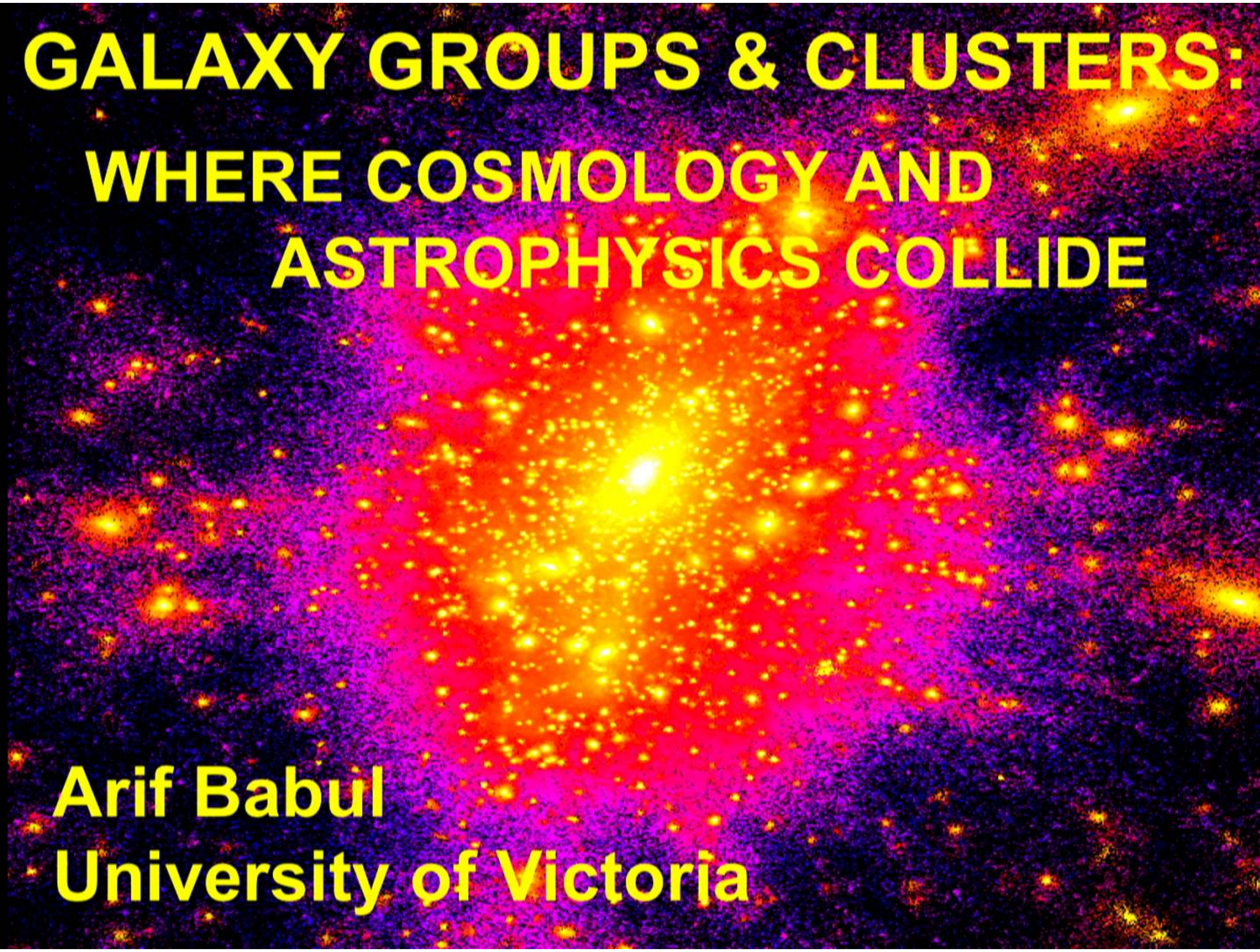
Title: Groups and Clusters of Galaxies: Where Cosmology and Astrophysics Collide

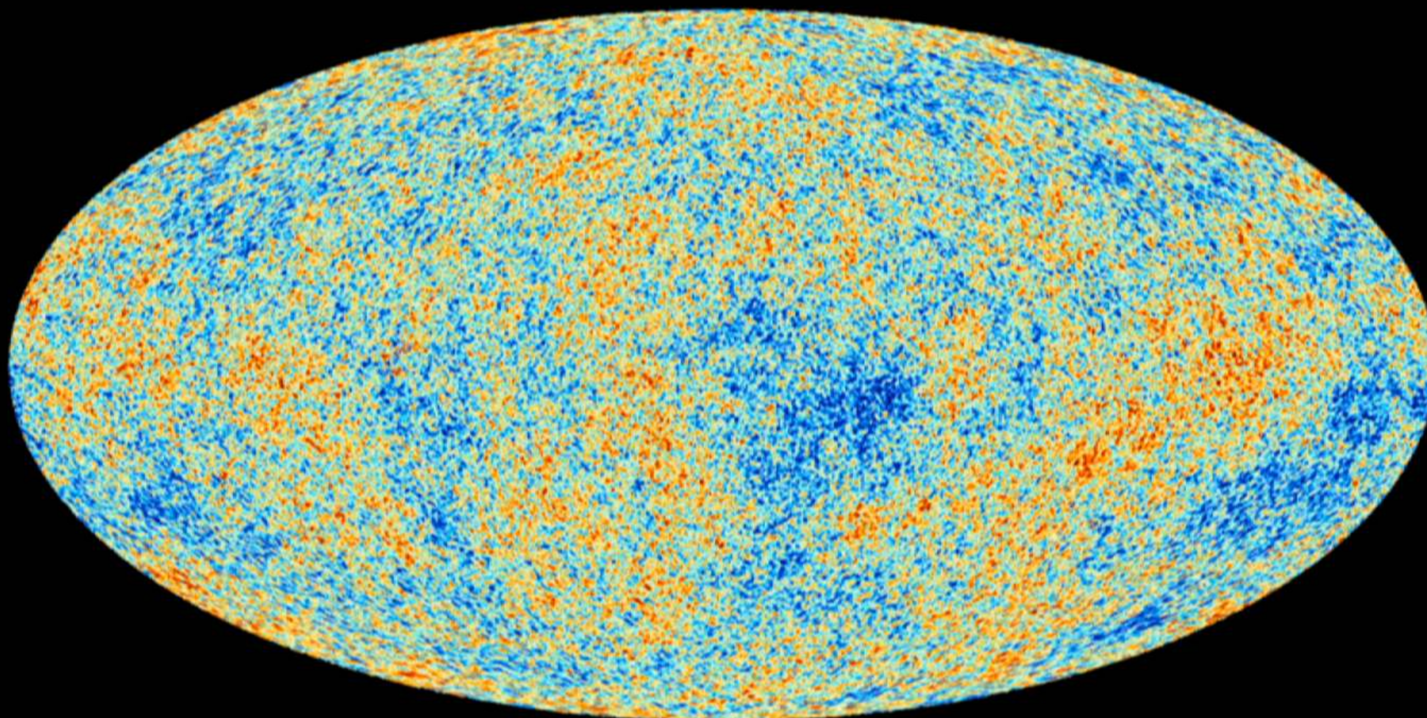
Date: Apr 15, 2014 11:00 AM

URL: http://pirsa.org/14040133

Abstract: Groups and clusters of galaxies are the most massive gravitationally bound objects in the Universe. They are also the most recent cosmic objects to form. In the currently accepted models of cosmic structure formation, the number density distribution of the most massive of these systems, and how this has been changing with time, depend sensitively to the parameters describing the large-scale geometry and the expansion history of the universe. However, to exploit galaxy clusters as cosmological probes, we must be able to relate their observable properties to their total mass. I will discuss our ongoing effort to calibrate the X-ray/SZ observations to the total mass for the 50 clusters comprising the Canadian Cluster Comparison Project (CCCP) sample. Resulting scaling relations, the associated scatter, and even how these change with time, invariably depend on "astrophysics" unfolding in these systems. The precision with which the cosmological parameters can be determined depends critically on how well we understand why groups and clusters manifest the observed properties that they do. This, however, has proven challenging. I will provide an update of the current state of affairs and highlight some of the key gaps in our understanding of the underlying physics.


GALAXY GROUPS & CLUSTERS:
WHERE COSMOLOGY AND
ASTROPHYSICS COLLIDE
Arif Babul
University of Victoria

CMB EXPERIMENTS HERALDED THE AGE OF PRECISION COSMOLOGY

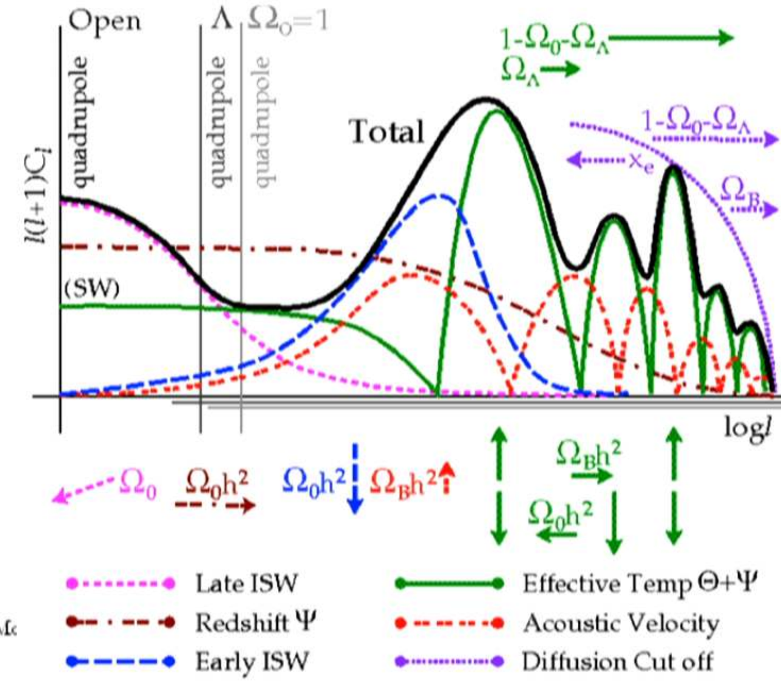


Just Six Number?

Age of universe	t_0
Hubble constant	H_0
Baryon density	Ω_b
Physical baryon density	$\Omega_b h^2$
Dark matter density	Ω_c
Physical dark matter density	$\Omega_c h^2$
Dark energy density	Ω_Λ
Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_\mathcal{R}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8
$l(l+1)C^{TT}_{220}/2\pi$	C_{220}
Scalar spectral index	n_s
Redshift of matter-radiation equality	z_{eq}
Angular diameter distance to matter-radiation eq.[c]	$d_A(z_{eq})$
Redshift of decoupling	z_*
Age at decoupling	t_*
Angular diameter distance to decoupling [c,d]	$d_A(z_*)$
Sound horizon at decoupling [d]	$r_s(z_*)$
Acoustic scale at decoupling [d]	$l_A(z_*)$
Reionization optical depth	τ
Redshift of reionization	z_{reion}
Age at reionization	t_{reion}

Parameters for Extended M

Total density [f]	Ω_{tot}
Equation of state [g]	w_0, w_1
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$
Neutrino density [j]	$\Omega_\nu h^2$
Neutrino mass [j]	$\sum m_\nu$
Number of light neutrino families [k]	N_{eff}



Hu, Sugiyama, & Silk (1995)

Just Six Number?

