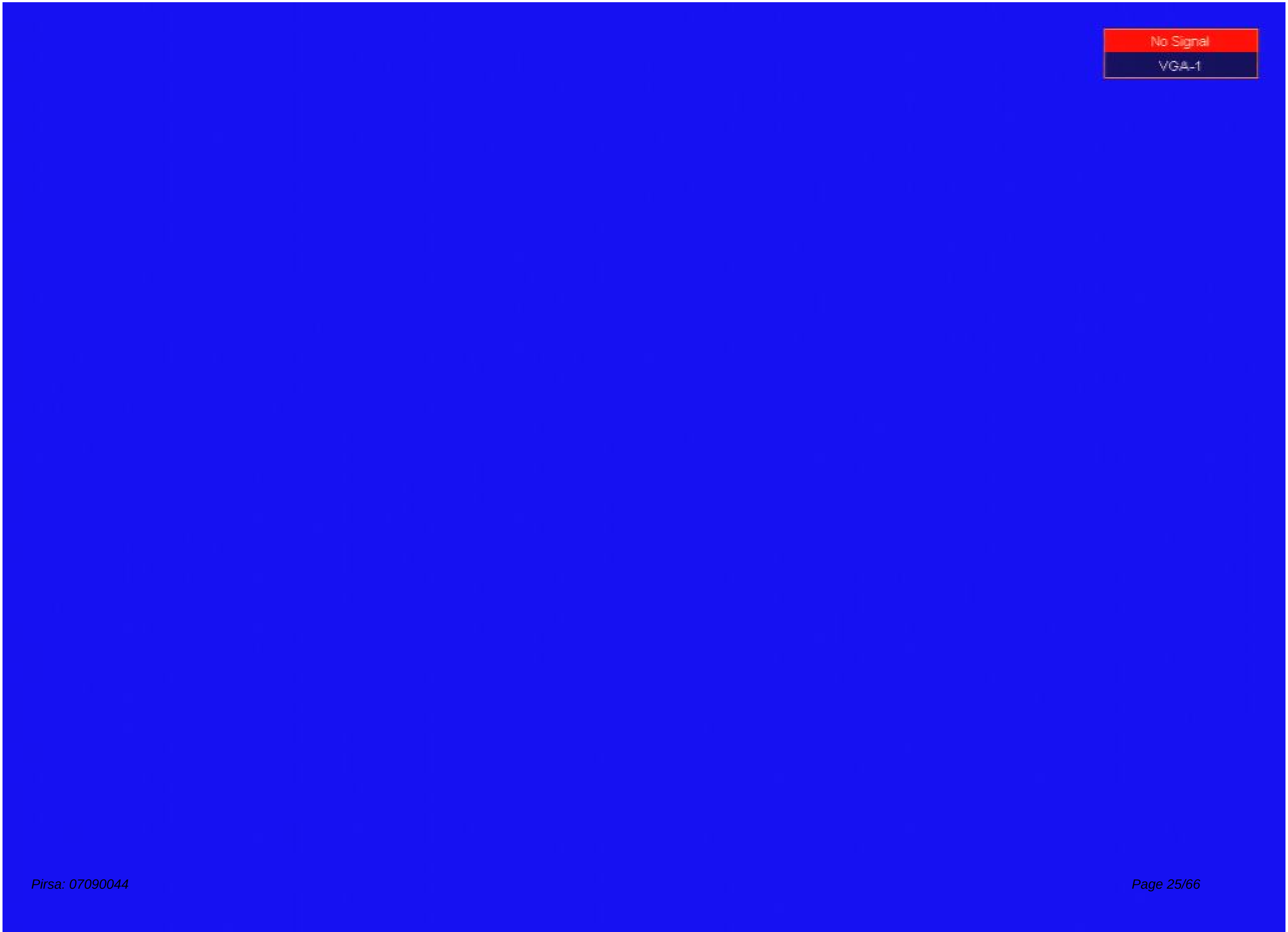
Observations (now really) confront simulations:



Observations:
XMM-Newton
Prat etal 2005

Simulations:
Borgani etal
Evrard etal


No Signal
VGA-1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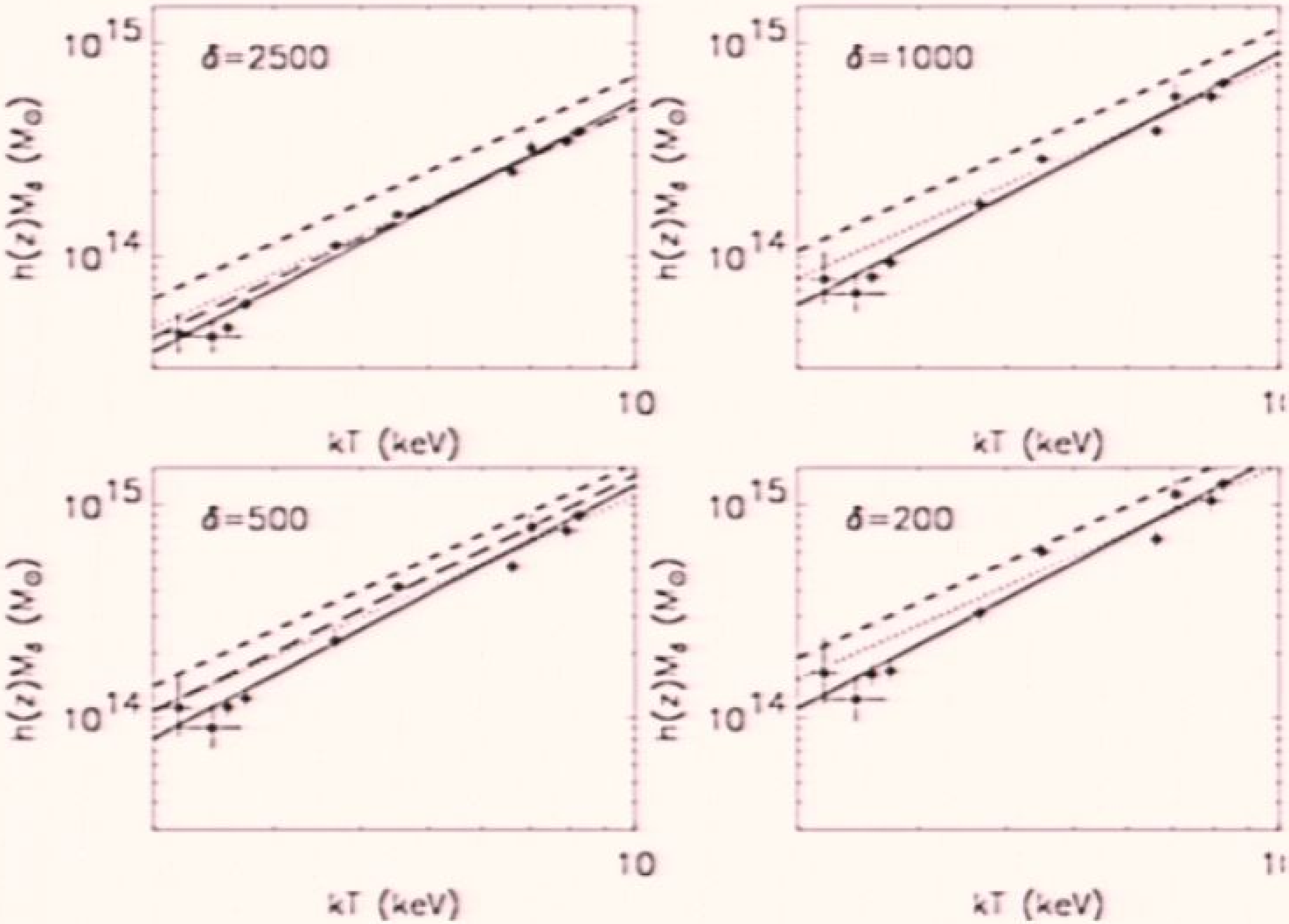

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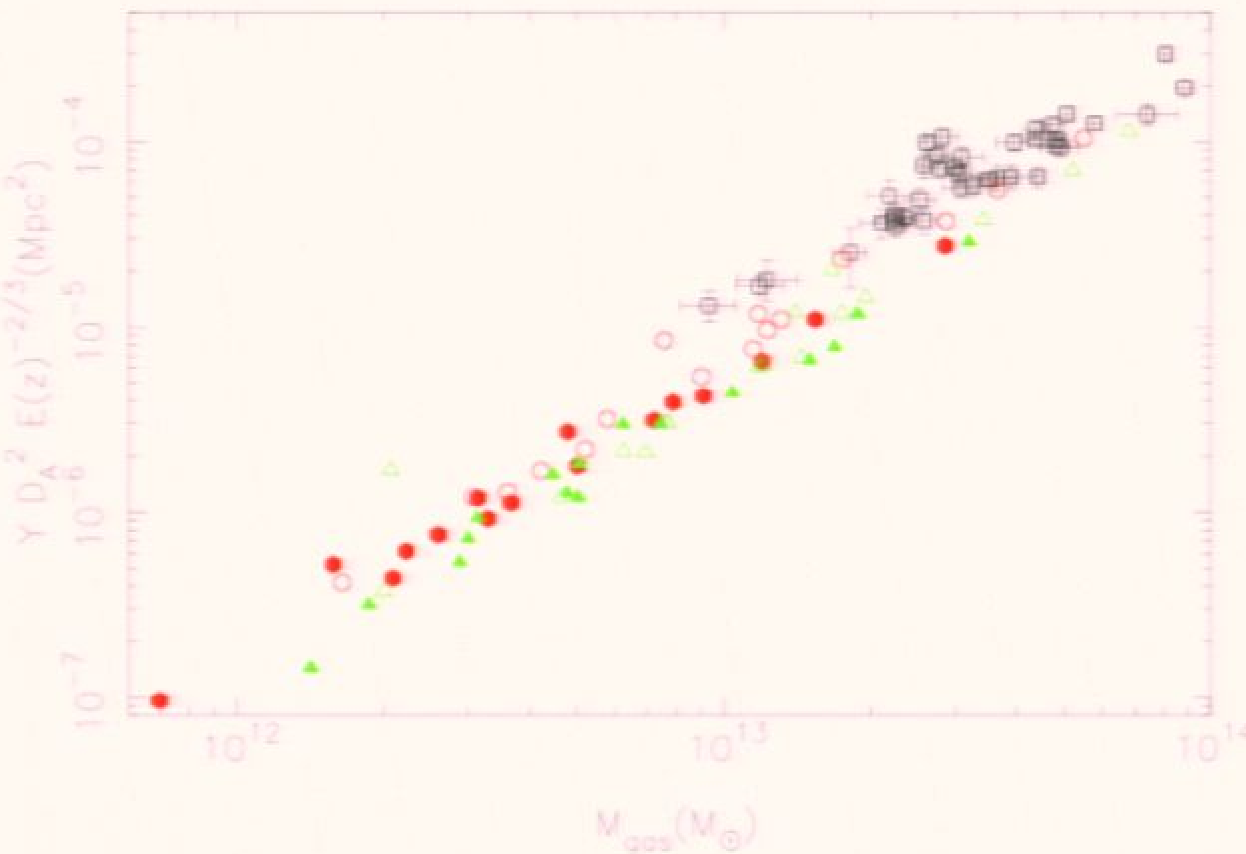

