# Tomographic cross-correlation of the CMB lensing and galaxy clustering – systematic errors from cross-talk between redshift bins of galaxies

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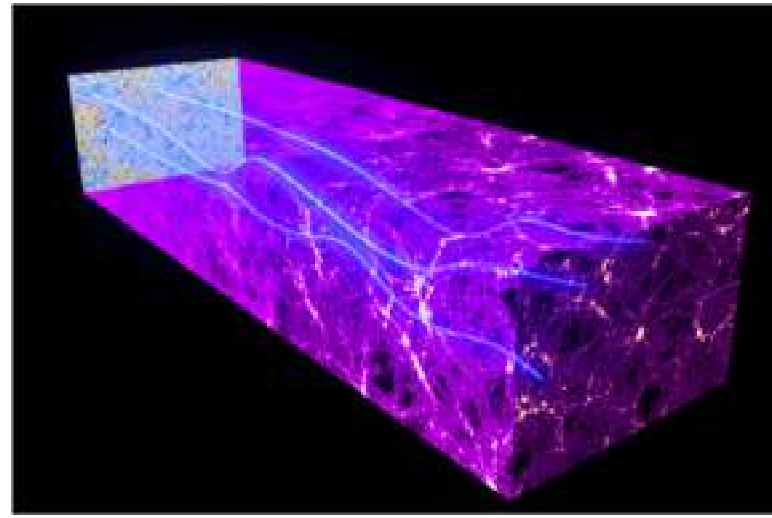
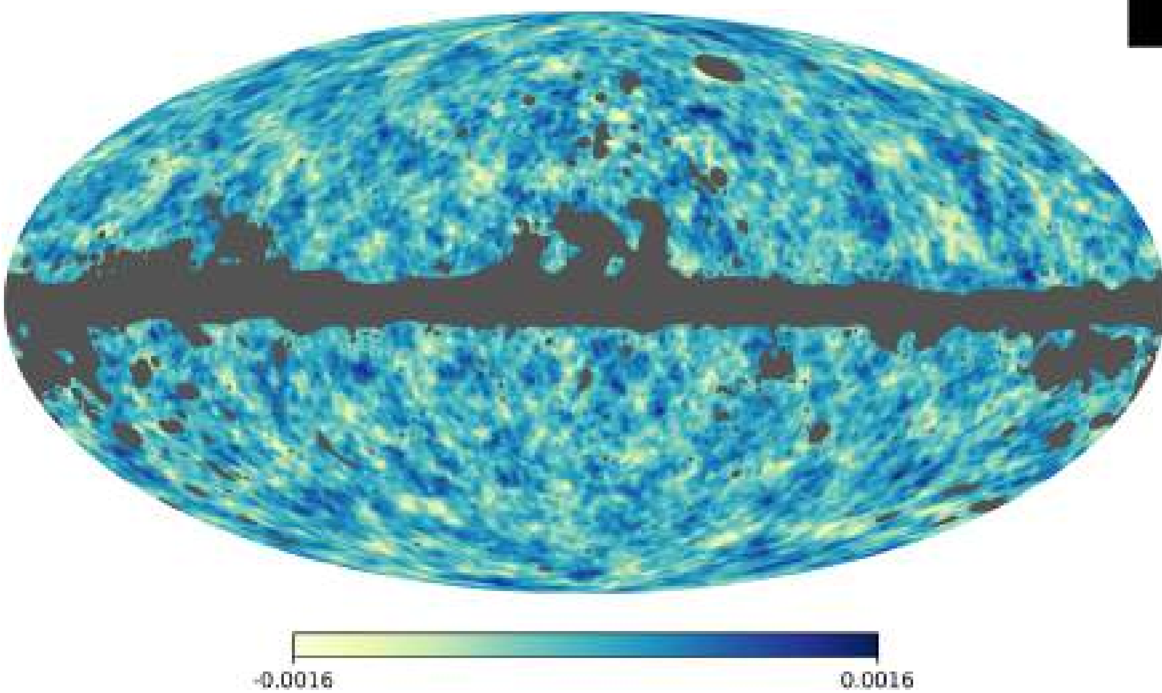
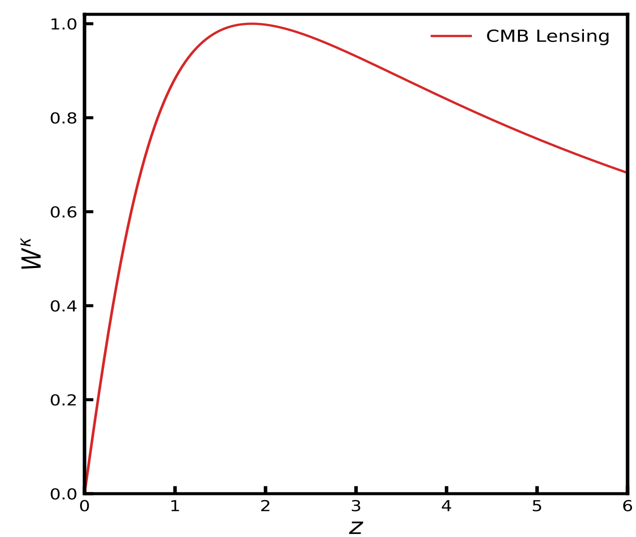
# CMB lensing

- Deflection of the CMB photon paths by the large scale structure of the Universe ( ~3’ )
- Correlation of deflection angles over the sky
- Reconstruction of lensing potential from perturbations of statistical properties of CMB anisotropy
- Tracer of dark matter distribution in broad redshift range



$$\phi(\hat{n}) = -\frac{2}{c^2}\int_0^{\chi_{rec}} d\chi \frac{D_{ls}}{D_l D_s}\Psi(\chi_0 - \chi, \chi\hat{n})$$




Planck collaboration et al. (2020)

# Cross-correlation between CMB lensing and galaxy surveys

- Broad CMB lensing kernel does not allow tracing time evolution of dark matter
- Needed cross-correlation of CMB lensing map with objects with known redshift (galaxies, quasars, radio sources, etc.)
- Splitting redshift distribution on redshift bins (cosmic tomography: White et al. 2022; Pandey et al. 2022; Chang et al. 2022; Sun et al. 2022; Krolewski et al. 2021; Hang et al. 2021; Peacock & Bilicki 2018 )

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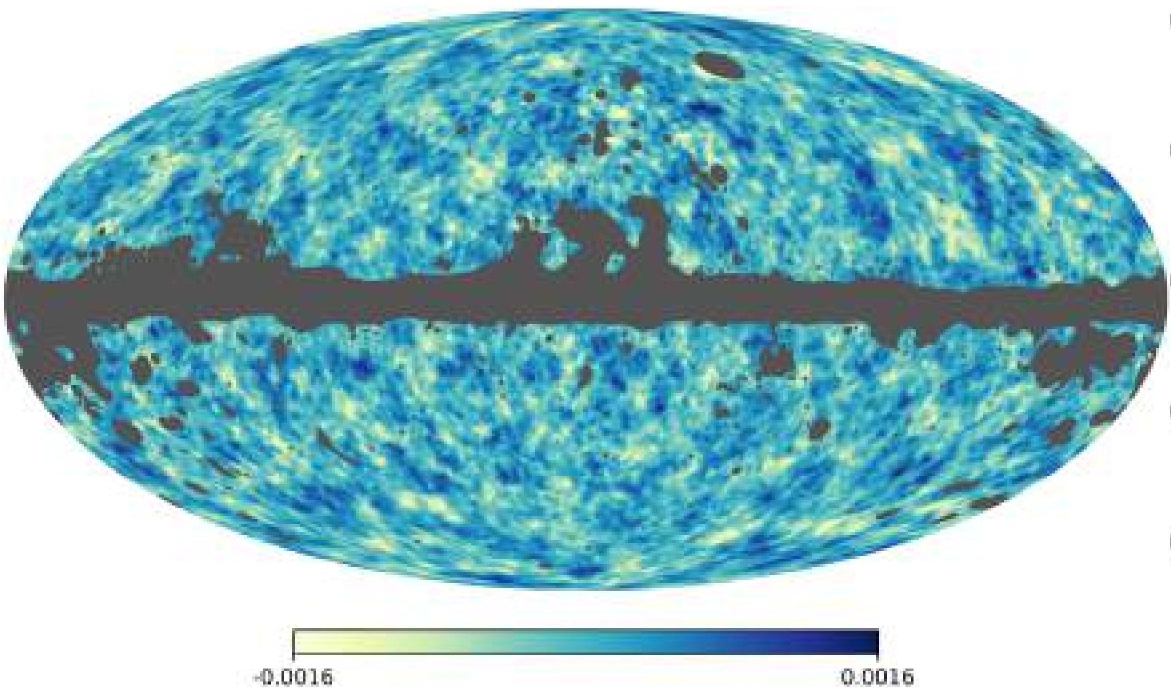


