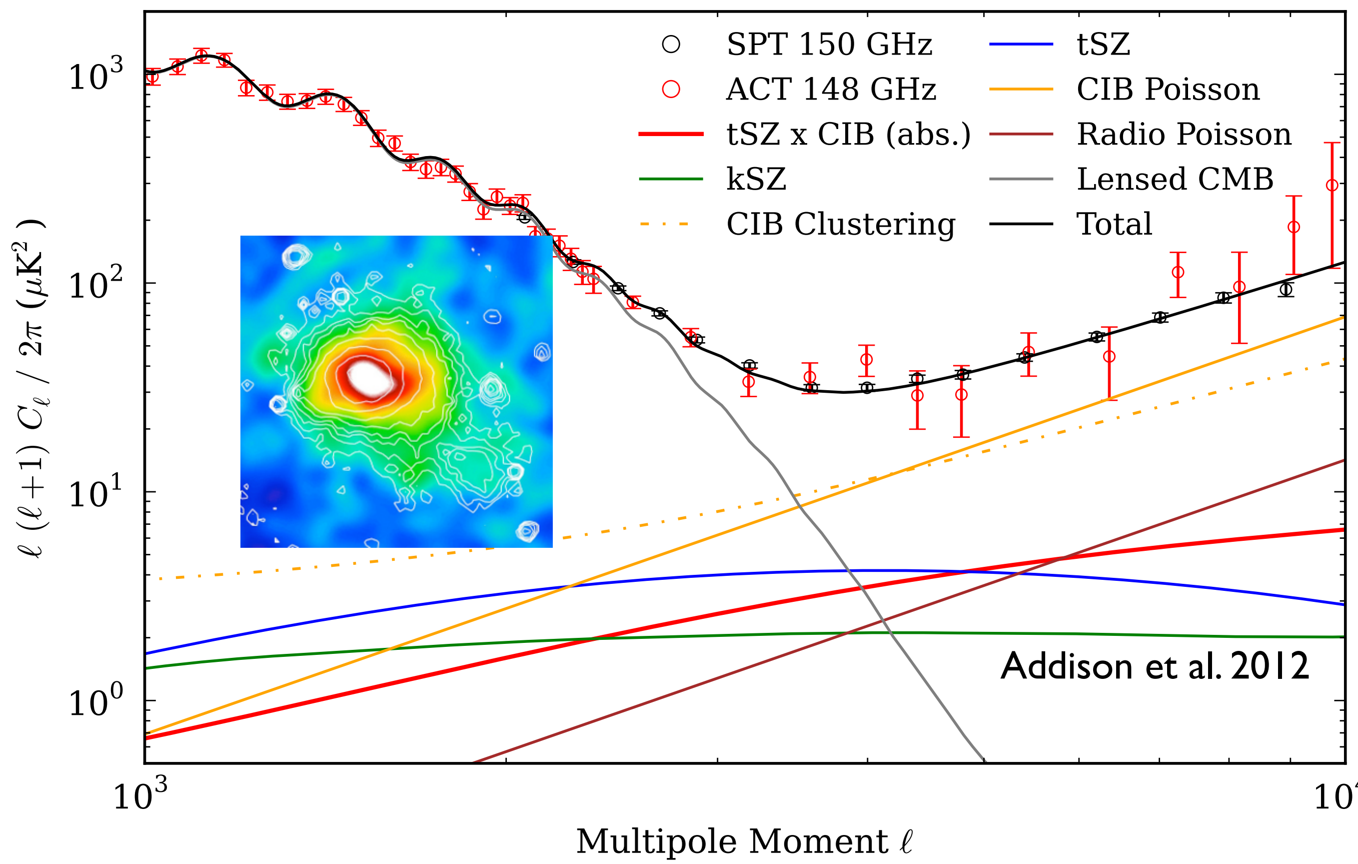
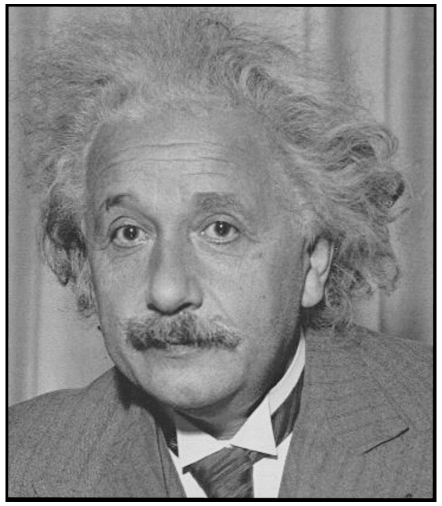
Synergies between future CMB surveys, Euclid and LSST

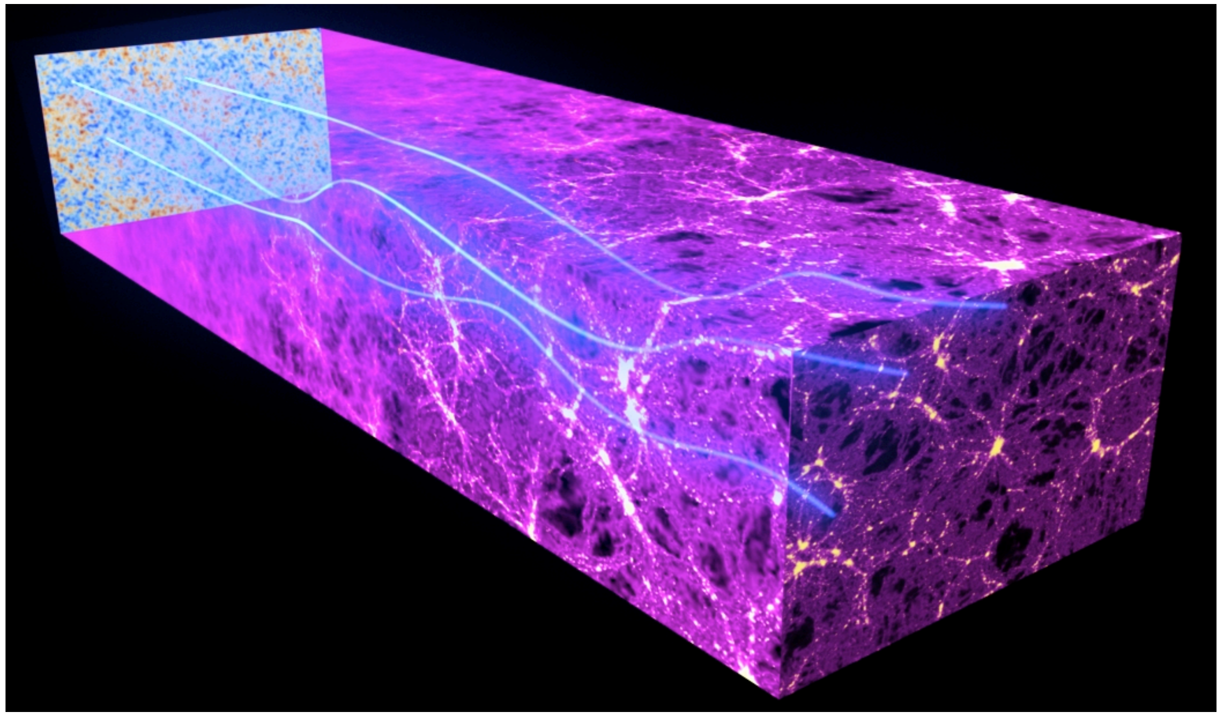
Giulio Fabbian

Is CMB "the" CMB?

- CMB is a snapshot of the universe at z 1100.... plus something else
- Contamination by astrophysical objects and galactic foregrounds
- Imprint of large scale structures:
  - (weak) Gravitational lensing
  - Sunyaev-Zeldovich (SZ) effect



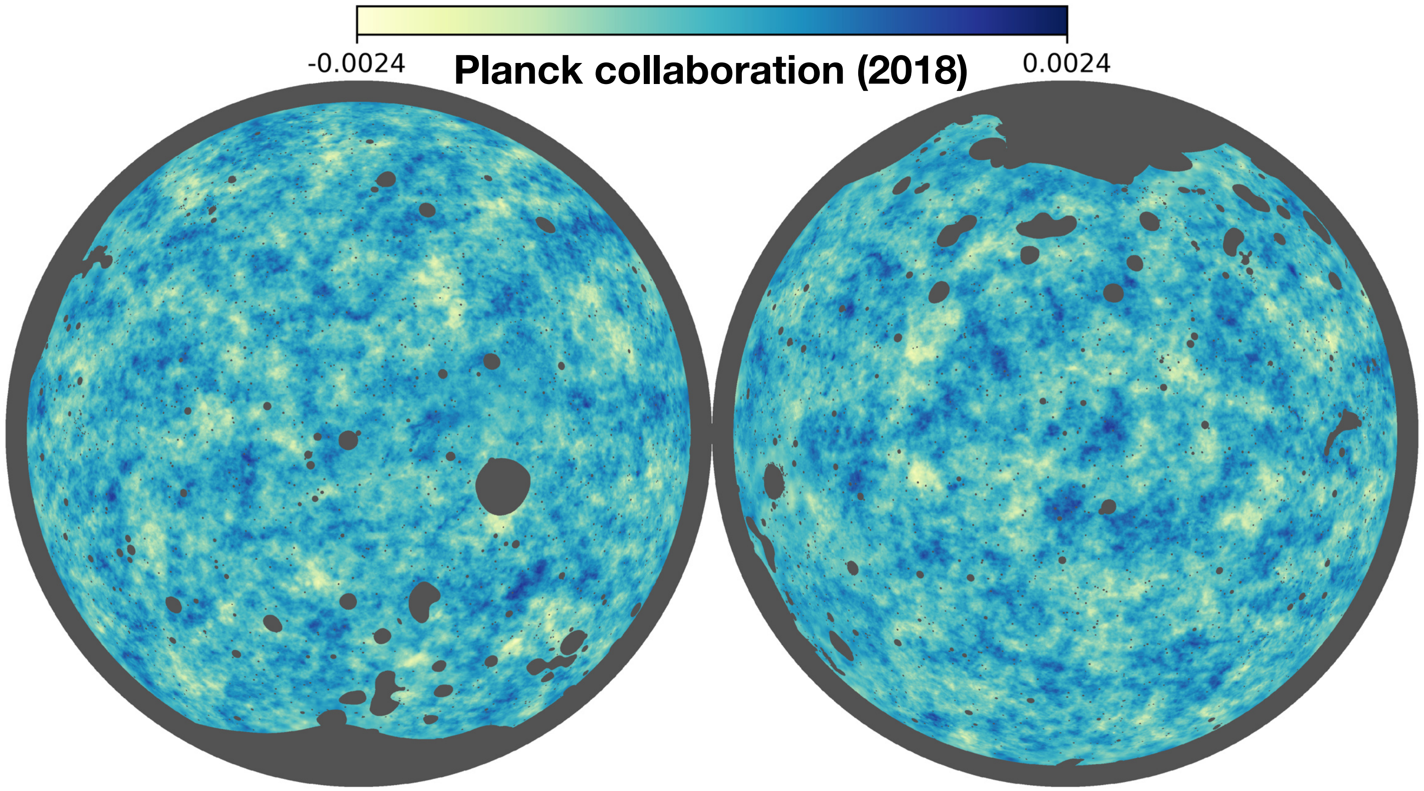


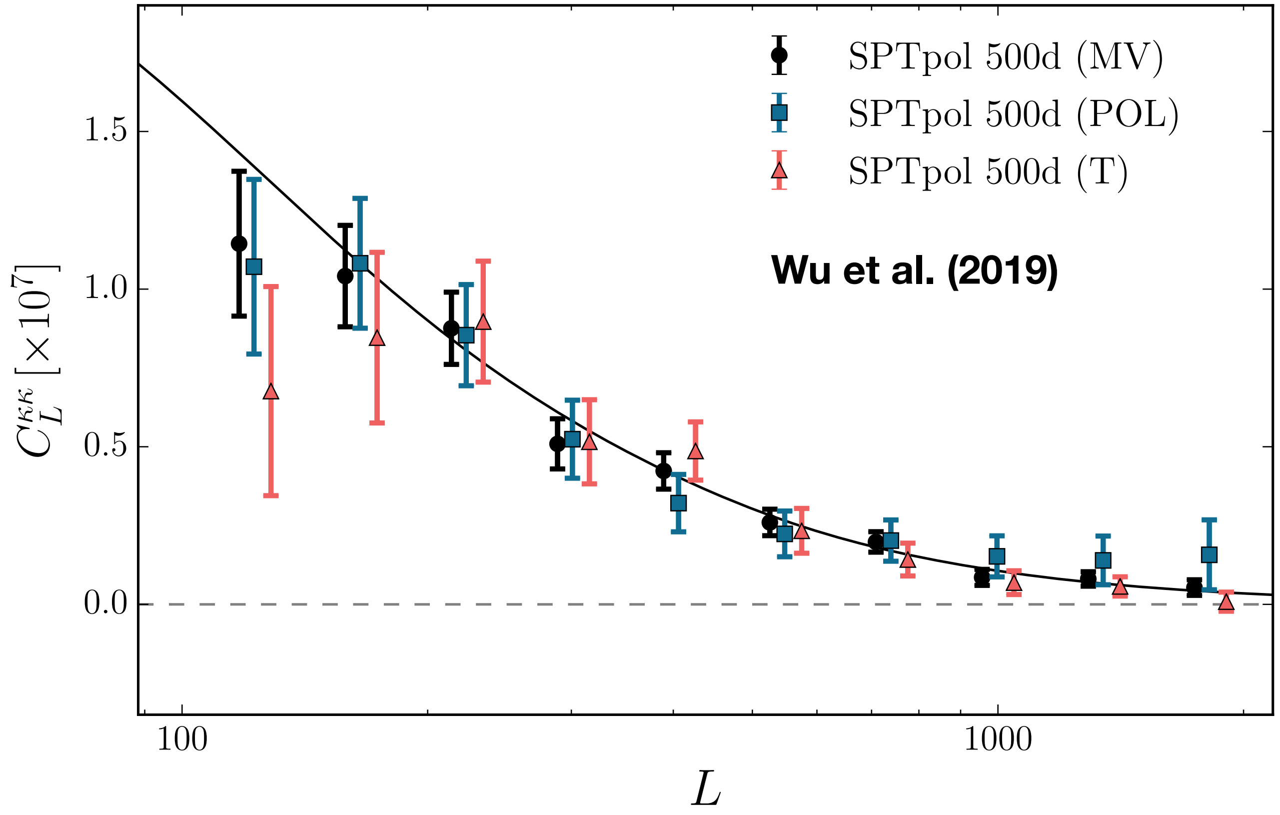


CMB lensing state of the art 2019

- High-significance measurements, precision cosmological probe after Planck

$$\psi(\boldsymbol{\theta}) = -2\int_0^{\chi_s} \frac{D_A(\chi_s-\chi')}{D_A(\chi')D_A(\chi_s)}\Psi(\boldsymbol{\theta},\chi')d\chi' \qquad \beta(\boldsymbol{\theta},\chi_s) = \boldsymbol{\theta} + \nabla\psi(\boldsymbol{\theta})$$





- **Milestone**: CMB polarization dominates the sensitivity (starting this year)

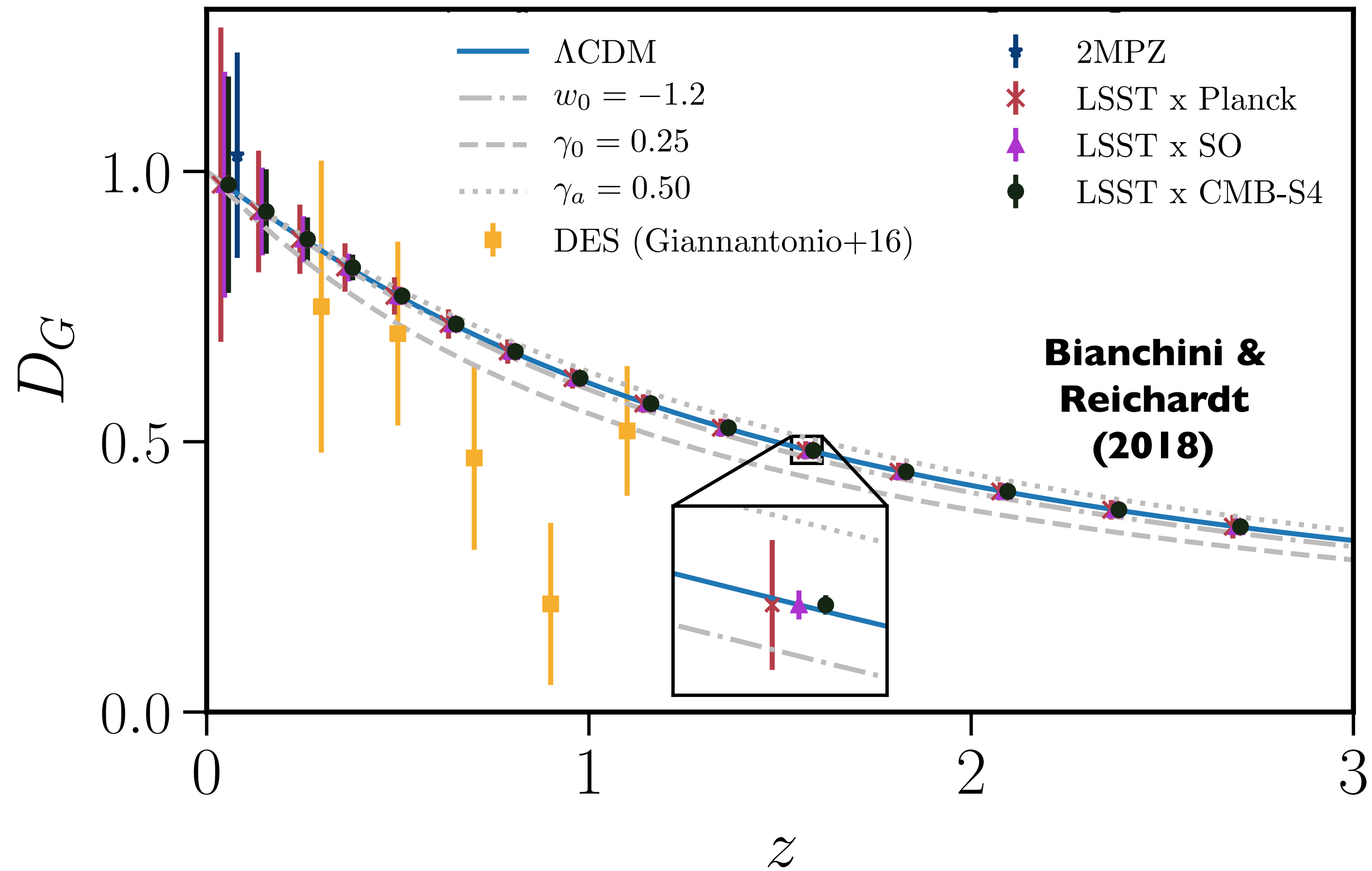
Cross-correlation basis and examples

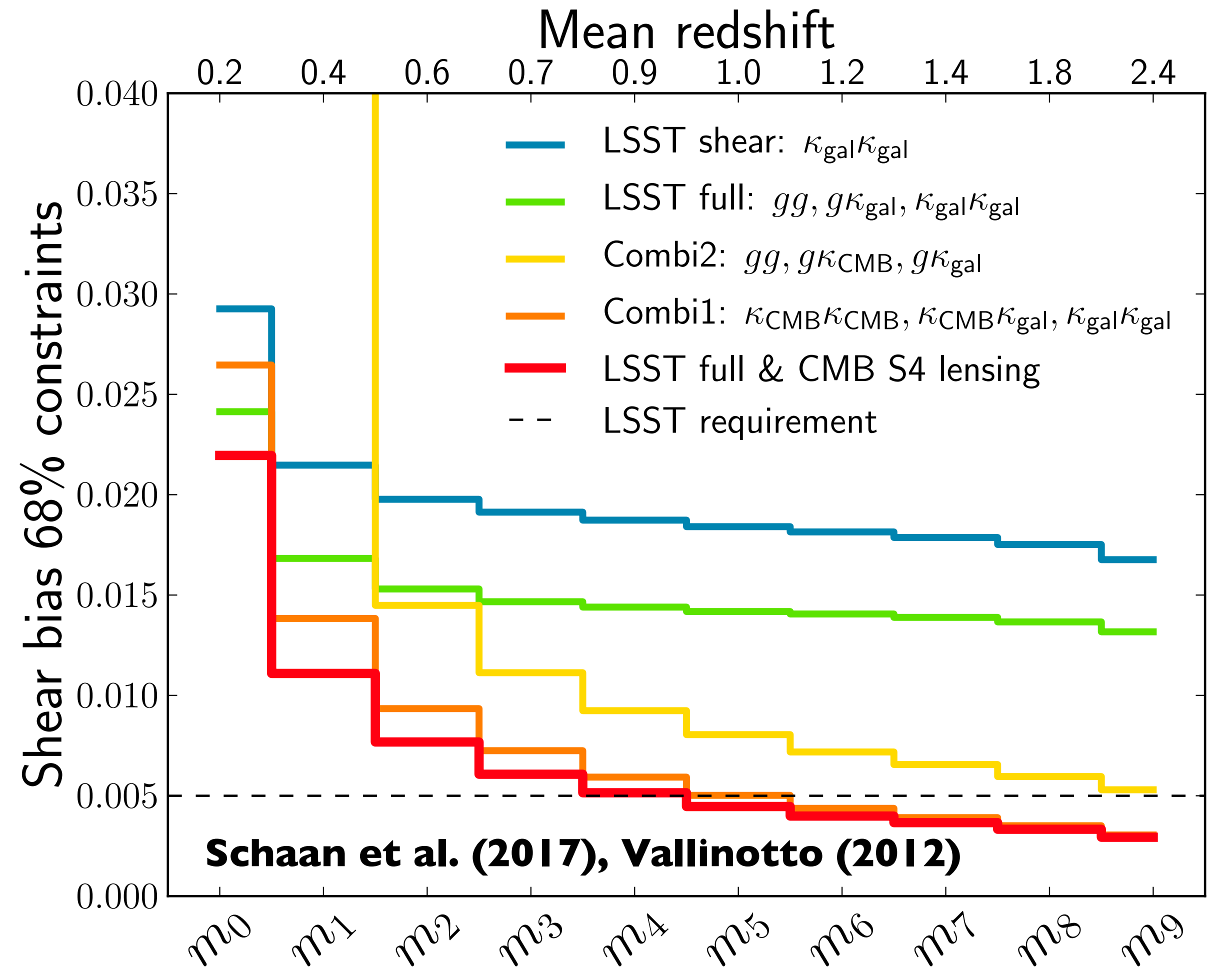
$$C_L^{AB} \approx \int \frac{d\chi}{\chi^2} W_A(\chi) W_B(\chi) P_\delta \left(k = \frac{L+1/2}{\chi}, z(\chi) \right)$$

$$W_g(\chi) = b_g(z) \frac{1}{n} \frac{dn}{dz} \frac{dz}{d\chi}$$

$$W_\kappa(\chi, \chi_s) = \gamma(\chi) \chi^2 \left(\frac{1}{\chi} - \frac{1}{\chi_s} \right) \Theta(\chi_s - \chi)$$