Observations:
Bonamente etal 2007
With SZA

Simulations:
Nagai & Kravtsov 2006

<u>Part Three:</u> "The impact of Part Two - The mismatch between obs and sim clusters"

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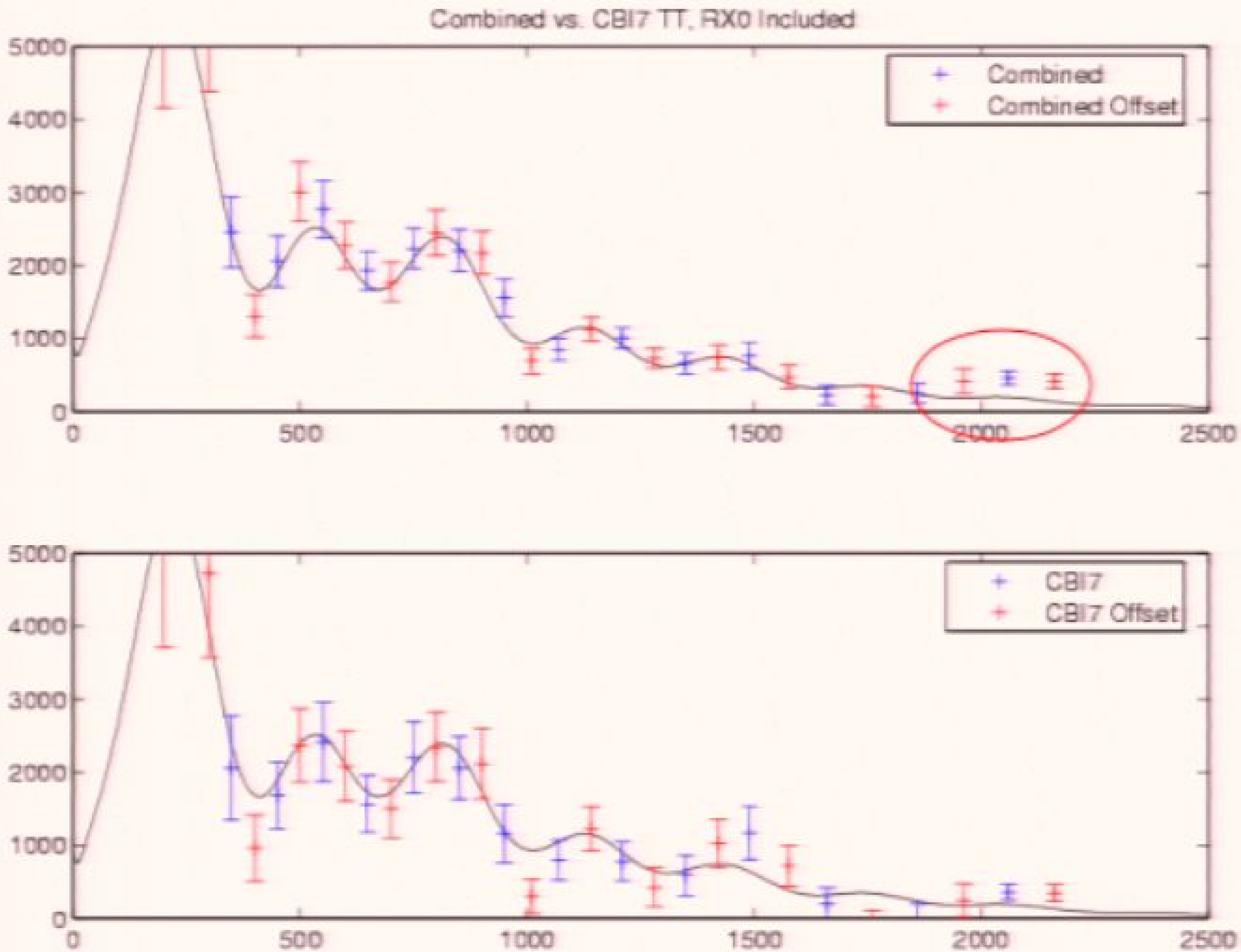
Bottomline - Bias in mass estimation will bias cosmological results.

The story is not too scary, "You Just Have to be Careful"

Examples: 1) CBI
2) RCS-1

Current Best CBI Spectrum (from Jon Sievers)

Top panel – new spectrum! Will be published soon.
Data on which current excess results based.

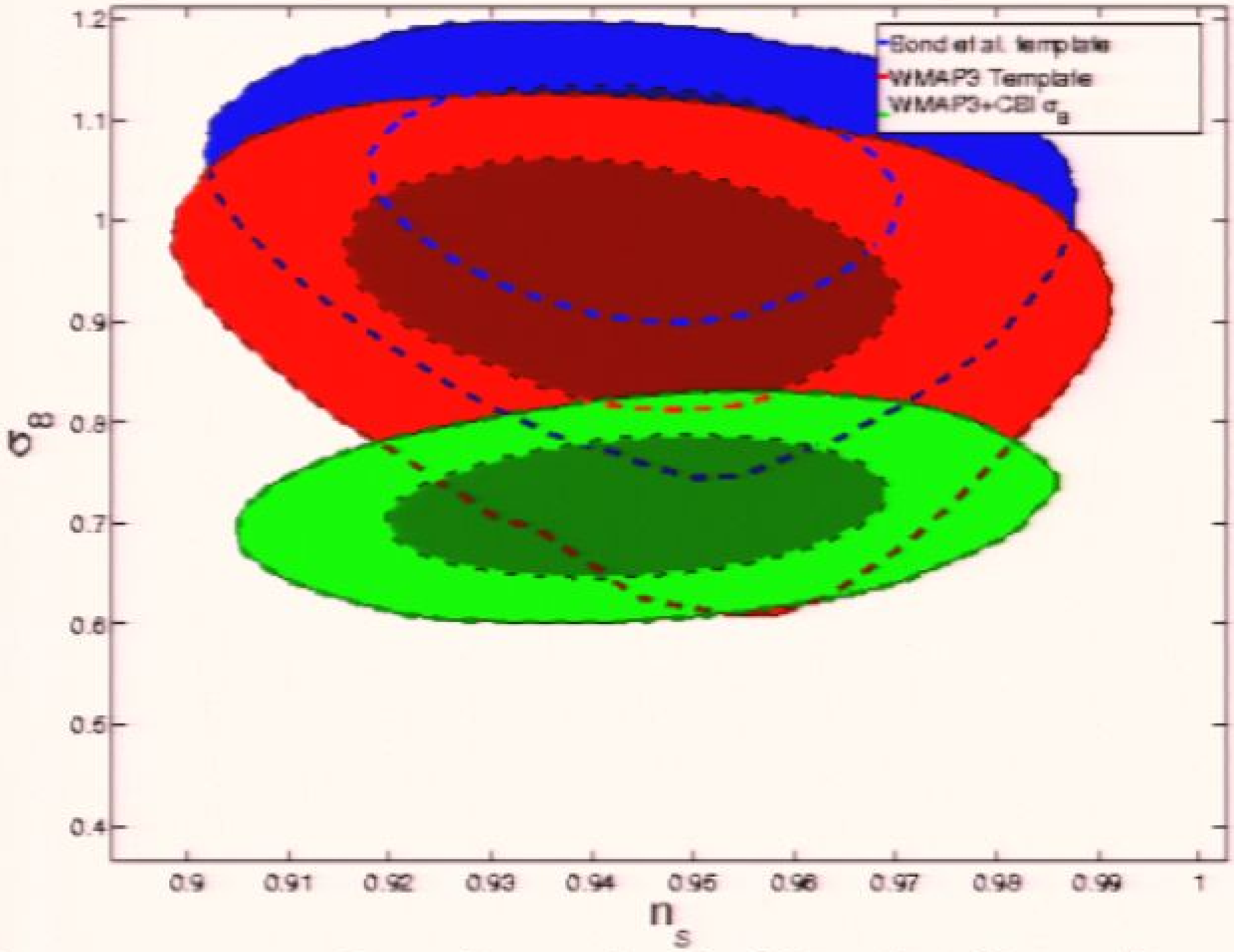


Bottom – old best TT spectrum.

Top – current best spectrum.

NB: two binnings shown. Red/blue points *not* independent.

CBI Inferred σ_8



Do full parameter analysis with all CMB (including latest CBI, WMAP3).

Inferred σ_8 for Bond et al. template is 1.00±0.1, for Komatsu & Seljak template is 0.93±0.1.

So, whats going on?

Errors assume Gaussian noise in PS only. Doesn't include errors from non-Gaussianity of clusters, uncertainty in faint source counts (~35% increase)

Did we get our fluxes/cluster right?

We've already seen that sims don't yet give observed scalings.
The same is true for WMAP SZ template clusters→ The simple normalization is to the total gravitational mass (~adiabatic!). However, lower masses are observed to have more energy than estimated.

