Canadian Cluster Comparison Project

"it's good for the masses!"

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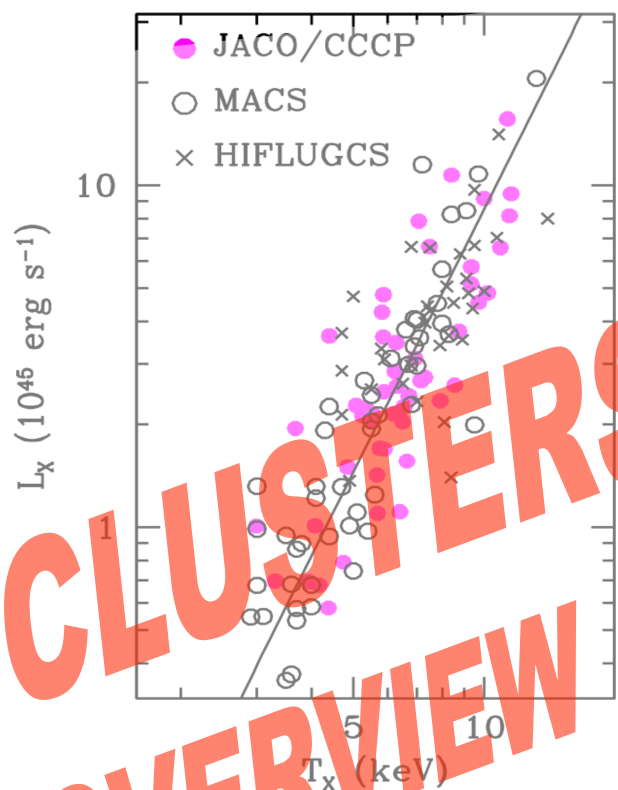
CCCP

CLUSTERS FOR COSMOLOGY: OVERVIEW AND PROGRESS REPORT

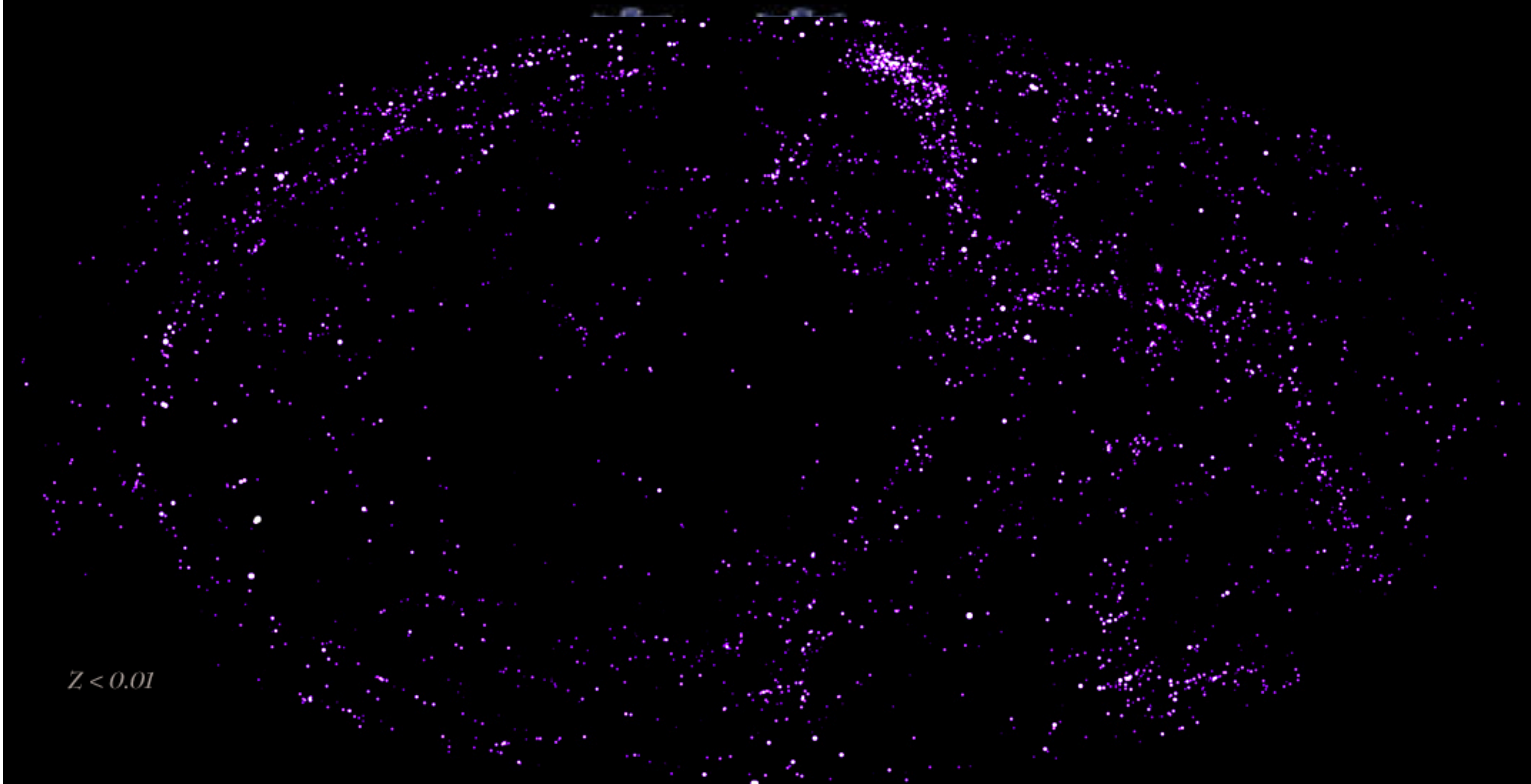


- 50 clusters with $0.15 < z < 0.55$ ($z \sim 0.25$)
- CFHT accessible: $-15^o <$ dec $< 65^o$
- $T_x > 3$ keV
- High quality two color optical data
- CFHT12K with B and R
- CFHT Megacam g' and r'
- All except 3 have Chandra
- 3+21 have XMM
- For details see Mahdavi et al. 2013

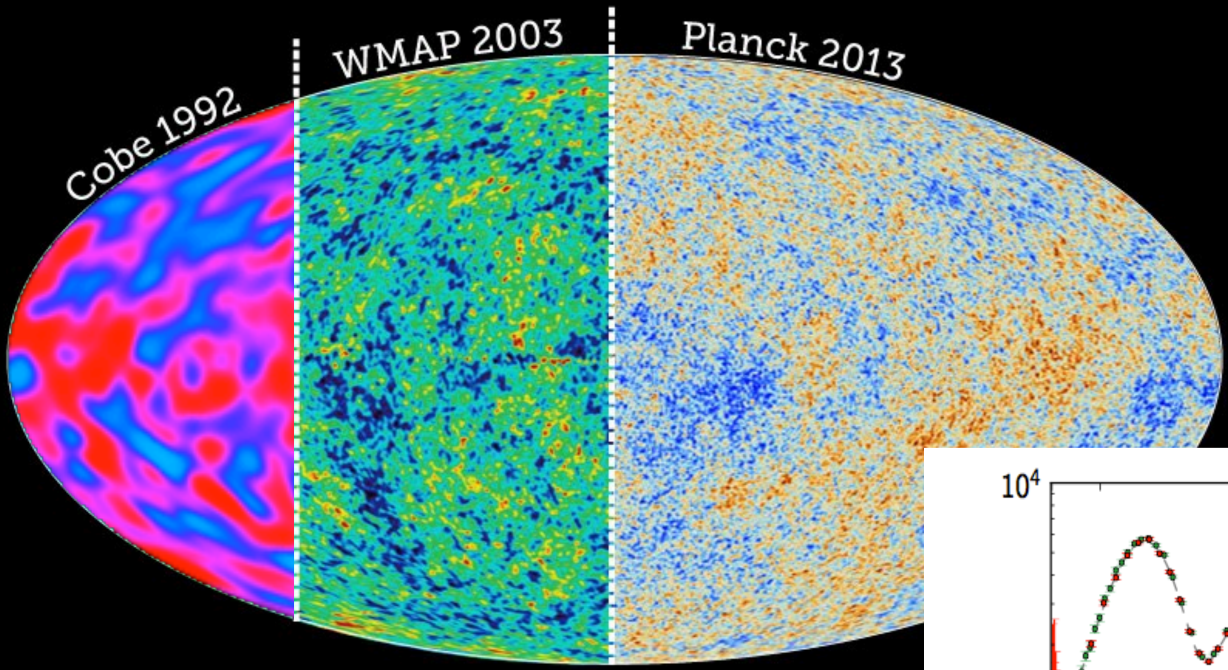
THE HOLY GRAIL OF COSMOLOGY

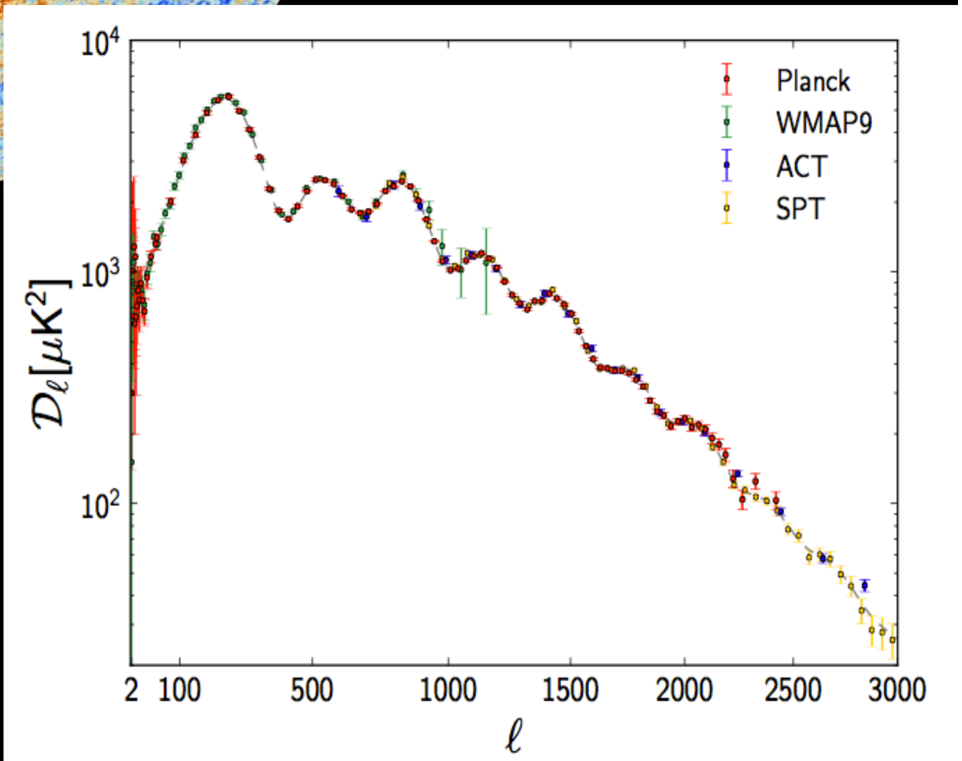
- What is the make-up of the Universe?
- What is the nature of dark matter?
- What is the nature of dark energy?
- What is the present-day cosmic expansion rate?
- How is the expansion rate evolving?
- What is the large-scale geometry of space-time?