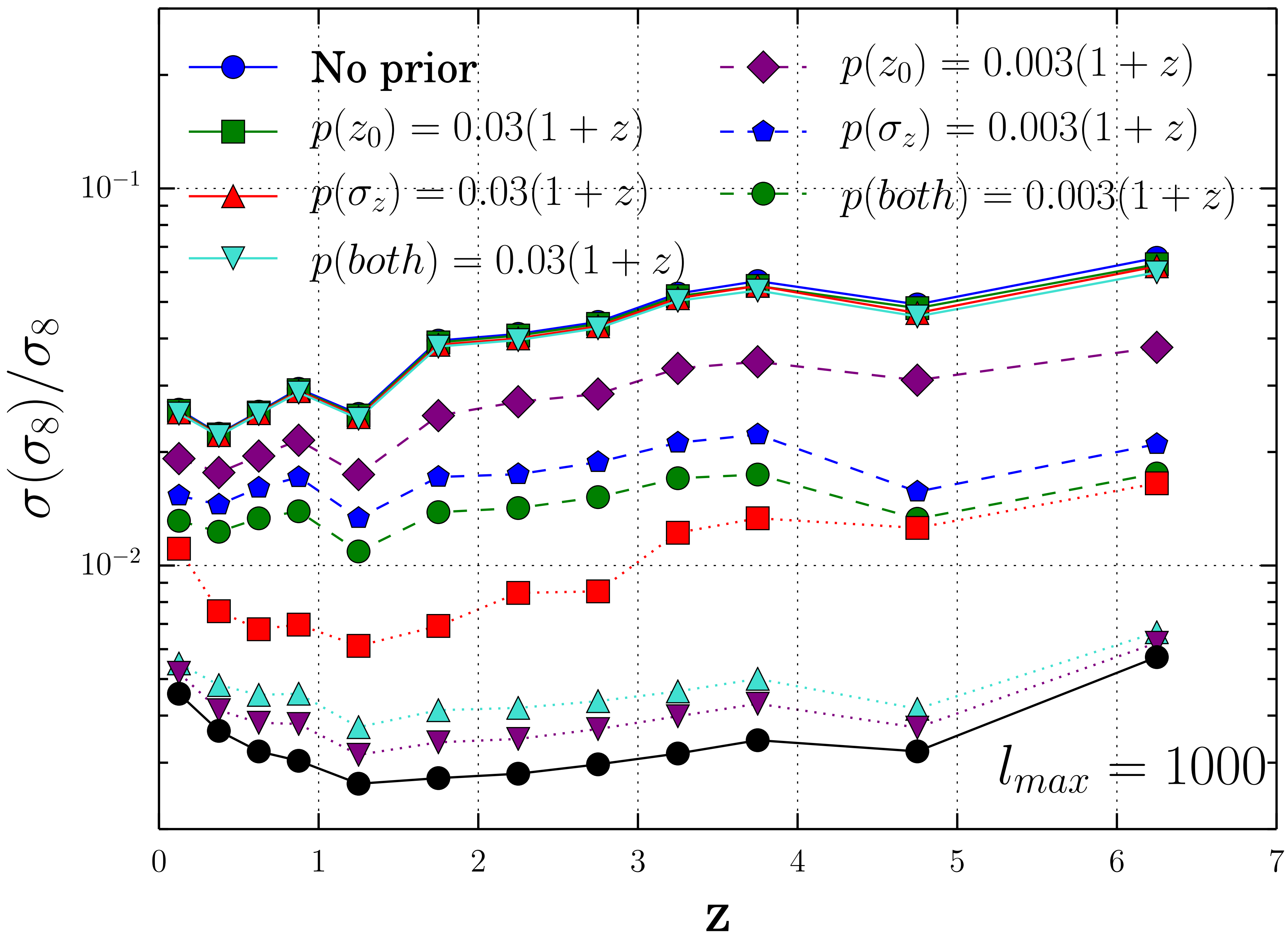
$$P(k,z) = P(k,0) D^2(z)$$





Redshift self-calibration with number counts

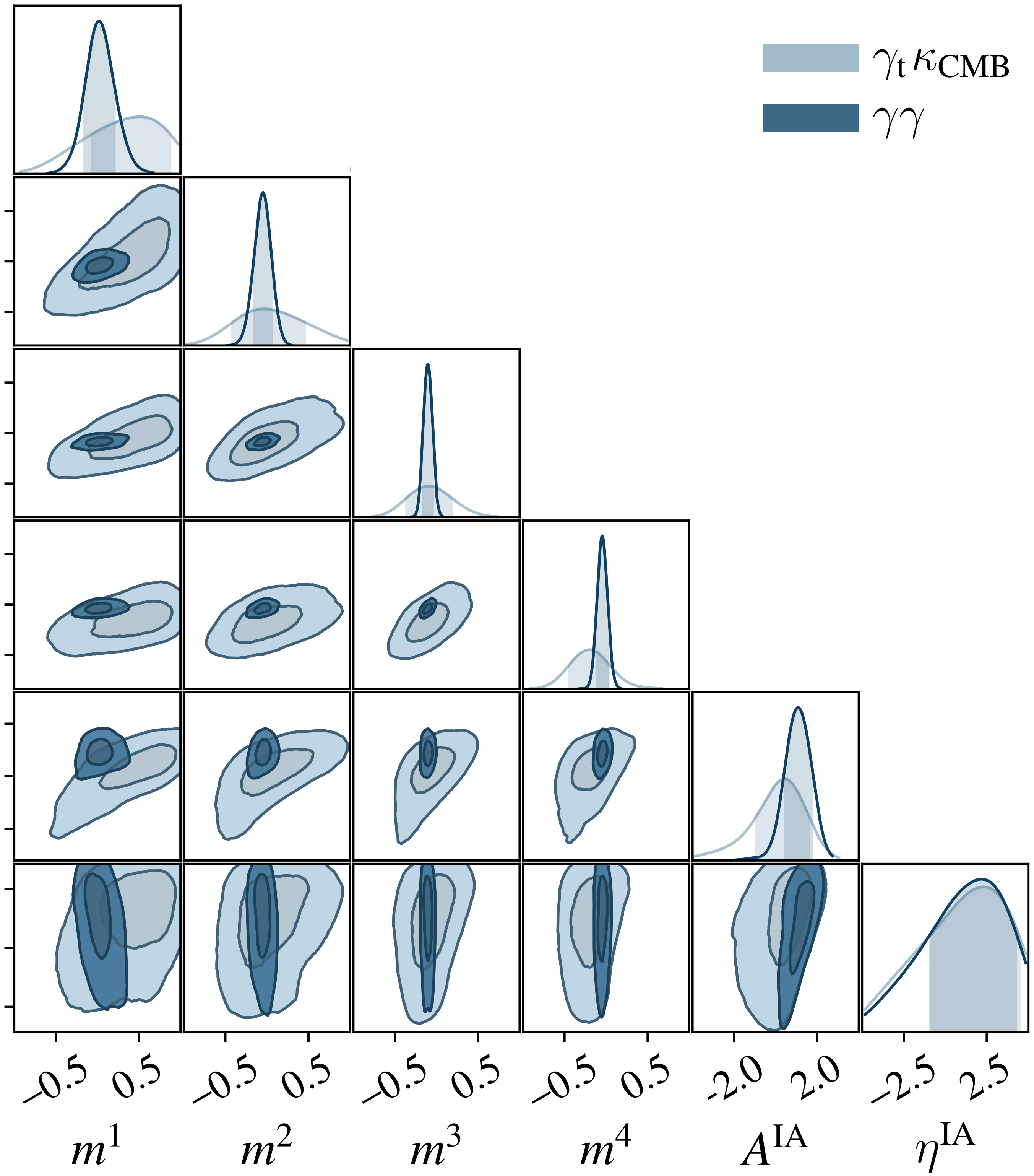
- Self-calibration of galaxy redshift distribution can be achieved in S4/LSST era.
- Competitive w.r.t. results with priors on photometric redshift!



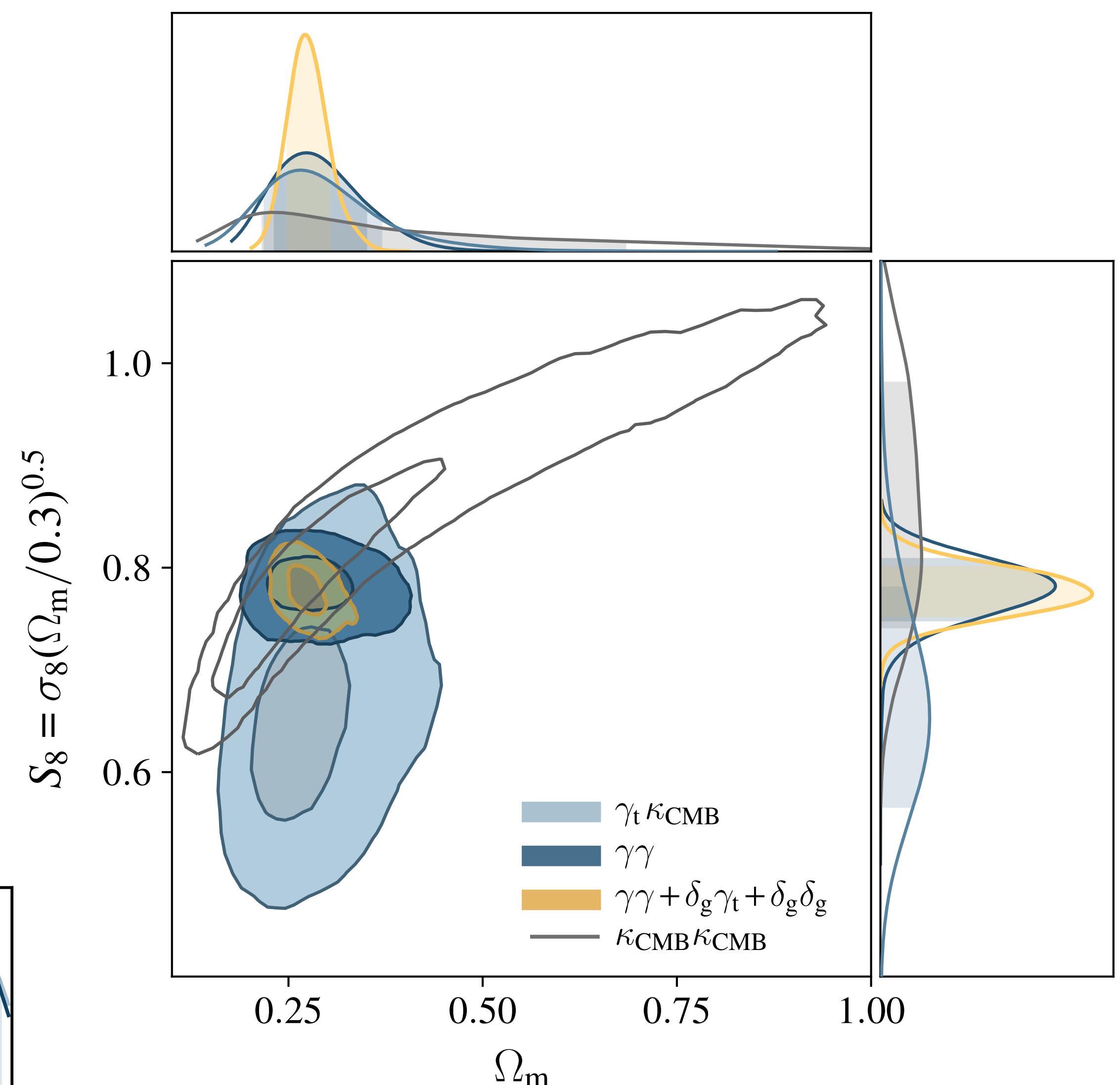
Cawthon (2018)

State of the art: DES & co.

- Systematics in cosmic shear measurements not yet mitigated by CMB-cross correlation

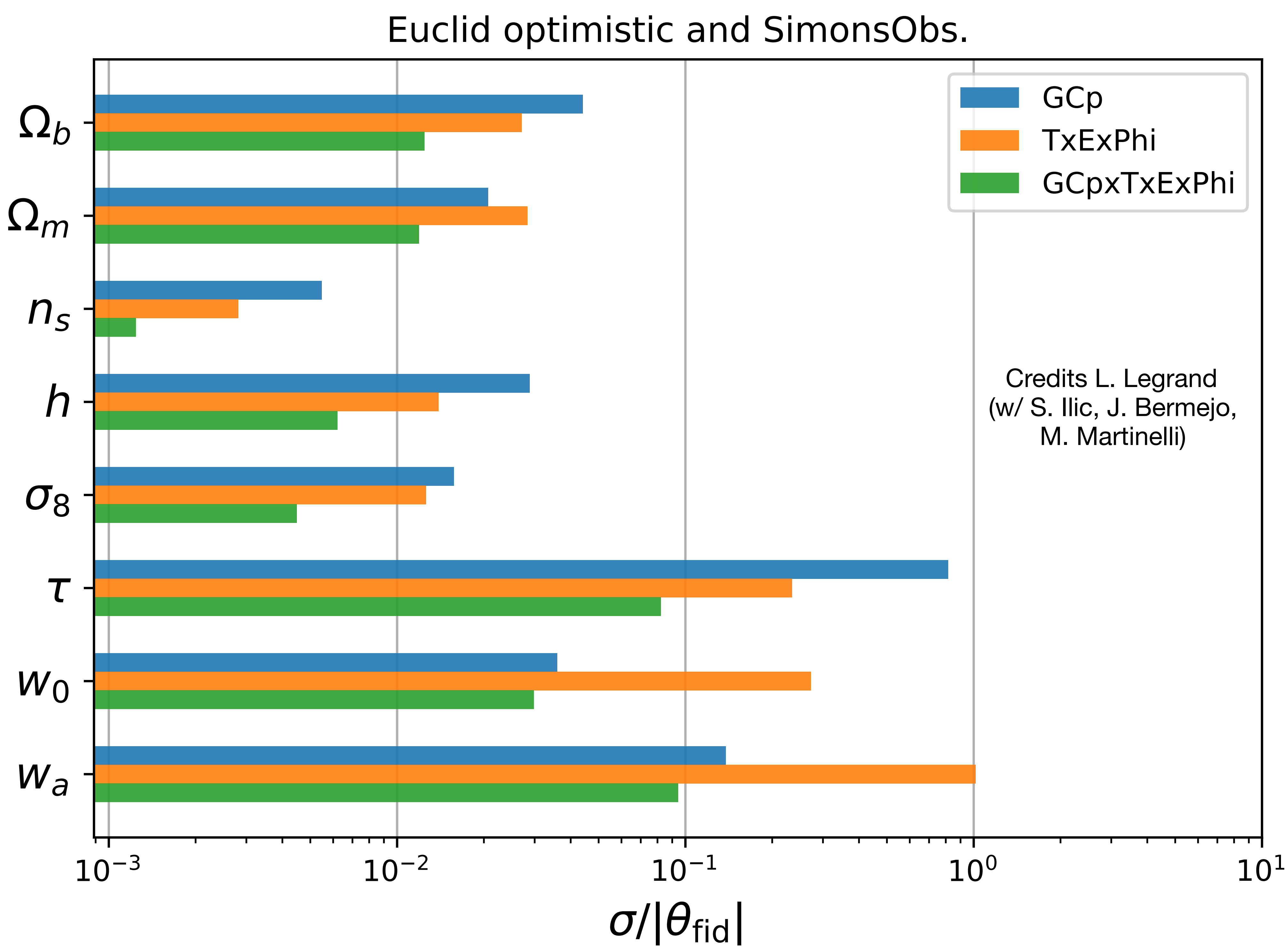


Omori et al. 2019
(DES collaboration)



Euclid projections (preliminary)

- Using only photometric survey and CMB observables will significantly improve cosmological parameters (also Merkel+2017)



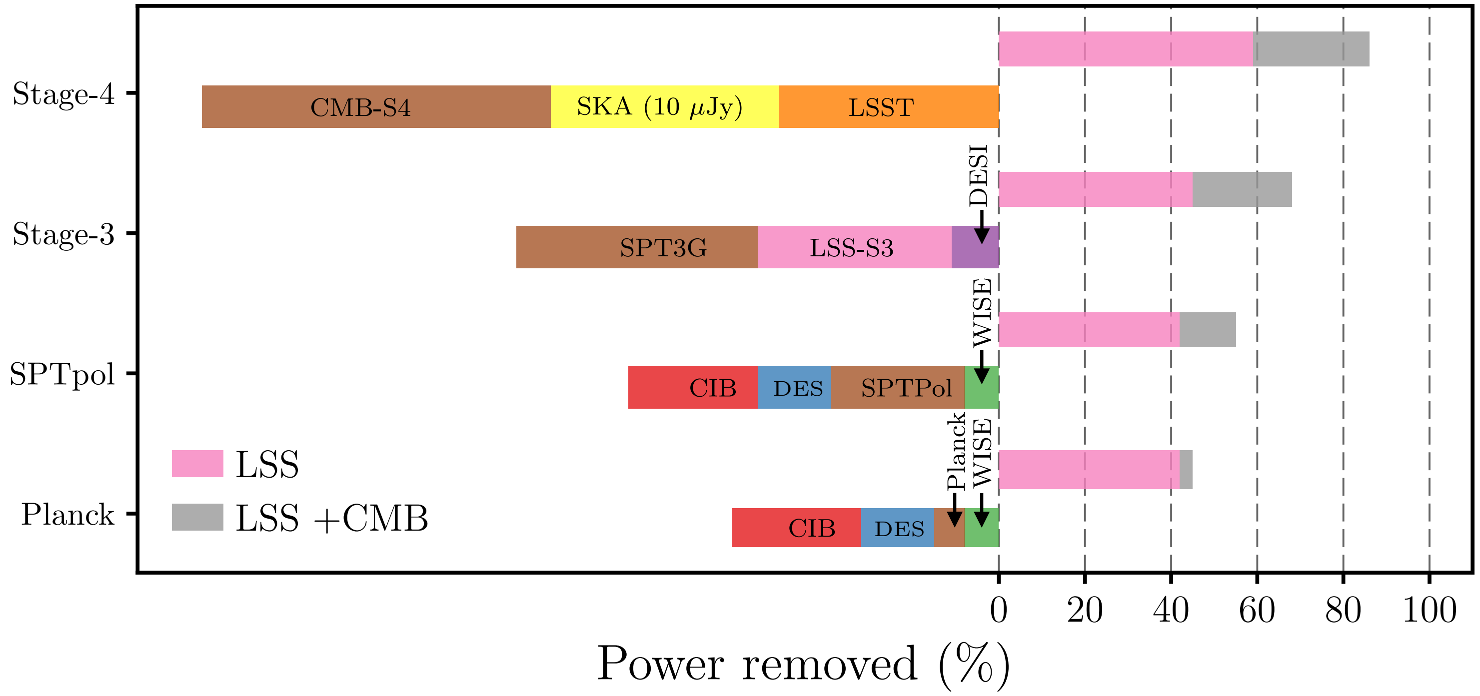
Enhanced large-scale cosmology

- Primordial f_{NL}^{local}: scale-dependent galaxy bias effect. $\sigma(f_{NL}^{local}) \approx 0.7$ through cosmic-variance cancellation techniques (Schmittfull & Seljak 2018).

