Higher order lensing effects in CMB lensing cross-correlation with LSS

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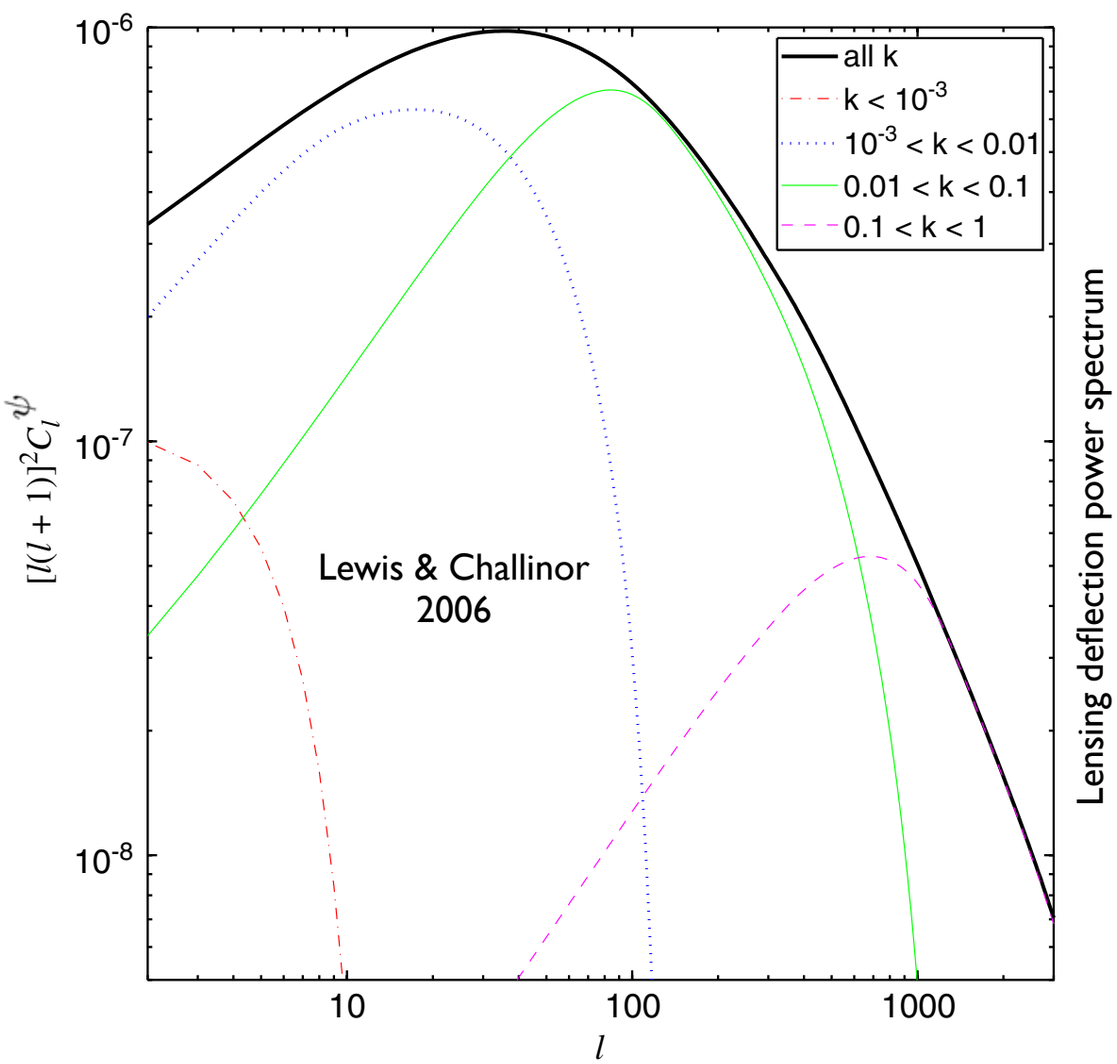
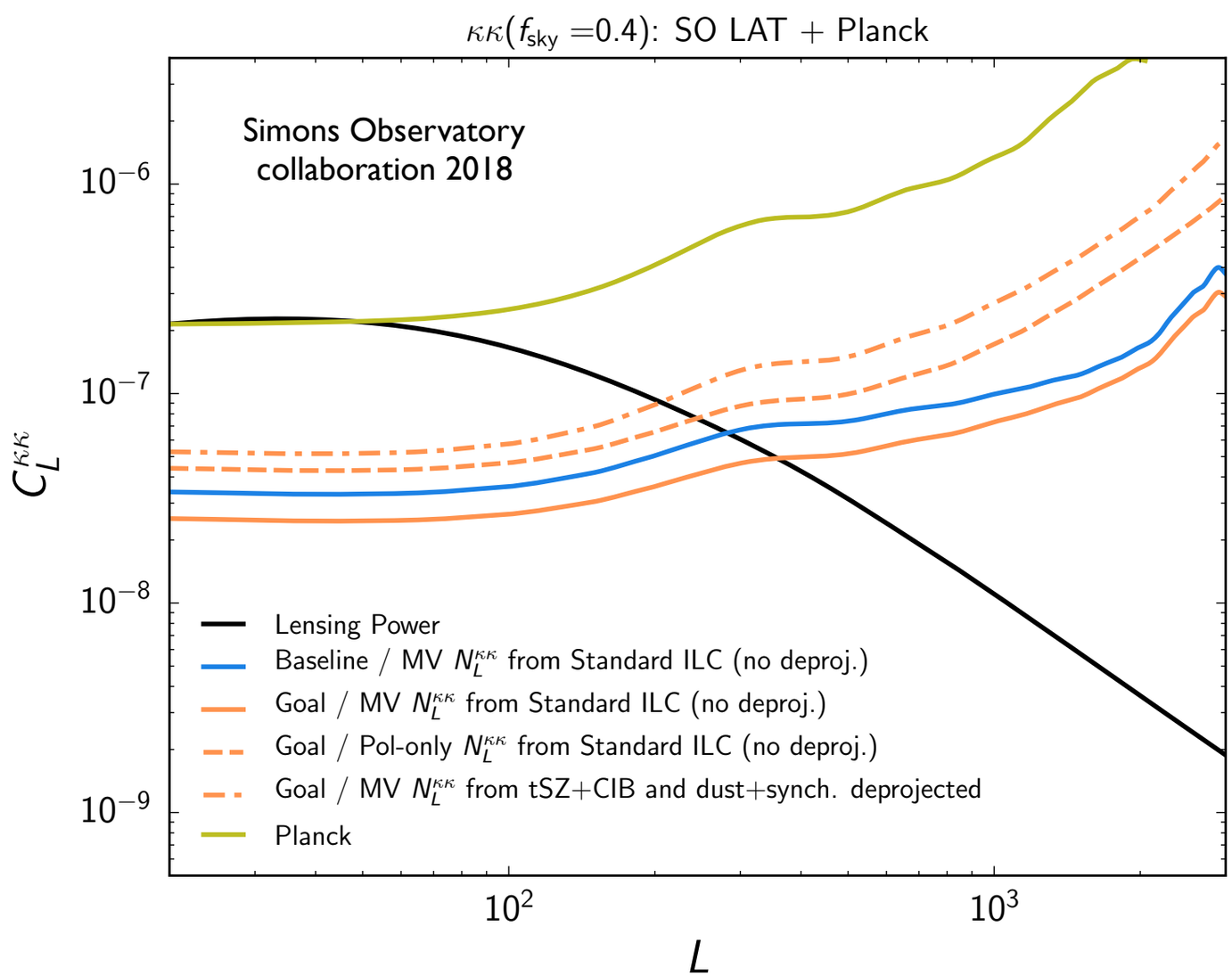
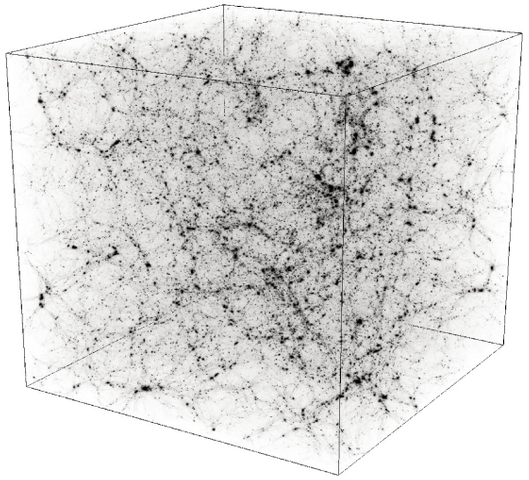
Are we ready for precision cross-correlation?

- Is our forward modeling sufficiently good for the high-precision era?
- How non-linear evolution affects lensing observables and cross-correlation?
- Is the Born (single deflection) approximation good enough?





How to include non-linearities?