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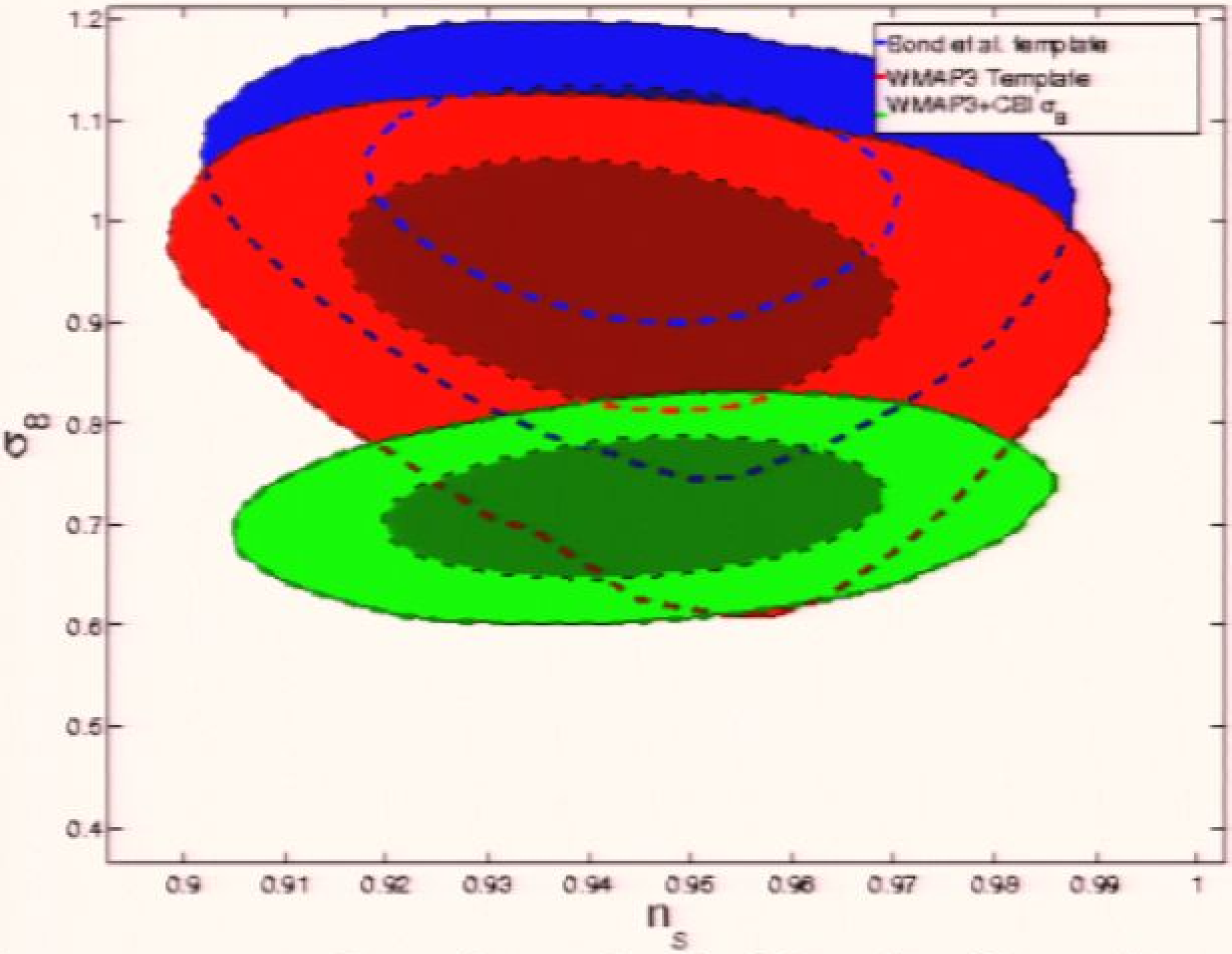

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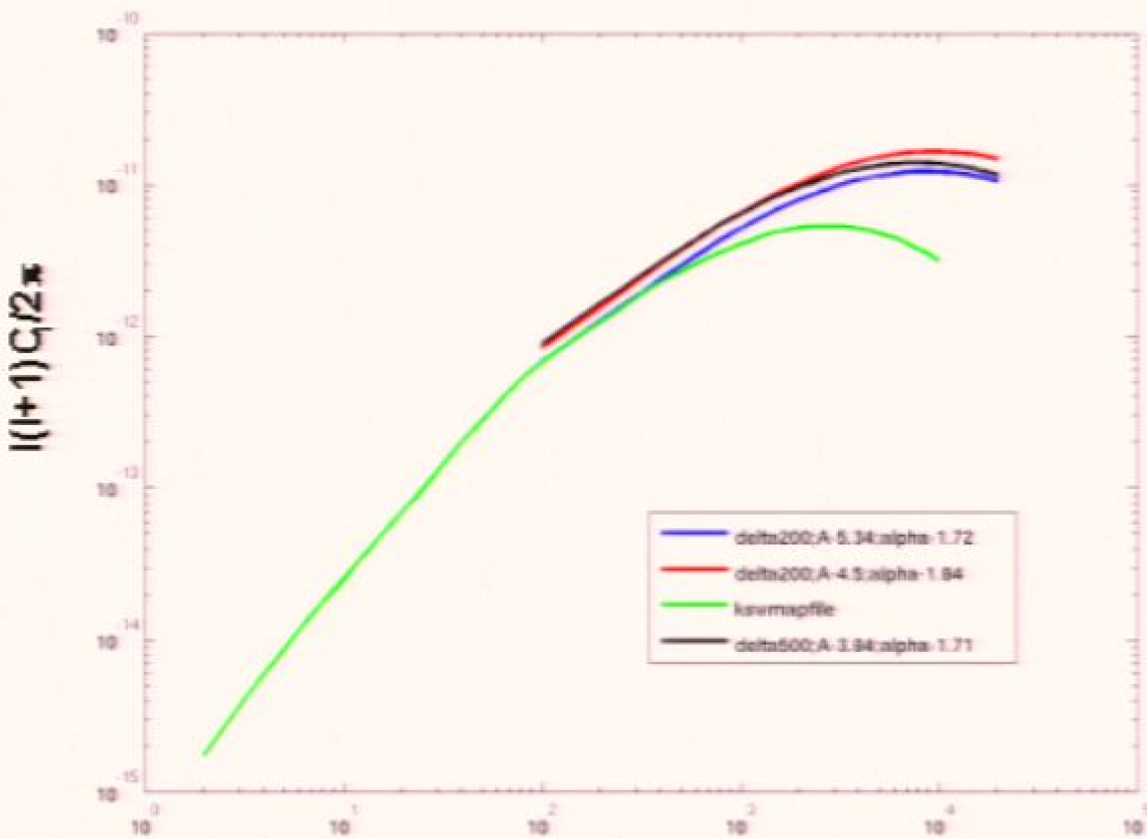