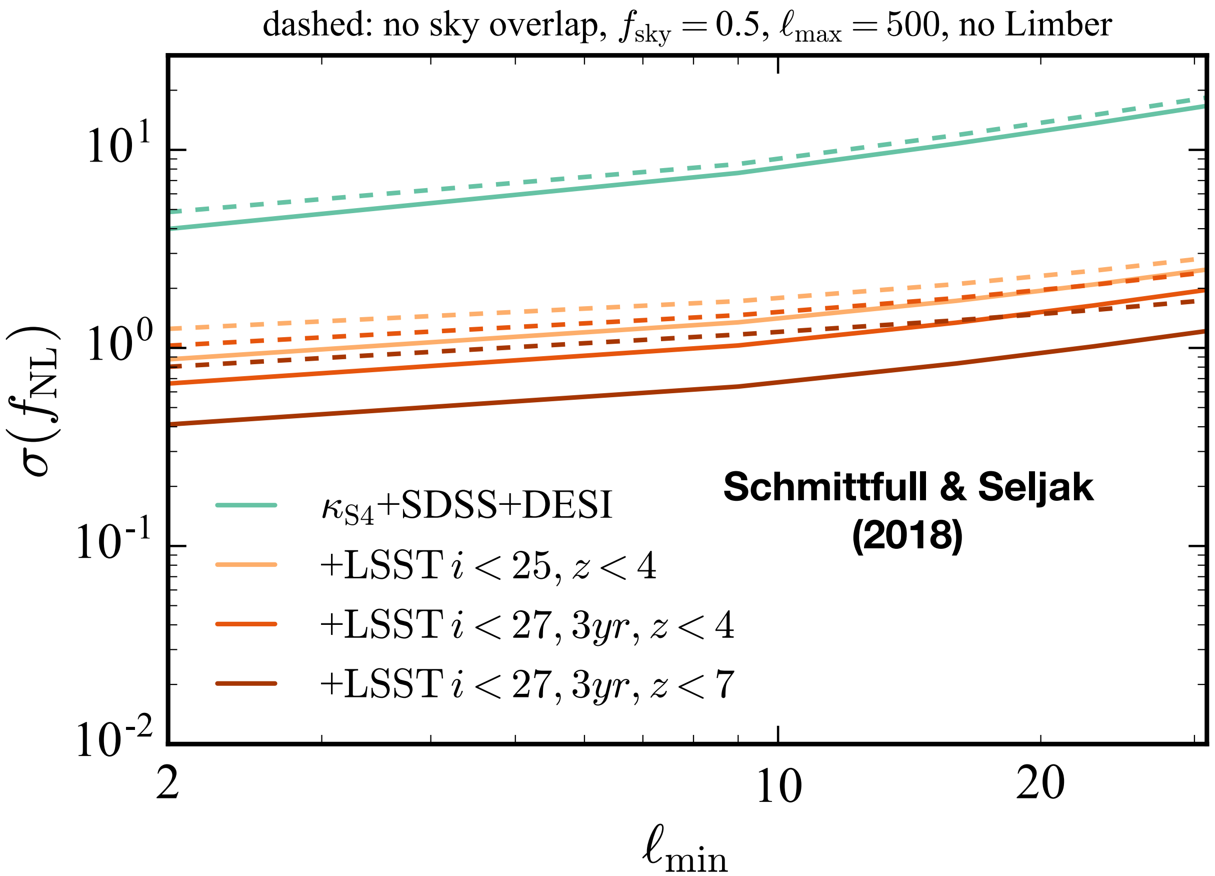
- Can enhance inflation constraints with B-mode delensing with external tracers

$$\hat{B}^{\rm lens}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') f(\mathbf{l},\mathbf{l}') E^N(\mathbf{l}') I(\mathbf{l}-\mathbf{l}')$$

  - Avoids problem of internal delensing biases removal.

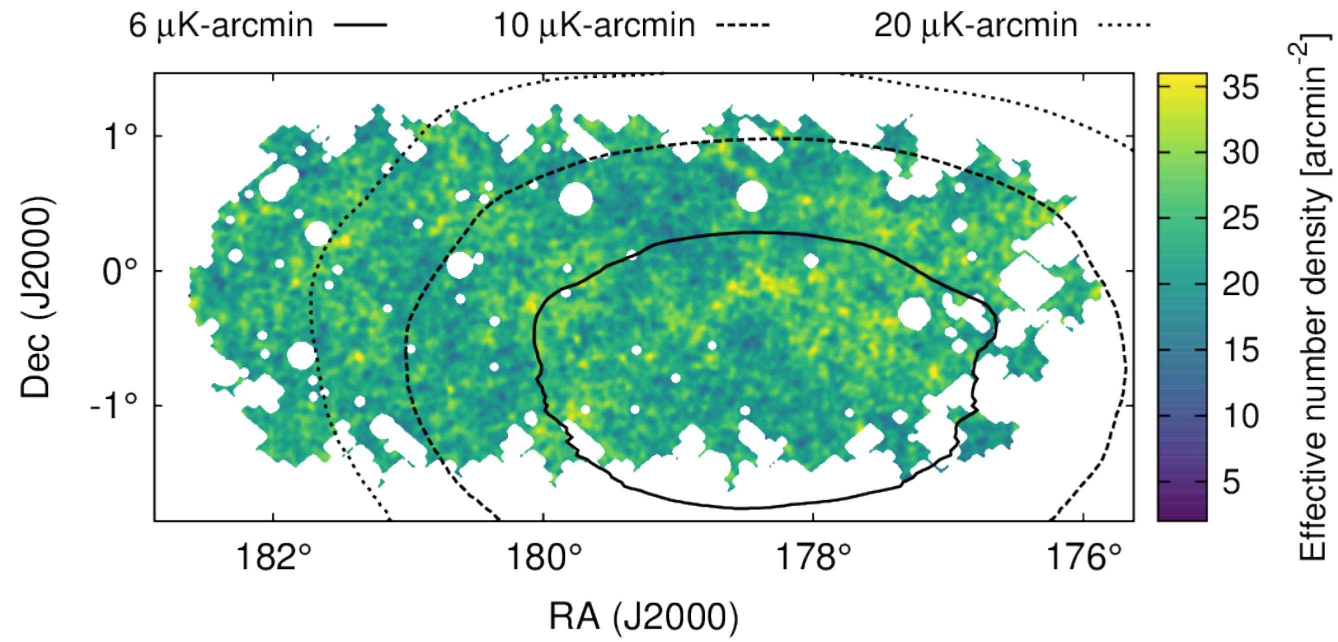


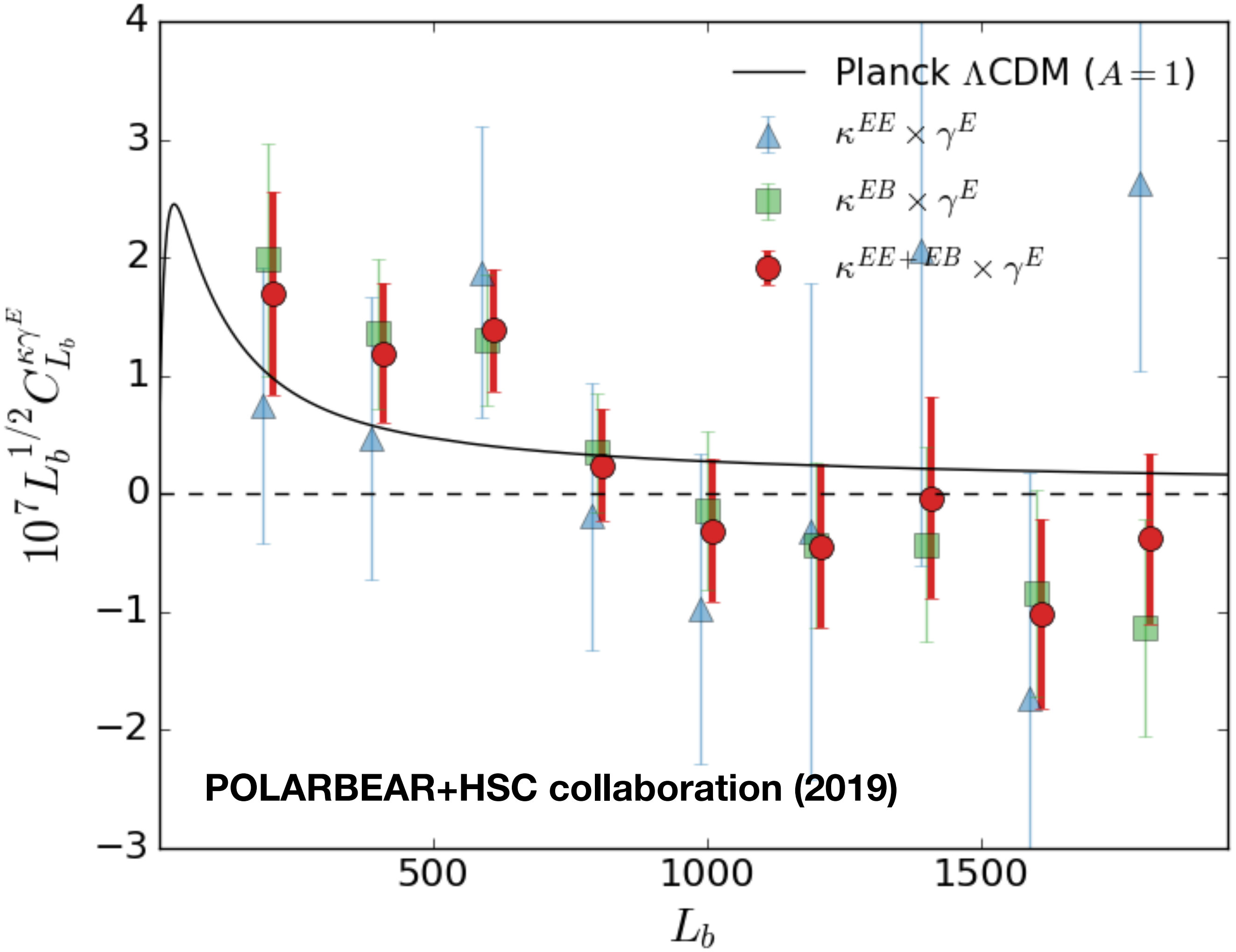
Manzotti (2018)

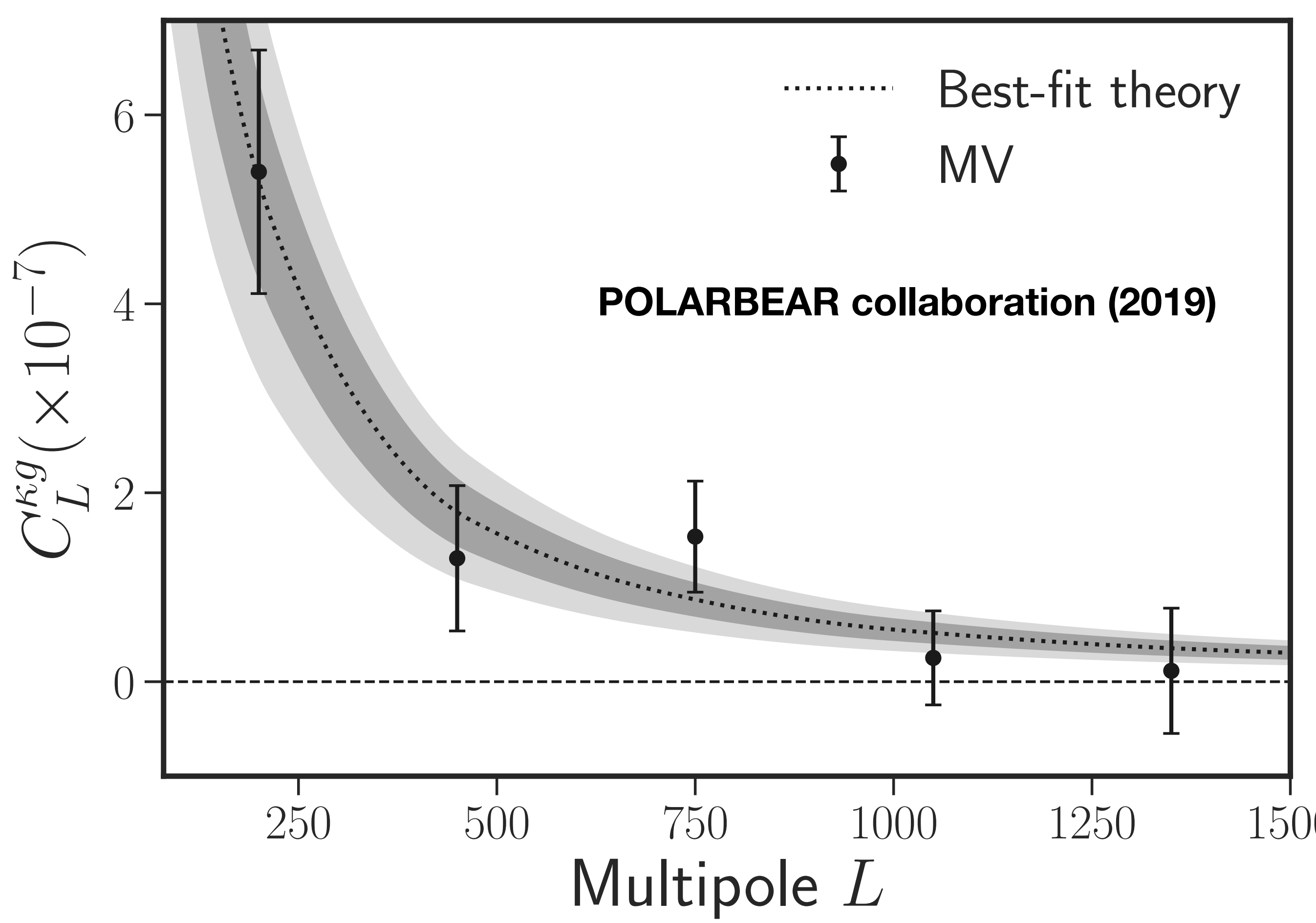


Cross-correlation with “polarized” CMB lensing

- EB+EE reconstruction channels deep enough to allow cross-correlation
  - POLARBEAR x HSC : 3.5σ
  - POLARBEAR x H-ATLAS: 4.8σ

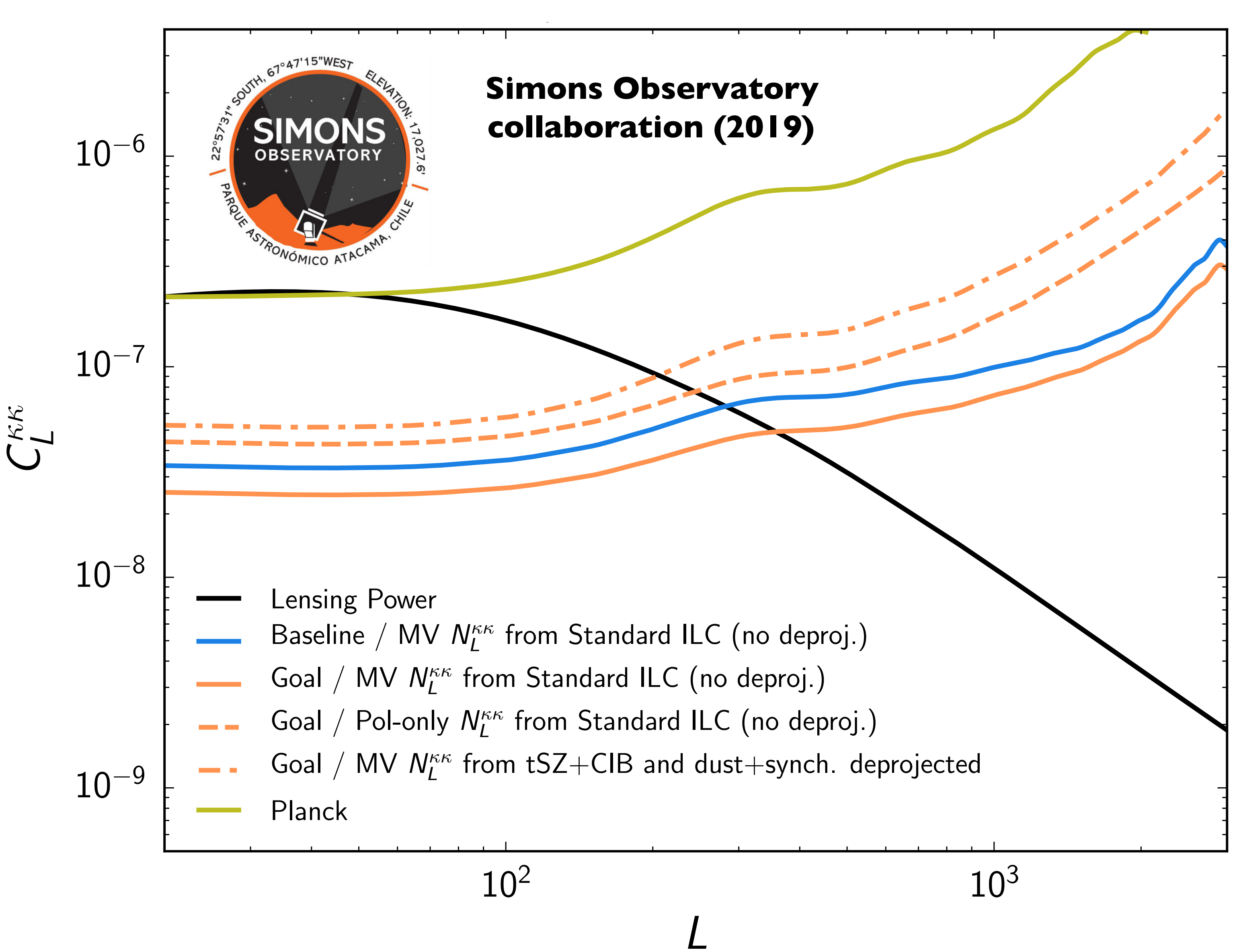


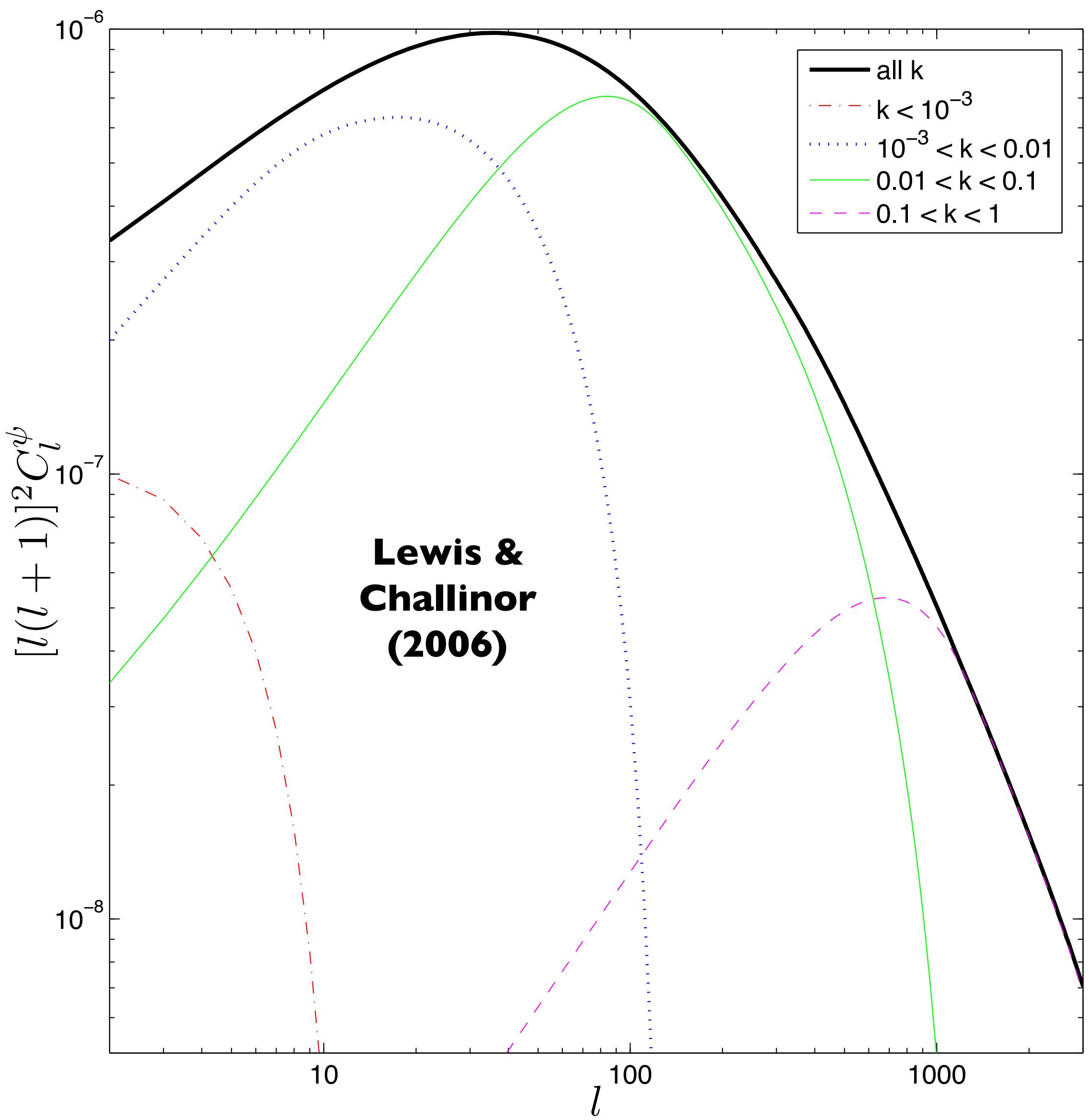




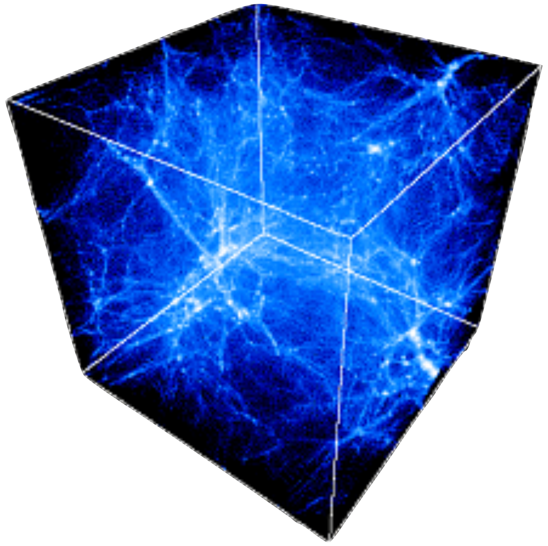
Are we ready for precision cross-correlation?