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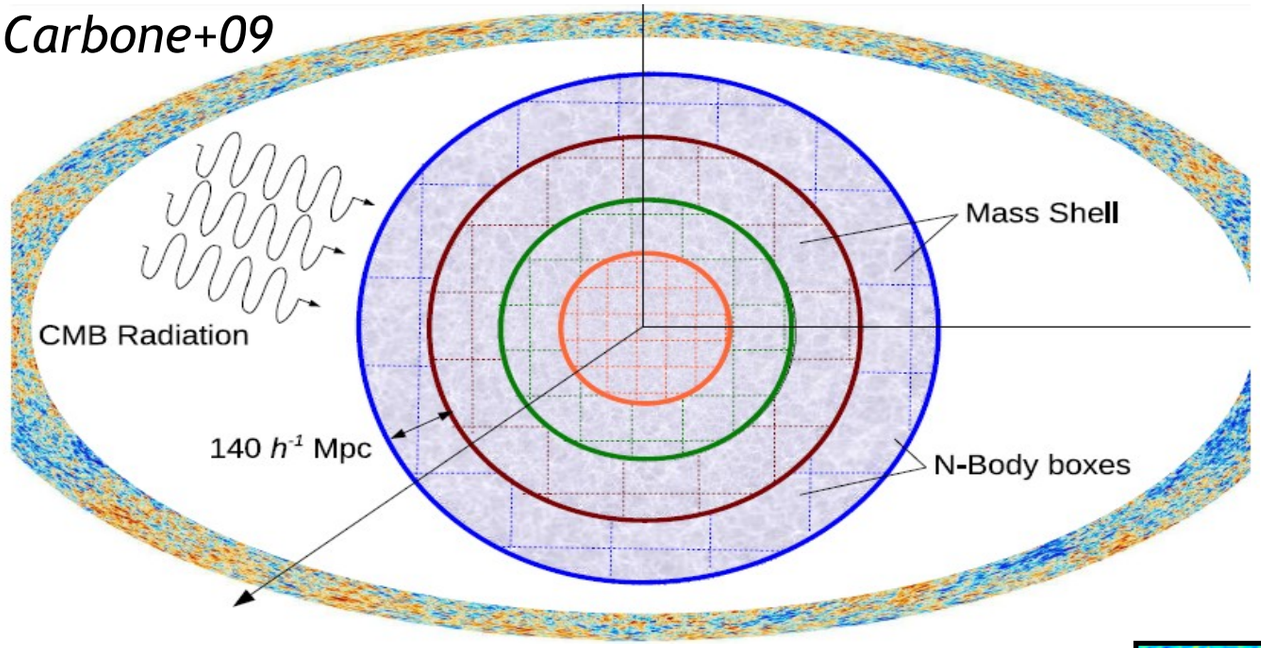
Carbone+09



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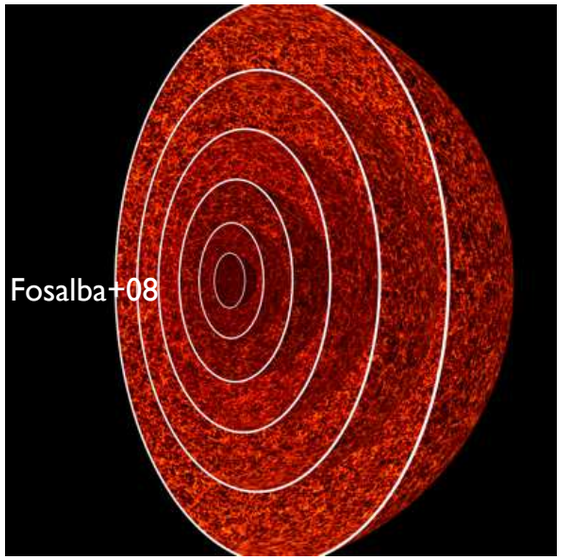


$$K^{(k)}(\hat{\mathbf{n}}) = \frac{4\pi G}{c^2}\frac{1+z_k}{D_A(\eta_k)}\Delta_\Sigma^{\theta(k)}(\hat{\mathbf{n}})$$

- Non-linearities fully accounted

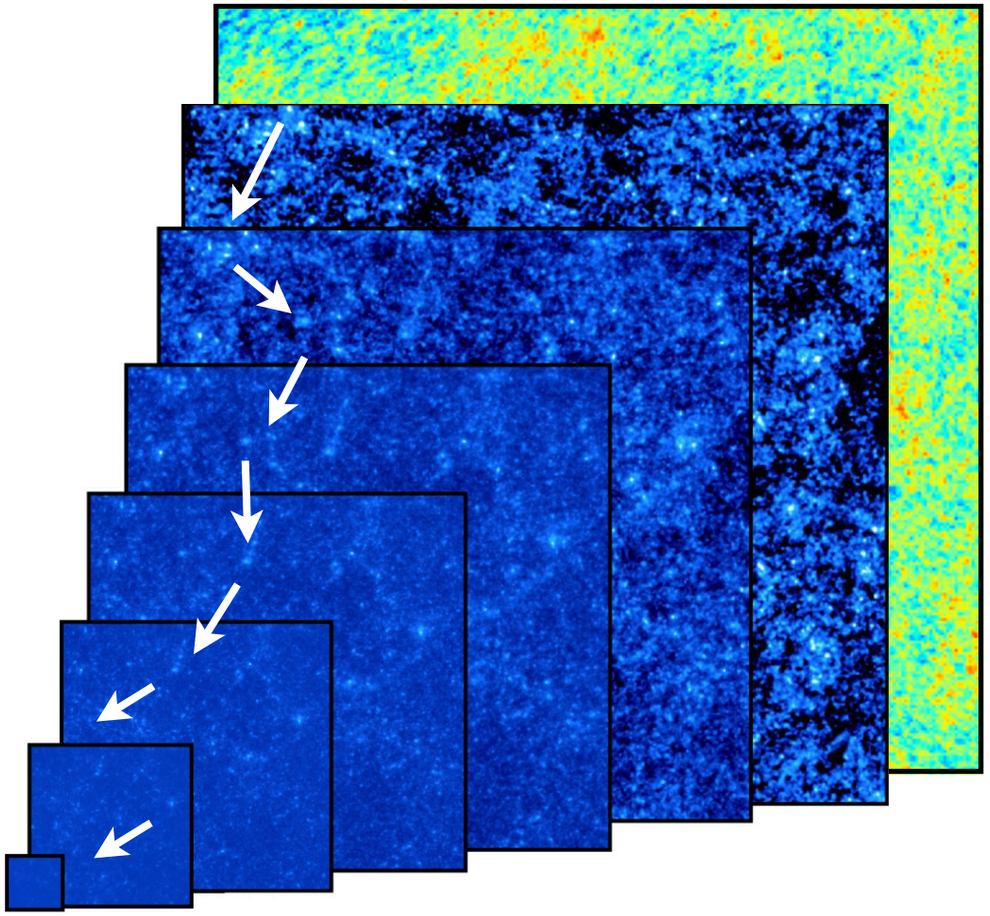
$$\psi_{\ell m}^{(k)} = \frac{-2}{\ell(\ell+1)}K_{\ell m}^{(k)} \qquad {}_1\alpha_{\ell m}^{(k),E} = \sqrt{\ell(\ell+1)}\psi_{\ell m}^{(k)}$$

- Flexible post-processing method

$$A_{ij}^N(\boldsymbol{\theta},\chi_N) = I_{ij} - \sum_{k=0}^{N-1}\frac{D_{k,N}}{D_N}U_{ip}^{(k)}(\boldsymbol{\beta}^{(k)},\chi_k)A_{pj}^{(k)}(\boldsymbol{\theta},\chi_k)$$

- Capitalize on LSS survey simulation effort

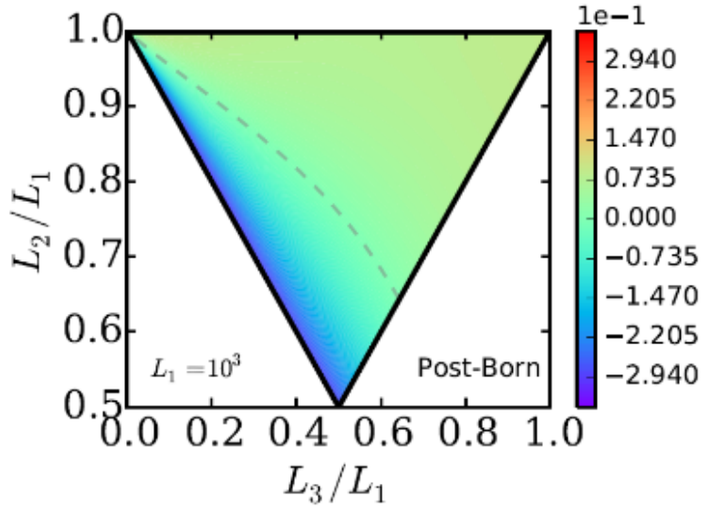
$$A_{ij} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2+\omega \\ -\gamma_2-\omega & 1-\kappa+\gamma_1 \end{pmatrix}$$

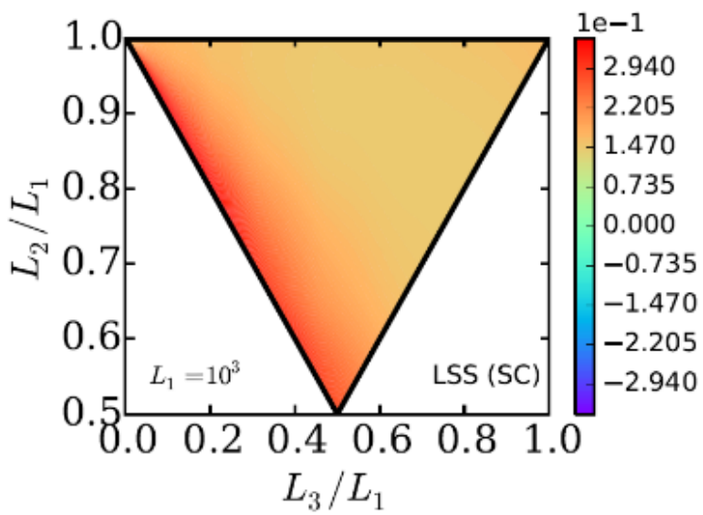


Calabrese, Carbone, GF+ (2015)
GF, Calabrese, Carbone (2018)