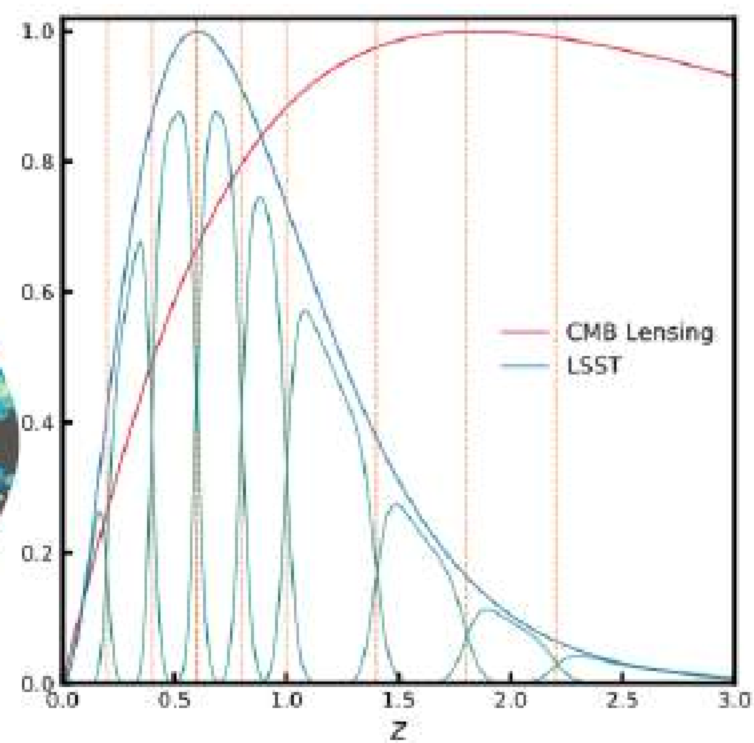


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- Power spectrum of cross-correlation between CMB lensing and galaxy density contrast

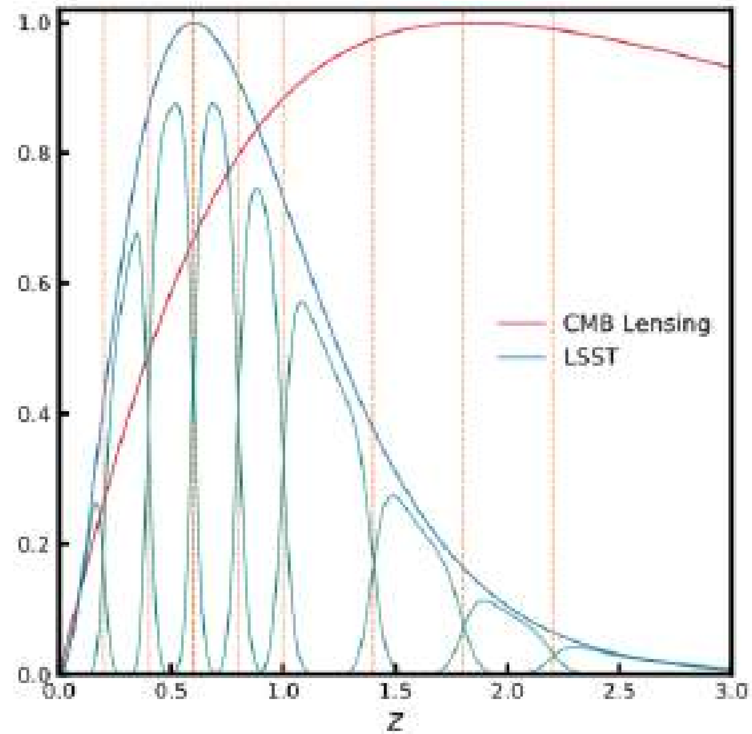
$$C_\ell^{\kappa g} = \int_0^{\chi_*} \mathrm{d}\chi \frac{W^\kappa(\chi)\, W^g(\chi)}{\chi^2}\, P_m\left(k = \frac{\ell + 1/2}{\chi}, z(\chi)\right) \qquad \theta \sim \frac{\pi}{\ell}$$

$$\kappa(\hat{\mathbf{n}}) = -\frac{1}{2}\nabla^2\phi(\hat{\mathbf{n}})$$

$$g = \frac{n - \bar{n}}{\bar{n}}$$

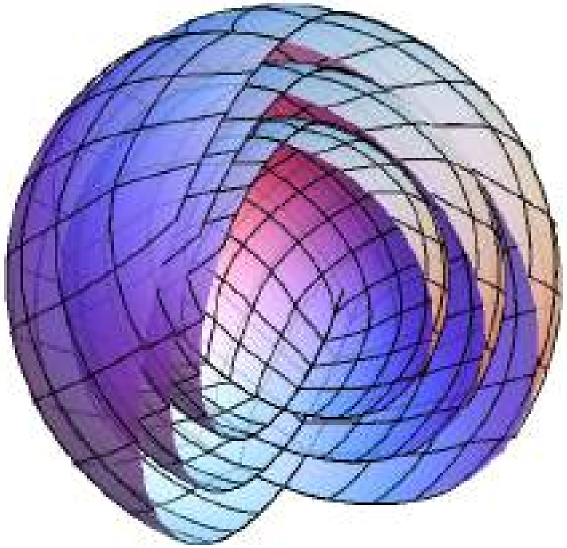
$$W^\kappa(\chi) = \frac{3\,\Omega_m}{2\,c^2} H_0^2 (1+z)\,\chi\, \frac{\chi_* - \chi}{\chi_*}$$

$$\mathrm{W}^g(\chi) = b(z(\chi))\, \frac{H(\chi)}{c}\, \frac{\mathrm{d}N}{\mathrm{d}z(\chi)}$$



# Testing tomographic cross-correlation

- How well can we measure cross-correlations in different redshift bins given photometric redshift errors?
- Test using simulations of forthcoming galaxy photometric surveys (LSST)
- 300 simulations of correlated log-normal galaxy over-density (with LSST Science Book redshift distribution) and CMB lensing convergence fields (consistent with Planck CMB lensing map) using Full-sky Lognormal Astro-fields Simulation Kit (FLASK) code (Xavier et al. 2016)



# Tomographic binning of redshift distribution

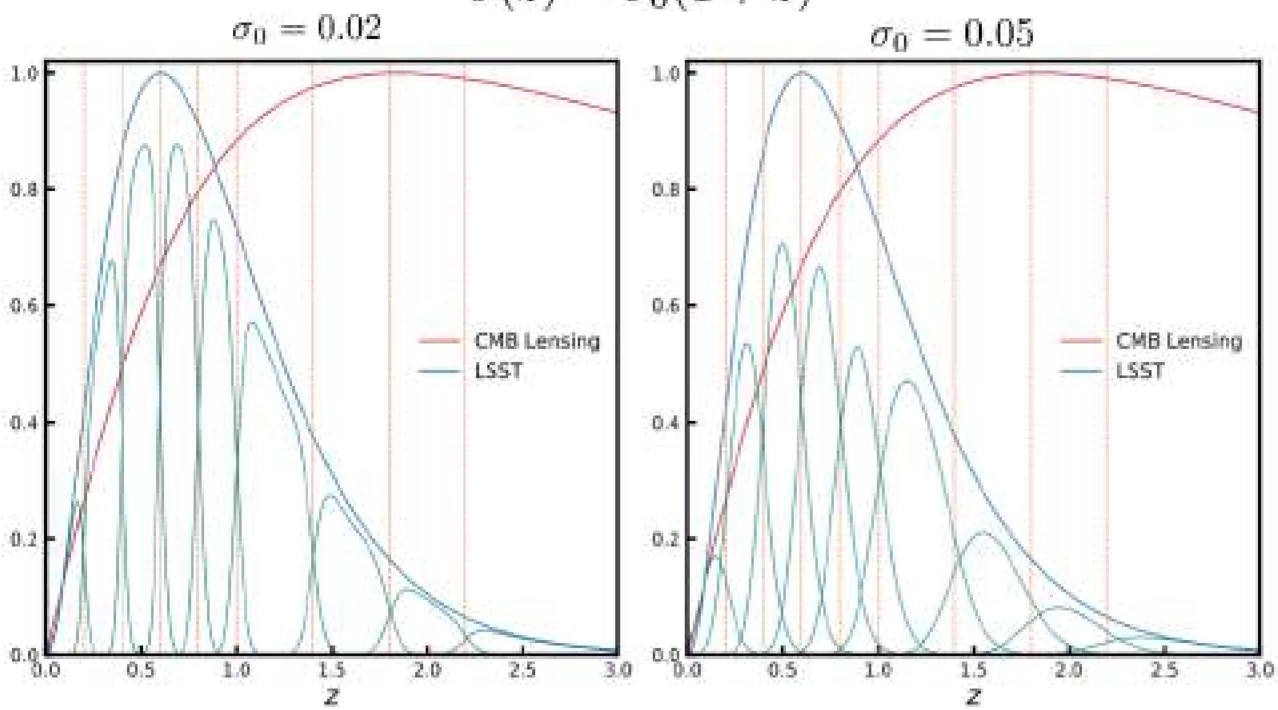
- Photometric redshifts $z_p$ obtained by adding Gaussian photo-z errors to true redshifts $z_t$

