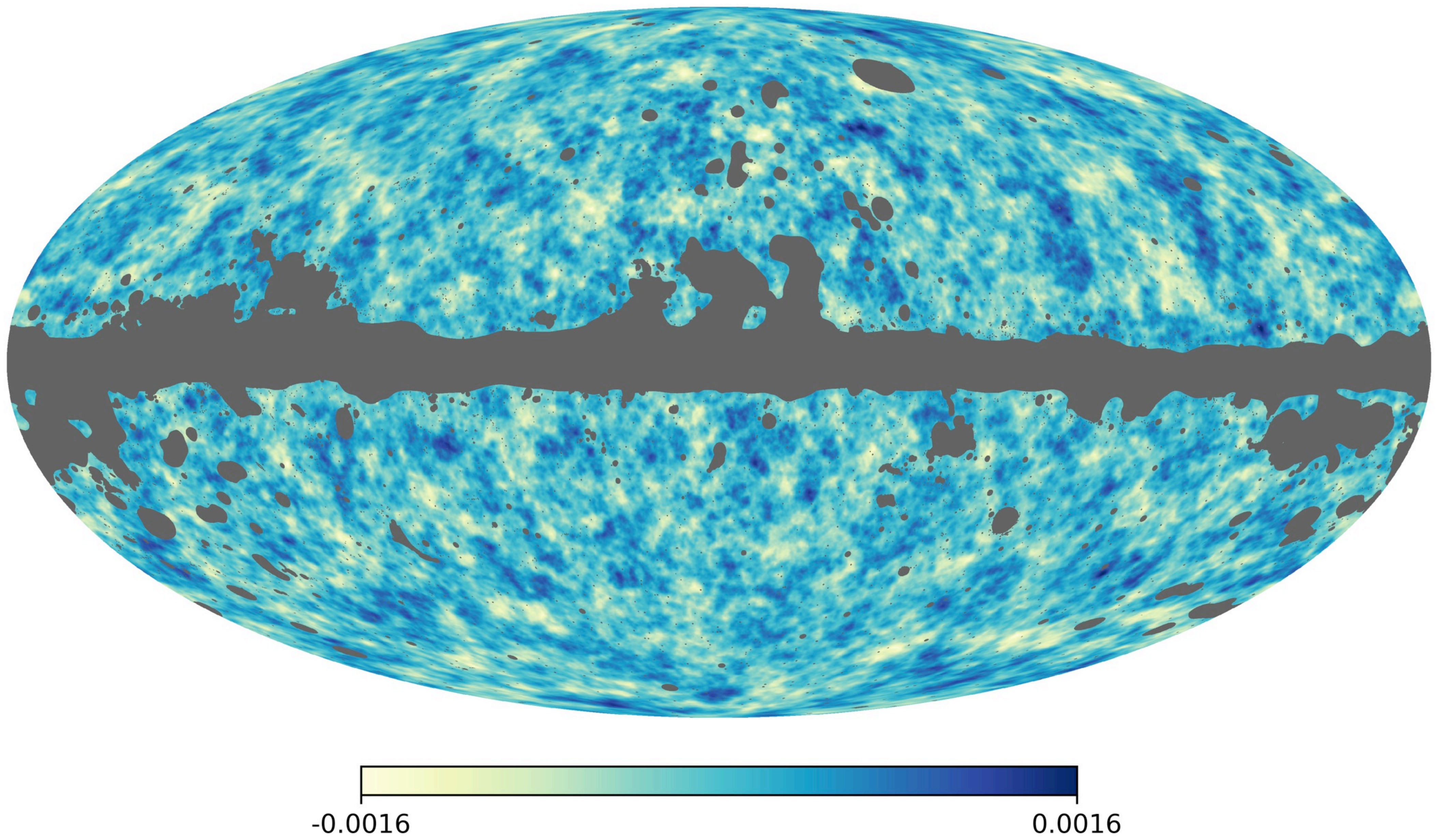
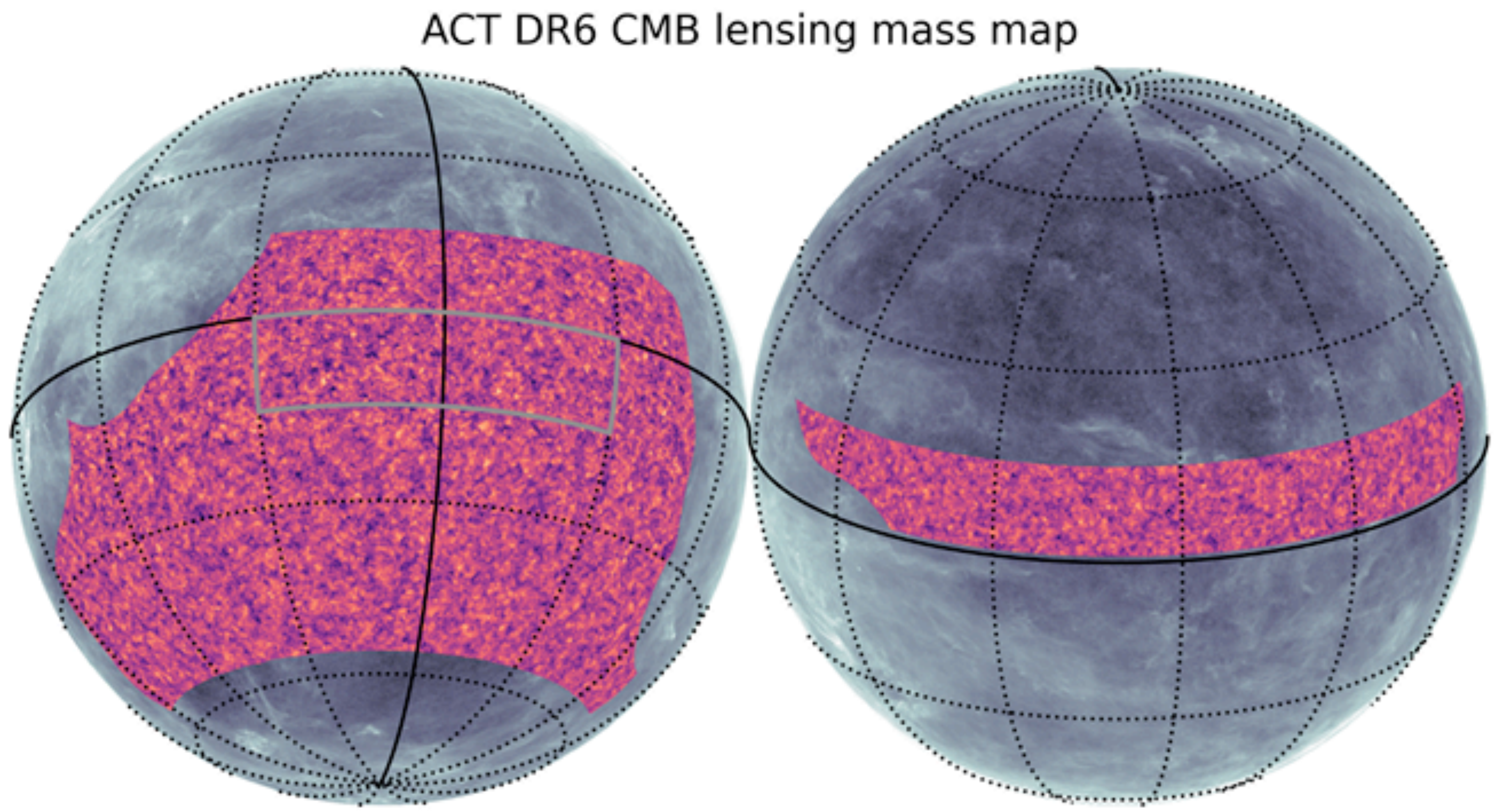
Gravitational lensing signal reconstruction from the CMB and intensity maps





