SZ Cosmology with Planck

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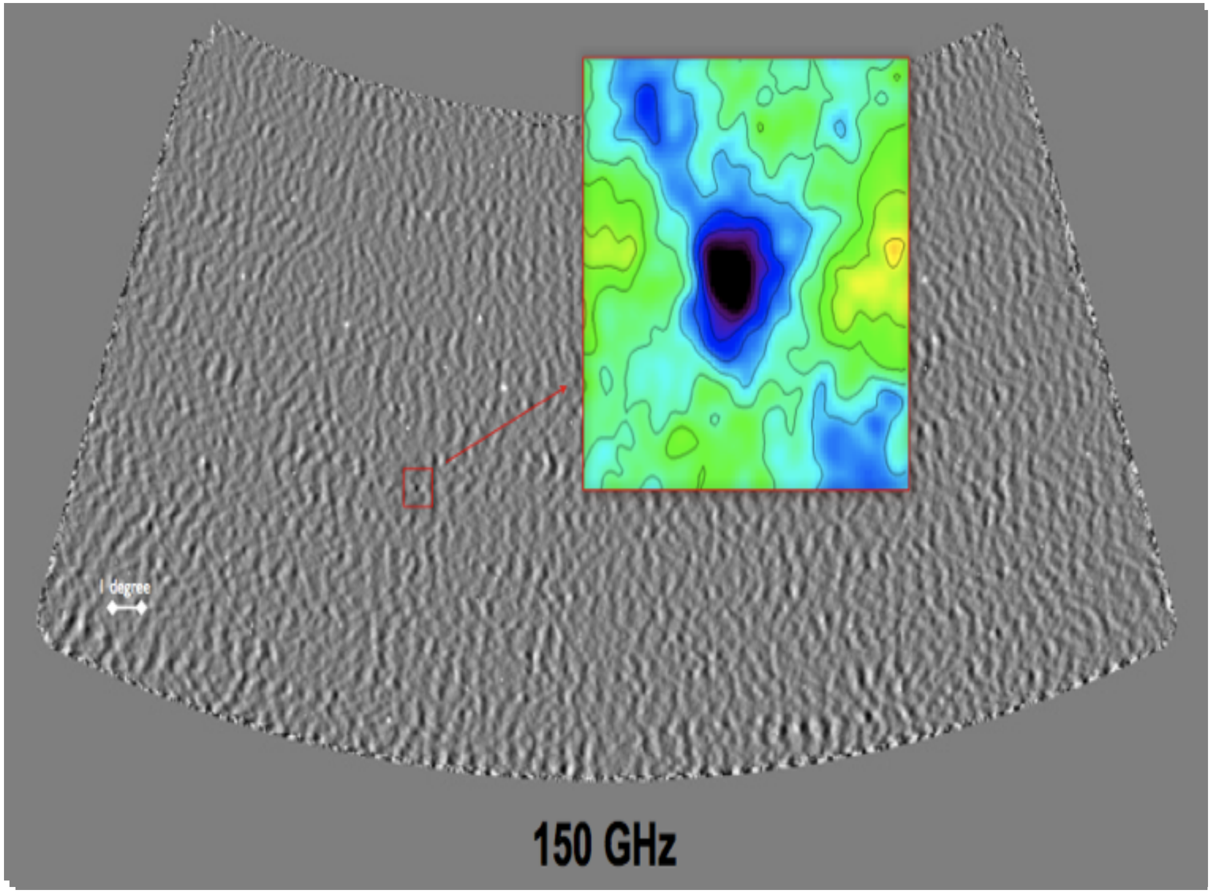
TIFR

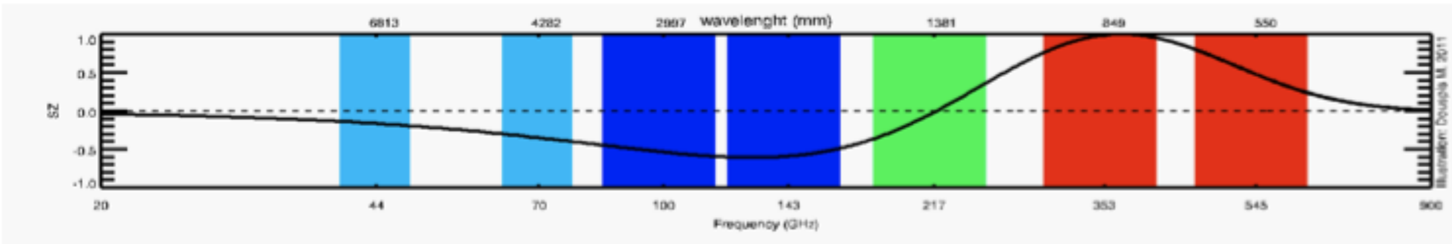
We detect clusters in SZ regularly these days?



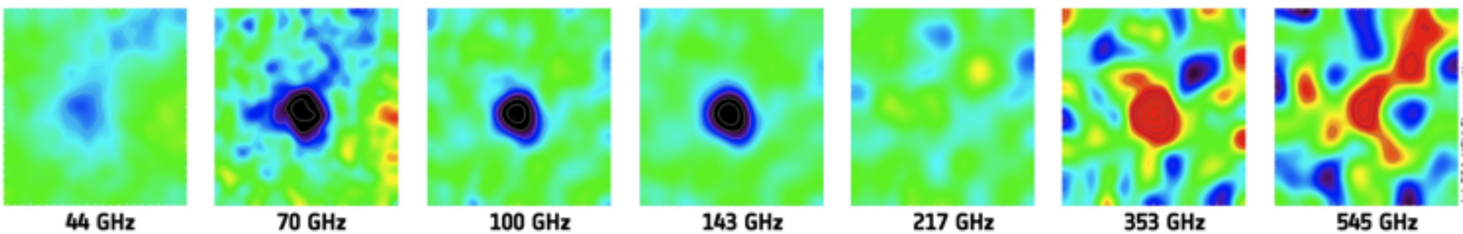
SPT sky

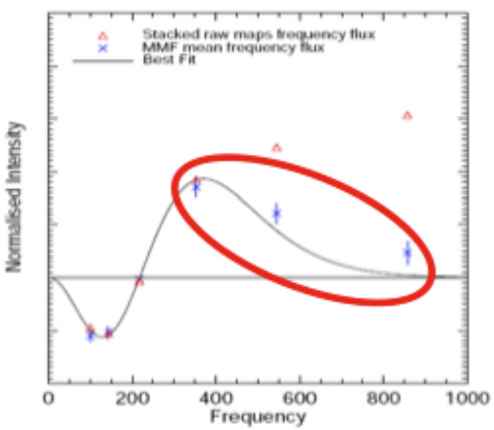
$$\frac{\Delta T}{T_{\rm CMB}} = g(\nu)\, y \longrightarrow y(\mathbf{n}) = \int n_e \frac{K_{\rm B} T_{\rm e}}{m_{\rm e} c^2} \sigma_T \, {\rm d}s$$

Planck has the best multi-frequency coverage



Planck's frequency coverage on A2319



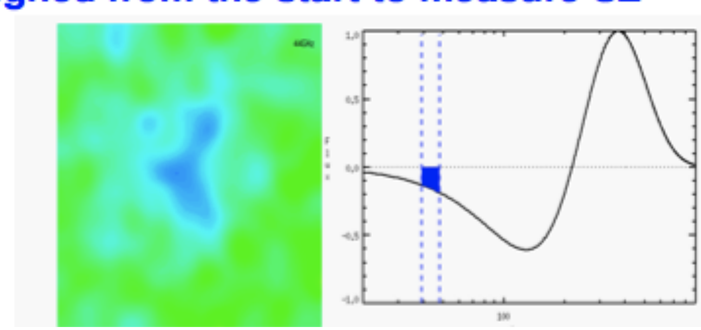


Average Spectrum over the ESZ clusters

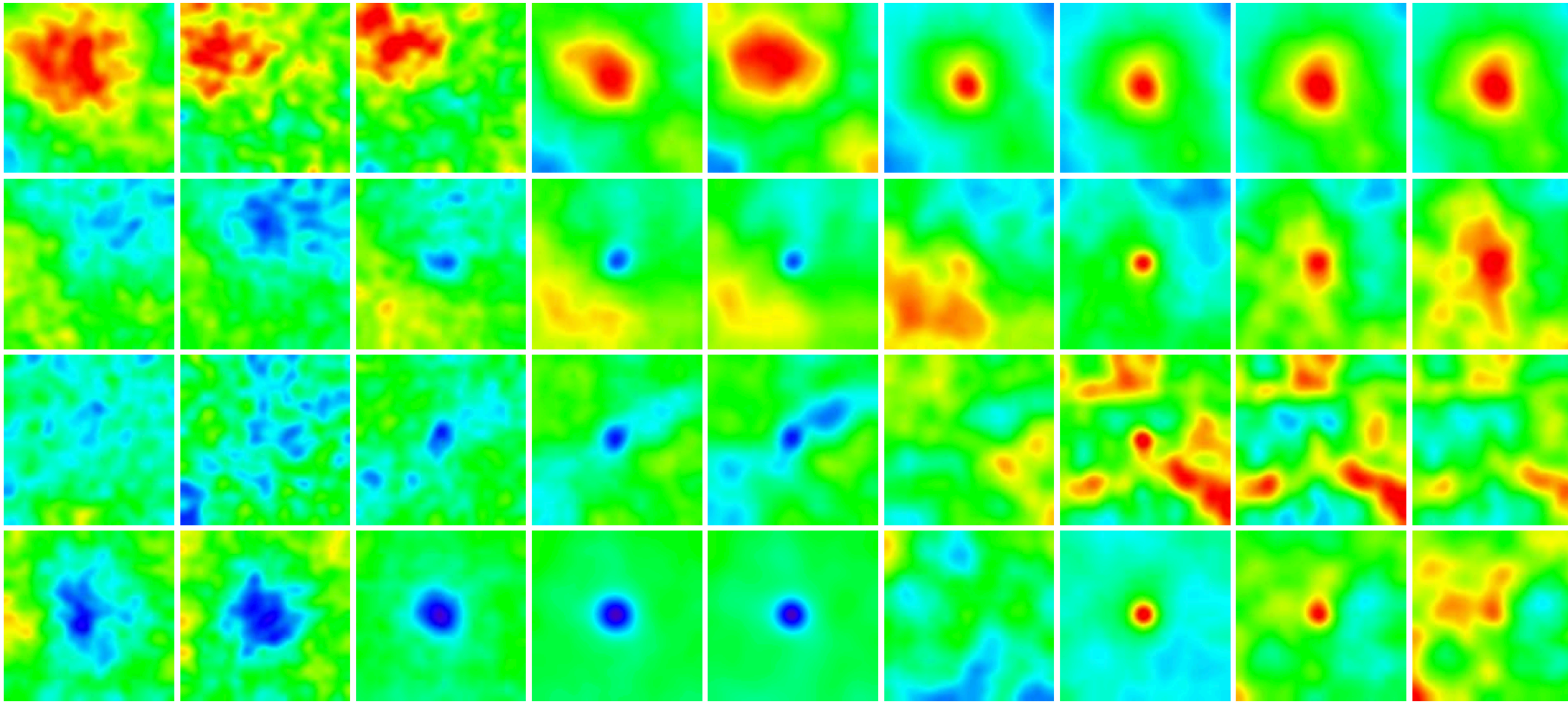
(Planck collaboration arXiv1101.2024)

- **All-sky survey**
- **Frequency range from 30 to 857 GHz**
- **Blind detection of the "positive" SZ effect**

