# Cross-correlation of the 2MASS Galaxies with the thermal SZ Effect


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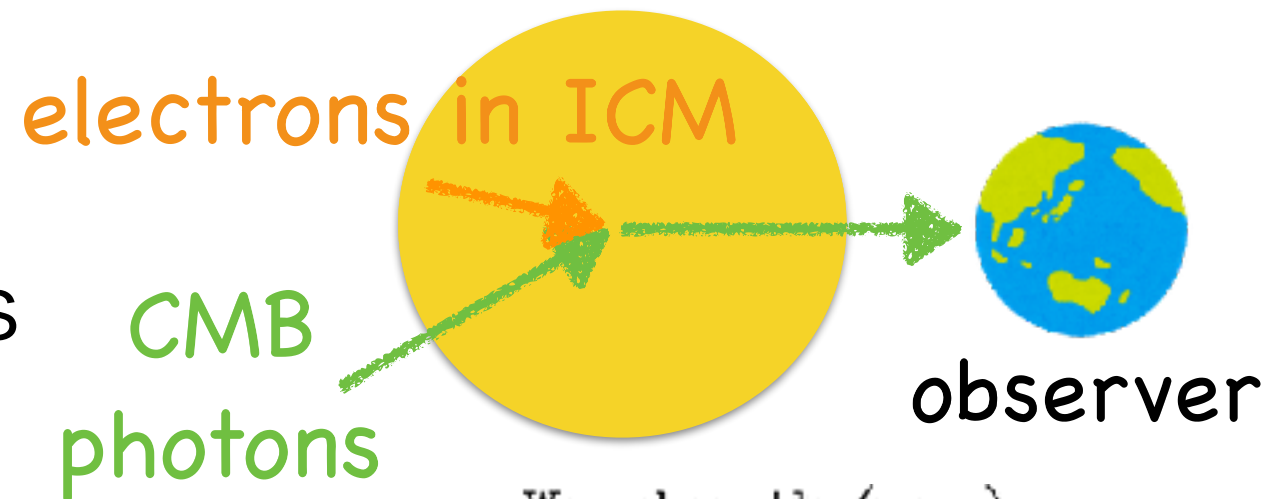
# The thermal Sunyaev-Zel'dovich (tSZ) Effect

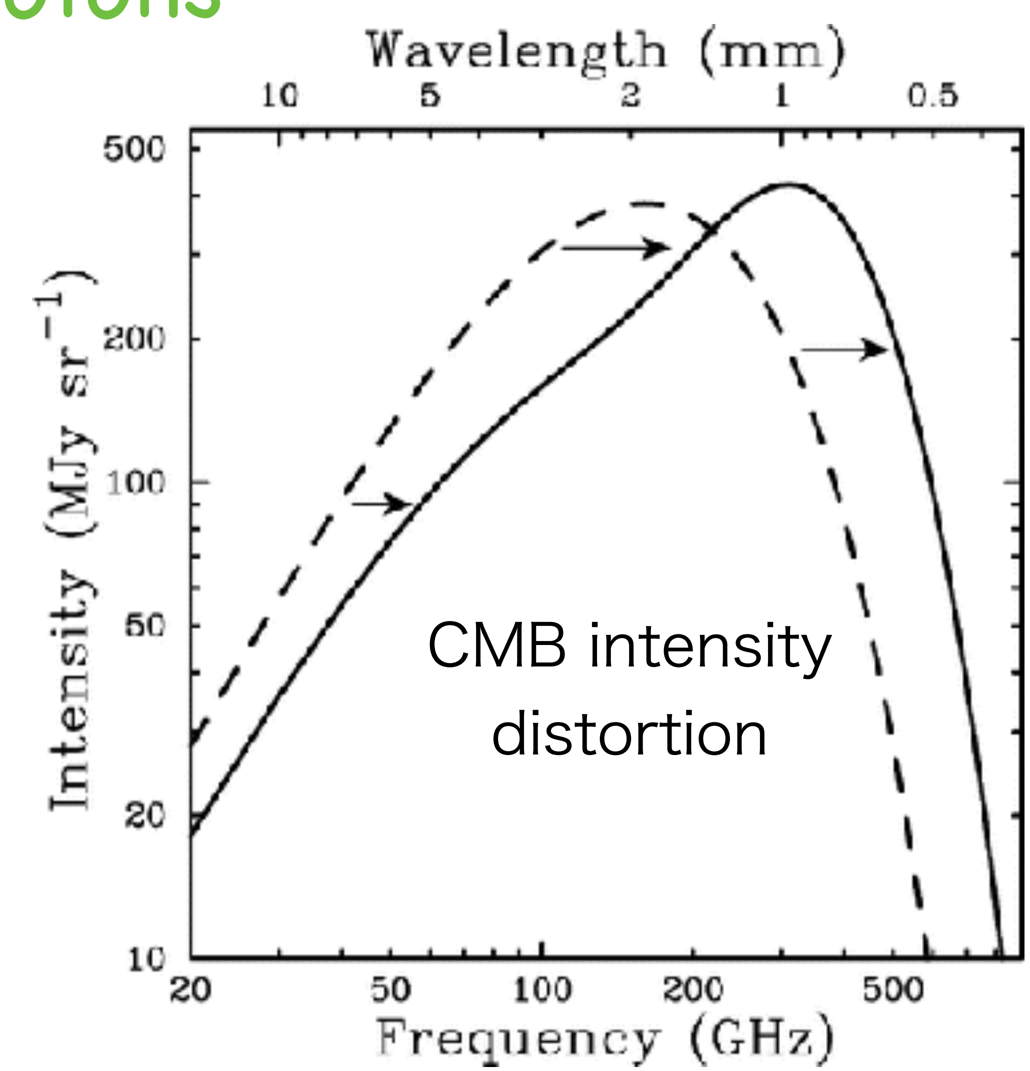
(Sunyaev & Zel'dovich 1972)

- Cosmic microwave background (CMB) photons are inverse Compton scattered by energetic electrons in ICM

- Characterized by the Compton-y parameter

$$\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} = f_\nu(x) \underbrace{\left(\frac{k_B \sigma_T}{m_e c^2}\right) \int n_e(l) T(l) dl}_{\text{Compton-y}}$$