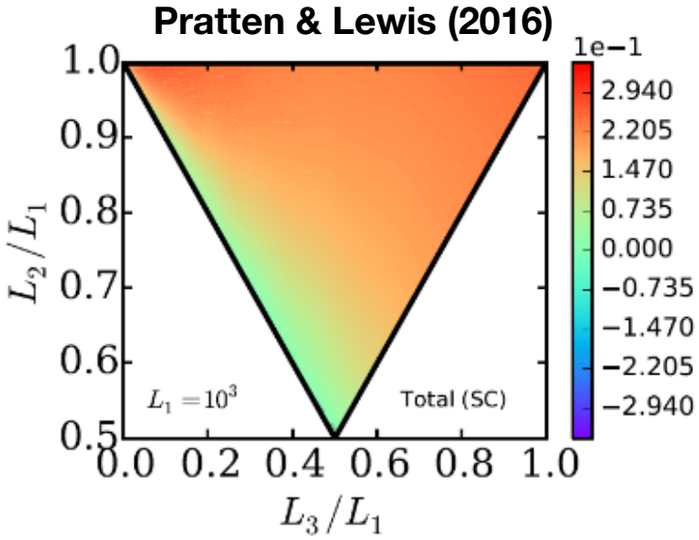
Higher-order corrections: non-Gaussianities

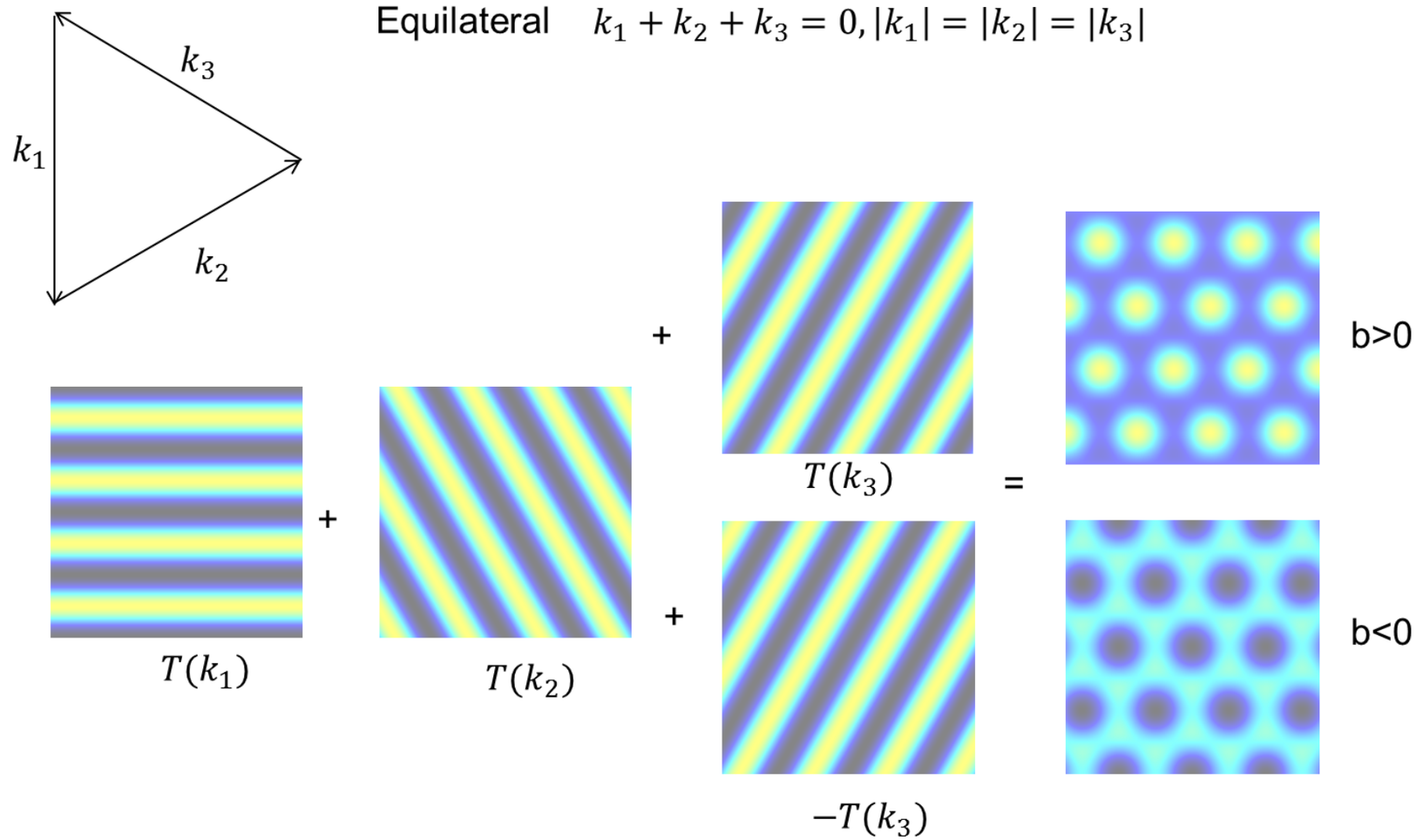
$$(L_2 L_3)^{1/2}\, b^{\kappa\kappa\kappa}_{L_1 L_2 L_3} / (C^{\kappa\kappa}_{L_1} C^{\kappa\kappa}_{L_2} C^{\kappa\kappa}_{L_3})^{1/2}$$





Pratten & Lewis (2016)





Primer on higher-oder bias measurements

- Exploit our numerical simulation setup to isolate single sources of bias at all scales
  - Lens primordial CMB realizations (or galaxies) with different combination of deflection fields
  - Subtract average of the same CMB skies lensed with Gaussian deflections
  - Cross-correlate with external tracers

$$\mathbf{d}^{post-Born} = \nabla\psi^{eff} + \nabla \times \Omega^{eff}$$

$$d_\alpha(\mathbf{L})^{Post-Born} - d_\alpha(\mathbf{L})^{Born,Gauss} \rightarrow \text{All terms}$$

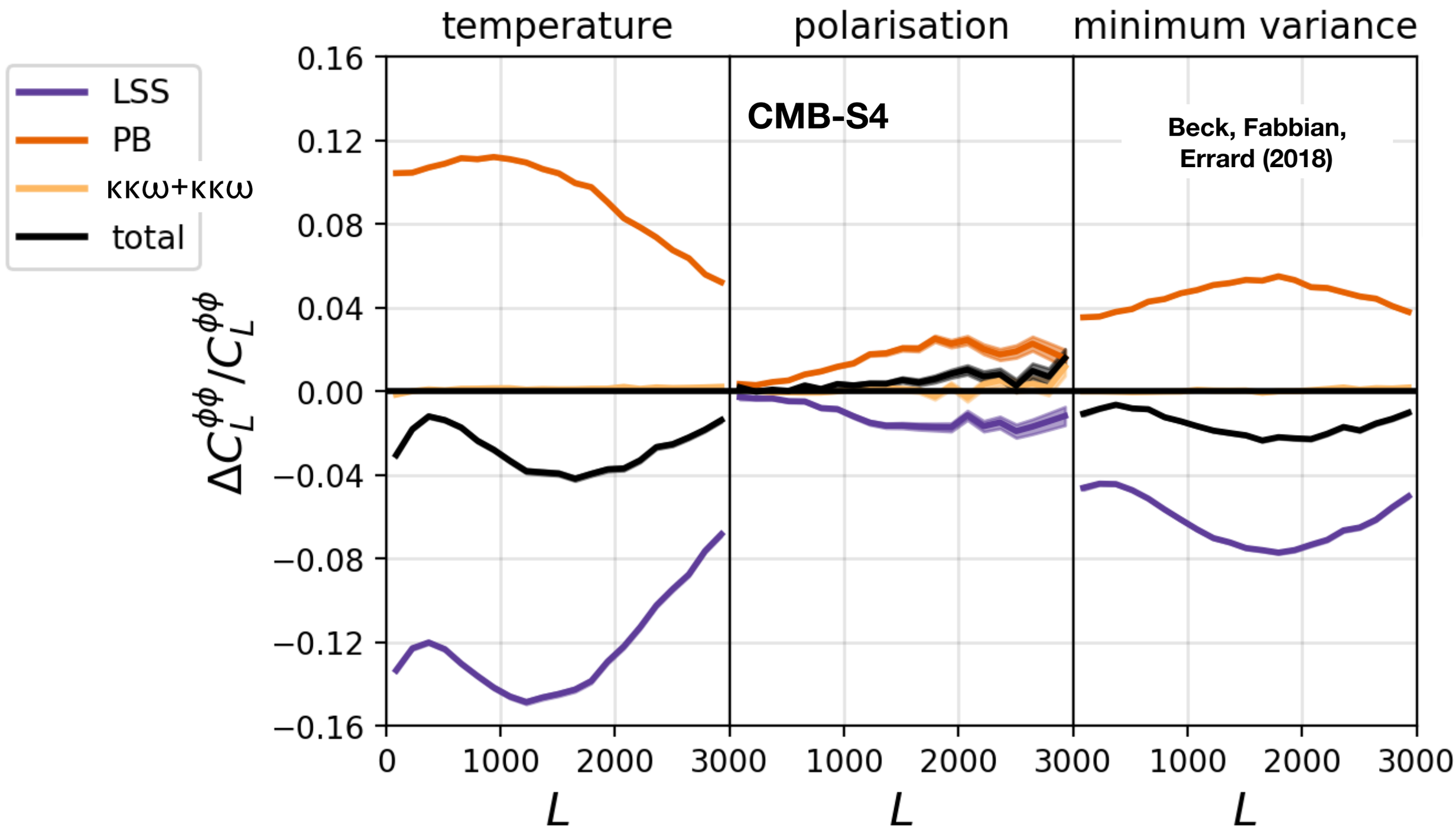
$$d_\alpha(\mathbf{L})^{PB,grad} - d_\alpha(\mathbf{L})^{Born,Gauss} \rightarrow \kappa\kappa\kappa^{LSS}$$

$$d_\alpha(\mathbf{L})^{PB,grad} - d_\alpha(\mathbf{L})^{Born} \rightarrow \kappa\kappa\kappa^{Post-Born}$$

$$d_\alpha(\mathbf{L})^{Post-Born} - d_\alpha(\mathbf{L})^{PB,grad} \rightarrow \kappa\kappa\omega + \kappa\omega\omega$$