$$\frac{dN(z_p)}{dz_p} = \int dz_t \frac{dN(z_t)}{dz_t} p(z_p - z_t|z_t) \qquad p(z_p - z_t|z_t) = G(z_t, \sigma(z_t)) \qquad \sigma(z) = \sigma_0(1+z)$$

- Tomographic binning of the true redshift distribution

$$\frac{dN^i(z_p)}{dz_p} = \int dz_t \frac{dN(z_t)}{dz_t} W^i(z_t) p^i(z_p - z_t|z_t) \qquad W^i(z_t) = \begin{cases} 1, & \text{if} \quad z^i_{\rm min} \le z_t < z^{i+1}_{\rm min} \\ 0, & \text{otherwise} \end{cases}$$

$$\sigma(z) = \sigma_0(1+z)$$

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# Power spectra for tomographic analysis

- Power spectra for galaxies with photometric redshifts are related to power spectra for galaxies with true redshifts by (Zhang et al. 2010):

$$C_{ij}^{gg,\mathrm{Ph}}(\ell) = \sum_k P_{ki} P_{kj} C_{kk}^{gg,\mathrm{Tr}}(\ell)$$

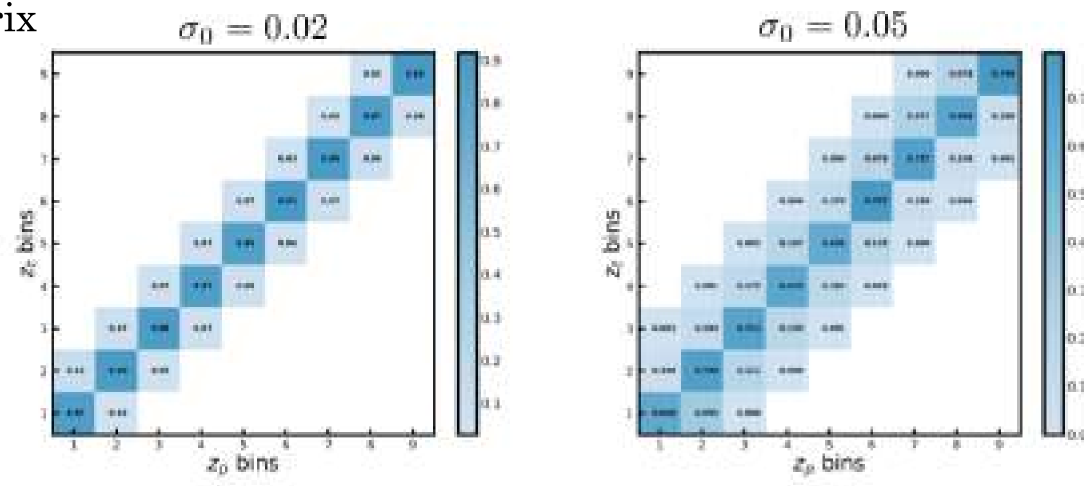
$$C_i^{\kappa g,\mathrm{Ph}}(\ell) = \sum_k P_{ki} C_{kk}^{\kappa g,\mathrm{Tr}}(\ell)$$

where $P_{ij} \equiv \frac{N_{i \to j}}{N_j^{Ph}}$ is so called scattering matrix

- Zhang et al. (2017) proposed algorithm, Non-negative Matrix Factorization, to solve

for $P_{ij}$ and $C_{kk}^{Tr}(\ell)$ having $C_{ij}^{Ph}(\ell)$

- With estimation of the true redshift distribution it is possible fast method of computation of the scattering matrix




(a) $\langle P \rangle$ (b) $\langle P \rangle$

$$|\langle P - P^{True} \rangle| < 0.006$$

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# Power spectra for tomographic analysis

- Naive approach to model power spectra for galaxies with photo-z

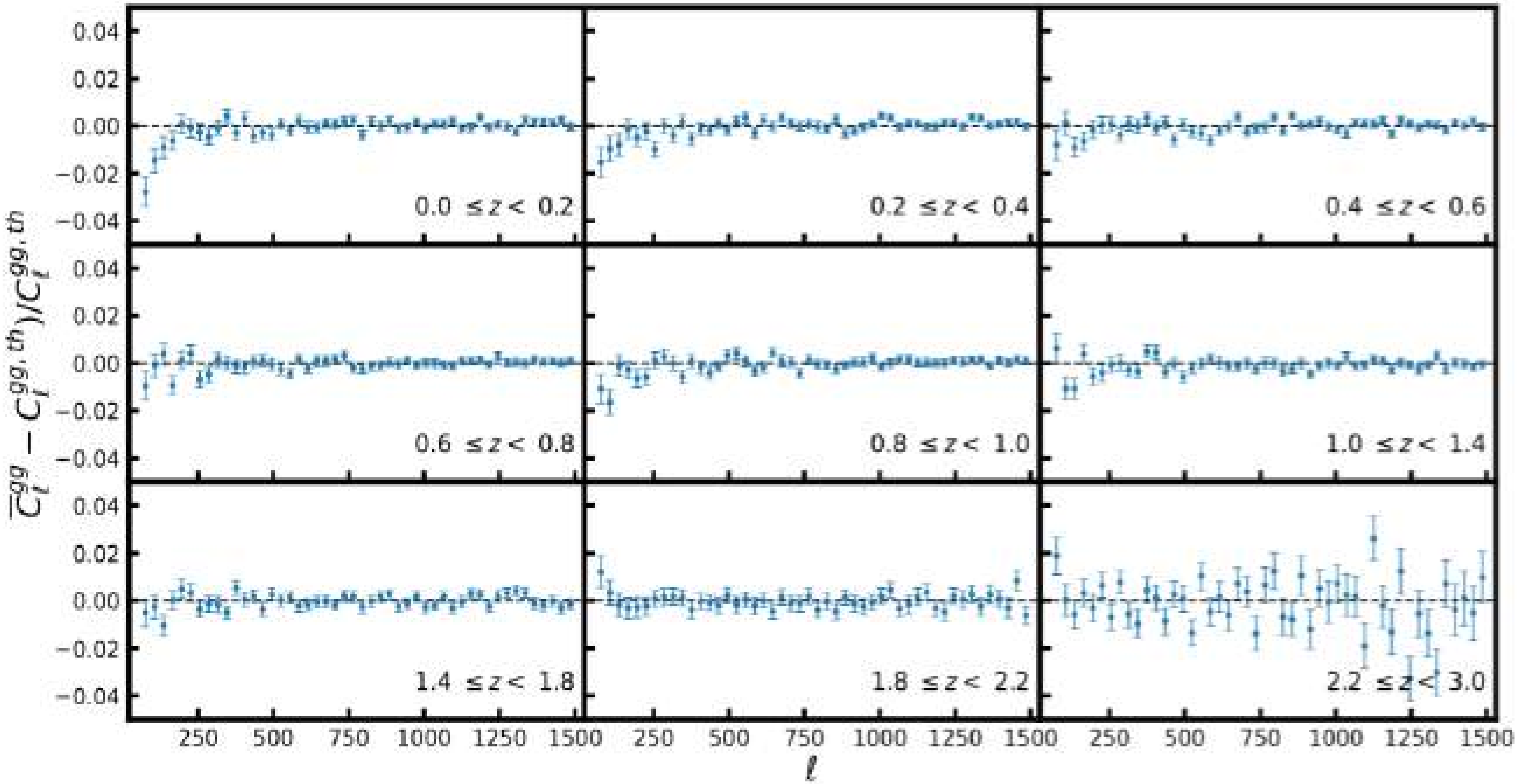
$$C_i^{gg,Ph}(\ell) = \int_0^{\chi_*} \frac{\mathrm{d}\chi}{\chi^2} \left( b(z_p) \frac{dN^i(z_p)}{dz_p} \right)^2 P_m \left( k = \frac{\ell + 1/2}{\chi}, z_p(\chi) \right)$$

$$C_i^{\kappa g,Ph}(\ell) = \int_0^{\chi_*} \frac{\mathrm{d}\chi}{\chi^2} W^\kappa(\chi)\, b(z_p) \frac{dN^i(z_p)}{dz_p} P_m \left( k = \frac{\ell + 1/2}{\chi}, z_p(\chi) \right)$$