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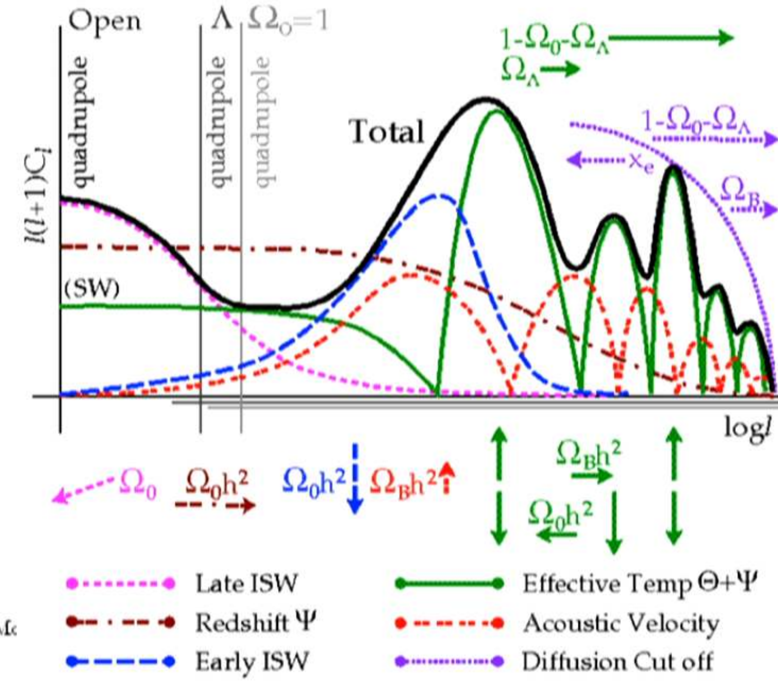
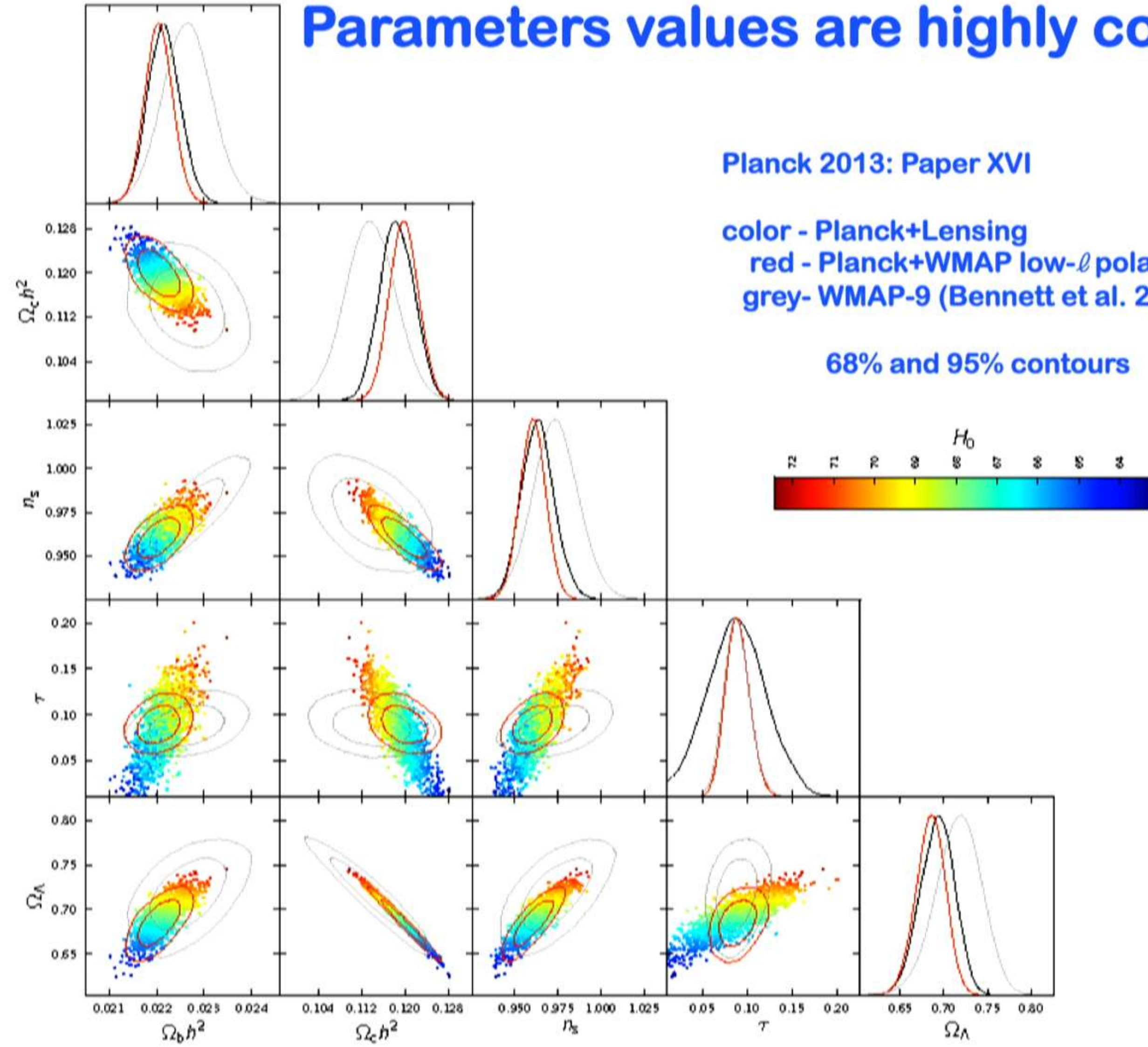
Parameters for Extended M

Total density [f]	Ω_{tot}	
Equation of state [g]	w_o, w_1	W_o= -1
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	0
Neutrino density [j]	$\Omega_\nu h^2$	
Neutrino mass [j]	$\sum m_\nu$	0.06 eV
Number of light neutrino families [k]	N_{eff}	~3



Hu, Sugiyama, & Silk (1995)

Parameters values are highly correlated

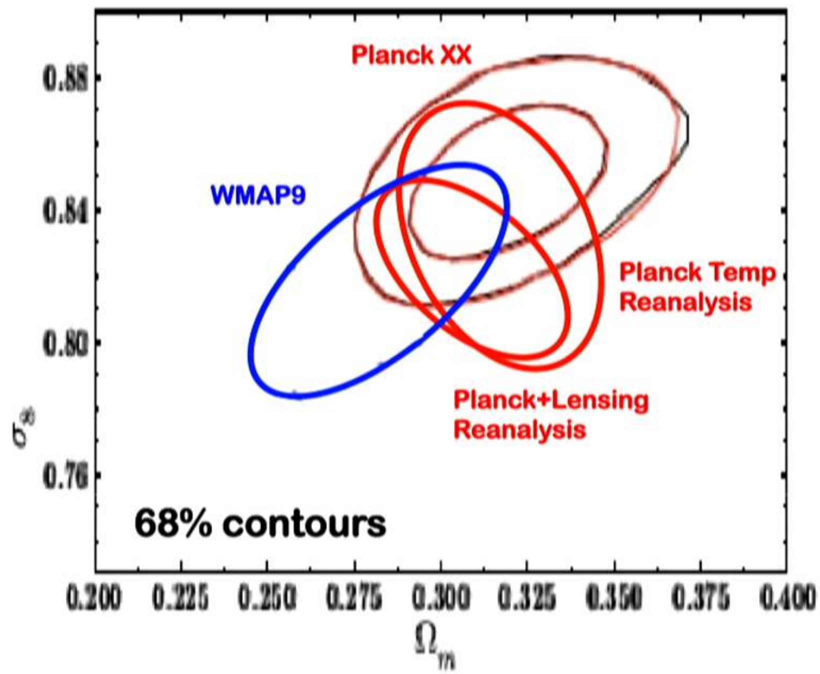


Planck 2013: Paper XVI

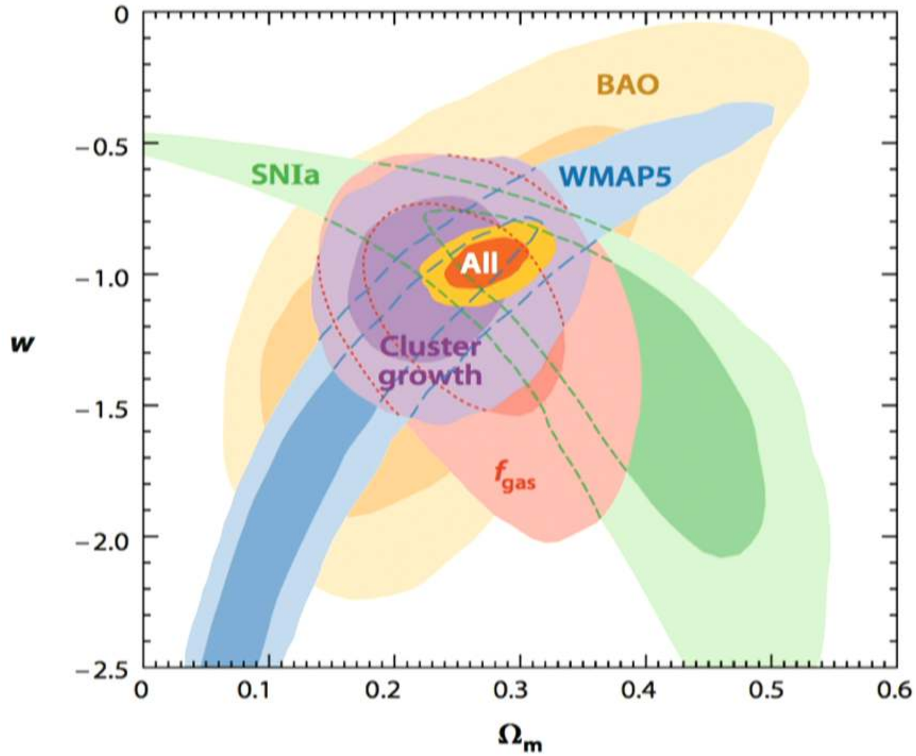
color - Planck+Lensing
red - Planck+WMAP low-ℓ polarization
grey- WMAP-9 (Bennett et al. 2012}

68% and 95% contours

WMAP AND PLANCK EXHIBIT OFFSETS

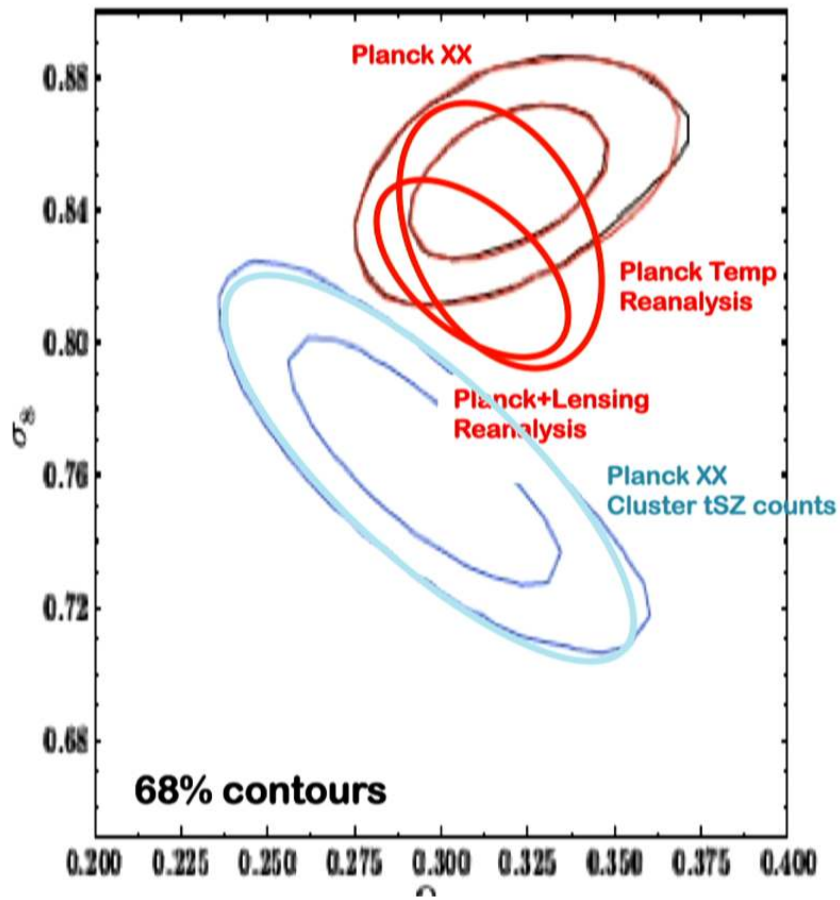


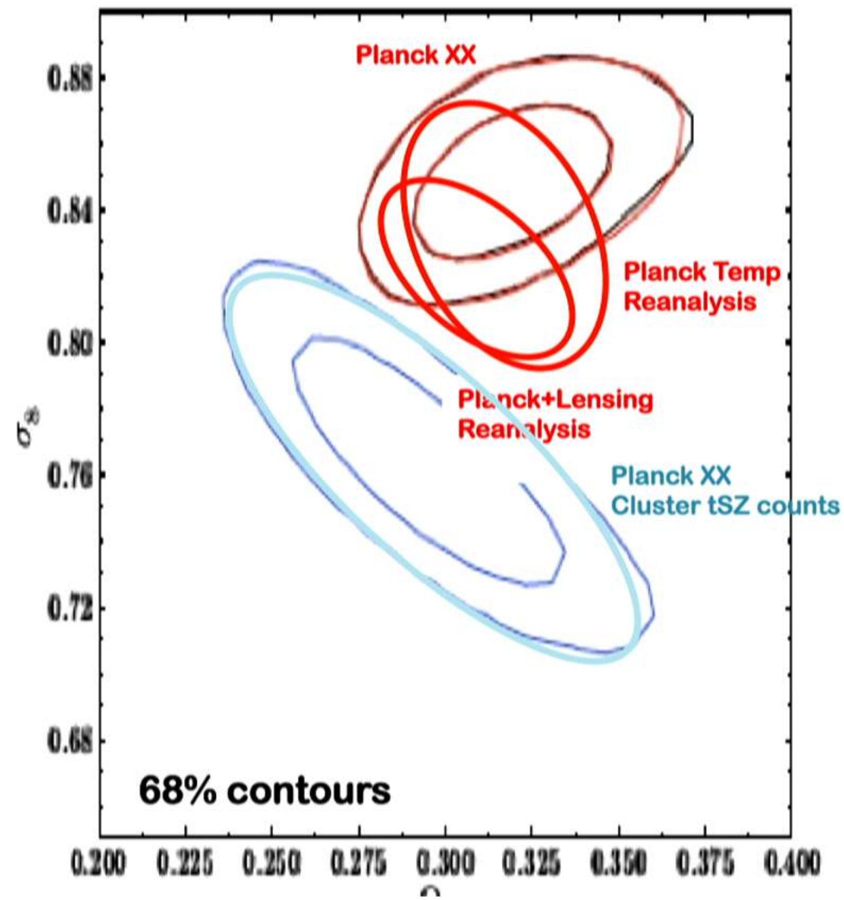
USE OF COMPLEMENTARY PROBES CAN GREATLY REDUCE UNCERTAINTIES



CMB MEASURES PARAMETERS AT HI-Z
CLUSTERS/LSS MEASURE PARAMETERS AT LOW-Z

Allen, S.W. *et al.* arXiv:1307.8152


Planck XX
Planck Temp
Reanalysis
Planck+Lensing
Reanalysis
Planck XX
Cluster tSZ counts
68% contours
0.88
0.84
0.80
0.76
0.72
0.68
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400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0.72
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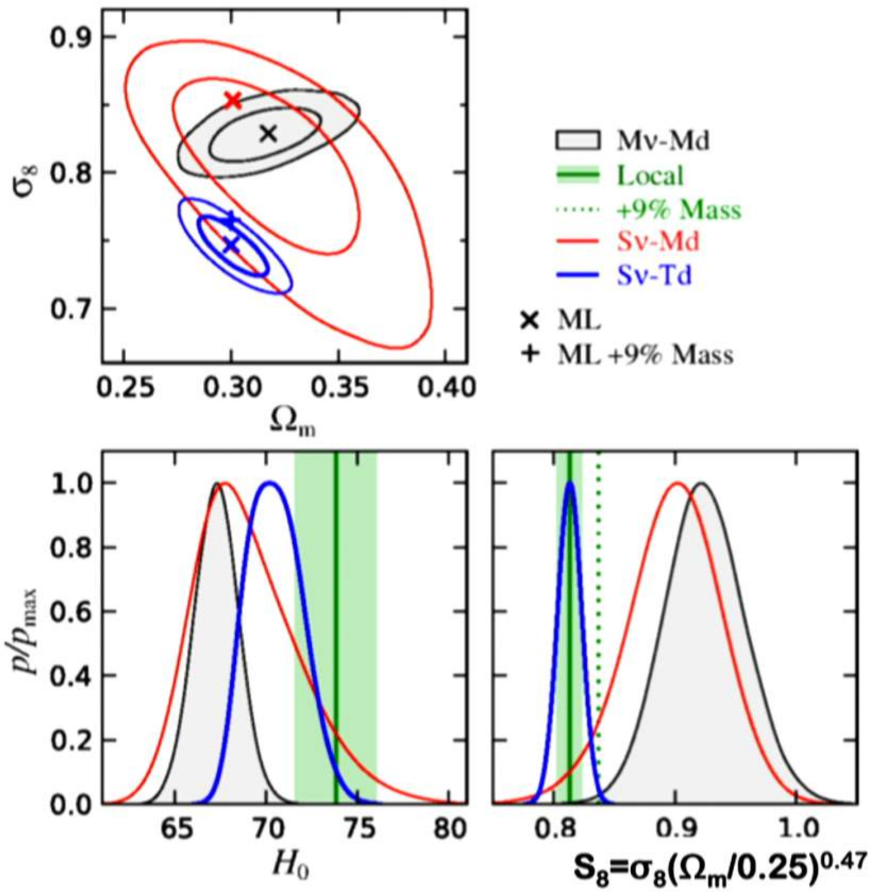
σ_8
0.200 0.225 0.250 0.275 0.300 0.325 0.350 0.375 0.400

TENSION BETWEEN HI-Z and LO-Z PARAMETERS: CASE FOR NON-MINIMAL MODEL?