Julien Carron, DPT UNIGE

Cosmology in the Alps 2024

Swiss National Science Foundation

Sebastian Belkner (Unige), Louis Legrand (Unige), Omar Darwish (Unige), Giulio Fabbian, Antony Lewis (Sussex), Mark Mirmelstein (Sussex), the CMB-S4 collaboration…

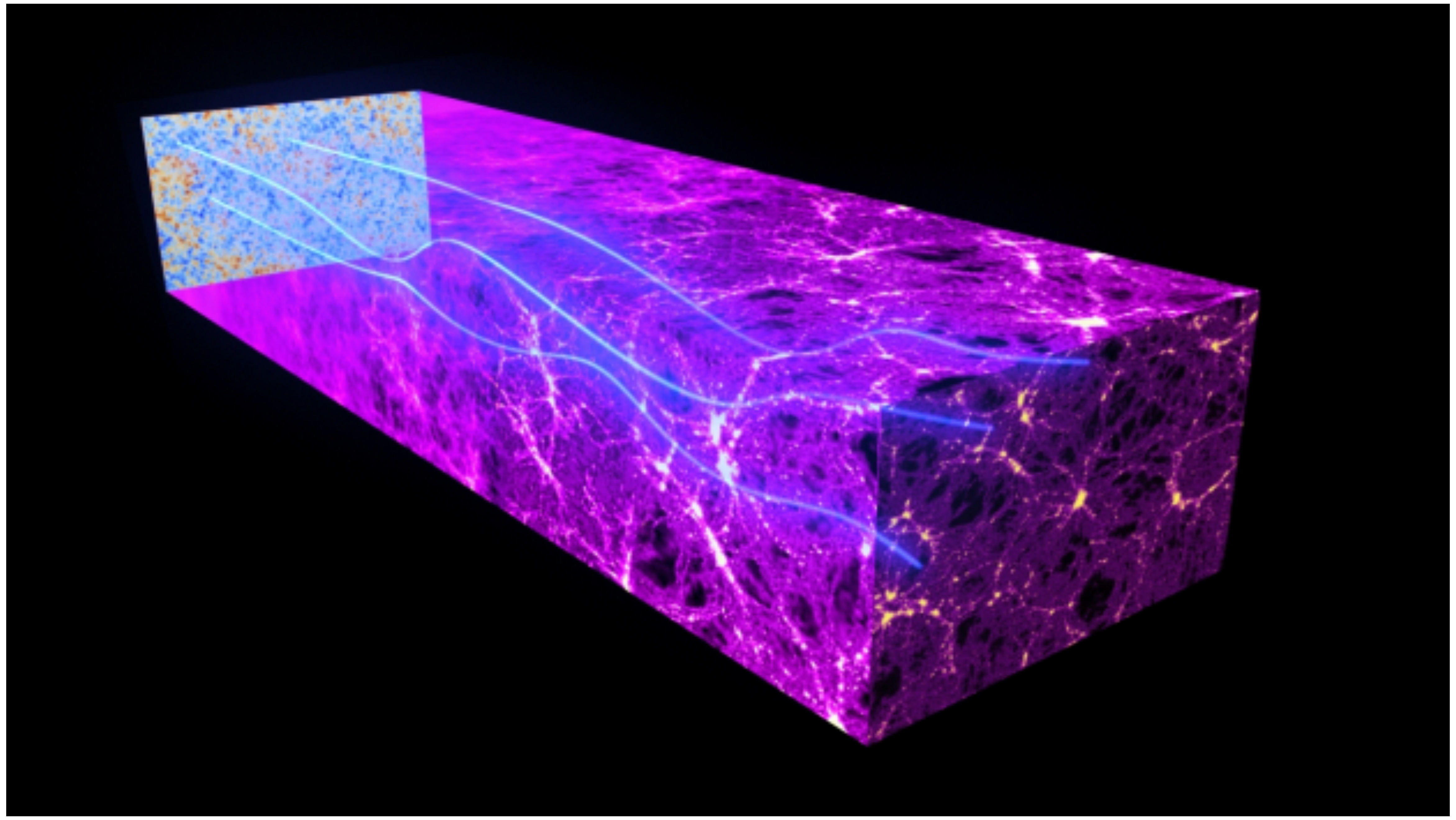
UNIVERSITÉ DE GENÈVE

Outline

- *Most recent cosmology results in Cosmic Microwave Background lensing from Planck and ACT*

- *Optimal lensing reconstruction methods for future experiments.*
  (+ fast spherical harmonic transforms and the impact of non-Gaussian deflections)