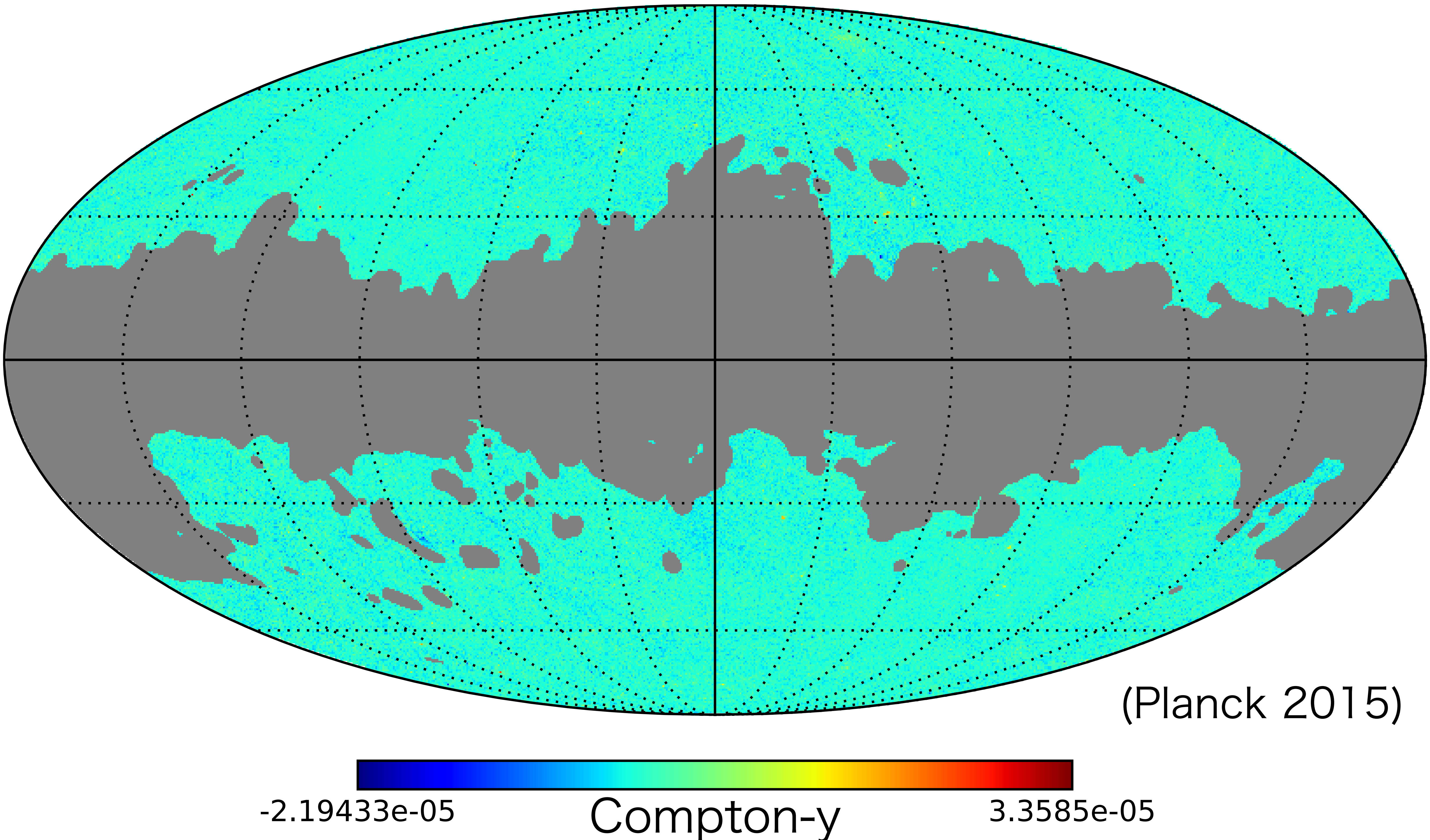


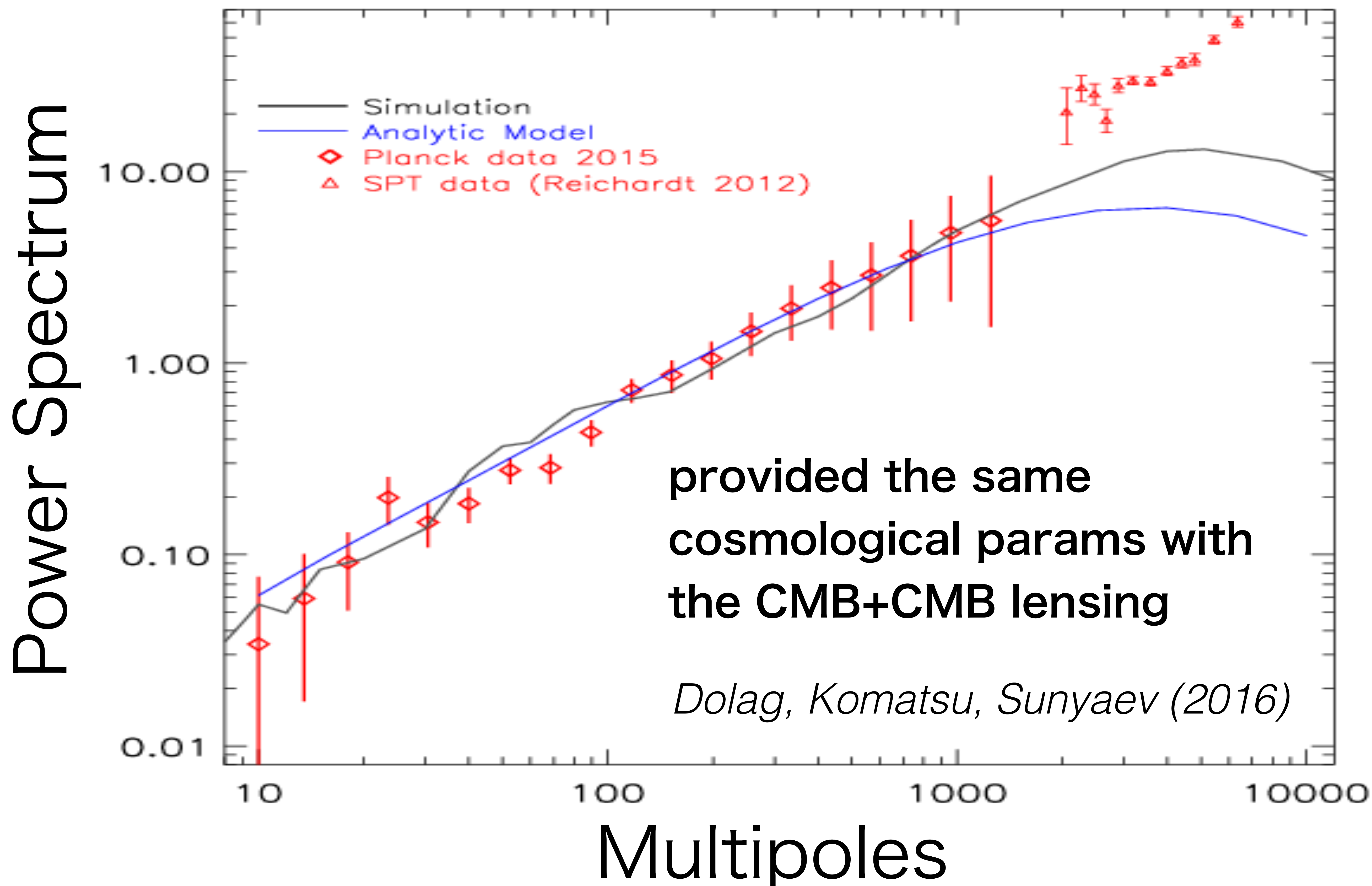

(Carlstrom et al. 2002)

# Full-sky Map of ALL HOT GAS

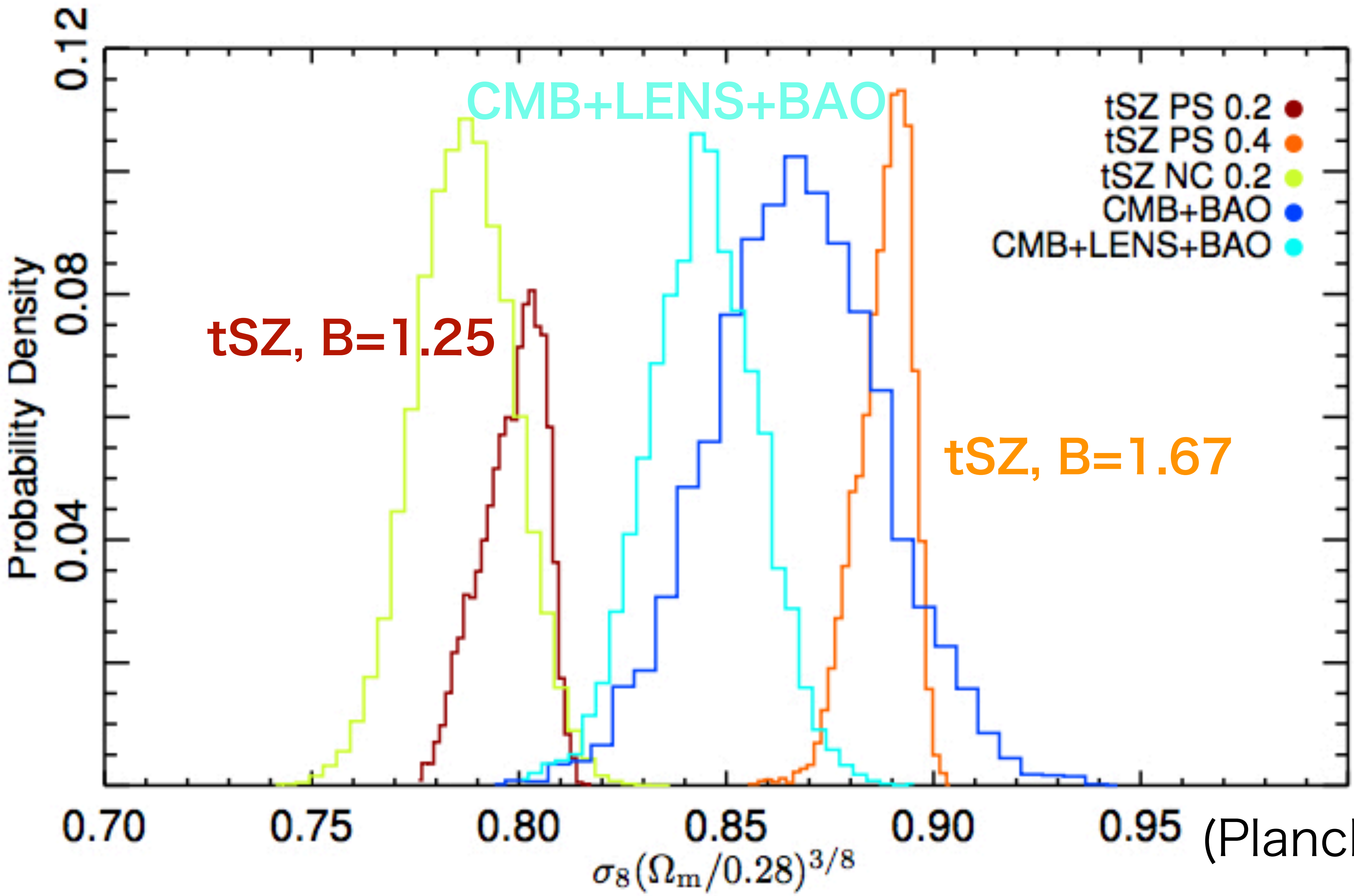
# [z<1]