# Tests for simulations without photo-z errors

- Estimation of the angular power spectra

$$\hat{C}_L^{xy} = \sum_{L'} K^{-1}_{LL'} \left( \tilde{C}_{L'}^{xy} - \left\langle \tilde{N}_{L'}^{xy} \right\rangle_{MC} \right) \qquad \tilde{C}_\ell^{xy} = \frac{\sum_m \tilde{a}^x_{\ell m} \tilde{a}^{y*}_{\ell m}}{2\ell + 1}$$

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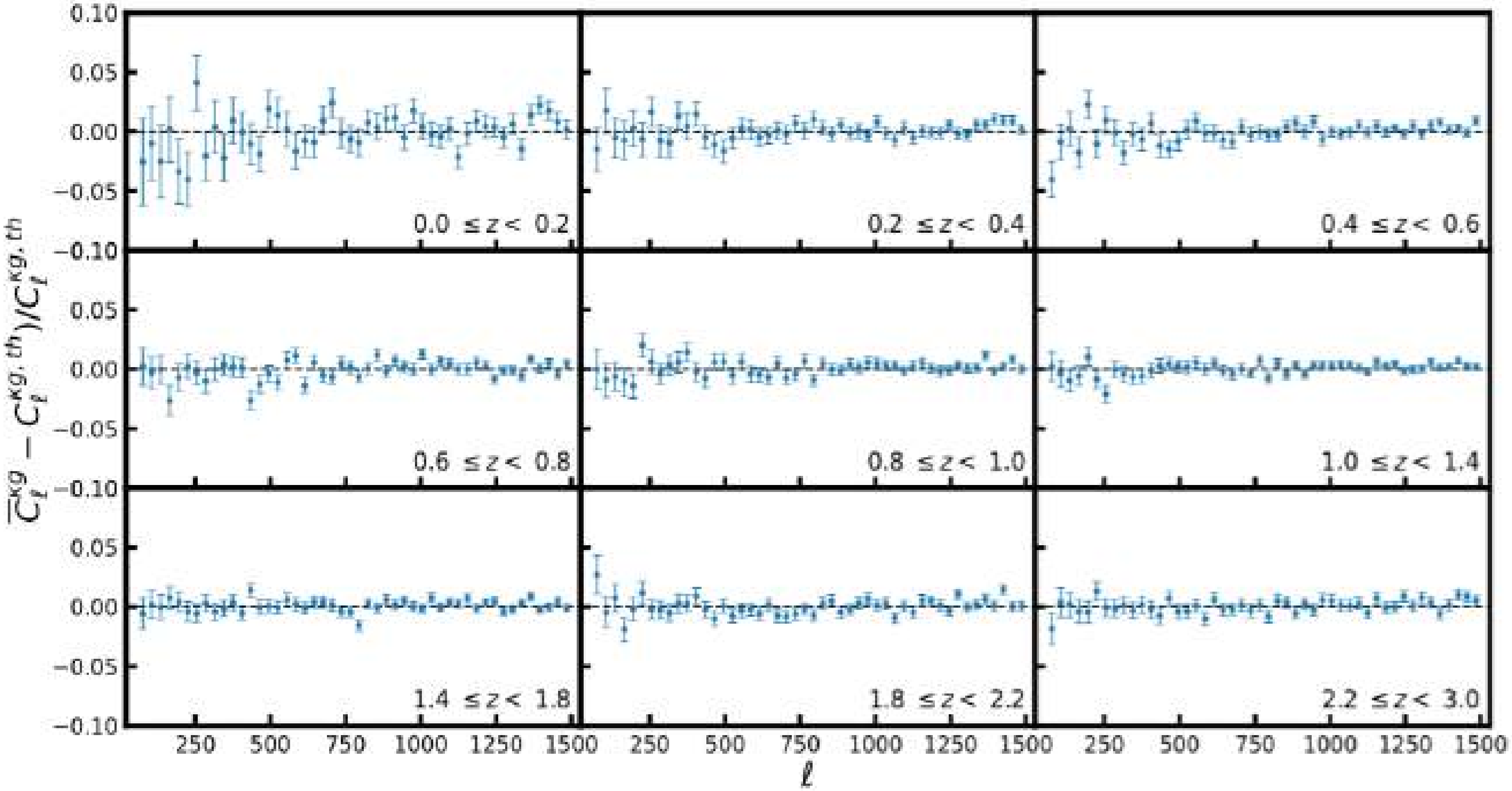
# Tests for simulations without photo-z errors

- Estimation of the angular power spectra

$$\hat{C}_L^{xy} = \sum_{L'} K_{LL'}^{-1} \left( \tilde{C}_{L'}^{xy} - \left\langle \tilde{N}_{L'}^{xy} \right\rangle_{MC} \right) \qquad \tilde{C}_\ell^{xy} = \frac{\sum_m \tilde{a}_{\ell m}^x \tilde{a}_{\ell m}^{y*}}{2\ell + 1}$$

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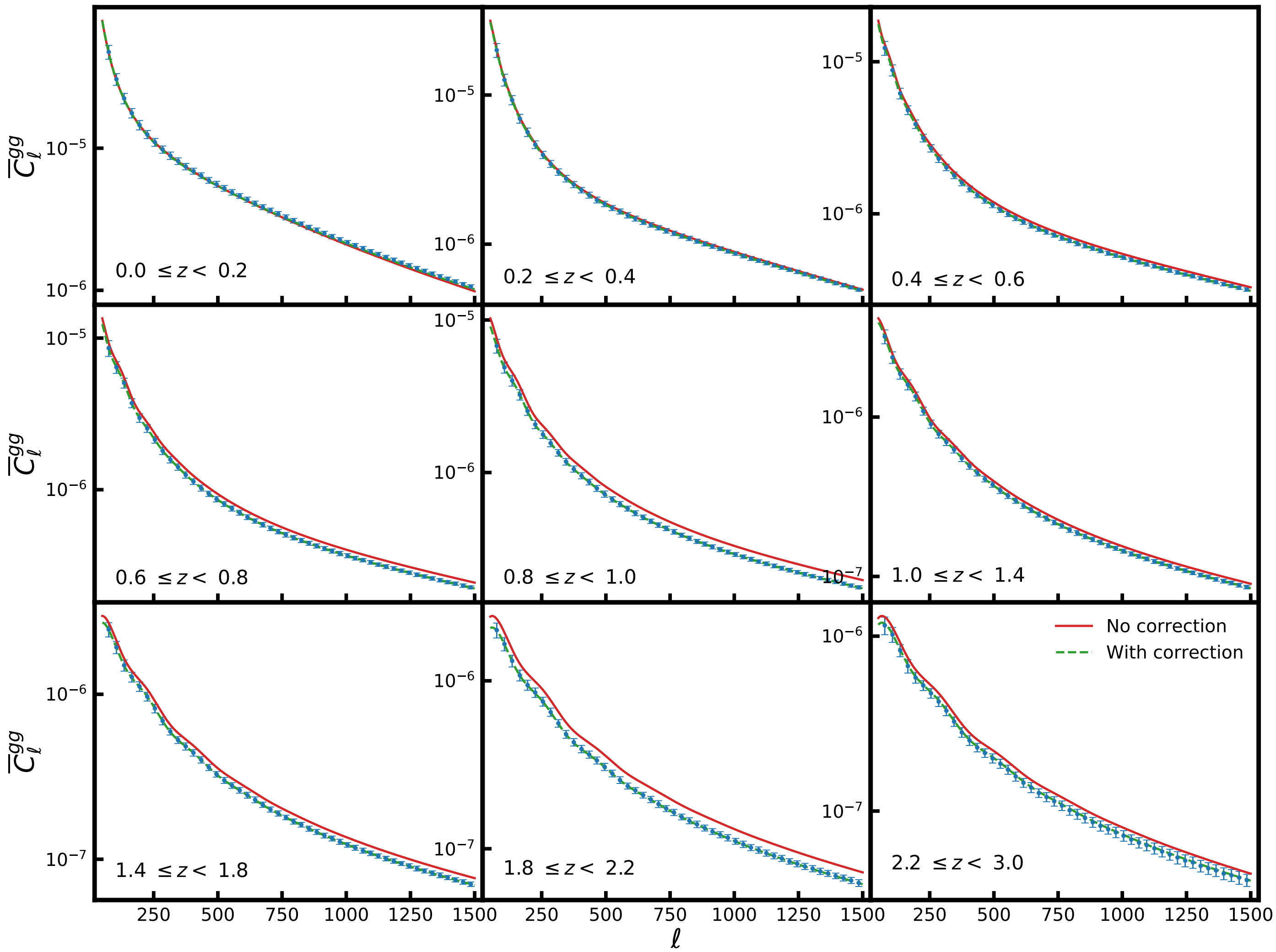
$\sigma_0 = 0.02$