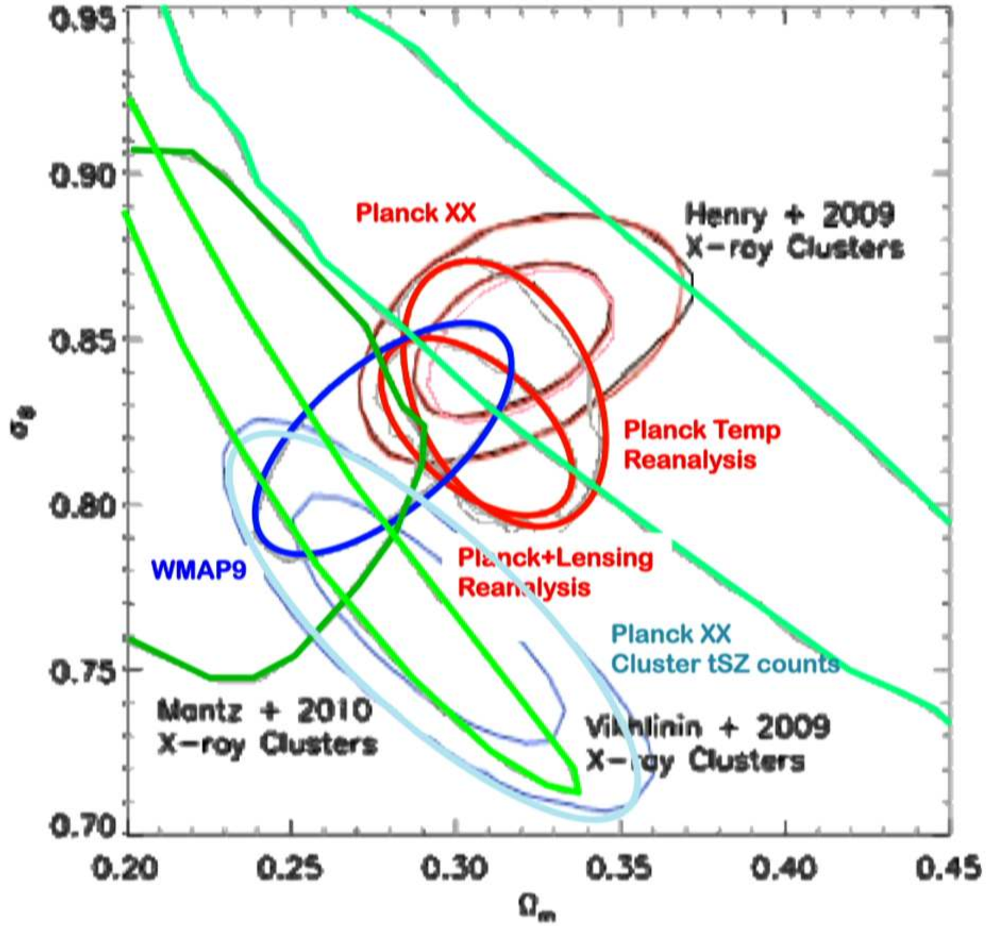
Wyman…Hu et al. (2014) argue:

ΔN_{eff} =1 (extra sterile ν)
M_s ~ 0.4 eV

Others argue for running of spectral index, etc.

Recent BICEP2 adds more fuel to this fire…

LETTING THE CAT OUT OF THE BAG (PARTLY)....



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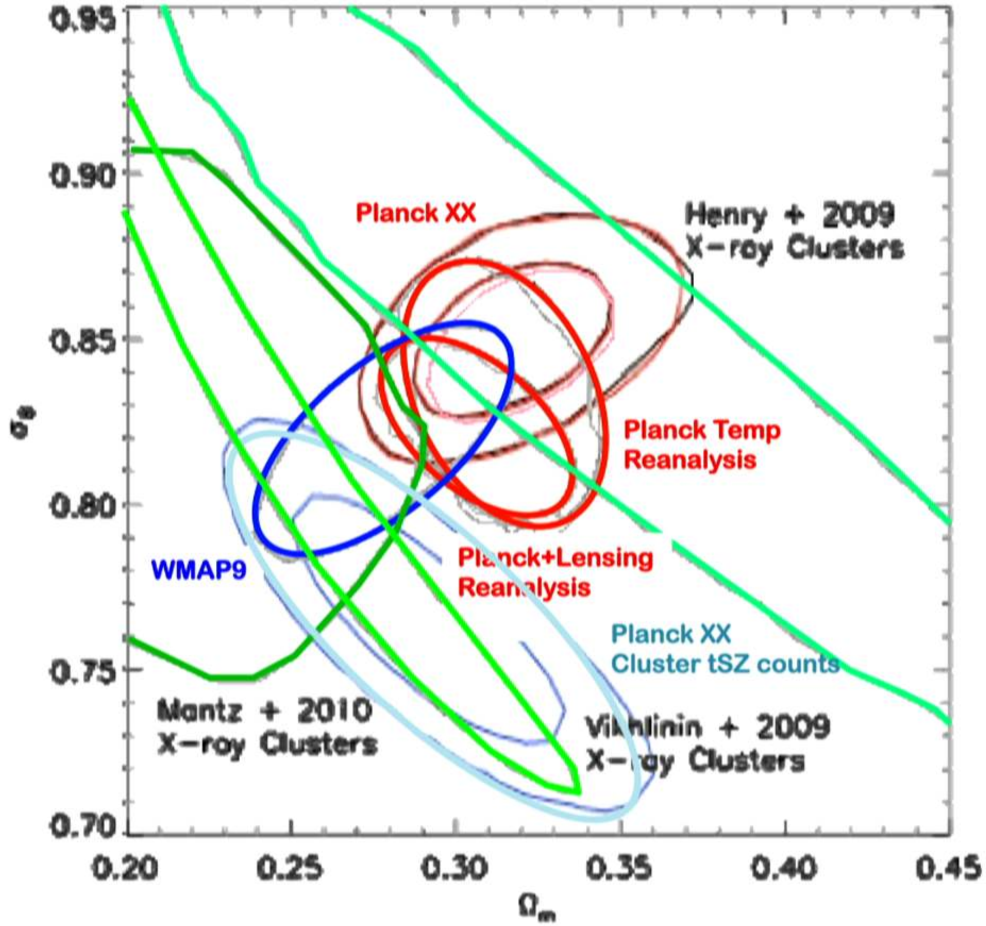
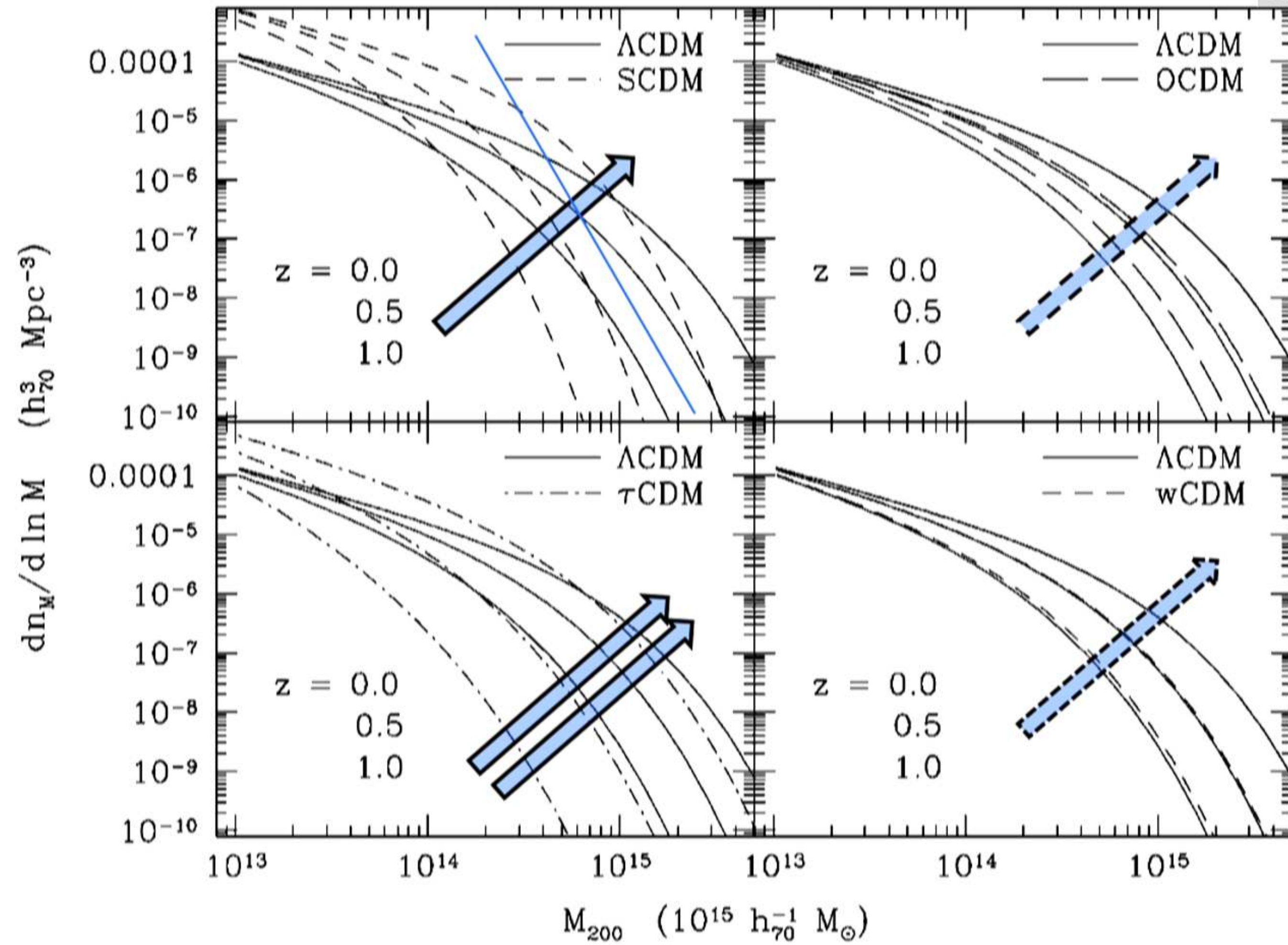
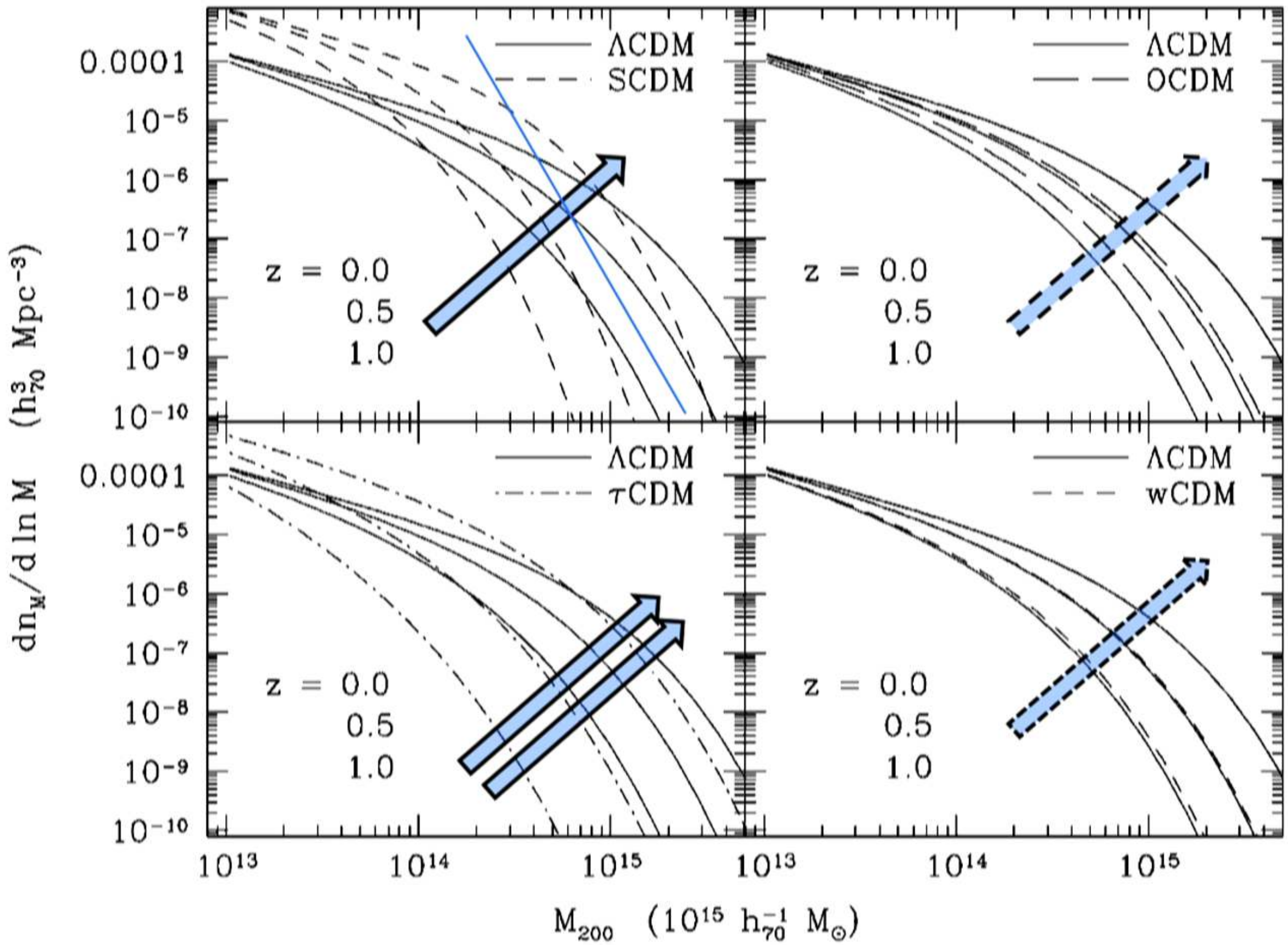