# The ΛCDM fits!



# Constraint on the cosmological params



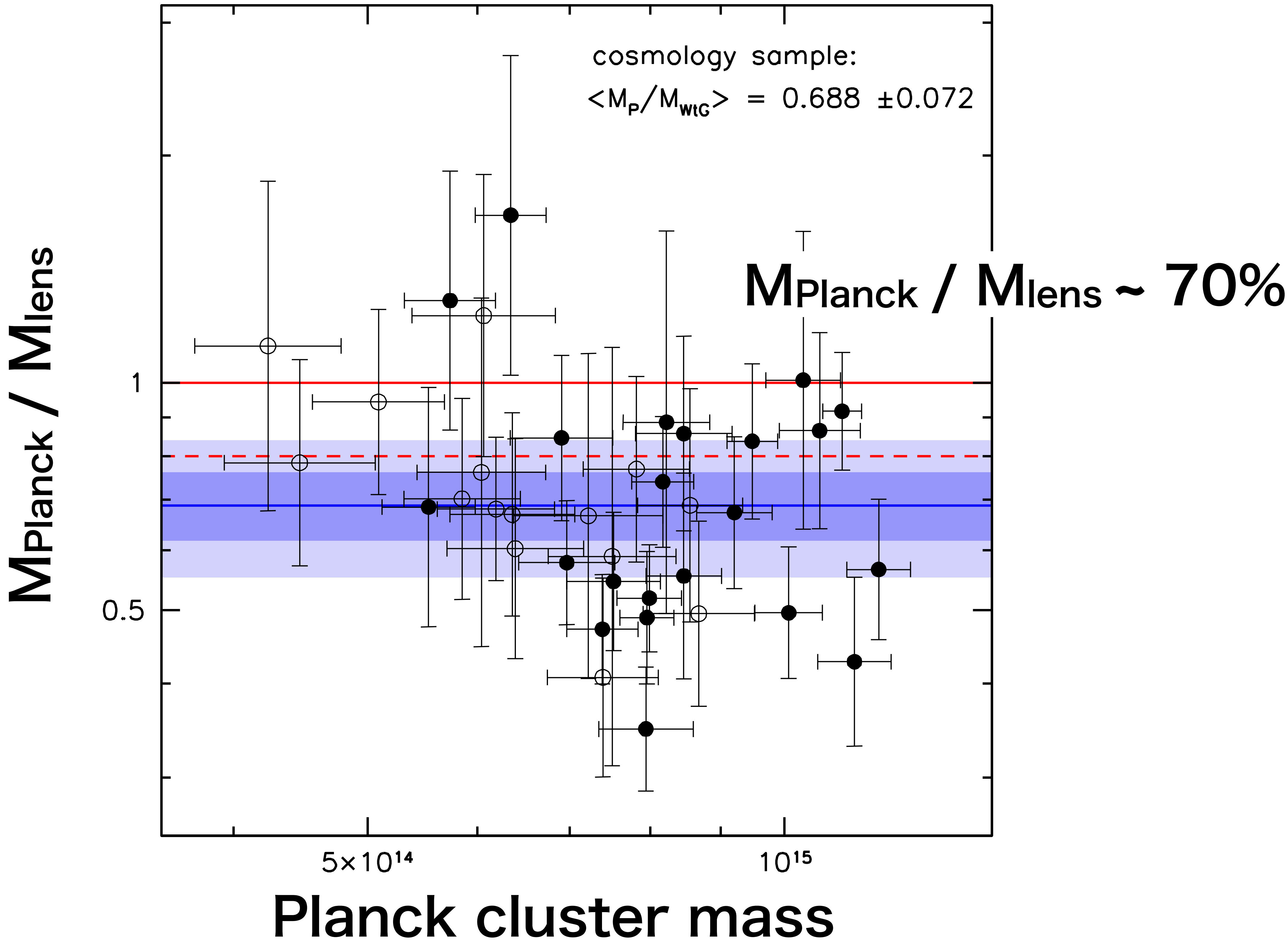

(Planck 2015)

- tSZ amplitude is a sensitive probe of $\sigma_8\Omega_m$
- However strongly degenerate with the mass bias B

# The mass bias

- The mass bias $B = M_{true} / M_{obs}$
- Cosmological parameters strongly degenerate with B
  - $M_{obs}$ should be ~35% lower than $M_{true}$ to reconcile with the CMB
  - Numerical simulations yield 5-20% of mass bias

# Planck cluster mass vs lensing mass




(von der Linden+ 2014)

# Questions

- Is the mass bias really originated from the gas physics (e.g., non-thermal pressure)? or due to some systematics in the observations?
- Is there any mass or redshift dependence of the mass bias?

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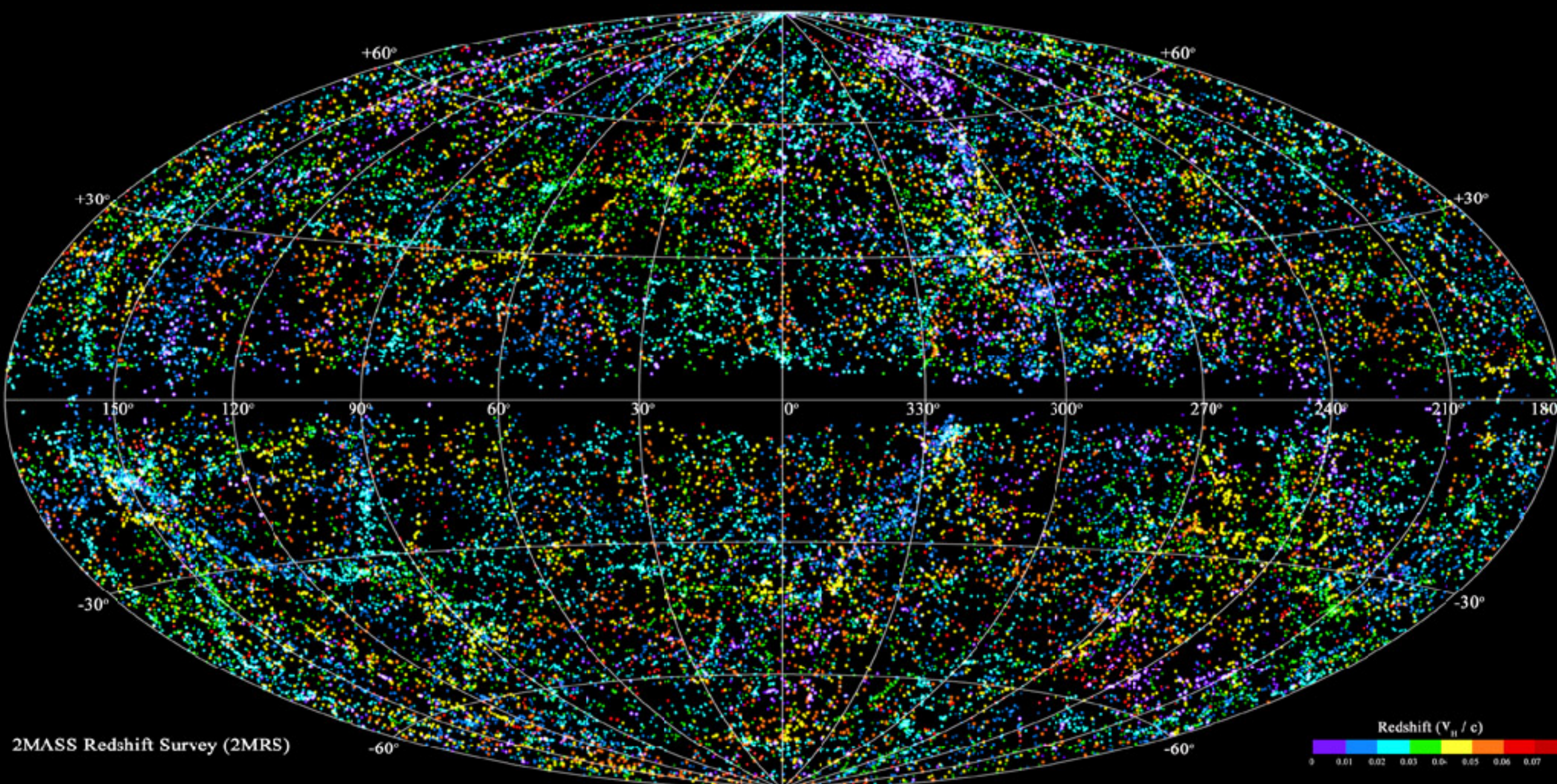
=> Cross correlation!

# This work: tSZ-2MRS cross correlation




- Go to **local universe**!
  - median z~0.03 (~0.3 for CMB lensing, ~0.1 for SDSS)

# 2MASS redshift survey (2MRS)

(Huchra et al. 2012)

- ~43,500 galaxies with spectroscopic redshifts over the full sky
  - redshift distribution peaks at $z \sim 0.03$
- Mass range of groups or clusters: $10^{11} < M_{vir}/M_{sun} < 10^{16}$

# 2MASS redshift survey (2MRS)

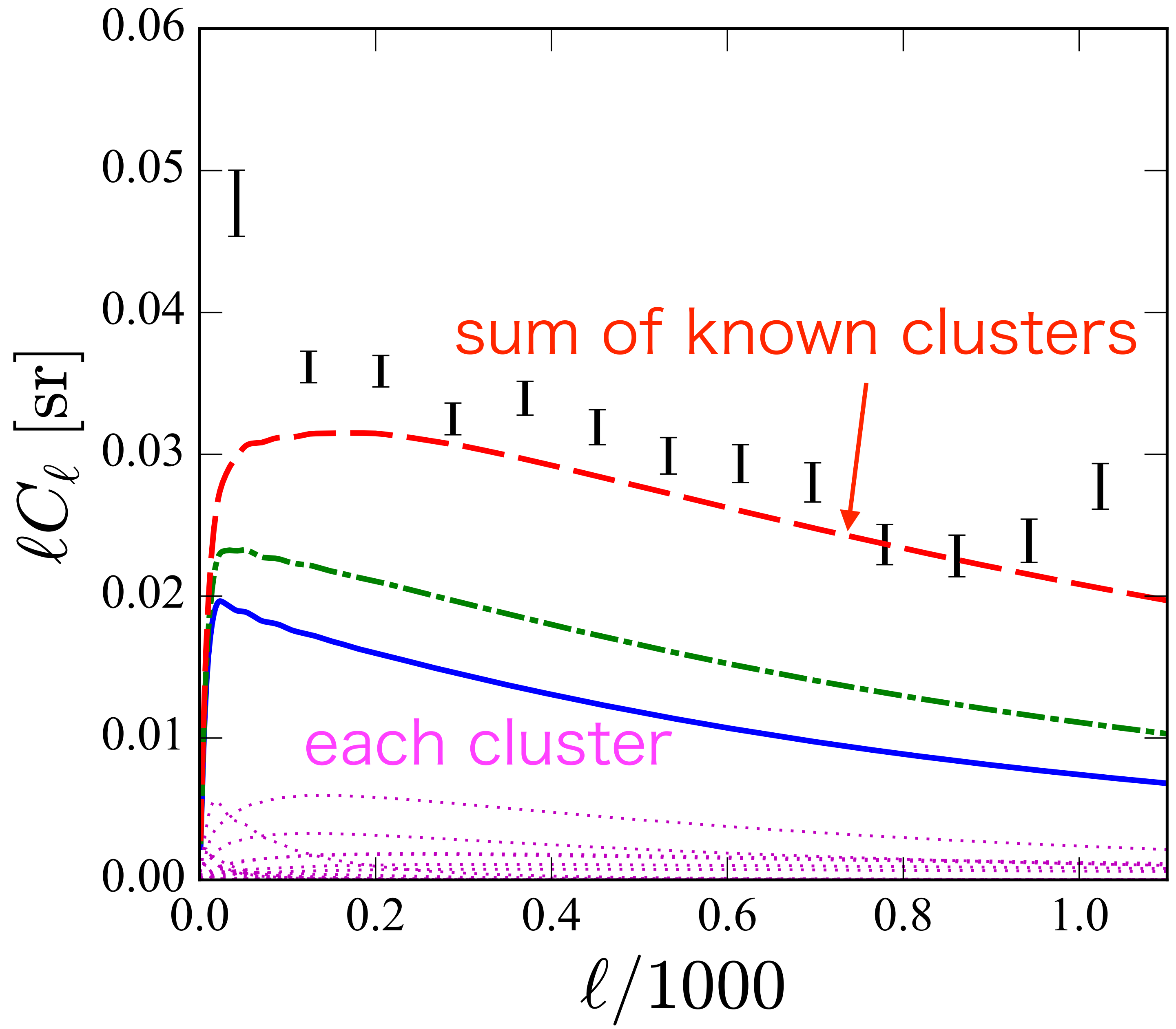
(Huchra et al. 2012)