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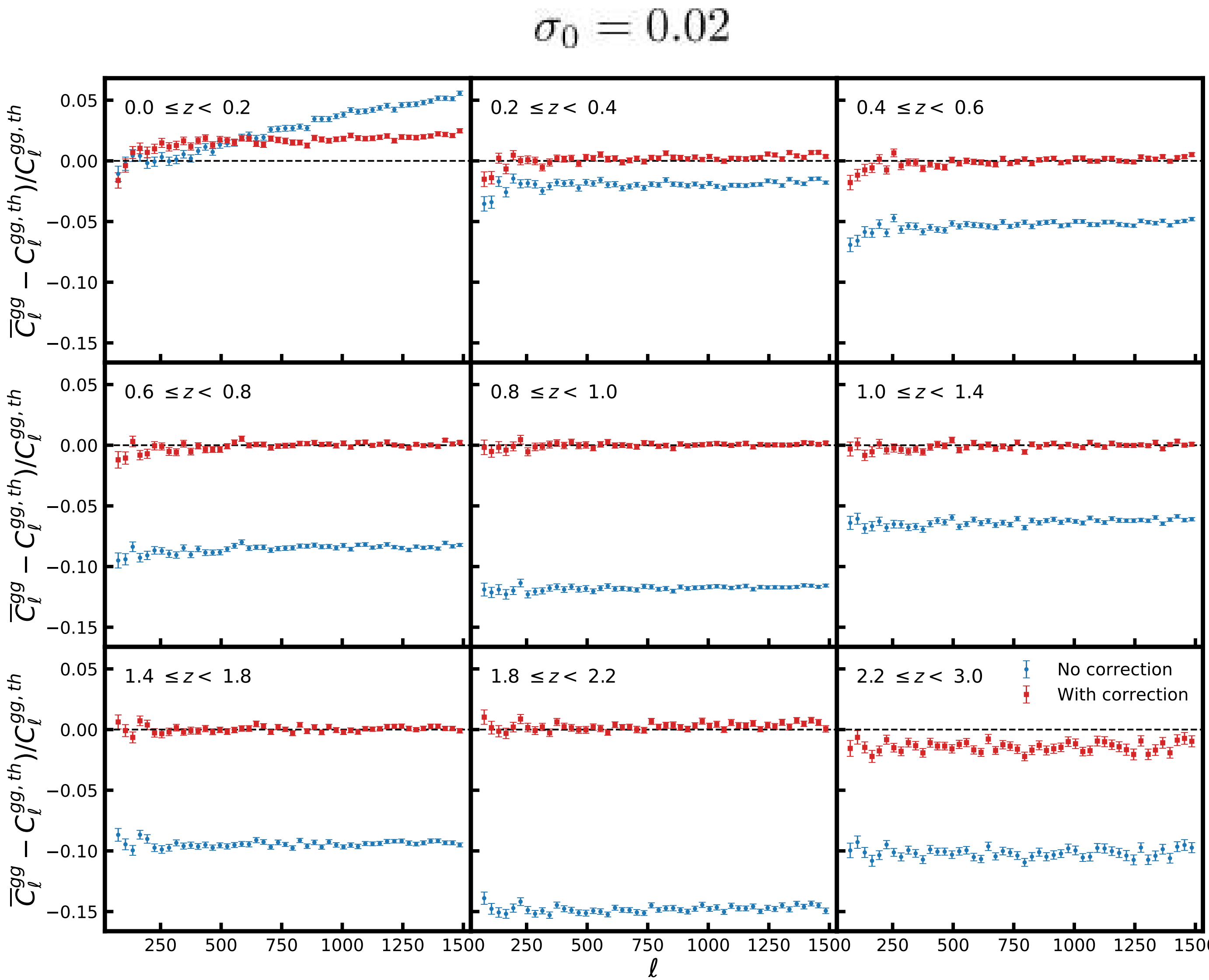
# Tests for simulations with photo-z errors

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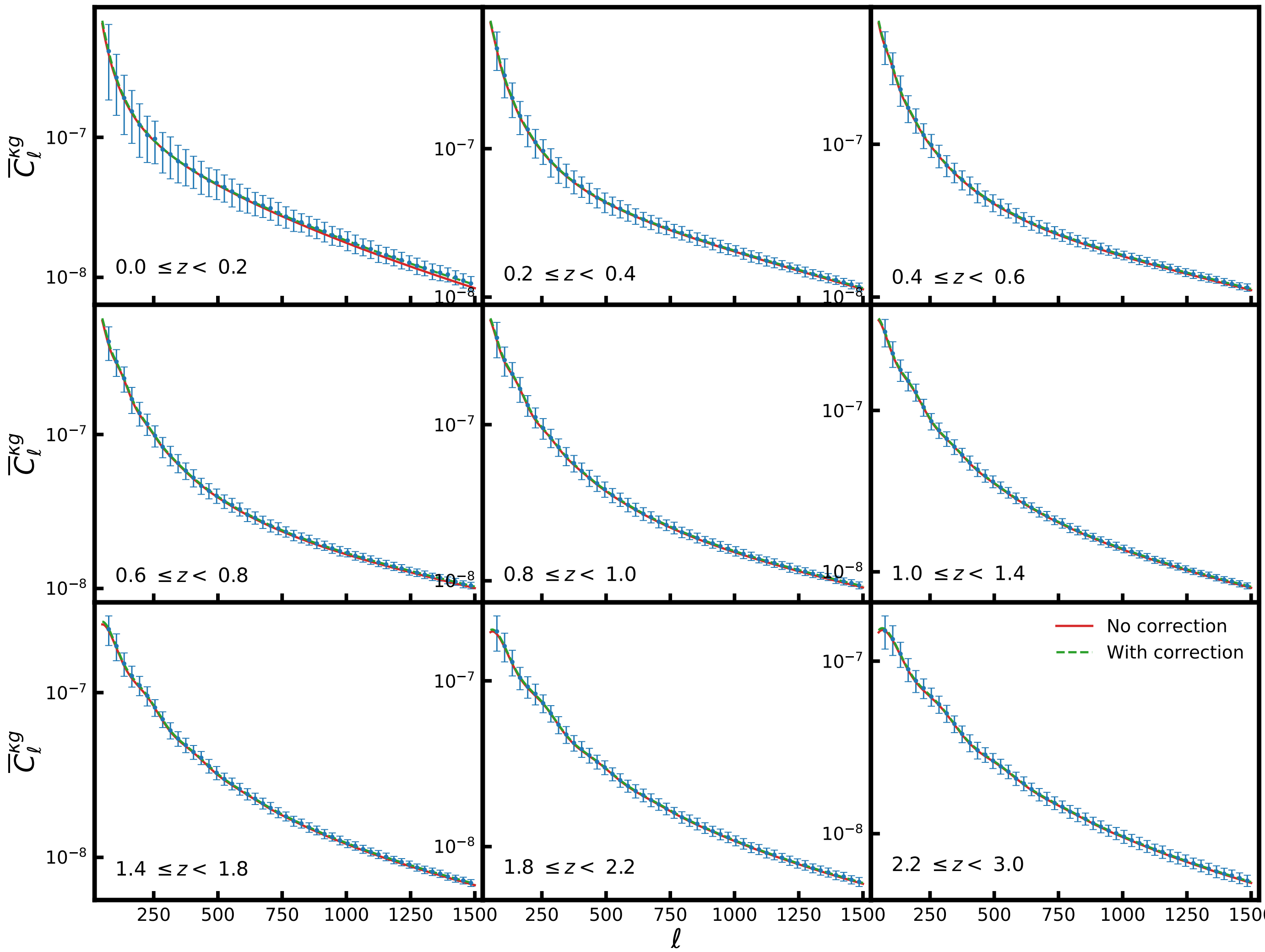