- **How was galaxy formation, and the observed large-scale structure traced by the galaxies, seeded?**

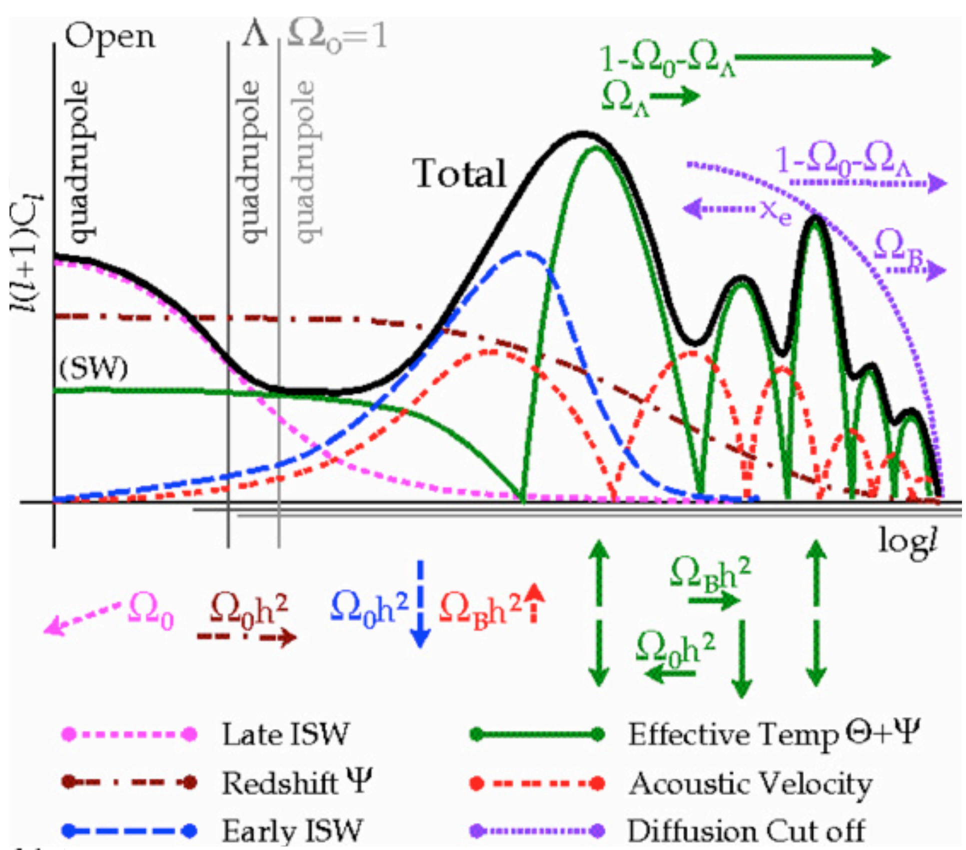


CMB EXPERIMENTS HERALDED THE AGE OF PRECISION COSMOLOGY





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 Models

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}

Locations and amplitudes of the peaks in the CMB power spectrum depend on values of both astrophysical and cosmological parameters.

The Minimal Model

Just Six Numbers?

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	$\Omega_c h^2$
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Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_{\mathcal{R}}$
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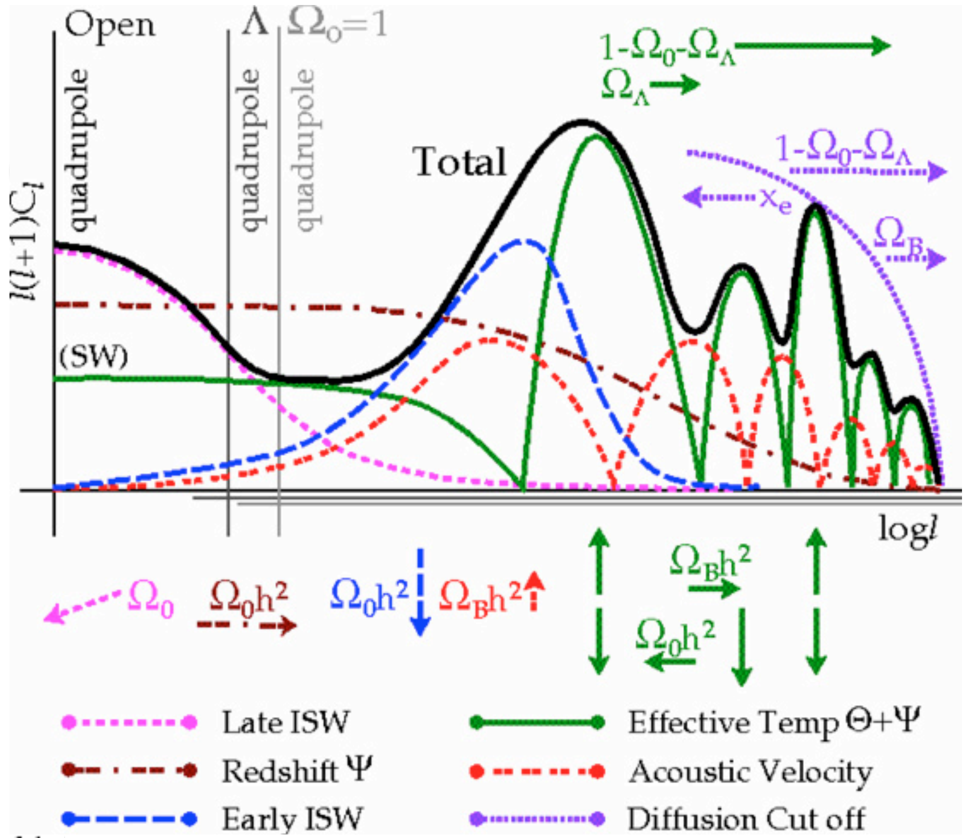


Parameters for Extended Models

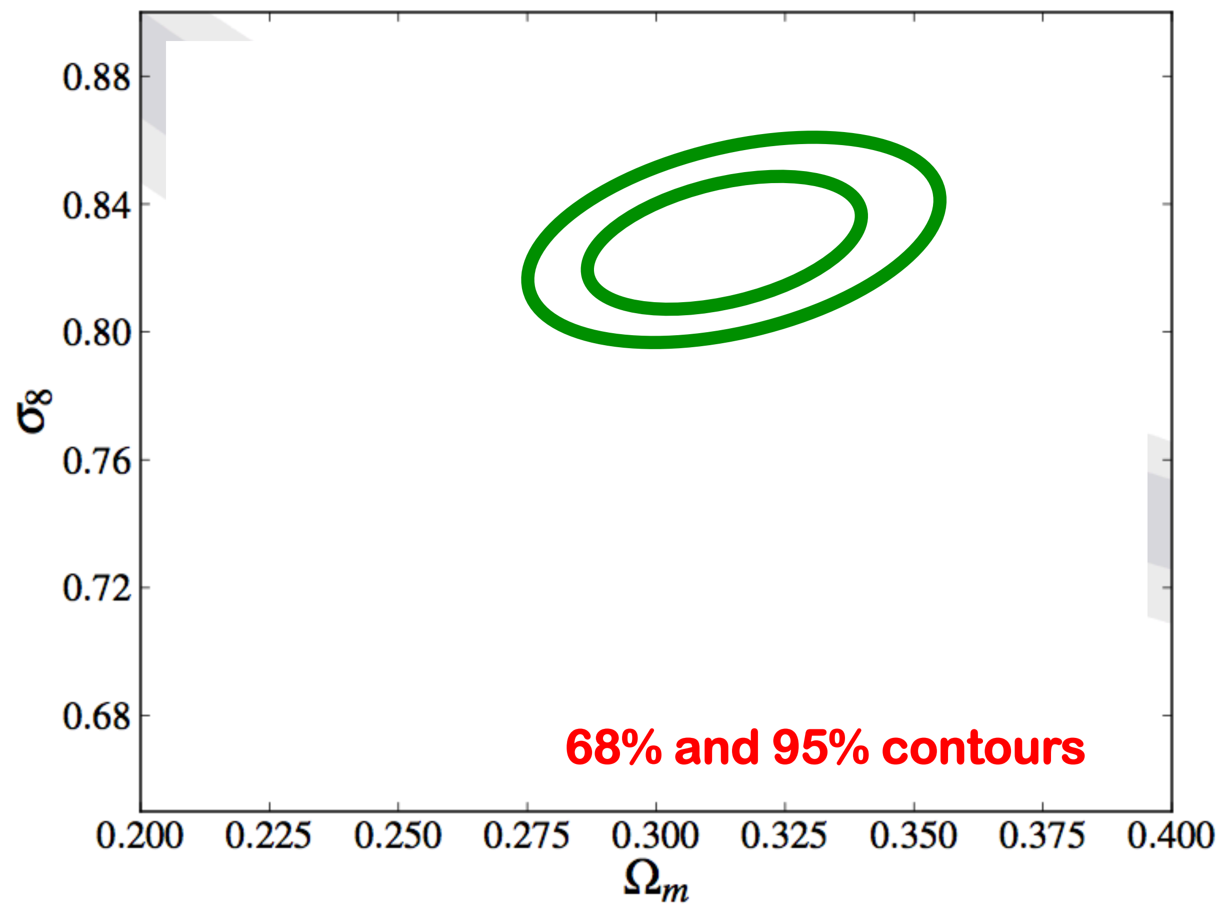
Total density [f]	Ω_{tot}	
Equation of state [g]	w_o, w_1	W_o= -1
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	0
Neutrino density [j]	$\Omega_\nu h^2$	
Neutrino mass [j]	$\sum m_\nu$	0.06 eV
Number of light neutrino families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

EVEN THEN, THE PARAMETERS ARE DEGENERATE

FOCUS ON THE $\Omega_m - \sigma_8$ PLANE

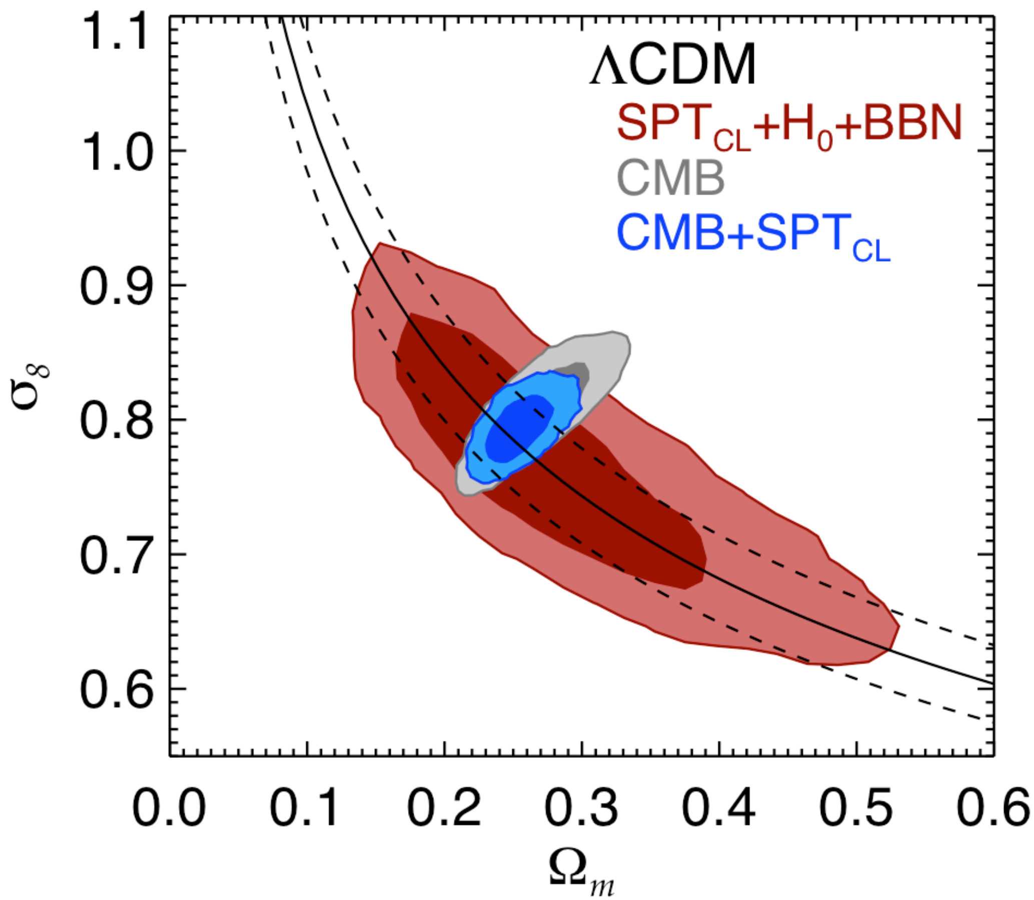
$\Omega_m = 0.315 \pm 0.017$
Ho = 67.3 ± 1.2
$\sigma_8 = 0.829 \pm 0.012$