- What can we learn?
  - **Gas physics in the local universe**
    — How do local galaxies trace gas?
  - would provide a great constraint on “the local universe simulation” (e.g. Dolag, Komatsu & Sunyaev 2016; Nuza, Dolag & Saro 2010)

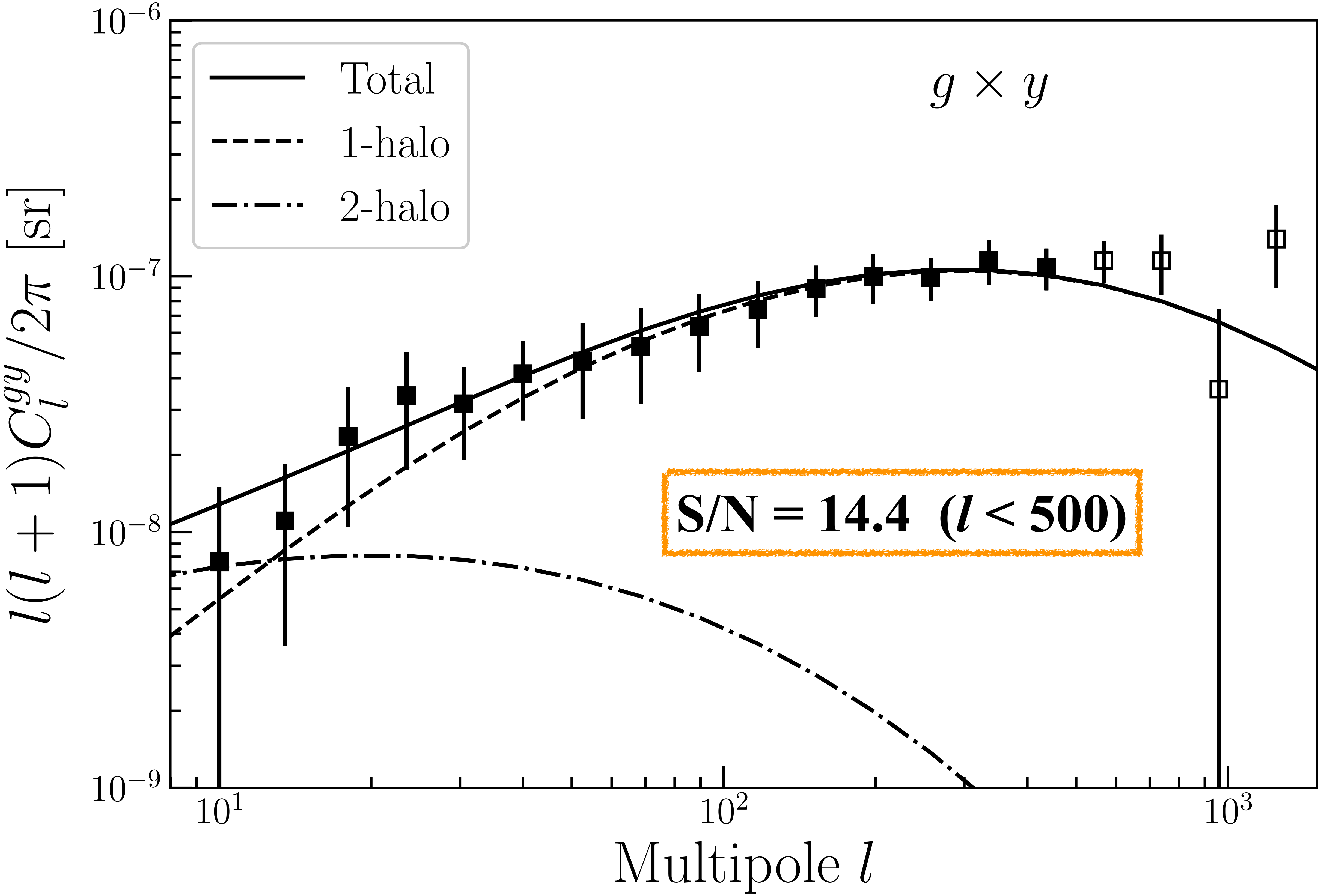
# The 2MRS auto-power spectrum

## (Ando et al. 2018)

- Surprisingly, significantly detected even at large multipoles
  - despite ~1 galaxy/deg$^2$
- It is almost completely explained by the contributions from known groups and clusters
  - good for tracing SZ!



# The tSZ x 2MRS cross-power spectrum



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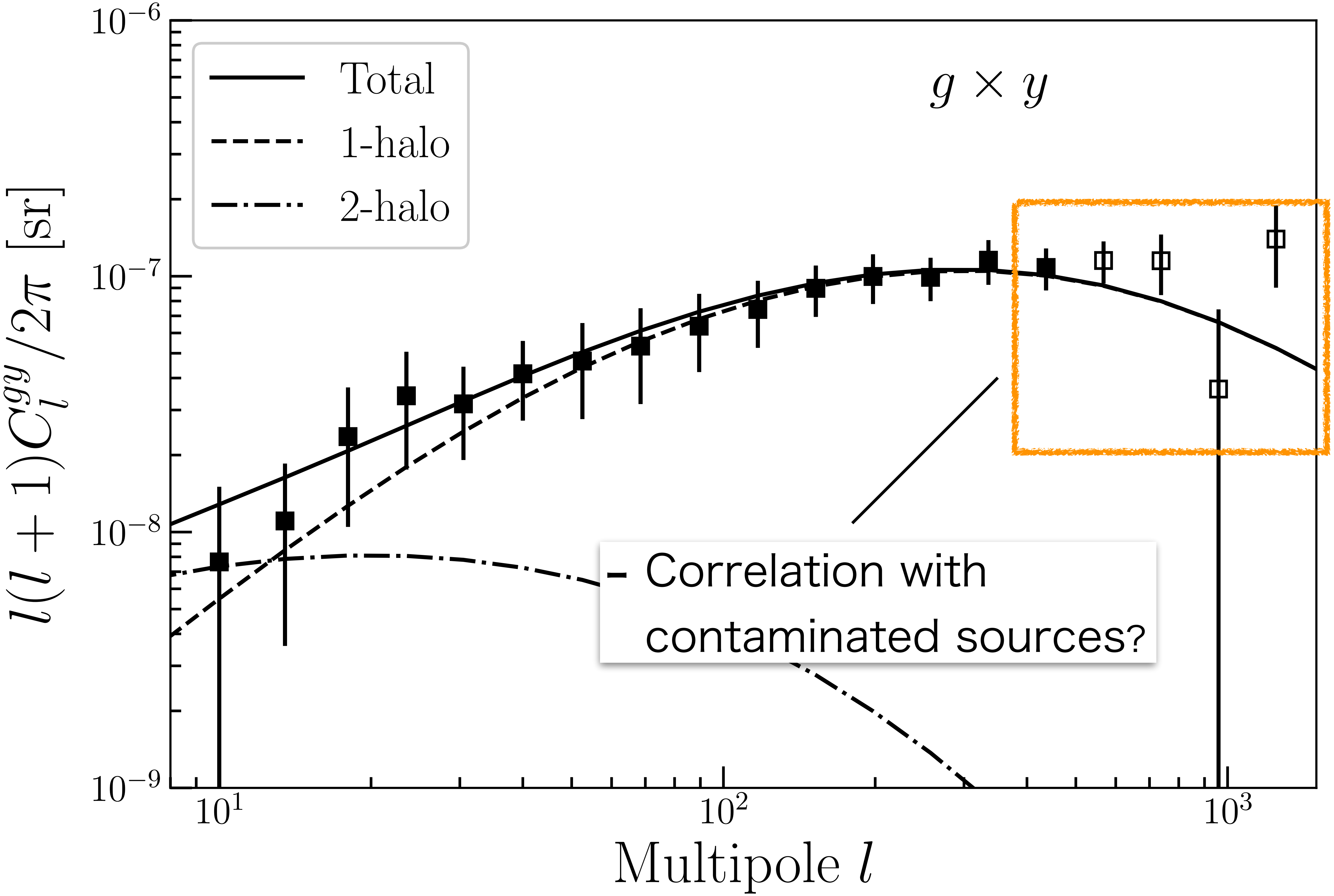