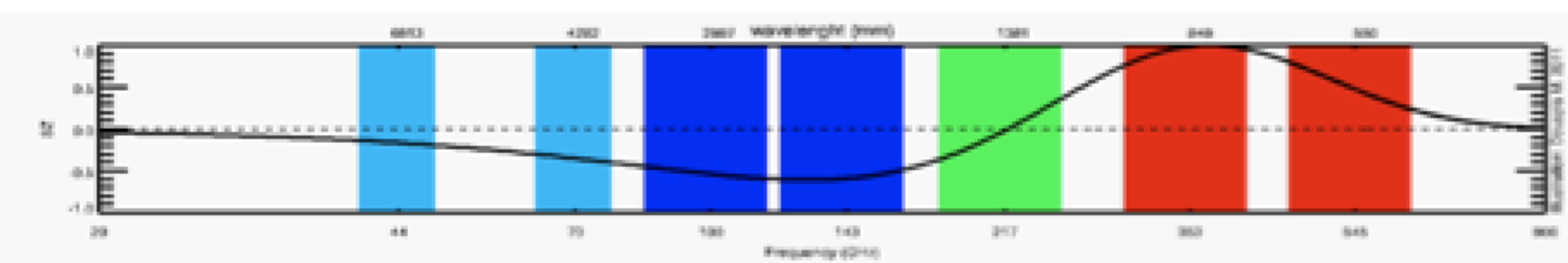
→ Planck, designed from the start to measure SZ



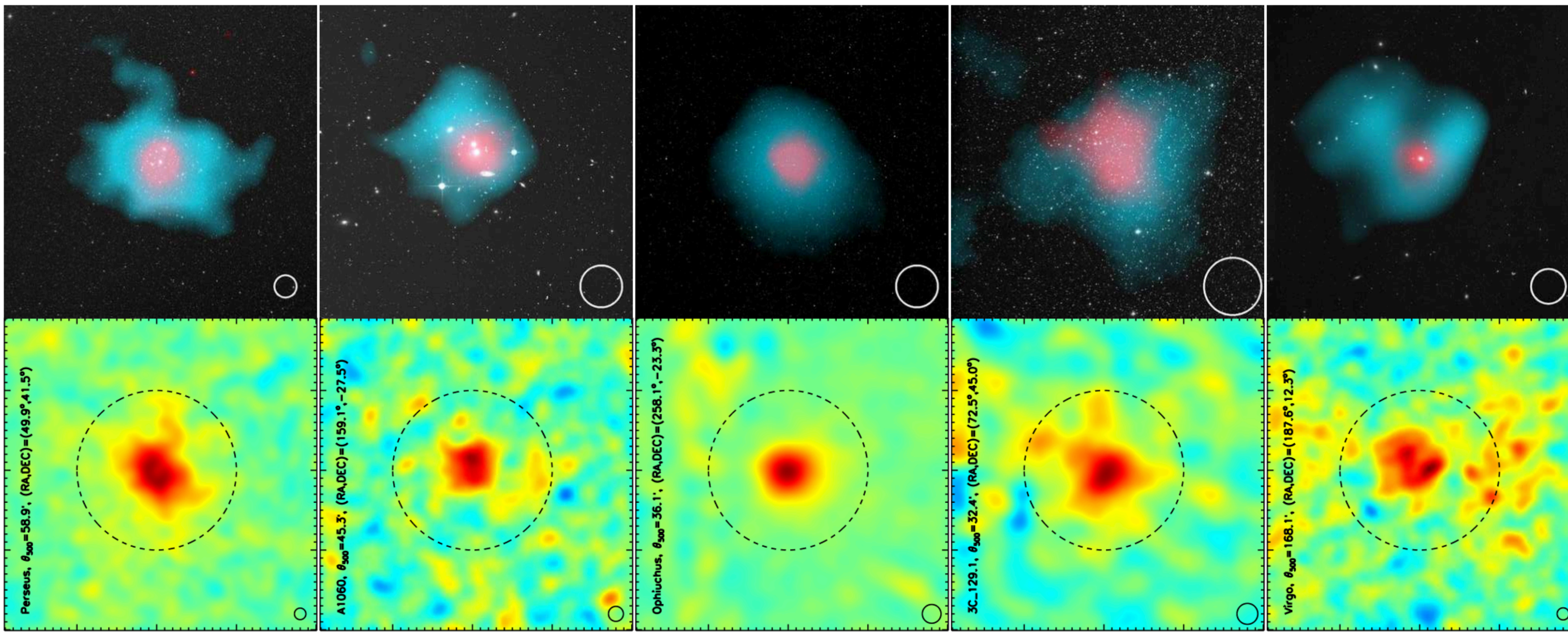
A sample of SZ clusters in Planck



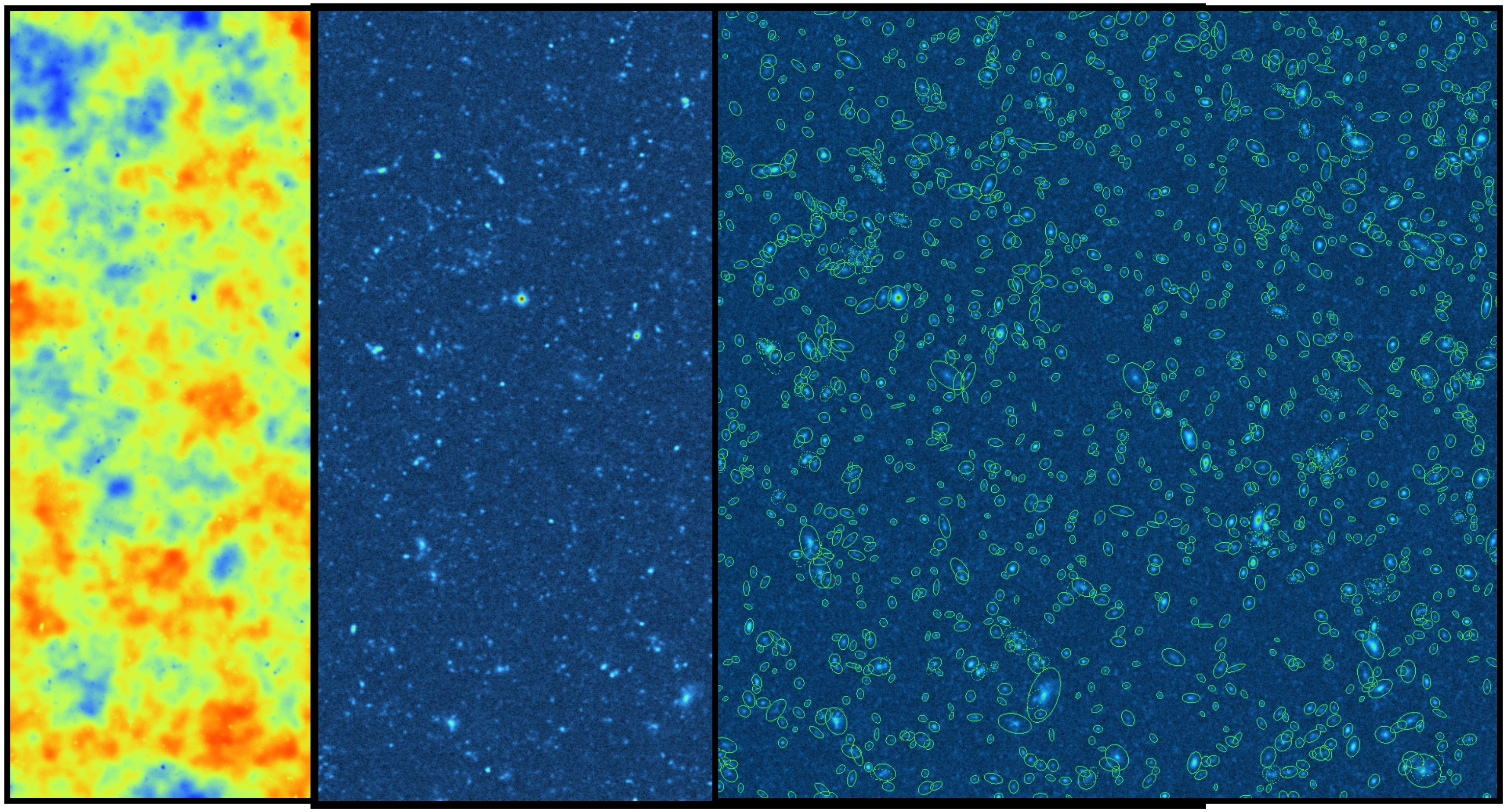
30 44 70 100 143 217 353 545 857 GHz



Cosmology done with a smaller sample of `validated' clusters



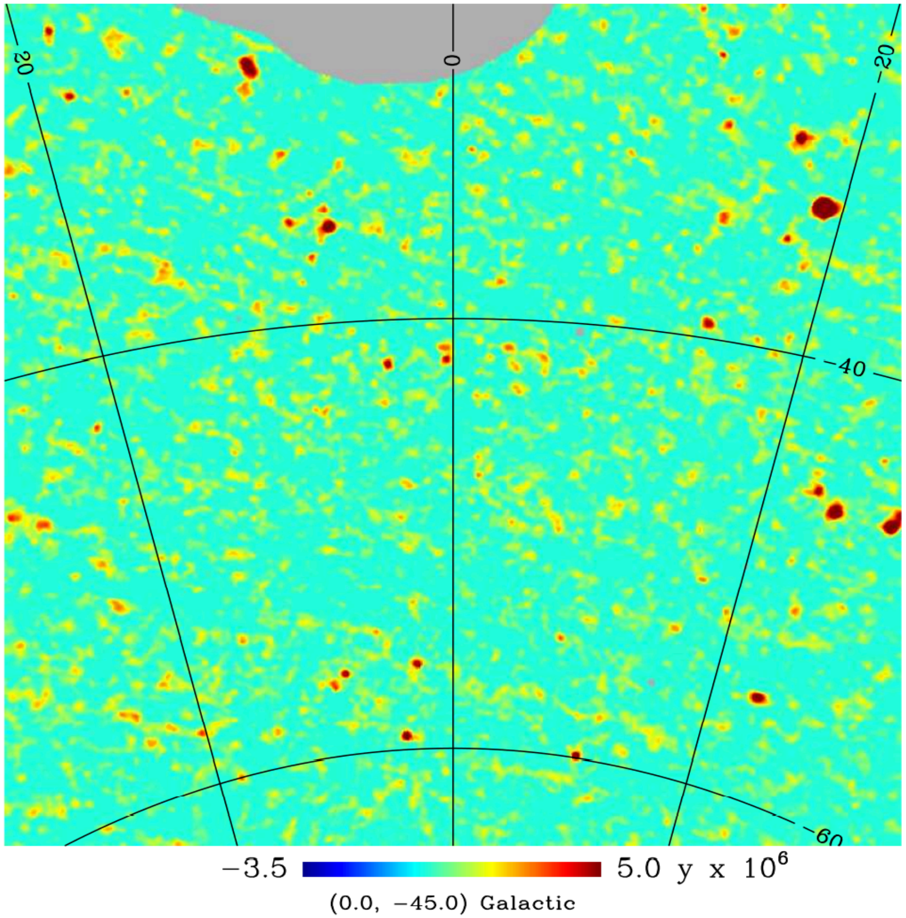
What is the SZ sky ?