CMB Lensing

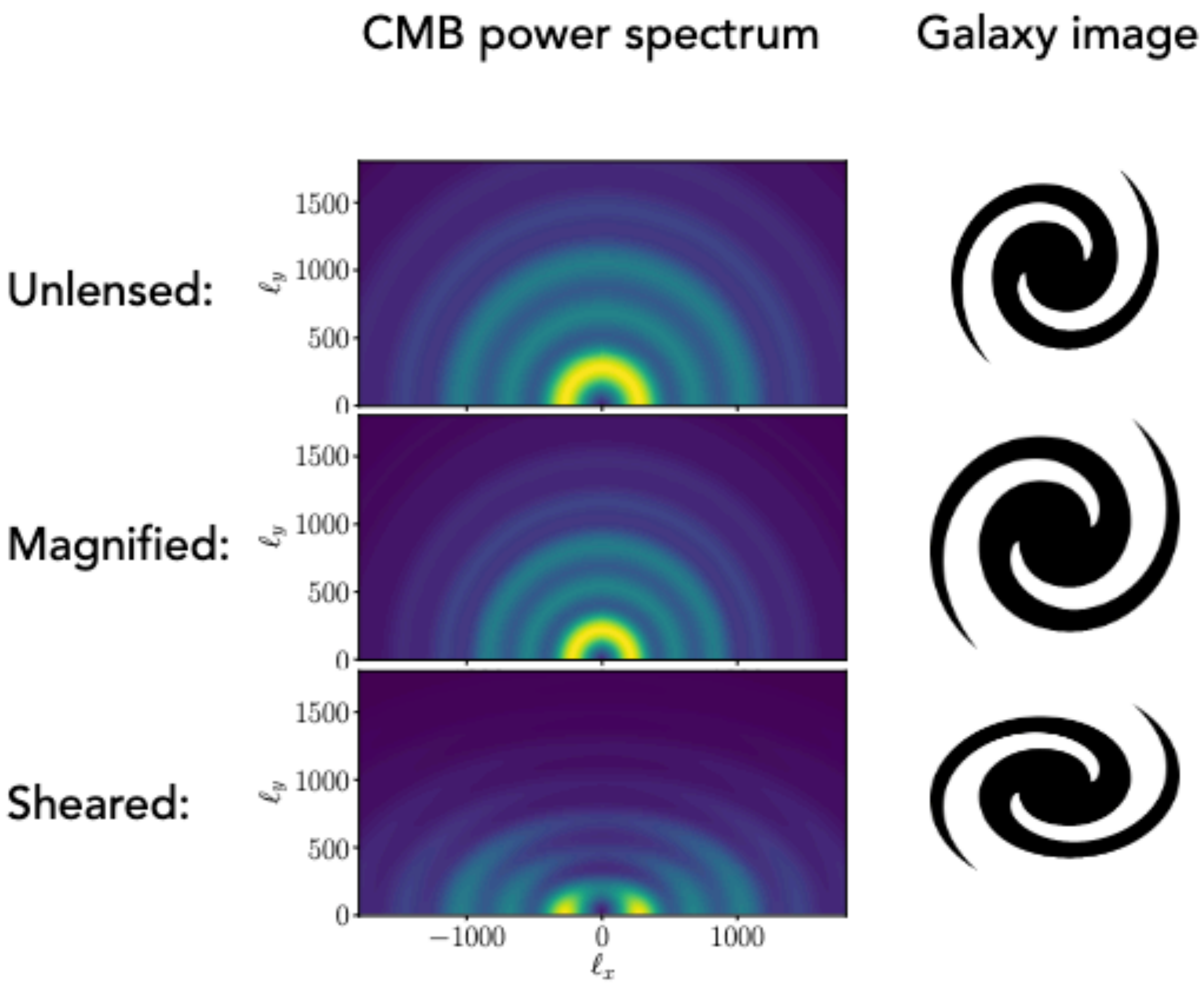


$$\phi(\hat{n}) = -2 \int_0^{\chi_*} d\chi \left(\frac{\chi_* - \chi}{\chi \chi_*} \right) \Psi(\hat{n}, \chi)$$

- *Deflections α of a few arcmin by ~100 Mpc sized lenses, $\alpha = \nabla \phi$, deflections coherent over a few degrees*
- *Most efficient at $z \sim 2$, mostly linear scales*
- *Leading non-linear effect on the CMB*

Effect on local 2D CMB spectrum

Schaan et al 2018



$$C_{\boldsymbol{\ell}} = C^0_\ell \left[1 + \kappa \frac{\partial \ln \ell^2 C^0_\ell}{\partial \ln \ell} + \gamma \cos(2\theta_\ell) \frac{\partial \ln C^0_\ell}{\partial \ln \ell} \right]$$