68% confidence Interval



Ade et al. 2013: Planck Collaboration XVI

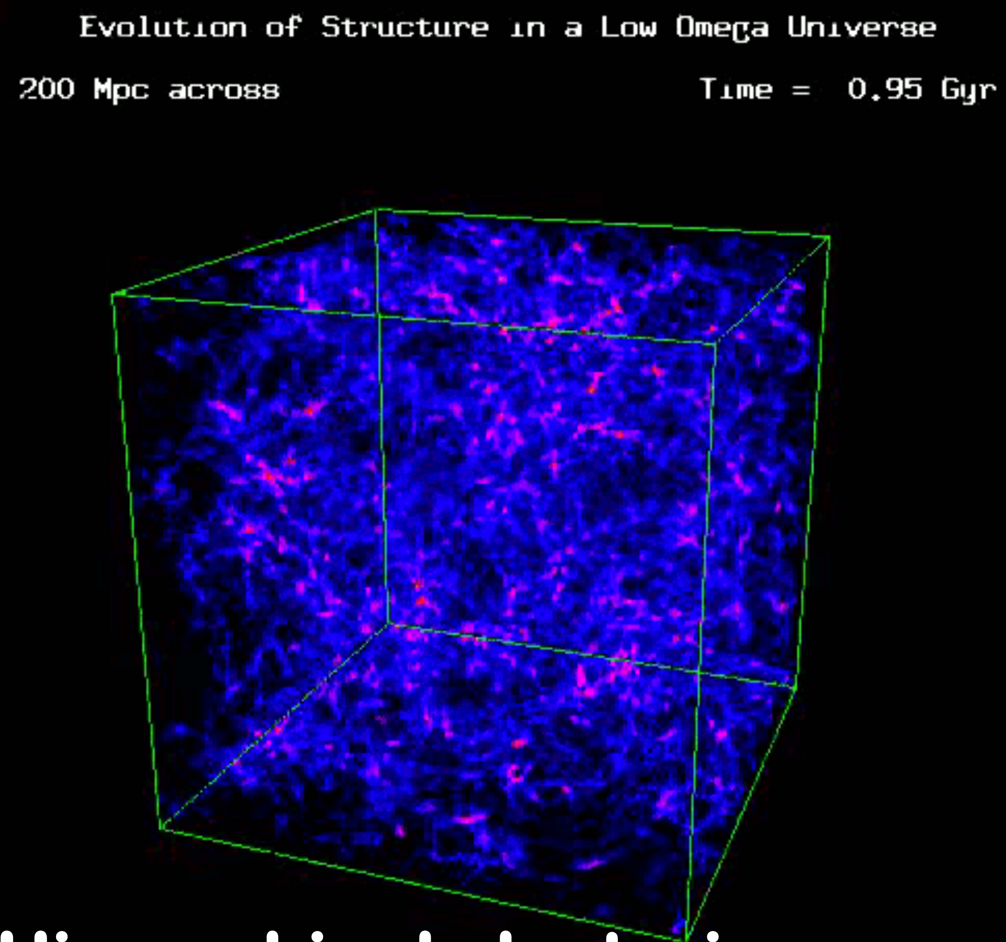
USE OF COMPLEMENTARY PROBES CAN GREATLY REDUCE UNCERTAINTIES

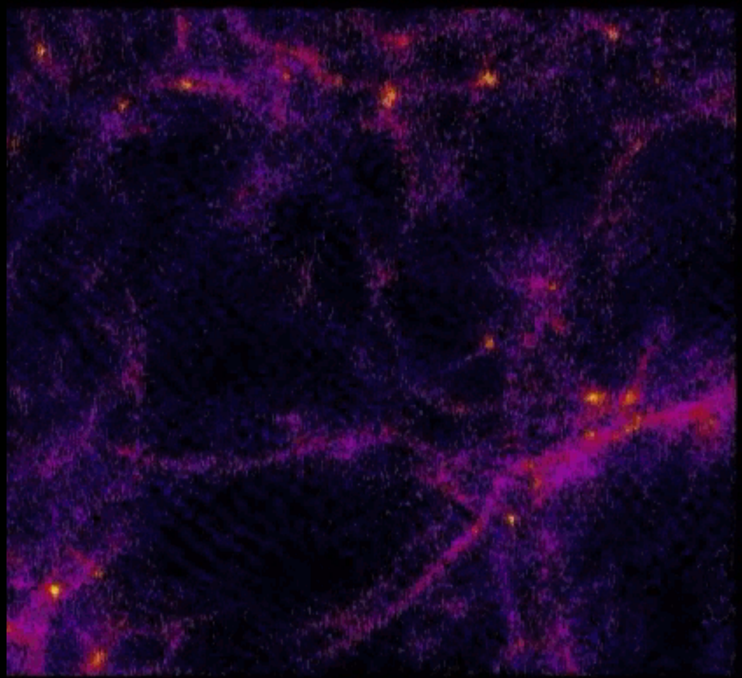


CMB MEASURES PARAMETERS AT HI-Z
CLUSTERS/LSS MEASURE PARAMETERS AT LOW-Z

Benson et al 2011 (SPT+WMAP7)

WHY ARE CLUSTERS USEFUL COSMO PROBES?



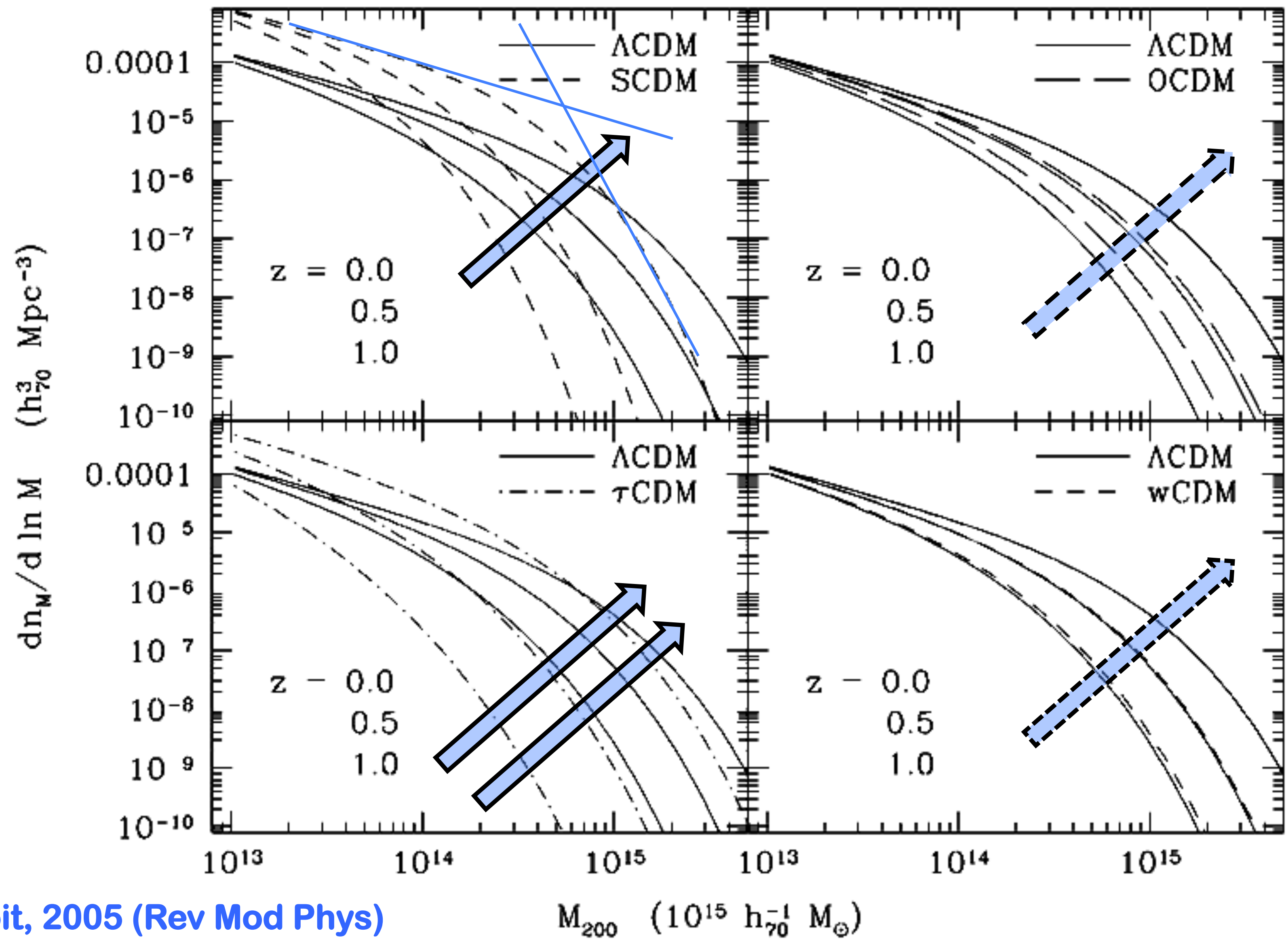


Hierarchical clustering:

Massive structures are built up thru mergers of smaller structures

Cluster formation is ongoing.
Rate of assembly depends of cosmology.

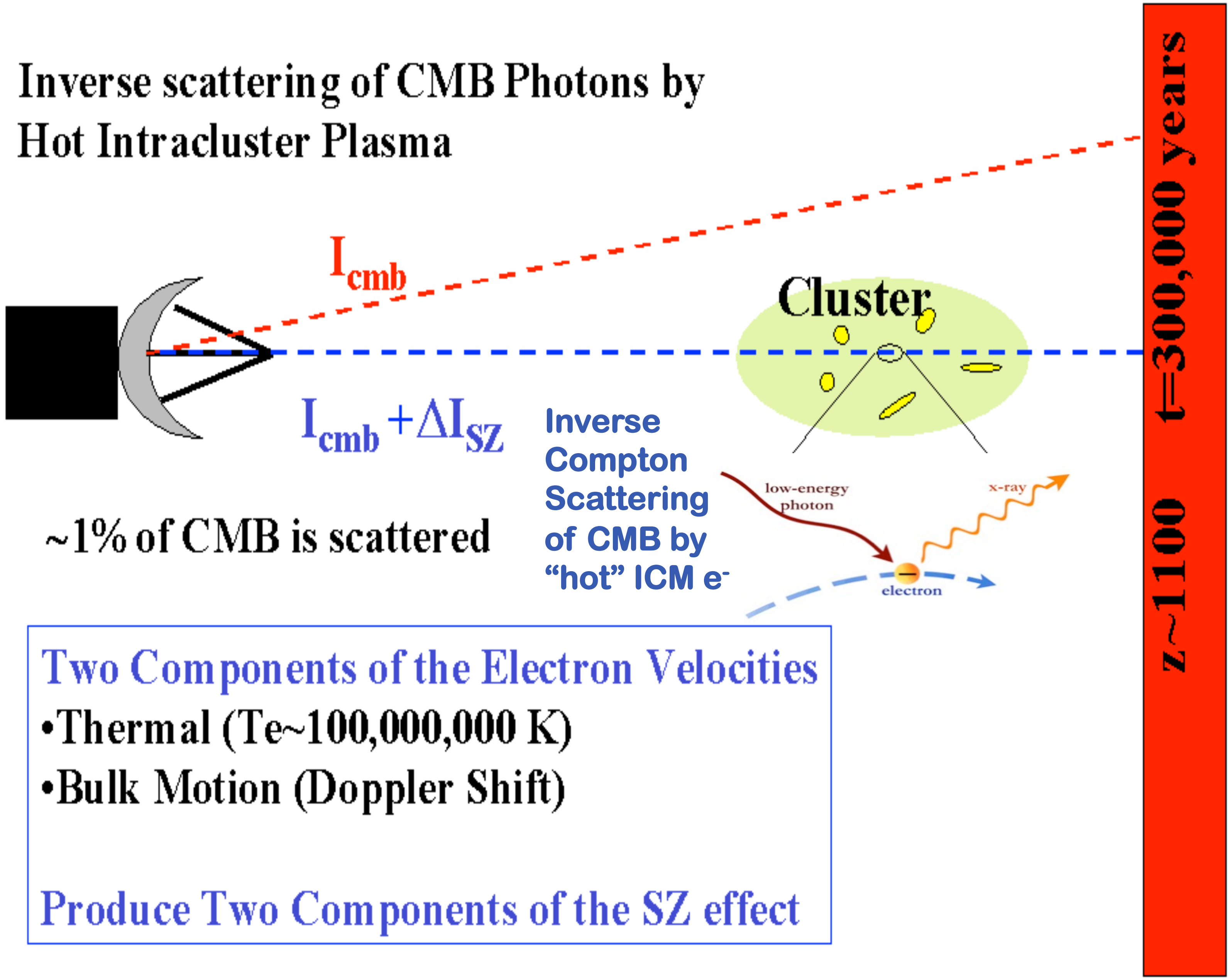
CLUSTER MASS FUNCTION AND ITS GROWTH IS A PROBE OF RECENT COSMOLOGICAL EVOL.