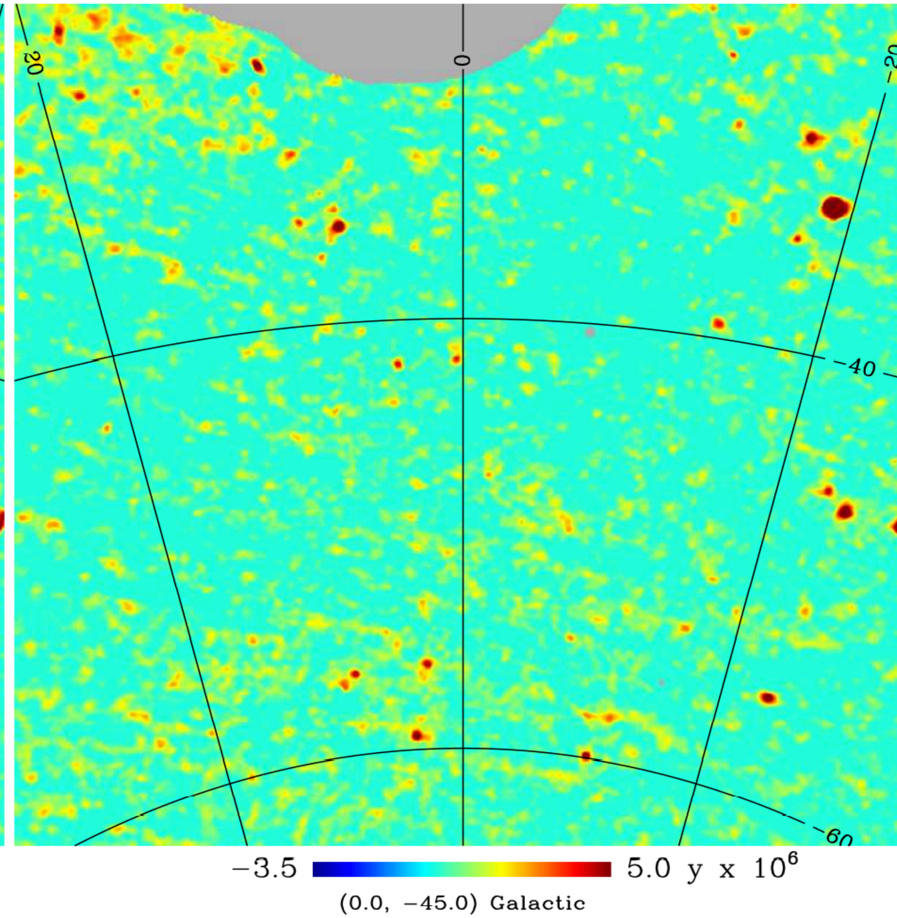
Diego & SM

The Planck SZ sky

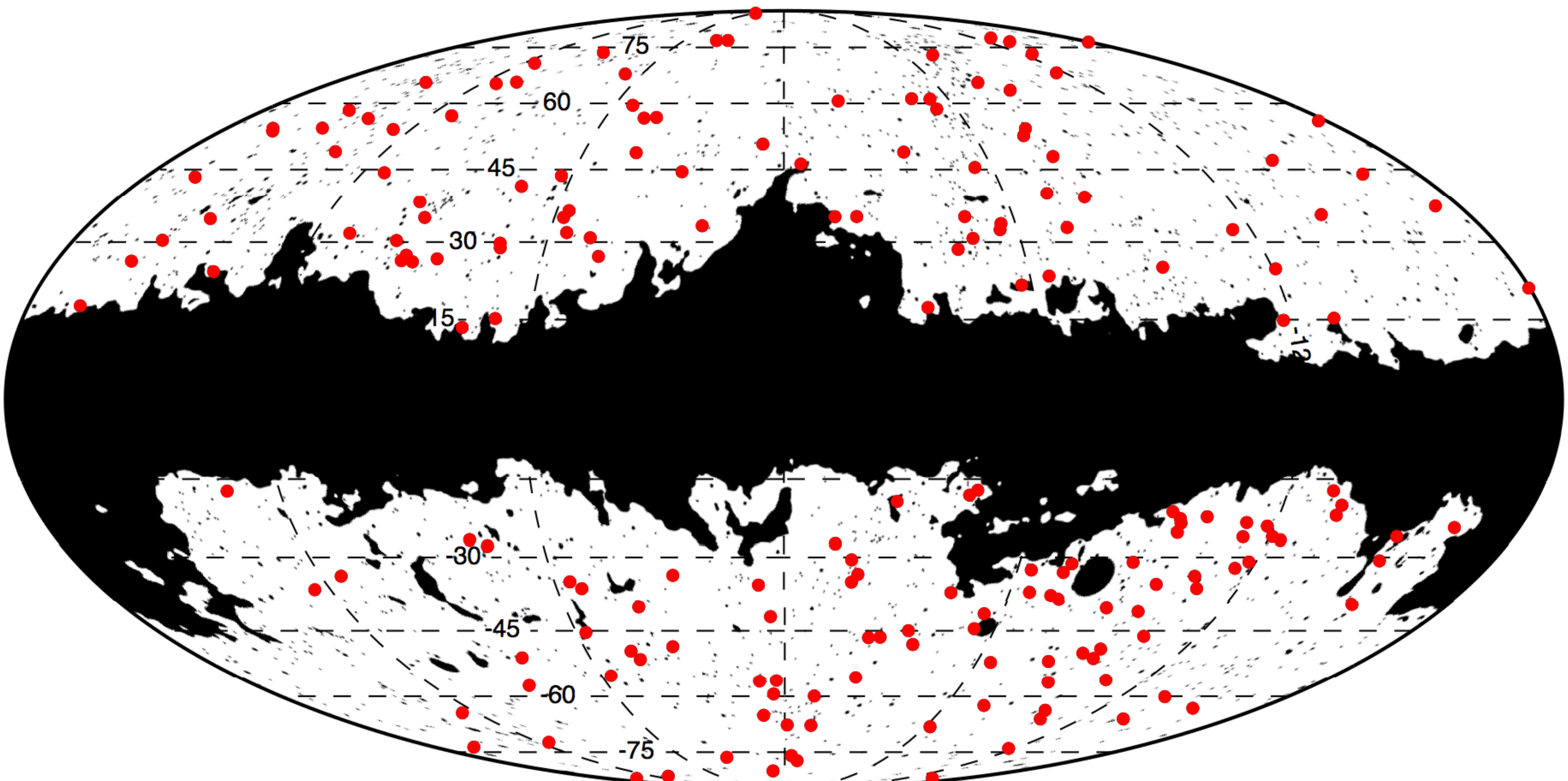
NILC tSZ map



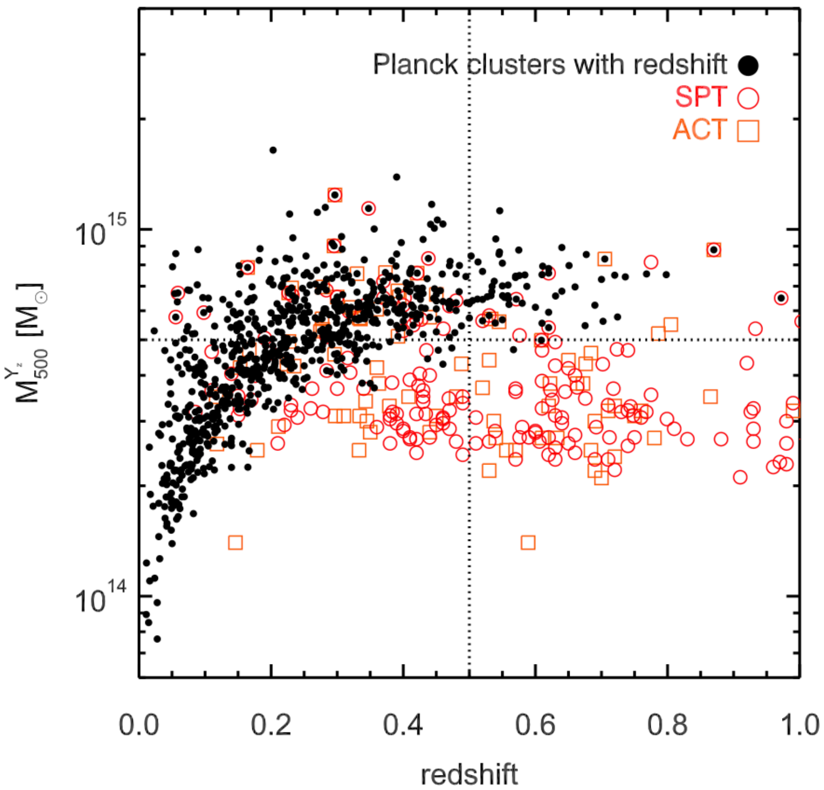
MILCA tSZ map

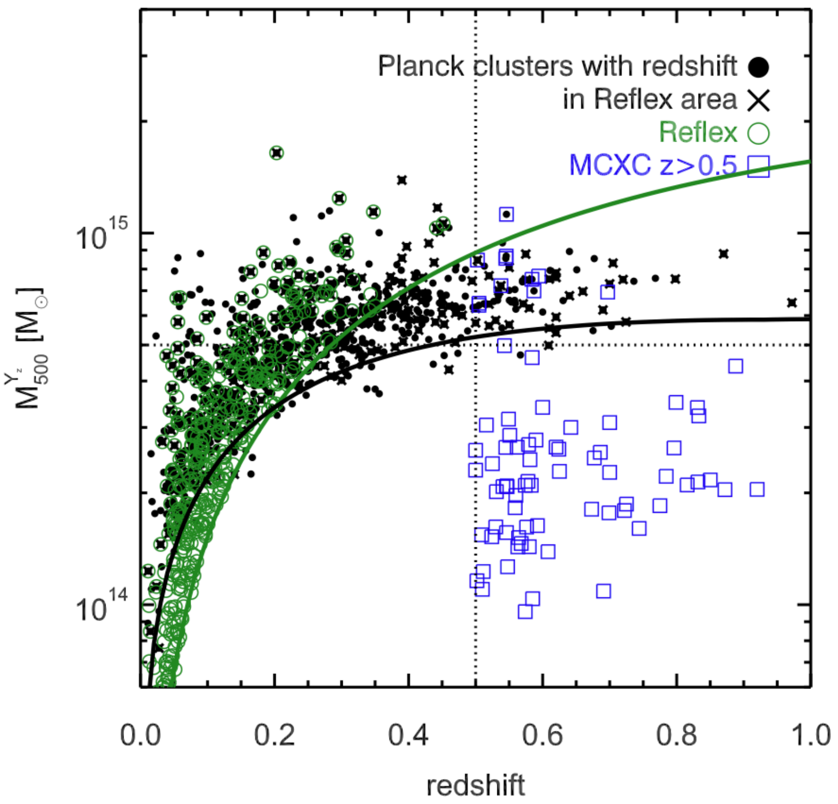


Planck has the biggest SZ sample

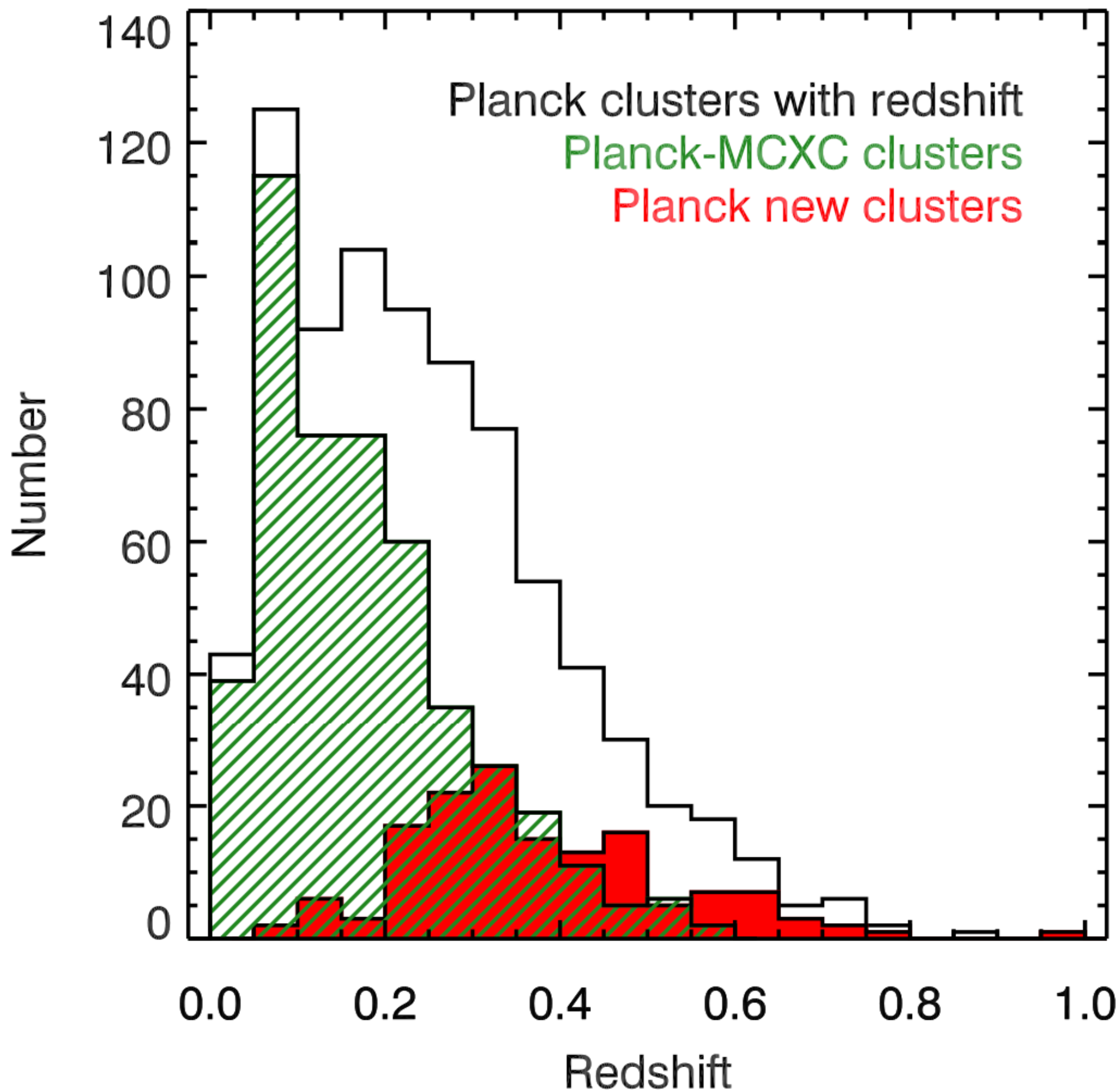


Planck vs Others





Planck cluster distribution



Primer on cosmology with numbers

$$n_i = \int_{z_i}^{z_{i+1}} dz \frac{dN}{dz} \rightarrow \frac{dN}{dz} = \int d\Omega \int dM_{500}\, \hat{\chi}(z, M_{500}, l, b)\, \frac{dN}{dz\, dM_{500}\, d\Omega}$$

Completeness

$$\hat{\chi} = \int dY_{500} \int d\theta_{500} P(z, M_{500}|Y_{500}, \theta_{500})\, \chi(Y_{500}, \theta_{500}, l, b)$$

$$\frac{dN}{dM_{500}}(M_{500}, z) = f(\sigma)\, \frac{\rho_m(z=0)}{M_{500}}\, \frac{d \ln \sigma^{-1}}{dM_{500}}$$

$$\sigma^2 = \frac{1}{2\pi^2} \int dk\, k^2 P(k,z) |W(kR)|^2$$

$$f(\sigma) = A \left[1 + \left(\frac{\sigma}{b} \right)^{-a} \right] \exp\left(-\frac{c}{\sigma^2} \right)$$

Cluster Cosmo – Can't avoid astrophysics

Scaling