Re-calibrated to different observed scaling relations

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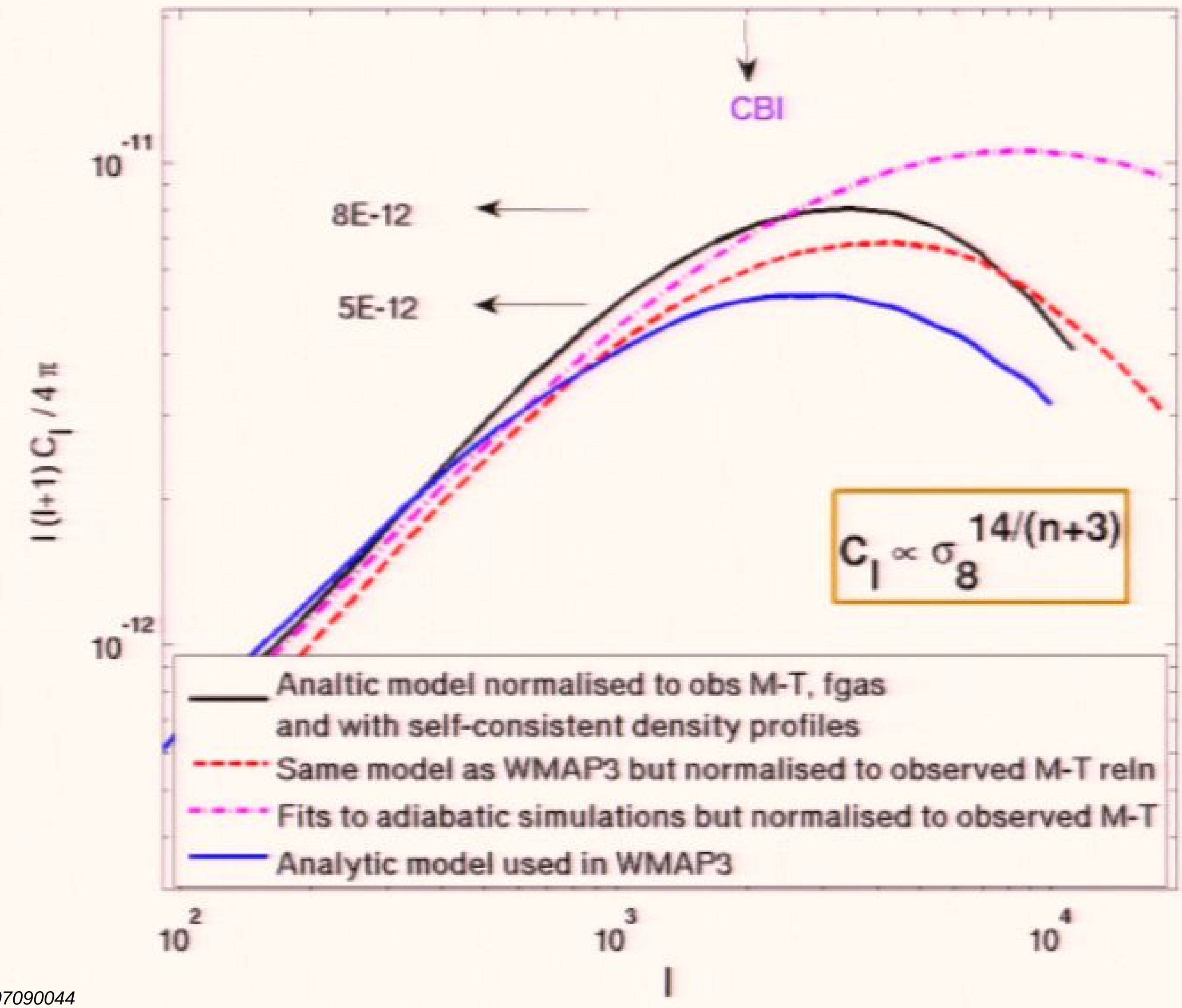
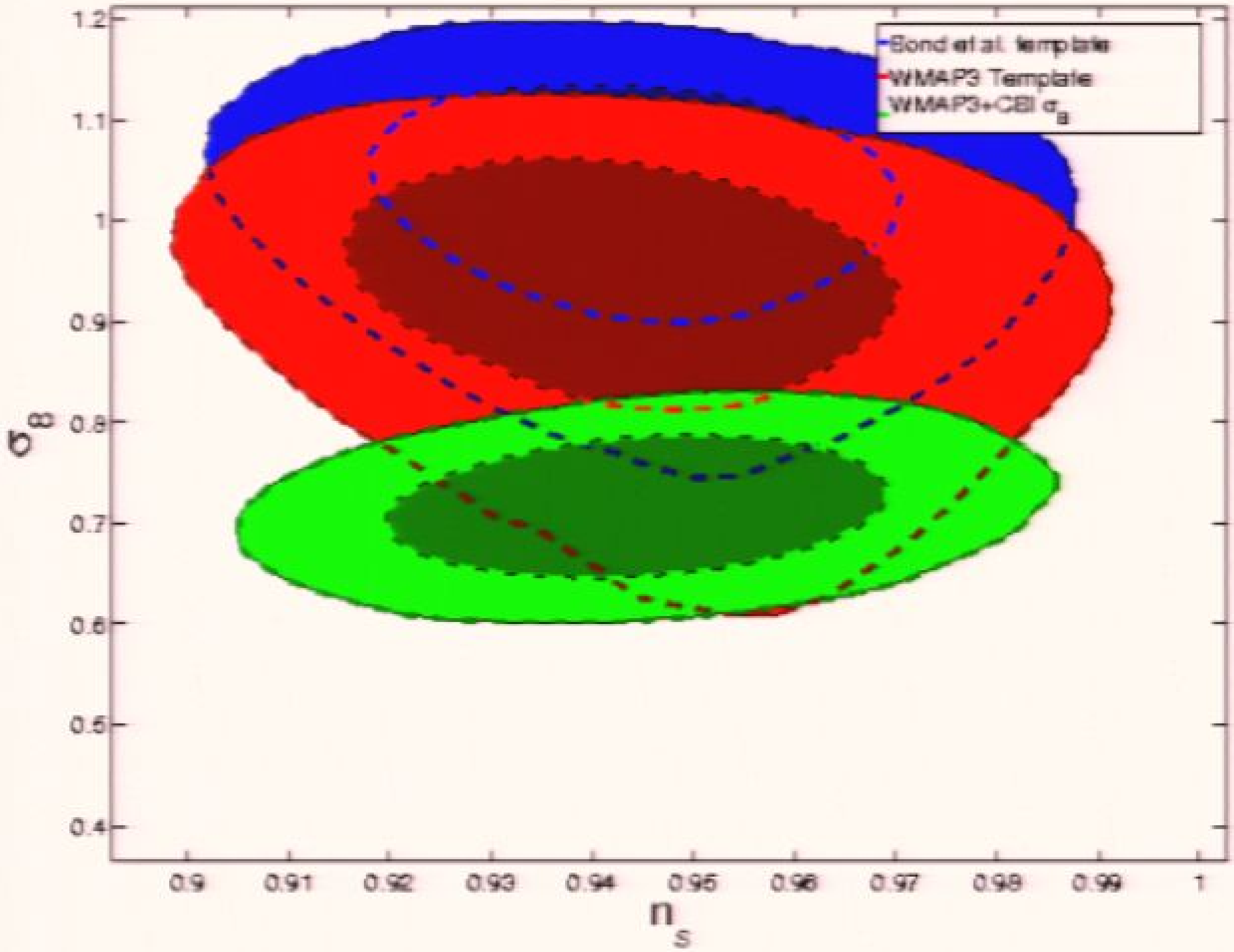
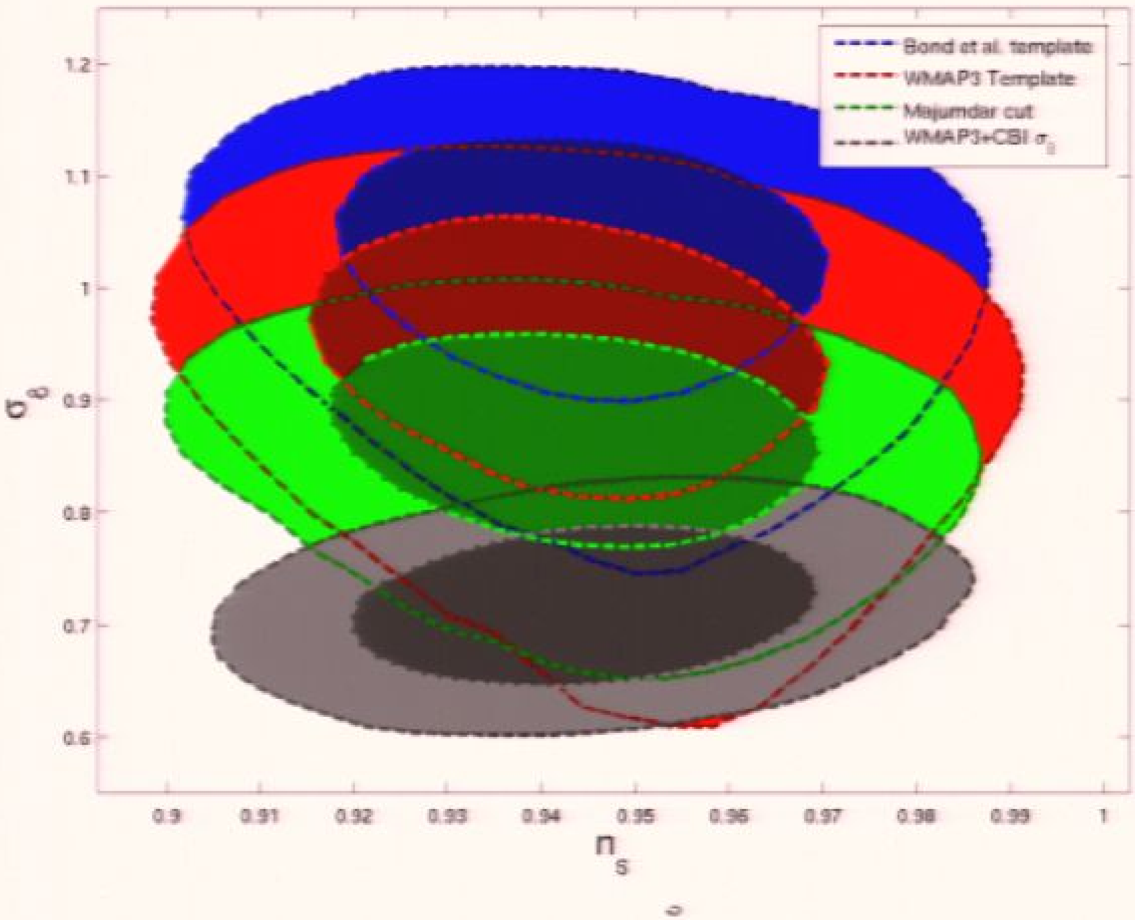


Doing things
A little more
carefully

‘Improved’ Inferred σ_8



'Improved' Inferred σ_8



New $\sigma_8 = 0.83 \pm 0.07$

Now, consistent with WMAP3 to 1-sigma

Still need to do proper Markov chains with the full SZ Cl spectra and not just sigma-8 scaling of SZ Cl

More on biases …

We can have improved simuations-- more physics
That would give new simulation mass-obs.
The million $ question is whether its right? Whether
Cosmological studies will be unbiased?

--> Ask Christoph for more on this :-)

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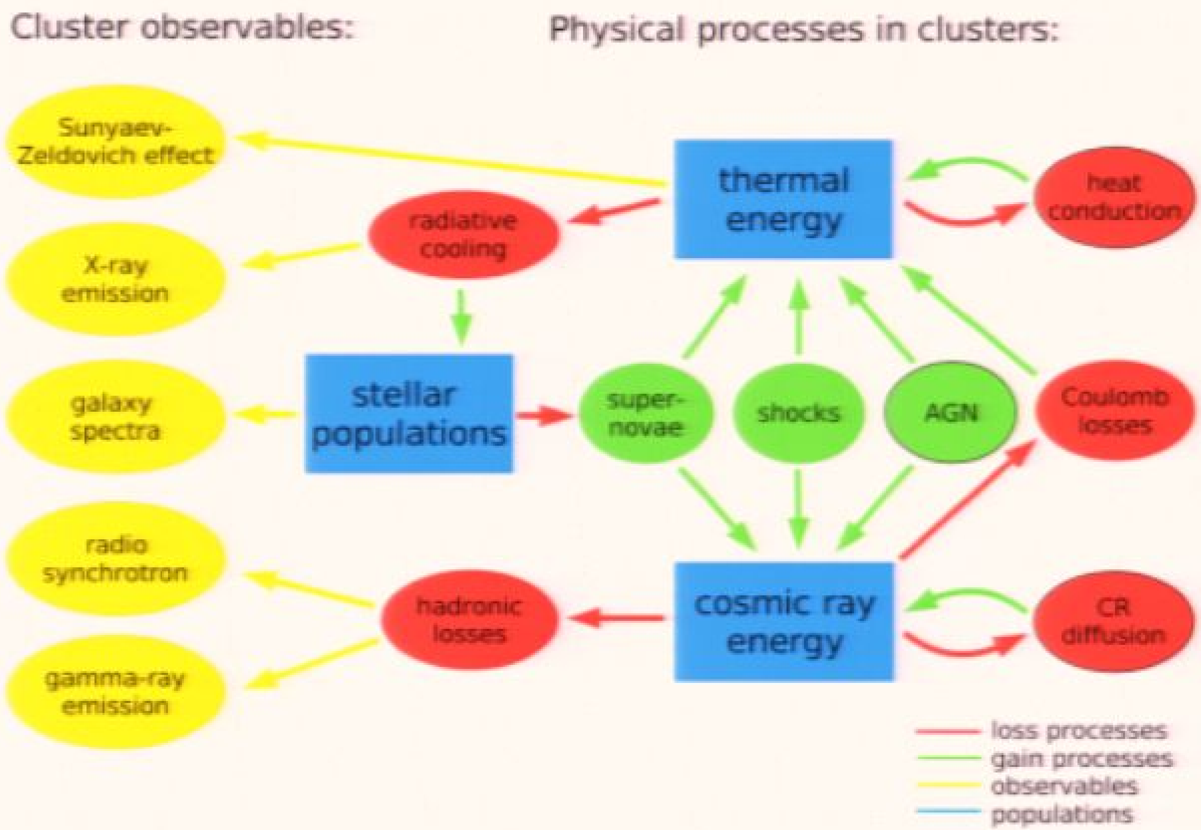