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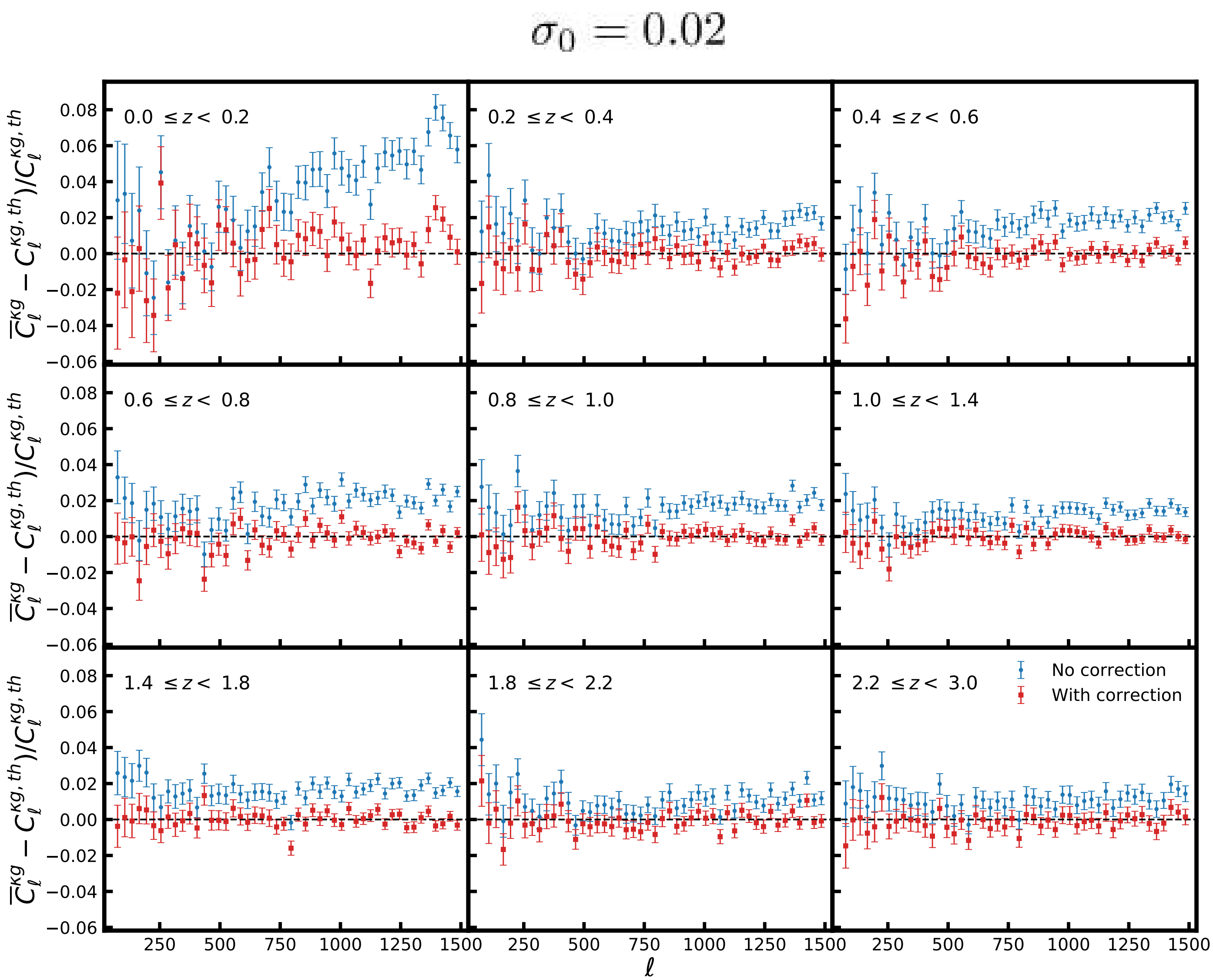


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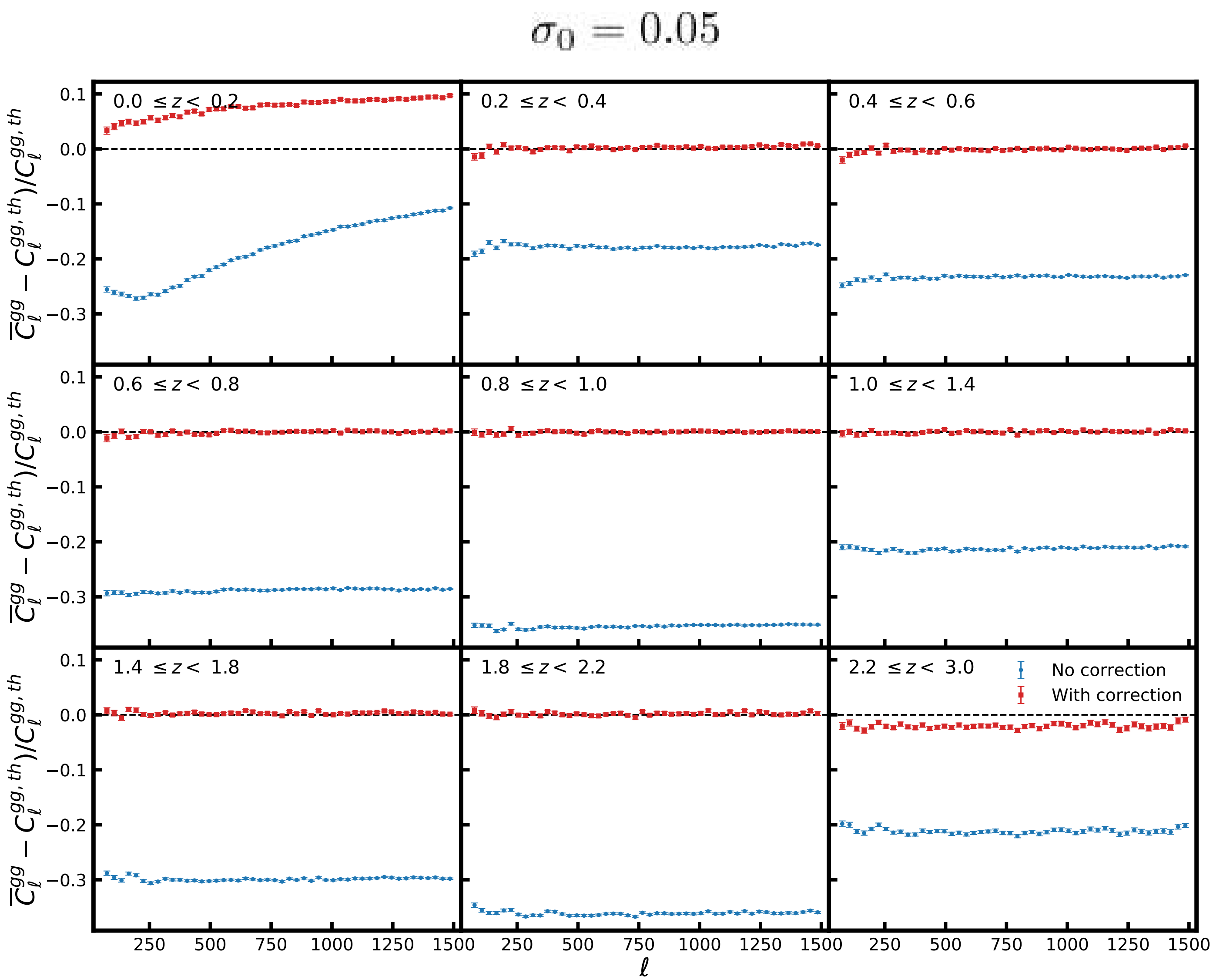