$$E^{-\beta}(z)\left[\frac{D_{\mathrm{A}}^{2}(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^{2}}\right] = Y_{*}\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,\mathrm{M}_{\mathrm{sol}}}\right]^{\alpha}$$

Distribution

$$\mathcal{P}(\log Y_{500}) = \frac{1}{\sqrt{2\pi\sigma_{\log Y}^{2}}}\exp\left[-\frac{\log^{2}(Y_{500}/\bar{Y}_{500})}{2\sigma_{\log Y}^{2}}\right]$$

Selection/
Completeness

$$\chi_{\mathrm{erf}}(Y_{500},\theta_{500},l,b) = \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{Y_{500}-X\,\sigma_{Y_{500}}(\theta_{500},l,b)}{\sqrt{2}\,\sigma_{Y_{500}}(\theta_{500},l,b)}\right)\right]$$

Noise

$$\sigma_{Y_{500}}(\theta_{500},l,b) = \left[\int d^{2}k\,\boldsymbol{F}^{t}_{\theta_{500}}(\boldsymbol{k})\cdot\boldsymbol{P}^{-1}(\boldsymbol{k},l,b)\cdot\boldsymbol{F}_{\theta_{500}}(\boldsymbol{k})\right]^{-1/2}$$

The Algorithm

We want from the SZ maps $Y_{500} - M_{500}$

We use from Xray obs $Y^X_{500} = M^X_g T^X$

To get $Y^X_{500} - M^X_{500}$

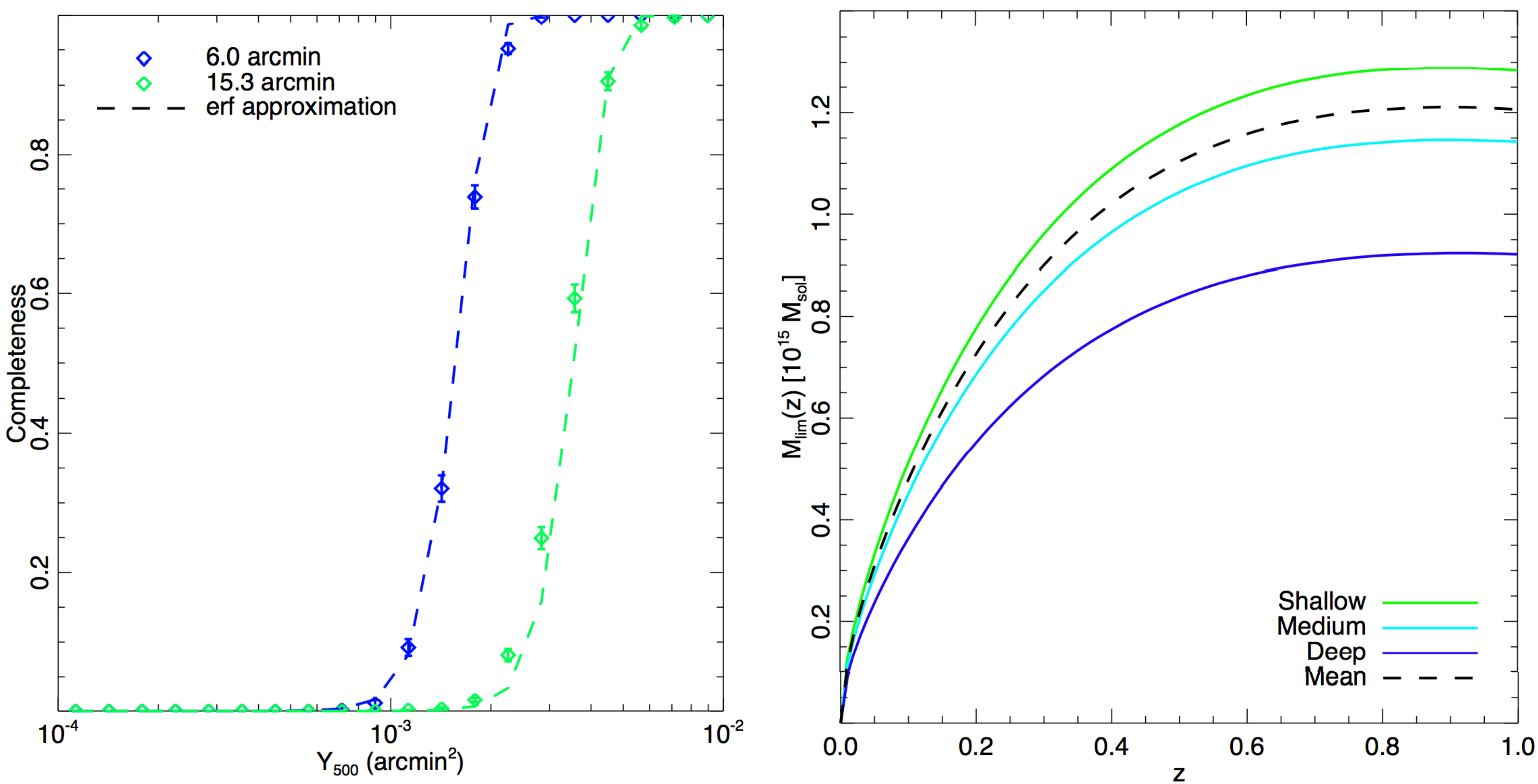
$M^X_{500} - R^X_{500}$

But, then

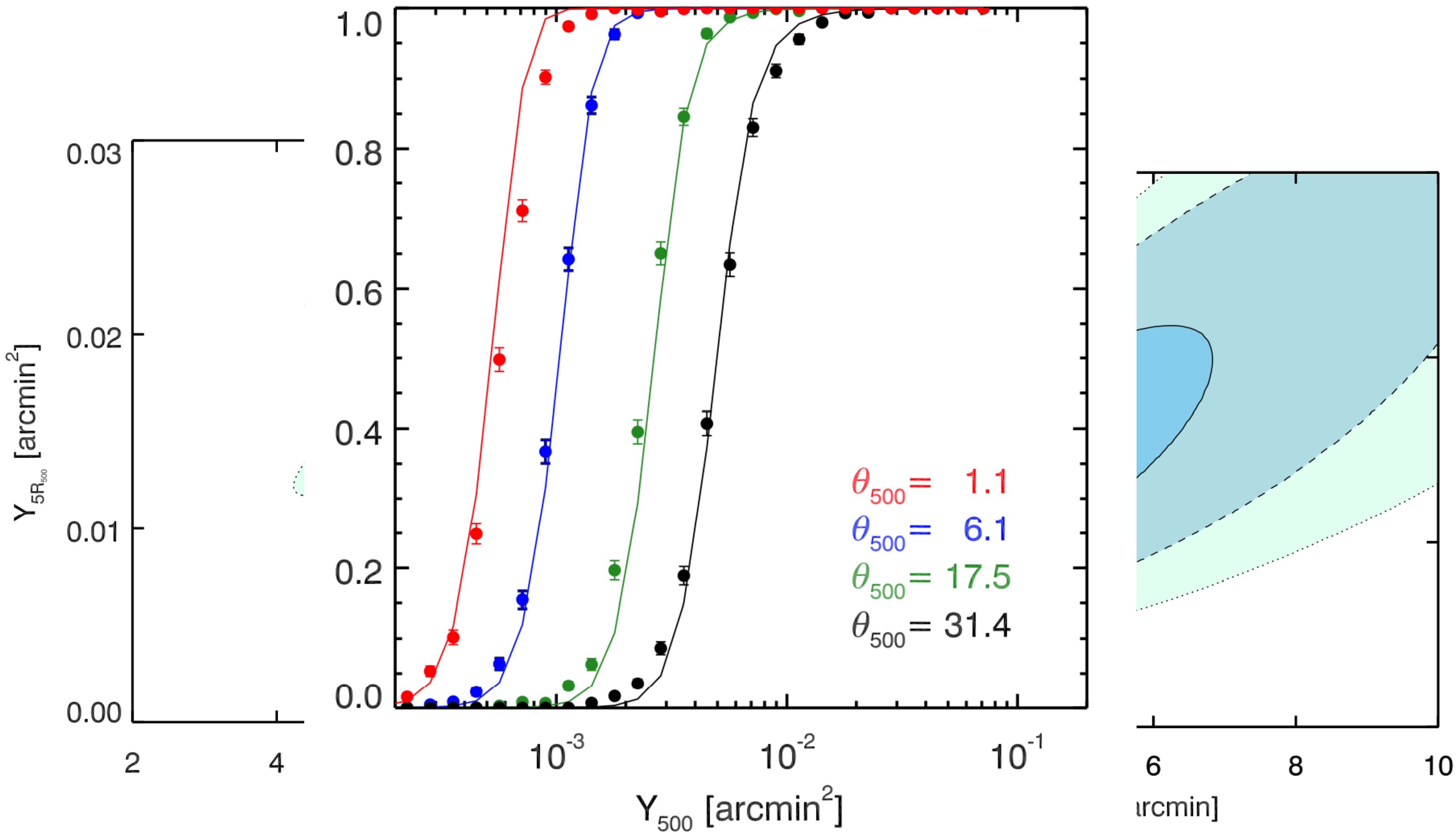
$$M_{500}^{\rm obs} = (1-b)\, M_{500}^{\rm true}\,,$$
$$R_{500}^{\rm obs} = (1-b)^{1/3}\, R_{500}^{\rm true}$$

