Thermal history of the Universe probed by a joint analysis of the thermal Sunyaev–Zeldovich effect and galaxy surveys

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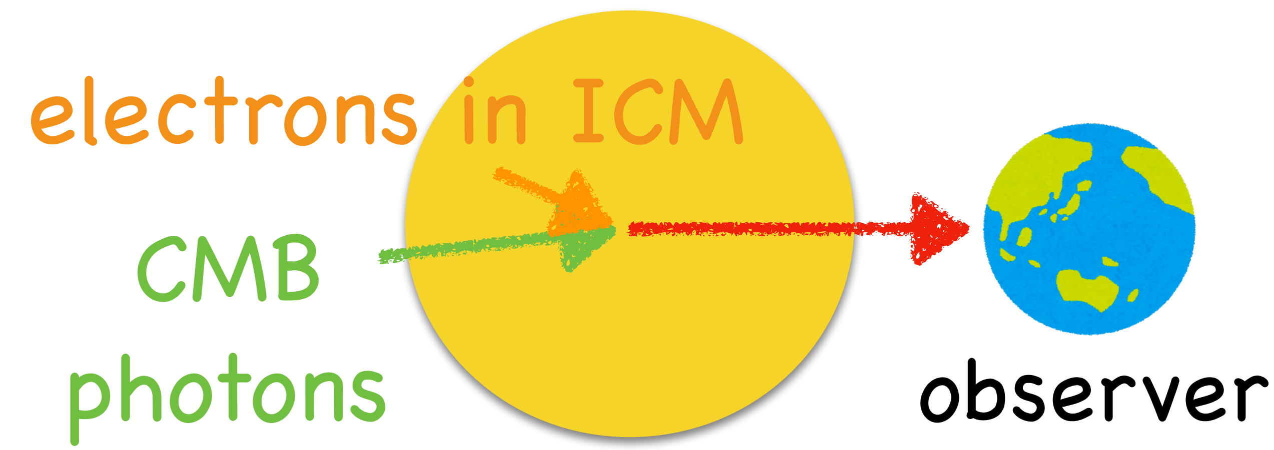
THANKS

- First of all, I’d like to appreciate this KAKENHI for supporting **my work** and **my life**
- Spent 2yrs in MPA and 2yrs in IPMU
- Research activities
    - PFS Cosmology
        - developed the simulation tools for Subaru SSP
    - Developed the tools for tomographic analysis og thermal hot gas (RM et al. 2018, RM et al. 2020)
- KAKENHI induced the accelerating expansion of my Universe!

The thermal Sunyaev-Zel'dovich (tSZ) Effect

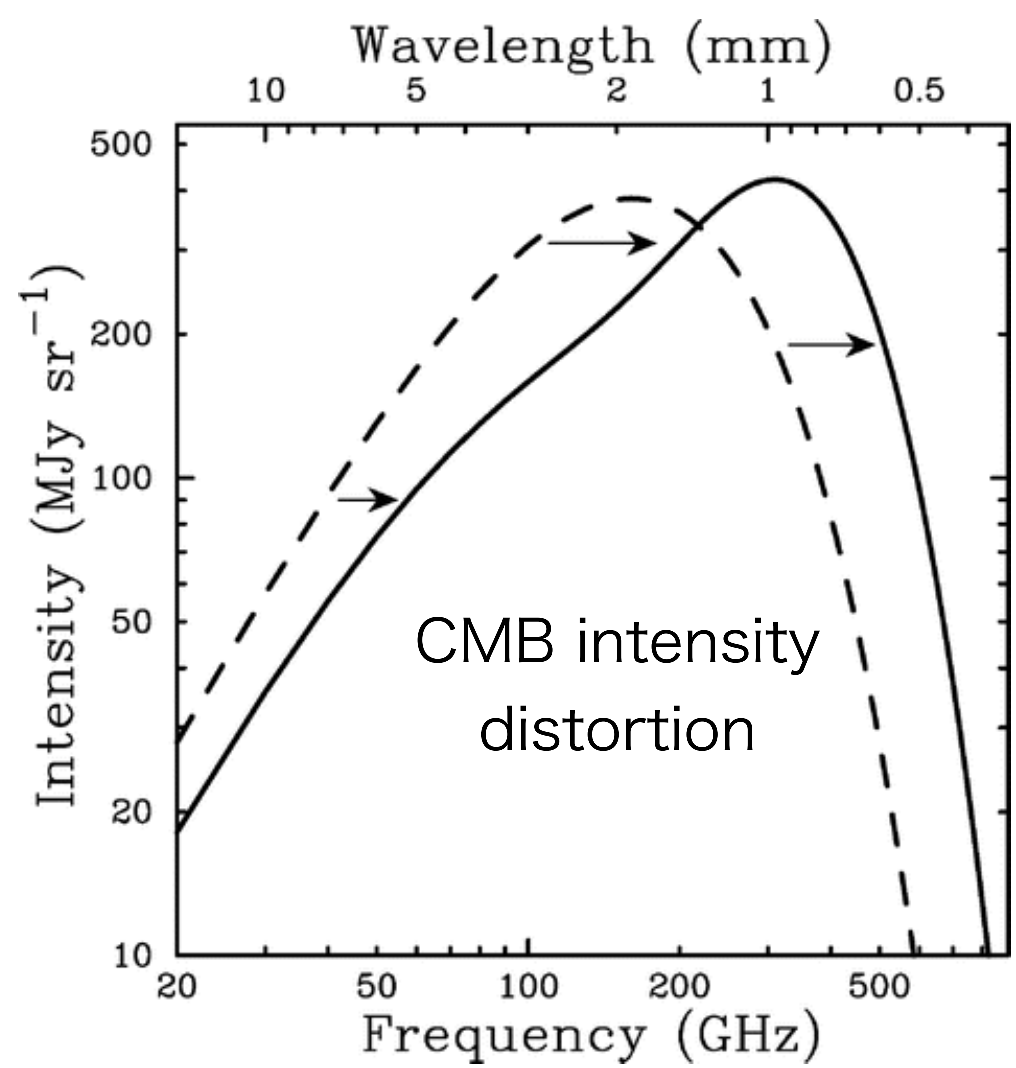
(Sunyaev & Zel'dovich 1972)