Voit, 2005 (Rev Mod Phys)

CURRENT MICROWAVE EXPERIMENTS THAT STUDY THE CMB CAN ALSO DETECT CLUSTERS VIA SZ EFFECT

Inverse scattering of CMB Photons by Hot Intracluster Plasma



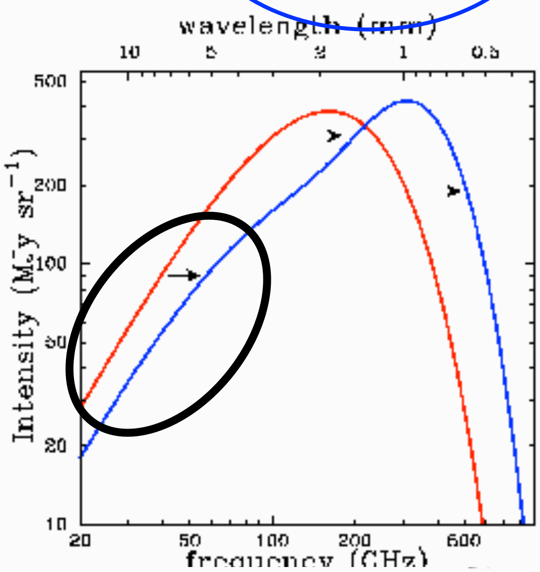
Two Components of the Electron Velocities

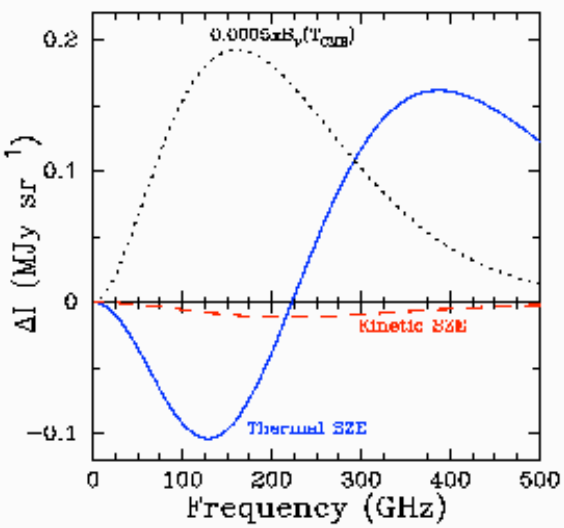
- Thermal (Te~100,000,000 K)
- Bulk Motion (Doppler Shift)

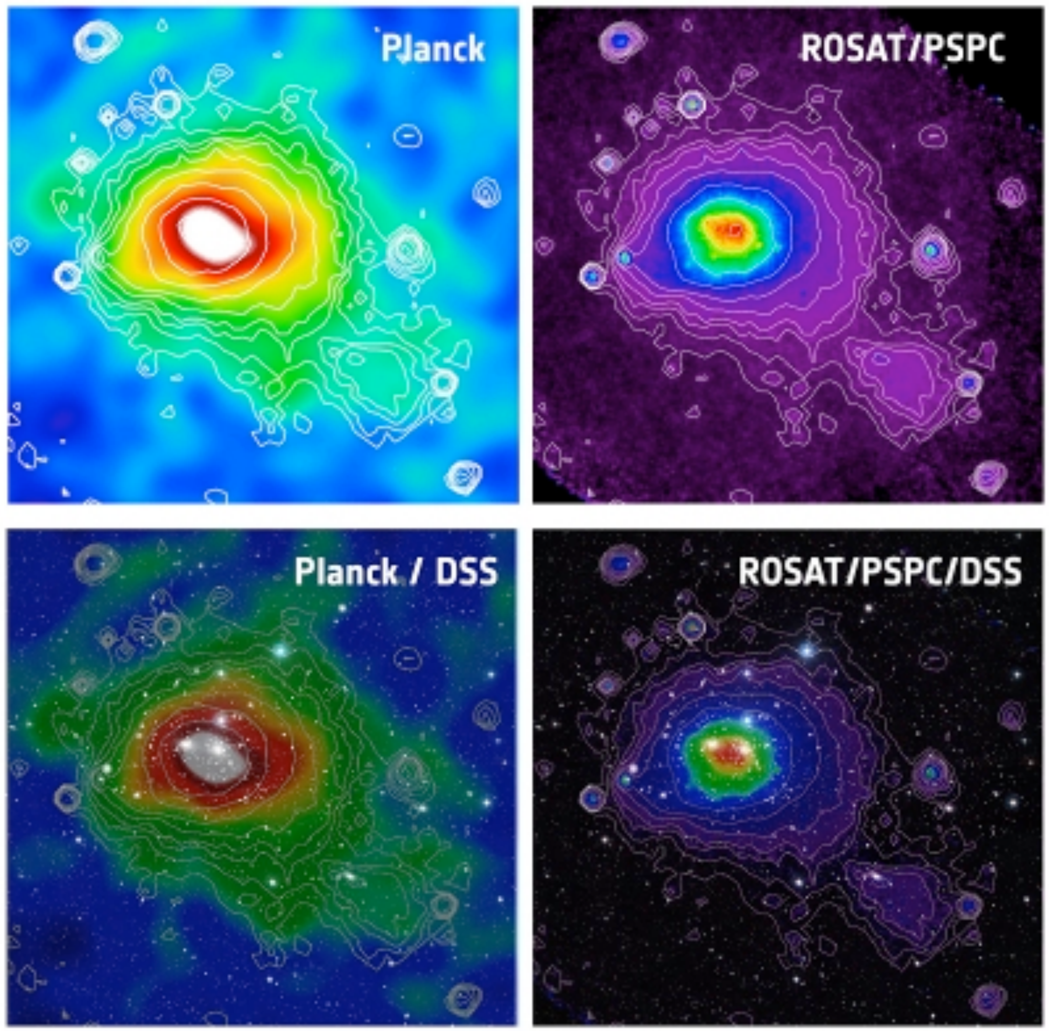
Produce Two Components of the SZ effect

DETECTING CLUSTERS VIA SZ EFFECT

$$\frac{\Delta T}{T_{\rm CMB}} = g(x)\int dl\, n_e(l)\, \frac{k_B\, T_e(l)}{m_e c^2}\, \sigma_T = y$$ (compton y parameter)







Inverse Compton Scattering of CMB by “hot” ICM e$^-$

FOCUS ON THE $\Omega_m - \sigma_8$ PLANE

PRIMARY CMB RESULTS

$\Omega_m = 0.315 \pm 0.017$
Ho = 67.3 ± 1.2
$\sigma_8 = 0.829 \pm 0.012$

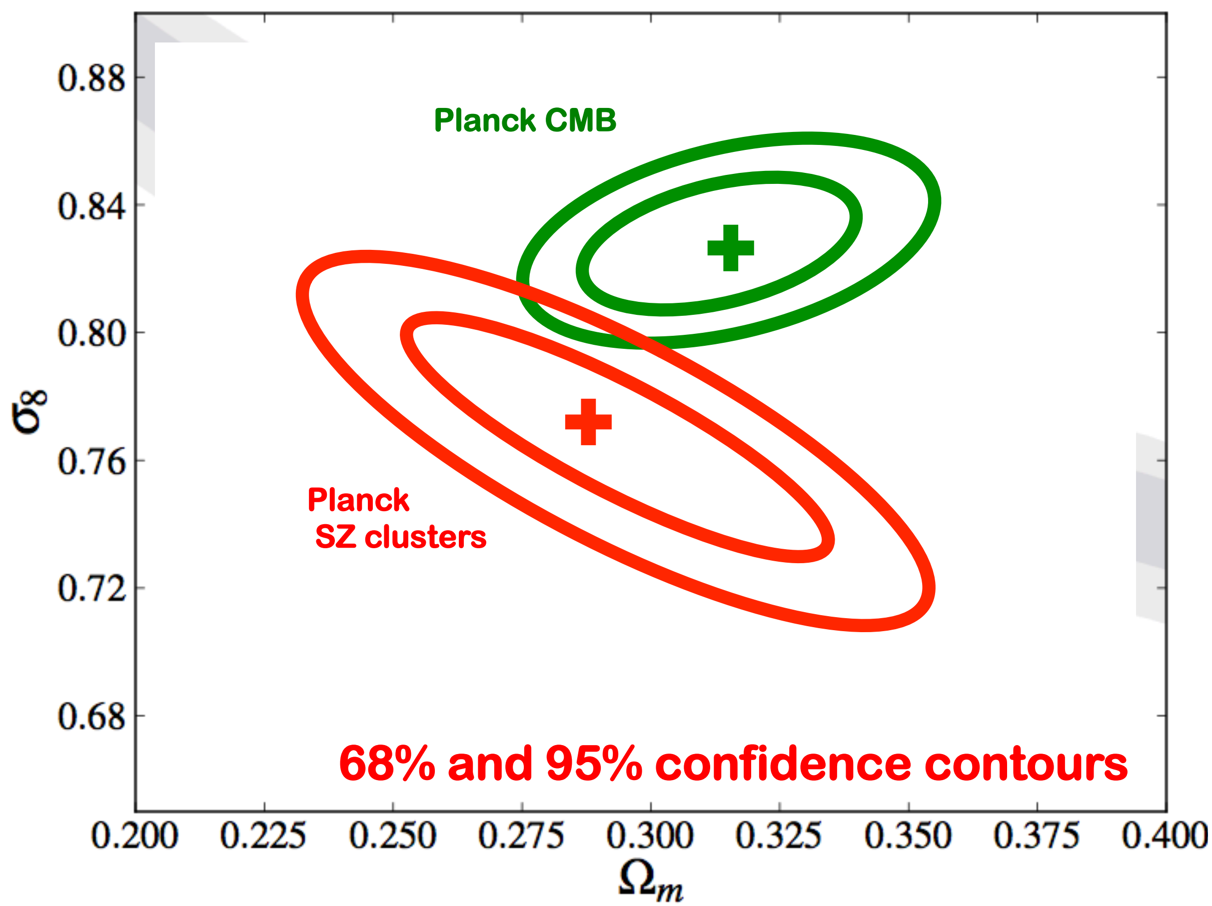
LOCAL ESTIMATE OF Ho

Ho = 73.8 ± 2.4

From clusters:

$\Omega_m = 0.29 \pm 0.02$
$\sigma_8 = 0.77 \pm 0.012$

Ade et al. 2013: Planck Collaboration XX/XXI



Planck CMB is measuring cosmology at t ~ 370,000 yrs.

Planck Clusters gives cosmology at more recent epoch.

SO WHAT'S GOING ON?

- ◆Systematics in the Planck CMB data

  Spergel et al. (2014) and others have looked at this.
  Moves CMB results towards Clusters but not enough.