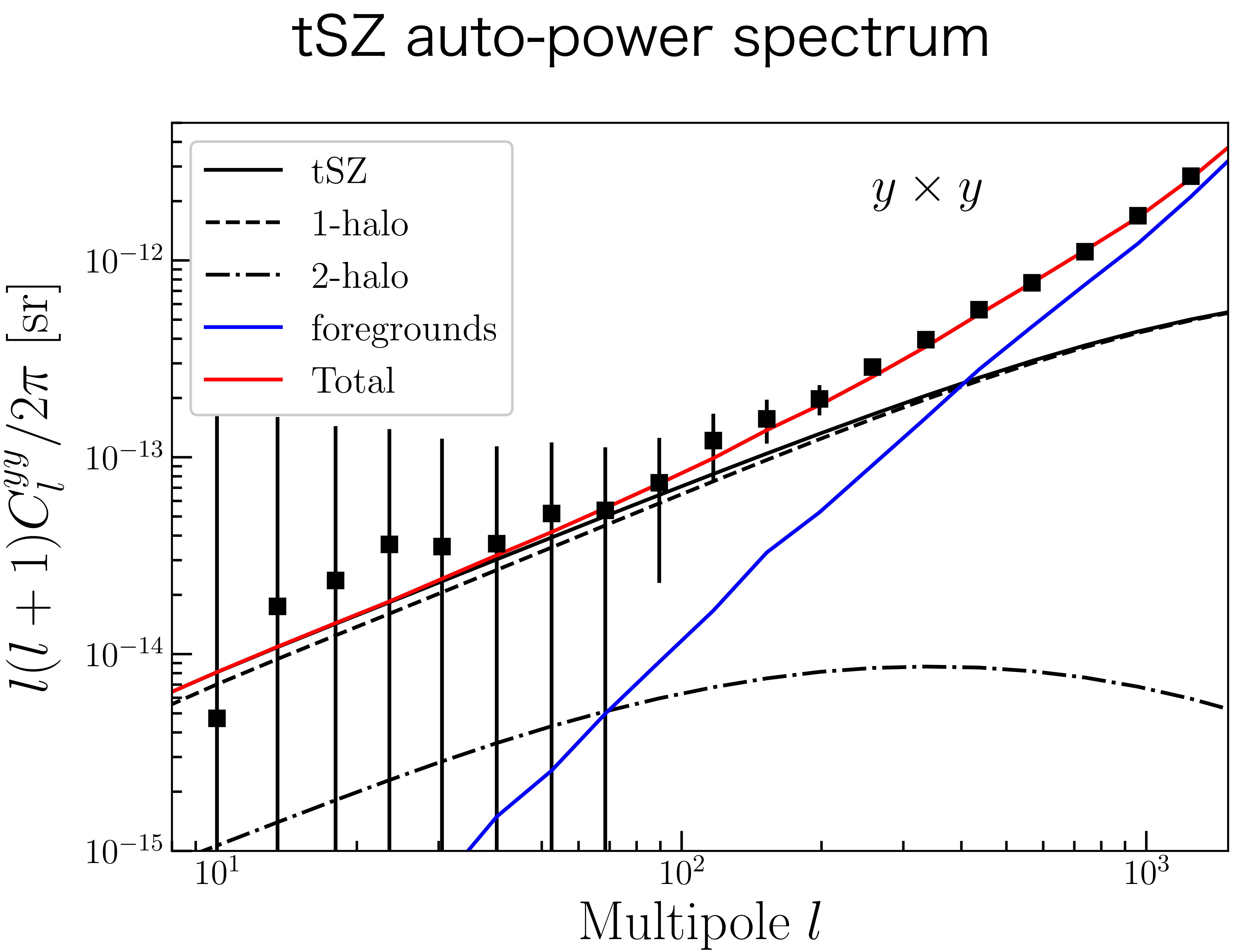

tSZ auto-power spectrum
tSZ
1-halo
2-halo
foregrounds
Total
$y \times y$
$l(l+1)C_l^{yy}/2\pi$ [sr]
Multipole $l$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^1$
$10^2$
$10^3$

# Halo model

- 1-halo

$$C_l^{\mathrm{AB,1h}} = \int \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \tilde{u}_l^{\mathrm{A}}(M, z) \tilde{u}_l^{\mathrm{B}}(M, z)$$

- 2-halo

$$C_l^{\mathrm{AB,2h}} = \int \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} b_l^{\mathrm{A}}(z) b_l^{\mathrm{B}}(z) P_{\mathrm{lin}}(l/\chi, z)$$

Mass function: Magneticum Pathfinder sim. (Bocquet+ 2016)

# Model: galaxies

$$\tilde{u}_l^g = \frac{W^g(z)}{\chi^2} \frac{1}{\langle n_g(z) \rangle} \sqrt{2\langle N_{\rm sat}|M\rangle \tilde{u}_{\rm sat}(l/\chi, M) + \langle N_{\rm sat}|M\rangle^2 \tilde{u}_{\rm sat}(l/\chi, M)^2}$$

- Halo occupation distribution (HOD)

$$\langle N_{\rm cen}|M\rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M - \log M_0}{\sigma_{\log M}}\right)\right]$$

$$\langle N_{\rm sat}|M\rangle = \left(\frac{M - M_0}{M_1}\right)^\alpha \Theta(M - M_0)$$

- $\tilde{u}_{\rm sat}$ : Fourier transform of the NFW profile

# Model: tSZ

$$\tilde{u}_l^y(M,z) = \frac{4\pi r_{500}}{l_{500}^2} \int_0^\infty \mathrm{d}x \; x^2 \frac{\sigma_T}{m_e c^2} P_e(x) \frac{\sin(lx/l_{500})}{lx/l_{500}}$$

- Electron pressure profile

$$P_e(x) = 1.65 \; h_{70}^2 \; \mathrm{eV \; cm}^{-3}$$

$$\times E^{8/3}(z) \left[ \frac{M_{500}}{3 \times 10^{14} h_{70} M_\odot} \right]^{2/3+\alpha_p} p(x)$$

- mass bias

$$M_{500} = M_{500,\mathrm{true}} / B(1+z)^\beta$$

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Free parameters

# Covariance matrix

- Gaussian term

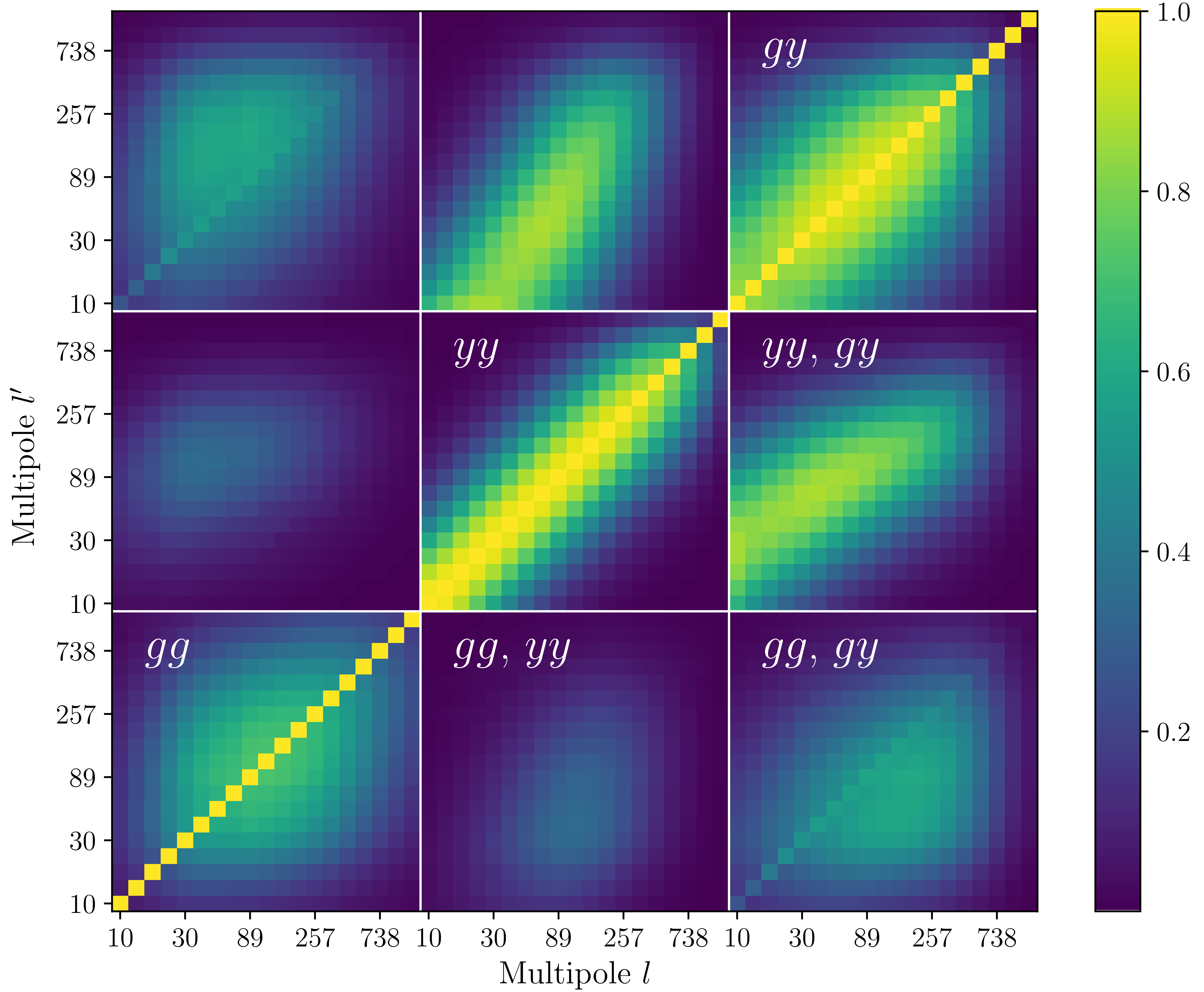
$$\mathrm{Cov}^{\mathrm{G}}(C_{l_1}^{\mathrm{AB}}, C_{l_2}^{\mathrm{CD}}) = \frac{\delta_{l_1 l_2}}{f_{\mathrm{sky}}(2l_1+1)\Delta l_1}\left[\hat{C}_{l_1}^{\mathrm{AC}}\hat{C}_{l_2}^{\mathrm{BD}} + \hat{C}_{l_1}^{\mathrm{AD}}\hat{C}_{l_2}^{\mathrm{BC}}\right]$$