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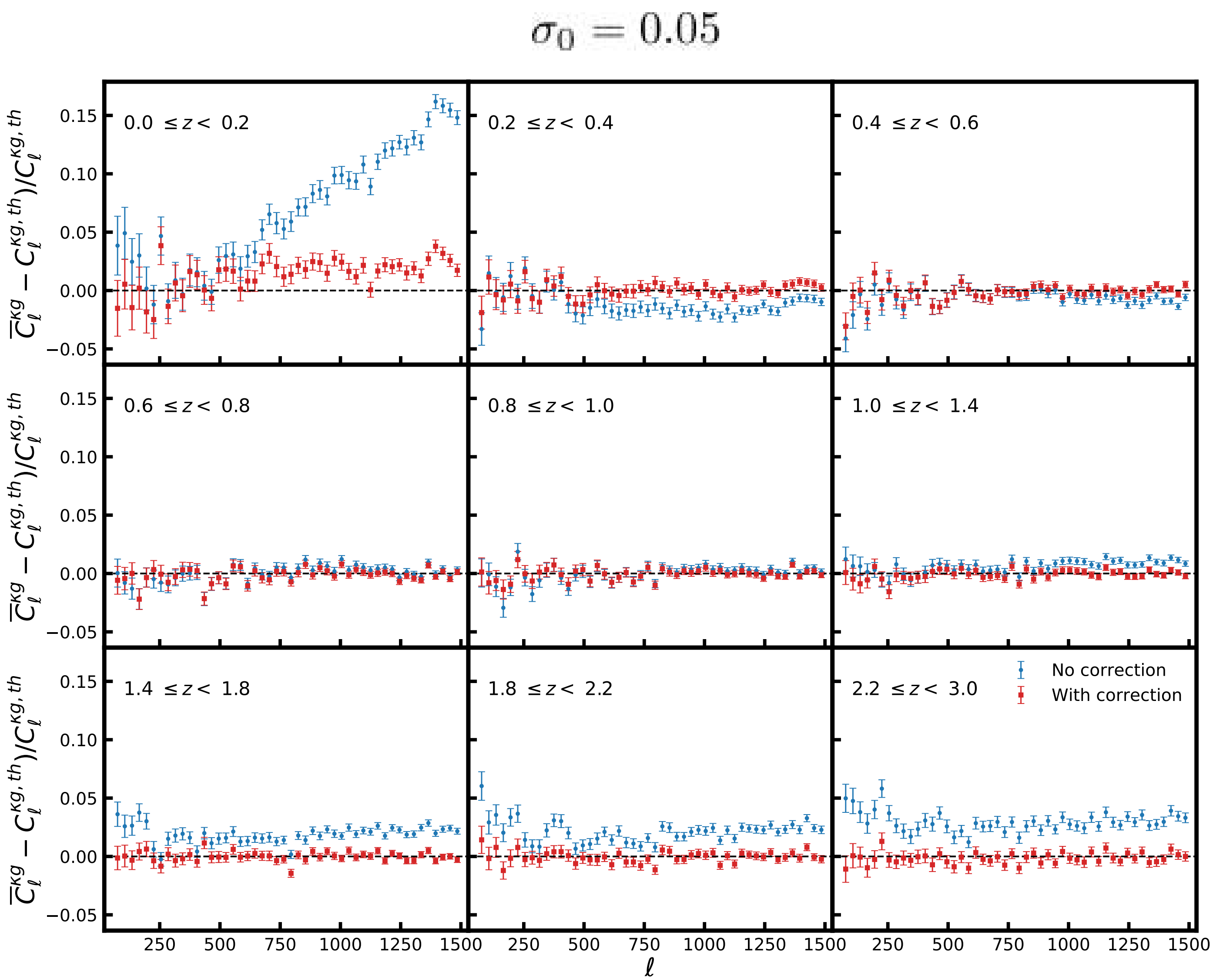


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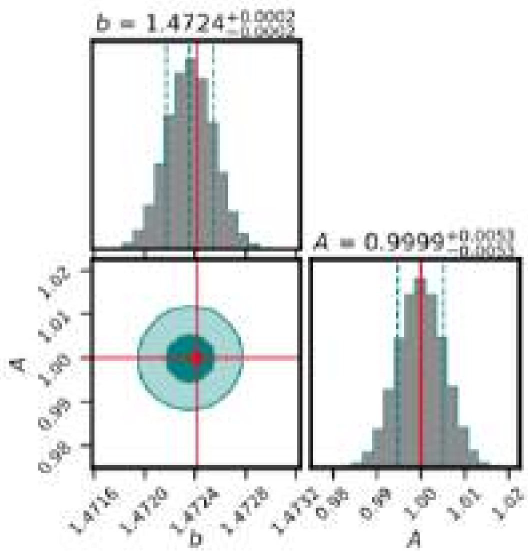
Fitting parameters using the maximum likelihood method:

$$\mathcal{L}(\hat{C}_L|b,A) = \frac{1}{\sqrt{(2\pi)^{N_L} det(\mathrm{Cov}_{LL'})}} \times$$

$$\times \exp\left\{ -\frac{1}{2}[\hat{C}_L - C_L(b,A)](\mathrm{Cov}_{LL'})^{-1}[\hat{C}_{L'} - C_{L'}(b,A)] \right\}$$

- Linear galaxy bias: $b(z) = 1 + \frac{b_0 - 1}{D(z)}$ $\quad C_L^{gg} \propto b(\bar{z})^2\, C_L^{gg,\mathrm{fid}}$
- Amplitude of cross-correlation A : scales the amplitude of the cross-power spectrum (equals 1 for the ΛCDM model) $\quad C_L^{\kappa g} \propto A\, b(\bar{z})\, C_L^{\kappa g,\mathrm{fid}}$




Bin 5 $(0.8 \leq z < 1.0)$

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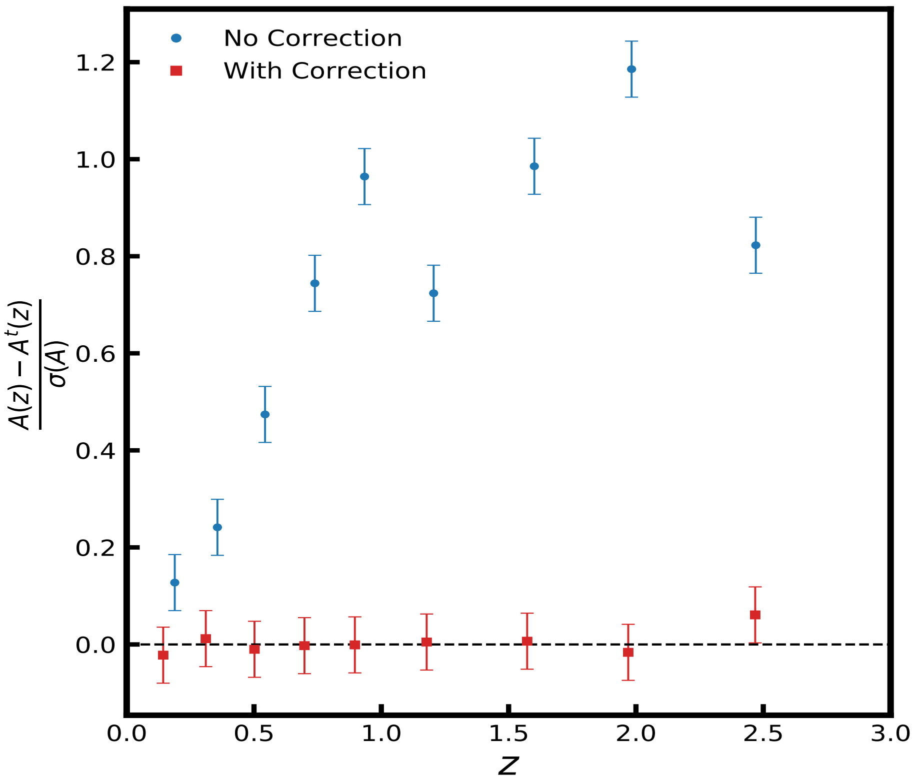
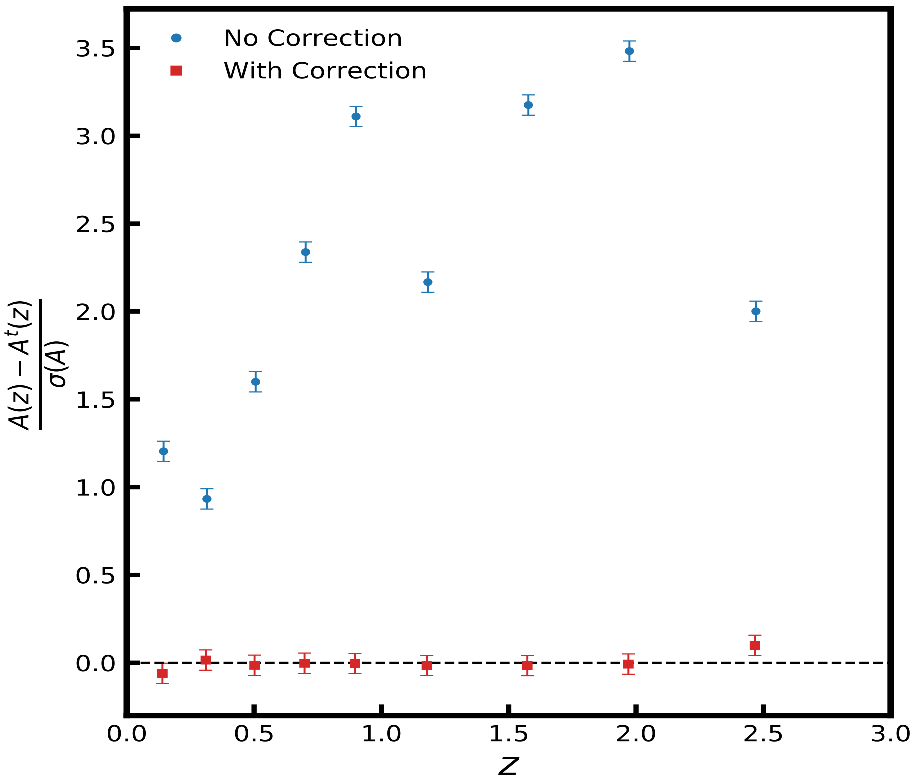
# Estimation of the parameters