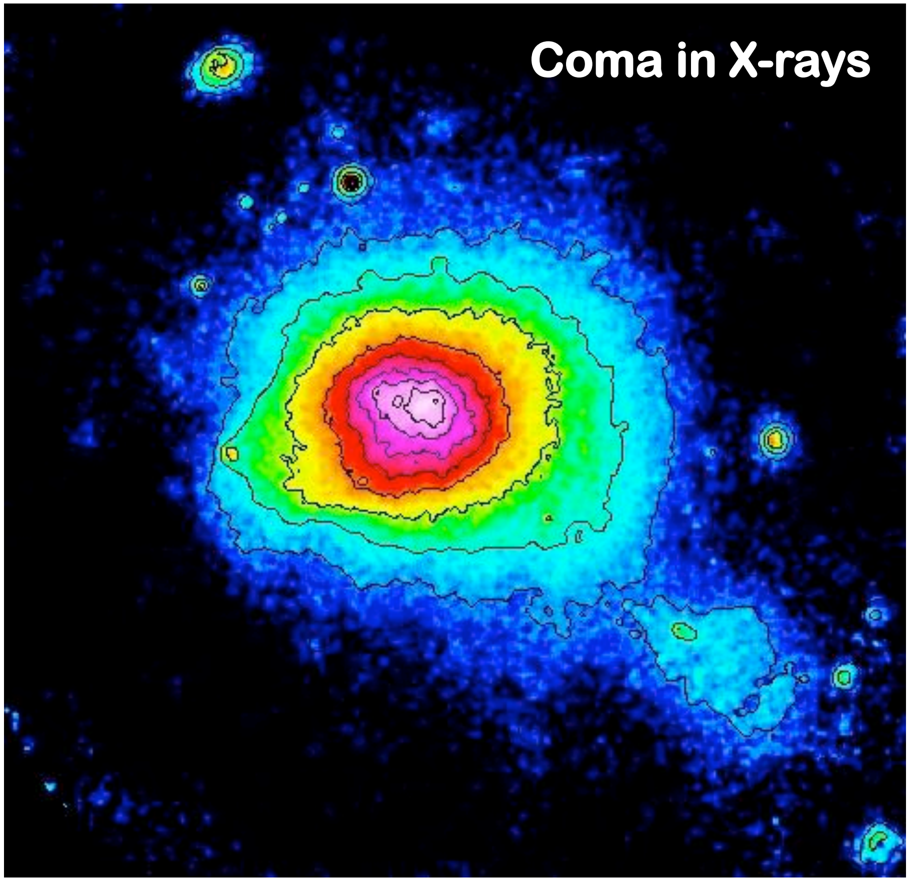
- ◆Systematics in the Planck SZ Cluster analysis

  Focus of CCCP analysis (Remainder of this talk).

- ◆Failure of the vanilla (six-parameter) model ➔ new physics

  Exploits the fact that CMB and Cluster measurements are at different epoch. (Premature in light of above but interesting proposals are circulating.)

PLANCK SZ CLUSTER ANALYSIS:
PREMISED ON MEASURING CLUSTER MASS FUNCTION



HSE: $$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

CLUSTERS ARE LARGELY DARK
mass cannot be easily measured

PLANCK MEASURE Ysz

FOR SUBSET OF CLUSTERS WITH X-RAY DATA, USE X-RAY DATA TO ESTIMATE MASS: Mx

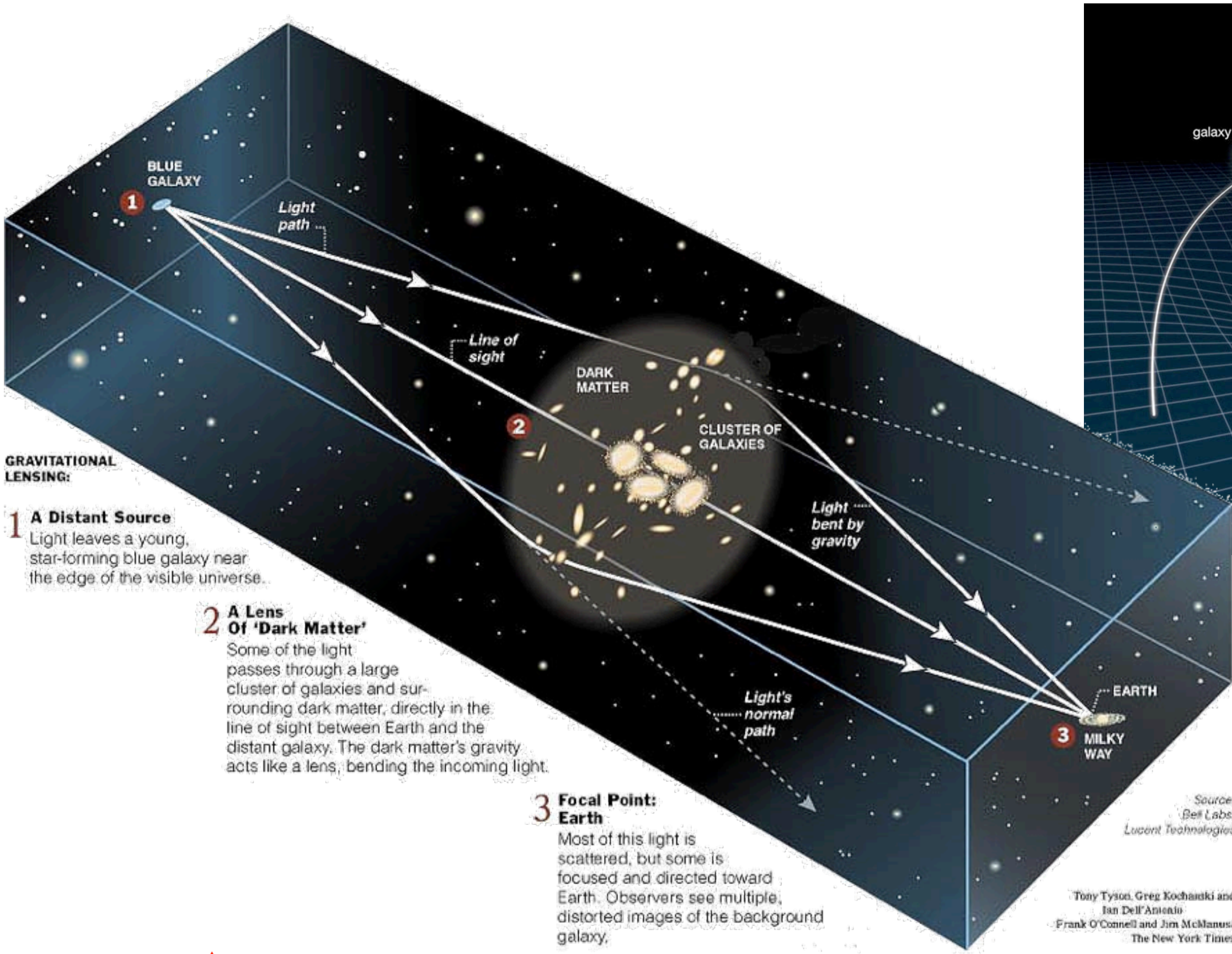
Mx IS A BIASED ESTIMATOR OF TRUE MASS M: $M_x = \xi M$

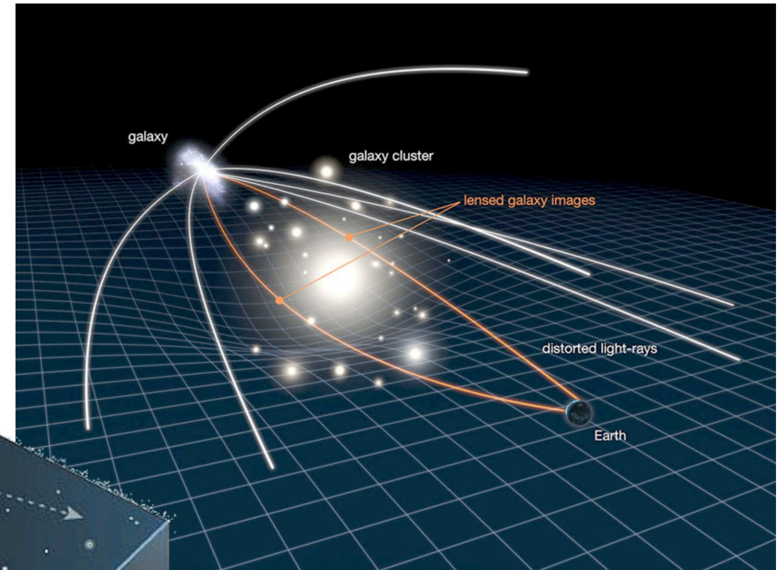
PLANCK: $\xi = [\ 0.7, 1.0\ ]$
$\langle \xi \rangle = 0.8$

USE RESULTING Ysz – M TO DERIVE MASSES OF ALL OTHER CLUSTERS (MASS-OBSERVABLE)

IF USE $\langle\xi\rangle = 0.6$ INSTEAD OF 0.8, THE TENSION IS RESOLVED

WE CAN EMPIRICALLY ESTABLISH Ysz – M FOR CLUSTERS IN THE NEARBY UNIVERSE – USING WEAK GRAV LENSING!