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

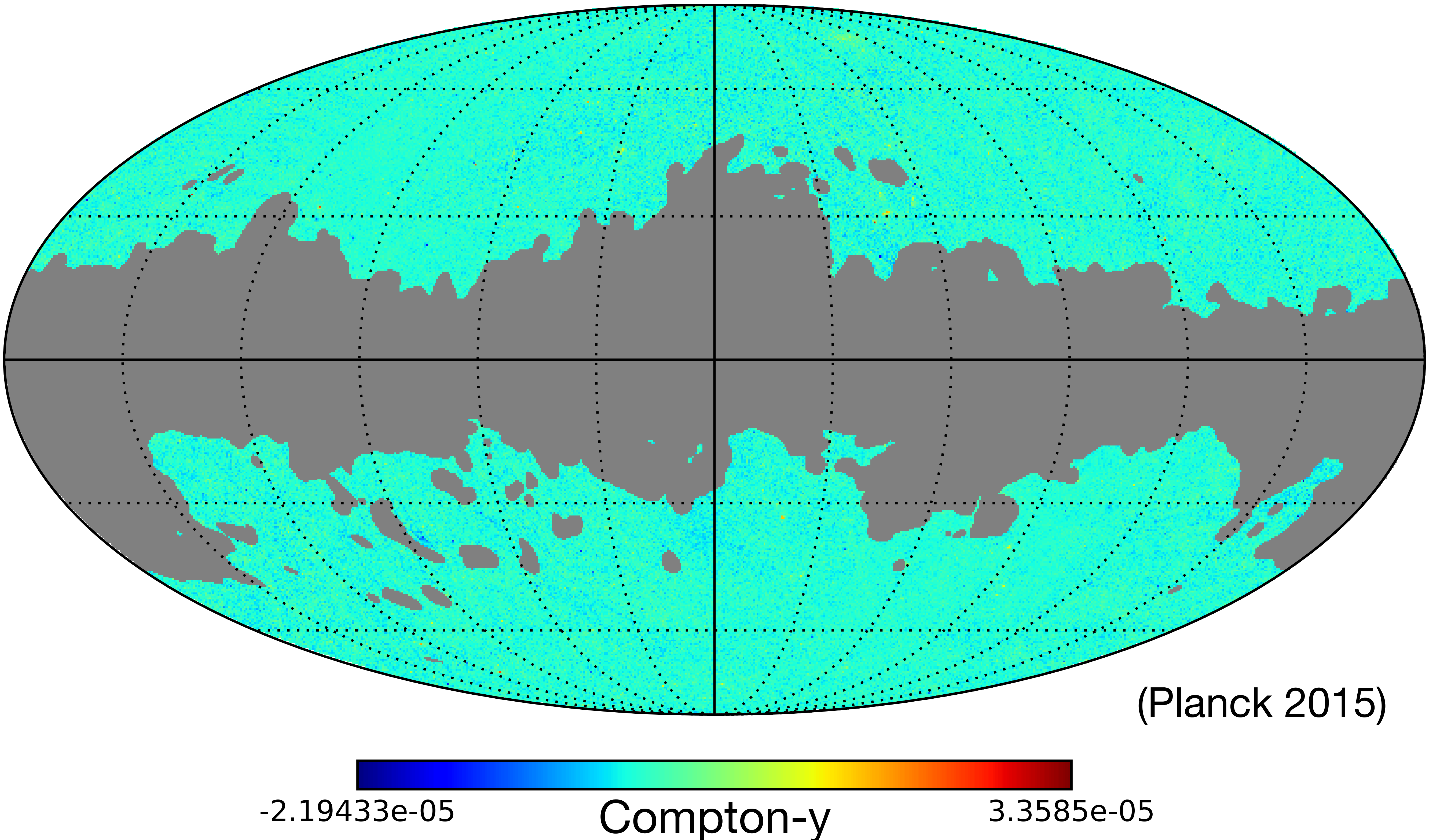
- Characterized by the Compton-y parameter

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

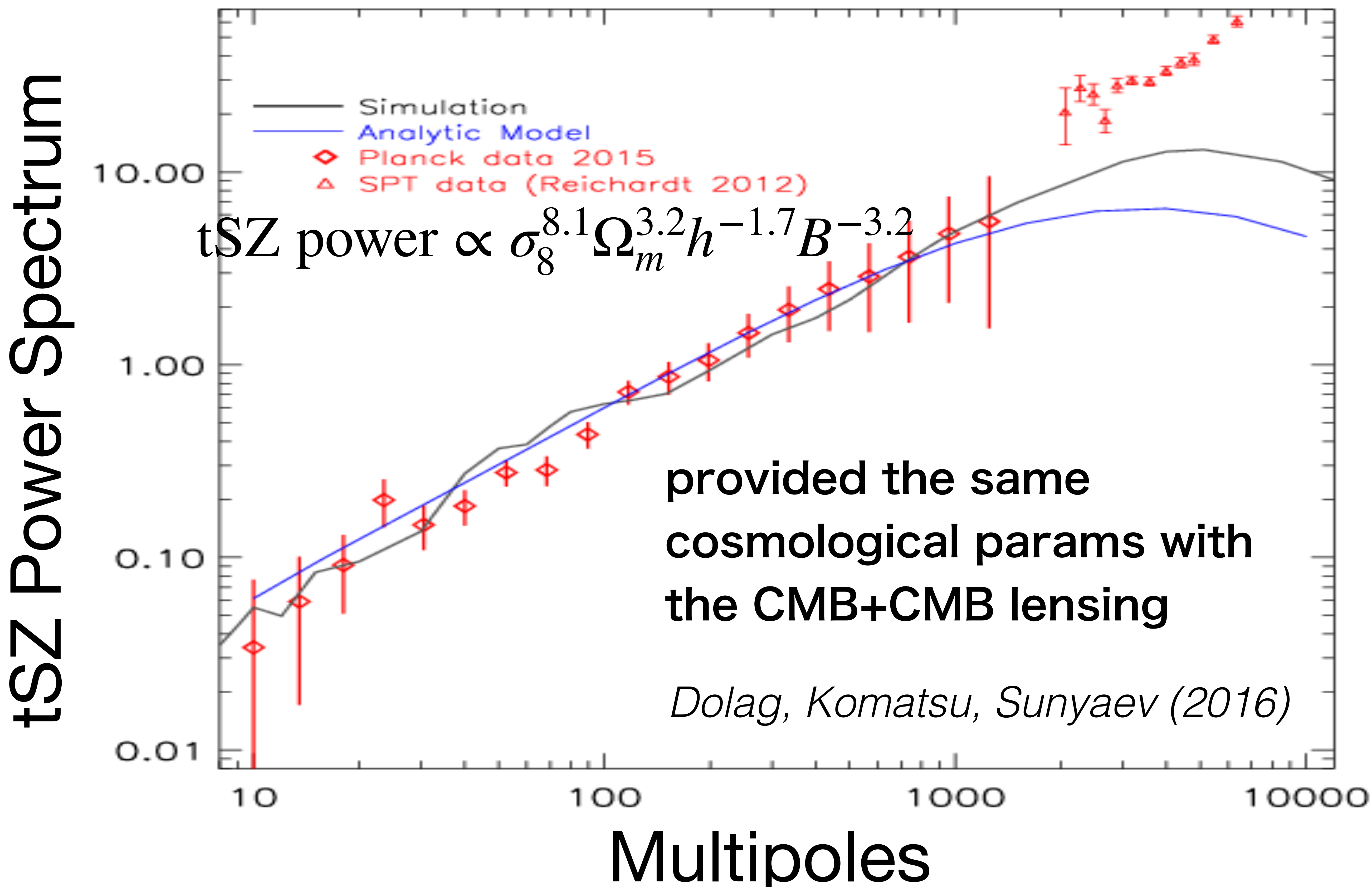


(Carlstrom et al. 2002)

Full-sky Map of ALL HOT GAS



The ΛCDM fits!