- Non-Gaussian term

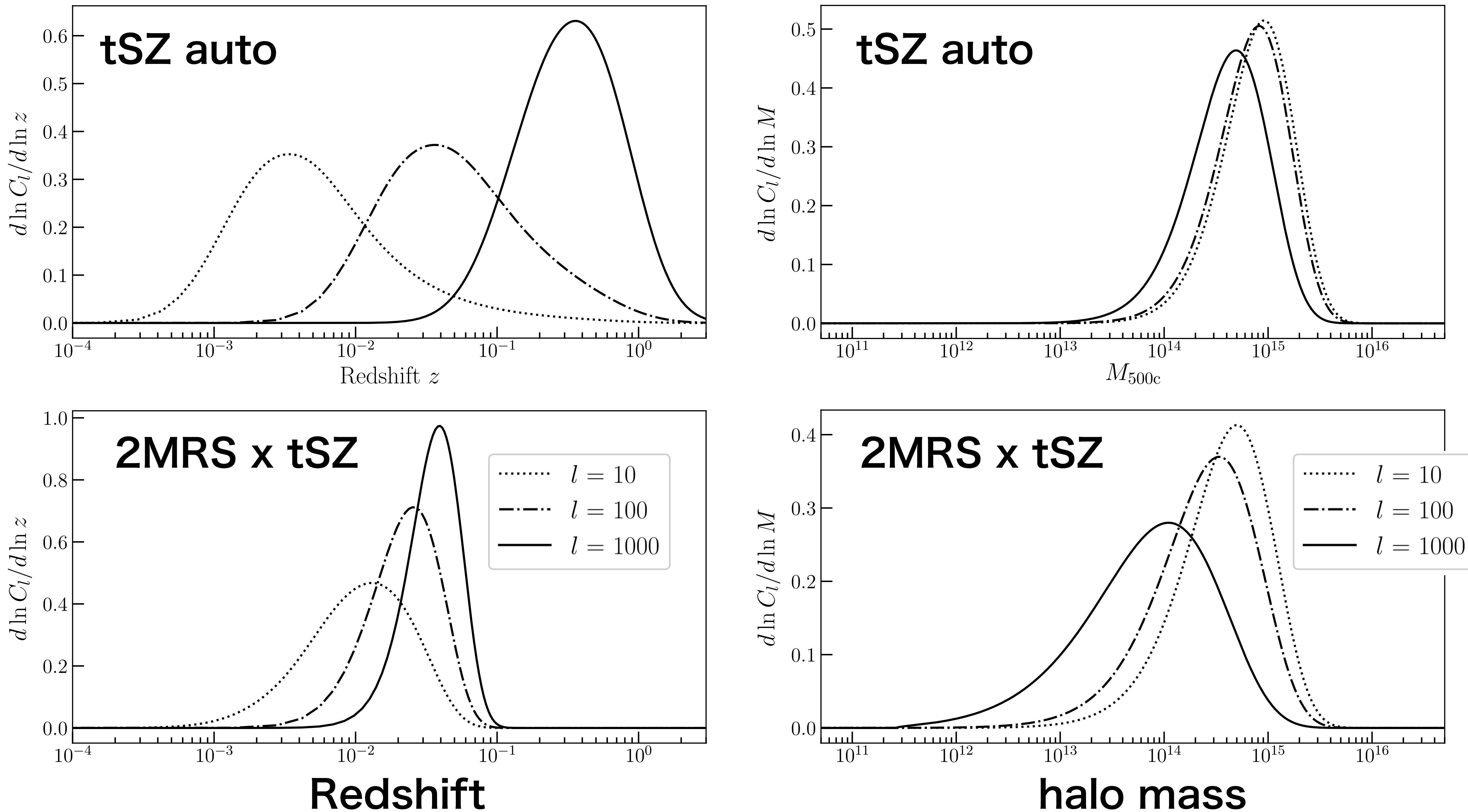
$$\mathrm{Cov}^{\mathrm{NG}}(C_l^{AB}, C_{l'}^{CD}) = \frac{1}{4\pi f_{\mathrm{sky}}} T_{ll'}^{ABCD}$$

$$T_{ll'}^{ABCD} = \int_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \tilde{u}_l^A \tilde{u}_l^B \tilde{u}_{l'}^C \tilde{u}_{l'}^D$$