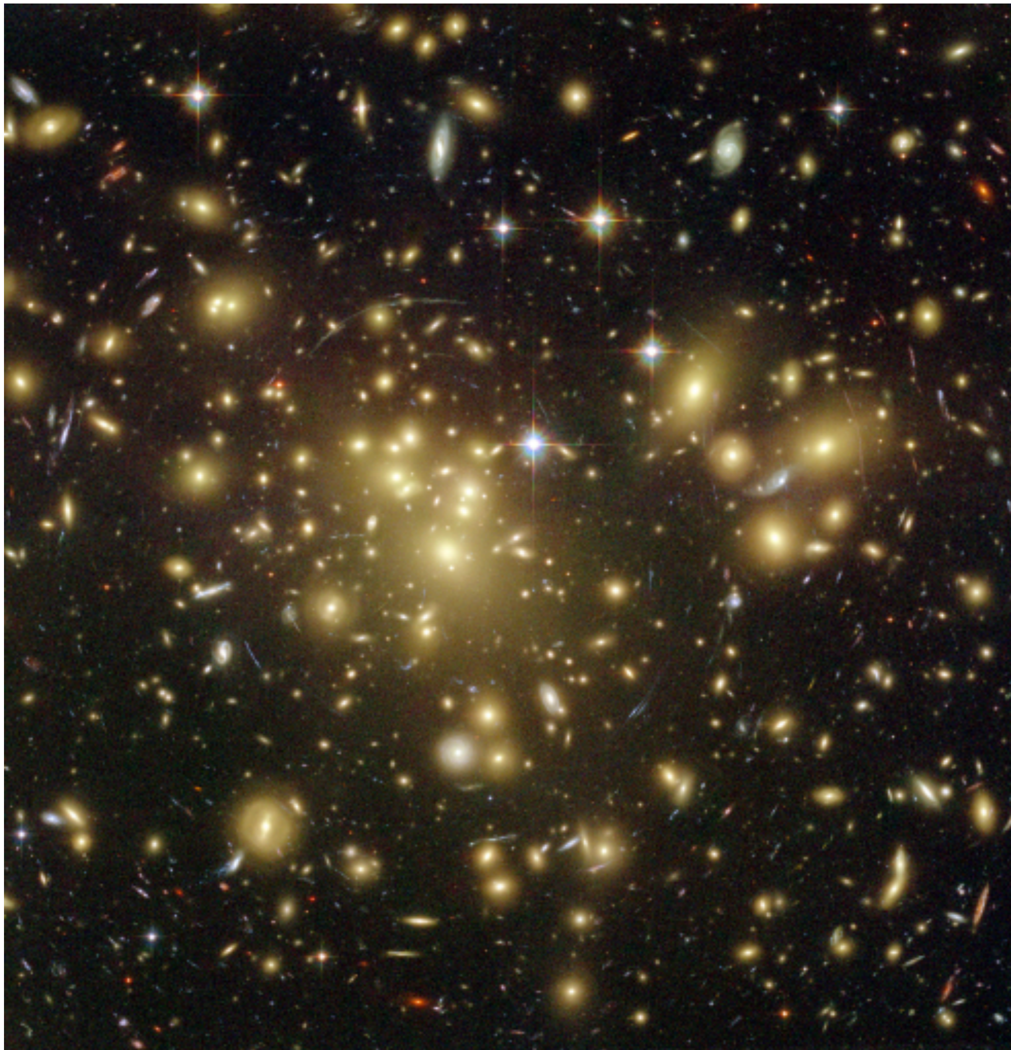




CCCP

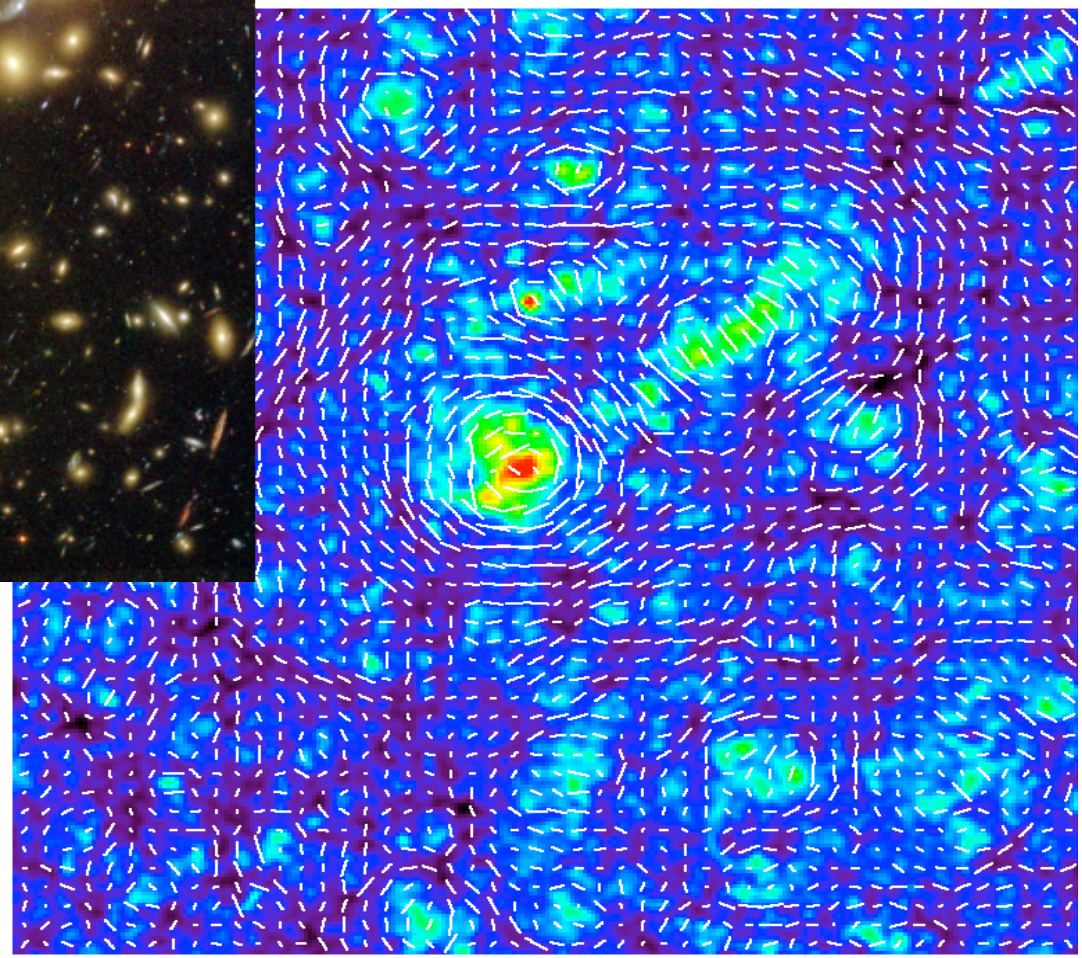
Canadian Cluster Comparison Project

it's good for the masses!



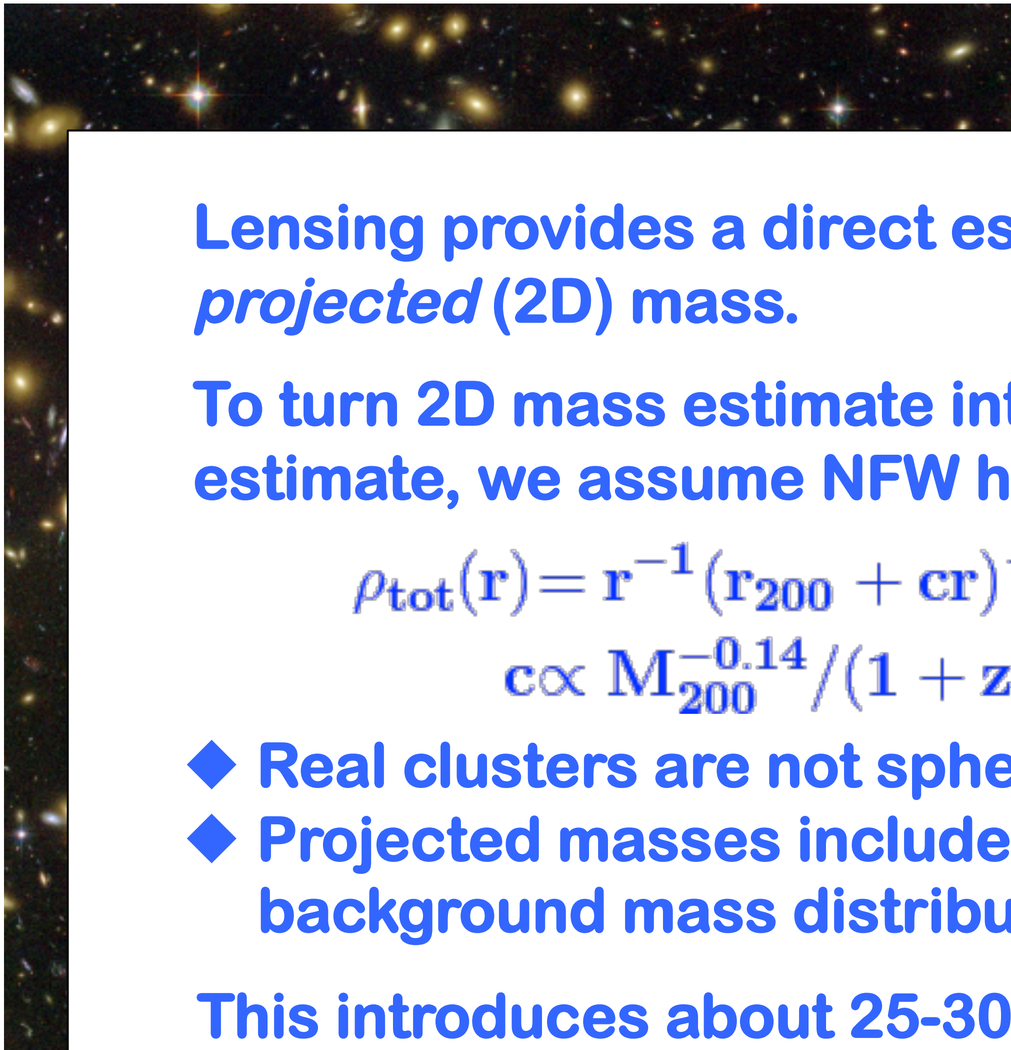
$$\gamma_1 = \tfrac{1}{2}(\partial_1^2 - \partial_2^2)\psi$$
$$\gamma_2 = \partial_1\partial_2\psi,$$

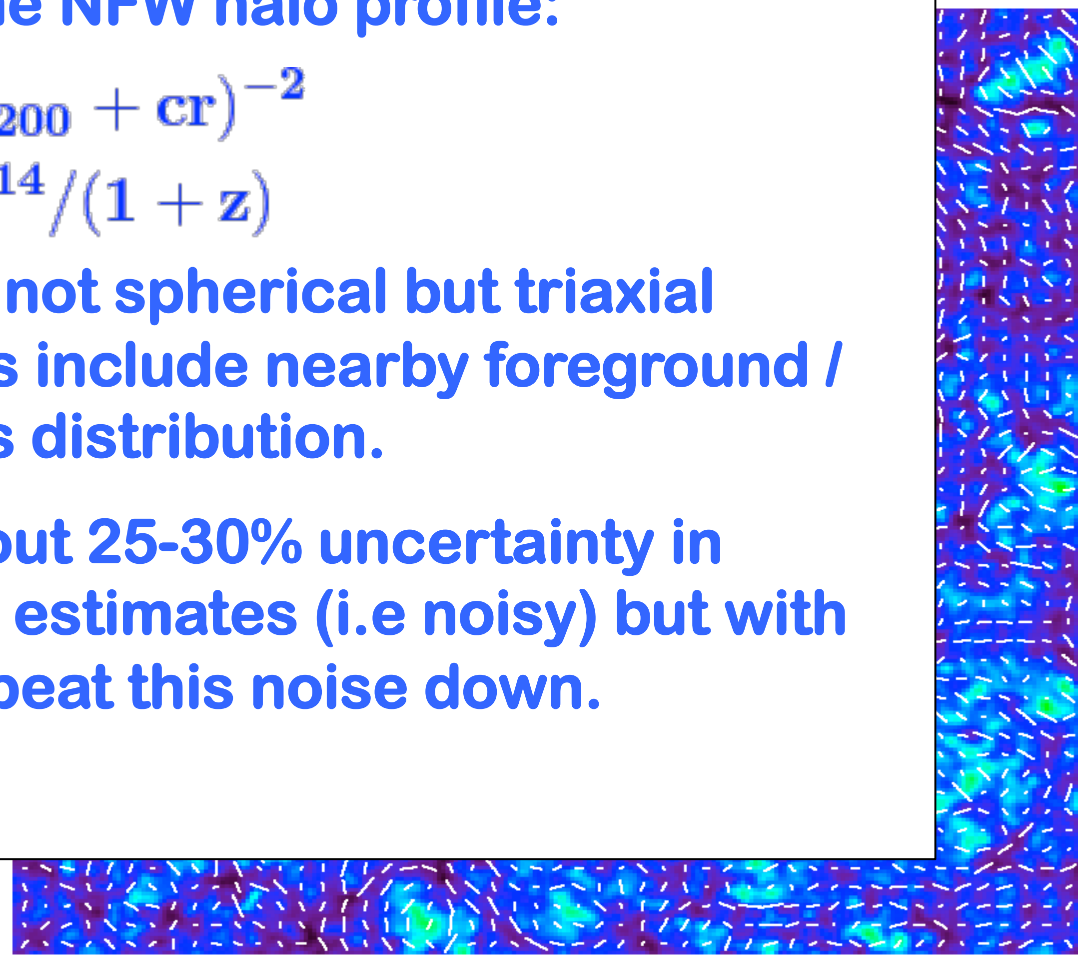
$$\kappa = \frac{1}{2}(\partial_1^2 + \partial_2^2)\psi,$$



$$\kappa(\theta) = \frac{\Sigma(\theta)}{\Sigma_{\rm crit}},$$

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_{\rm OS}}{D_{\rm OL}D_{\rm LS}},$$





Lensing provides a direct estimate of the *projected* (2D) mass.