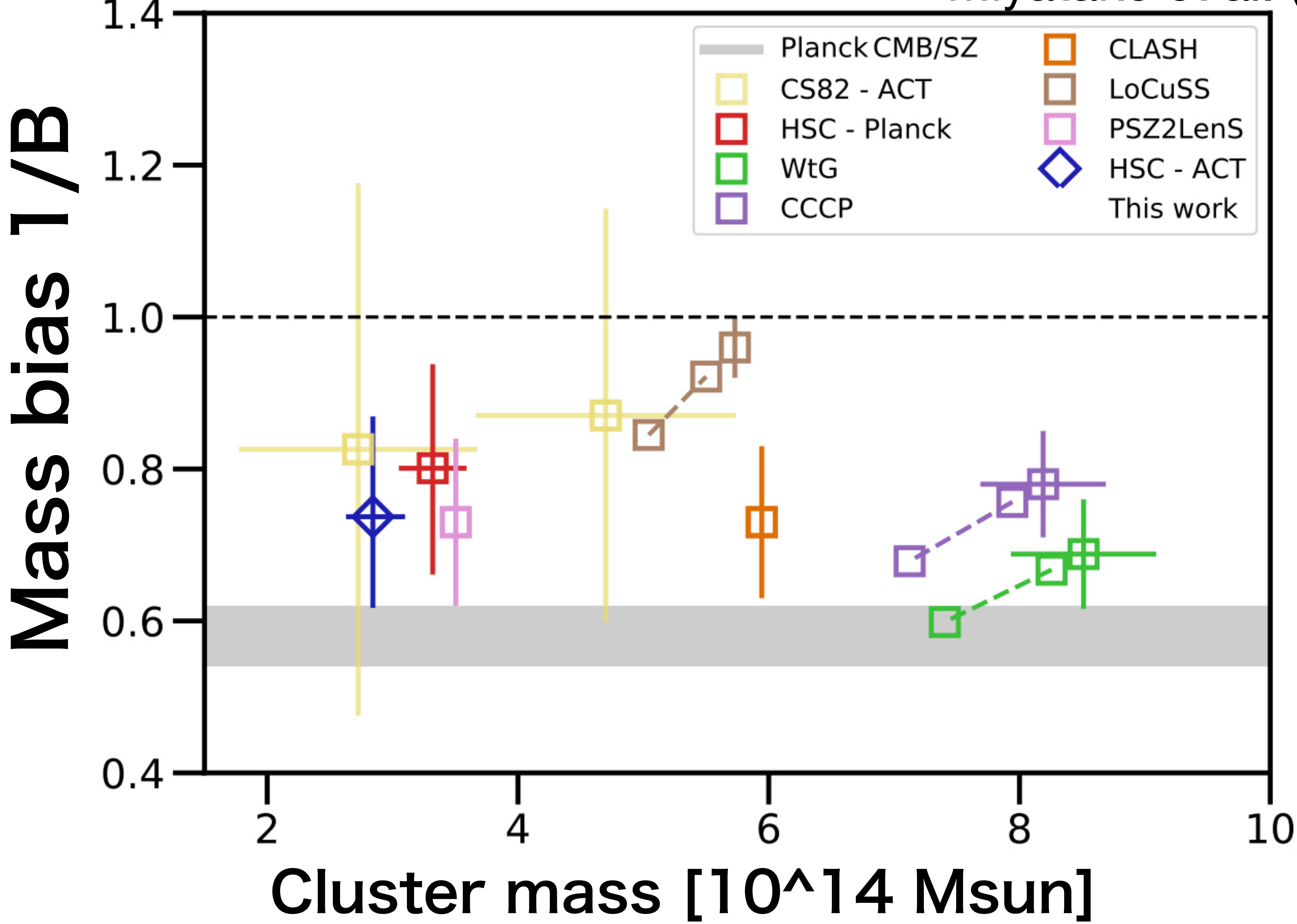


The largest uncertainty: mass bias

- The mass bias $B = M_{true} / M_{obs}$
  - Planck cluster mass is calibrated by the X-ray observation assuming hydrostatic equilibrium => bias
- Cosmological parameters strongly degenerate with *B*
  - M_{obs} should be ~40% lower than M_{true} to reconcile with the CMB+CMB lensing
  - Numerical simulations yield 5-20% of mass bias

Planck cluster mass vs lensing mass - HSC results

Miyatake et al. (2018)



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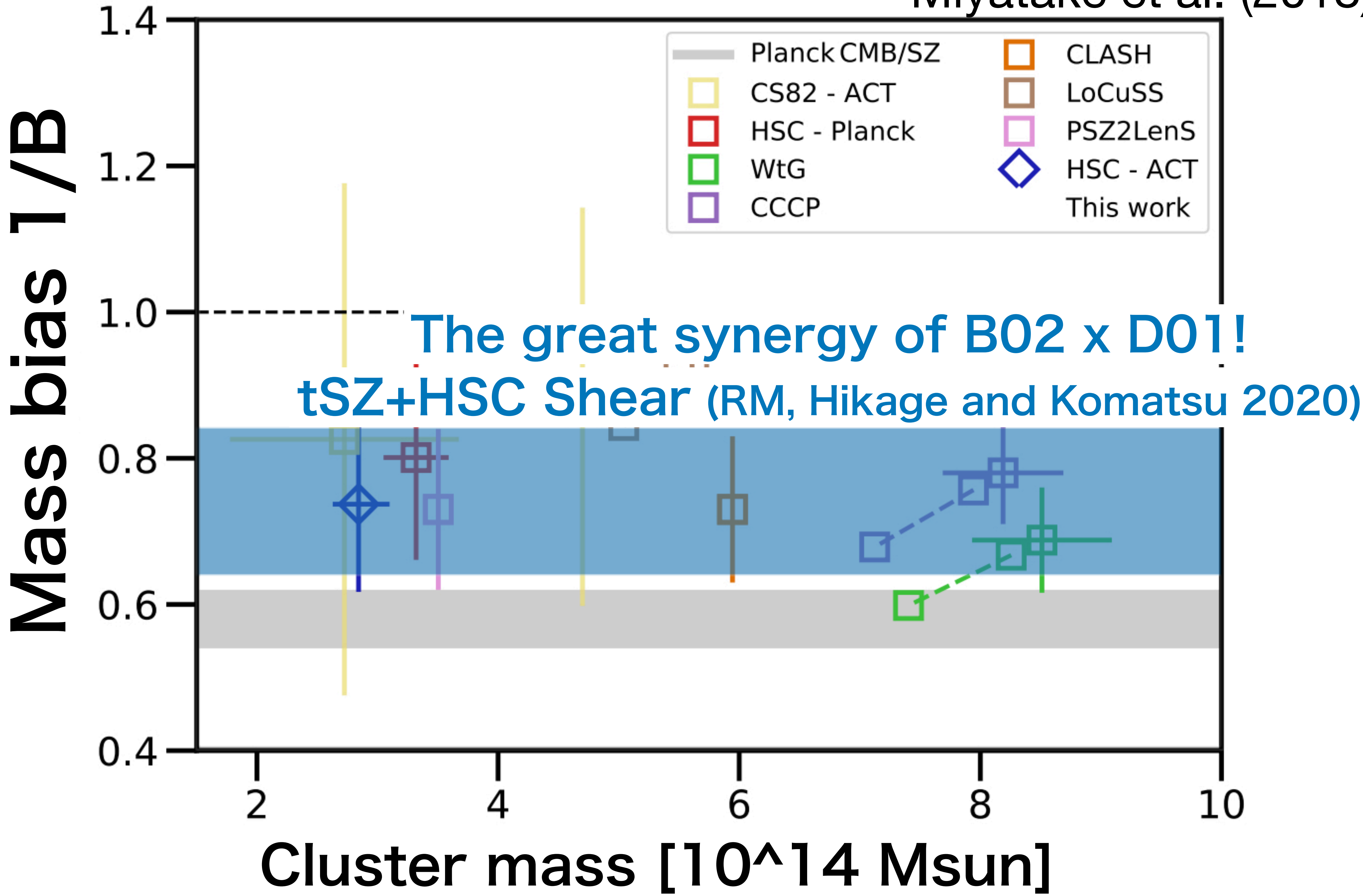