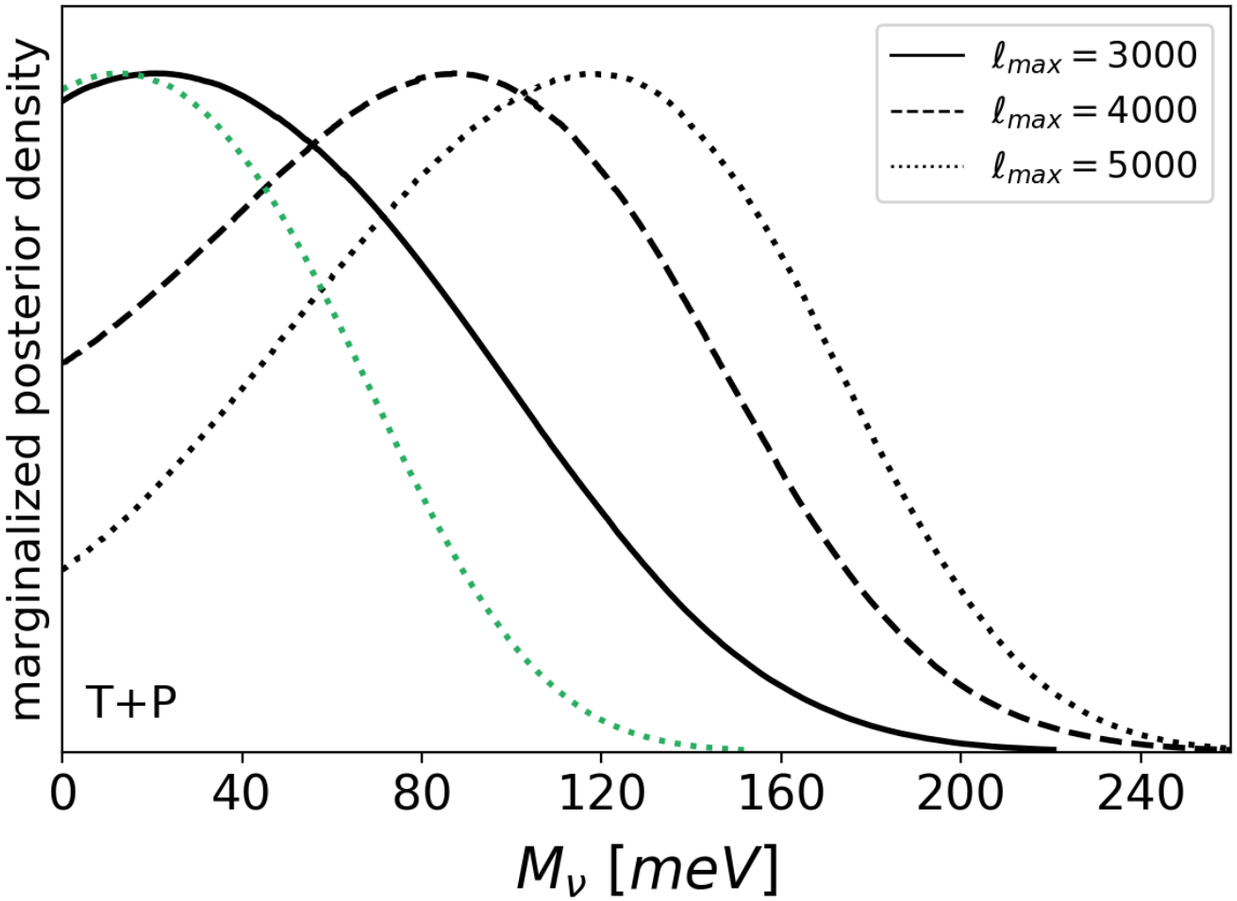
Bias on lensing reconstruction from higher-order

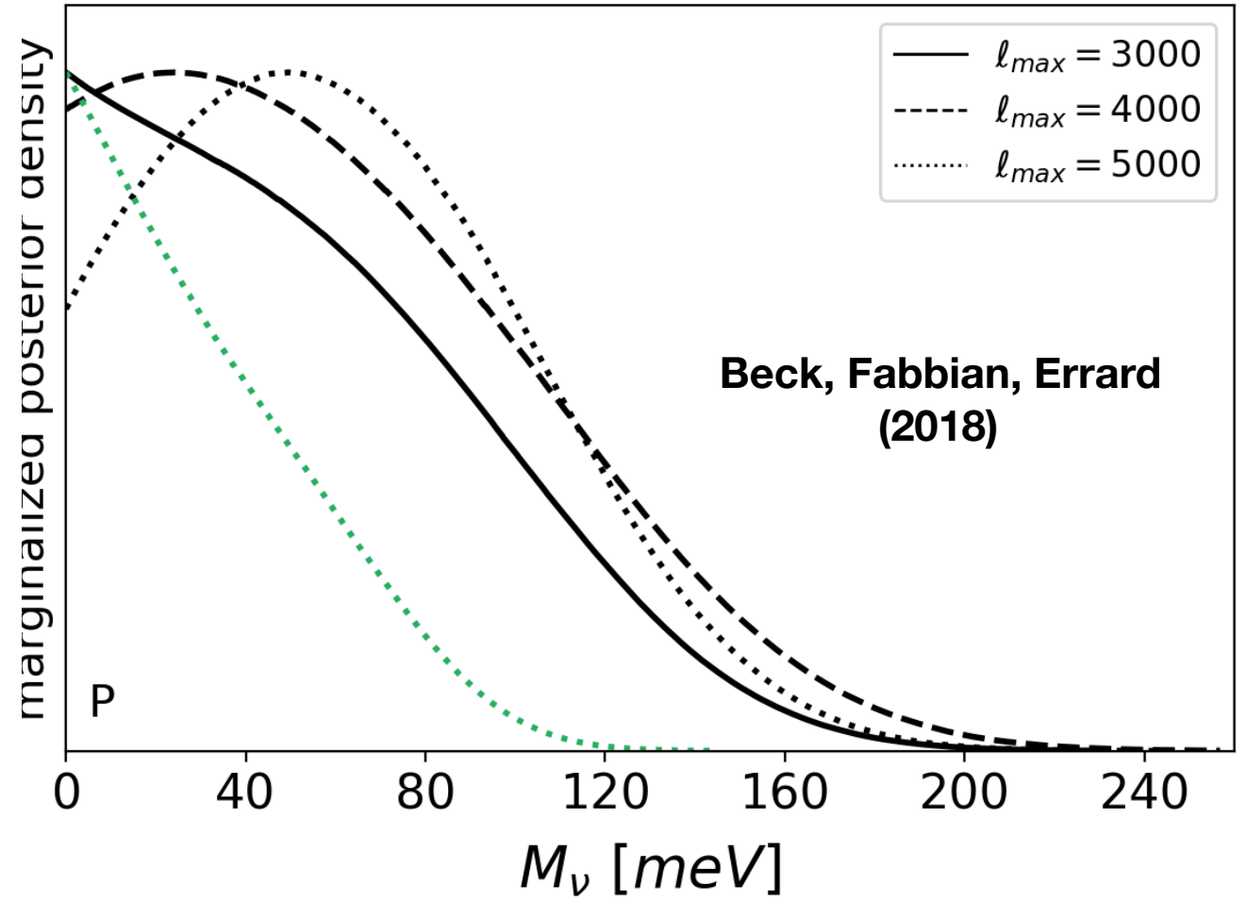
$$\hat{C}_L^{\phi\phi,ABCD} \approx C_L^{\phi\phi} + N_L^{(0),ABCD} + N_L^{(1),ABCD} + N_L^{(3/2),ABCD} + \mathcal{O}\left[(C_L^{\phi\phi})^2\right]$$