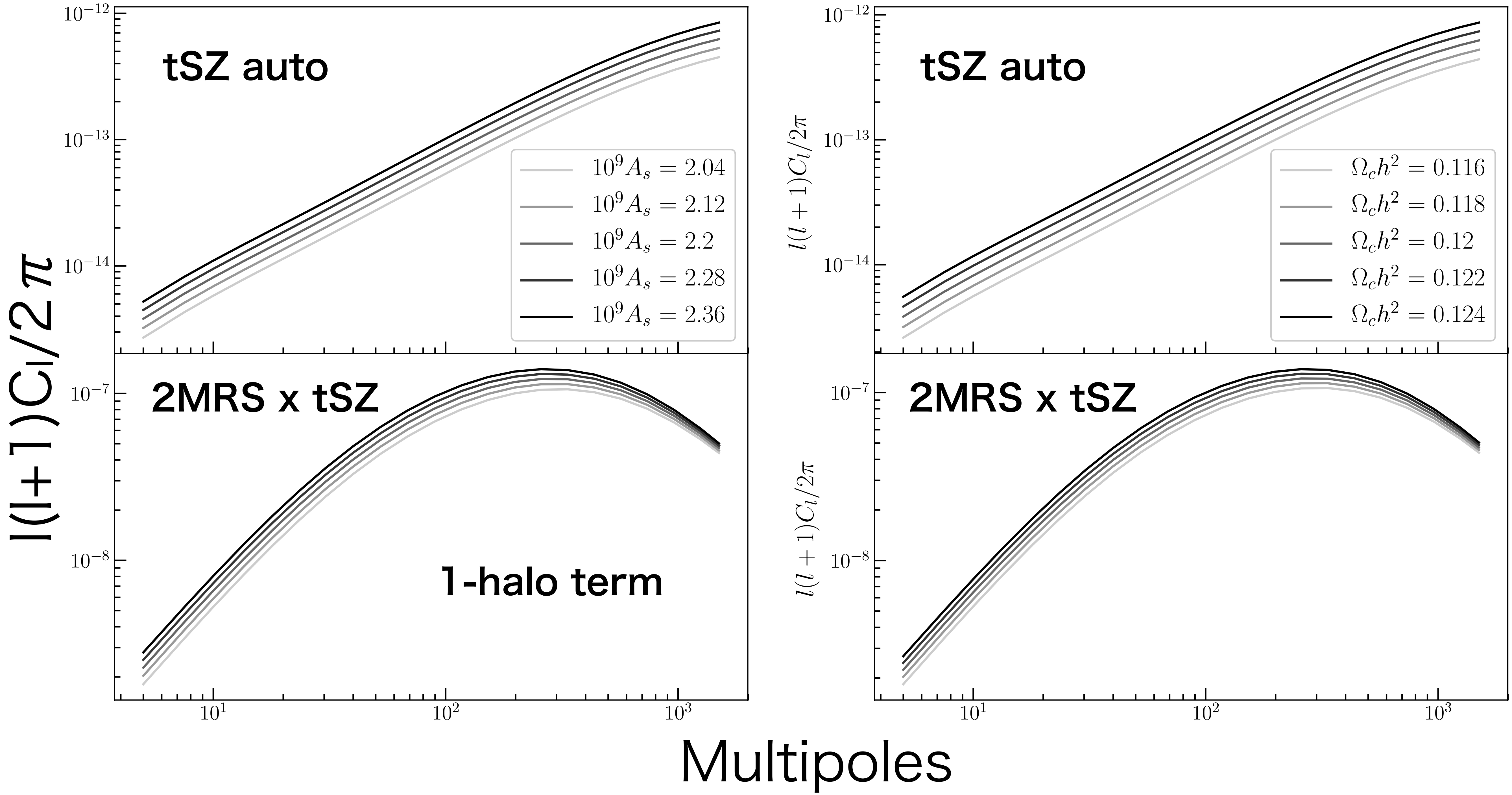
# Covariance matrix



# Mass and redshift distribution

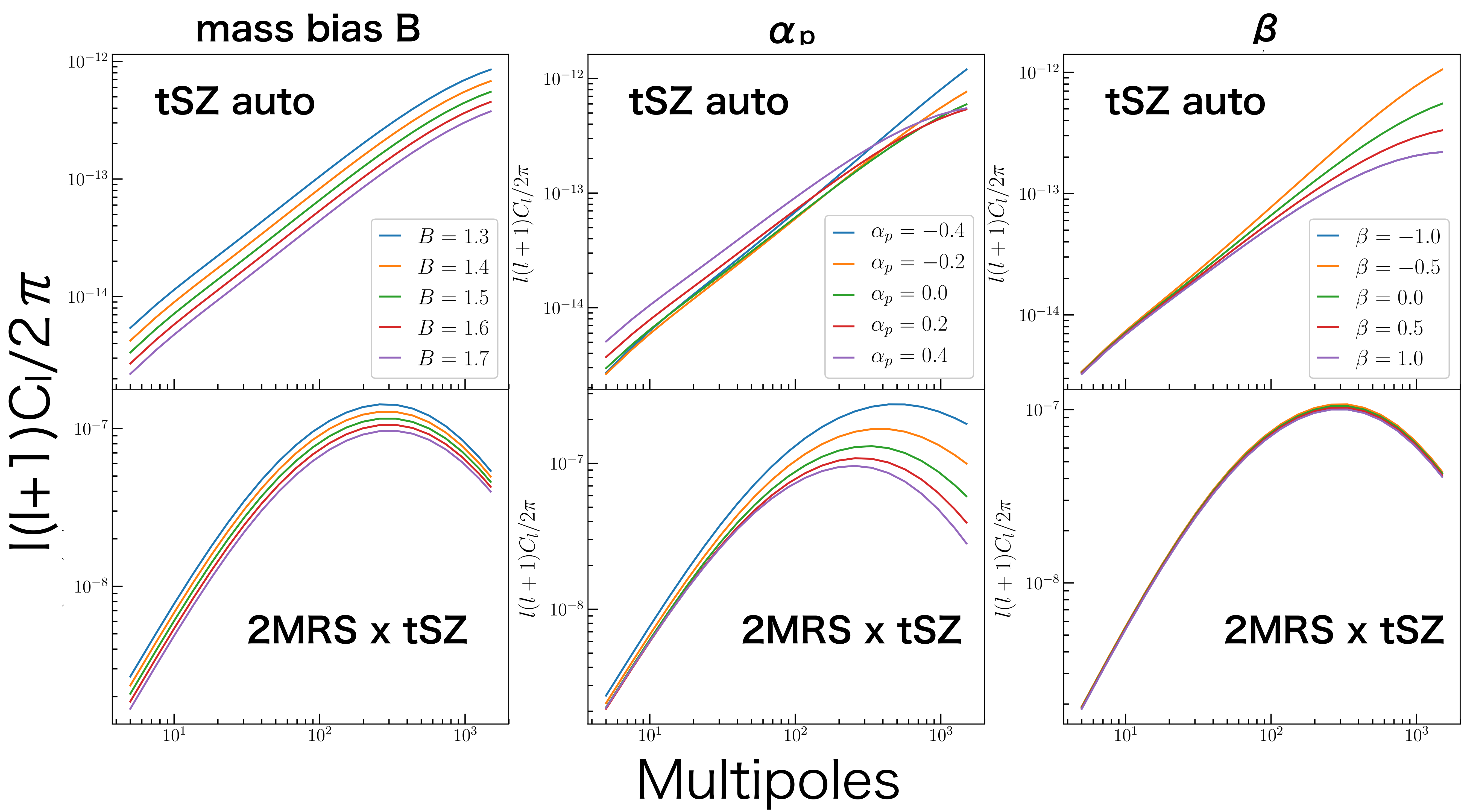


# parameter dependence




$$C_l^{\rm yy} \propto A_s^4(\Omega_c h^2)^{10},\ C_l^{\rm gy} \propto A_s^2(\Omega_c h^2)^5$$

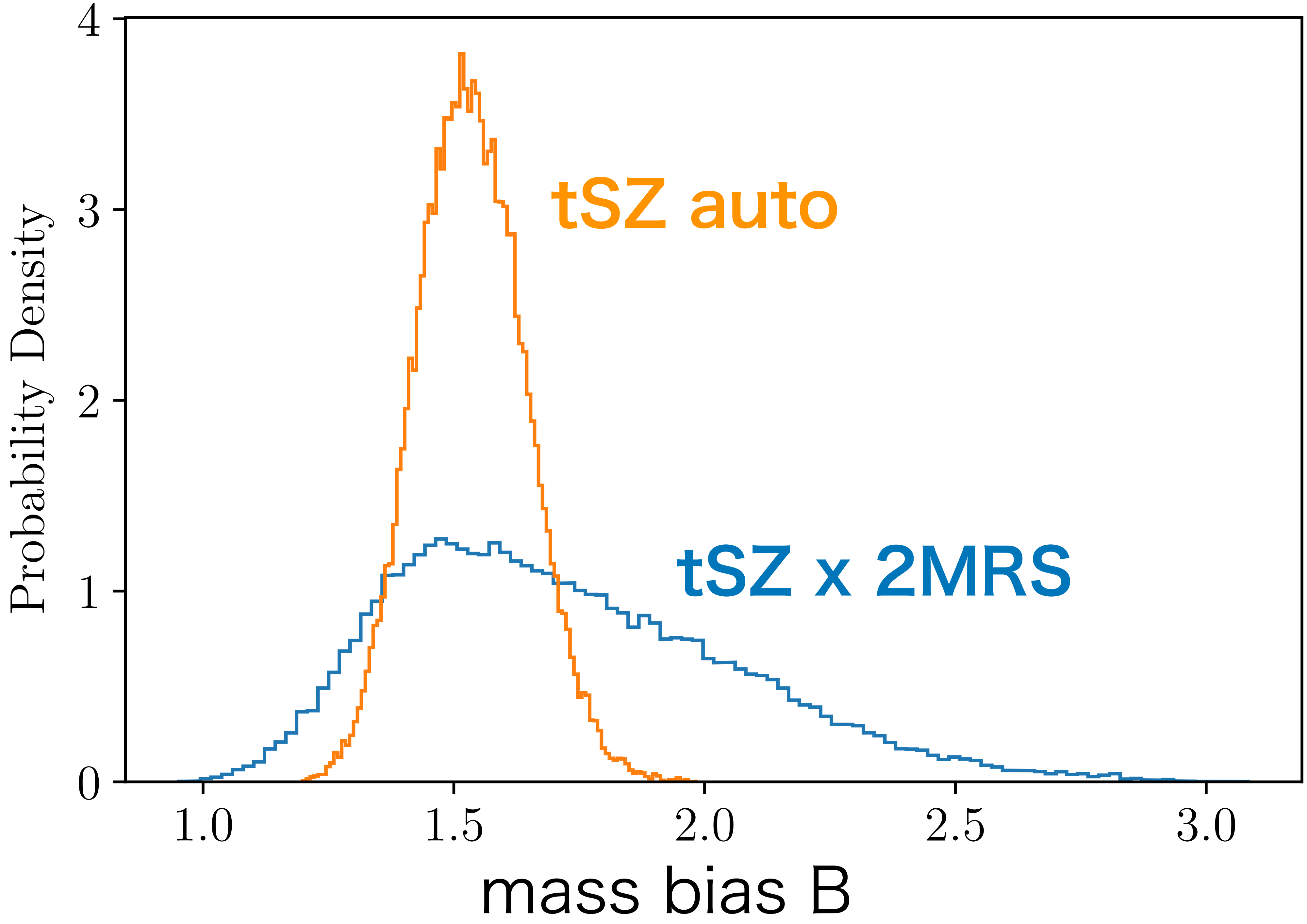
# parameter dependence



# MCMC fitting

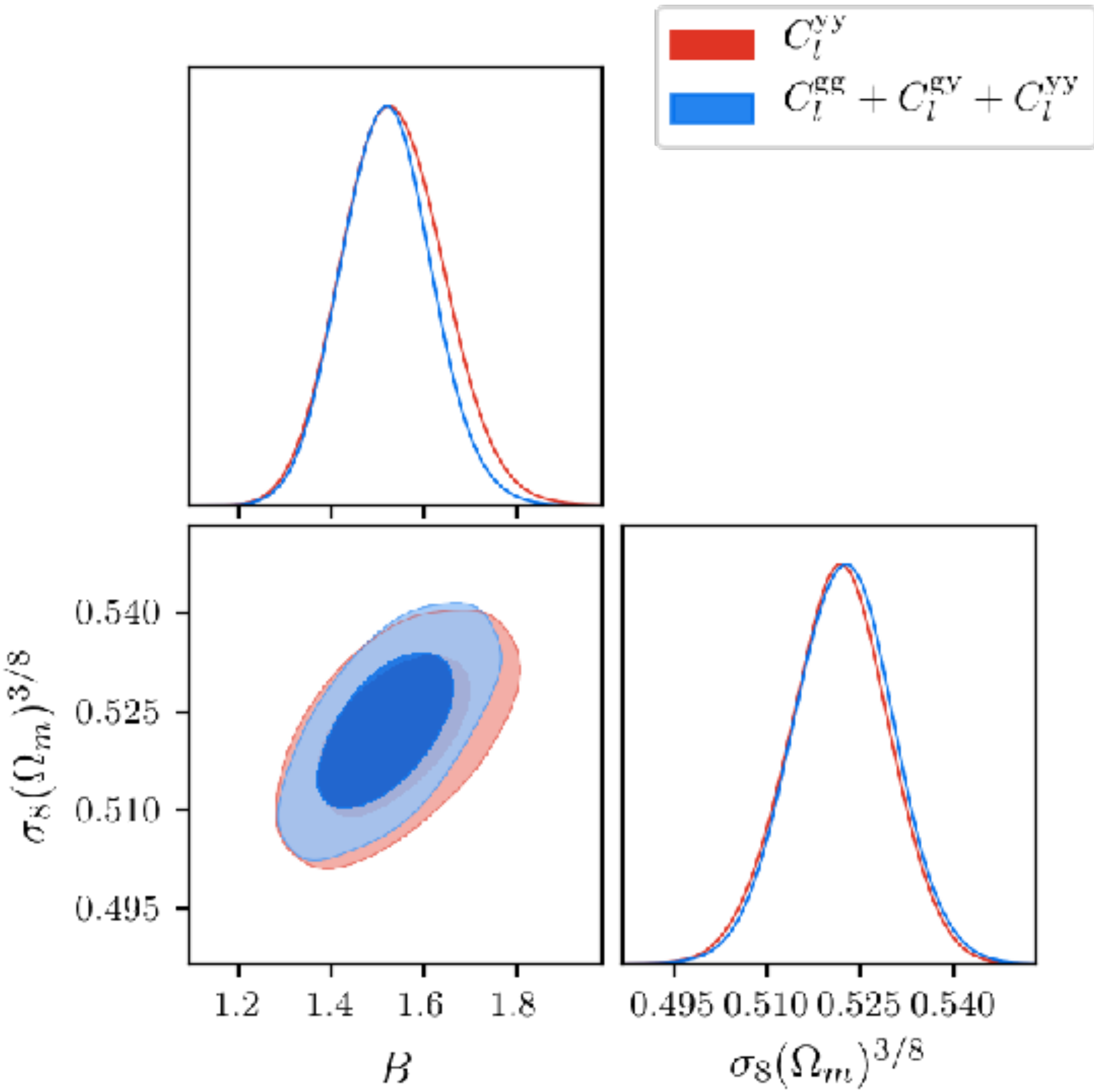
- Free parameters are
  - Cosmological parameters: $\Omega_c h^2$, $\ln(A_s)$
    - Planck prior assumed (CMB+CMB lensing)
  - Galaxies
    - 3 HOD parameters and 2 parameters for radial distribution of satellite galaxies
  - tSZ
    - B, $\alpha_p$, $\beta$ and the amplitude of the contaminated sources (CIB, IR and radio point sources)