Questions

- 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?
    - But all the redshift information is compressed

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    - But all the redshift information is compressed

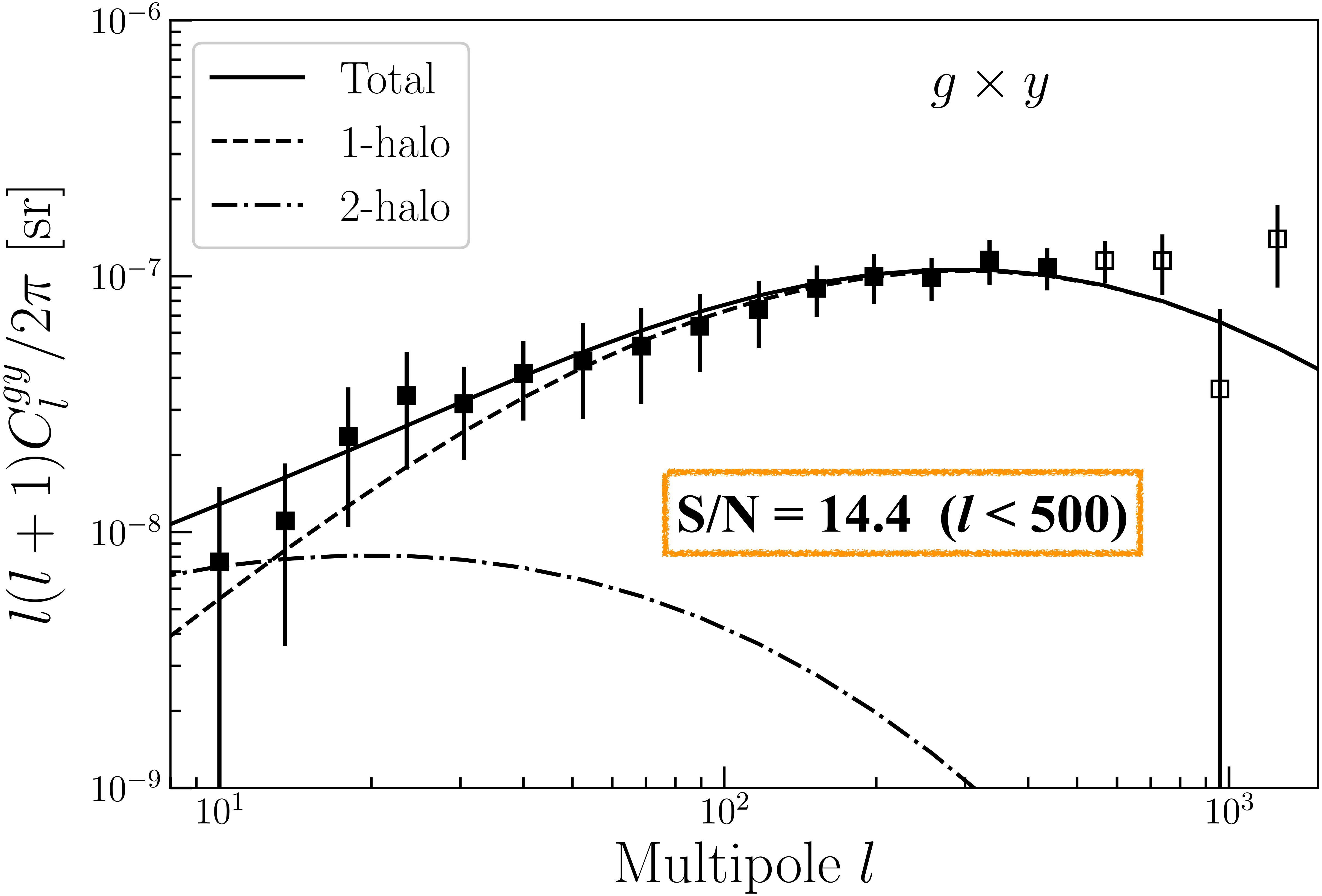
=> Cross correlation!

Cross with 2MASS redshift survey

(RM et al. 2018)

- 2MRS (Huchra et al. 2012)
  - Redshift distribution peaks at $z \sim 0.03$
  - Mass range of groups or clusters: $10^{11} < M_{vir}/M_{sun} < 10^{16}$
- What can we learn?
  - Gas physics in the local universe — How do local galaxies trace gas?

The tSZ x 2MRS cross-power spectrum



Power spectrum -- Halo model

$$C_l^{AB} = C_l^{AB,1h} + C_l^{AB,2h}$$

- 1-halo (intra-halo correlation)

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

- 2-halo (halo-halo correlation)

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

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

Model: tSZ

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

- Universal Pressure Profile (UPP; Arnaud et al. 2010)

$$P_e(x) = 1.65\ h_{70}^2\ \mathrm{eV\ cm}^{-3}$$
$$\times E^{8/3}(z) \left[\frac{M_{500}}{3\times 10^{14} h_{70} M_\odot}\right]^{2/3+\alpha_p} p(x)$$

- mass bias

$$M_{500} = M_{500,\mathrm{true}}/B$$

Model: tSZ

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Calibrated by the X-ray observations