Neutrino mass estimation

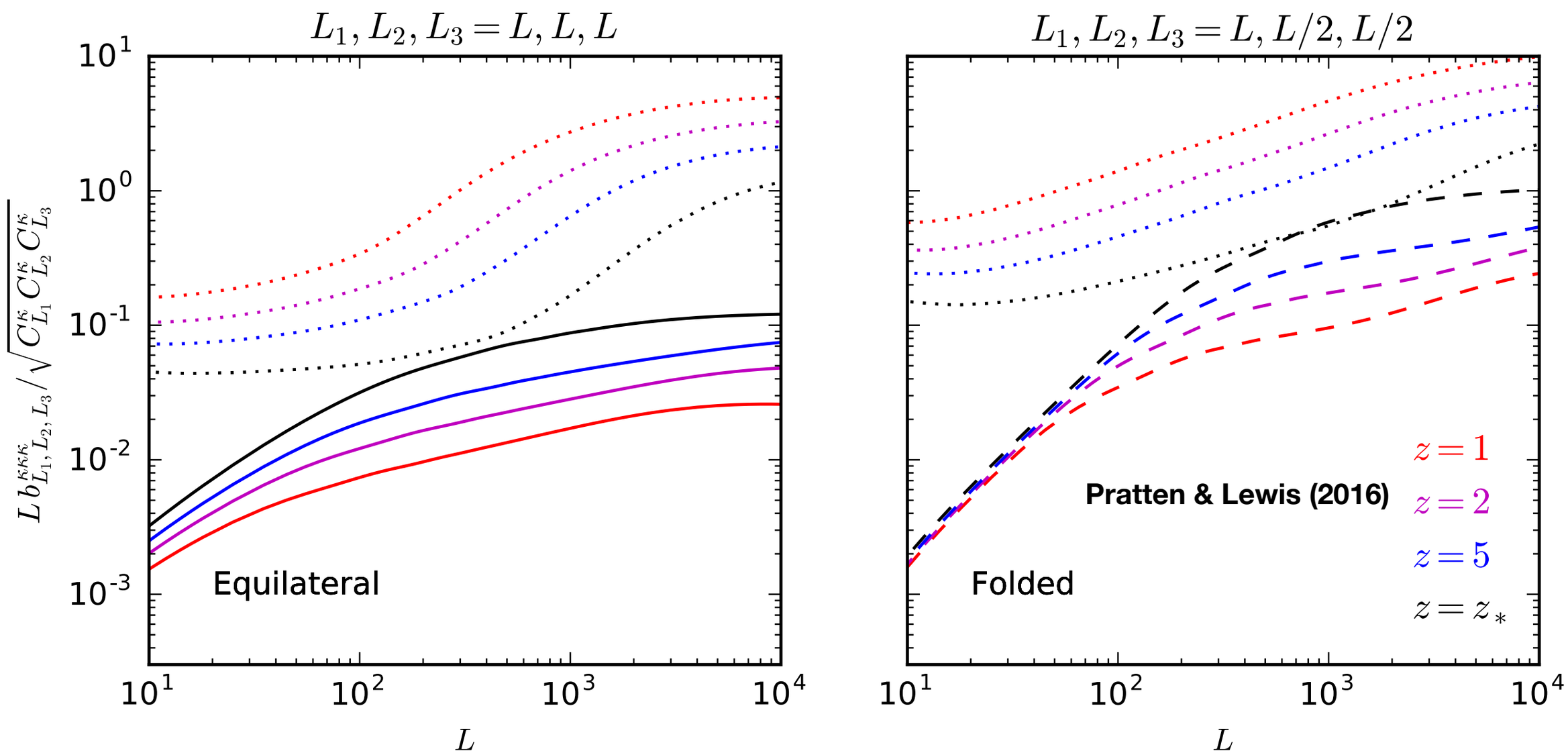
- Shape of the bias highly dependent on the maximum multipole included in the lensing reconstruction
- Bias on cosmological parameters at 1-2 sigma: neutrino mass more affected!
- Combination of data set potentially more robust but possible inconsistencies due to biases





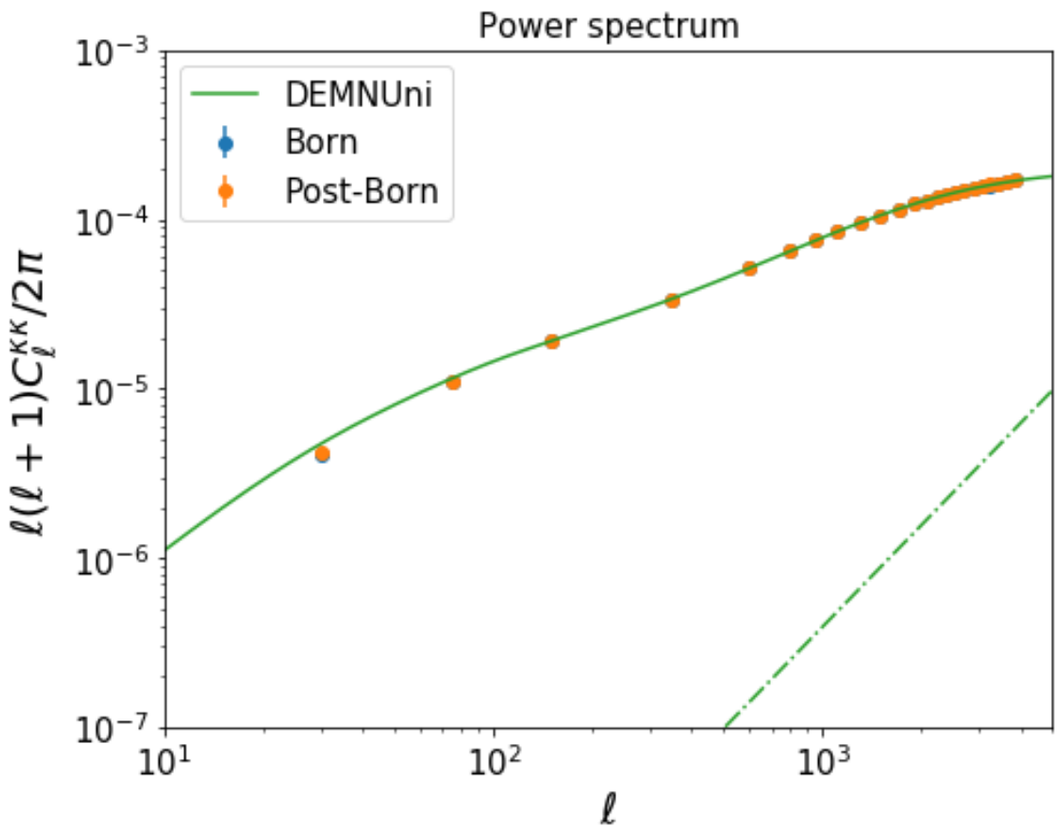
What about CMB lensing - LSS cross-correlation?

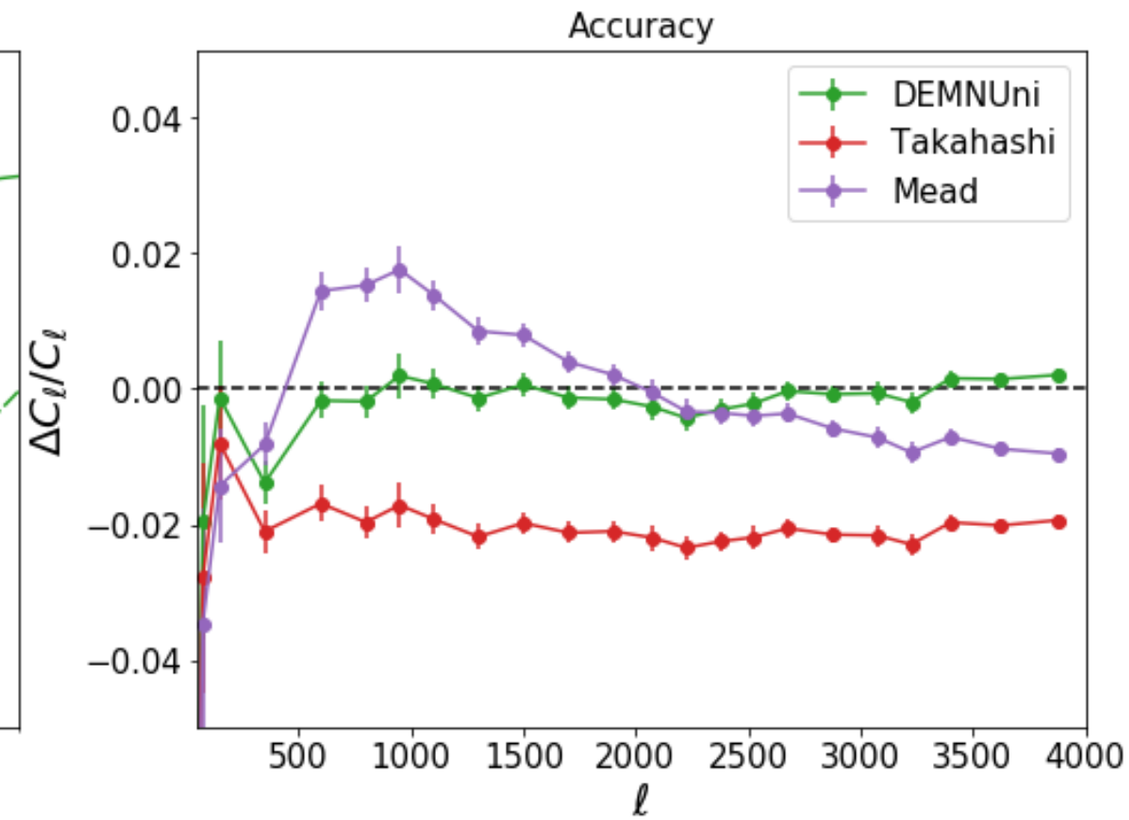
- Post-Born and LSS bispectrum term have different redshift dependencies!
- What happens if we "break the symmetry" of CMB lensing through cross-correlation with LSS tracers?