Mass bias calibrated from simulations

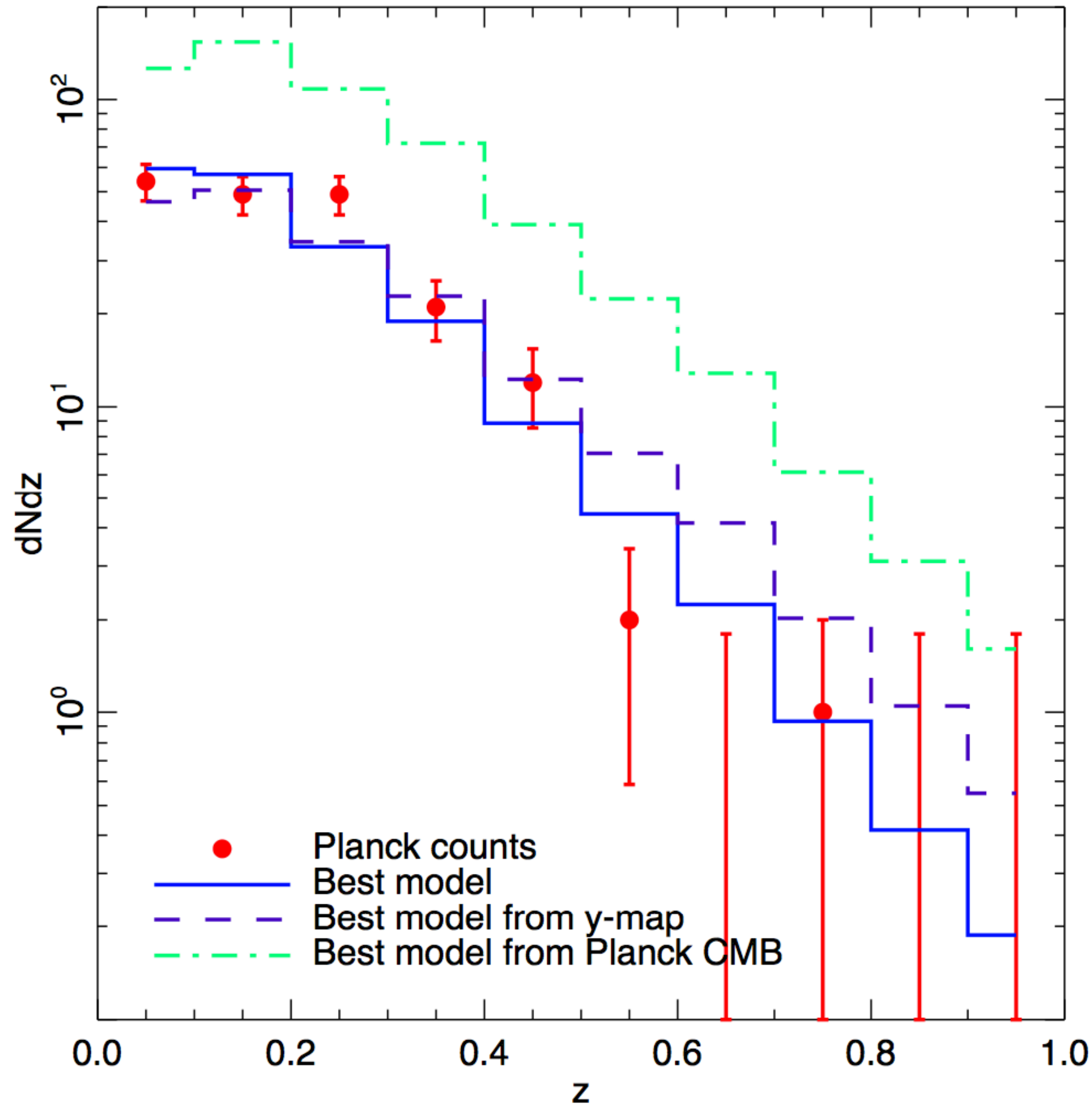
Real world has noise and we need to worry about completeness