- Are our forward modeling and estimators good enough for SO/S4, LSST/Euclid era?
- How non-linear evolution affects cross-correlation observables? Is the Born approximation good enough?
- Accurate coherent modelling to be done on full-sky: need efficient tools.





How to include non-linearities and post-Born?



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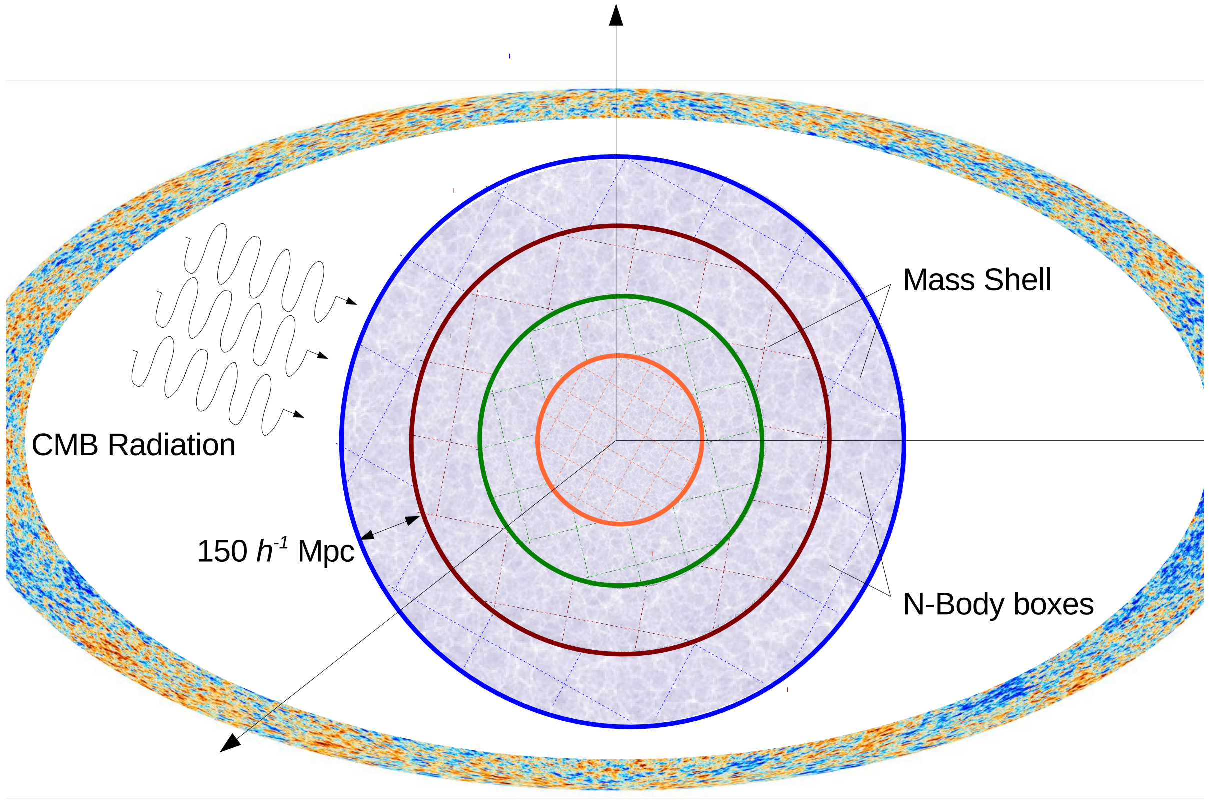

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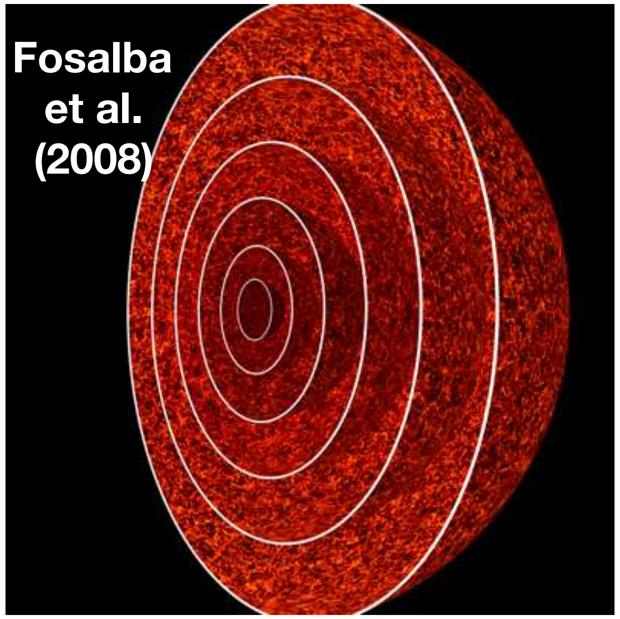

- N-body simulations (DEMNUni, Castorina+ 2016)

Fabbian & Stompor (2013)
Calabrese, Carbone, Fabbian+ (2015)
Fabbian, Calabrese, Carbone (2018)

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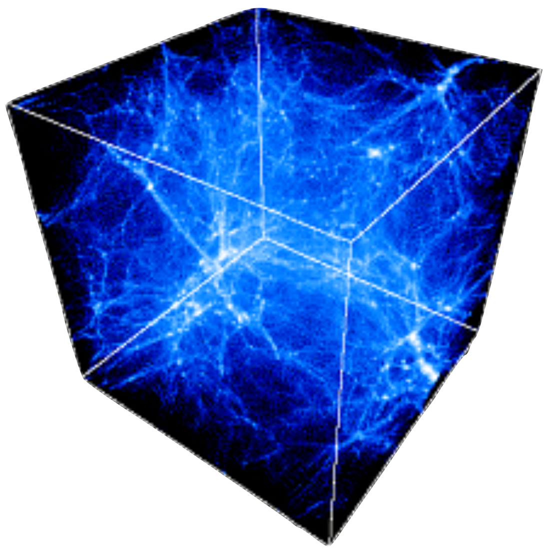

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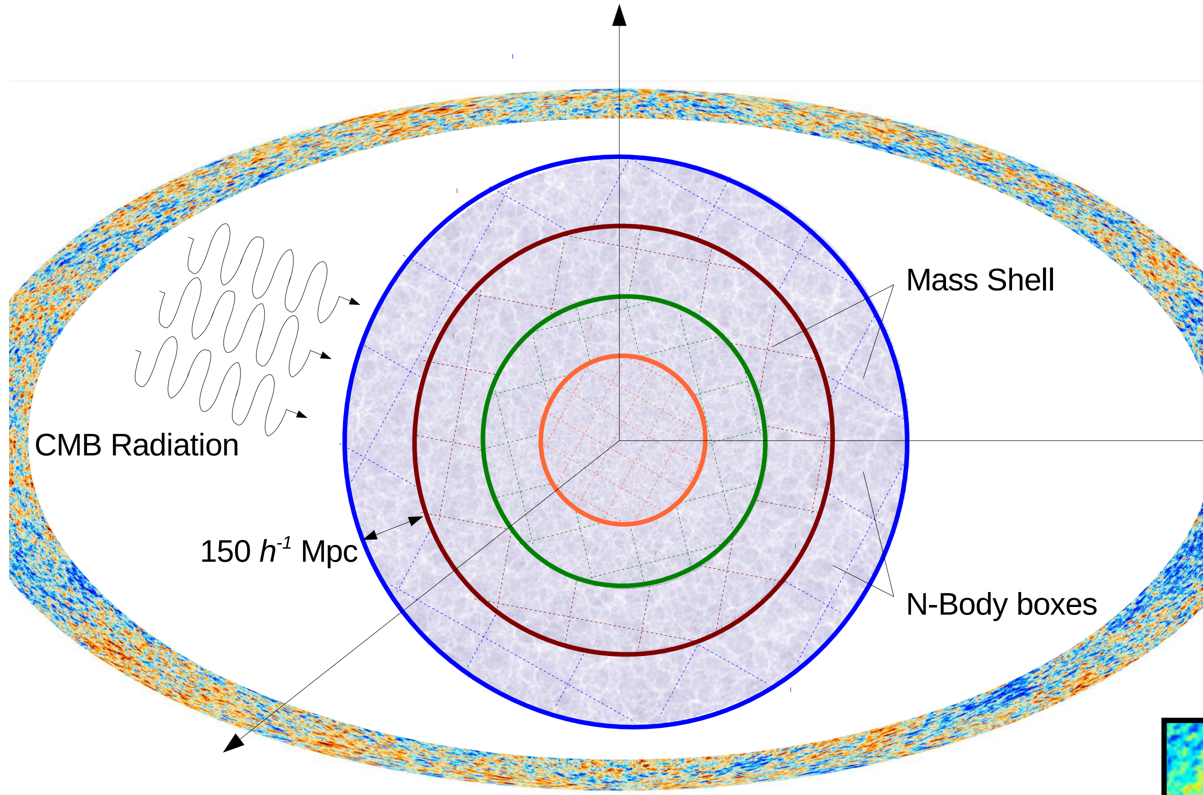

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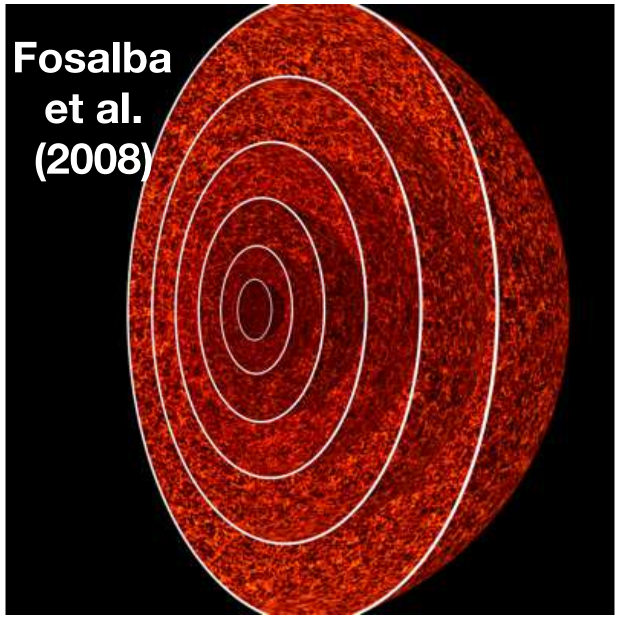
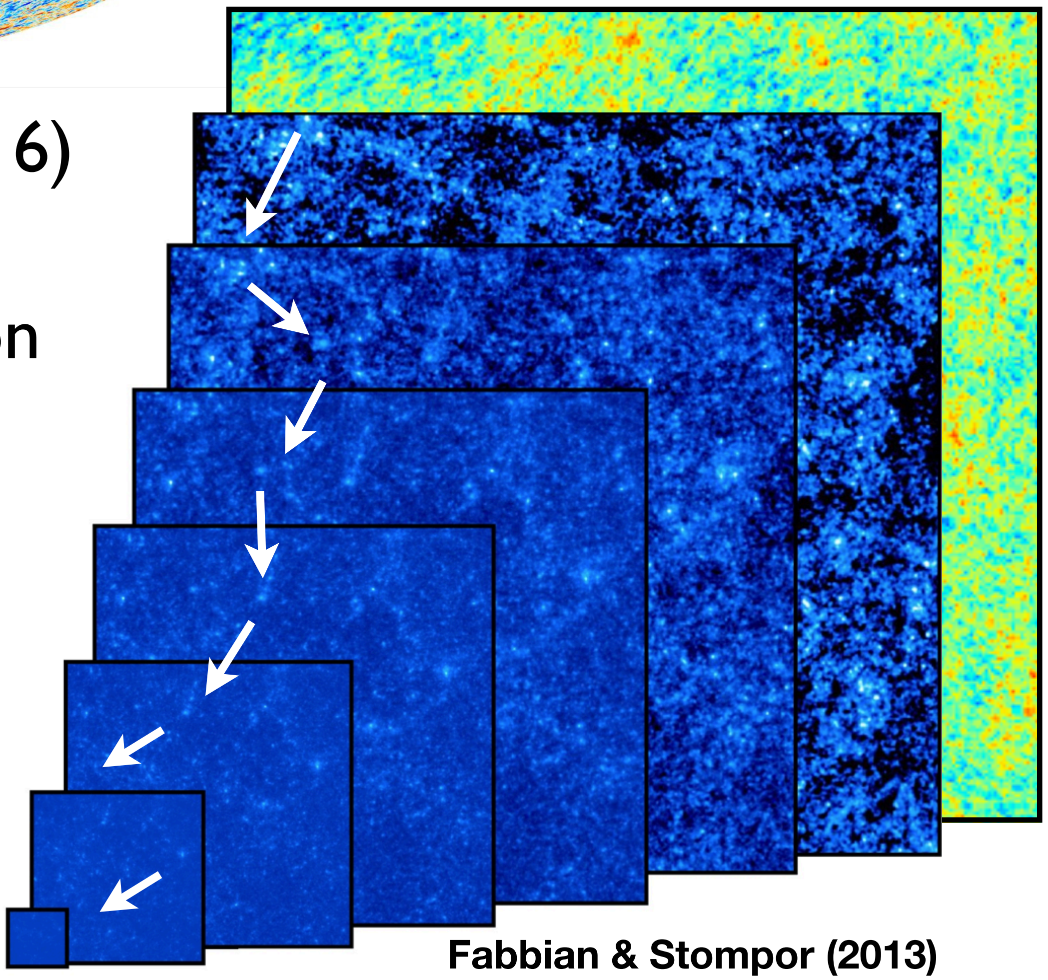


- N-body simulations (DEMNUni, Castorina+ 2016)
- Full-sky raytracing in multiple-lens approximation at arcsec resolution (Fabbian+2013, 2018)

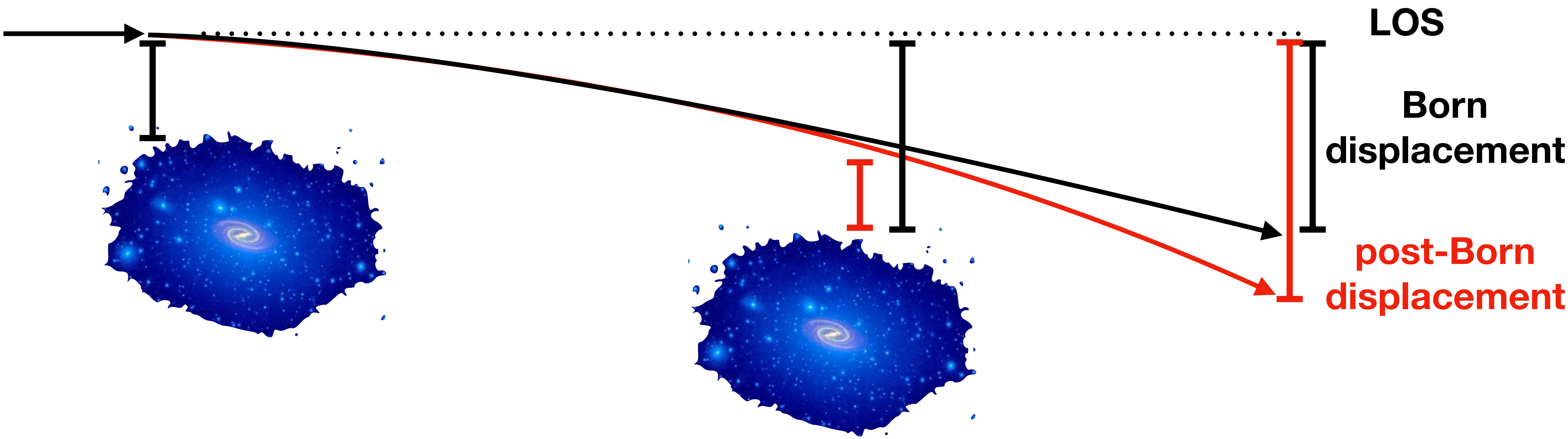
$$A_{ij}^{N}(\boldsymbol{\theta}, \chi_N) = \delta_{ij}^{K} - \sum_{k=0}^{N-1} \frac{D_{k,N}}{D_N} U_{ip}^{(k)}(\boldsymbol{\beta}^{(k)}, \chi_k) A_{pj}^{(k)}(\boldsymbol{\theta}, \chi_k)$$

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

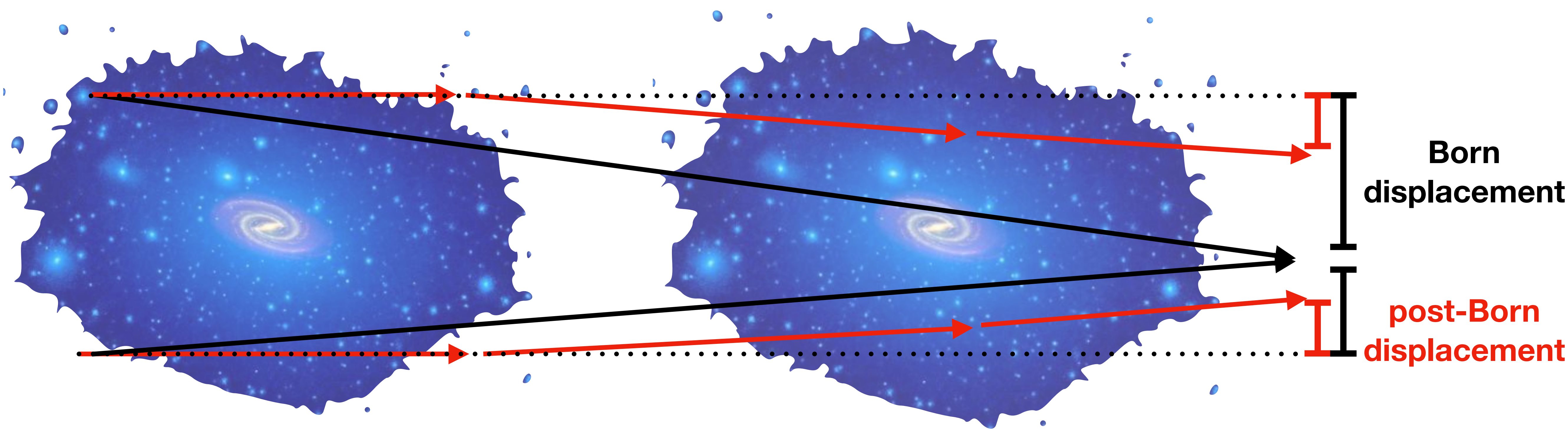


Fabbian & Stompor (2013)
Calabrese, Carbone, Fabbian+ (2015)
Fabbian, Calabrese, Carbone (2018)

Beyond Born corrections: what are they?