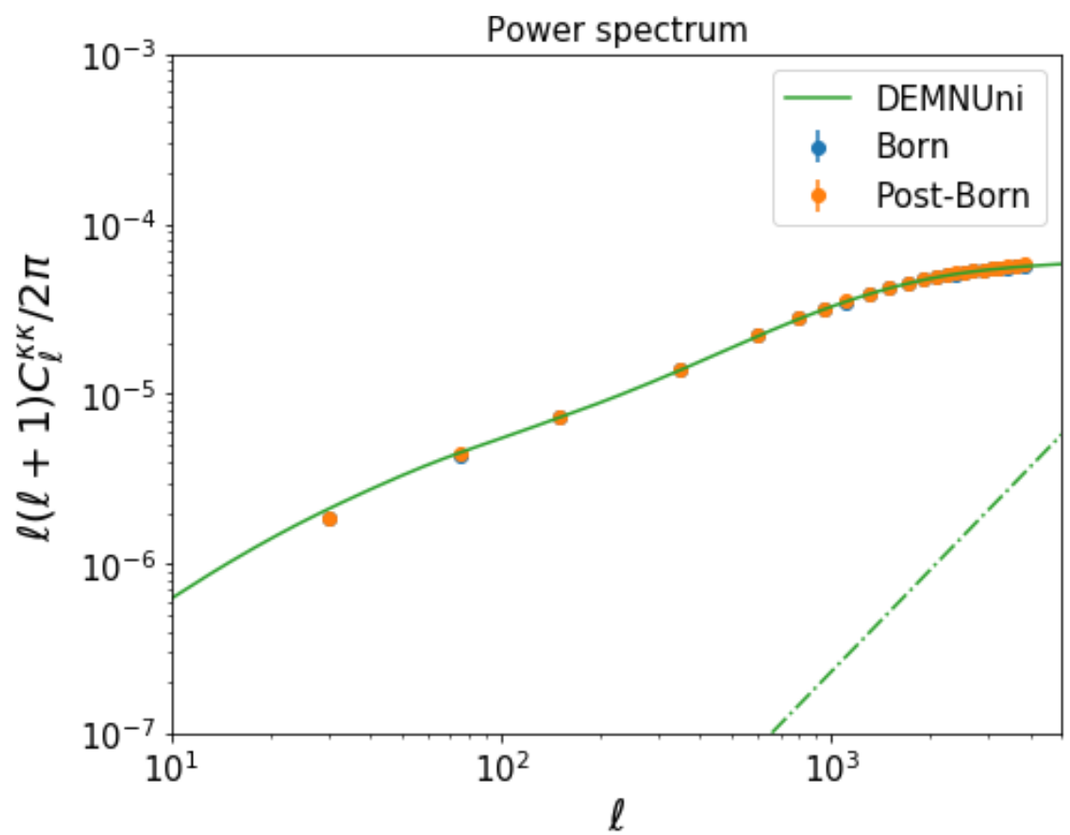
Galaxy lensing signal validation: power spectrum

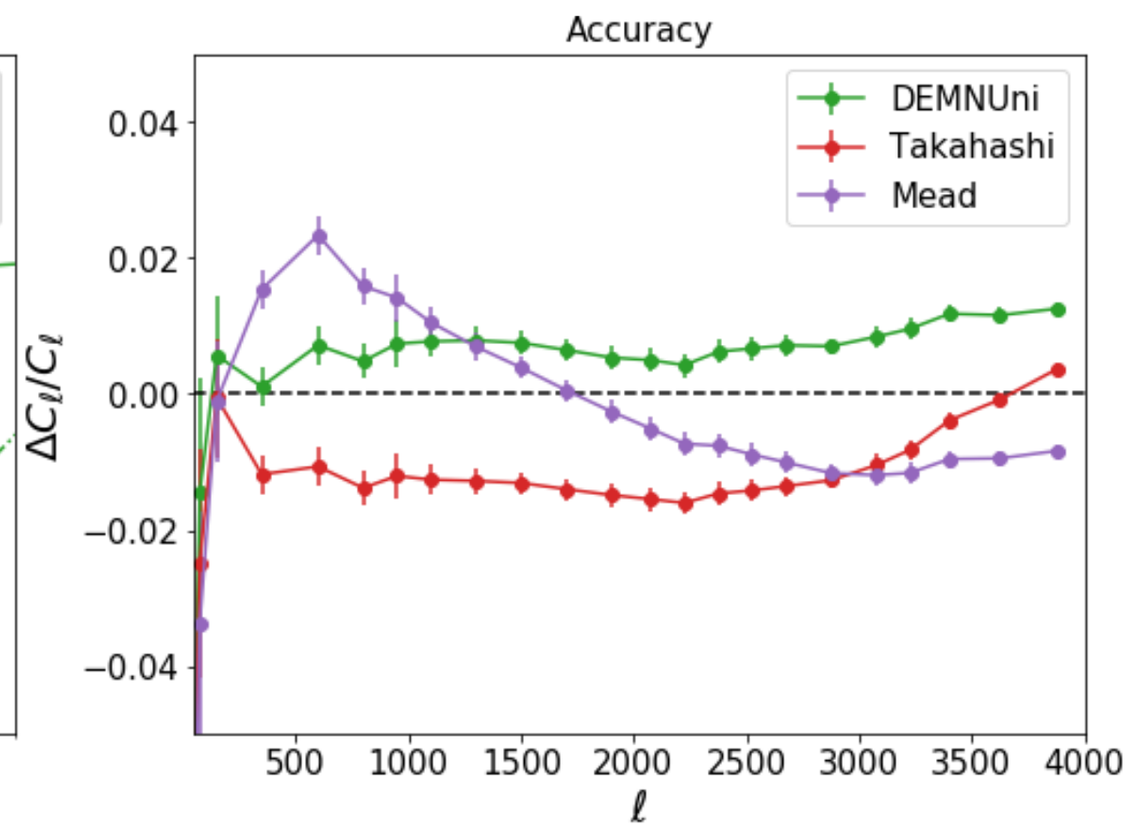
z=1





z=0.6



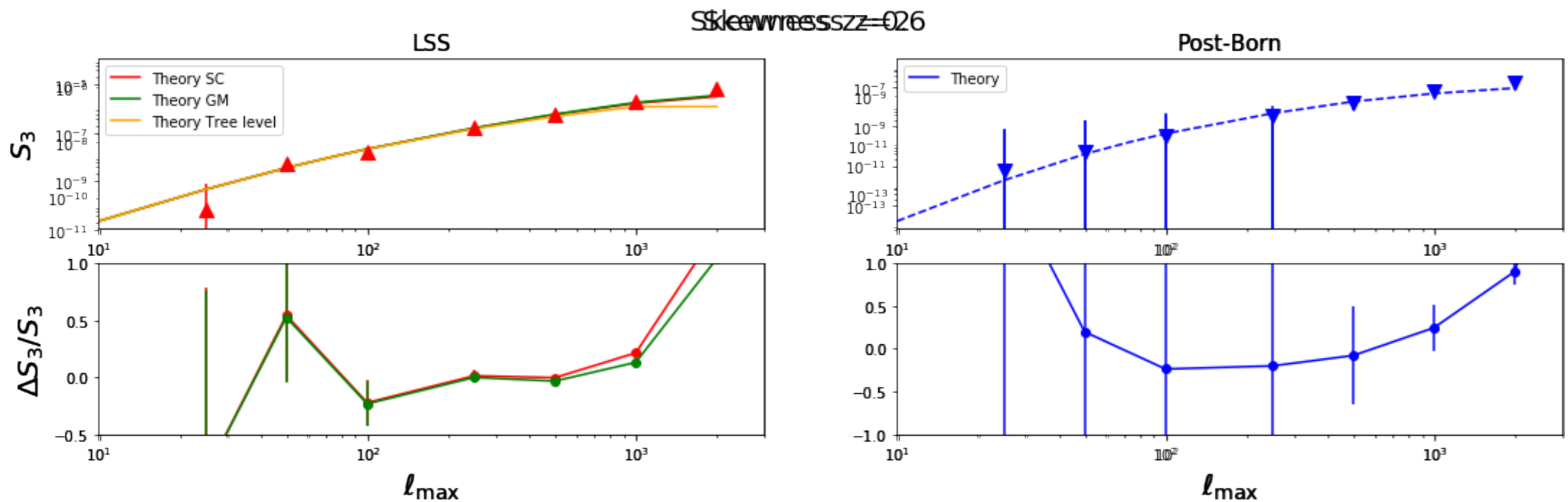


Galaxy lensing signal validation: bispectrum

$$S_3[X] = \langle XXX \rangle = \frac{1}{N_{\rm pix}} \sum_p^{N_{\rm pix}} X_p^3,$$