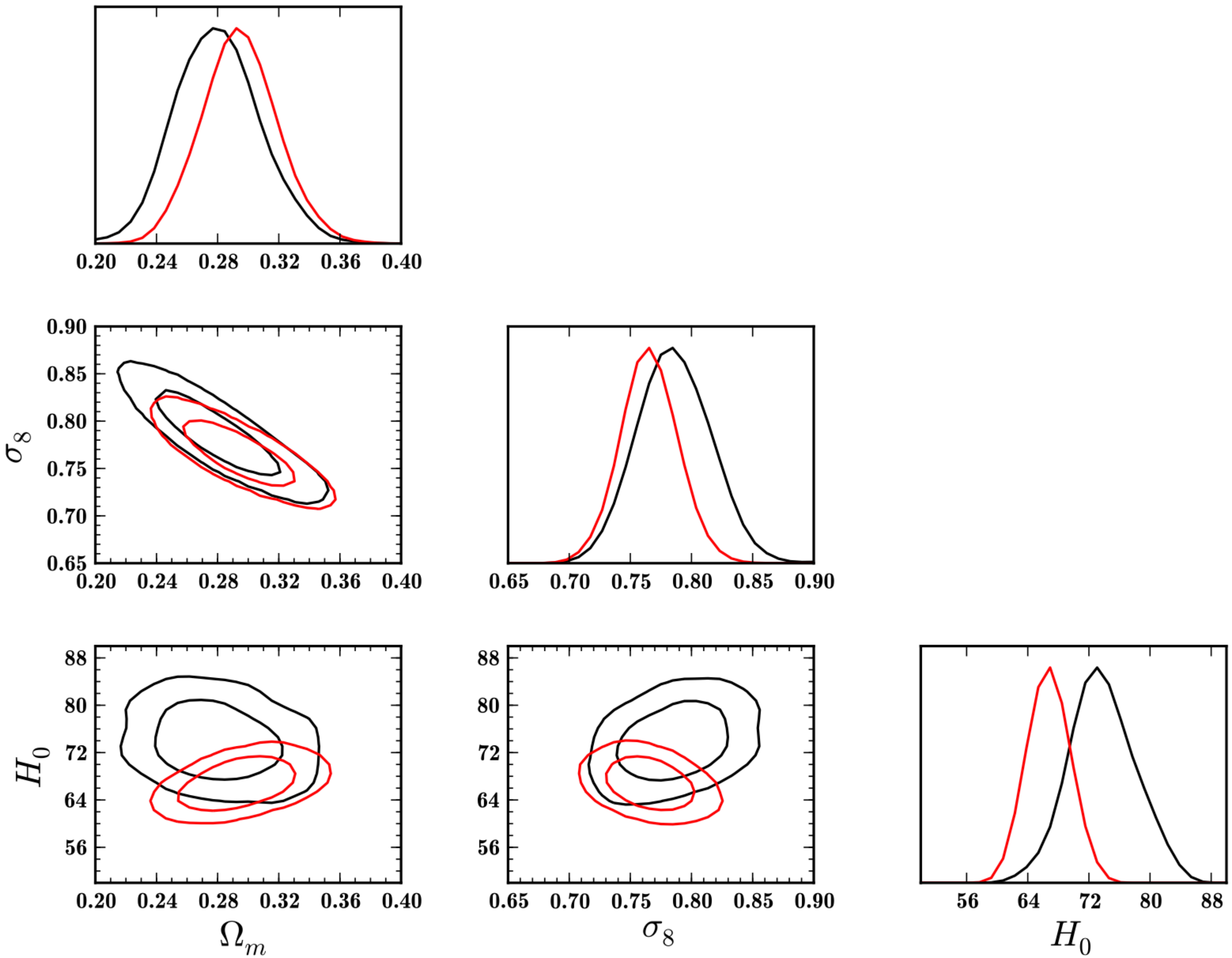
Completeness Issues



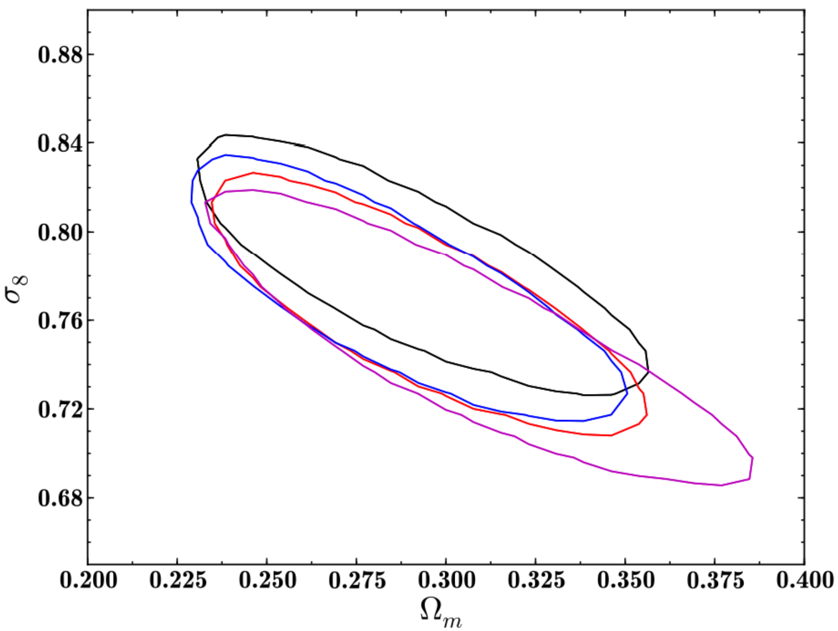
Number counts and bestfits



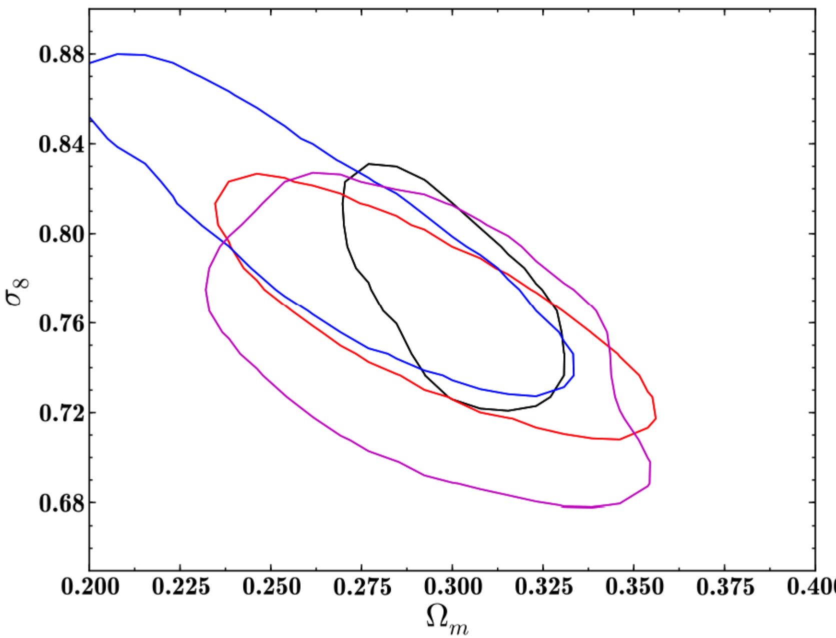
Cluster cosmology



Checks on systematics



S/N and algorithm



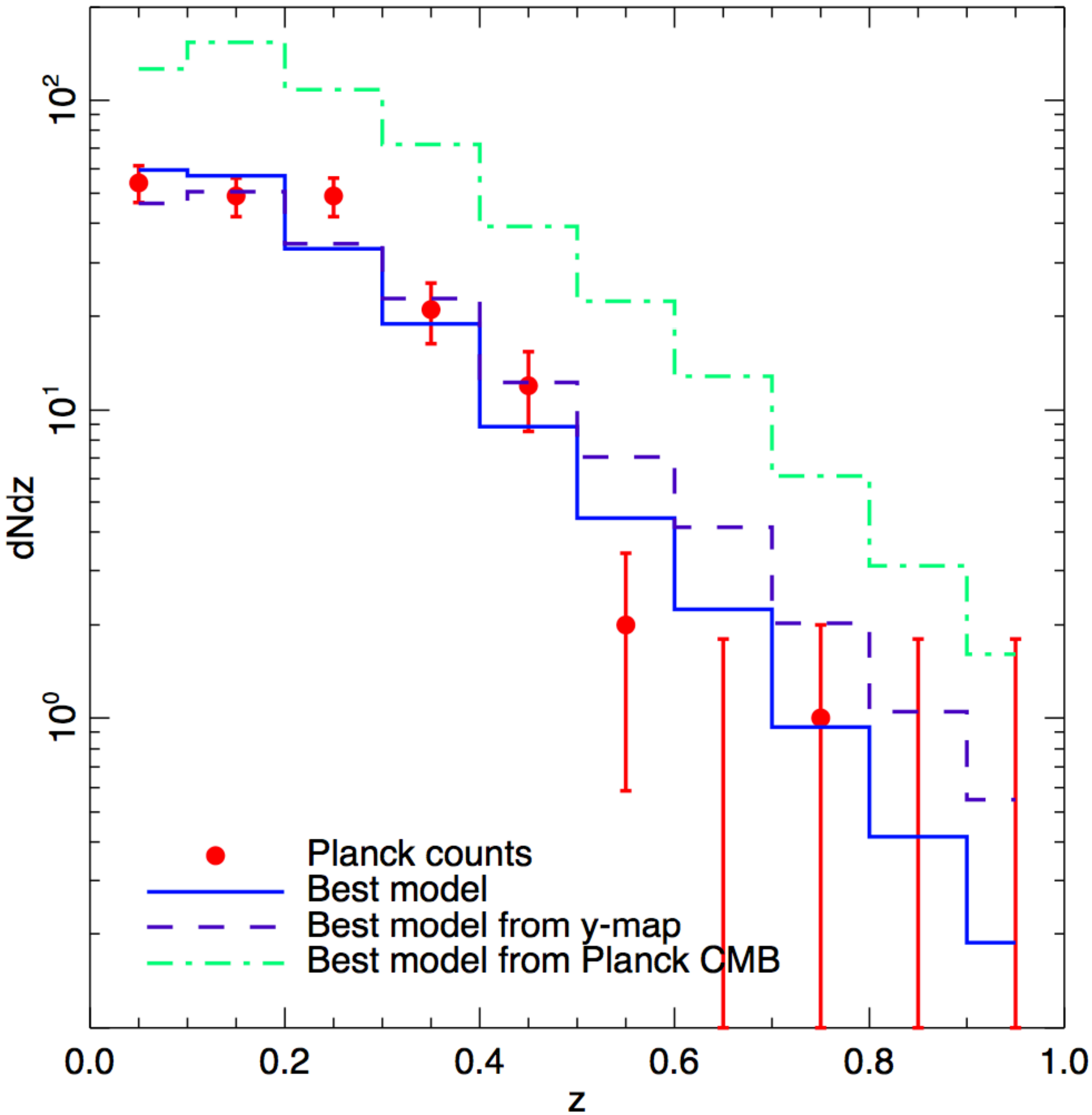
Mass bias and Mass function

The number problem

	$\sigma_8(\Omega_m/0.27)^{0.3}$	Ω_m	σ_8	$1-b$
Planck SZ +BAO+BBN	0.782 ± 0.010	0.29 ± 0.02	0.77 ± 0.02	0.8
Planck SZ +HST+BBN	0.792 ± 0.012	0.28 ± 0.03	0.78 ± 0.03	0.8
MMF1 sample +BAO+BBN	0.800 ± 0.010	0.29 ± 0.02	0.78 ± 0.02	0.8
MMF3 S/N > 8 +BAO+BBN	0.785 ± 0.011	0.29 ± 0.02	0.77 ± 0.02	0.8
Planck SZ +BAO+BBN (MC completeness)	0.778 ± 0.010	0.30 ± 0.03	0.75 ± 0.02	0.8
Planck SZ +BAO+BBN (Watson et al. mass function)	0.802 ± 0.014	0.30 ± 0.01	0.77 ± 0.02	0.8
Planck SZ +BAO+BBN ($1-b$ in [0.7, 1.0])	0.764 ± 0.025	0.29 ± 0.02	0.75 ± 0.03	[0.7,1]

Both σ_8 and Ω_M are higher from Planck CMB analysis !!

Planck vs Planck



The y-sky and SZ Cl (Theory Space)

Planck SZ works with the 'Halo Model' → $C_\ell^{SZ} = C_\ell^{1halo} + C_\ell^{2halos}$

$$C_\ell^{1halo} = \int_0^{z_{max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{min}}^{M_{max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|^2$$

$$\tilde{y}_\ell(M,z) = \frac{4\pi r_s}{l_s^2} \left(\frac{\sigma_T}{m_e c^2}\right) \int_0^\infty dx\, x^2 P_e(M,z,x) \frac{\sin(\ell_x/\ell_s)}{\ell_x/\ell_s}$$

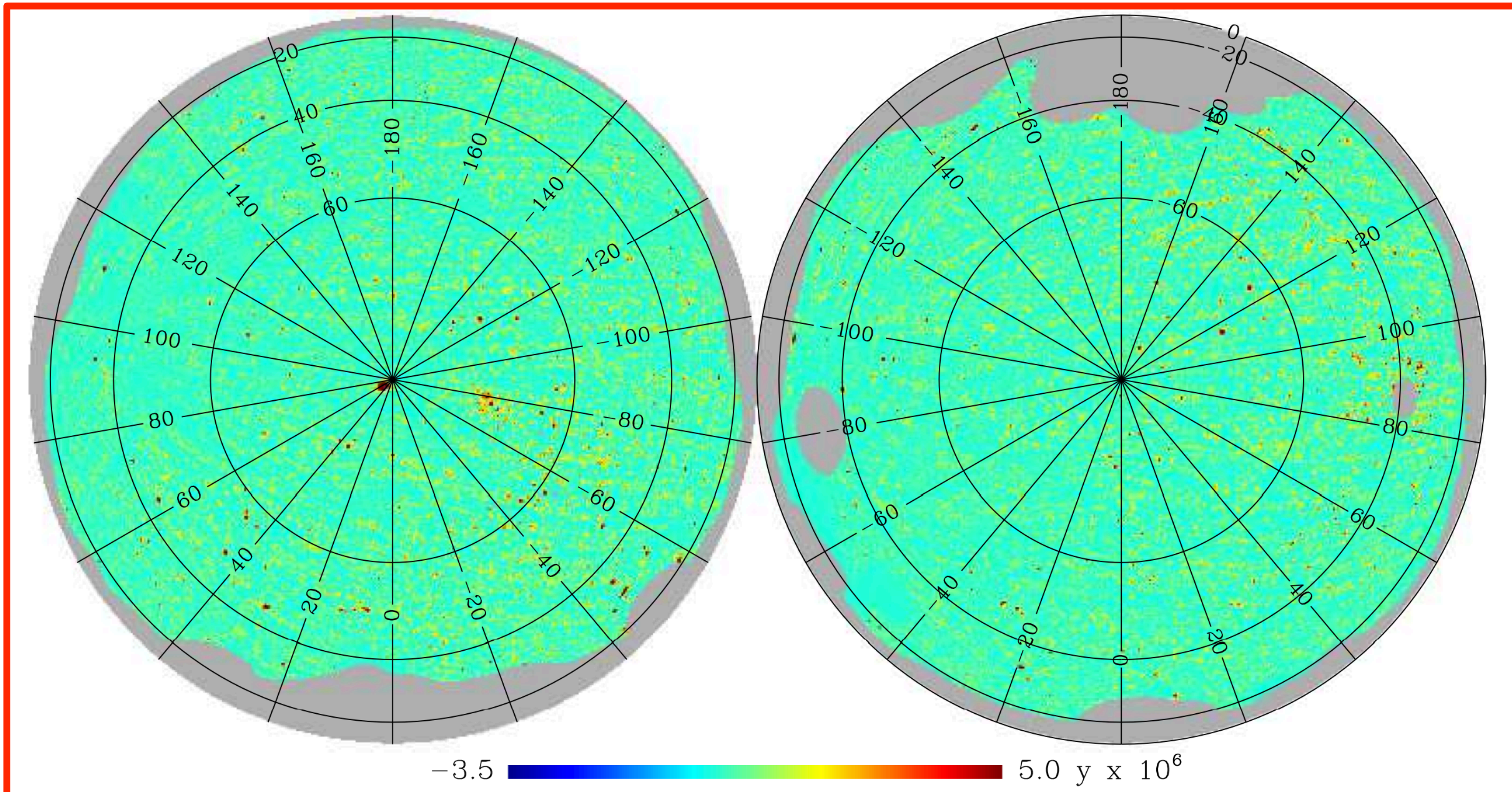
$$x = r/r_s,\ \ell_s = D_A(z)/r_s$$

$$C_\ell^{2halos} = \int_0^{z_{max}} dz \frac{dV_c}{dz d\Omega} \times \left(\int_{M_{min}}^{M_{max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|\ B(M,z)\right)^2 P(k,z)$$

$$1 + (\nu^2(M,z) - 1)/\delta_c(z)$$

$$\nu(M,z) = \delta_c(M)/D(z)\sigma(M)$$

The y-sky and SZ Cl (in Planck data)



$$C_\ell^{\mathrm{m}} = C_\ell^{\mathrm{tSZ}}(\Omega_{\mathrm{m}}, \sigma_8) + A_{\mathrm{CIB}}\, C_\ell^{\mathrm{CIB}} + A_{\mathrm{PS}}\,(C_\ell^{\mathrm{IR}} + C_\ell^{\mathrm{Rad}})$$

'Other' statistics of the y-sky (Theory Space)

N-point pdf (Halo model) →

$$\int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} \int d^2\theta \, y(\theta, M, z)^N$$

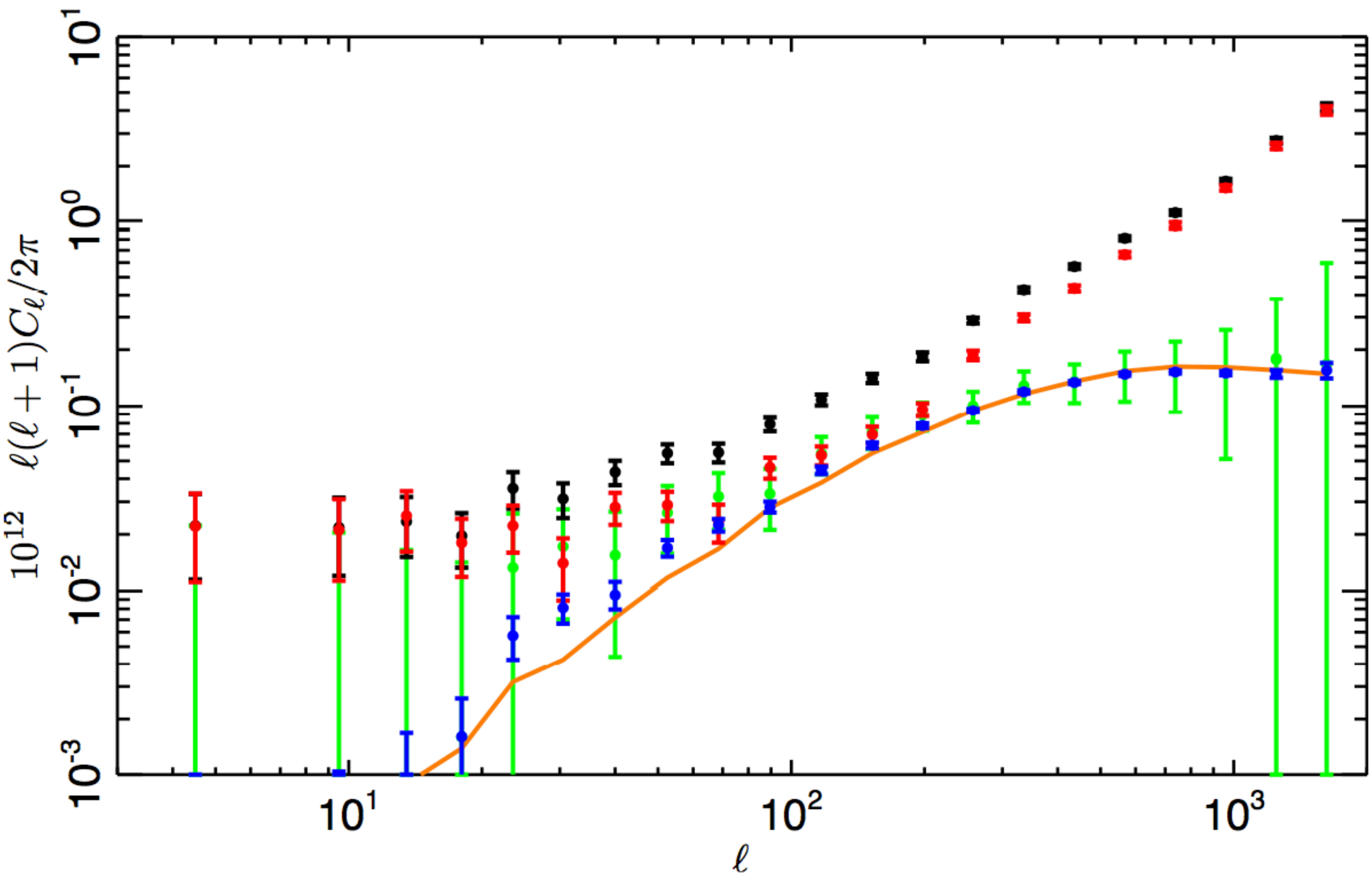
3-point stats/ Bispectrum →

$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} = \langle y_{\ell_1 m_1} y_{\ell_2 m_2} y_{\ell_3 m_3} \rangle$$