Lens quadratic estimation

- Fixed lenses introduce statistically-anisotropic correlations:

$$\Delta\langle X_{l_1 m_1} Y_{l_2 m_2}\rangle_{\mathrm{CMB}} = \sum_{LM} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \mathcal{W}^{XY}_{l_1 l_2 L} \phi_{LM}$$

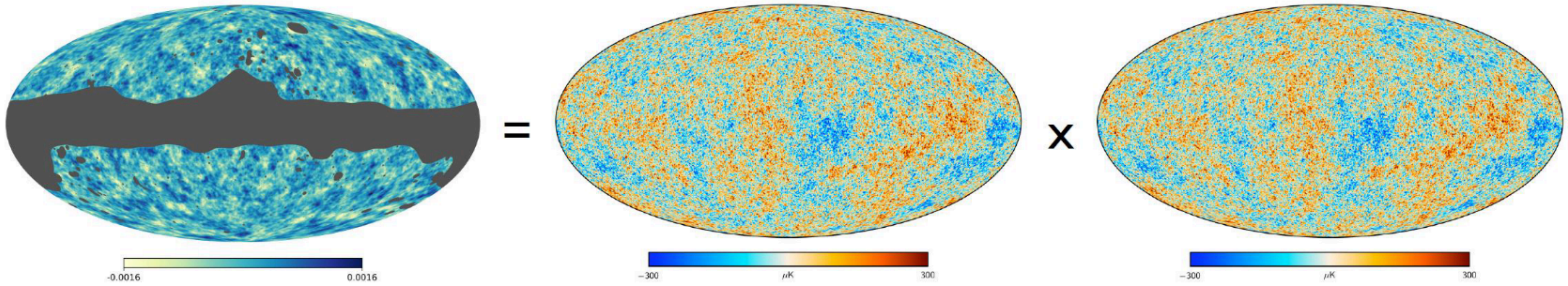
- Noisy lensing estimates from quadratic CMB combinations:

$$\hat{\phi}_{LM} = \frac{(-1)^M}{2} \frac{1}{\mathcal{R}^{XY}_L} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \left[\mathcal{W}^{XY}_{l_1 l_2 L}\right]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2}$$