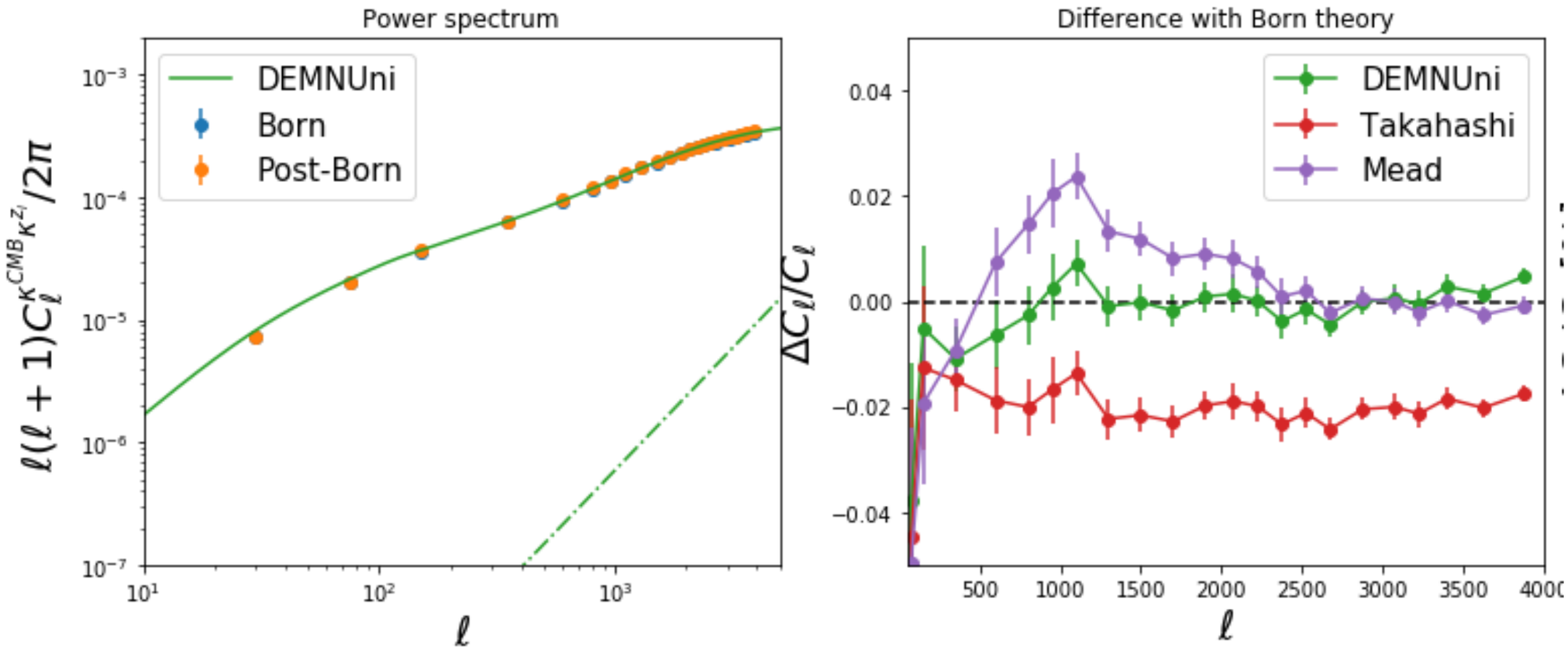
$$S_3[b_{L_1L_2L_3}] = \sum_{L_1L_2L_3}^{L_{\rm max}} \frac{(2L_1+1)(2L_2+1)(2L_3+1)}{(4\pi)^2} \begin{pmatrix} L_1 & L_2 & L_3 \\ 0 & 0 & 0 \end{pmatrix}^2 b_{L_1L_2L_3}$$

$$\sigma^2_{S_3} \simeq \frac{6}{4\pi} \sum_{L_1L_2L_3}^{L_{\rm max}} \frac{(2L_1+1)(2L_2+1)(2L_3+1)}{(4\pi)^2} \begin{pmatrix} L_1 & L_2 & L_3 \\ 0 & 0 & 0 \end{pmatrix}^2 C_{L_1}C_{L_2}C_{L_3}$$

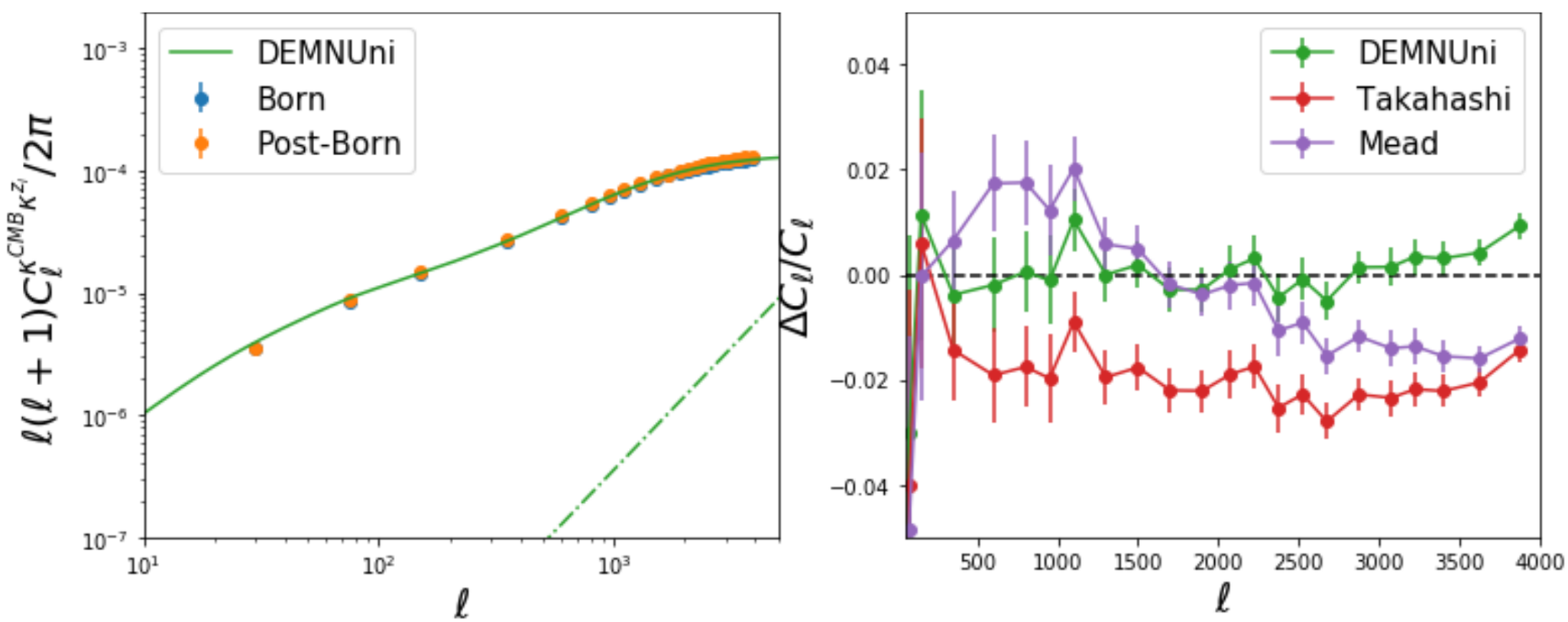


Cross-correlation signal validation

z=1



z=0.6



Biases for cross-correlation studies

- CMB lensing cross-correlation with galaxy shear/convergence: enhanced bias!
- Post-Born corrections: reduce the $N^{3/2}$
  - Somewhat not (that) important for galaxy lensing

Fabbian, Lewis et al.
(in prep.)

Euclid X CMBS4

Fabbian, Lewis et al. (in prep.)

Theoretical perturbative predictions

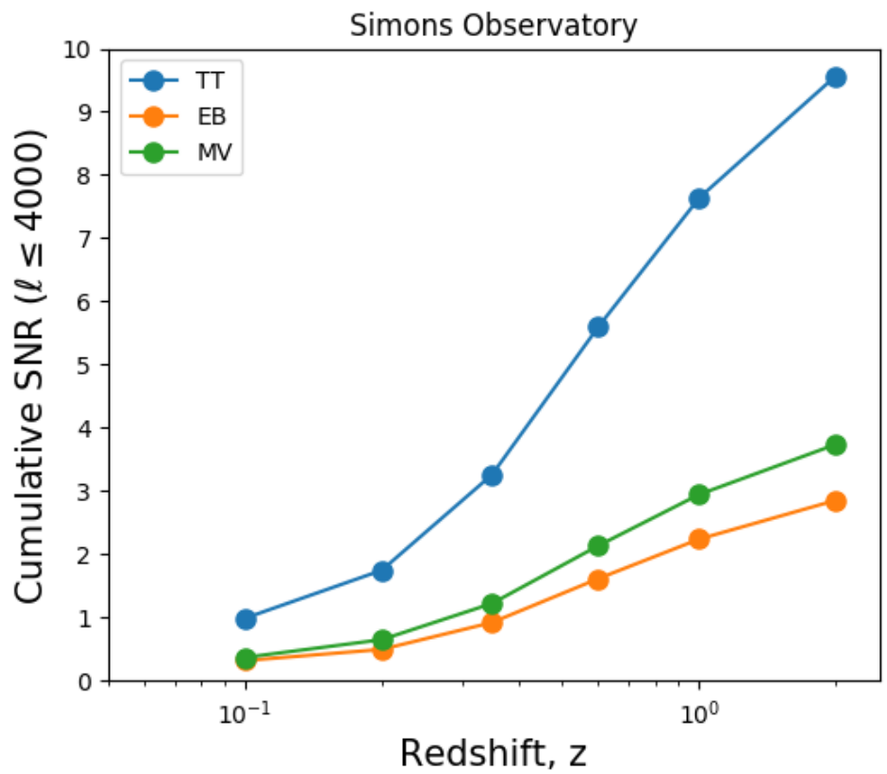
$$\langle \tilde{W} \tilde{X} \phi_{\rm ext} \rangle_{\mathcal{O}[(C^{\phi\phi})^{3/2}]} = \langle \delta W \delta X \phi_{\rm ext} \rangle + \langle W \delta^2 X \phi_{\rm ext} \rangle + \langle \delta^2 W X \phi_{\rm ext} \rangle$$

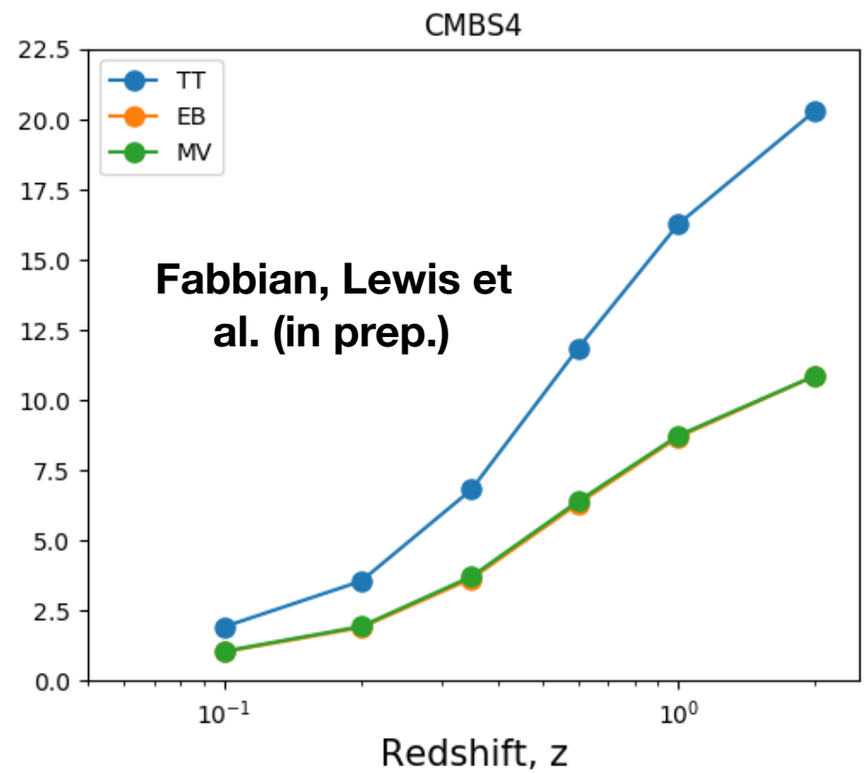
Fabbian, Lewis et al. (in prep.)