Lensing changes location of later lensing events

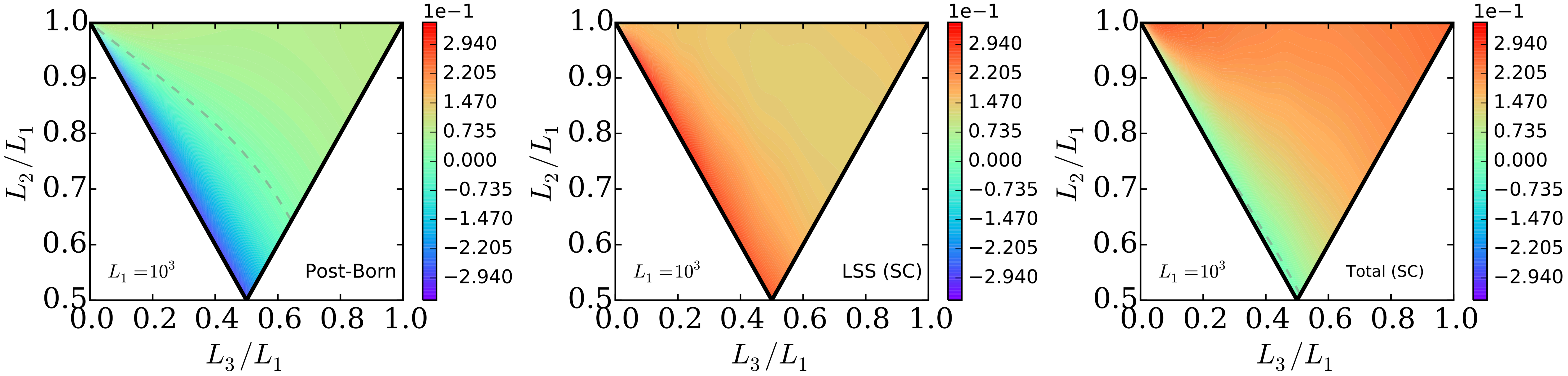


Size and shape of image affected by first lensing event

Non-Gaussian deflections: biases in CMB lensing

Pratten & Lewis (2016)

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



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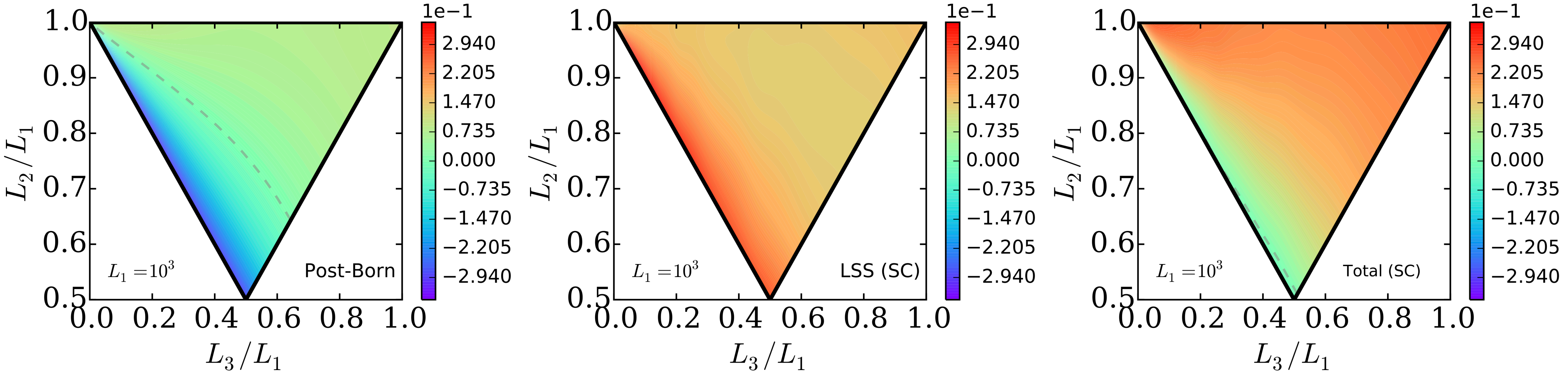

$$\hat{\phi}(\mathbf{L}) = A_L \int_{\mathbf{l}} g(\mathbf{l}, \mathbf{L}) \tilde{T}_{\rm expt}(\mathbf{l}) \tilde{T}_{\rm expt}(\mathbf{L} - \mathbf{l})$$

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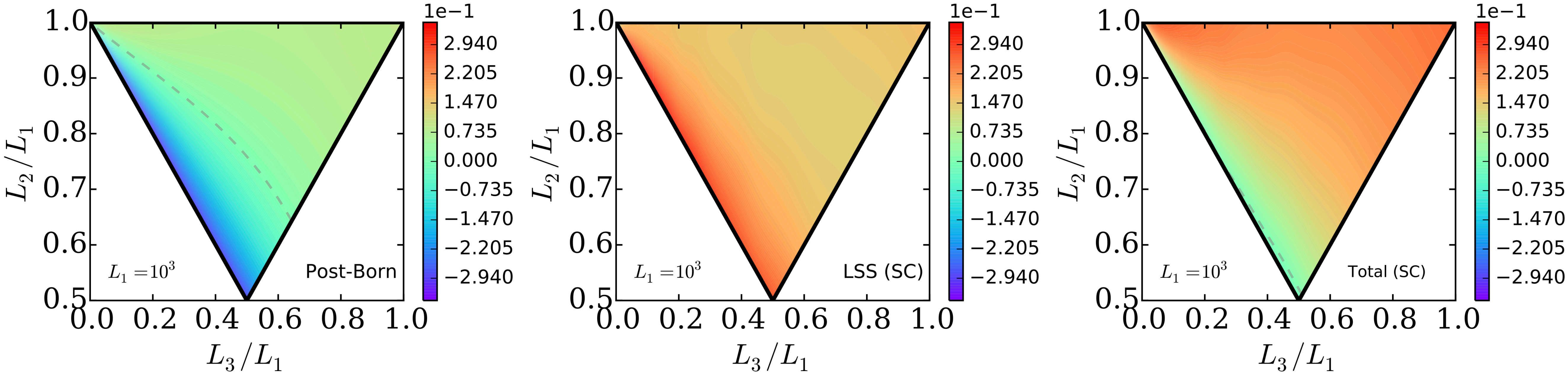

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$$\tilde{T}(\mathbf{l}) = T(\mathbf{l}) + \delta T(\mathbf{l}) + \delta^2 T(\mathbf{l}) + \mathcal{O}(\phi^3) \qquad \delta T(\mathbf{l}) = -\int_{\mathbf{l}'} \mathbf{l}'\cdot(\mathbf{l}-\mathbf{l}')T(\mathbf{l}')\phi(\mathbf{l}-\mathbf{l}')$$

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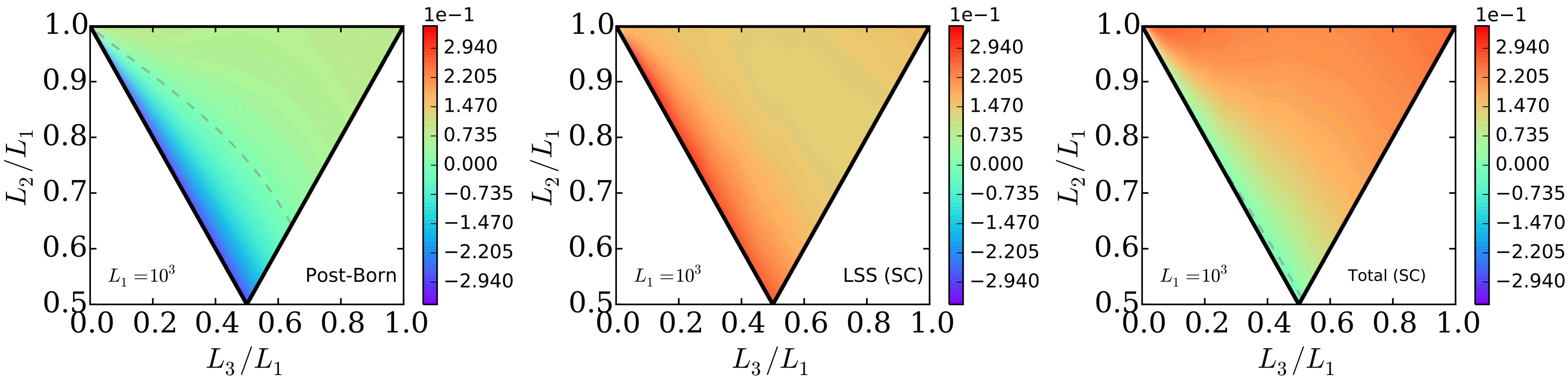

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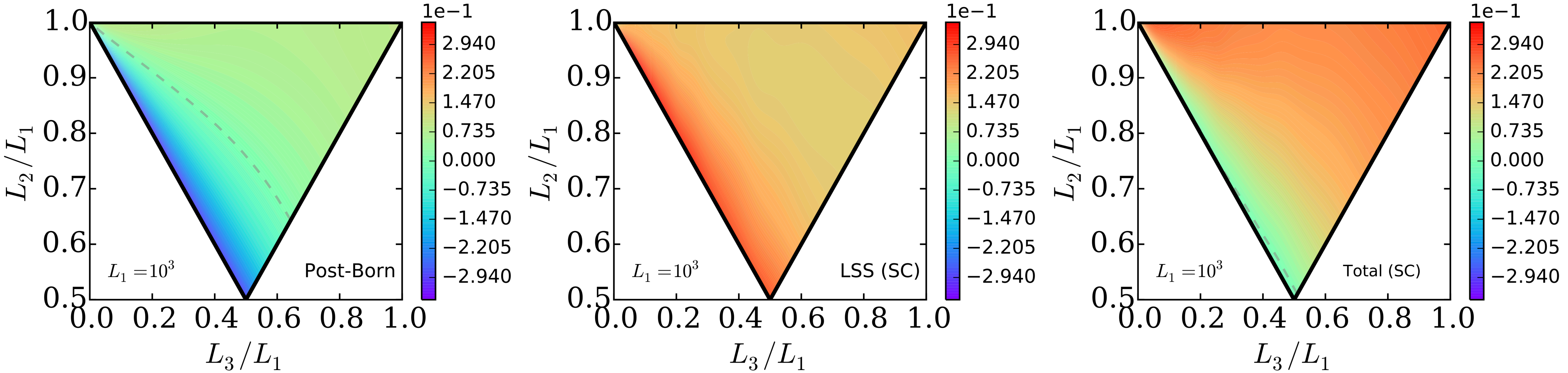
$$\langle \tilde{T}\tilde{T}\tilde{T}\tilde{T} \rangle = \langle \delta T \delta T \delta T T \rangle + \cdots = \boxed{\langle T_{,i}\phi_{,i} T_{,j}\phi_{,j} T_{,k}\phi_{,k} T \rangle} + \cdots$$

Böhm et al. (2016)

$$\boxed{C^{TT}_l B_\phi(\mathbf{l}_1 - \mathbf{l}, \mathbf{l}_2 + \mathbf{l}, -\mathbf{l}_1 - \mathbf{l}_2),}$$

Non-Gaussian deflections: biases in CMB lensing

Pratten & Lewis (2016) $(L_2 L_3)^{1/2}\, b^{\kappa\kappa\kappa}_{L_1 L_2 L_3} / (C^{\kappa\kappa}_{L_1} C^{\kappa\kappa}_{L_2} C^{\kappa\kappa}_{L_3})^{1/2}$



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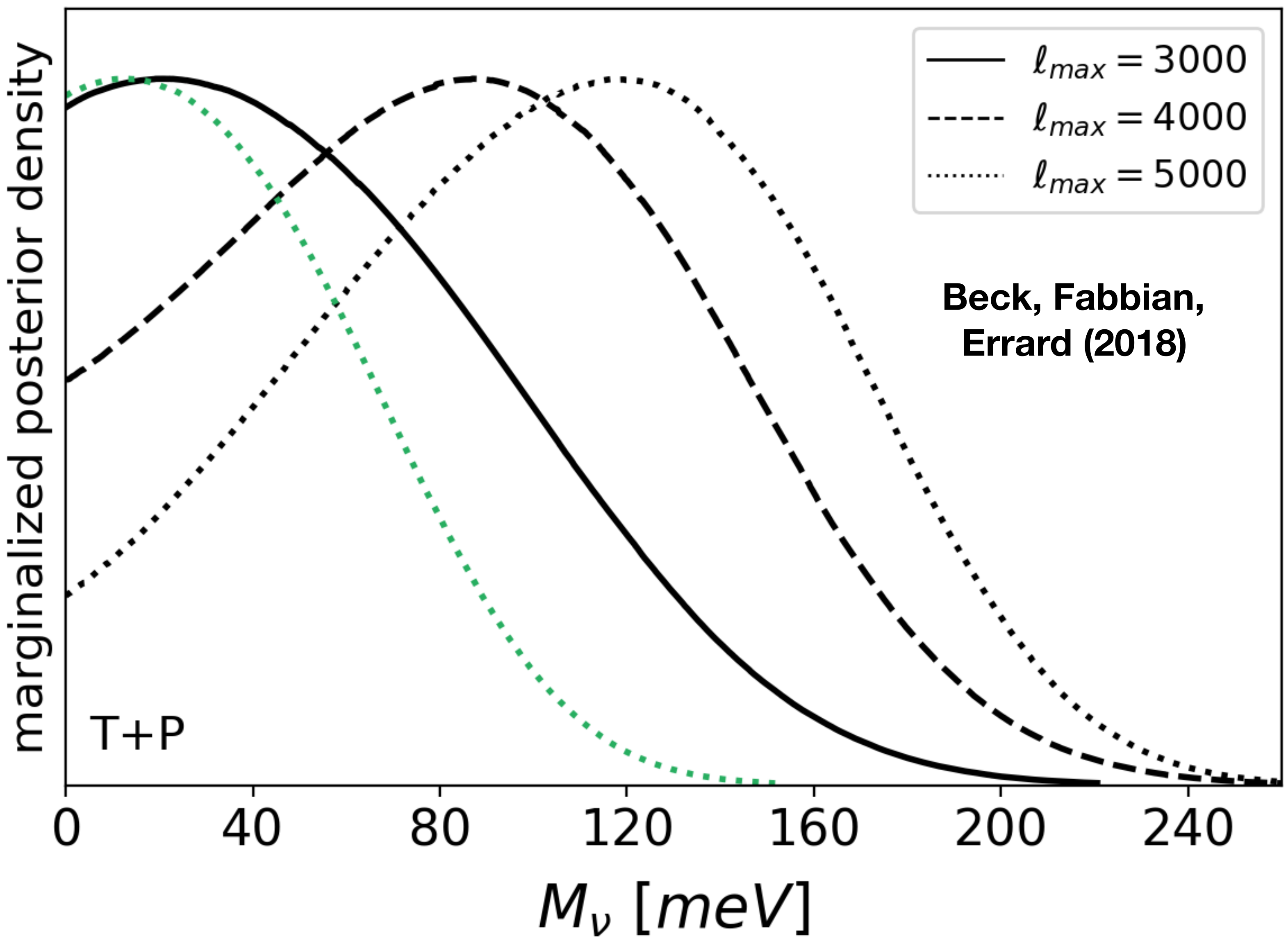
$$\langle \tilde{W} \tilde{X} \phi_{\rm ext} \rangle_{\mathcal{O}[(C^{\phi\phi})^{3/2}]} = \boxed{\langle \delta W \delta X \phi_{\rm ext} \rangle + \langle W \delta^2 X \phi_{\rm ext} \rangle + \langle \delta^2 W X \phi_{\rm ext} \rangle}$$

$$\boxed{C^{\bar{W}\bar{X}}_{l_5} B^{\phi_{\rm ext}\phi\phi}(L, l_1, l_3)}$$

Fabbian et al. (2019)

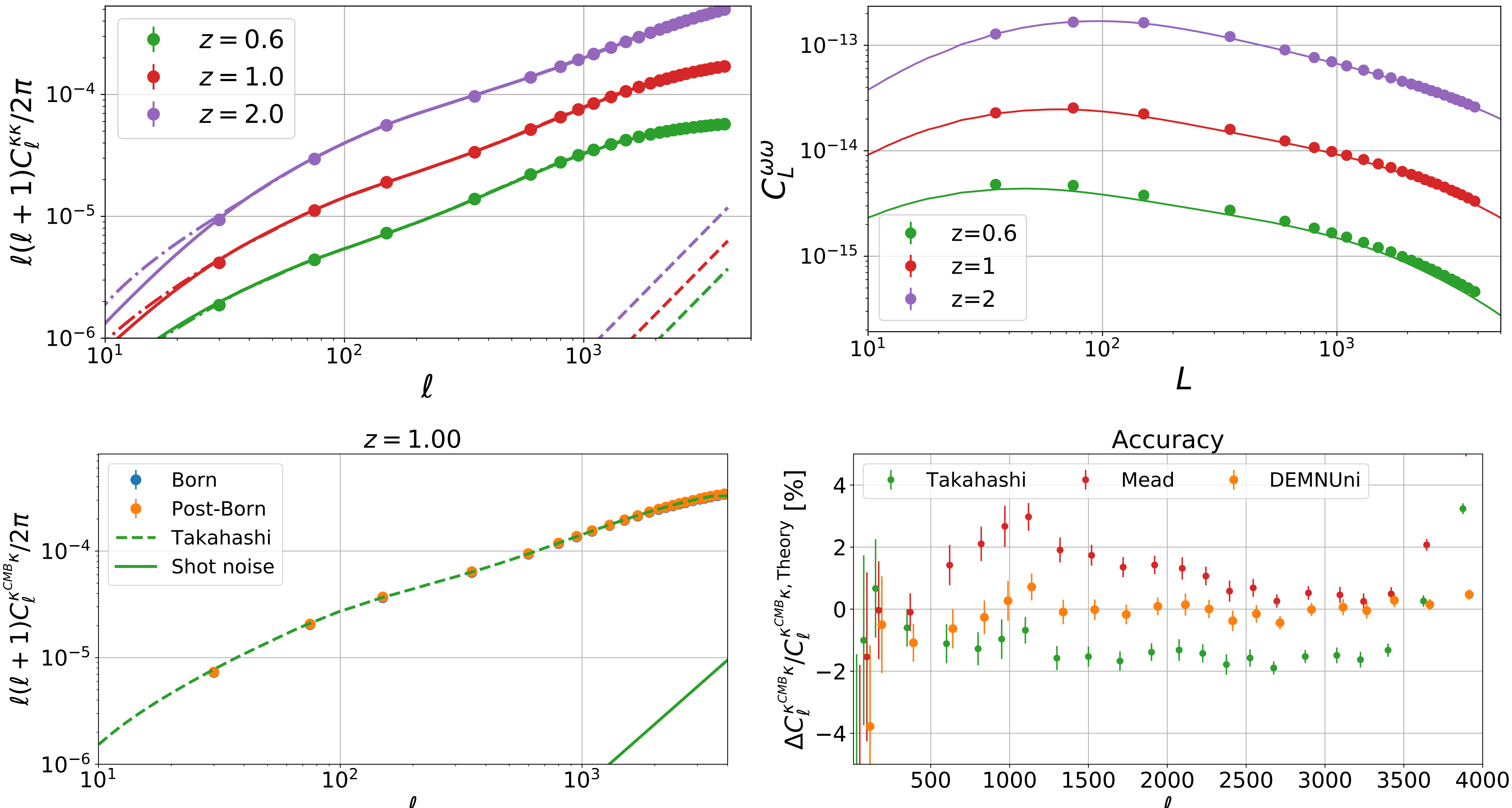
$N^{3/2}$ and cosmological parameters estimation

- Bias on cosmological parameters at 1-2 sigma if unaccounted: neutrino mass more affected!
- Data set combination more robust but possible inconsistencies due to $N^{3/2}$
- Effect dependent on lensing reconstruction channel: polarization less affected



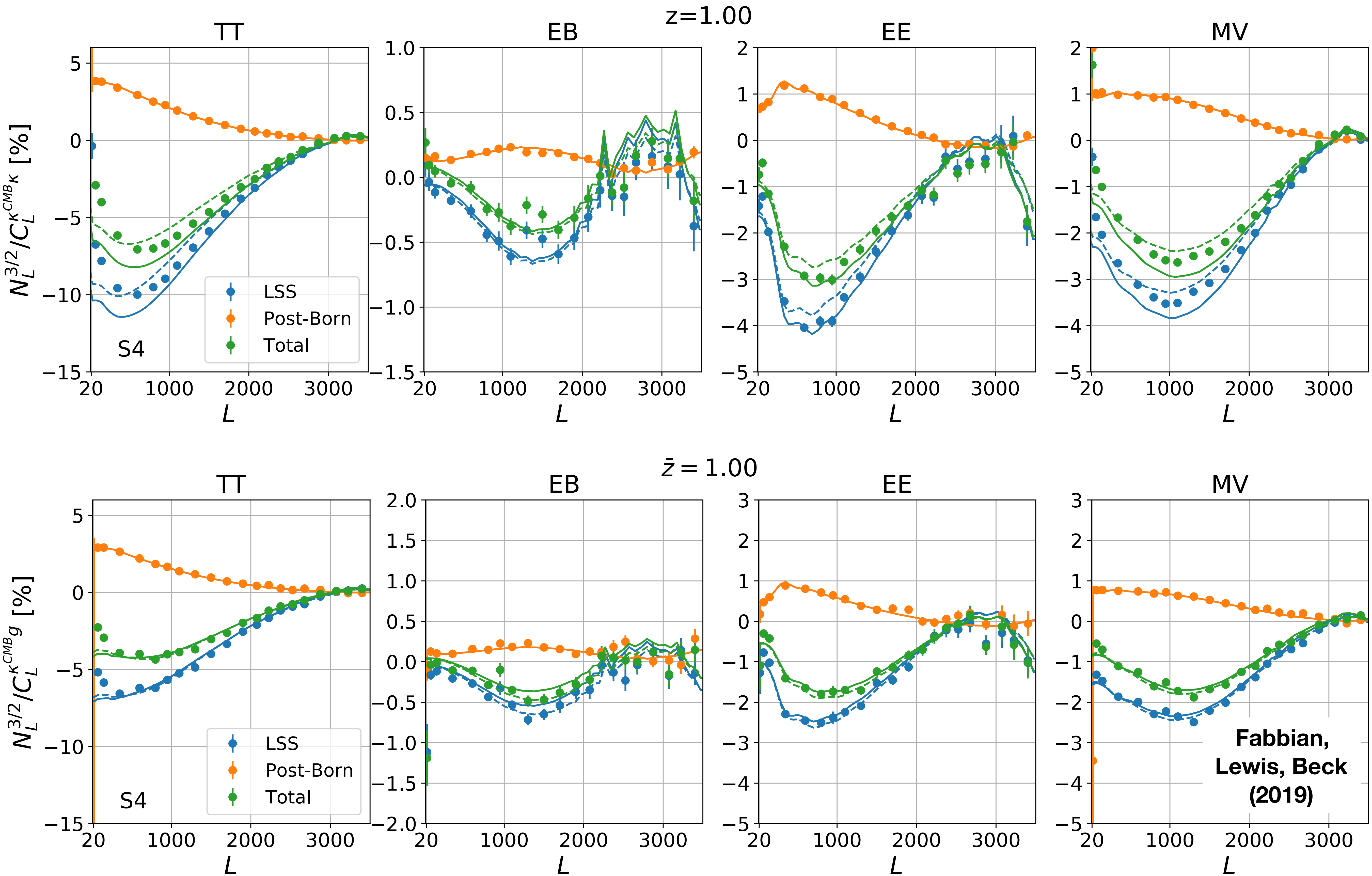
Coherent CMB lensing - LSS simulations

- Percent level agreement with semi-analytical models for non-linear matter power spectrum.