Pfrommer etal 2007

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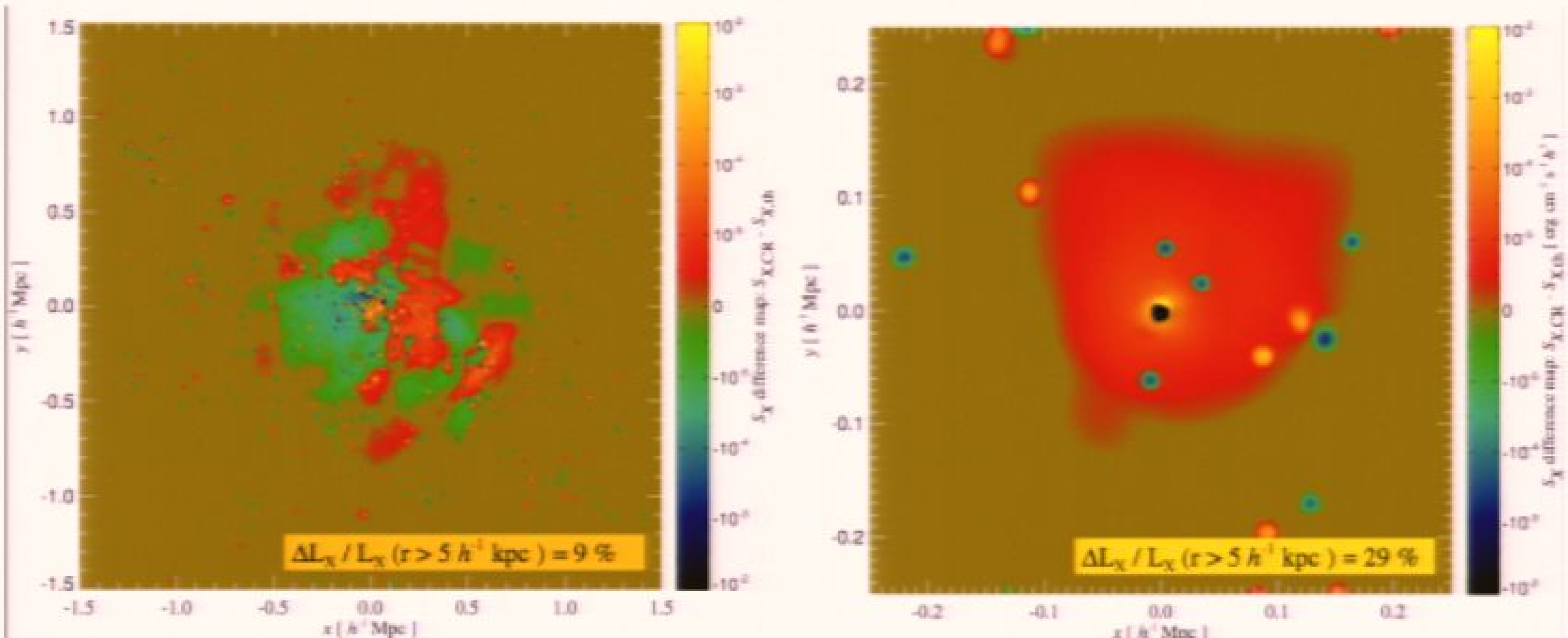

large merging cluster, $M_{vir} \simeq 10^{15} M_{\odot}/h$

cool core cluster, $M_{vir} \simeq 10^{14} M_{\odot}/h$

Pfrommer etal 2007

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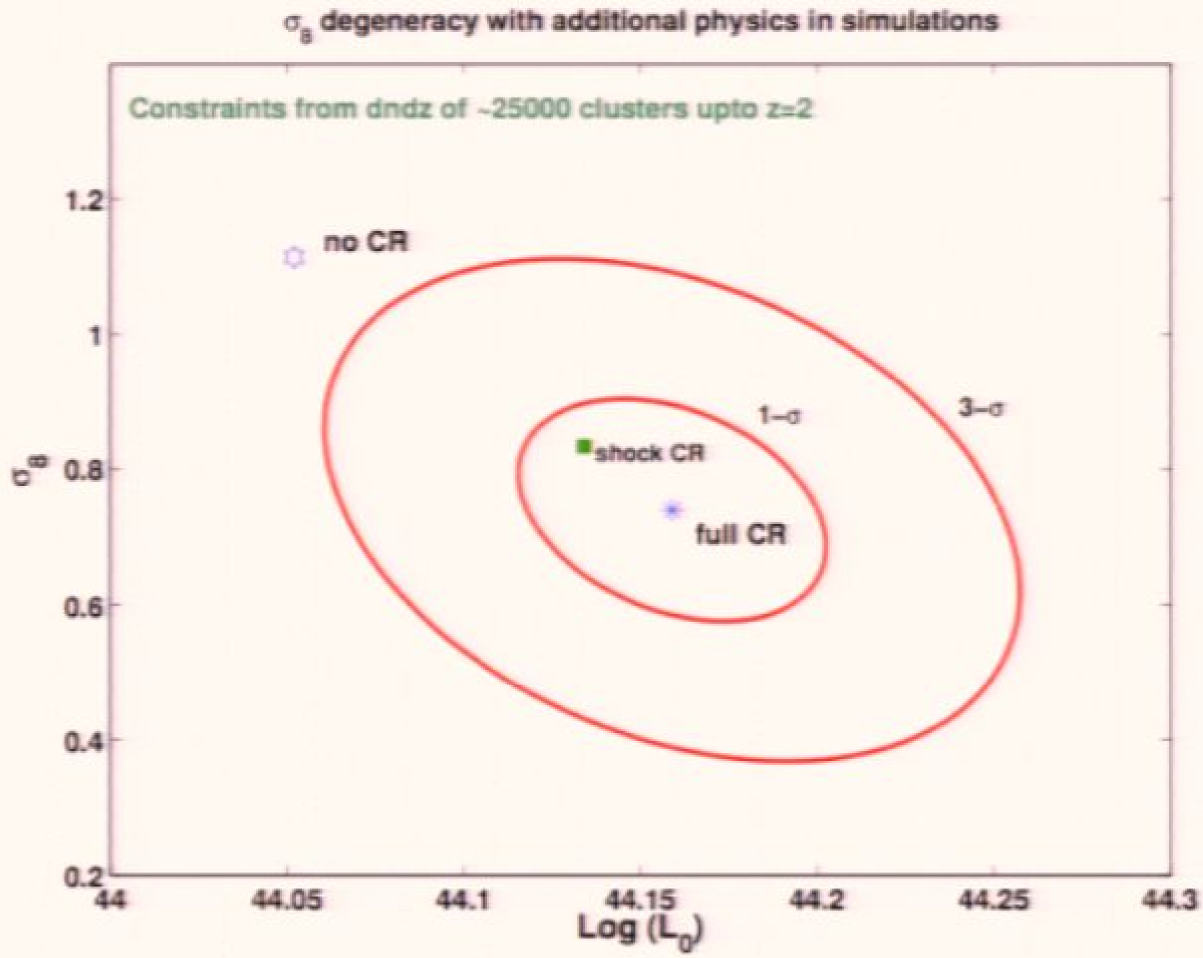

Part Four: "Leap of Faith" (Getting cosmology and cluster physics at one go)

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The Red-Sequence Cluster Survey (www.rcs2.org):

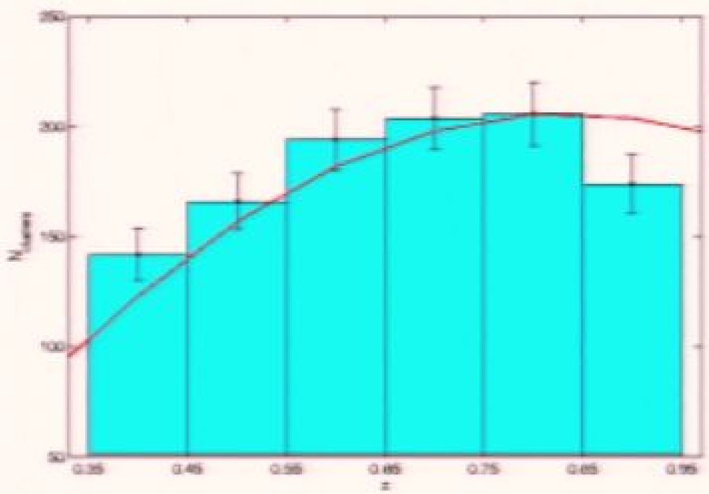
RCS-1 (completed) : 90 degs, 4000 candidates, $z < 1.5$
approx **1100 clusters** between $z \sim 0.2-0.9$ over Bgc>300

RCS-2 (ongoing) : Uses MegaCam at CFHT
1000 degs, 12000-14000 clusters
almost done ~ 800 deg; completion 2007 end

Uses the ubiquitous red-sequence of cluster early-type galaxies to identify clusters with a well-understood selection function. The mass proxy is the Bgc.

Side Comment 1: **First ever cosmology results using cluster counts !!**
Side Comment 2: **Large error bars --> Think about the <2000 error bars in CMB experiments in Lyman's talk**

RCS results:



The mass-obs reln:

$$M_{\Delta} = 10^{A_{Bgc}} B_{gc}^{\alpha} (1+z)^{\gamma}$$

ClusterMC analysis, there are 3+1 cluster parameters along with 4 cosmology parameters (Ω_M, σ_8, h, n_s: main prior on h)

To start, there are NO PRIORS on cluster parameters. Rely on only self-calibration of the underlying cluster counts in z-bins.

1. Weak lensing masses for a subsample of RCS/CNOC clusters (Hoekstra 07).

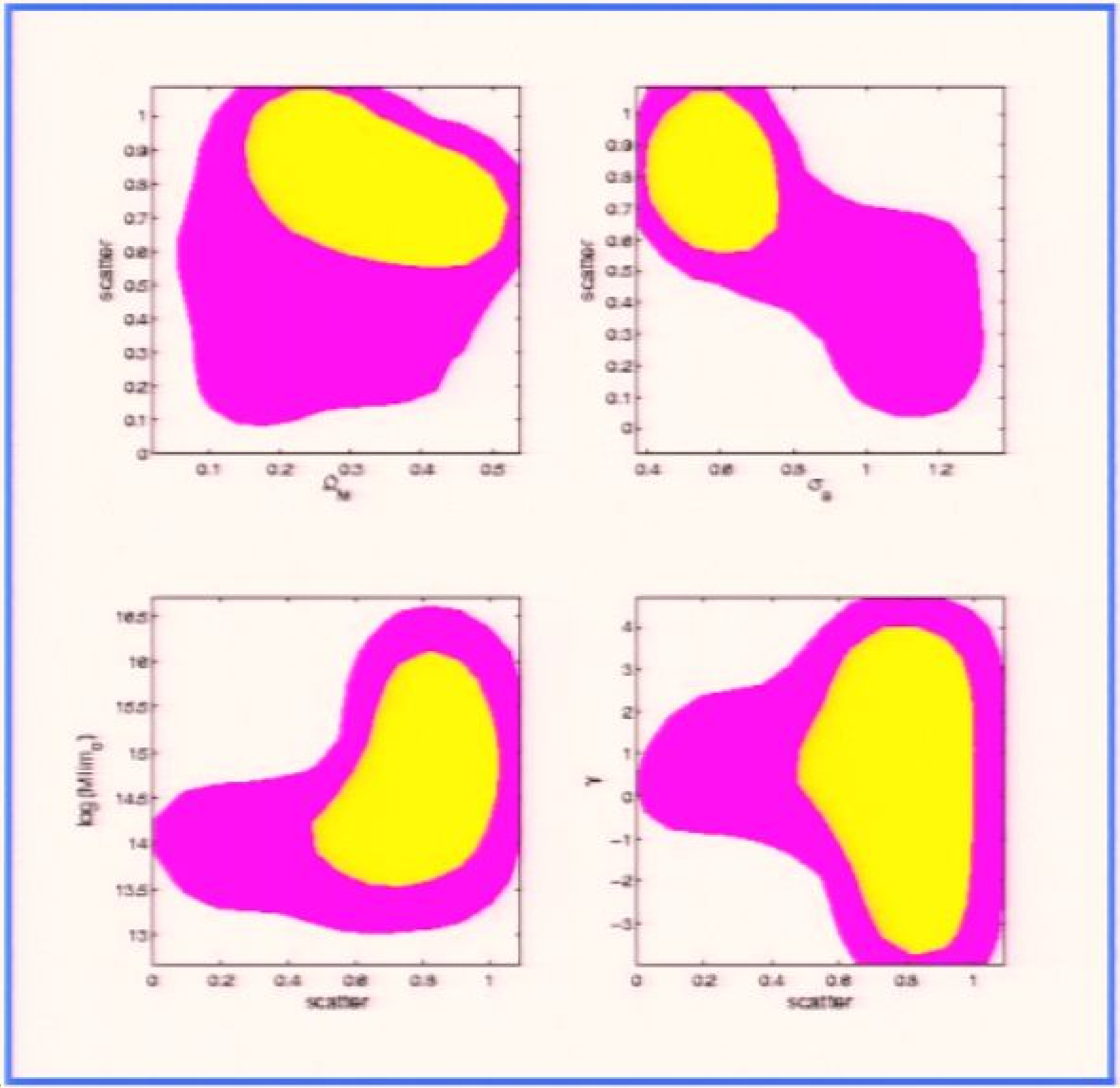
2. Dynamical masses for a subsample of 36 clusters between 0.3<z<0.9
   Wide field spectroscopy of 20,000 cluster galaxy redshifts. (Blindert etal 2007)