$$B(\ell_1 \ell_2 \ell_3) = \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$$

$$B(\ell_1 \ell_2 \ell_3) \simeq \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}{4\pi}} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} \tilde{y}_{\ell_1}(M,z) \tilde{y}_{\ell_2}(M,z) \tilde{y}_{\ell_3}(M,z)$$

SZ Power Spectrum & Contaminants

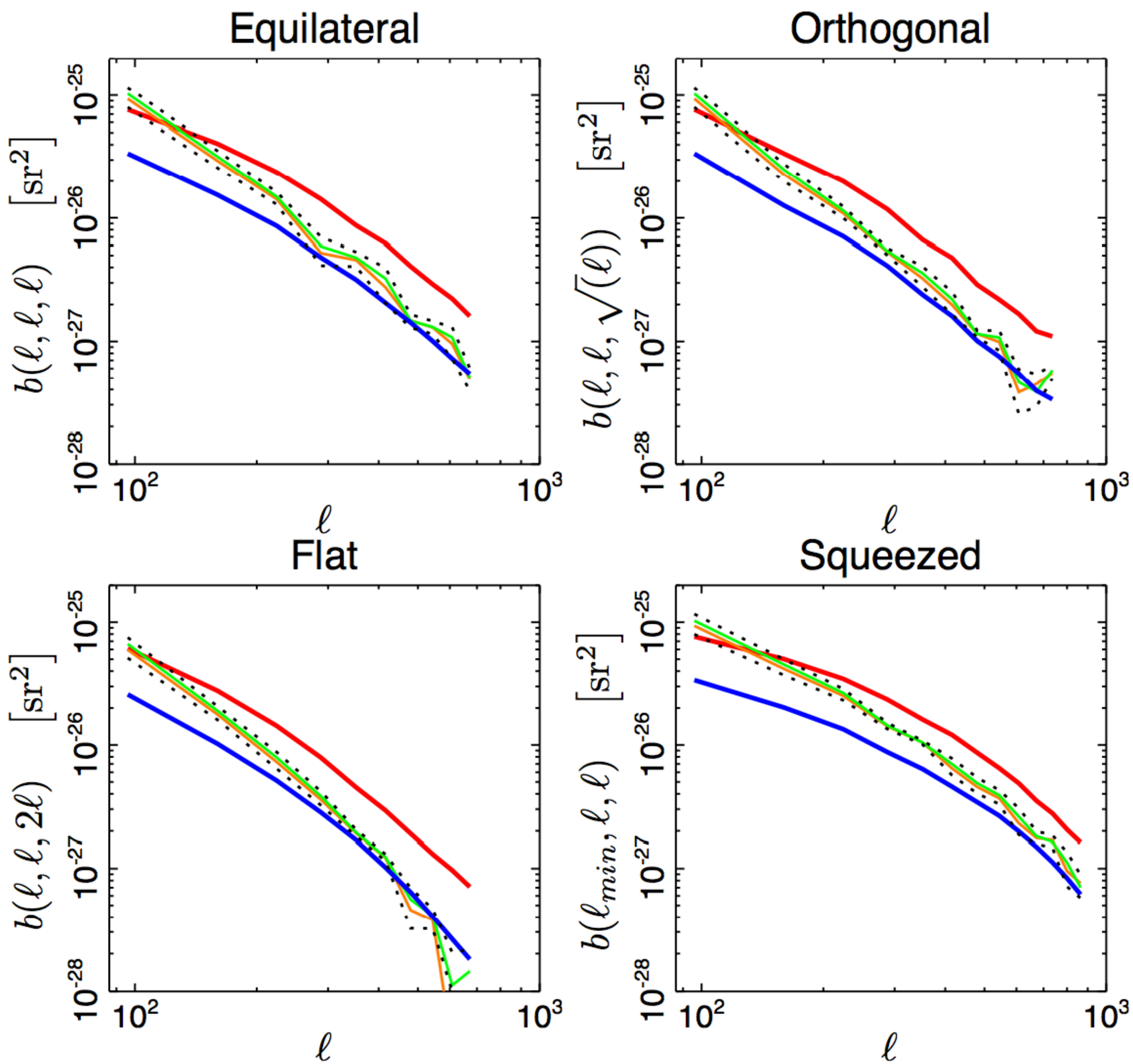


Planck simulations

Halo model and observed Cl

Planck data

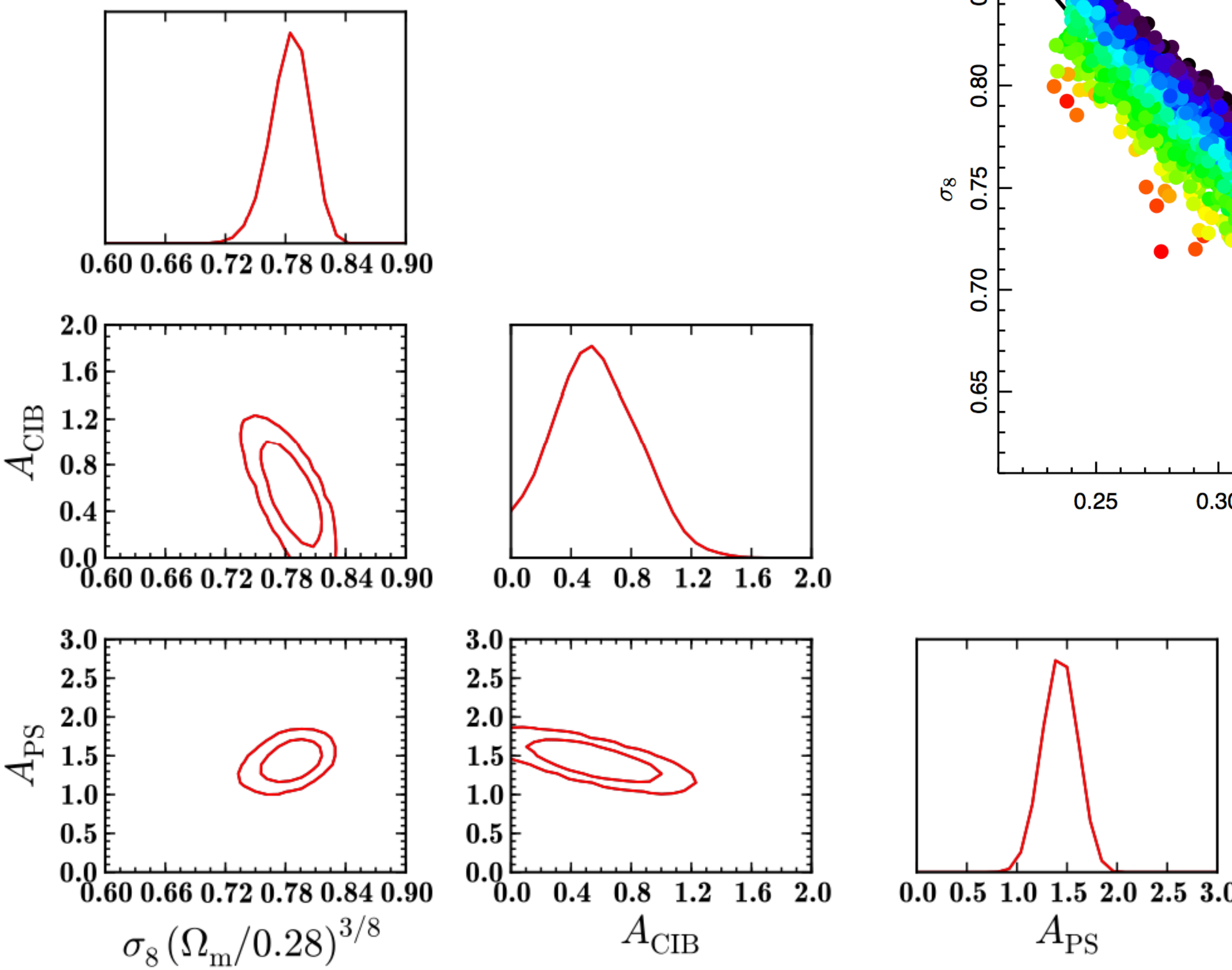
The observed stats of the SZ sky

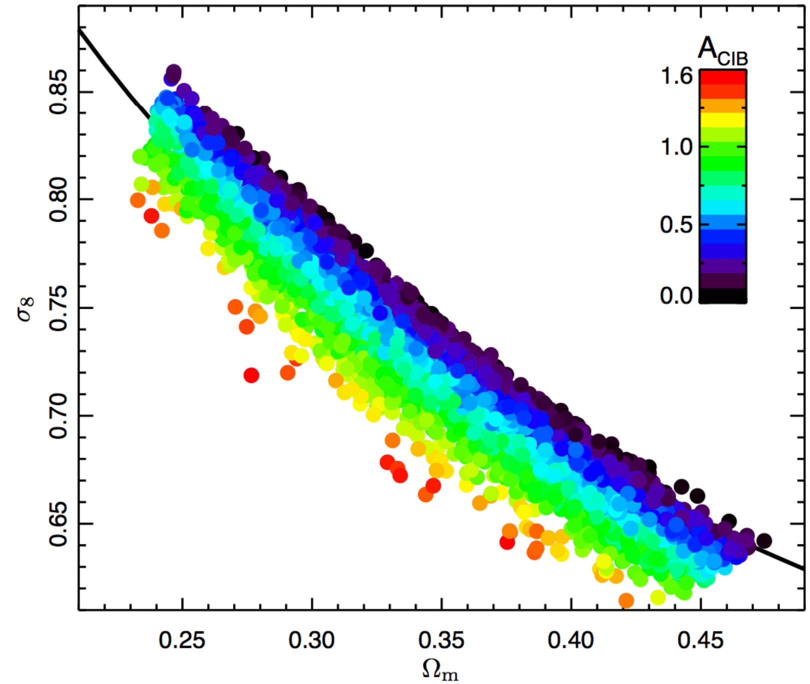


..and Bispectrum (no primordial fNL)