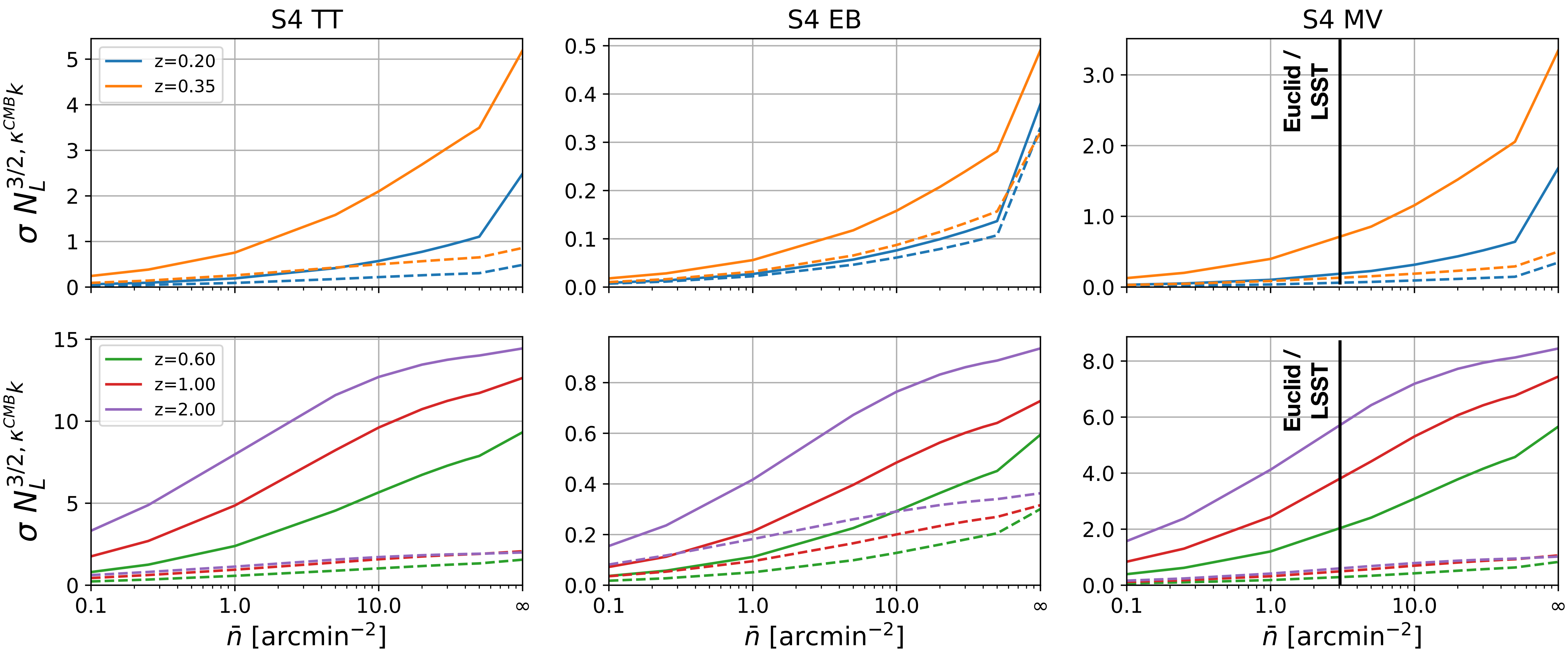


Fabbian, Lewis, Beck (2019)

Cross-correlation with external tracers for S4



$N^{3/2}$ detection prospects



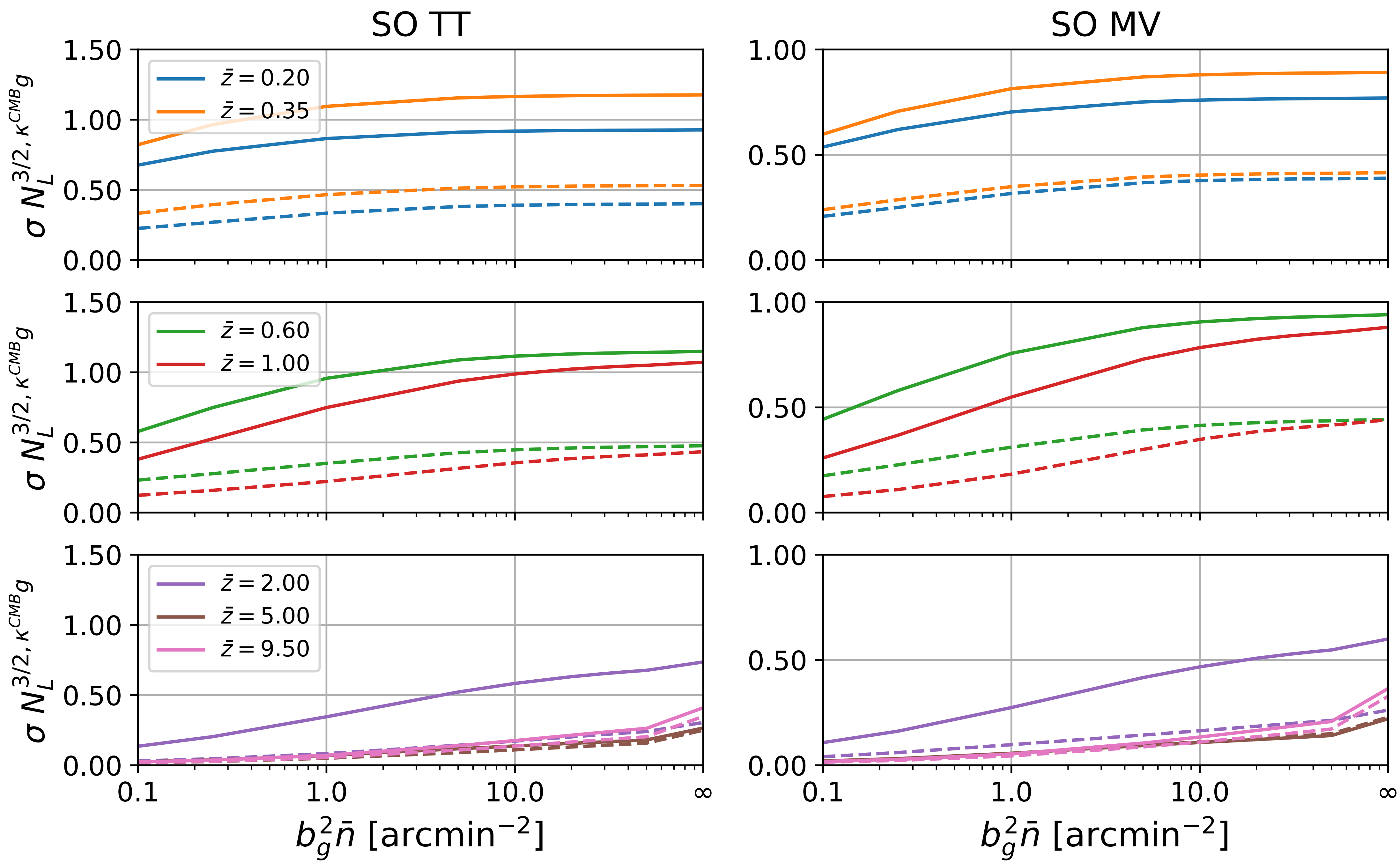
- Mimics intrinsic alignment on shear-CMB lensing correlation, prevent correct systematic marginalization (Hall & Taylor, Larsen & Challinor)

ΔA_{IA}	$z = 0.20$	$z = 0.35$	$z = 0.60$	$z = 1.00$	$z = 2.00$
TT	0.02 ± 0.07	0.09 ± 0.07	0.27 ± 0.07	0.57 ± 0.08	1.08 ± 0.11
EB	0.00 ± 0.7	0.00 ± 0.07	0.01 ± 0.07	0.02 ± 0.08	0.05 ± 0.10
MV	0.01 ± 0.06	0.03 ± 0.06	0.10 ± 0.06	0.21 ± 0.07	0.42 ± 0.08

$N^{3/2}$ detection prospects - II

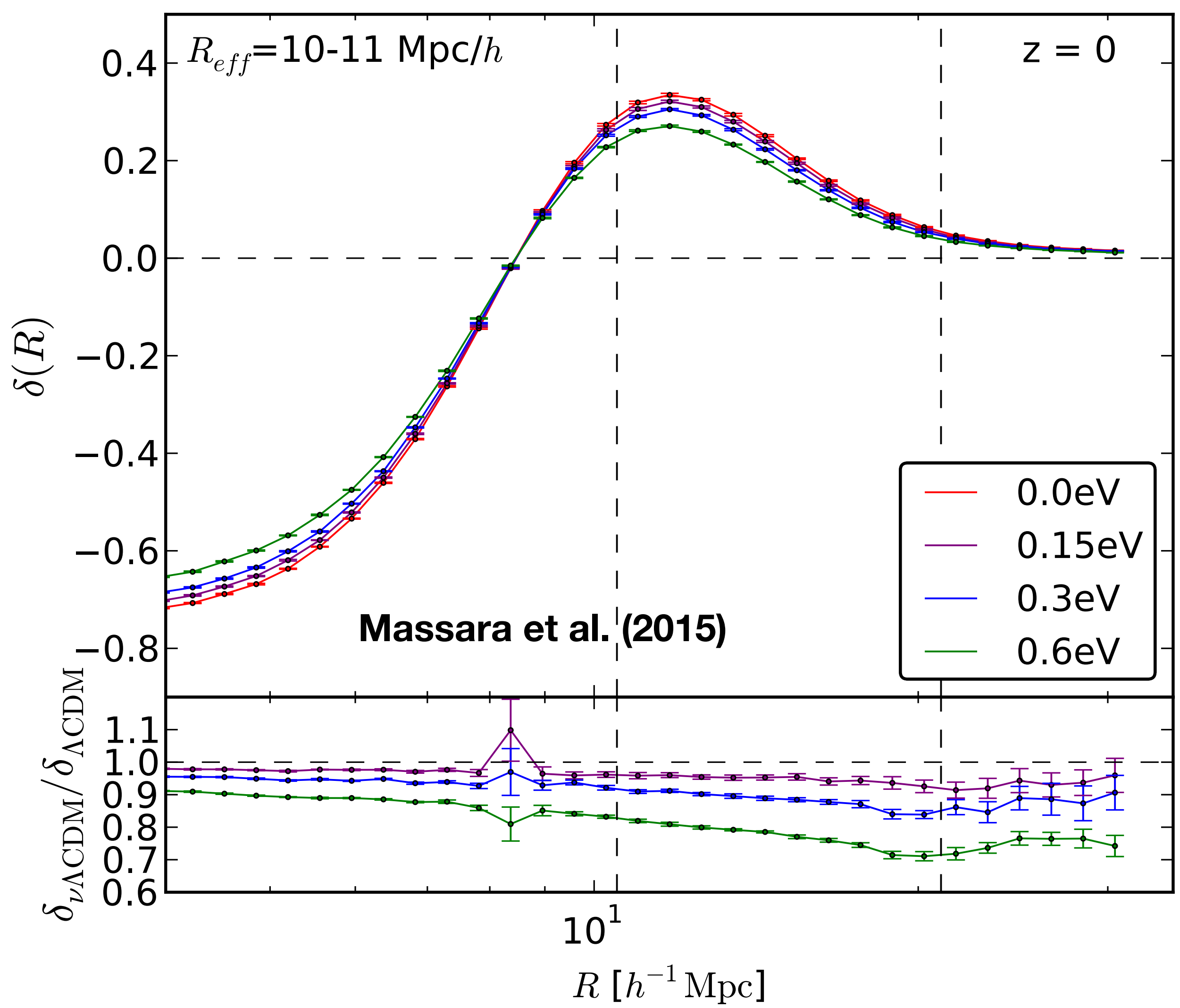
- High significance detection in galaxy cross-correlation with S4 (~5-10σ)

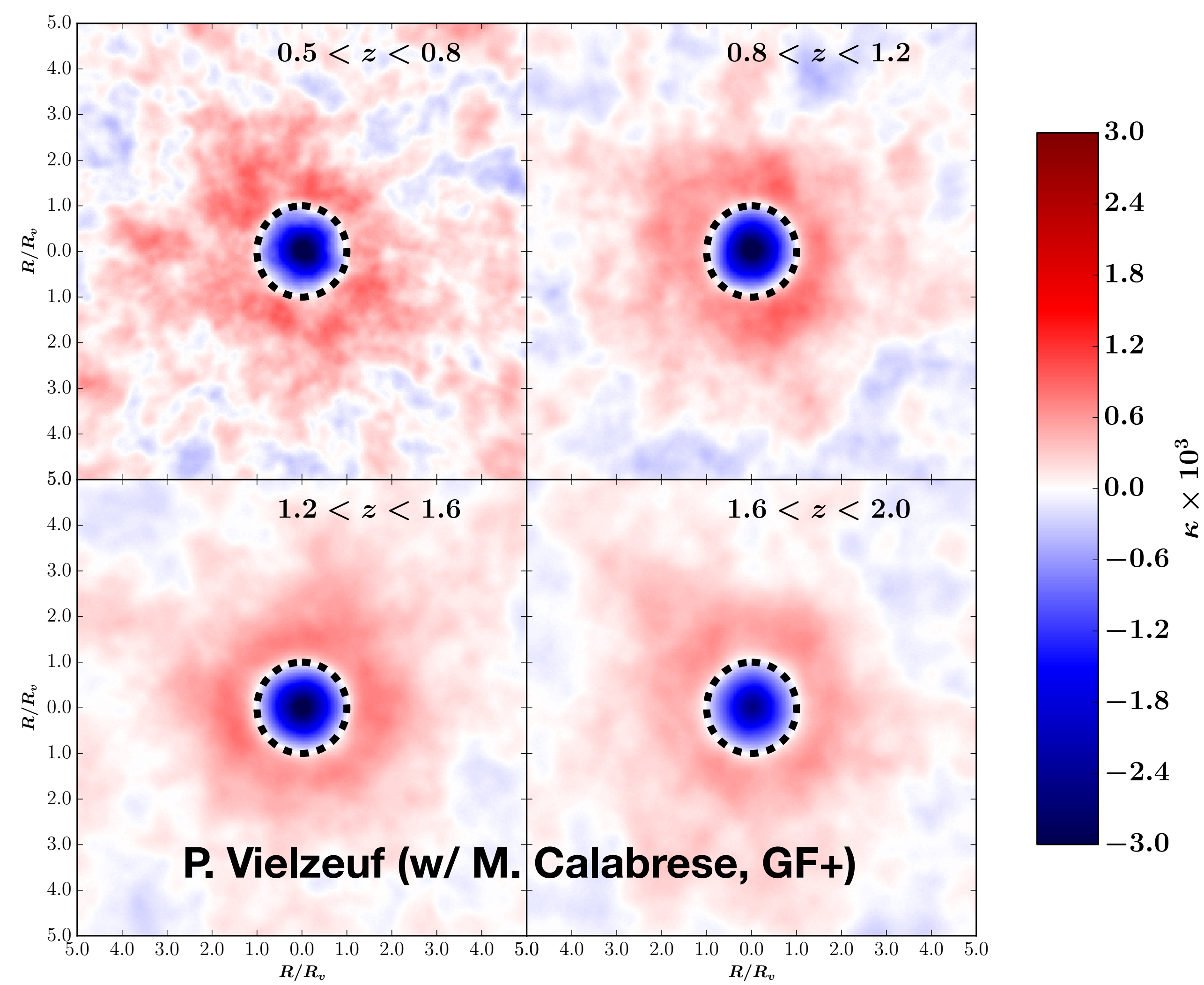
- For SO, $N^{3/2}$ will be detected in tomographic cross-correlation analysis and cosmic-variance cancellation regime



Ongoing work: alternative probes

- Cosmic voids: powerful probe of neutrino mass (e.g. Massara+2015). Can break $\sigma_8 - \Omega_\nu$ degeneracy with matter profile.
- Void profile from CMB lensing of DEMNUni simulations with massive neutrinos
- Applying pipeline to N-body simulations with non-standard cosmologies (e.g. MG)