Question: How much scatter?

- Scaling relations are the 'mean' relation between two cluster observables.
- Even the tightest scalings have some scatter.

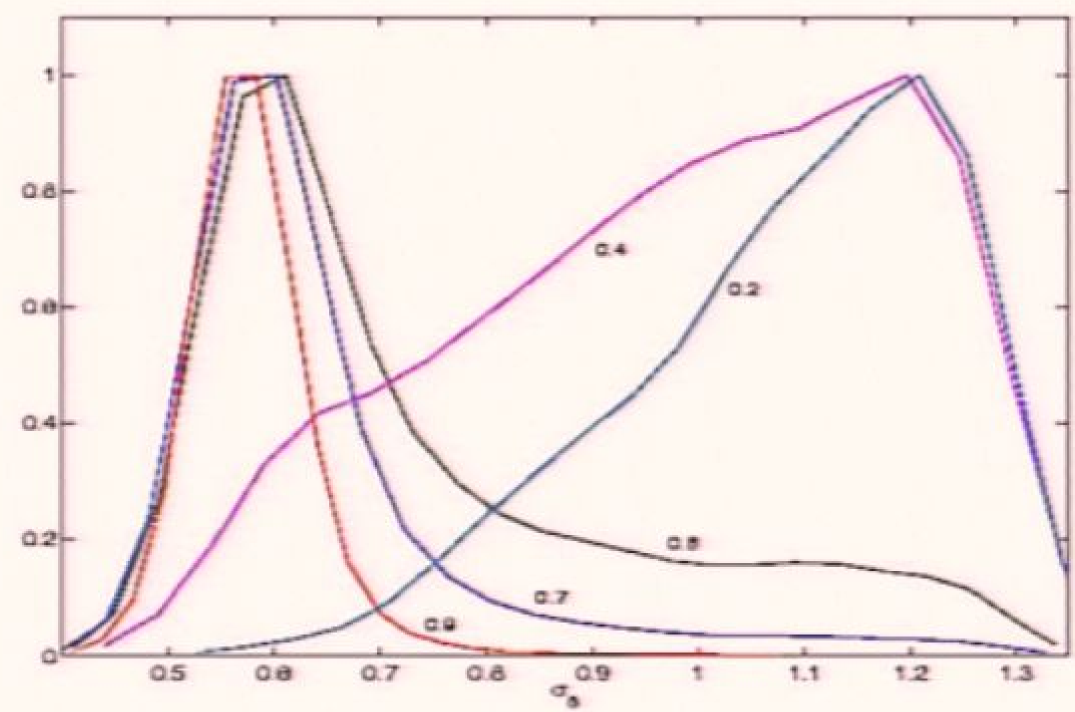
Relation	Scatter
$M\text{-}T_X$	20%-35% (obs/sims)
$M\text{-}L_X$	>30 % (obs/sims)
$M\text{-}Y_{SZ}$	10-15% (sims)
$M\text{-}f_g T_X$	10% (sims)
$M\text{-}B_{gc}$	30% (?)(obs, from CNOC clusters compared with XRay masses) This *appear* to be the natural prior to put on scatter

RCS-1 data has lots of degeneracies:



scatter is a key player

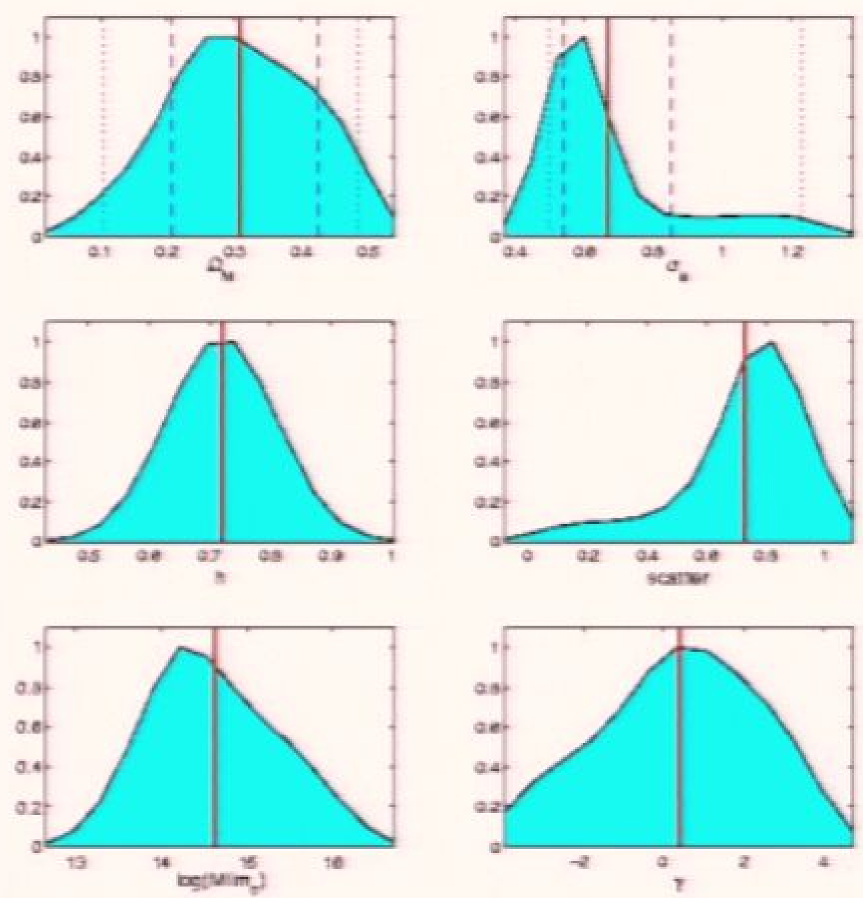
Scatter and cosmology...



σ_8 constraints with priors on scatter

Important when analyzing data from cluster surveys! Caution on using priors.
With future surveys: possible to self-calibrate with scatter.
dndz + dF/dM can constrain scatter (Lima & Hu, theory)

Cosmological constraints…



Results:

$\Omega_M = 0.3 +/- 0.1$

$\sigma_8 = 0.7 +/- 0.2$

Comments:

1. **First results!**

2. **Systematics are marginalized over -->**
   Means more clusters would give tighter constraints

   Means RCS2 having 12000 clusters will strongly constrain cosmo parameters. Improvement by factor 3+.

The Ω_M-σ_8 banana is similar to only weak lensing result shown by James. And this is marginalized over cluster uncertainties.

Past results: Couldn't resist showing this table from one of Douglas's papers…

Table 1. Some recent estimates of $_8$. The errors are typically statistical. We have tried to give values consistently for $_m \simeq 0.3$, while $\simeq 0.2$ is a typical value of the shape parameter. Methods used include: weak lensing (WL); optical clusters (OC); clusters normalized using weak lensing (WLC); the X-ray temperature function (XTF); the X-ray luminosity function (XLF); the power spectrum (PS); and the Sunyaev–Zel'dovich effect power spectrum (SZ). The two errors for the WL analysis by Refregier et al. (2002) are for statistical uncertainty and cosmic variance, respectively.

Authors	8	Error		Method
Van Waerbeke et al. (2001)	0.88	0.05	–	WL
Van Waerbeke et al. (2002)	0.98	0.06	0.2	WL
Bacon et al. (2003)	0.97	0.13	–	WL
Refregier et al. (2002)	0.93	0.17	0.21	WL
Hoekstra et al. (2002)	0.87	0.03	–	WL
Brown et al. (2003)	0.74	0.09	–	WL
Hamana et al. (2003)	0.73	0.27	0.21	WL
Jarvis et al. (2002)	0.71	0.14	0.21	WL
Bahcall et al. (2002)	0.72	0.06	–	OC
Viana et al. (2002)	0.61	0.10	0.1	WLC
Blanchard et al. (2000)	0.75	0.02	–	XTF
Henry (2000)	0.77	0.15	–	XTF
Oukbir & Arnaud (2001)	0.91	–	–	XTF
Pierpaoli et al. (2001)	1.02	0.07	0.23	XTF
Seljak (2001)	0.77	0.06	0.20	XTF
Reiprich & Böhringer (2002)	0.68	0.13	0.17	XLF
Borgani et al. (2001)	0.67	0.06	0.23	XLF
Schuecker et al. (2003)	0.71	0.03	–	XLF
Allen et al. (2003)	0.72	0.02	–	XLF
Lahav et al. (2002)	0.73–0.83	0.07	0.21	PS
Szalay et al. (2001)	0.91	0.06	0.19	PS
[illegible]d et al. (2002)	≥1	–	–	SZ PS
Komatsu & Seljak(2002)	1.05	0.05	–	SZ PS

A bit into the future ….

Larger Surveys with more clusters!