- mass bias

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Free parameters

- mass bias

$$M_{500} = M_{500,\mathrm{true}}/B$$

Covariance matrix

- Gaussian term

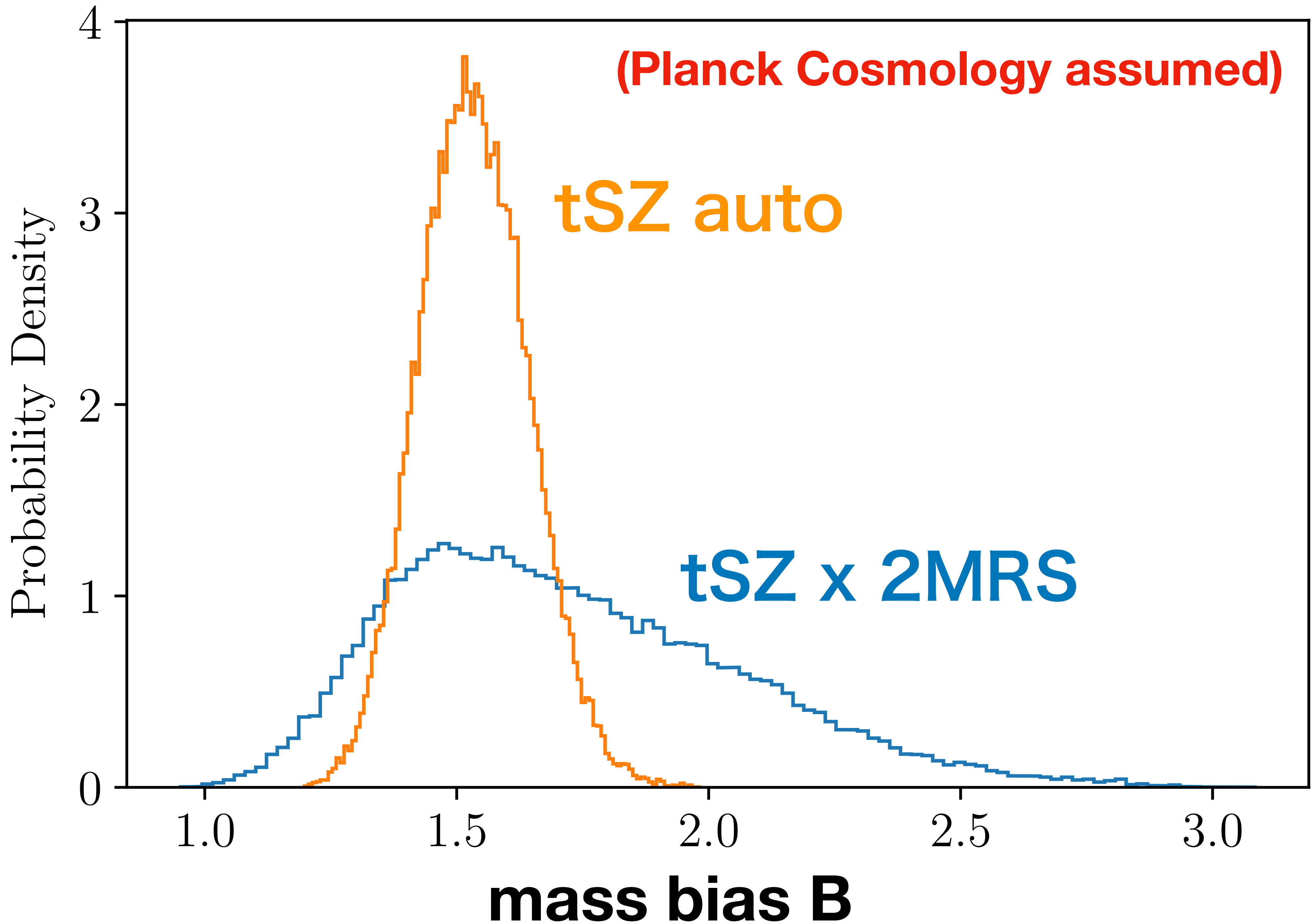
$$\mathrm{Cov}^{\mathrm{G}}(C_{l_1}^{\mathrm{AB}}, C_{l_2}^{\mathrm{CD}}) = \frac{\delta_{l_1 l_2}}{f_{\mathrm{sky}}(2l_1+1)\Delta l_1}\left[\hat{C}_{l_1}^{\mathrm{AC}}\hat{C}_{l_2}^{\mathrm{BD}} + \hat{C}_{l_1}^{\mathrm{AD}}\hat{C}_{l_2}^{\mathrm{BC}}\right]$$

- Non-Gaussian term

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

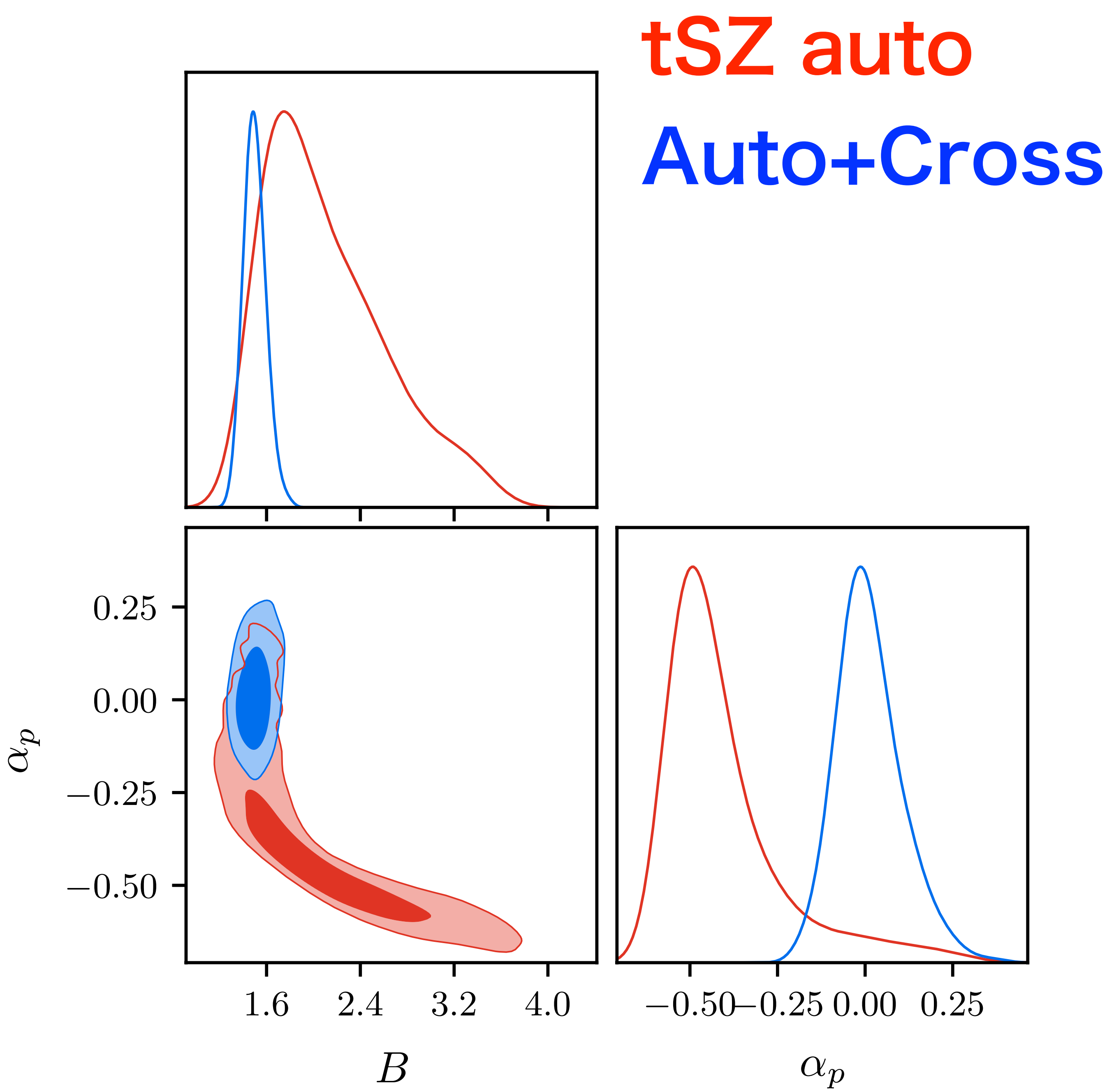
$$T_{ll'}^{ABCD} = \int_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \tilde{u}_l^A \tilde{u}_l^B \tilde{u}_{l'}^C \tilde{u}_{l'}^D$$