Theory

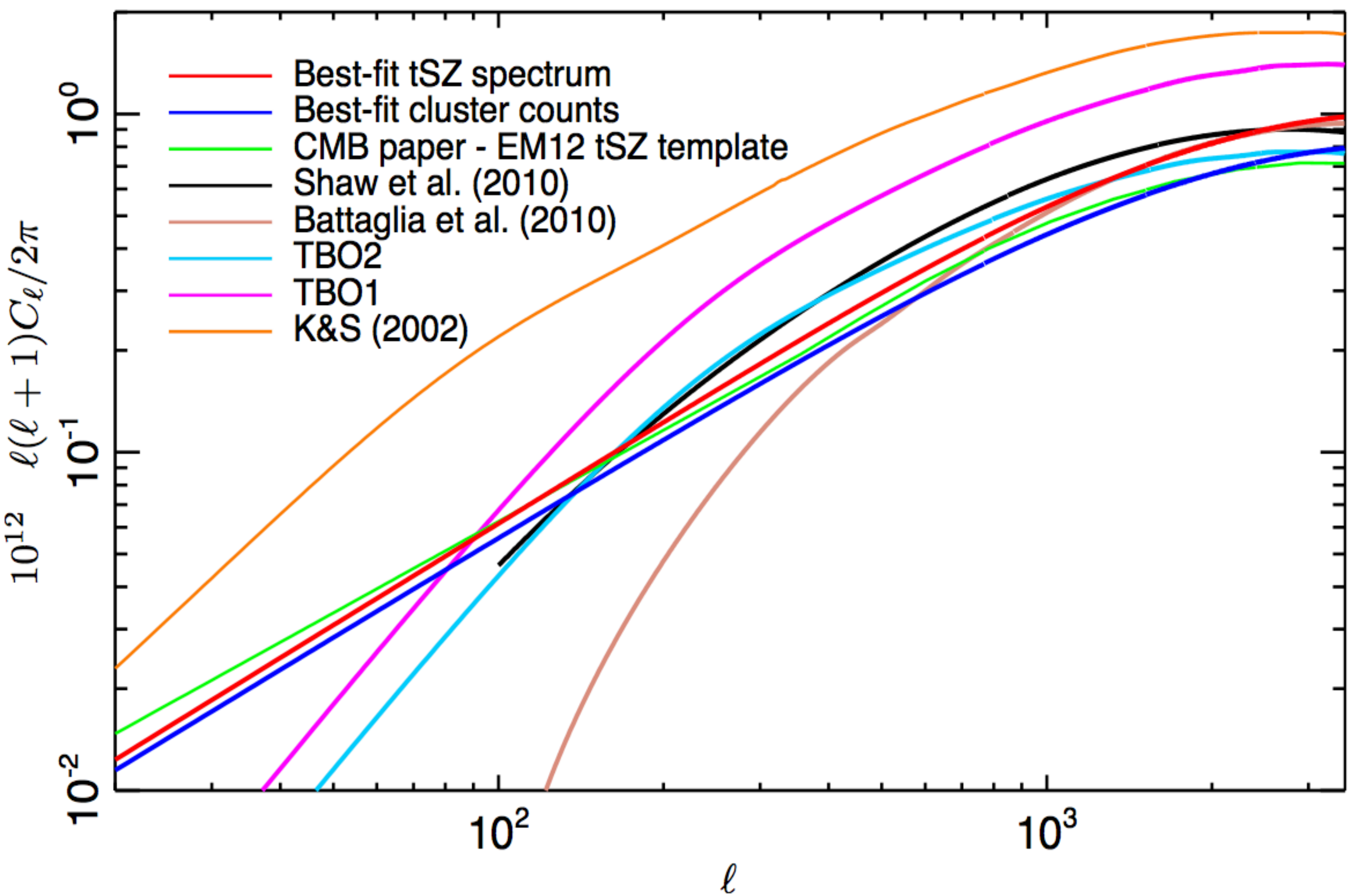
On to Cosmology...



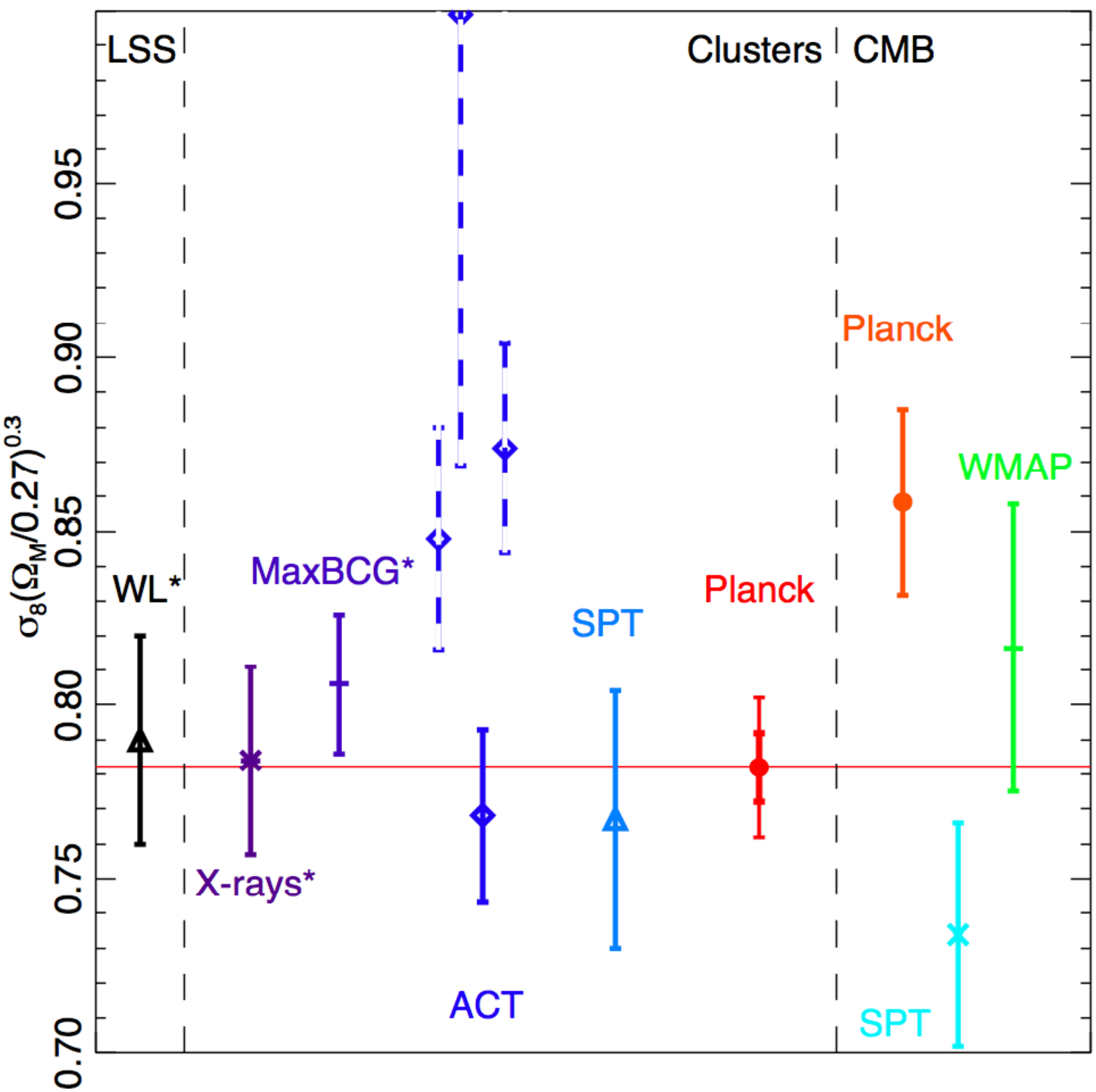


$\sigma_8 = 0.74 \pm 0.06,\ \Omega_m = 0.33 \pm 0.06$

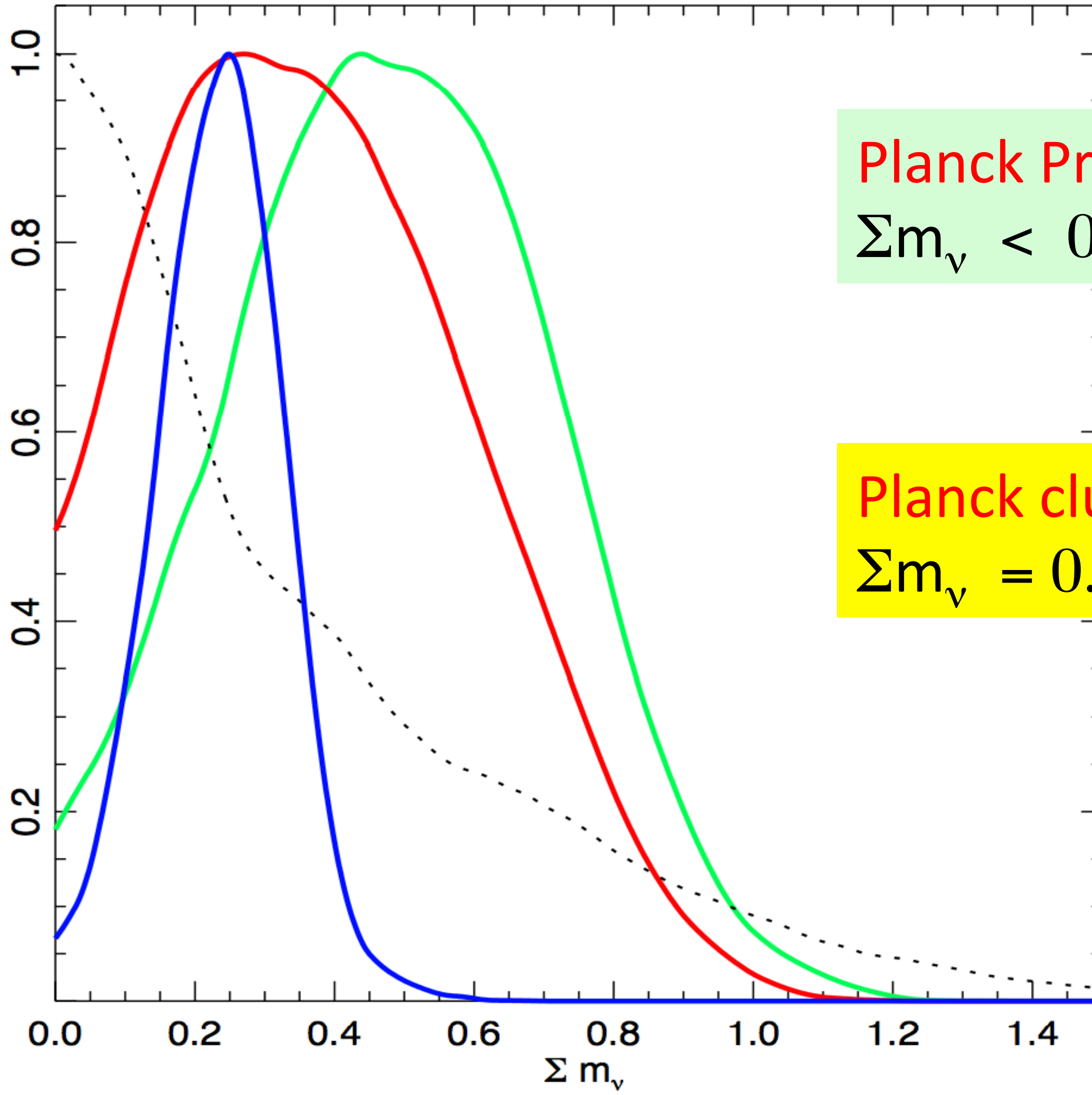
Bestfit models vs Observation



CMB vs non-CMB



Reconciliation?



Planck Primary

$\Sigma m_\nu < 0.93$ eV

Planck clusters

$\Sigma m_\nu = 0.22 +/- 0.09$ eV

Why do SZ cosmology or cluster cosmology?

Cosmology is the study of our Universe and primary CMB is snapshot when Universe was 0.002% of present age !

Clusters/SZ probes structures.

Can potentially probe Inflation models in greater detail, say dn_s/dk

Also, look at the very strong cosmological param dependence

$C_l \sim \sigma_8^{7\text{-}8}$

Bispectrum $\sim \sigma_8^{11\text{-}12}$

Small f_{NL} but still still can have large g_{NL} ☺

And then there is Neutrinos and Dark Energy ☺☺

Thanks