Input: DVI - 1600x900p@60Hz
Output: SDI - 1920x1080i@60Hz

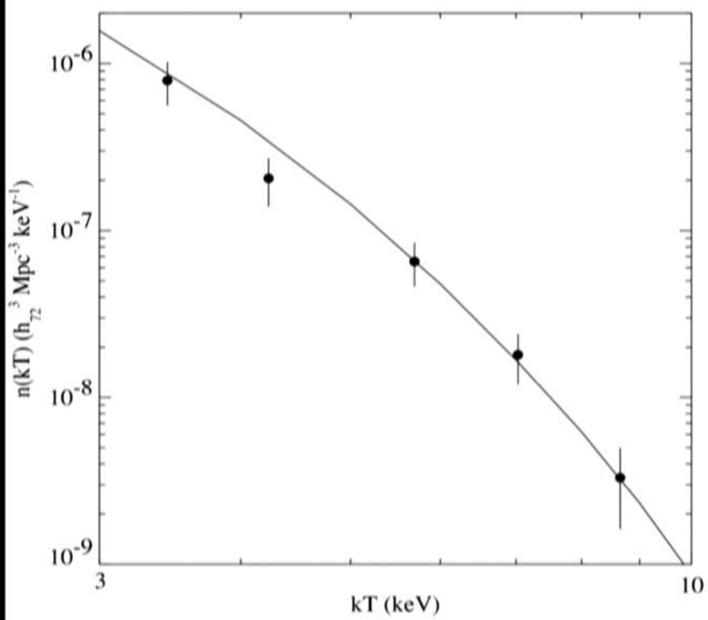


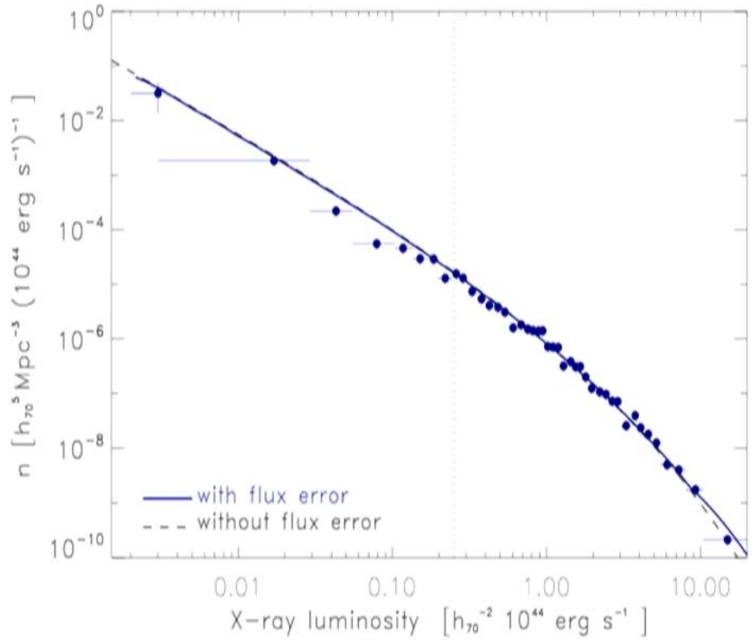
Voit, 2005 (Rev Mod Phys)



Voit, 2005 (Rev Mod Phys)

MASS-OBSERVABLE PROBLEM



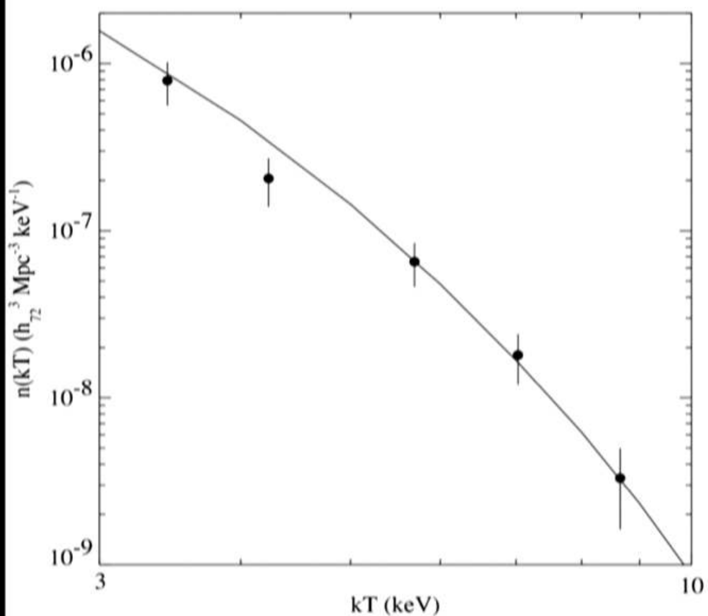


Henry et al. 2009:
HIFLUGCS cluster temperature function

Bohringer et al 2014:
REFLEX II cluster luminosity function

Single epoch luminosity or temperature function.
Need to map observable to Mvir

MASS-OBSERVABLE PROBLEM



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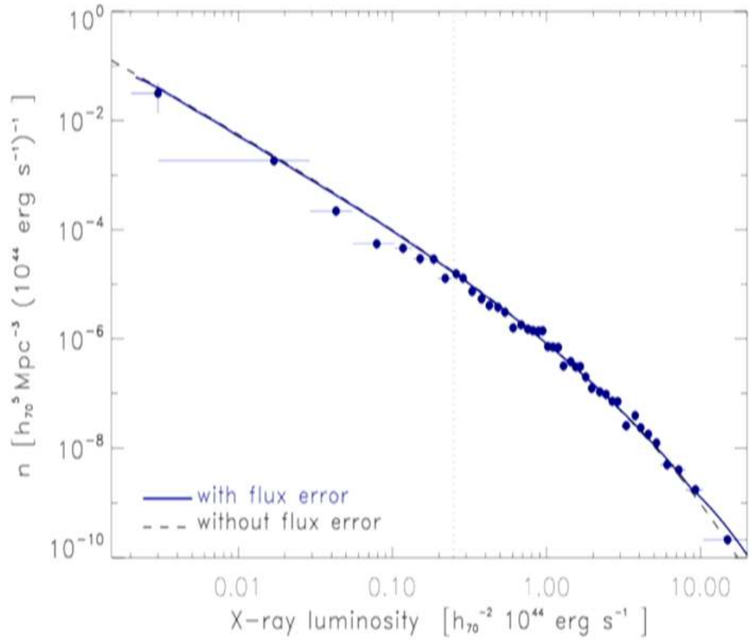

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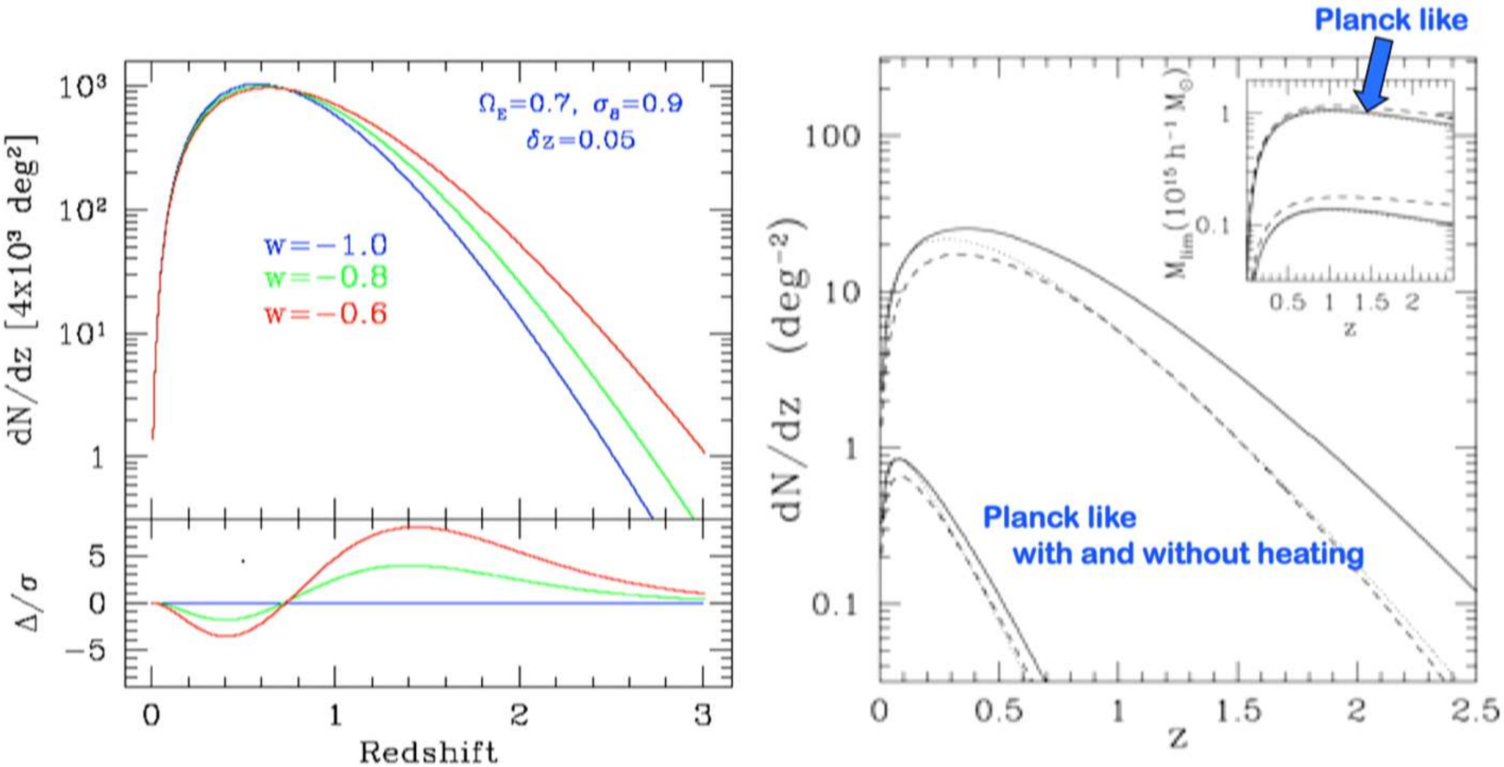
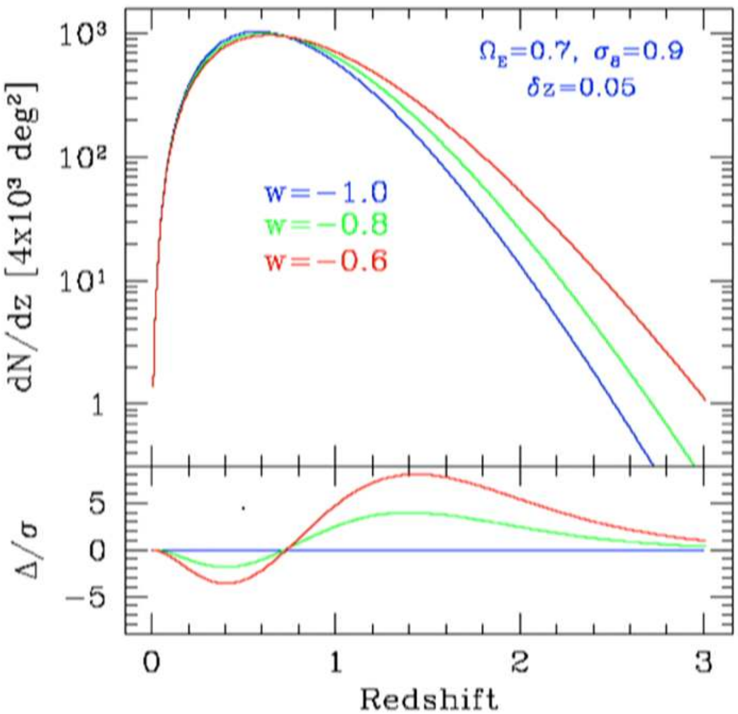