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

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

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

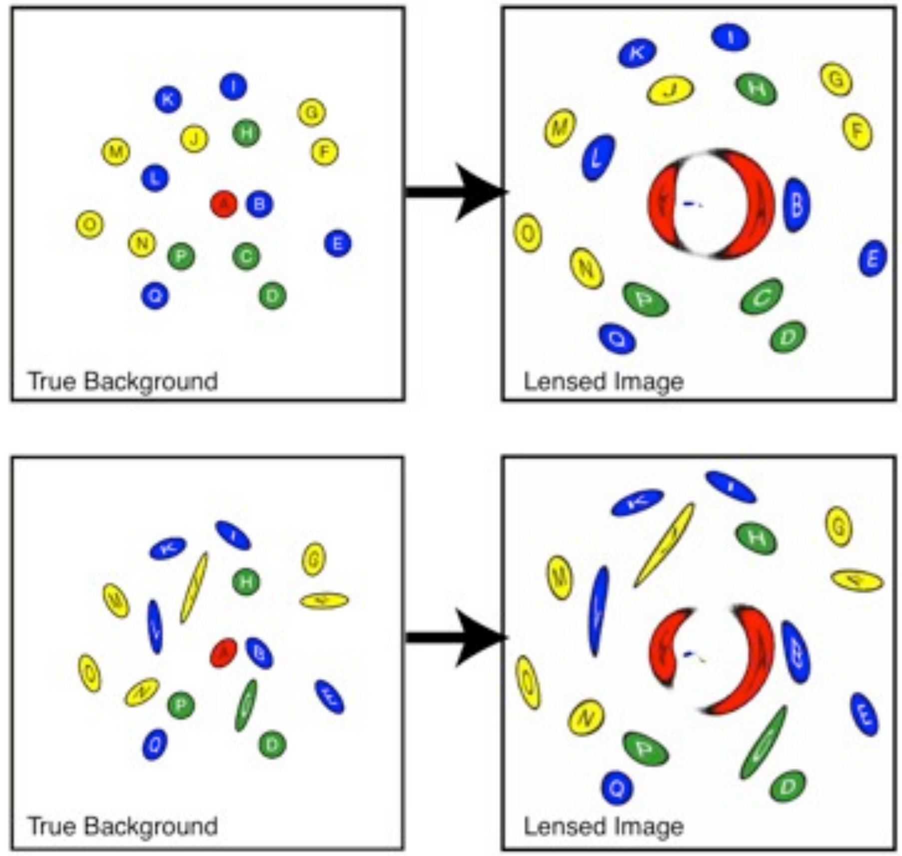
- **Real clusters are not spherical but triaxial**
- **Projected masses include nearby foreground / background mass distribution.**

This introduces about 25-30% uncertainty in individual WL mass estimates (i.e noisy) but with many objects, can beat this noise down.

THEORETICALLY SIMPLE, IN PRACTISE...

SOURCES OF NOISE:

Random intrinsic shape of galaxies.



Atmospheric seeing and telescope point spread function

Background noise in the CCD image

Foreground and cluster galaxies

Faint unresolved galaxies

Distance between lens and background galaxies

UNDERSTANDING SYSTEMATIC OFFSETS:

We have undertaken a thorough analysis of the entire pipeline to understand and quantify different sources of systematic biases:

$$\gamma_i^{obs} = (1+\mu)\ \gamma_i^{true} + c$$

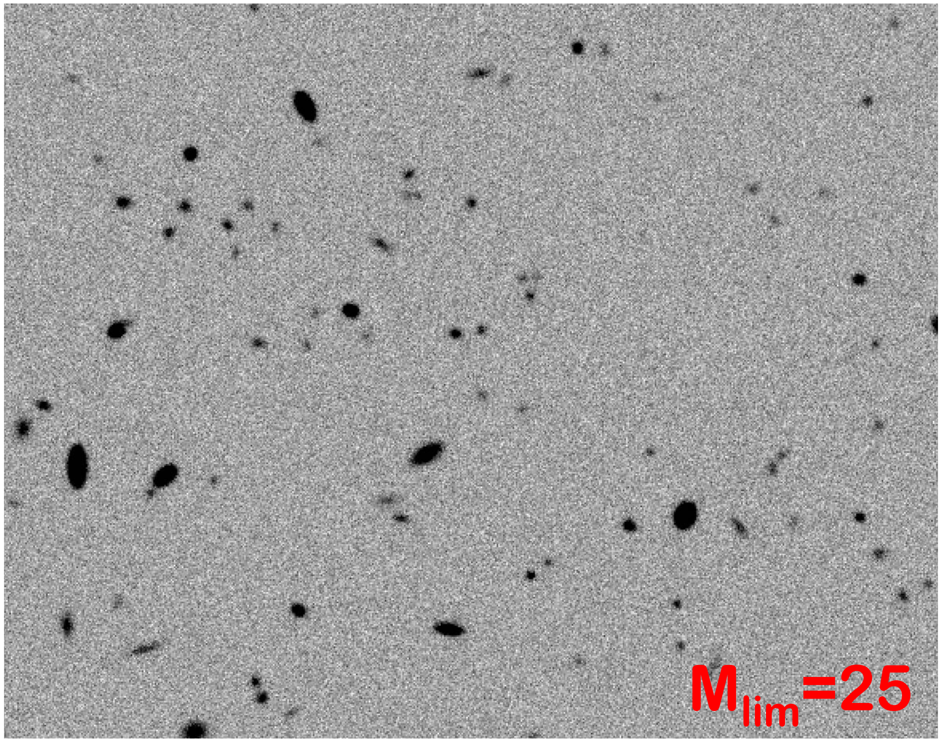
For cluster work: not important due to azimuthal avrg

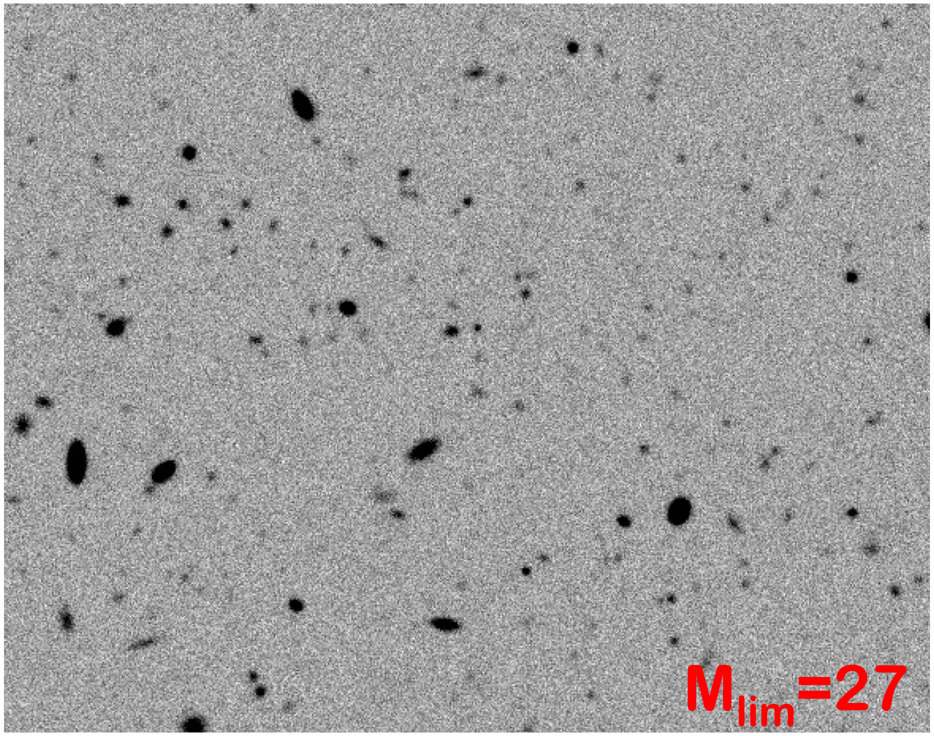
- Start with an input mock galaxy distribution
  - correct number counts and redshift distribution
  - appropriate ellipticity distribution (mag dependent)
- Apply a known shear due to intervening lens ➔ "truth"
- Create a lensed image; add "appropriate" noise level
- Impose correct PSF – size (seeing) and distortions
- Analyze mock images via identical pipeline/approach
- Compare results to true input to determine multiplicative and additive biases.

MOCK IMAGES MUST MATCH OBSERVATIONS IN ALL ASPECTS!

FAINT UNRESOLVED GALAXIES

MOCK IMAGE MUST INCLUDE THE POPULATION OF GALAXIES – EVEN IF UNRESOLVED – AT LEAST 1.5 MAGNITUDES FAINTER THAN THE LIMITING MAGNITUDE OF SOURCES USED IN THE LENSING ANALYSIS.

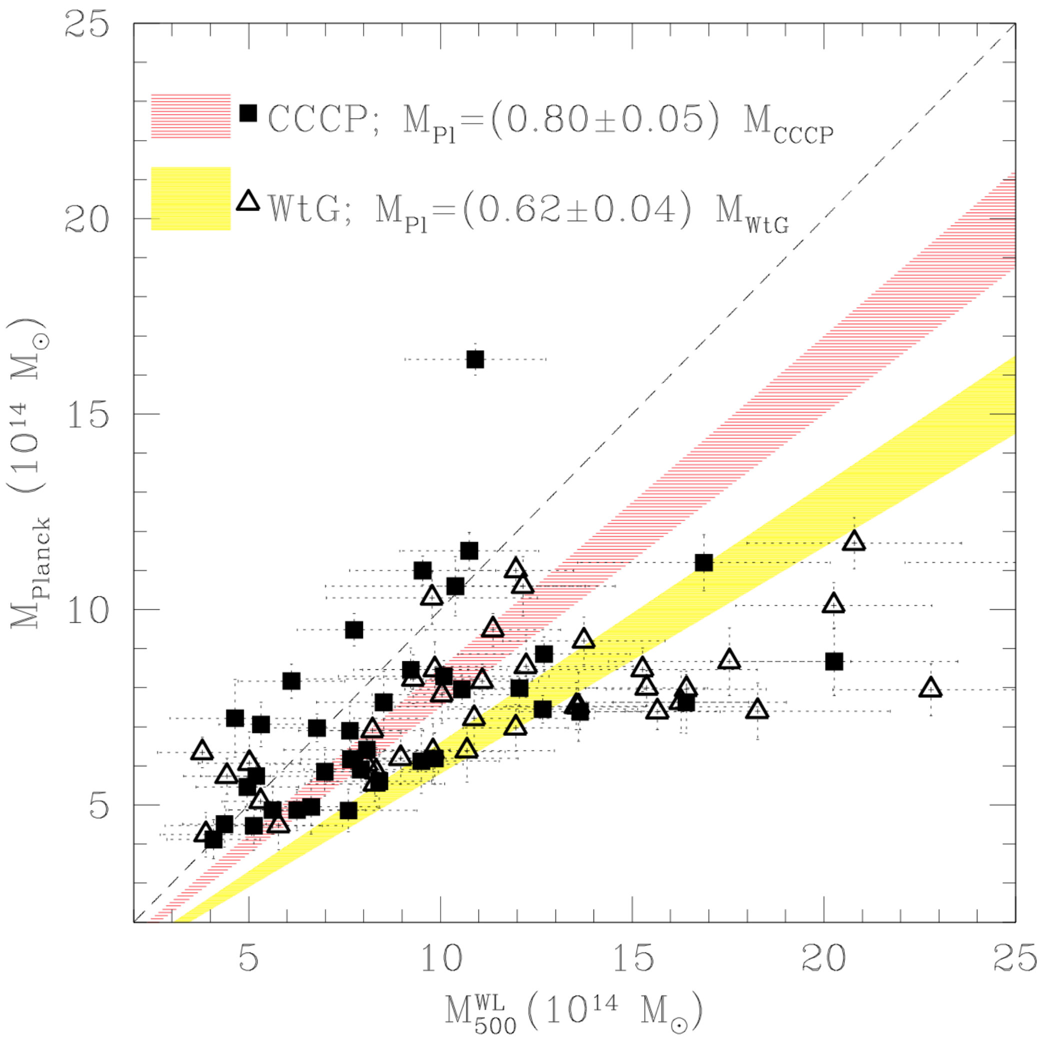




FAINT UNRESOLVED GALAXIES IMPACT SHAPES OF BRIGHTER SOURCE GALAXIES VIA BLENDING AND BY INTRODUCING CORRELATED NOISE IN THE IMAGES.