Consistency of the auto- and cross-spectra



- tSZ auto and 2MRS x tSZ prefers the same mass bias B
  => high B not due to the obvious systematics in the SZ data

α_p



(Mass dependence of mass bias)

tSZ auto + 2MRS x tSZ:

$B = 1.5$ +/- 0.1

$\alpha_p = 0.025$ +/- 0.11

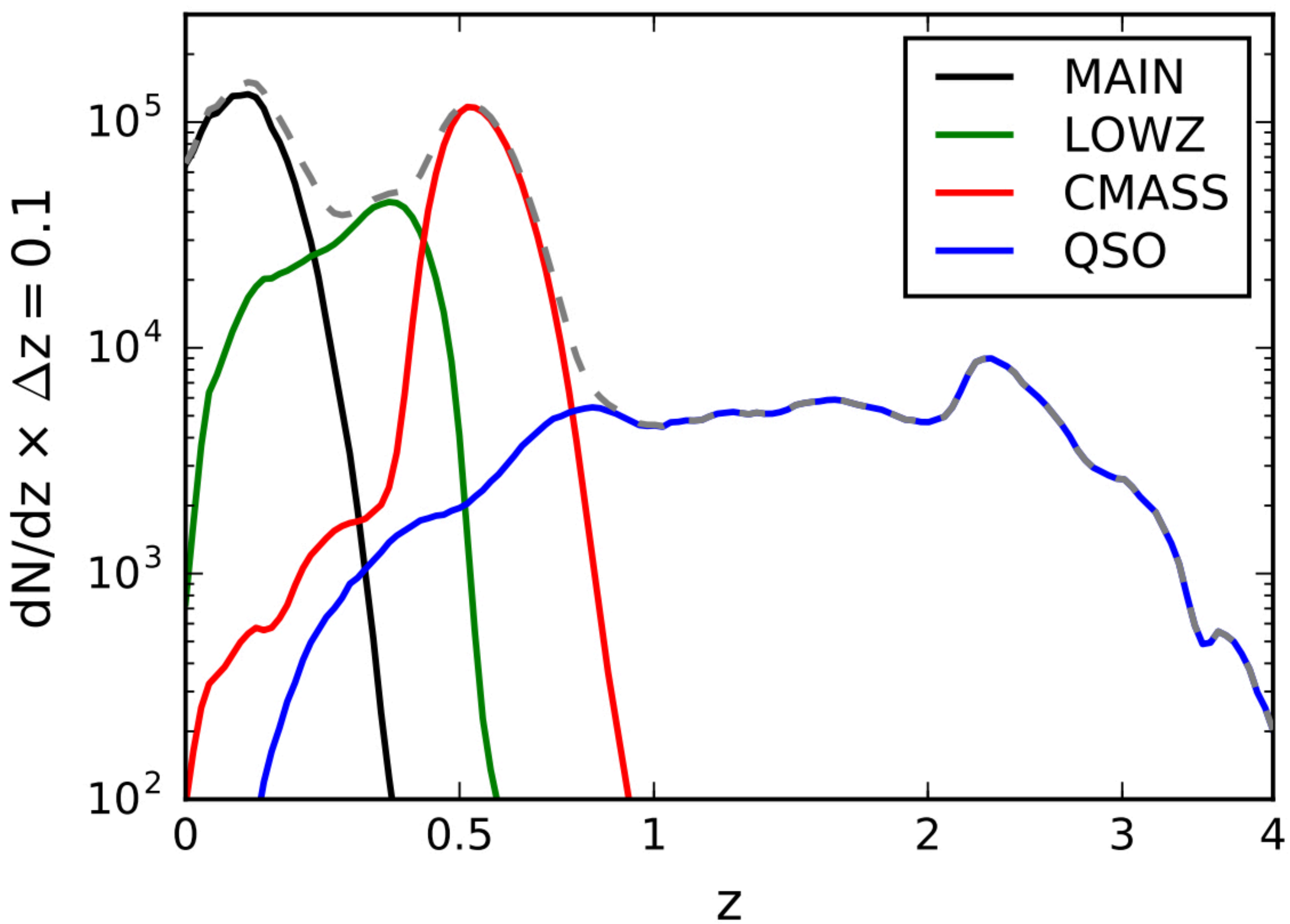
- The 2MRS x tSZ solves the degeneracy between α_p and B
- consistent with the self-similar model, or no mass dependence of B

tSZ x 2MRS

- First detection of the 2MRS x tSZ
- Assuming the Planck cosmology, 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

Go to high redshift

Redshift distribution of SDSS sample



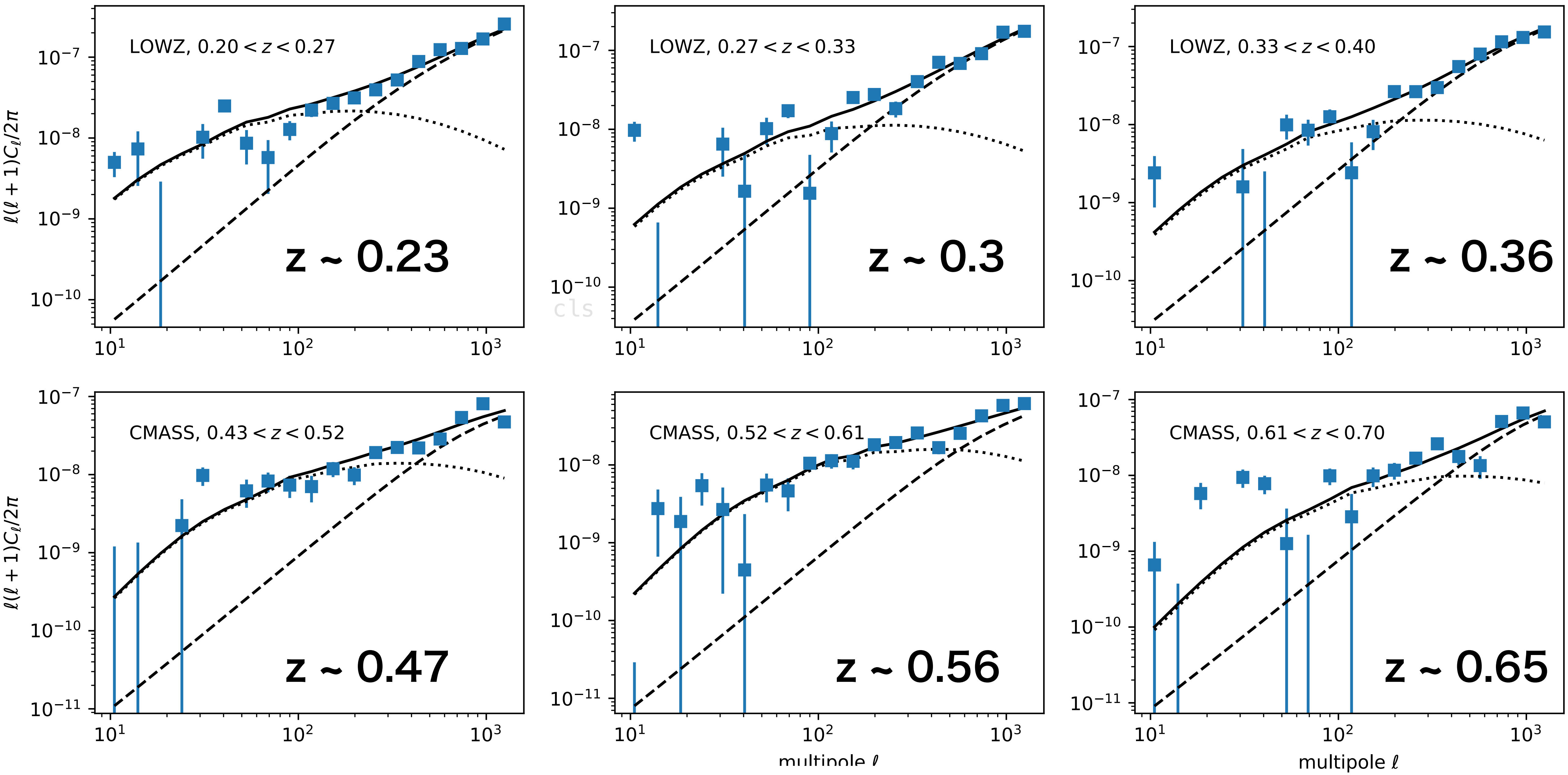
(Chiang & Menard 2019)