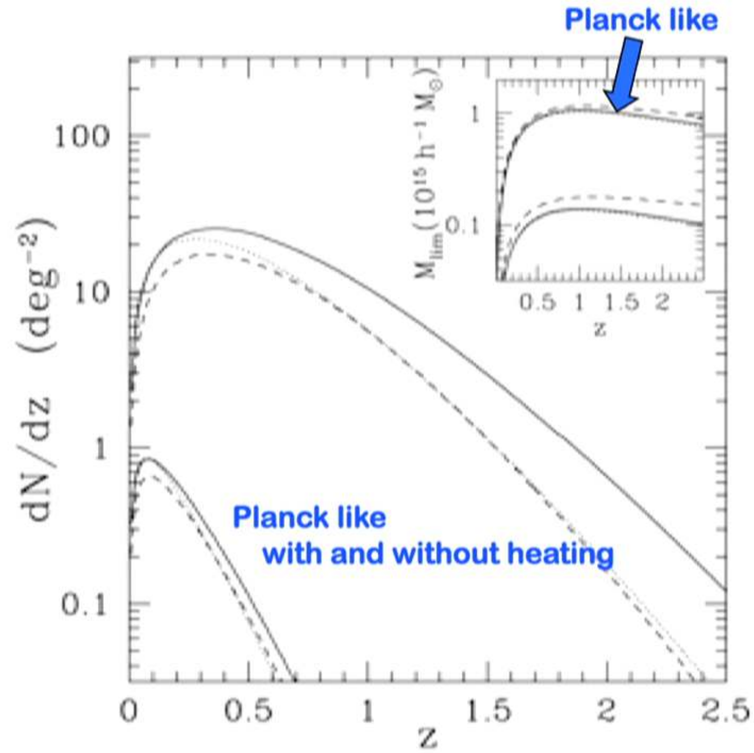
Left: SPT expectations
Need to map observable to Mvir at different redshifts

cluster counts: SZE

Frieman et al. 2008
Carlstrom et al. 2002

MASS-OBSERVABLE PROBLEM





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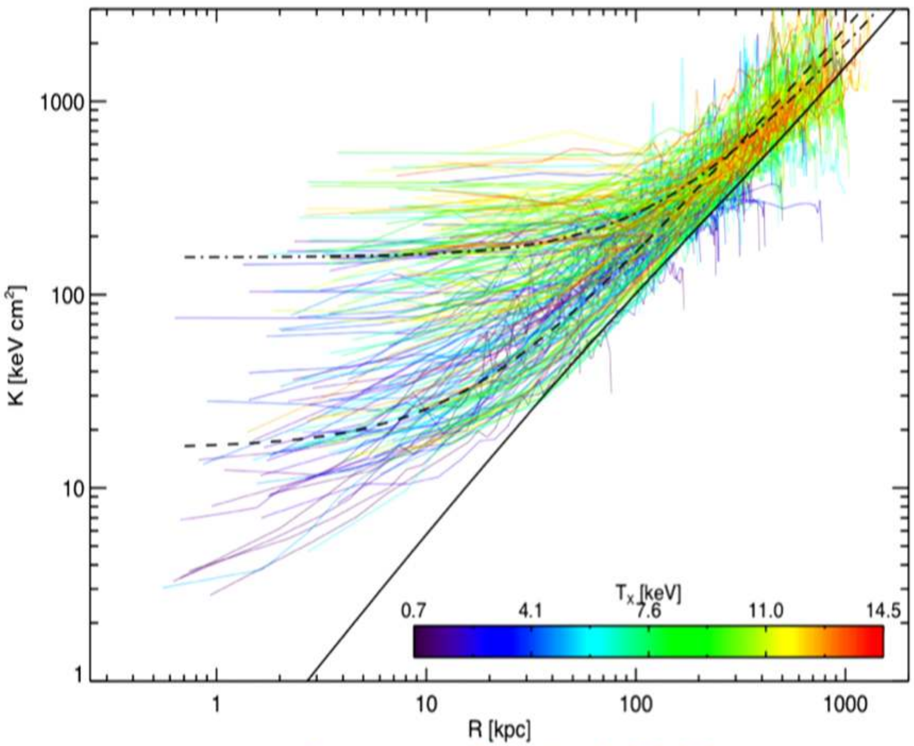
HEATING AND COOLING OF DIFFUSE CLUSTER GAS

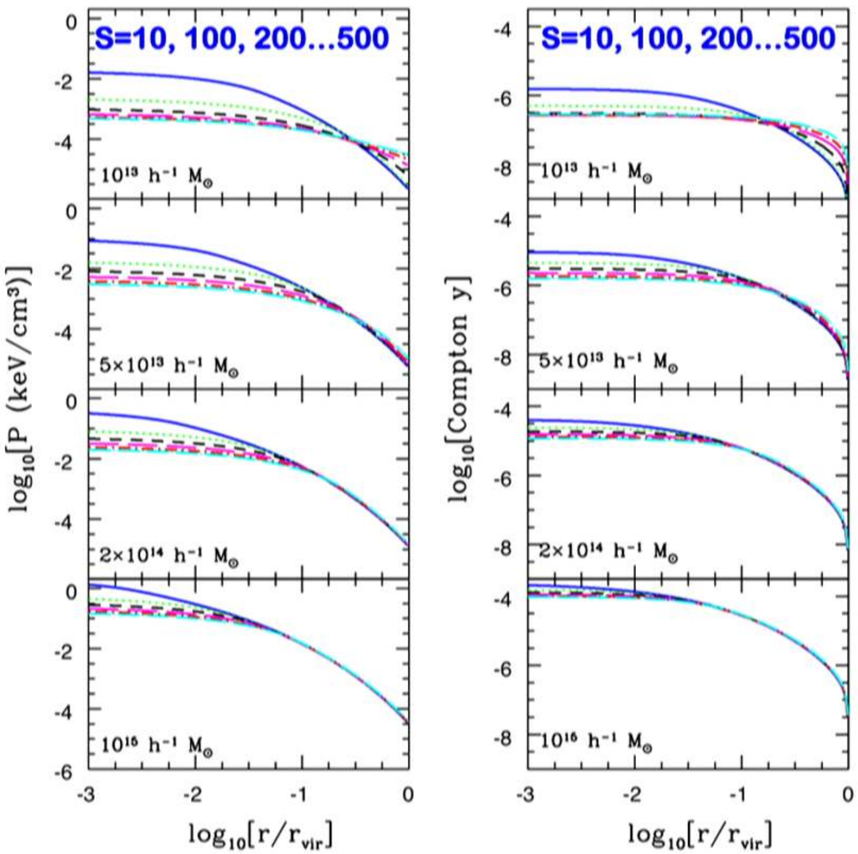


Cavagnolo et al 2008

$$K \equiv \left(\frac{P}{\rho^\gamma}\right)$$

$$\Longrightarrow \quad \frac{kT(r)}{n_e(r)^{2/3}}$$

Implications Of Varying Entropy Core Values: SZE



At a given mass, larger S results in:

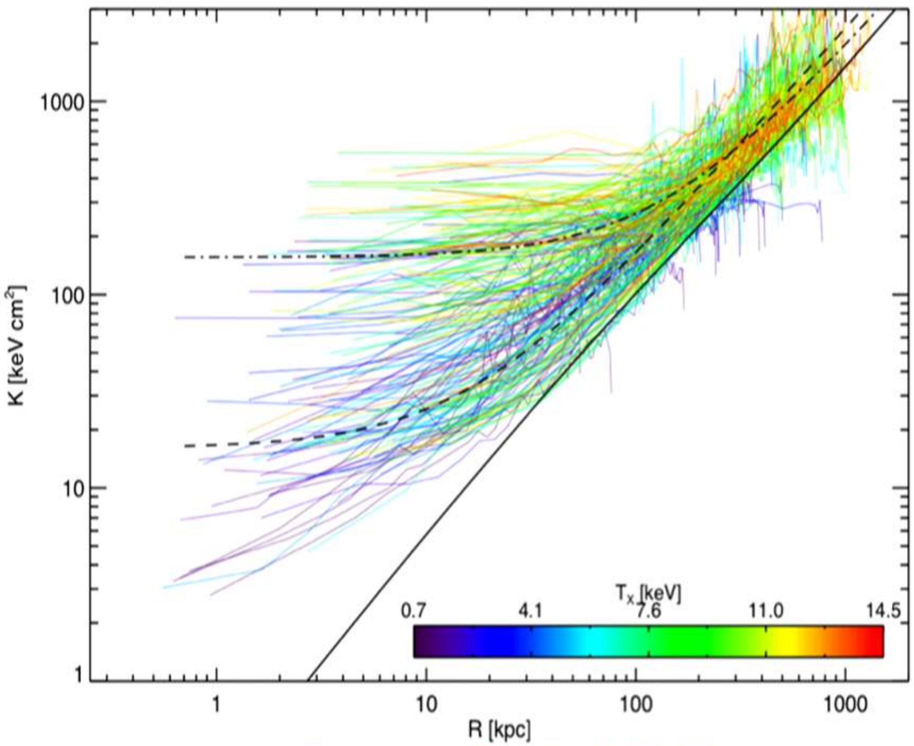
- **lower amplitude,**
- **flatter proj. y-profiles,**
- **higher signal outside the core**

With increasing mass, the fractional change is lower.

Changes are negligible for M > 10^{14} $M_\odot$

Holder, McCarthy, Babul

HEATING AND COOLING OF DIFFUSE CLUSTER GAS



Cavagnolo et al 2008

$$K \equiv \left(\frac{P}{\rho^\gamma}\right)$$

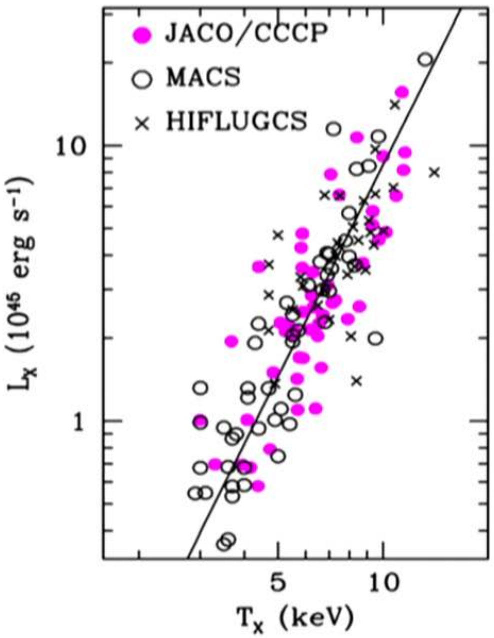
$$\Longrightarrow \frac{kT(r)}{n_e(r)^{2/3}}$$

Mass-Observable Relationship in the Local Universe

Canadian Cluster Comparison Project

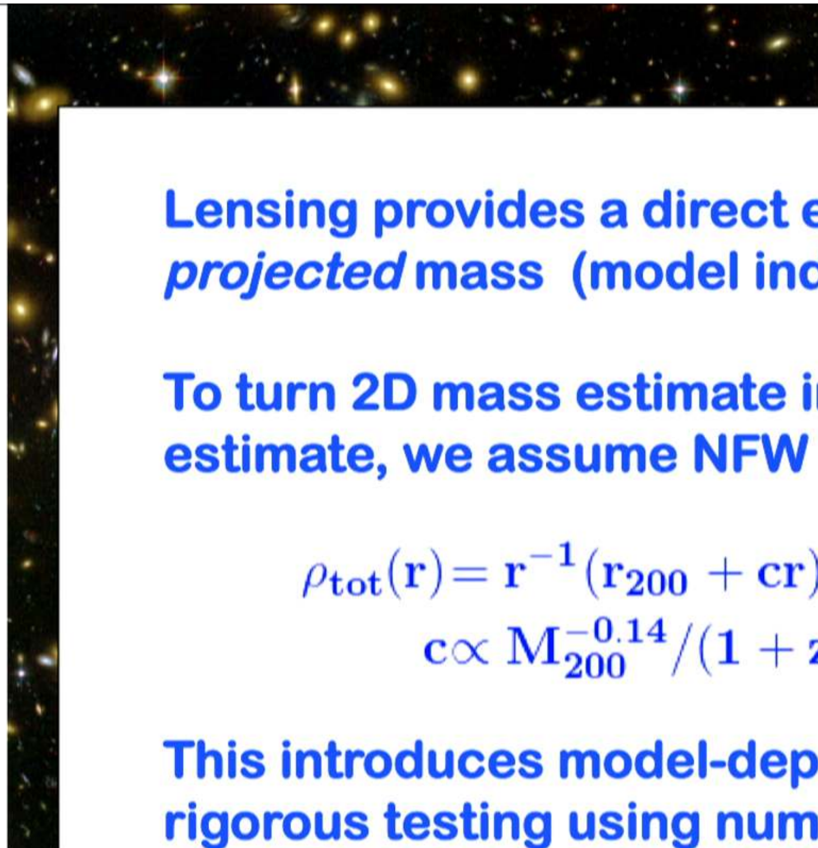
it's good for the masses!