$\sigma_0 = 0.02$




$\sigma_0 = 0.05$

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# Estimation of the parameters

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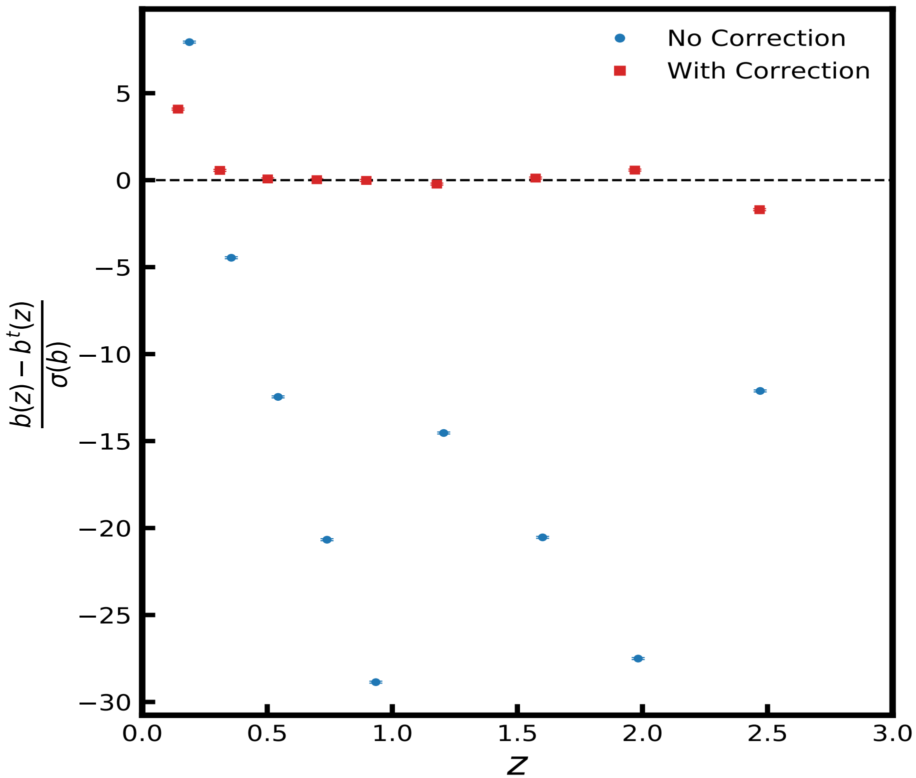


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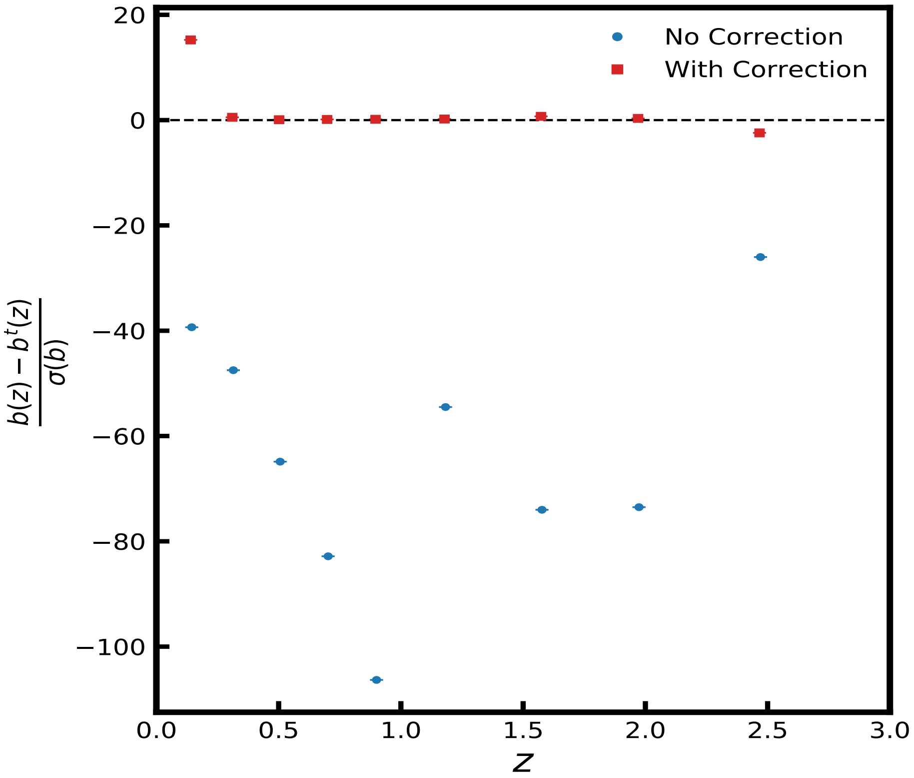


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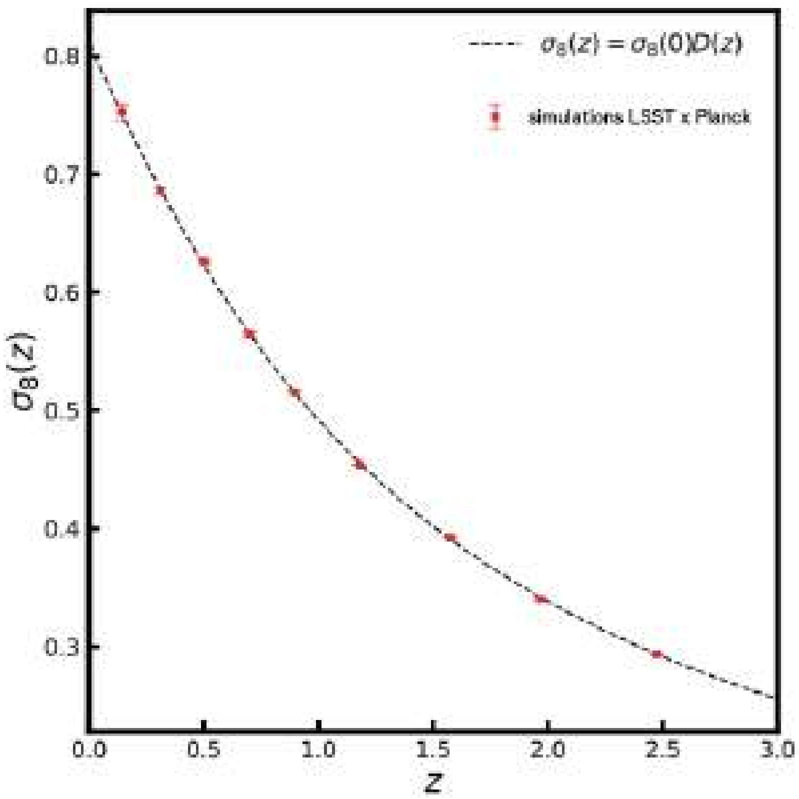


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# Conclusions

- Tomographic cross-correlation between CMB lensing map and galaxy surveys useful for tracing time evolution of the large-scale structure

- Systematic errors caused by redshift bin mismatch of galaxies with photo-z
  - ~10-15% for galaxy auto-power spectra, ~2% for cross-power spectra ( $\sigma_0 = 0.02$)
  - ~1 standard deviation for the correlation amplitude, ~10-20 standard deviations for the galaxy bias ( $\sigma_0 = 0.02$ )

- Needed correction for the redshift bin mismatch using scattering matrix formalism

- Possible fast computation of the scattering matrix using estimation of the true redshift distribution (needed accurate estimation of the photo-z error distribution)