- Take a cross-correlation with SDSS galaxies and quasar sample
  - wide redshift coverage $0 < z < 4.0$
- Redshift evolution of mass bias?
- Can ΛCDM fits to all data?

Redshift evolution of tSZ

(RM et al. 2020 in prep.)

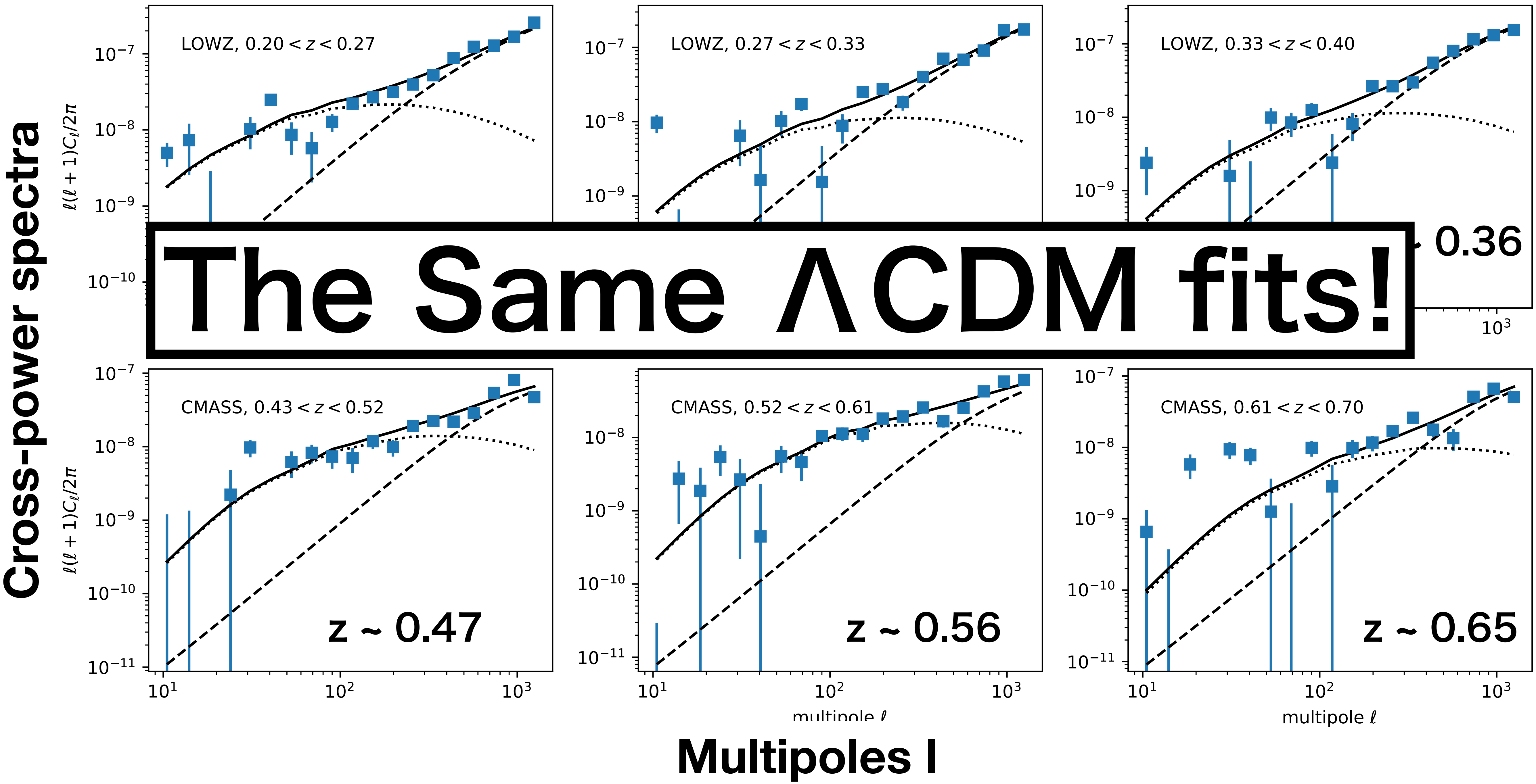
Cross-power spectra



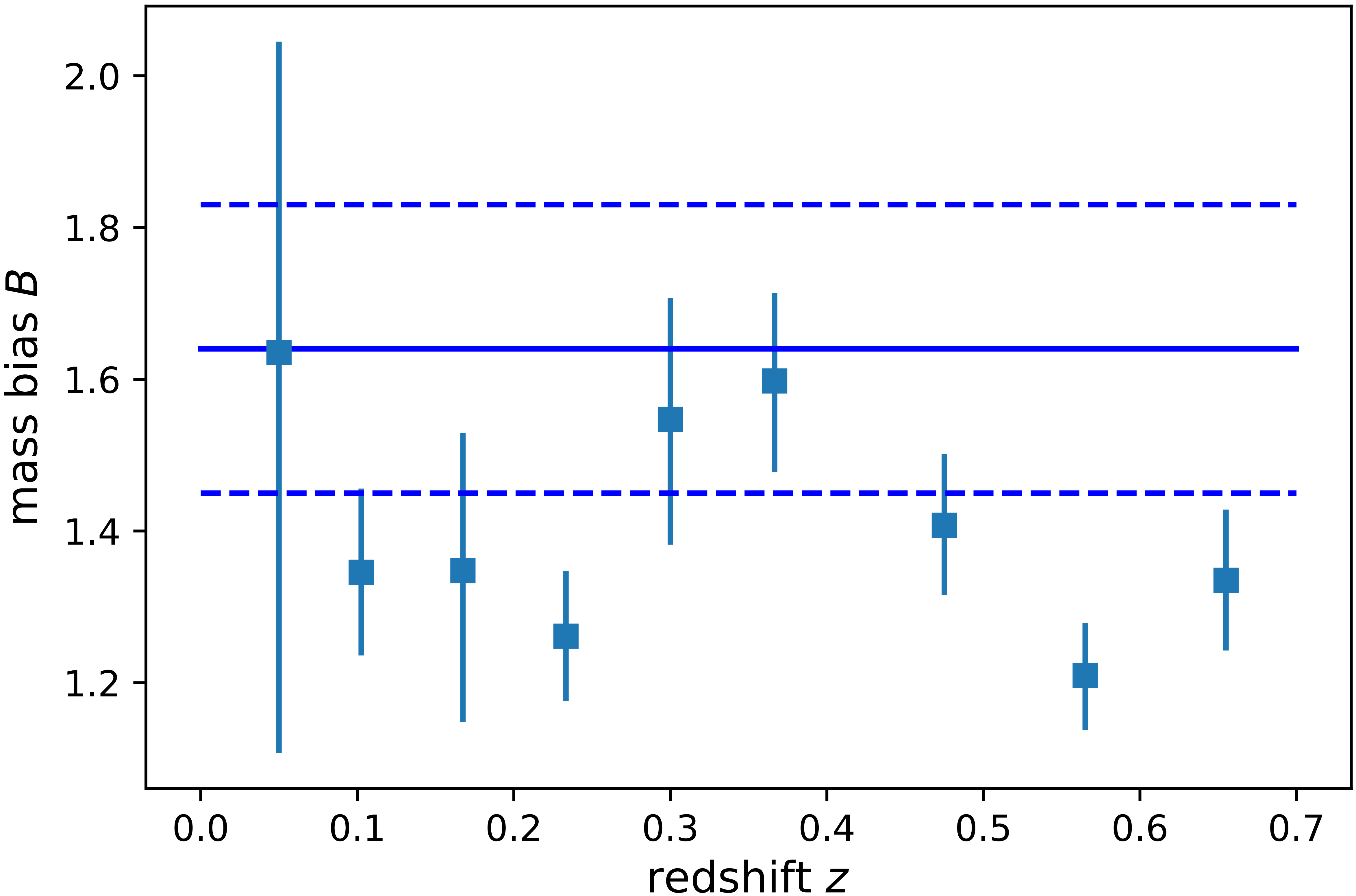
Multipoles l

Redshift evolution of tSZ

(RM et al. 2020 in prep.)

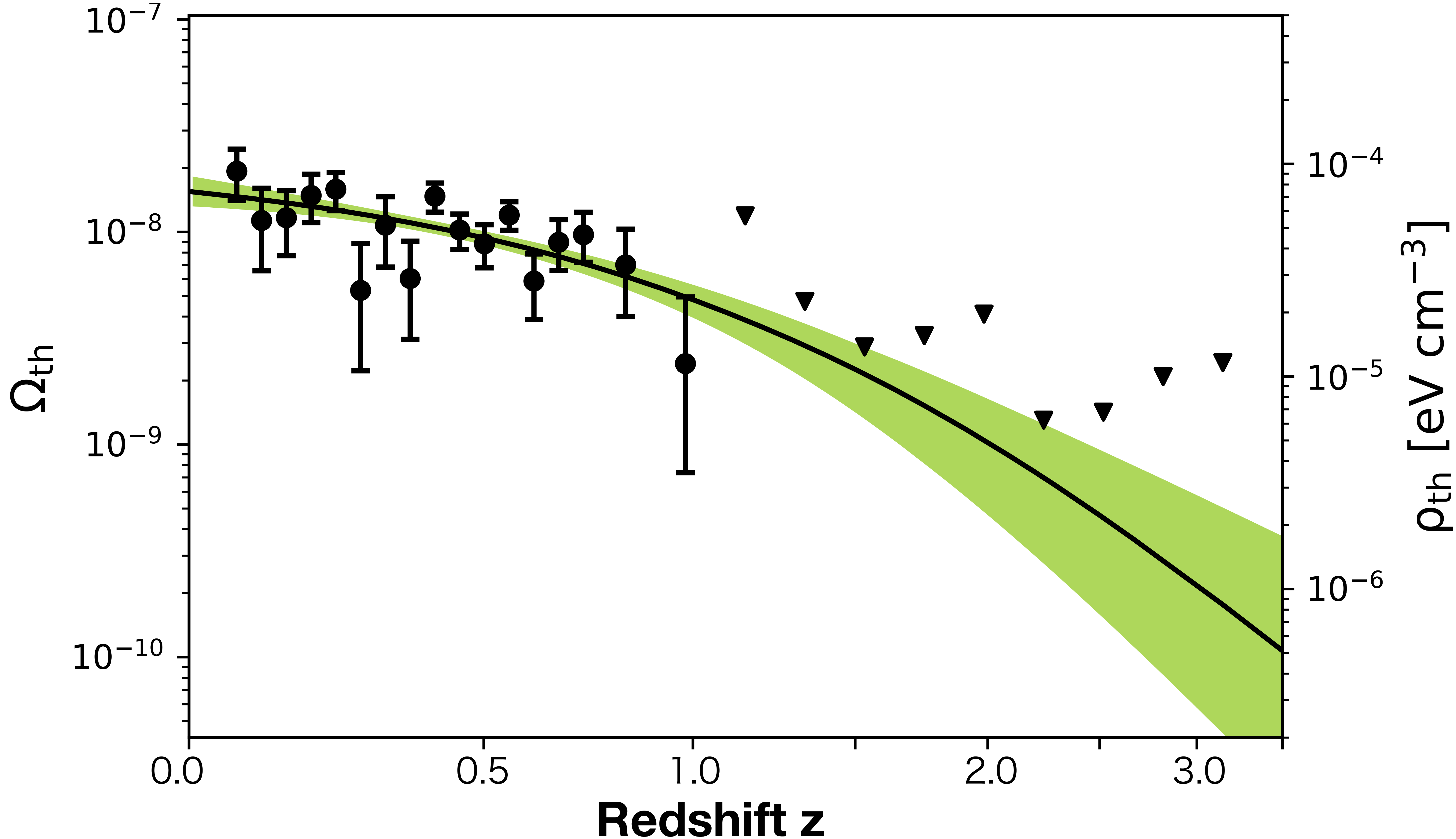


Redshift vs Mass bias
(preliminary!)



Thermal history of the Universe

(Chiang, RM et al. 2020 in prep.)



Summary

- Cluster mass bias is critical in cluster cosmology
- Planck+tSZ auto and 2MRS x tSZ yields higher mass bias than hydro simulations (RM et al. 2018)
- tSZ also may be in tension with primordial CMB (RM et al. 2020)
- ΛCDM can explain the redshift evolution of the tSZ with constant mass bias (RM et al. 2020 in prep.)