RCS-2 : 1000 deg, Expected N ~10-15k
SPT : 4000 deg, Expected N~20k-25k
eROSITA: whole sky, Expected N ~80k-100k

Bottomline -

More clusters means a) more ways to calibrate cluster uncertainties
b) tighter constraints, more ambitious like going for w(a)

Calibration, Complimentary Methods, Consistency Checks etc…

0. Just let dn/dz information self-calibrate the survey with simple scaling reln. (IMP: simulations + observations point to the structure of the scaling)

1. External mass calibration (say, weak lensing)
   (Majumdar & Mohr 2003,2004, Majumdar 2005)
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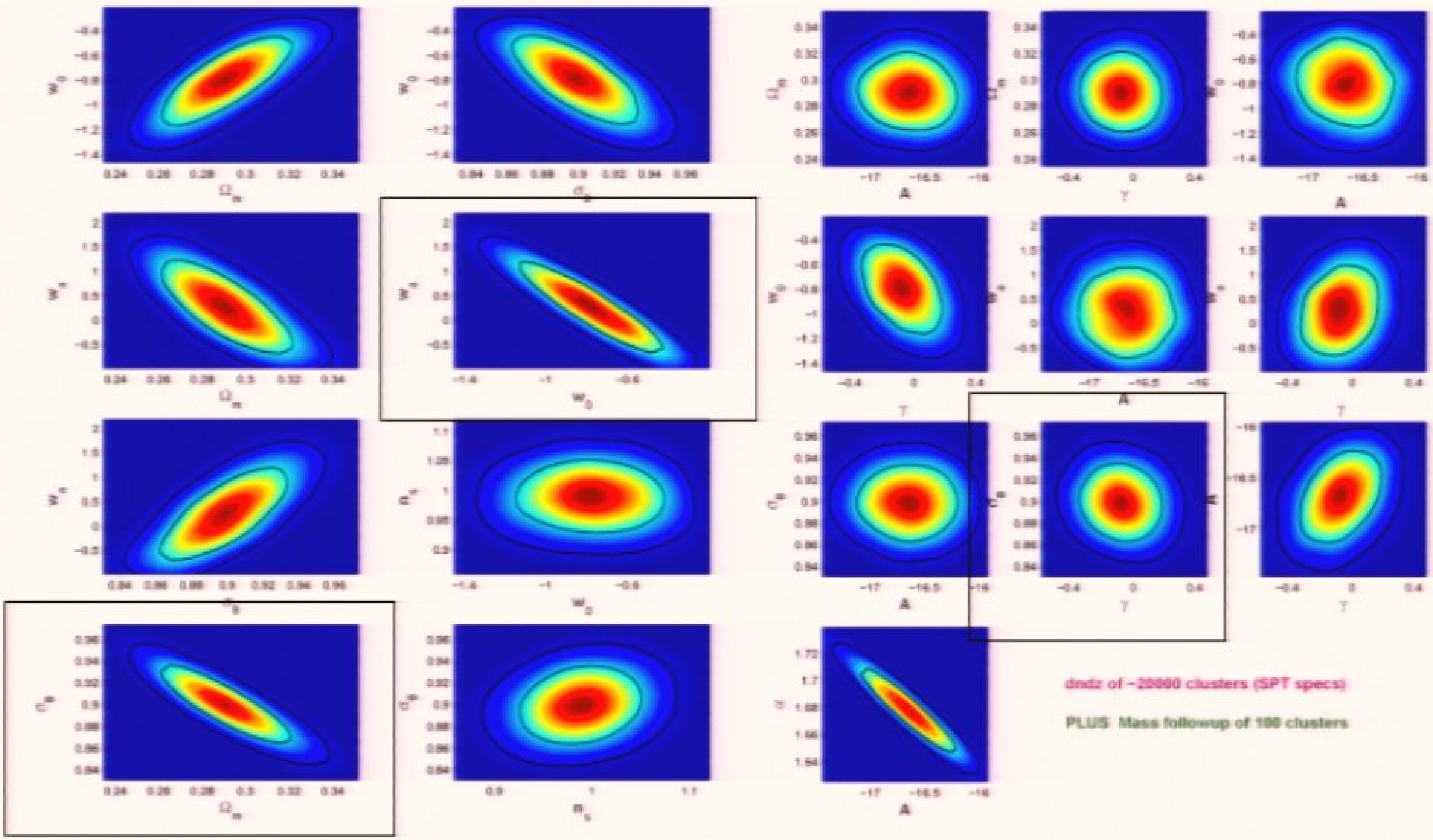
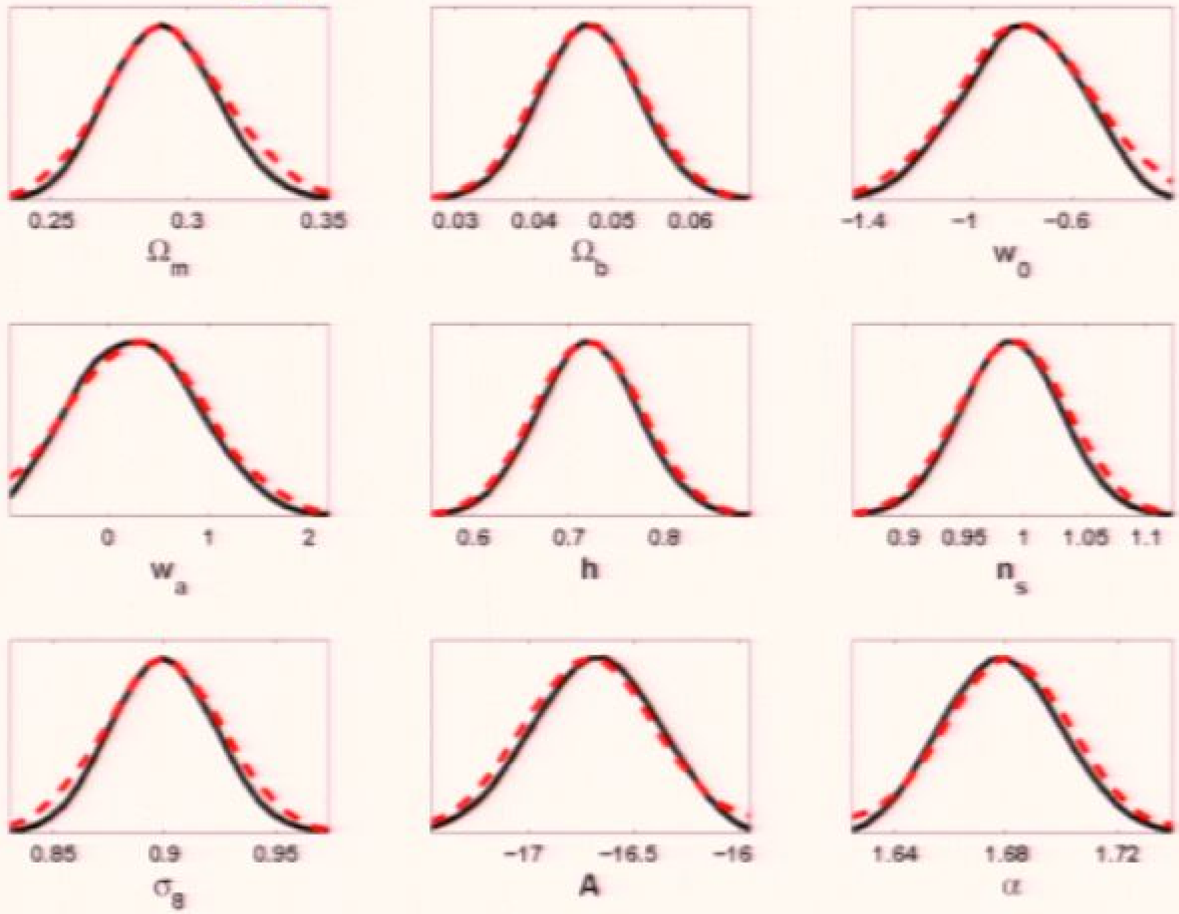
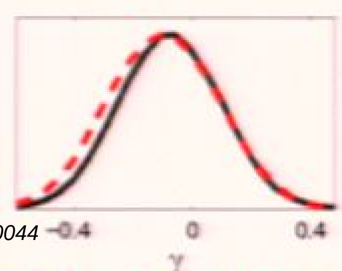
MANY

How well do we do with future surveys?
Ex: 20000 clusters + 100 indep mass measurements



The Rosy picture of cluster surveys…





dn/dz of 20000 clusters (SPT specs)

PLUS Mass Followup of 100 clusters

SPT: the forecasts
Clusters alone
20000 clusters

$\Delta\sigma_8 = 0.033$
$\Delta\Omega_M = 0.018$
$\Delta w_0 = 0.140$
$\Delta w_a = 0.450$

$\Delta w(-1) = 0.04$

With eROSITA,
Its almost a factor
of 2-3 tighter

Majumdar & Cox

What do we need to do?

Better observations-

Go for scatter (non-gaussian tails in scatter, luminosity dependent scatter, pin down non-standard evoluton in scaling)

Better redshift calibration

Better simulations -

Help in understanding the general nature and evolution of scaling relations.

Secondary mass calibration (lensing mass-halo mass)

Testing 'aggressive' self-calibration - examples

1. redshift dependence of theoretical halo-mass dependence will self-calibrate out as one can solve for a scaling between simulation defined halo mass and cluster observable

2. Systematic photometric redshift uncertainties will self-calibrate out (again in γ)

3. A redshift or mass dependence in AGN contamination will self-calibrate out mainly in γ (for Xray surveys).

To Conclude…

The age of large yield cluster surveys, and the promise to get tight cosmological constraints using clusters, have come.

We should not be afraid of using clusters for cosmology. We need just to be careful (the CBI example)

RCS-1 has shown that one can self-calibrate clusters to give sensible results. Future surveys are even more powerful.

There are may ways of calibration and consistency checks.

THANK YOU.