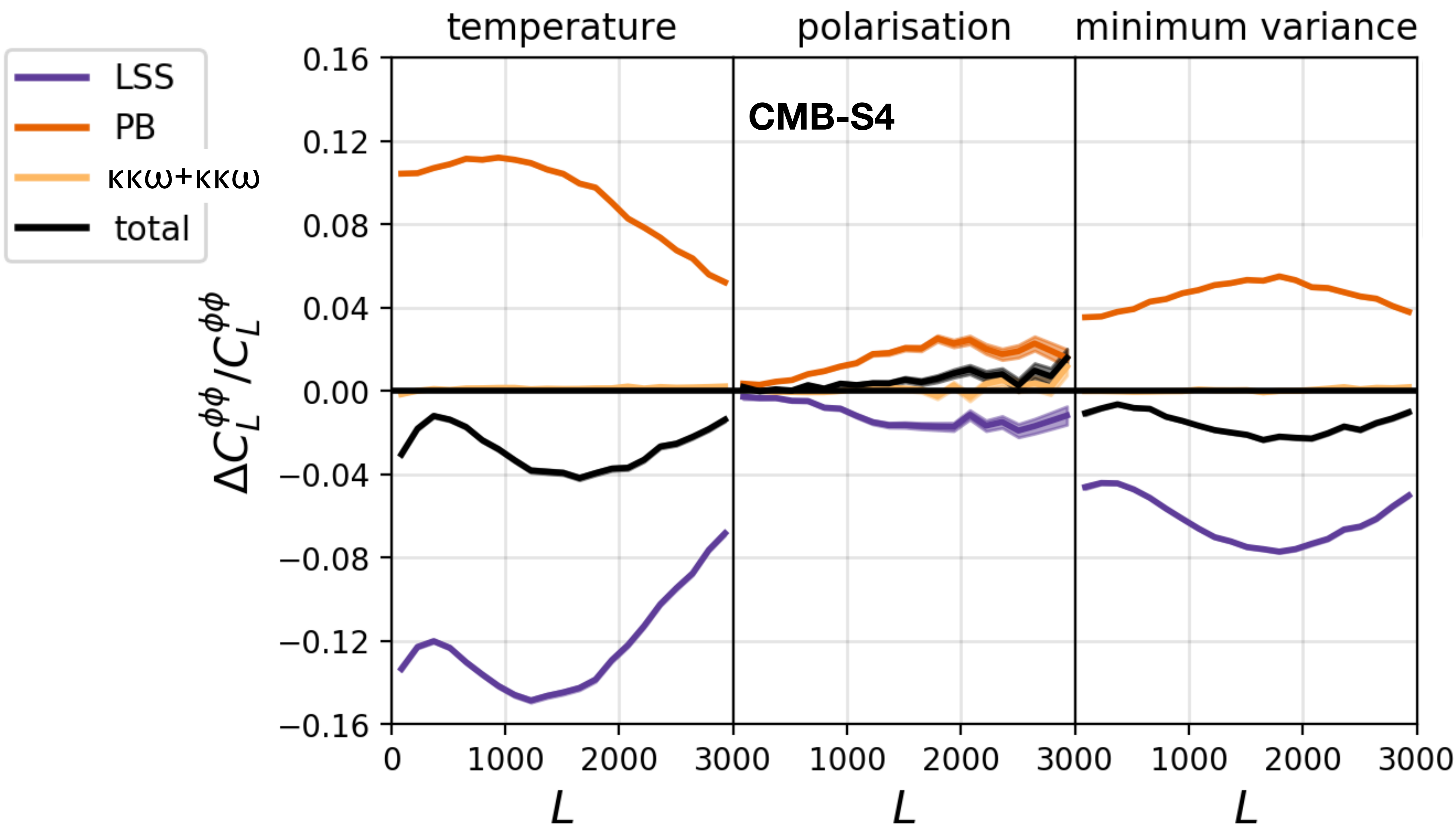




Conclusions

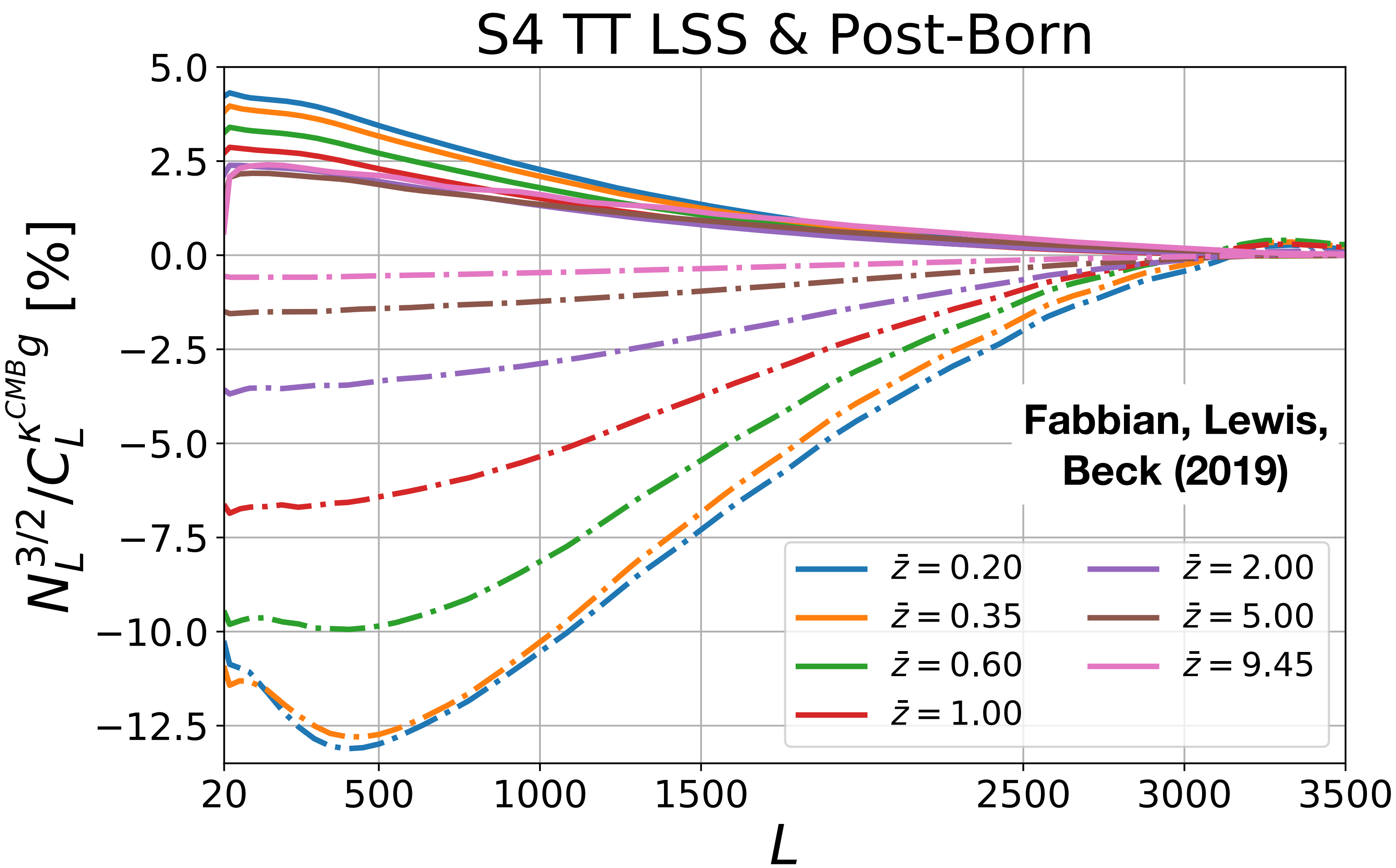
- **CMB lensing and LSS cross-correlation: less systematics and better cosmology.**
  - Increased statistical power, systematics self-calibration and marginalization.
- **In Euclid/LSST era we need accurate predictions.**
  - Theoretical modelling and approximations employed need to be well understood (numerical simulations as well).
  - E.g. $N^{3/2}$ bias can prevent robust cosmological analysis.
- **Additional synergies with SZ surveys to be explored.**
  - Can constraint halo thermodynamical properties, feedback processes.
- **More detailed synergies with EUCLID currently under investigation.**

Bias on lensing reconstruction from higher-order



Beck, Fabbian, Errard (2018). Also Böhm et al. (2018)

Redshift and CMB sensitivity dependencies



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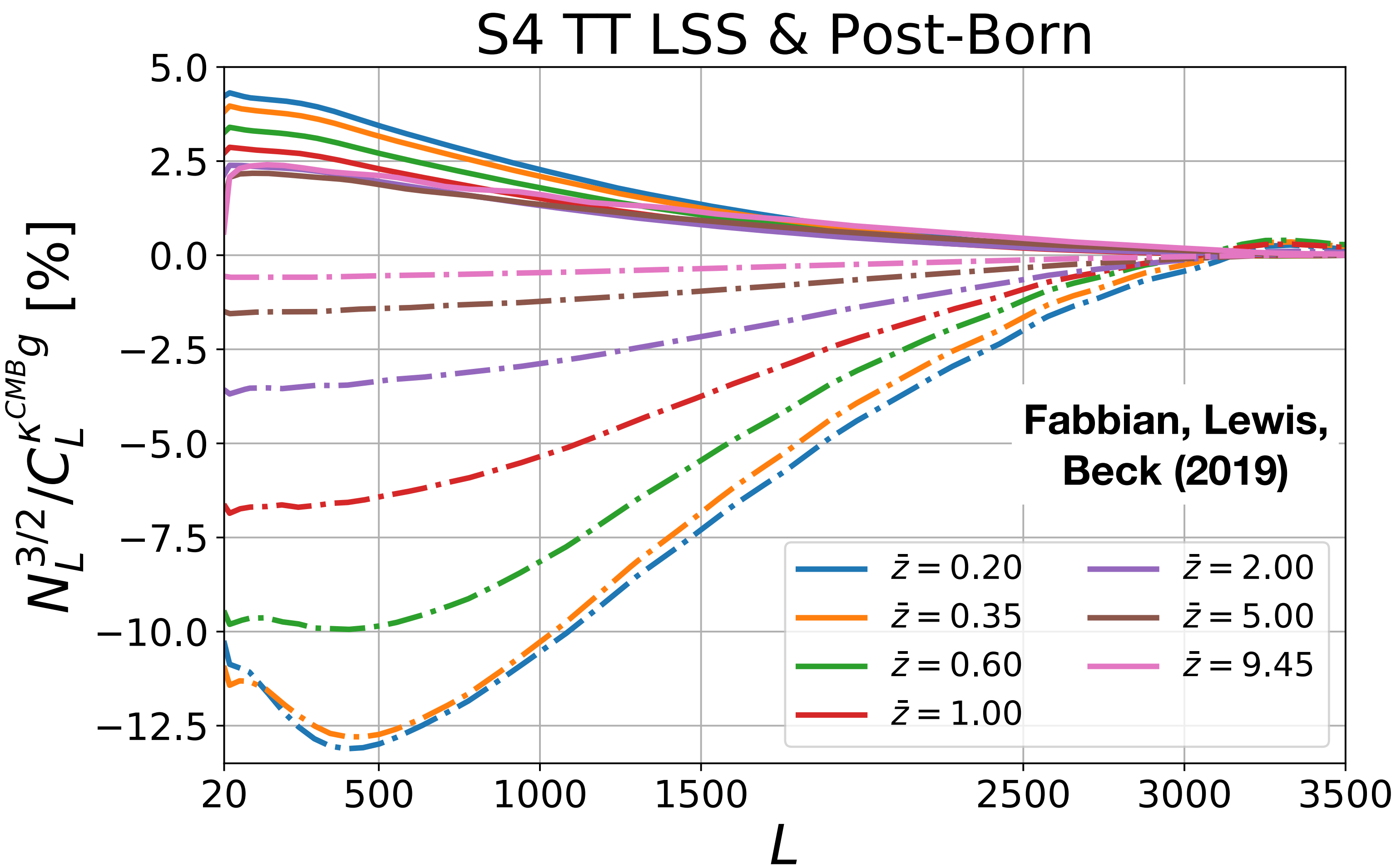
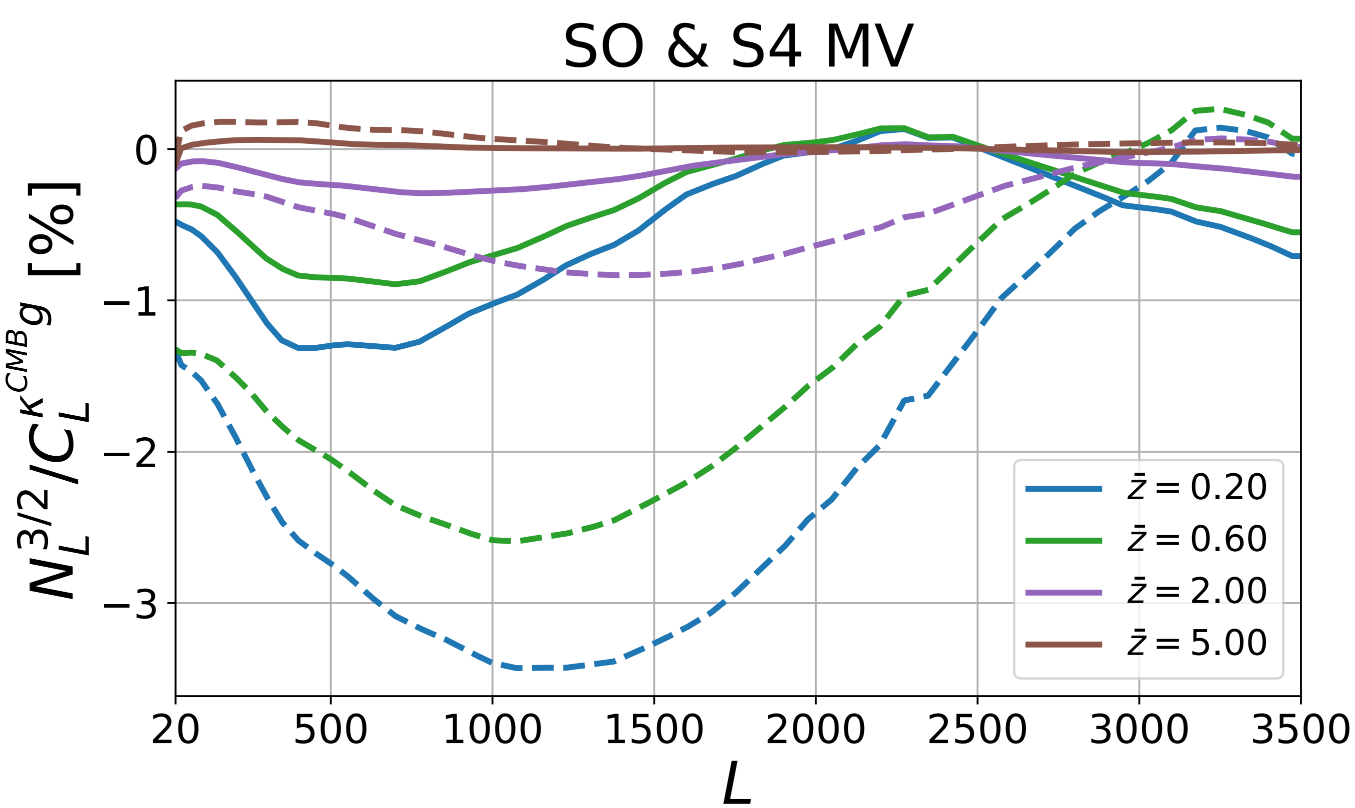
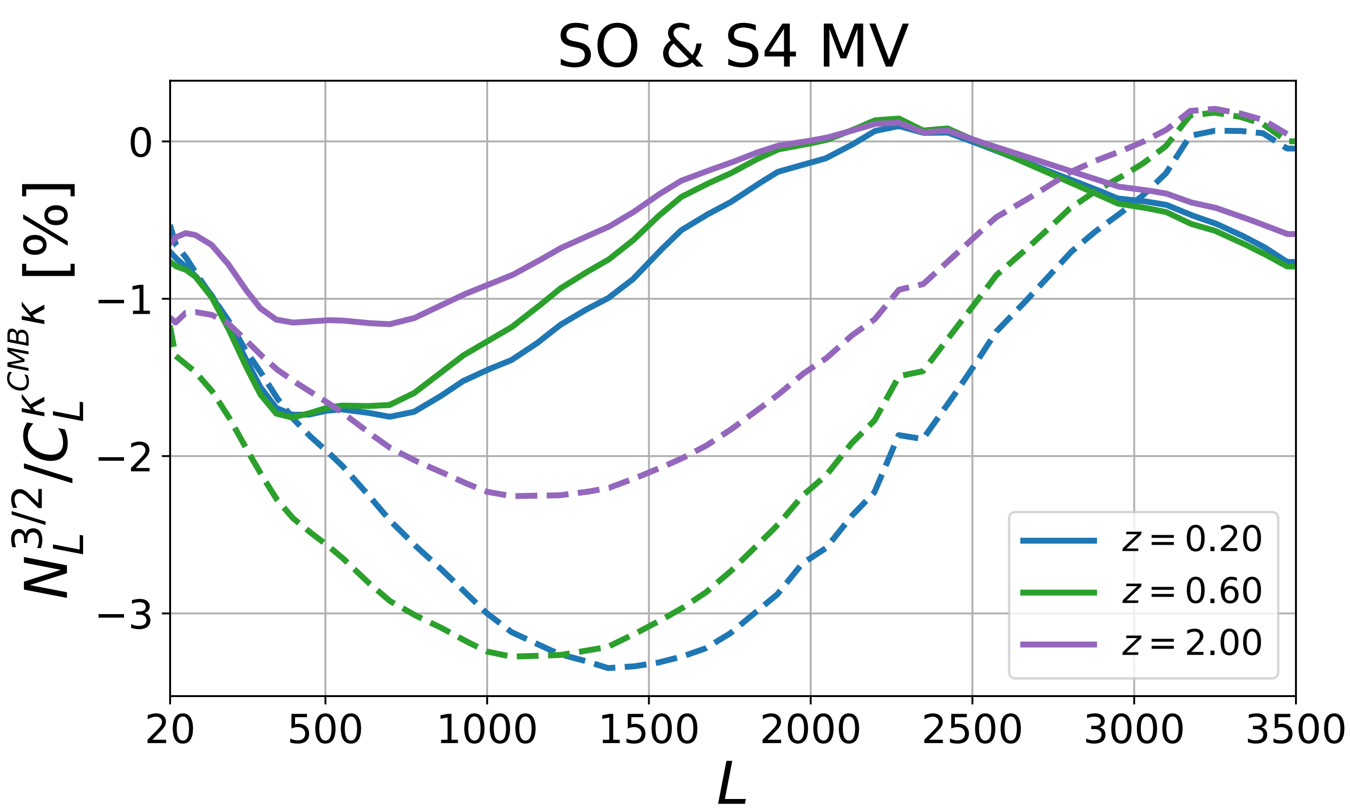
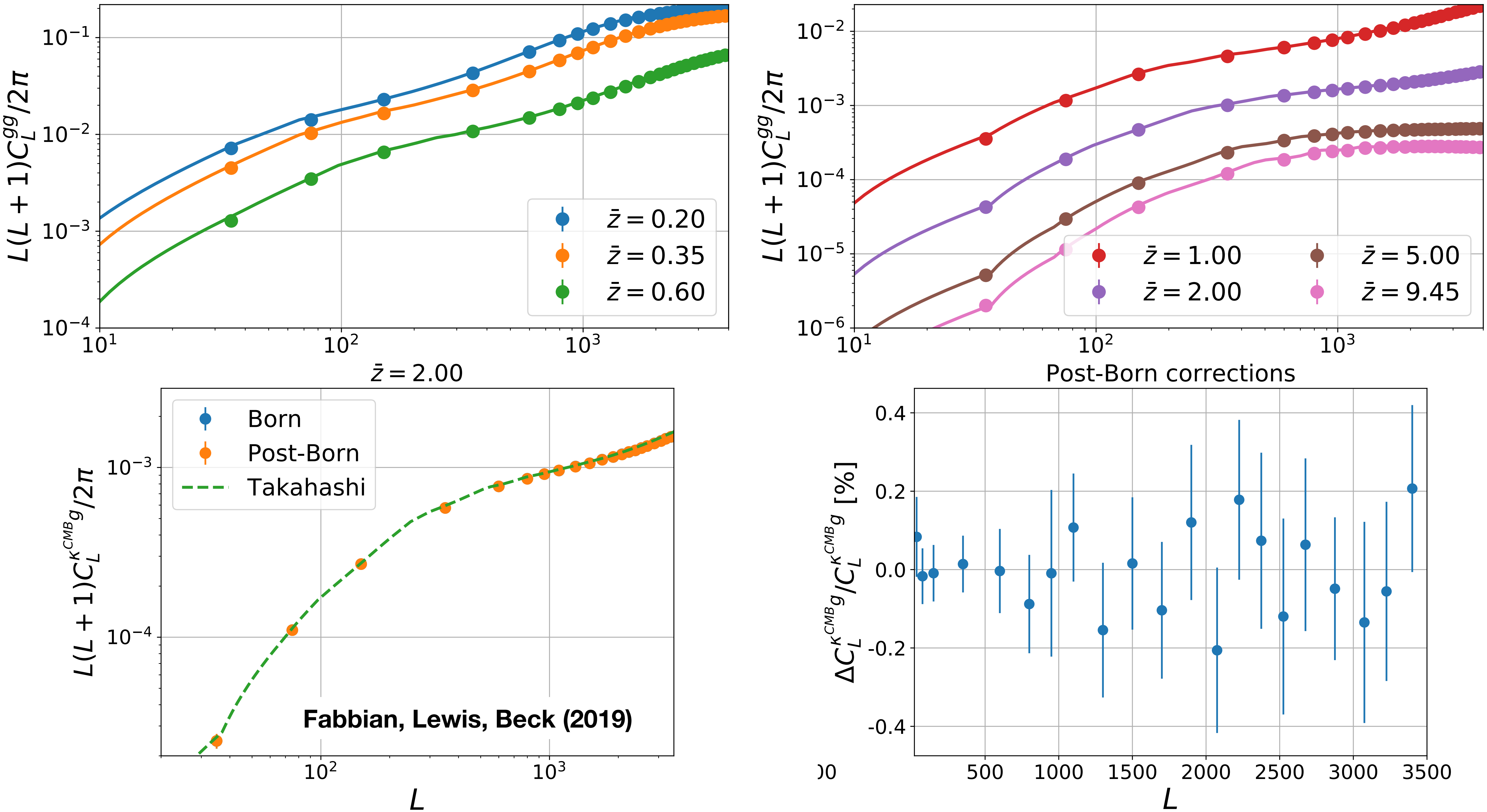