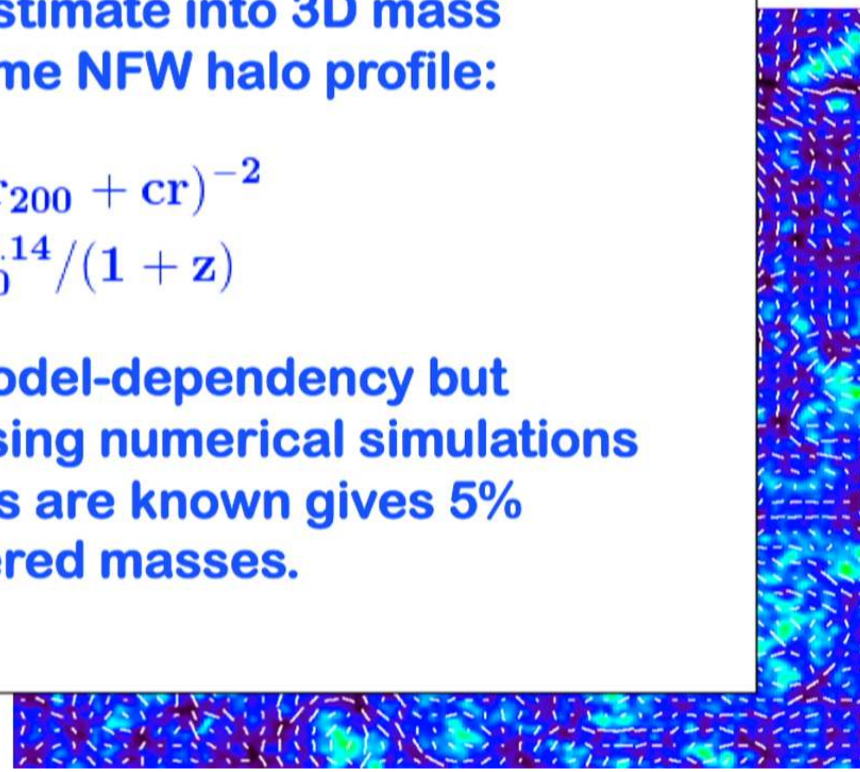
Henk Hoekstra   Arif Babul   Andisheh Mahdavi



- 50 clusters with $0.15 < z < 0.55$
- CFHT accessible: $-15^o < \mathrm{dec} < 65^o$
- $T_x > 3$ keV
- High quality two color optical data
- CFHT12K with B and R
- CFHT Megacam g' and r'
- All except 3 have Chandra
- 3+21 have XMM
- Not intended to be complete but representative

  ➔ For details see Mahdavi et al. 2013





Lensing provides a direct estimate of the *projected* mass (model independent)

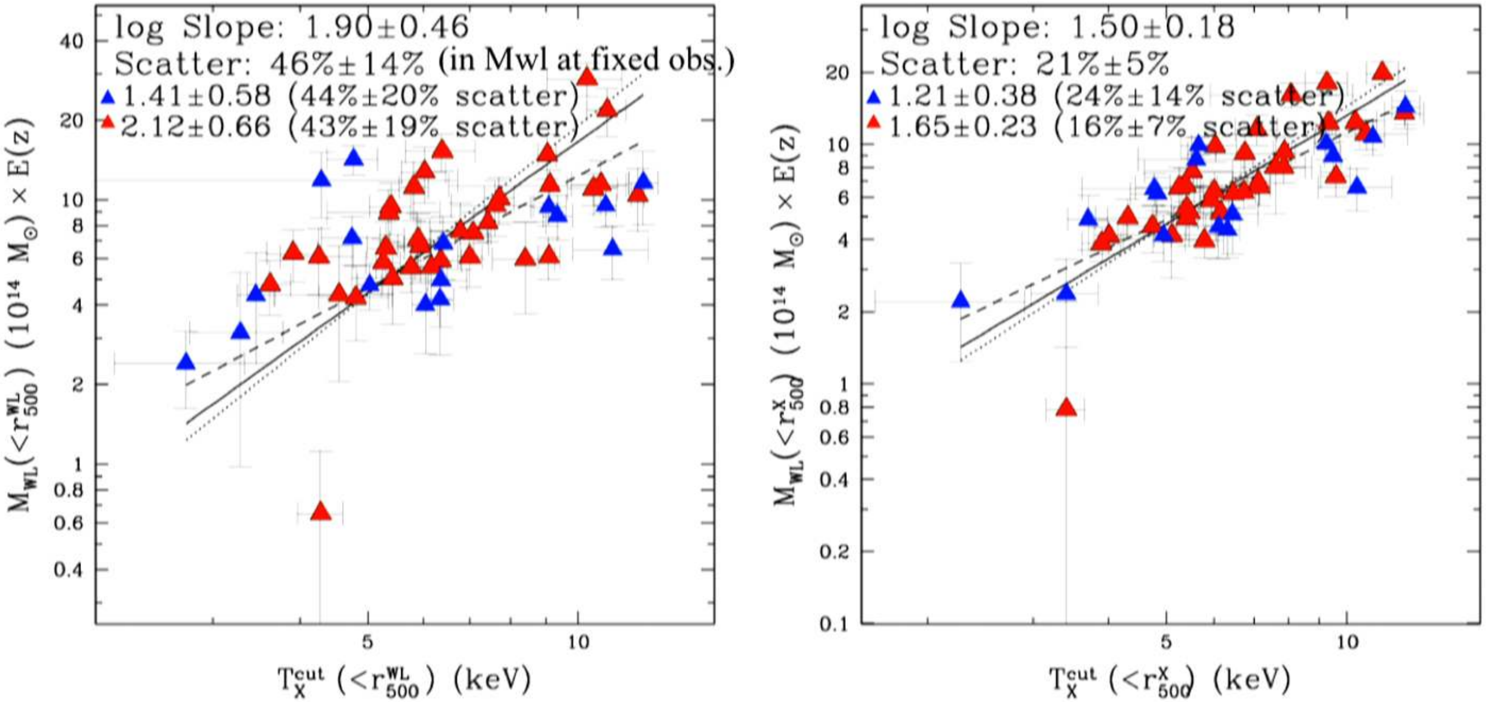
To turn 2D mass estimate into 3D mass estimate, we assume NFW halo profile:

$$\rho_{\mathrm{tot}}(\mathbf{r}) = \mathbf{r}^{-1}(\mathbf{r}_{200} + \mathbf{cr})^{-2}$$

$$\mathbf{c} \propto \mathbf{M}_{200}^{-0.14}/(1+\mathbf{z})$$

This introduces model-dependency but rigorous testing using numerical simulations where halo masses are known gives 5% variation in recovered masses.

Mass-Observable Relationship in the Local Universe

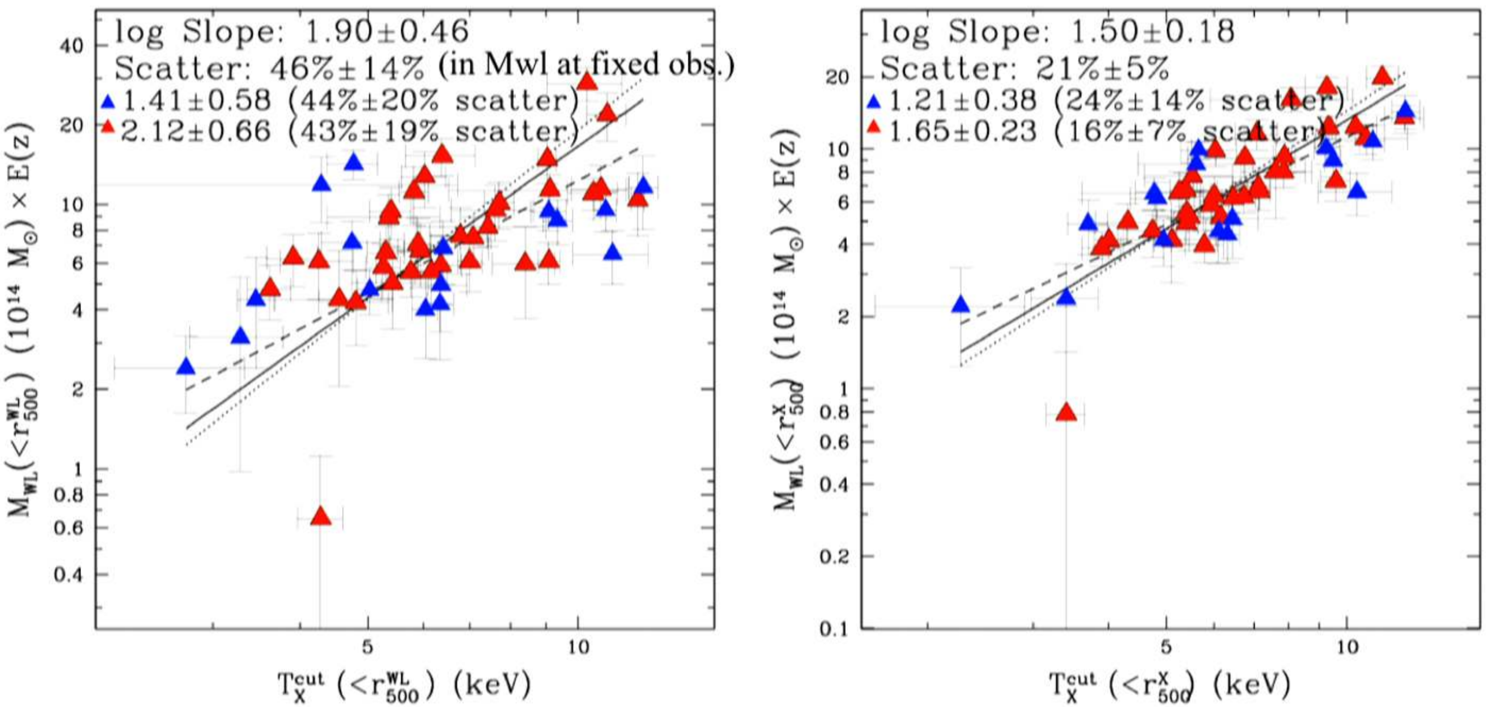


K(20 kpc) < 70 keV cm²
K(20 kpc) > 70 keV cm²

D_{BCG} < 0.01 Mpc
D_{BCG} > 0.01 Mpc

Mahdavi et al. 2013

Mass-Observable Relationship in the Local Universe



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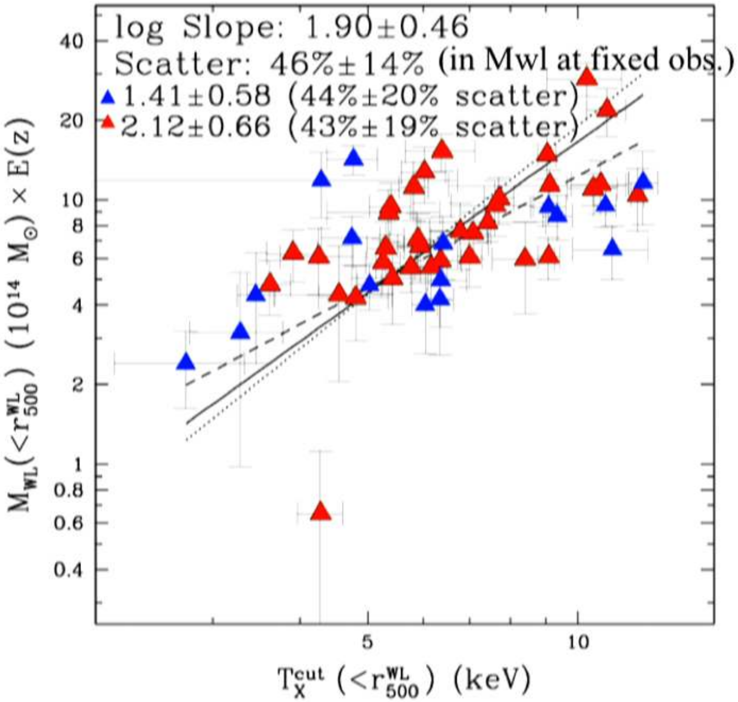

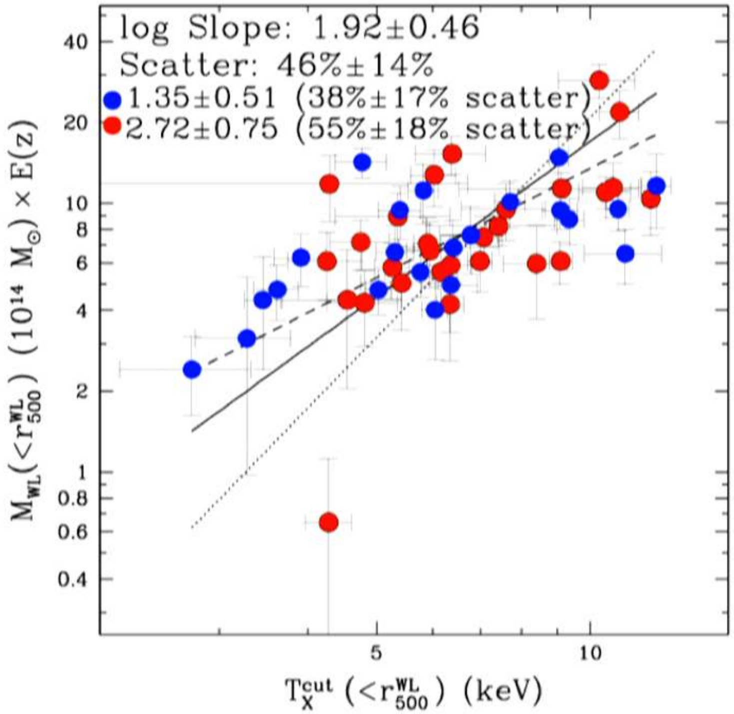

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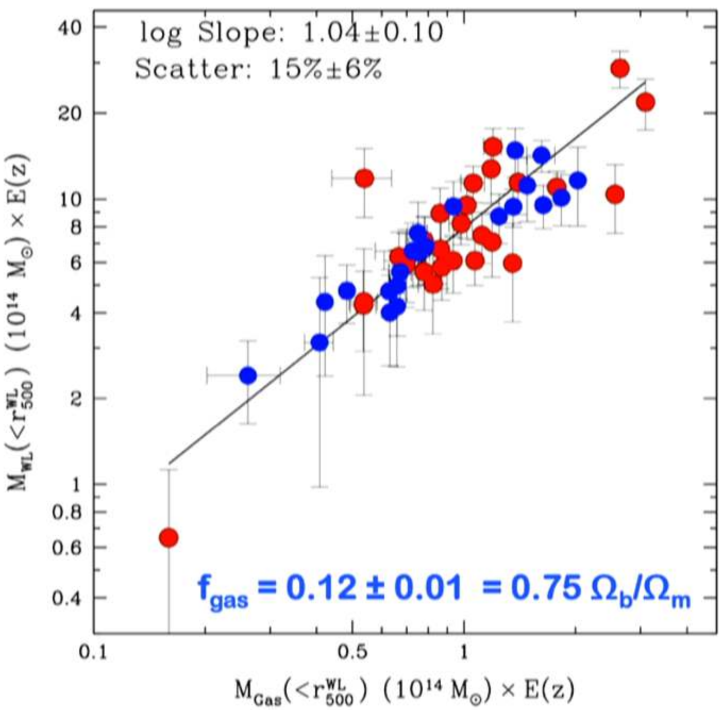
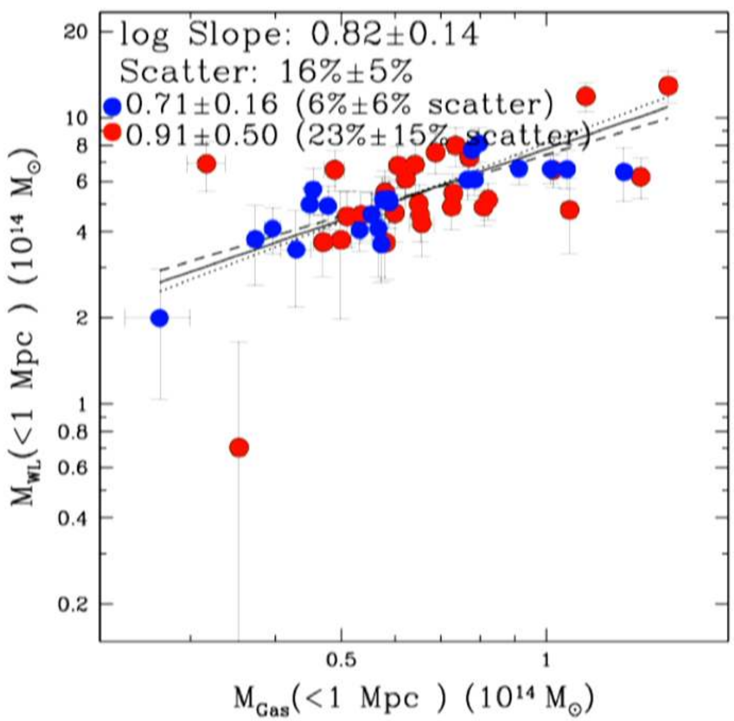