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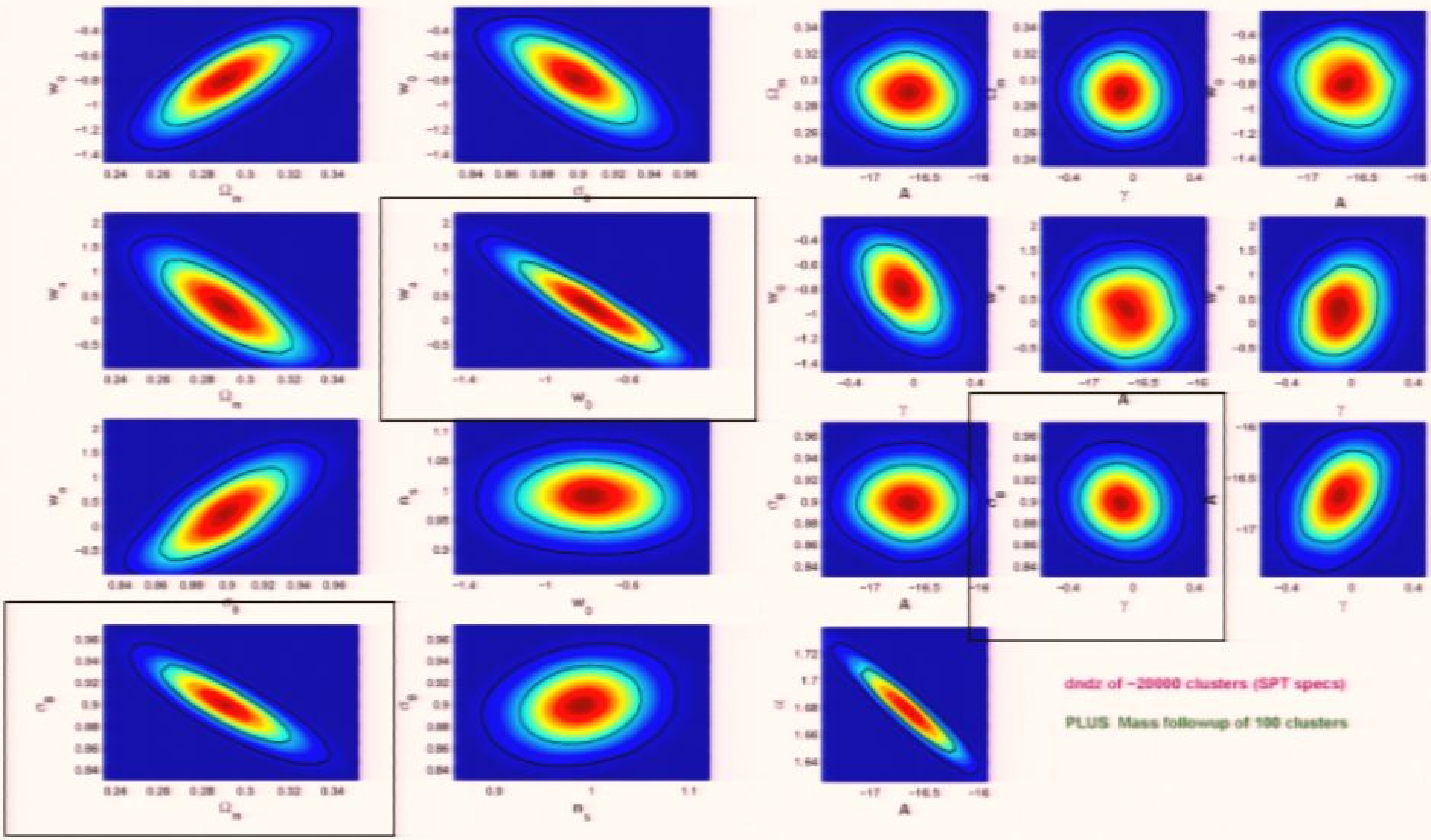

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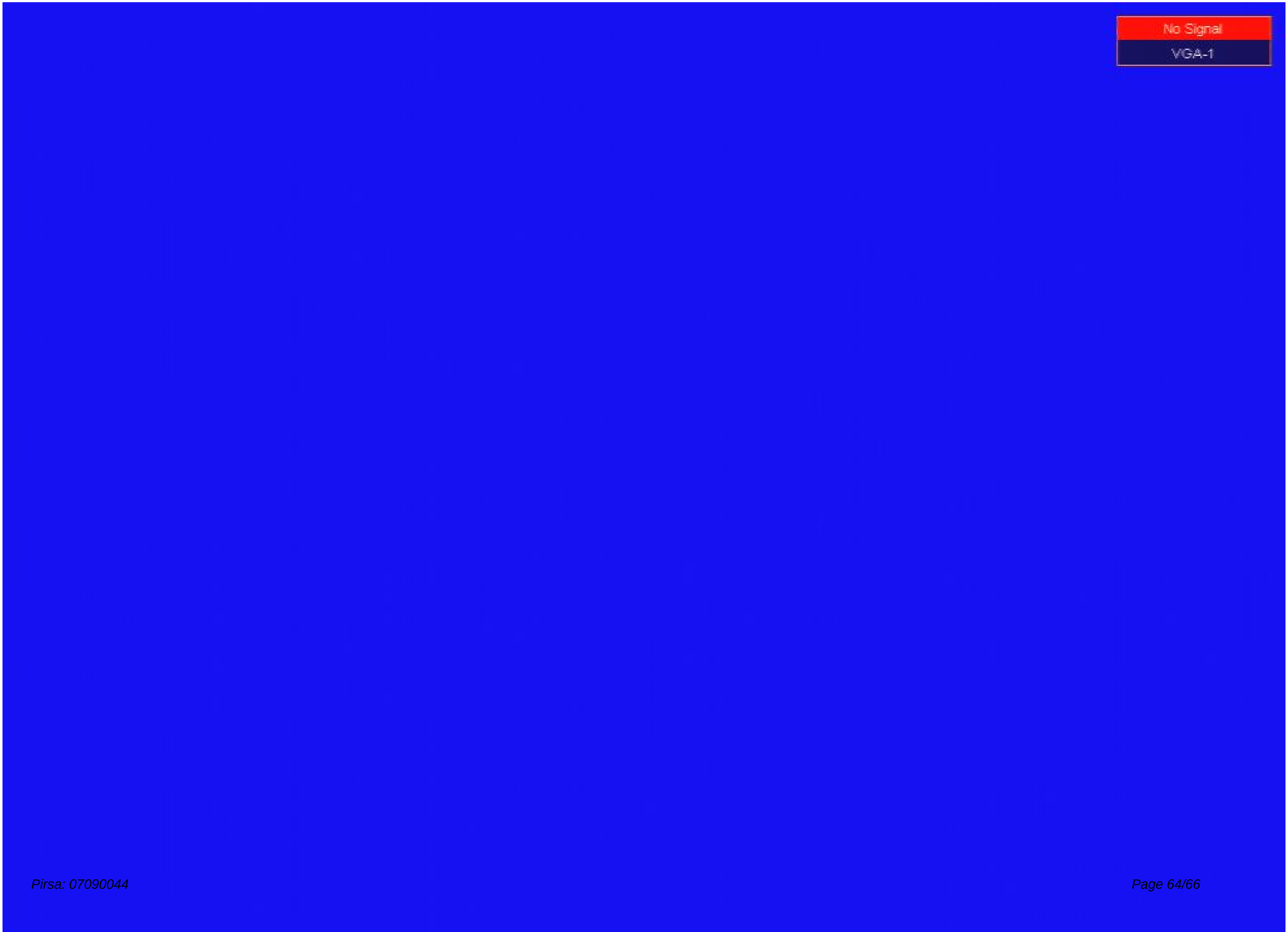
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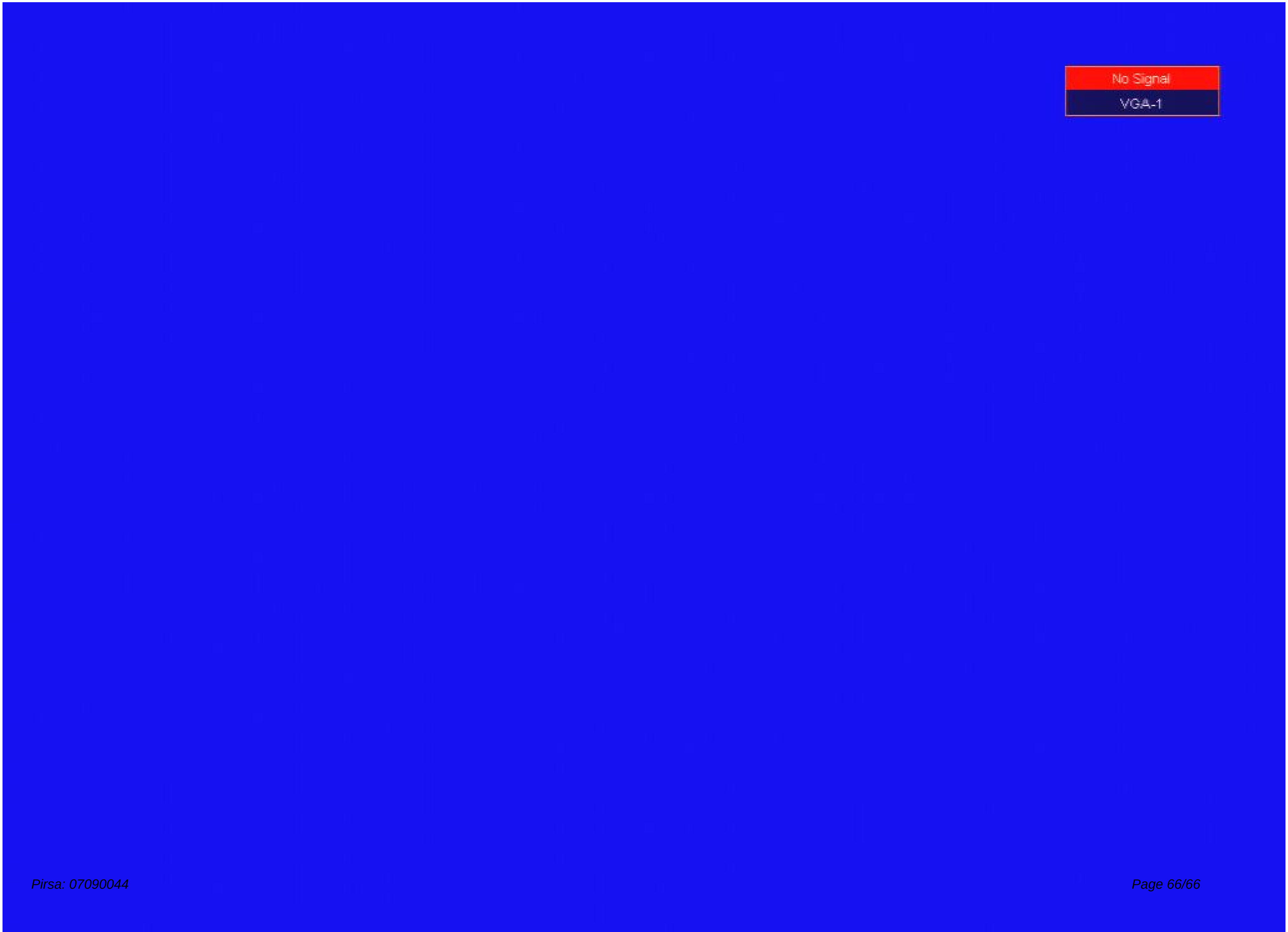
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