# Consistency of the auto- and cross-spectra



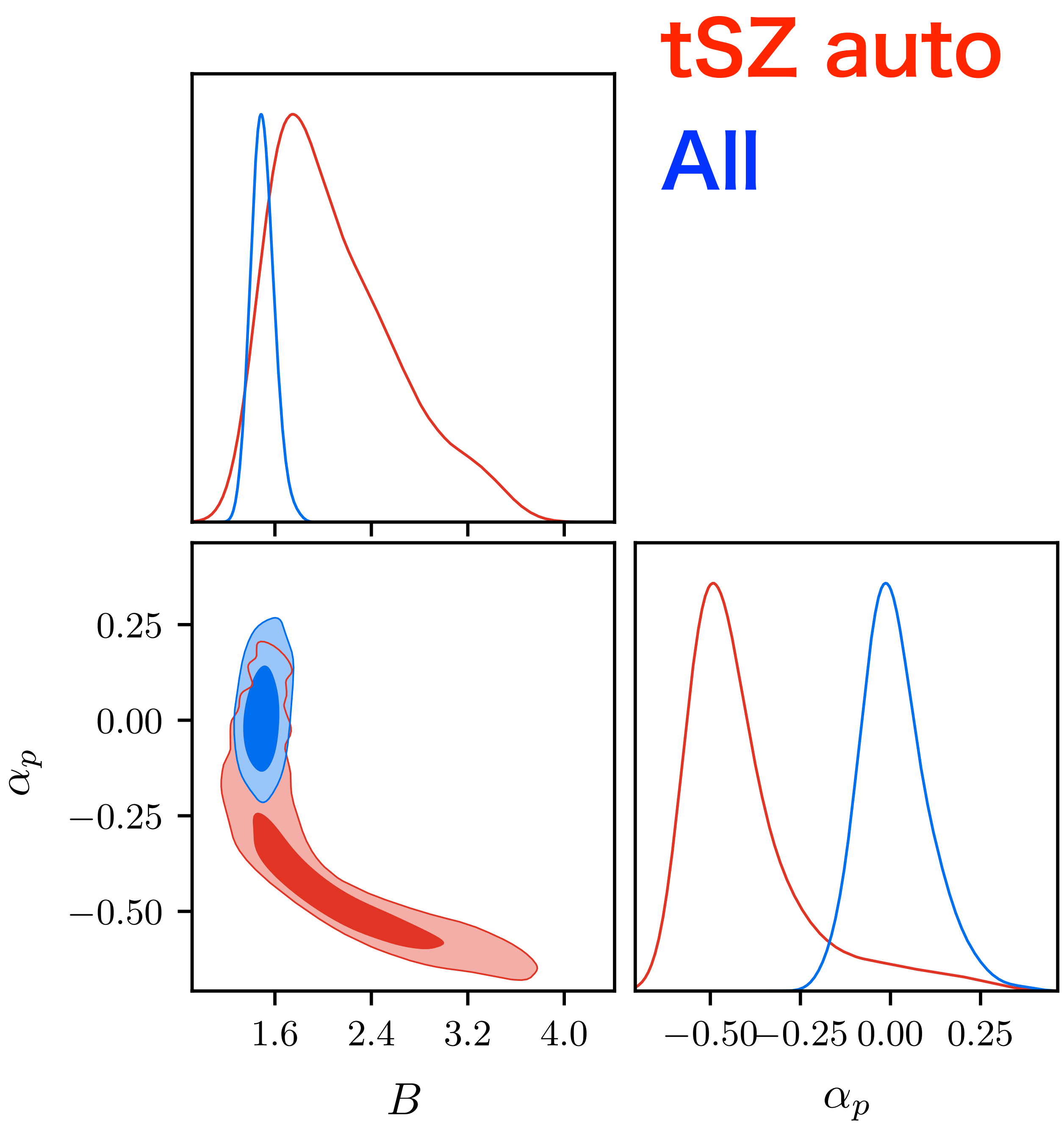

- tSZ auto and 2MRS x tSZ prefers the same mass bias

# Constraints on B




- $\alpha_{\rm p}$ and $\beta$ fixed
- B = 1.52 +/- 0.10
    - consistent with weak lensing survey
- The 2MRS-tSZ cross slightly improves the constraints

# $\alpha_p$



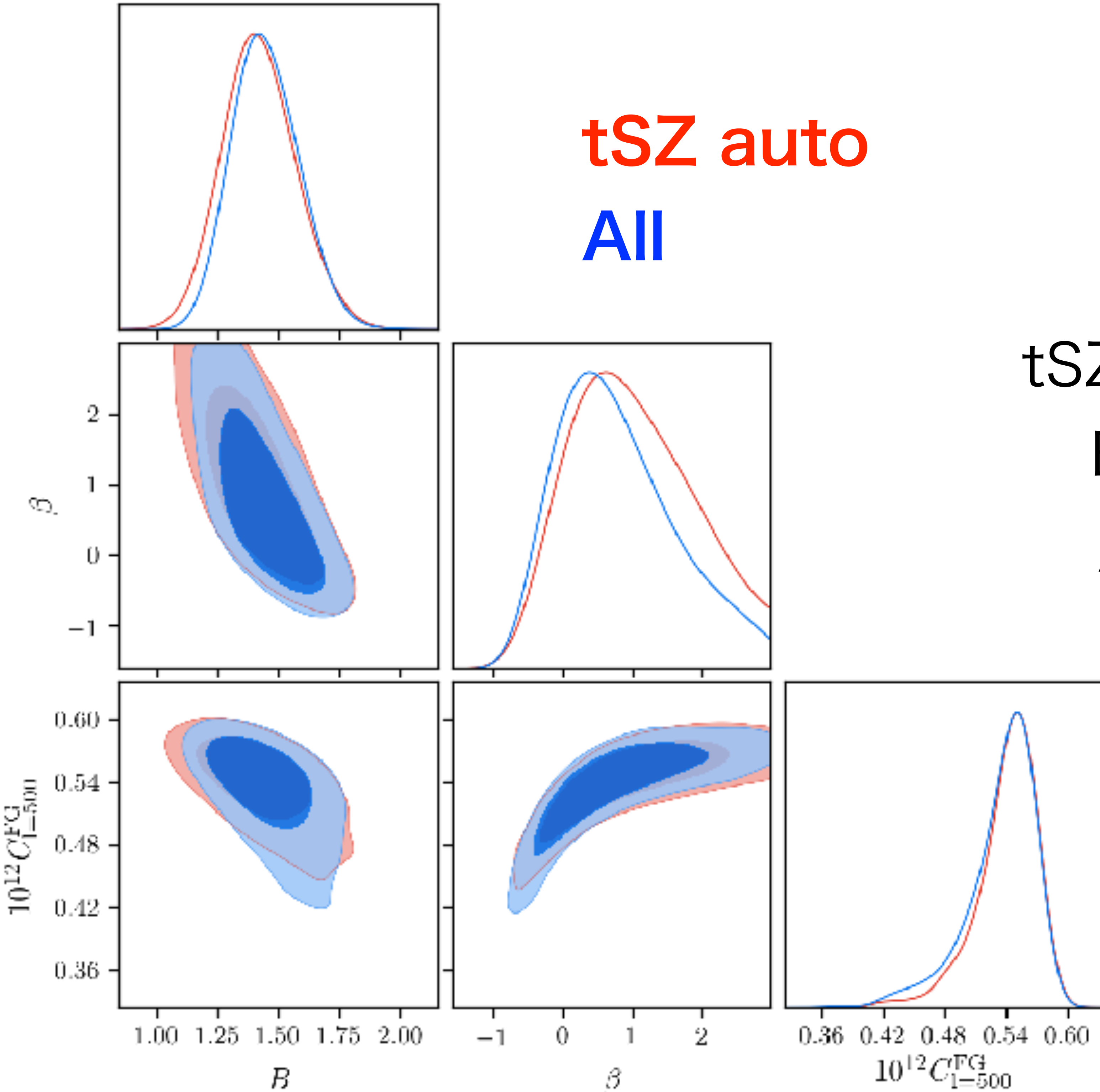

tSZ auto + 2MRS x tSZ:

B = 1.5 +/- 0.1

$\alpha_p$ = 0.025 +/- 0.11

- The 2MRS x tSZ solves the degeneracy between $\alpha_p$ and B
- consistent with the self-similar model, or no mass dependence of B

# $\beta$




tSZ auto + 2MRS x tSZ:

B = 1.42 +/- 0.15

$\beta$ = 0.97 +/- 0.87

- The 2MRS x tSZ does not help to constrain $\beta$
- need to constrain the amplitude of foregrounds

# Summary

- First detection of the 2MRS x tSZ
- Observed cluster mass should be 35% lower than the true mass
  - consistent results for the tSZ auto and tSZ-2MRS cross
- tSZ x 2MRS significantly improves a constraint on the mass - pressure relation
- No mass or redshift evolution of B is needed

# Beyond the local universe!