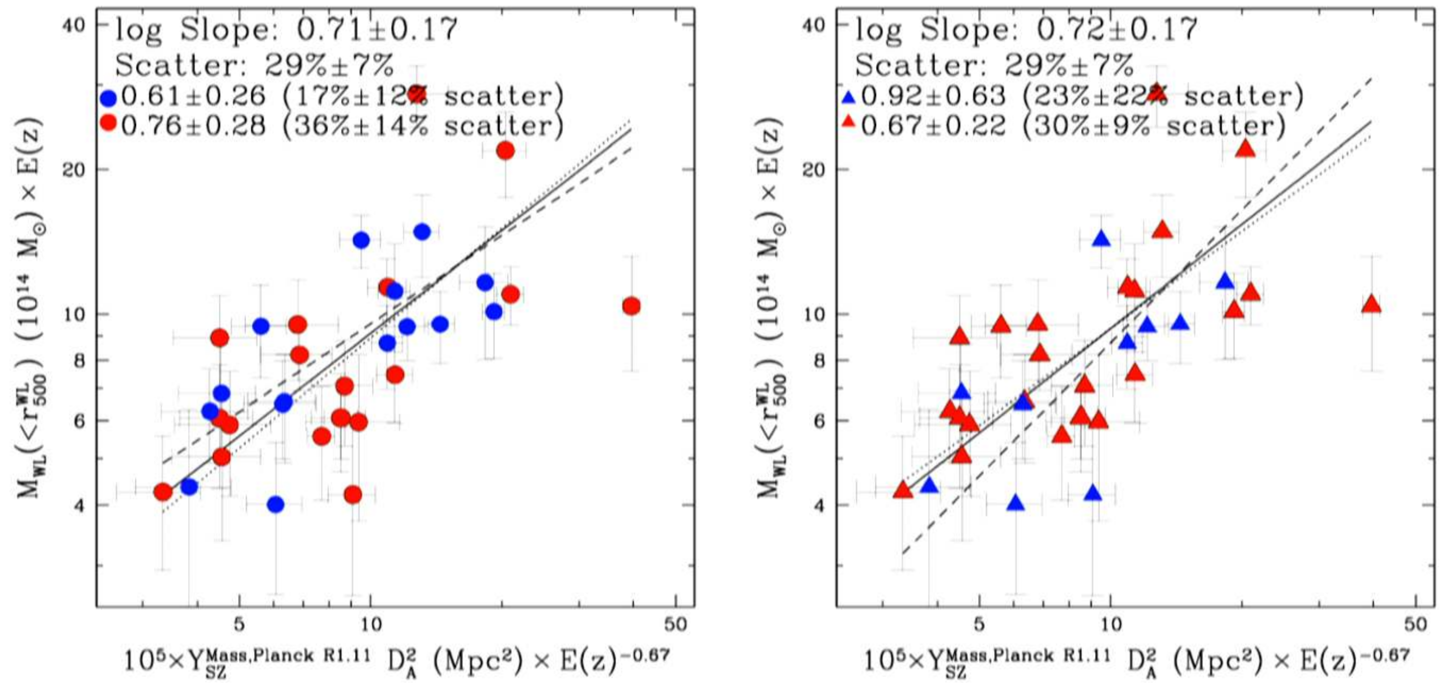


Rwl and Mgas(Rwl) are correlated so we use fixed aperture

▲ K(20 kpc) < 70 keV cm^2 ● D_{BCG} < 0.01 Mpc

▲ K(20 kpc) > 70 keV cm^2 ● D_{BCG} > 0.01 Mpc **Mahdavi et al. 2013**

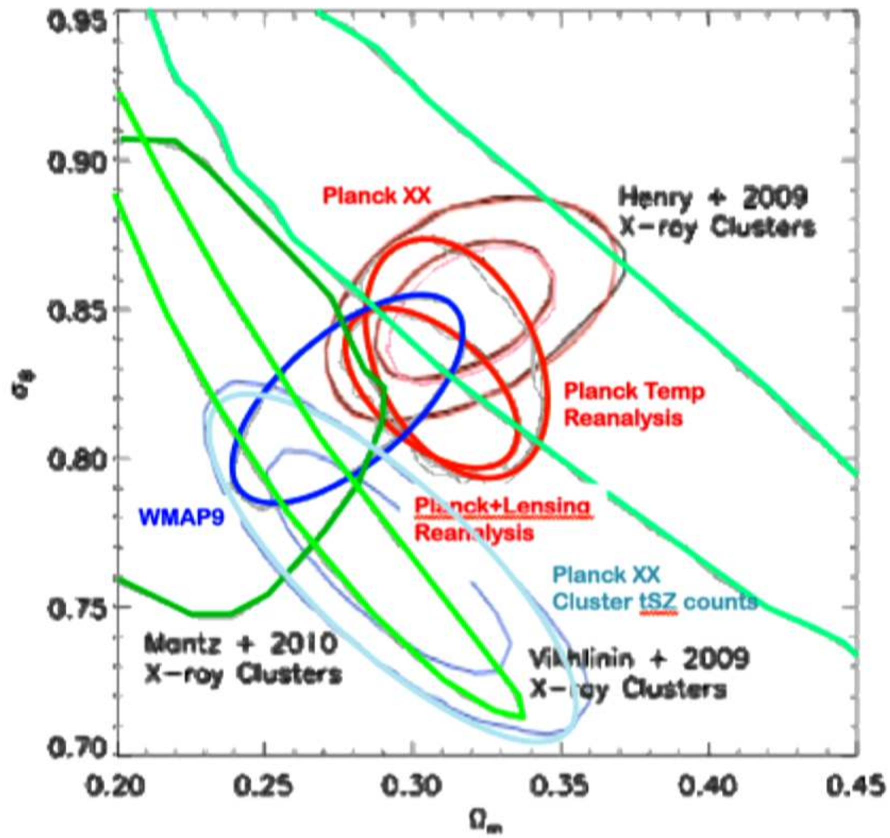
Mass-Observable Relationship in the Local Universe
PLANCK Y_{500}



moderate sensitivity to cluster thermal state;
moderate scatter

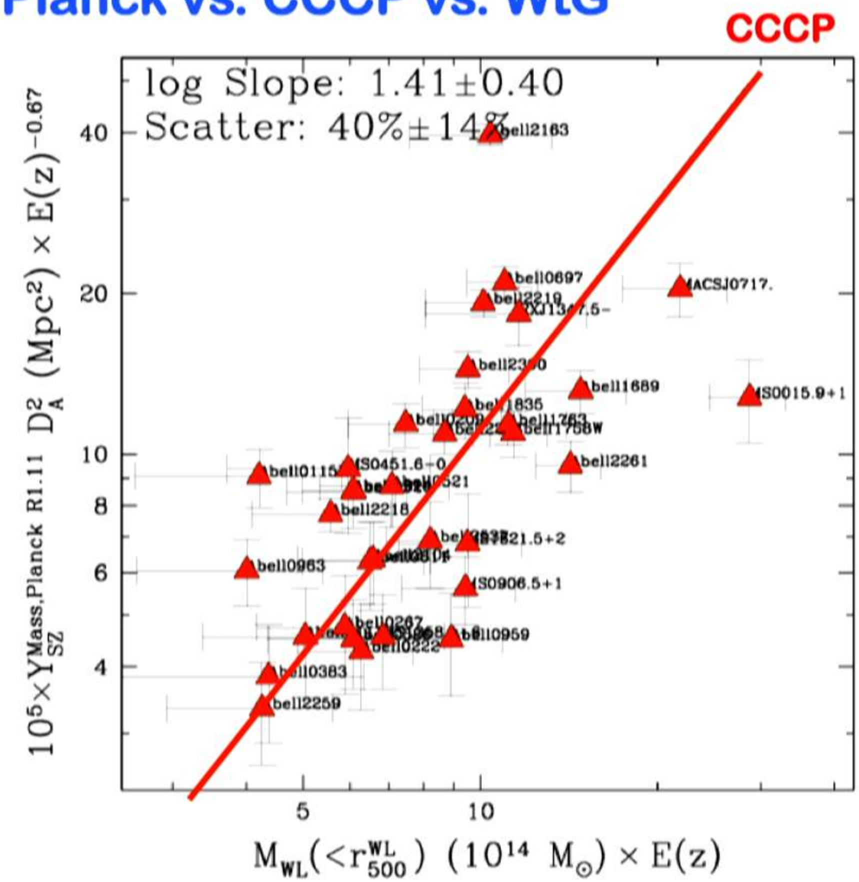
K(20 kpc) < 70 keV cm^2 — **D_{BCG} < 0.01 Mpc**
K(20 kpc) > 70 keV cm^2 — **D_{BCG} > 0.01 Mpc** — **Mahdavi et al. 2013**

ARE WE READY TO DO PRECISION COSMOLOGY?



LENSING MASS DISCREPANCY

Planck vs. CCCP vs. WtG



Testing WL Masses: $\gamma_i^{obs} = (1+\mu)\ \gamma_i^{true} + c$

For cluster work: not important due to azimuthal avrg

- Simulated clusters (ground truth)
- Input mock galaxy distribution
  - correct number counts
  - appropriate ellipticity distribution (mag dependent)
  - correct redshift distribution

- Create a lensed image
- Add "appropriate noise level"
- Impose correct PSF – size (seeing) and distortions

- Analyze mock images via identical pipeline/approach

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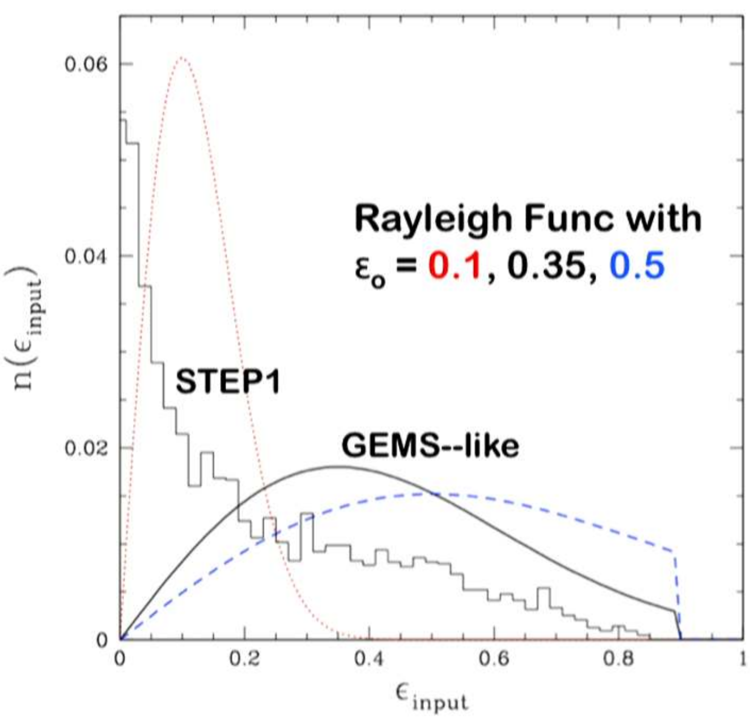
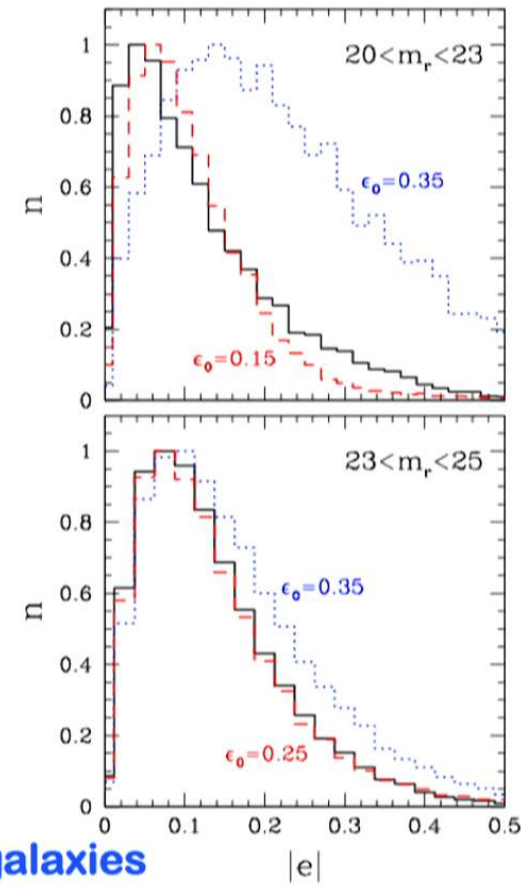