Coherent galaxy density simulations

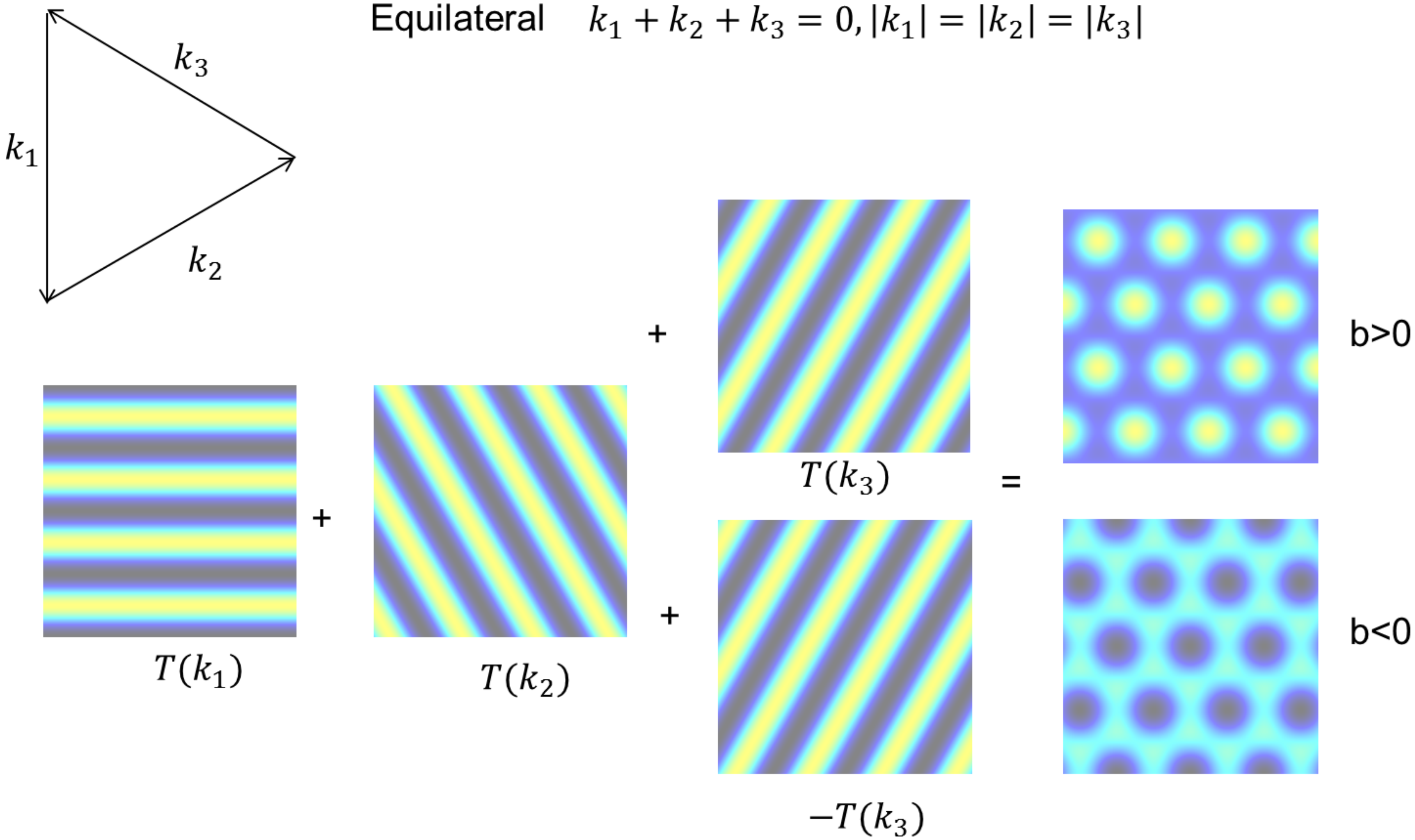
- Percent level accuracy coherent galaxy density simulations for z<9.45, sub percent post-Born corrections (first estimate)

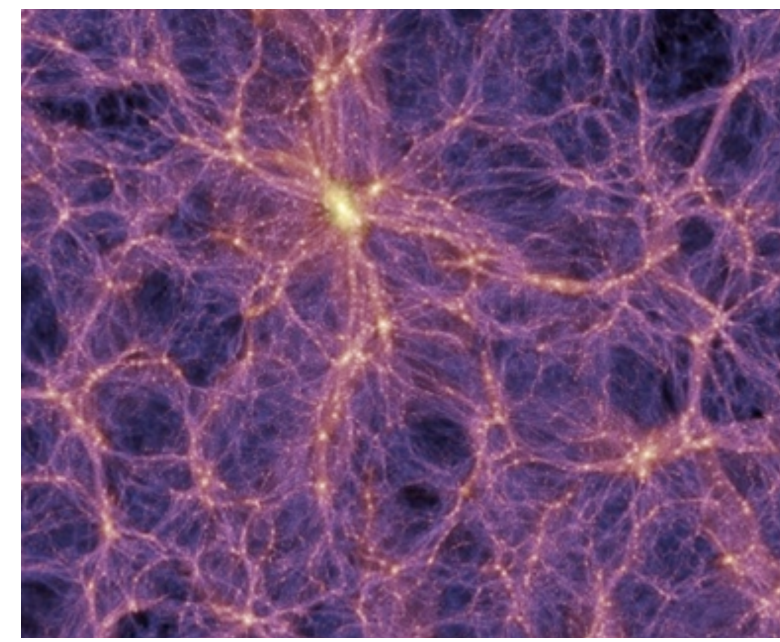


Real space non-Gaussianities

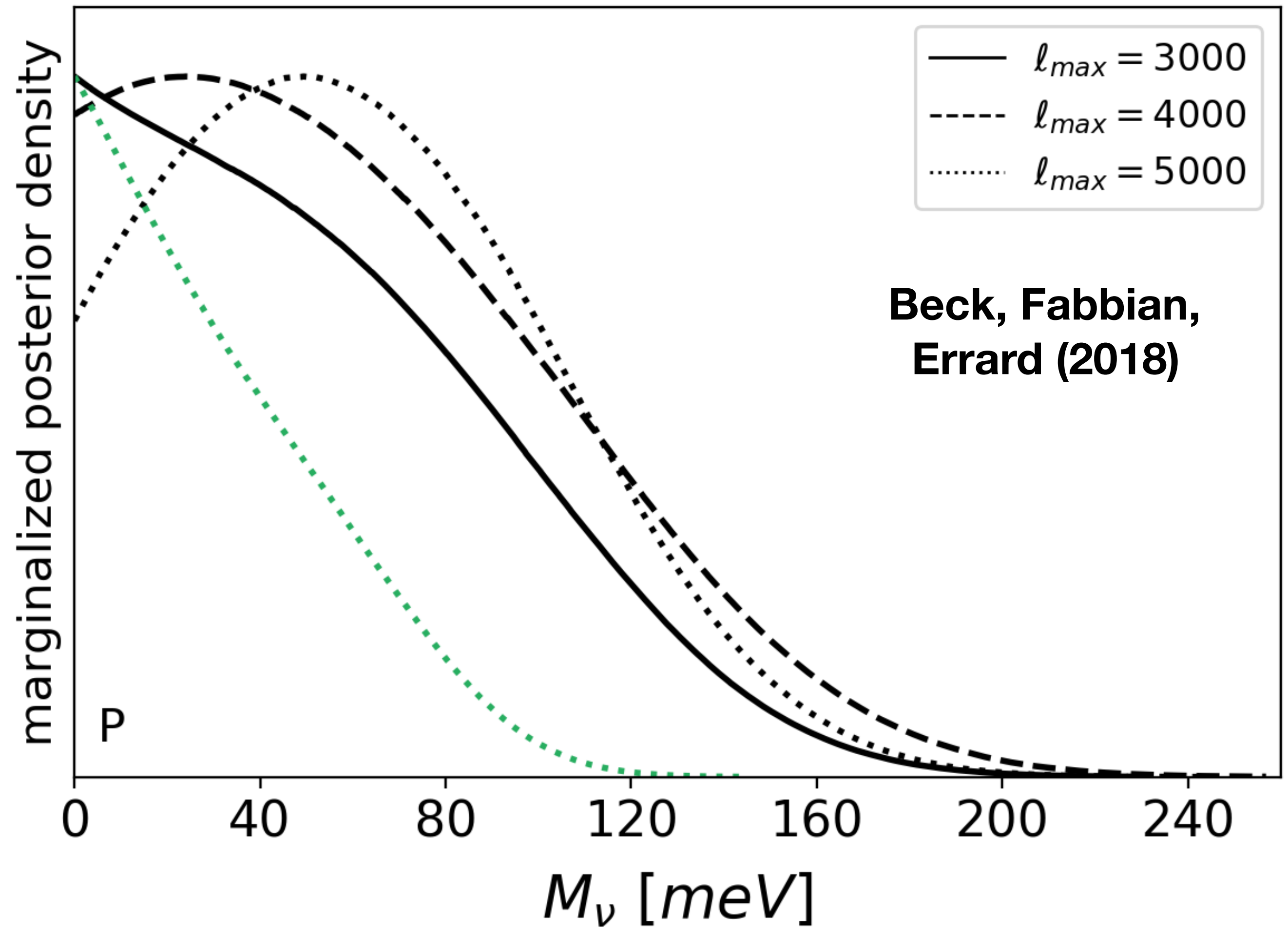
Lewis (2011)

Real space non-Gaussianities

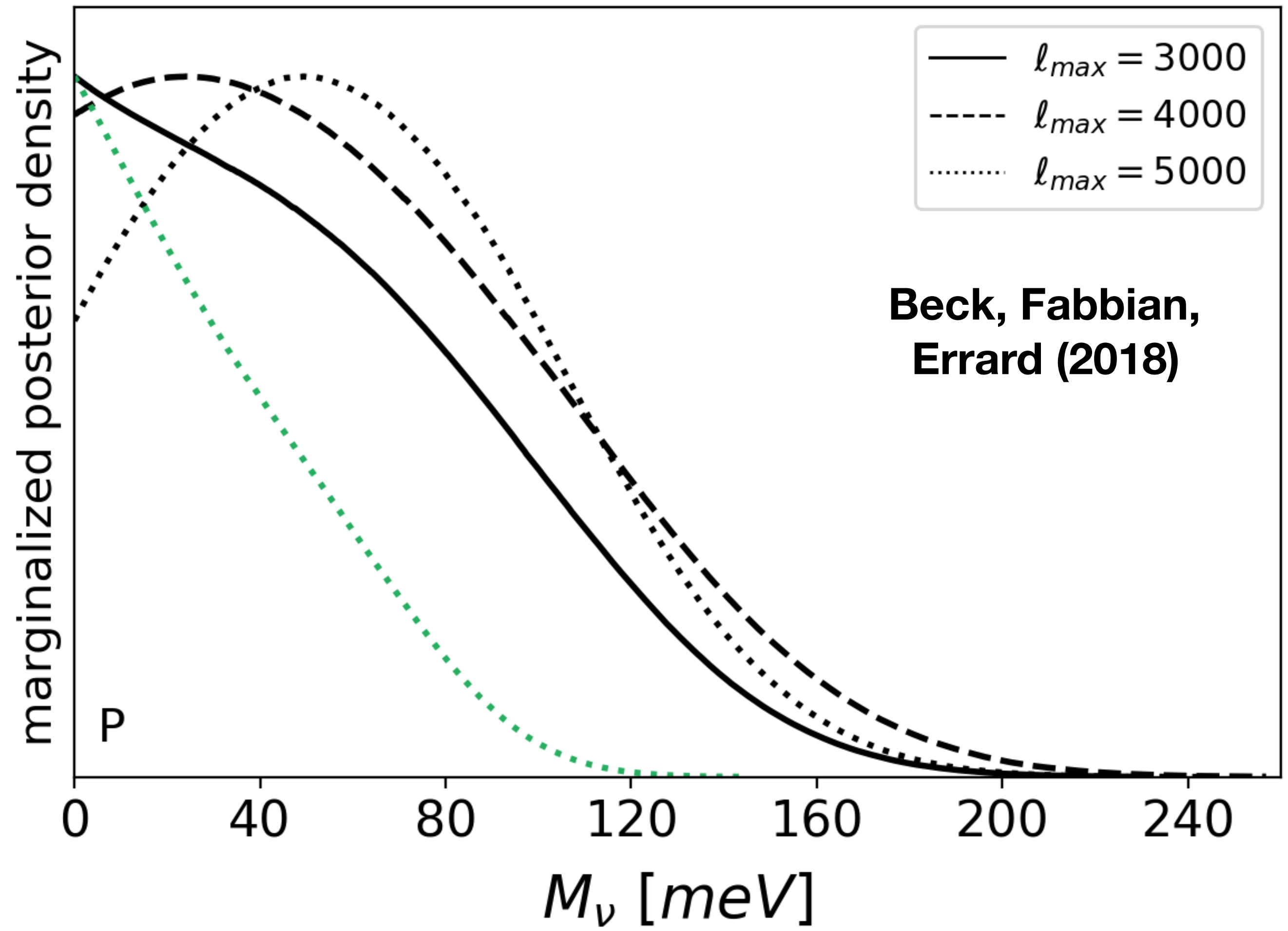




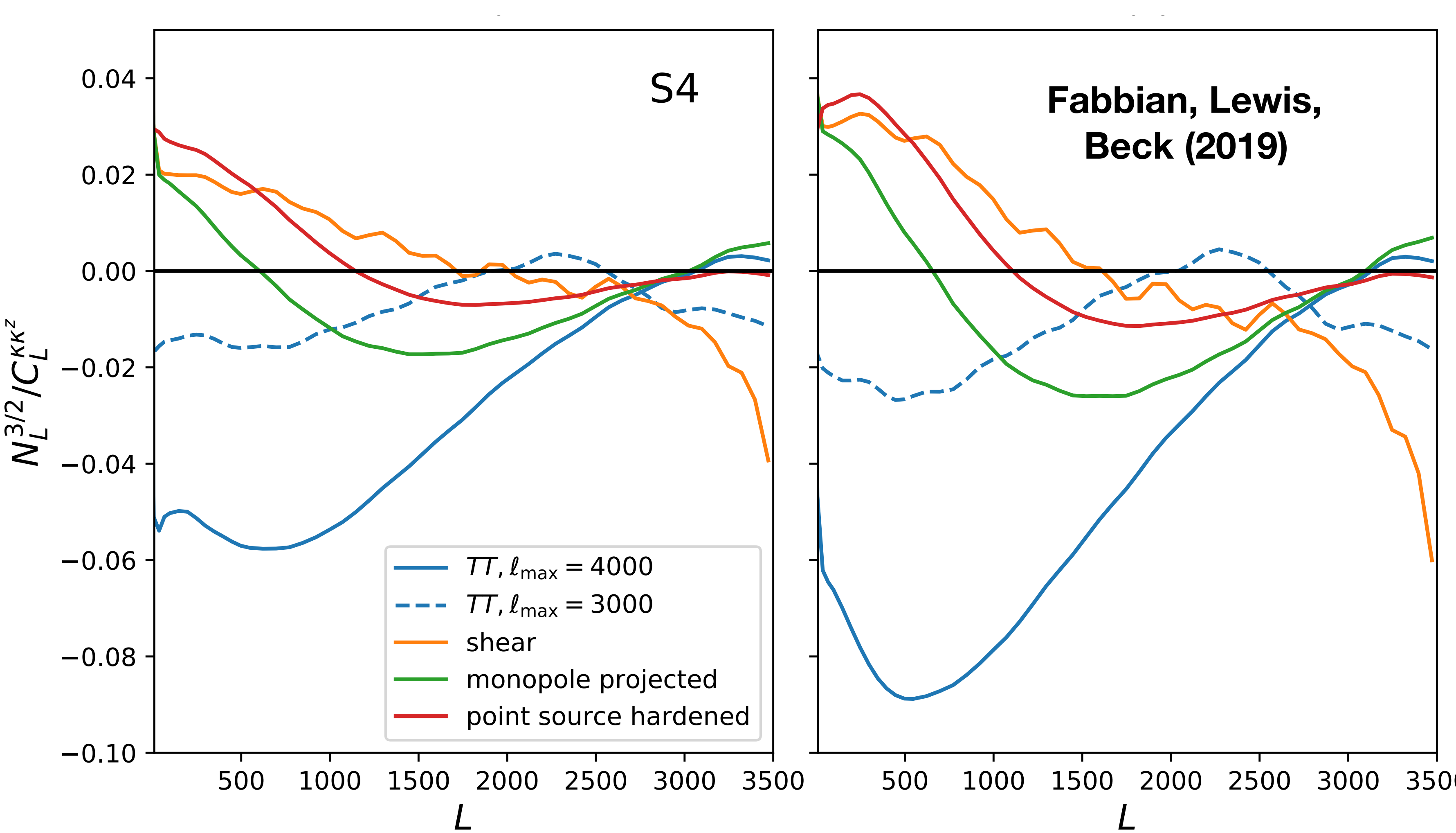
Lewis (2011)



Fabbian, Lewis, Beck (2019)



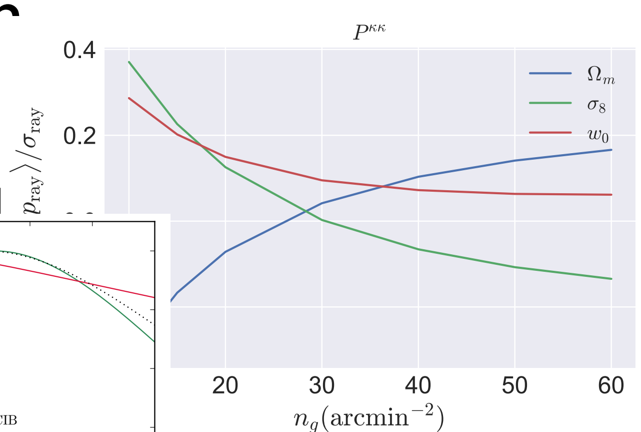
$\ell_{max} = 3000$
$\ell_{max} = 4000$
$\ell_{max} = 5000$
Beck, Fabbian, Errard (2018)
P
marginalized posterior density
0
40
80
120
160
200
240
M_ν [meV]

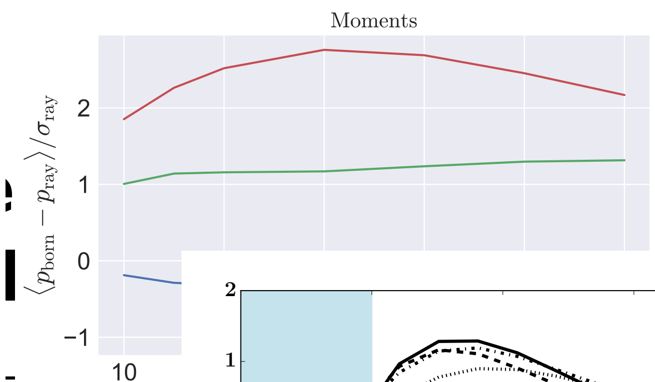


S4
Fabbian, Lewis, Beck (2019)
$N_L^{3/2}/C_L^{\kappa\kappa^z}$
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
$TT, \ell_{\rm max} = 4000$
$TT, \ell_{\rm max} = 3000$
shear
monopole projected
point source hardened
500
1000
1500
2000
2500
3000
3500
L

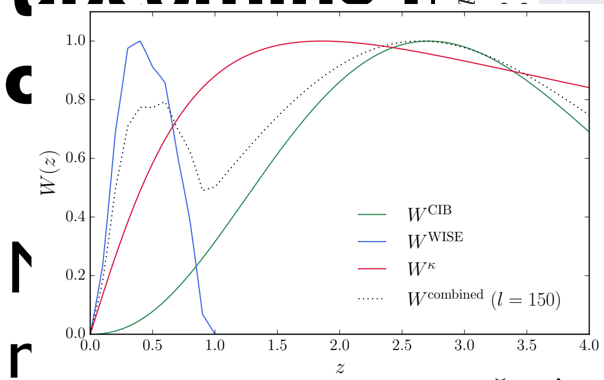
Delensing external tracers

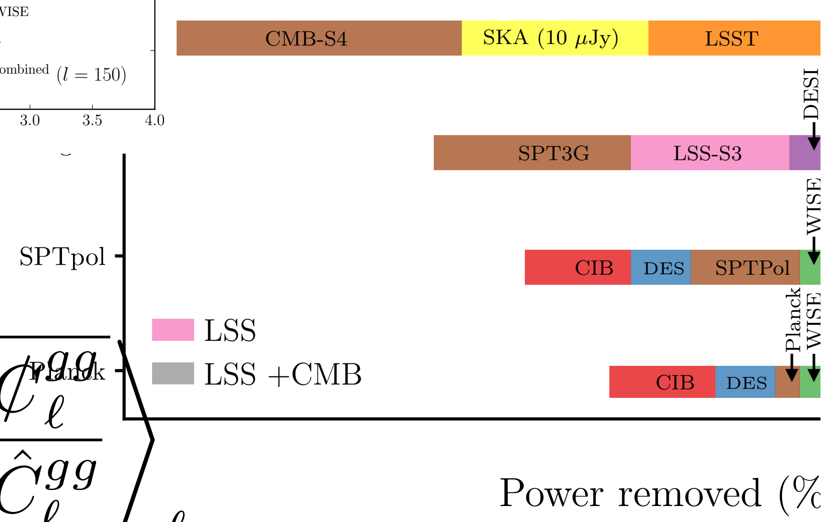
- **CMB lensing and LSS cross-correlation: less systematics and better cosmology.**
  - Additional statistical power and systematics self-calibration and marginalizatior





- **In upcoming h** **mations usually add**





$$\hat{D}_G = \left\langle \frac{\hat{C}_\ell^{\kappa g}}{C_\ell^{\kappa g}} \sqrt{\frac{C_\ell^{gg}}{\hat{C}_\ell^{gg}}} \right\rangle_\ell$$