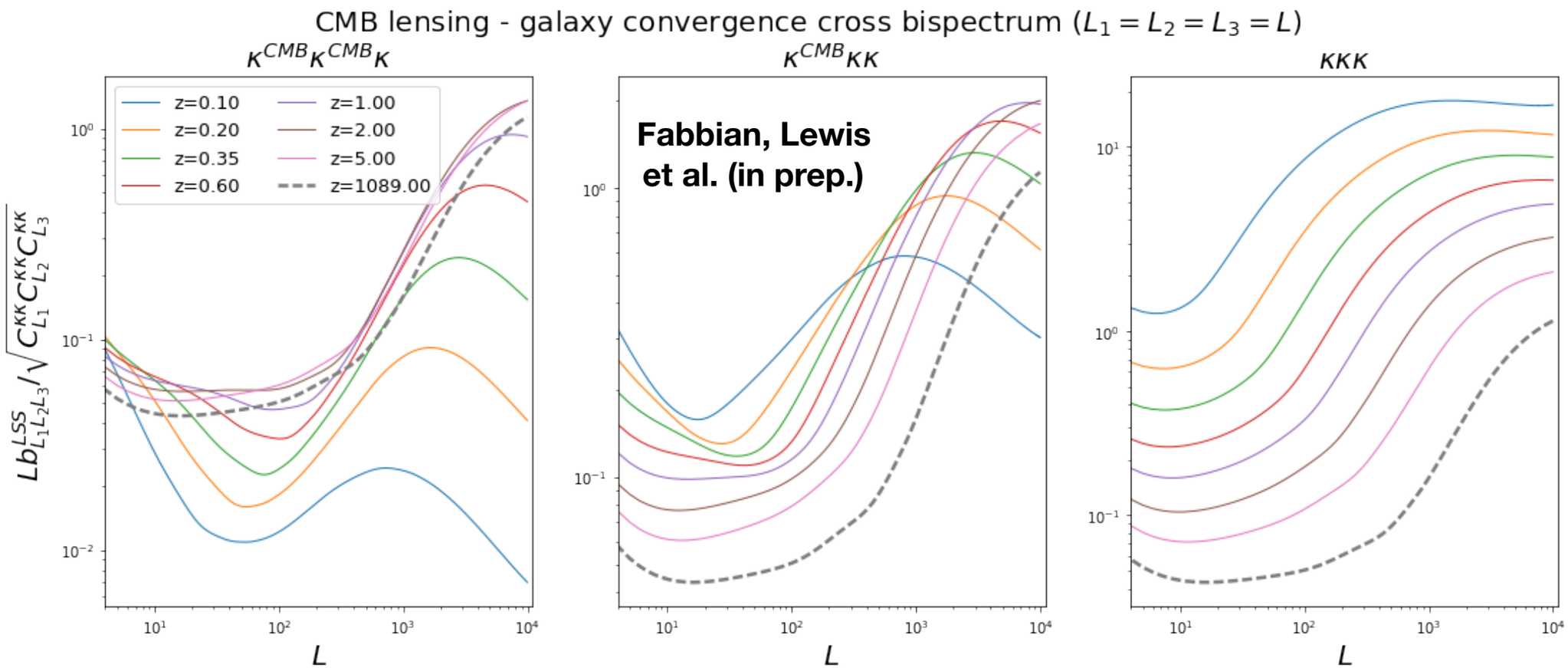
Simulation comparison

Fabbian, Lewis et al. (in prep.)

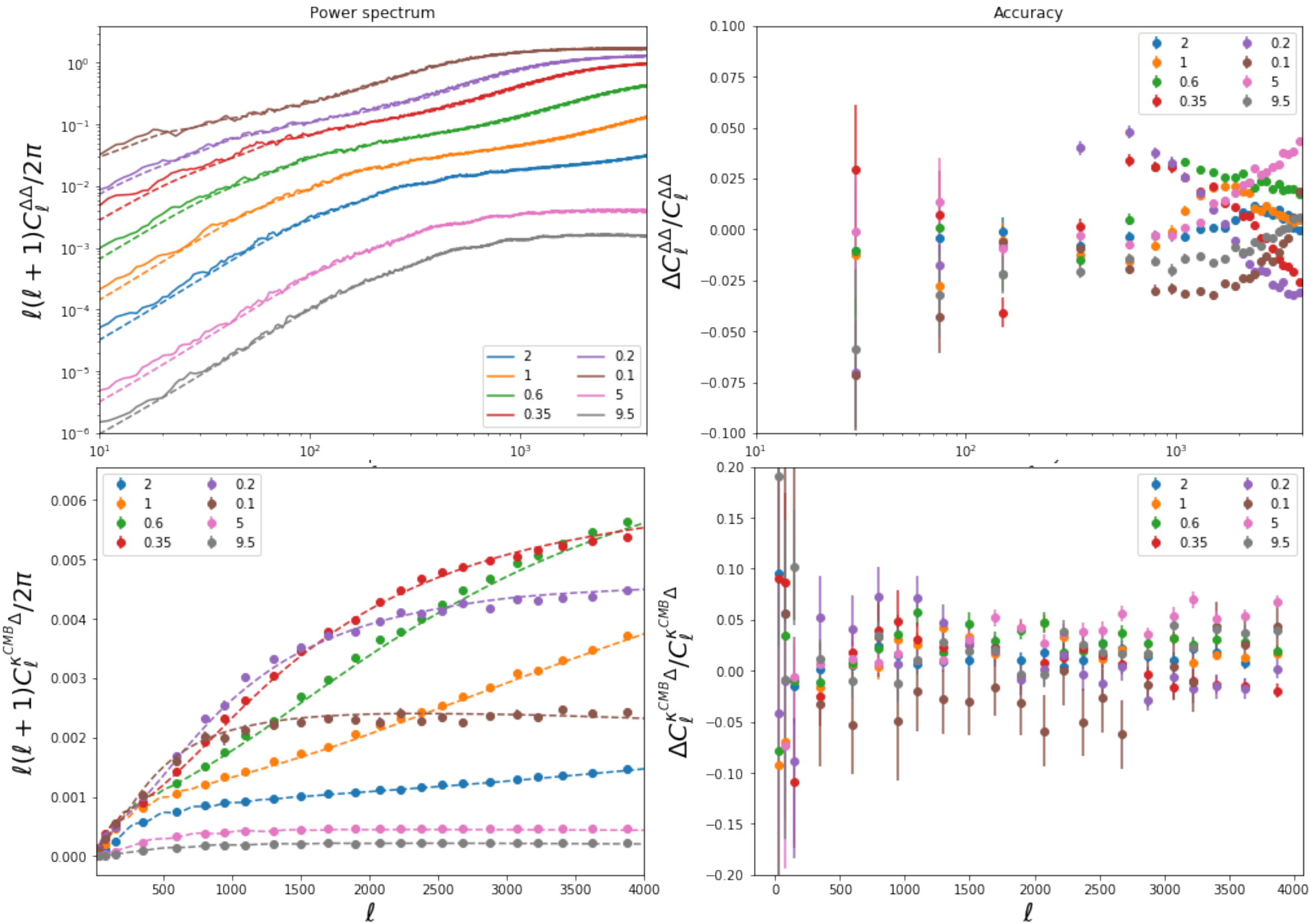
Redshift dependency and SNR







Coherent galaxy density simulations



Euclid X CMBS4

Z =0.6

Fabbian, Lewis et al. (in prep.)

Z =2.0

Euclid galaxy density X CMBS4

Fabbian, Lewis et al. (in prep.)

PRELIMINARY!

Post-Born power spectrum puzzle

- Need to pay attention to modelling in simulation for density cross-correlation
- LOS effect to be investigated

PRELIMINARY!

Fabbian, Lewis et al. (in prep.)

Conclusions

- Take away message: higher-order lensing effects are important in future experiment!
  - Will be detected with good significance for CMBS4 and CMBS4xEuclid
  - Will affect galaxy shear self-calibration (intrinsic alignment)
- We developed and tested end-to-end galaxy convergence simulations correlated with our CMB lensing pipeline
  - Good consistency with power spectrum and higher order statistics
- We measured higher-order biases for CMB cross-correlation with LSS tracers (convergence and density).
- We developed a theoretical framework to predict the value of the biases and account for them.