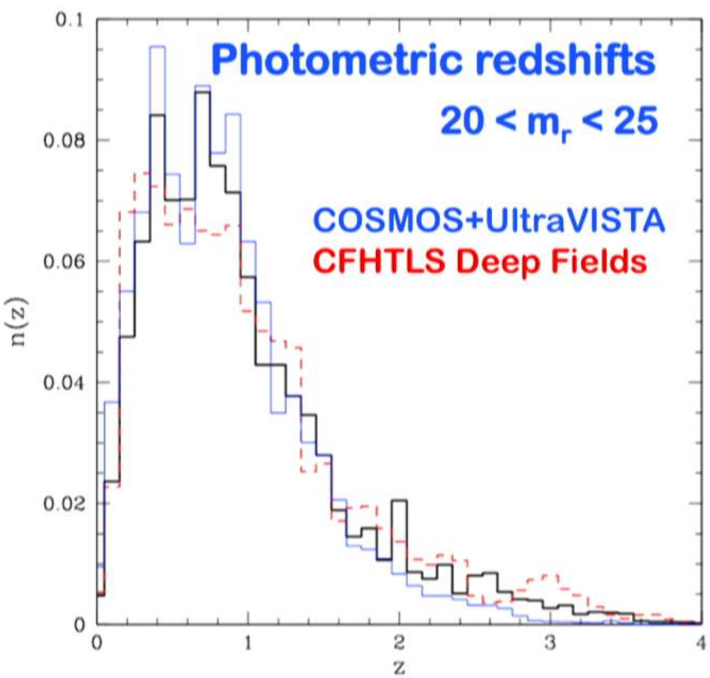


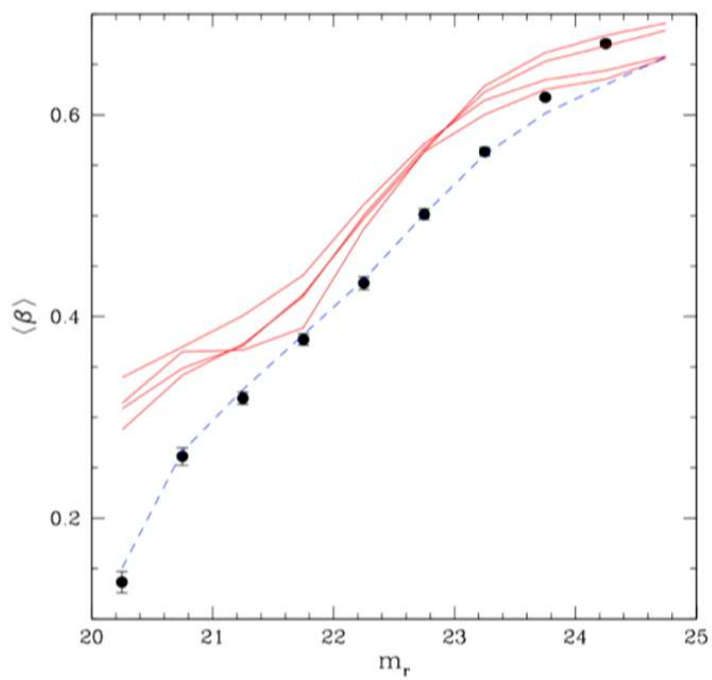
Galaxy parameters determined by "galfit"

➔ Gives greater weight to outer regions of galaxies

Testing WL Masses: $\gamma_i^{obs} = (1+\mu)\ \gamma_i^{true} + c$

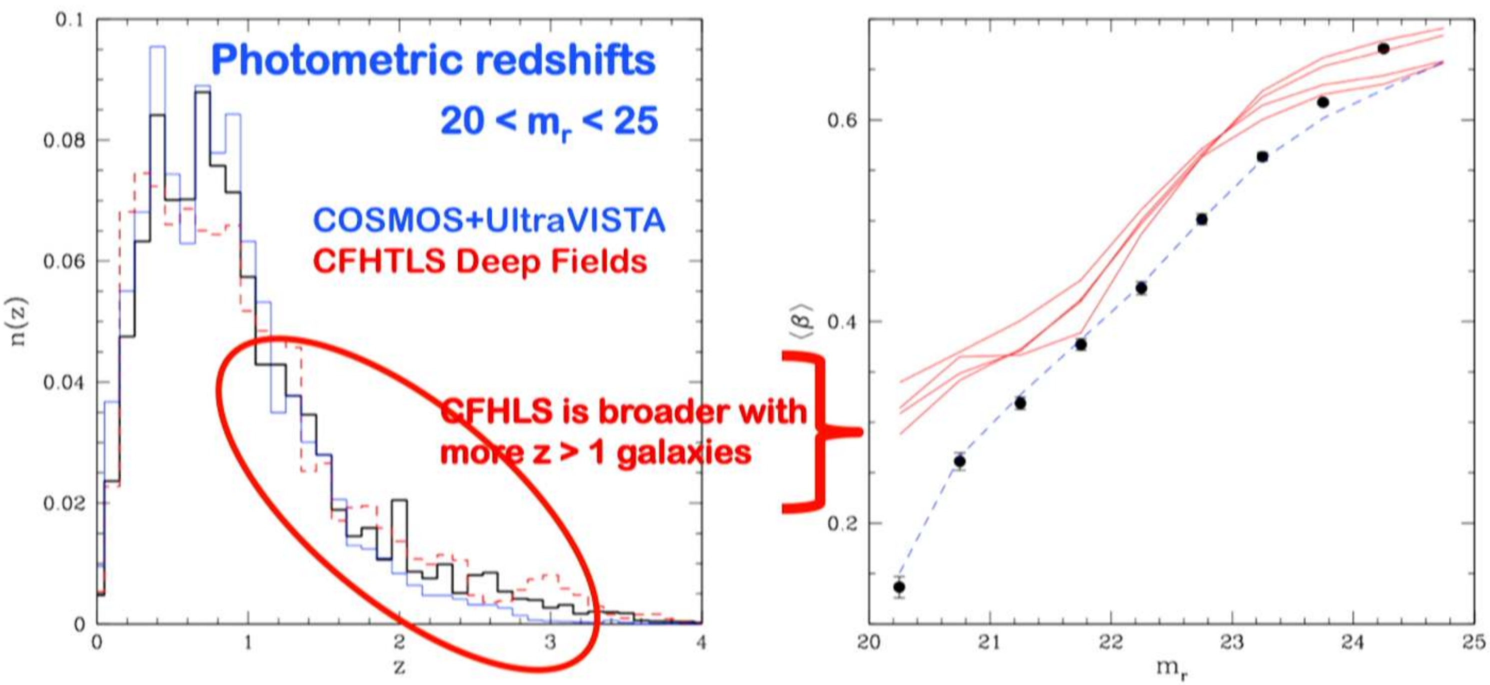
$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}} = 1/\beta \rightarrow (1+\mu)\beta$$



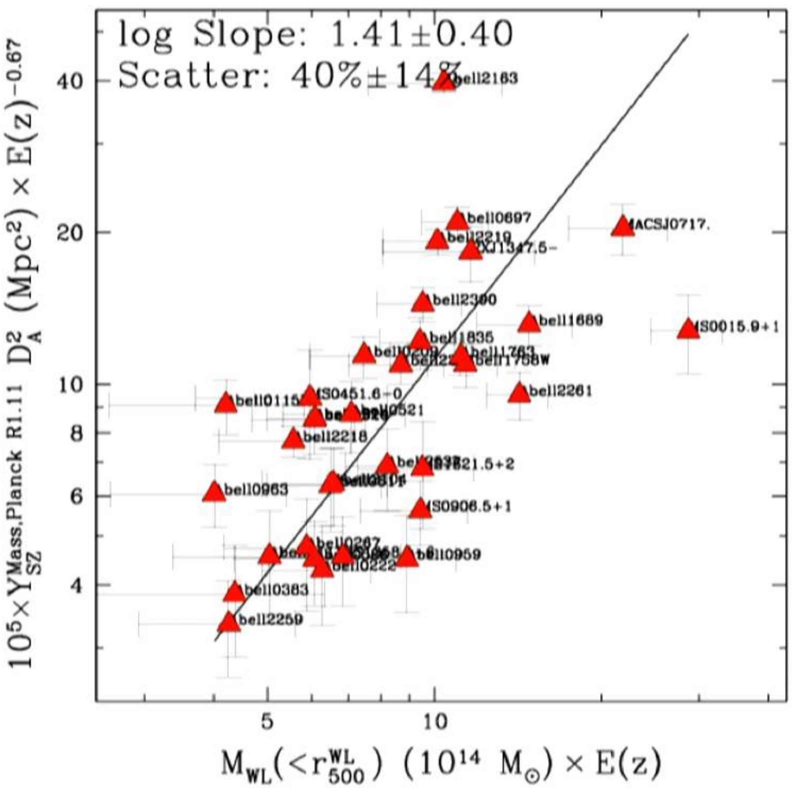


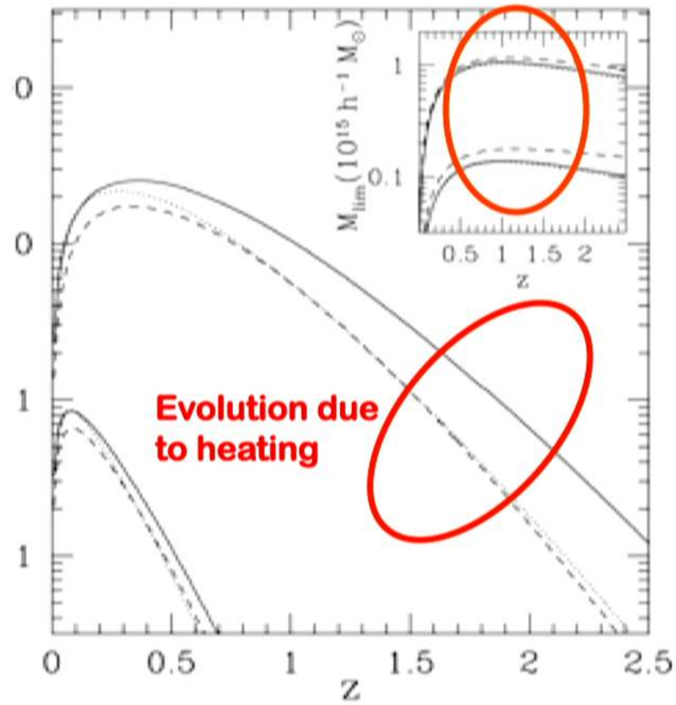
Testing WL Masses: $\gamma_i^{obs} = (1+\mu)\ \gamma_i^{true} + c$

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}}$$ =1/β ➔ (1+μ)β

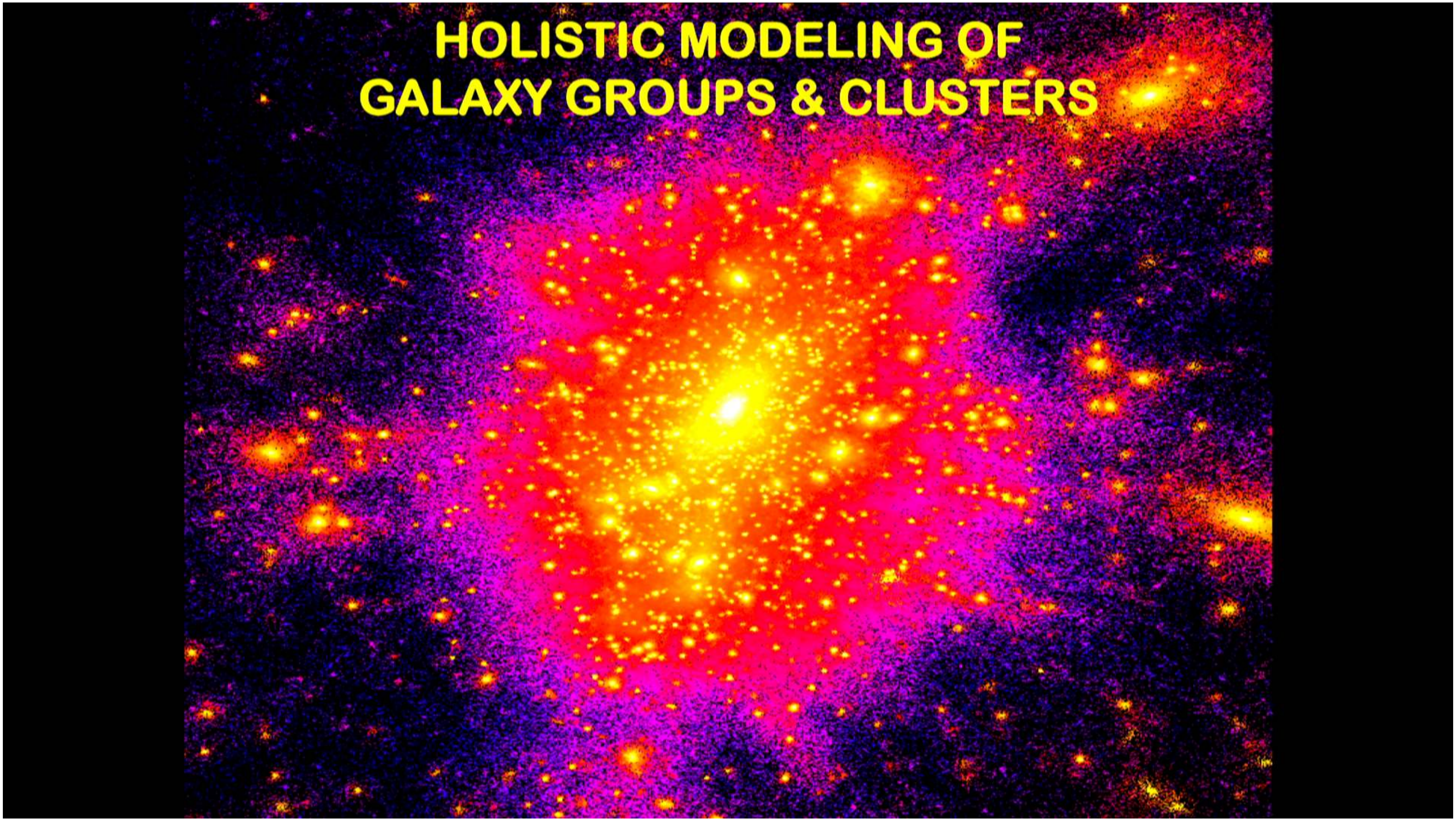


MASS-OBSERVABLE PROBLEM





What do the scaling relationship look like at earlier epochs?


HOLISTIC MODELING OF
GALAXY GROUPS & CLUSTERS