AND, COMBINING EVERYTHING TOGETHER…

WE COMPARE TO PLANCK MASSES

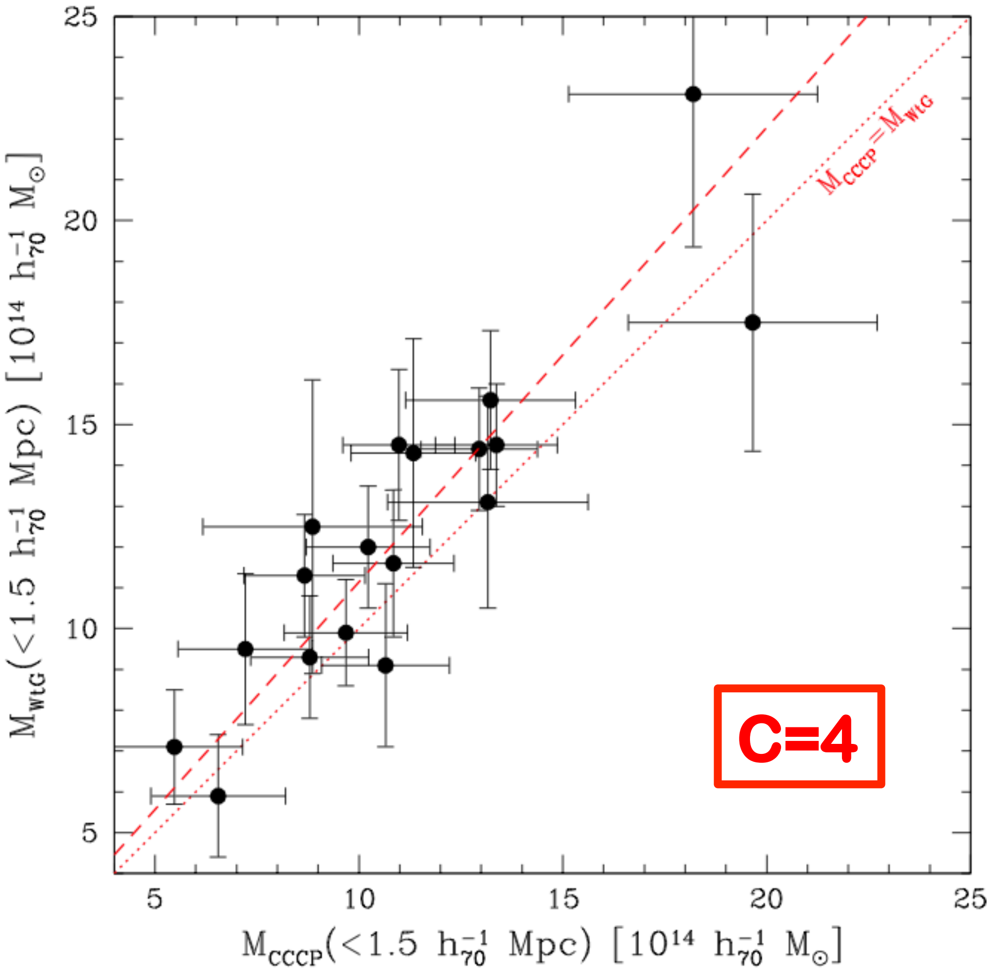


$$\frac{M_{500}^{Planck,Hydro}}{M_{500}^{WL}} = \xi = 0.8$$

THE VALUE OF ξ WITH CCCP MASSES IS SAME AS THAT ASSUMED IN PLANCK COSMOLOGY ANALYSIS.

TENSION BETWEEN PLANCK CLUSTER ANALYSIS AND PLANCK CMB ANALYSIS REMAINS.

SO WHAT THEN, NEW PHYSICS?



EXCITING BUT...

ANOTHER GROUP (WtG) HAS MEASURED WL MASSES AND FIND $\xi = 0.6$.

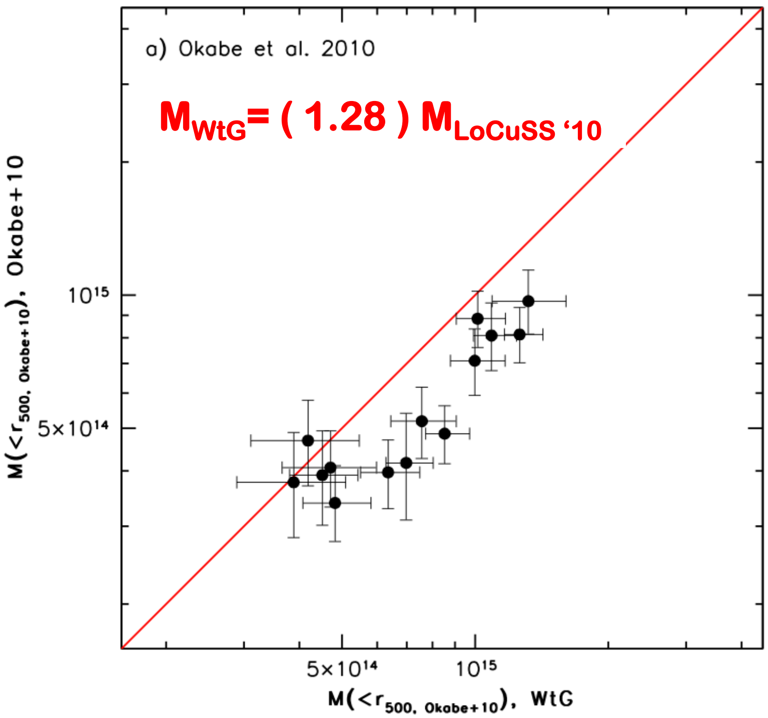
THIS WOULD RESOLVE THE TENSION BWT TWO PLANCK COSMOLOGY RESULTS

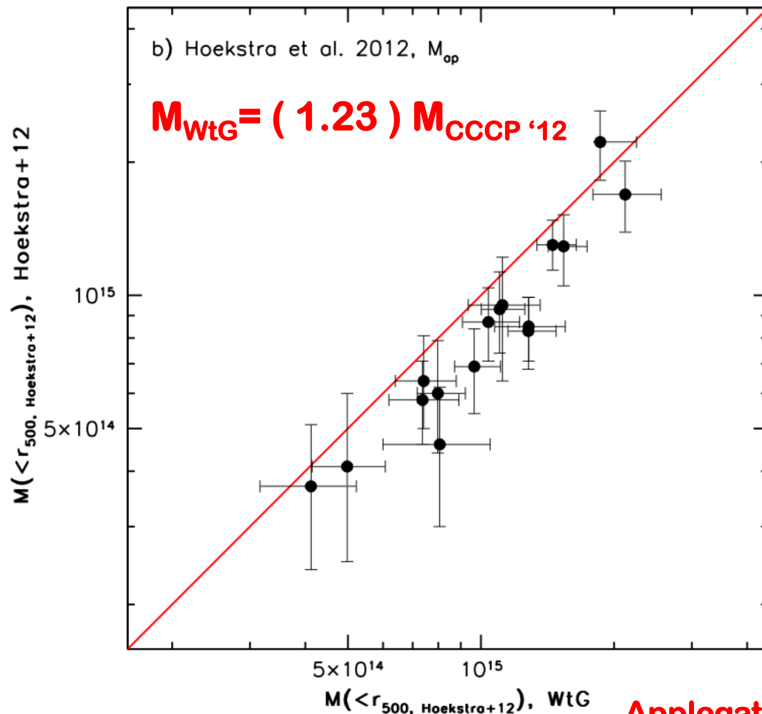
BUT...

$M_{WtG} = (1.11 \pm 0.04)\ M_{CCCP\ '14}$

11% !!!

AND….





Applegate et al 2014

For the same set of clusters, masses are systematically off by ~25 %, → bigger than statistical uncertainties

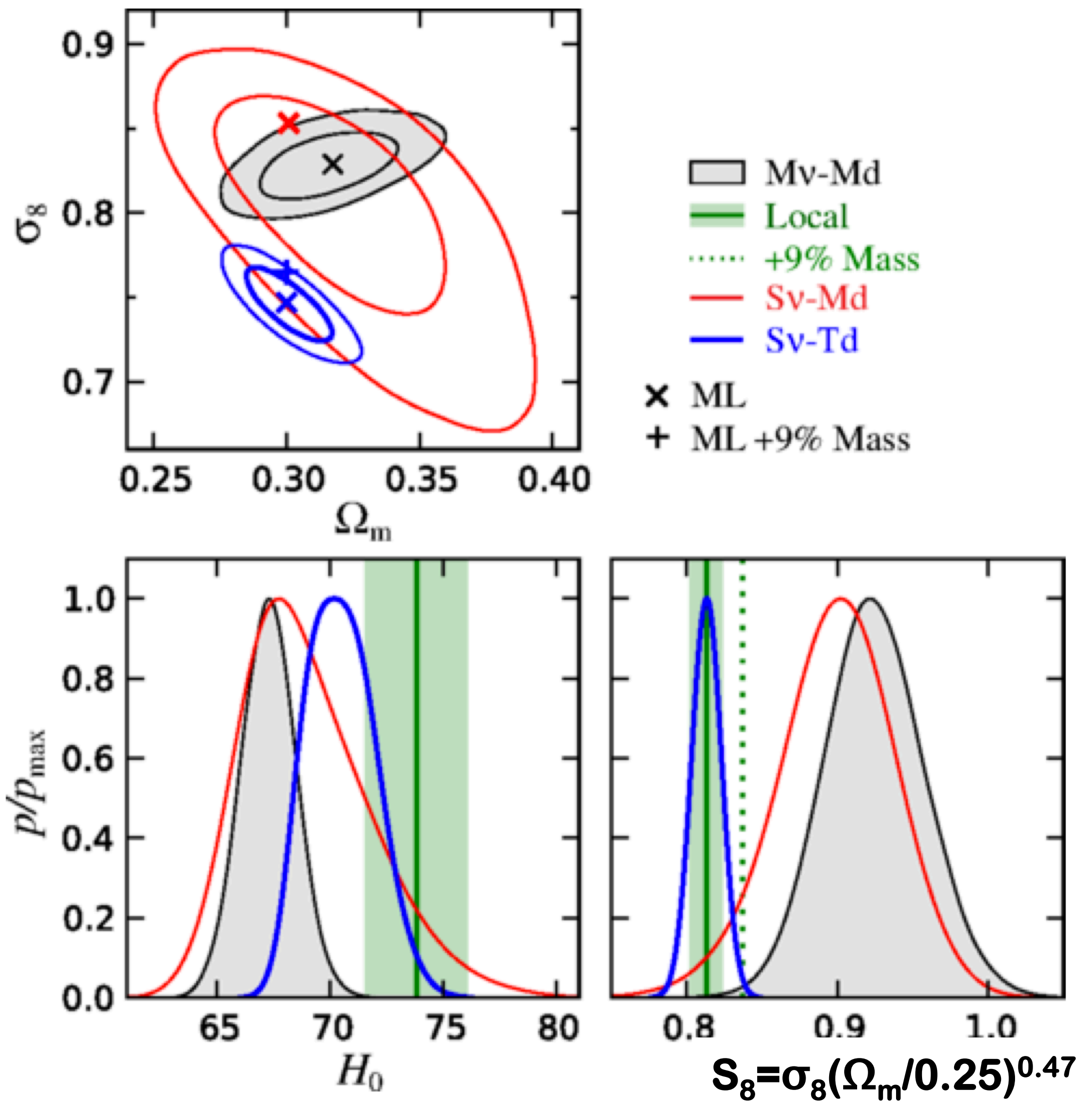
OBSTACLE TO "PRECISION COSMOLOGY WITH CLUSTERS"

SUMMARY

- **Planck CMB and Planck Cluster determinations of Ω_m and σ_8 are in tension.**
- **We use weak lensing mass determinations of 50 clusters to test the key assumption underpinning the Planck Clusters analysis.**
- **We have carried out an extensive analysis of systematic biases of our WL measurement and analysis pipeline.**
- **At the end of it all, our results support the Planck assumption.**
- **But another group (WtG) finds that Planck assumption is off by 15% but WtG masses are 10–20% larger than other determinations.**

OBSTACLE TO "PRECISION COSMOLOGY WITH CLUSTERS"

BUT WHAT NEW PHYSICS?
food for thought



TENSION BTW HI-Z & LO-Z PARAMETERS CAN BE RESOLVED:

ONE EXTRA STERILE ν

ΔN_{eff} =1
M_s ~ 0.4-0.8 eV