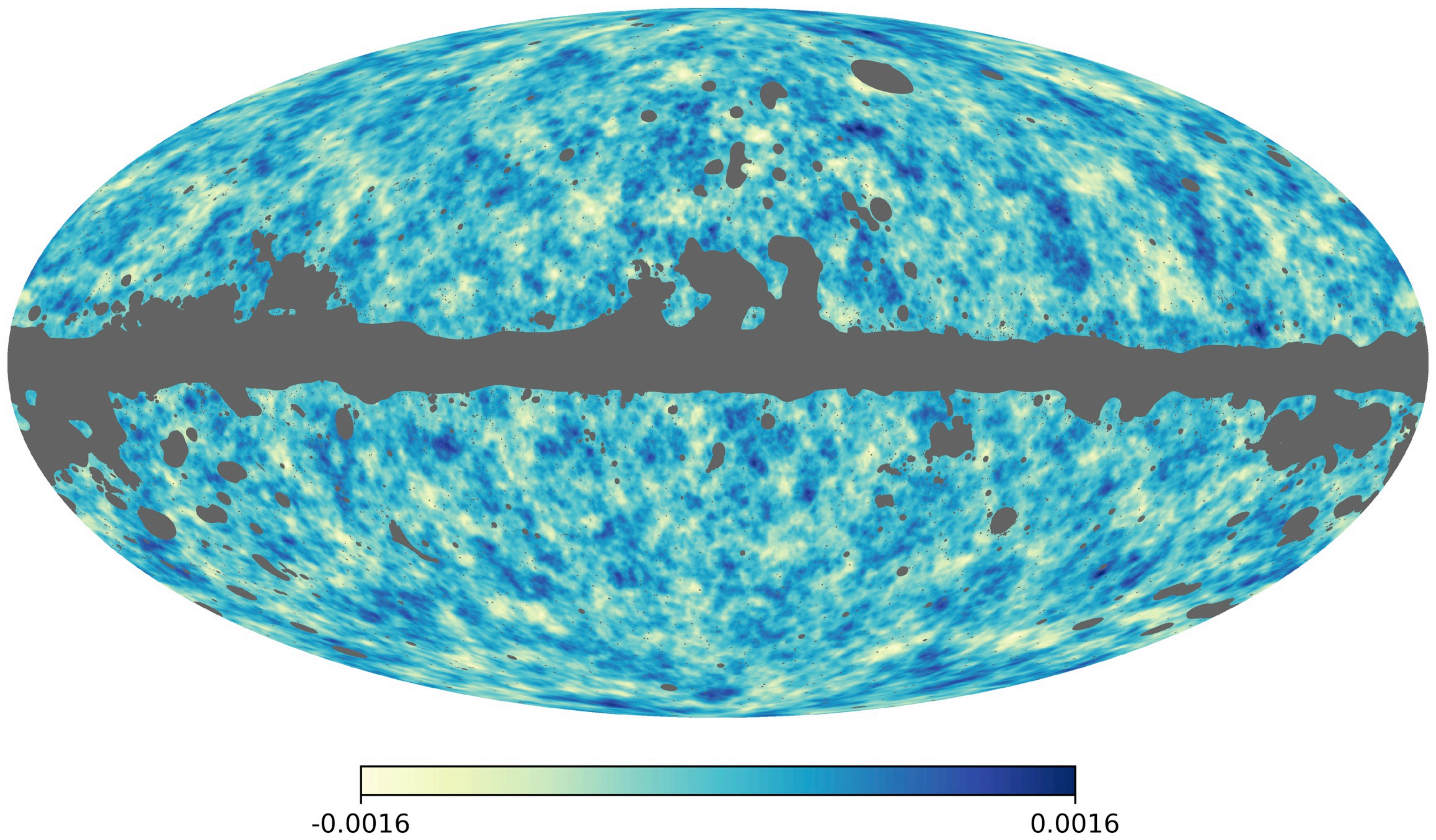
Normalisation

Known lensing-induced correlations

Inverse-variance-weighted CMB fields



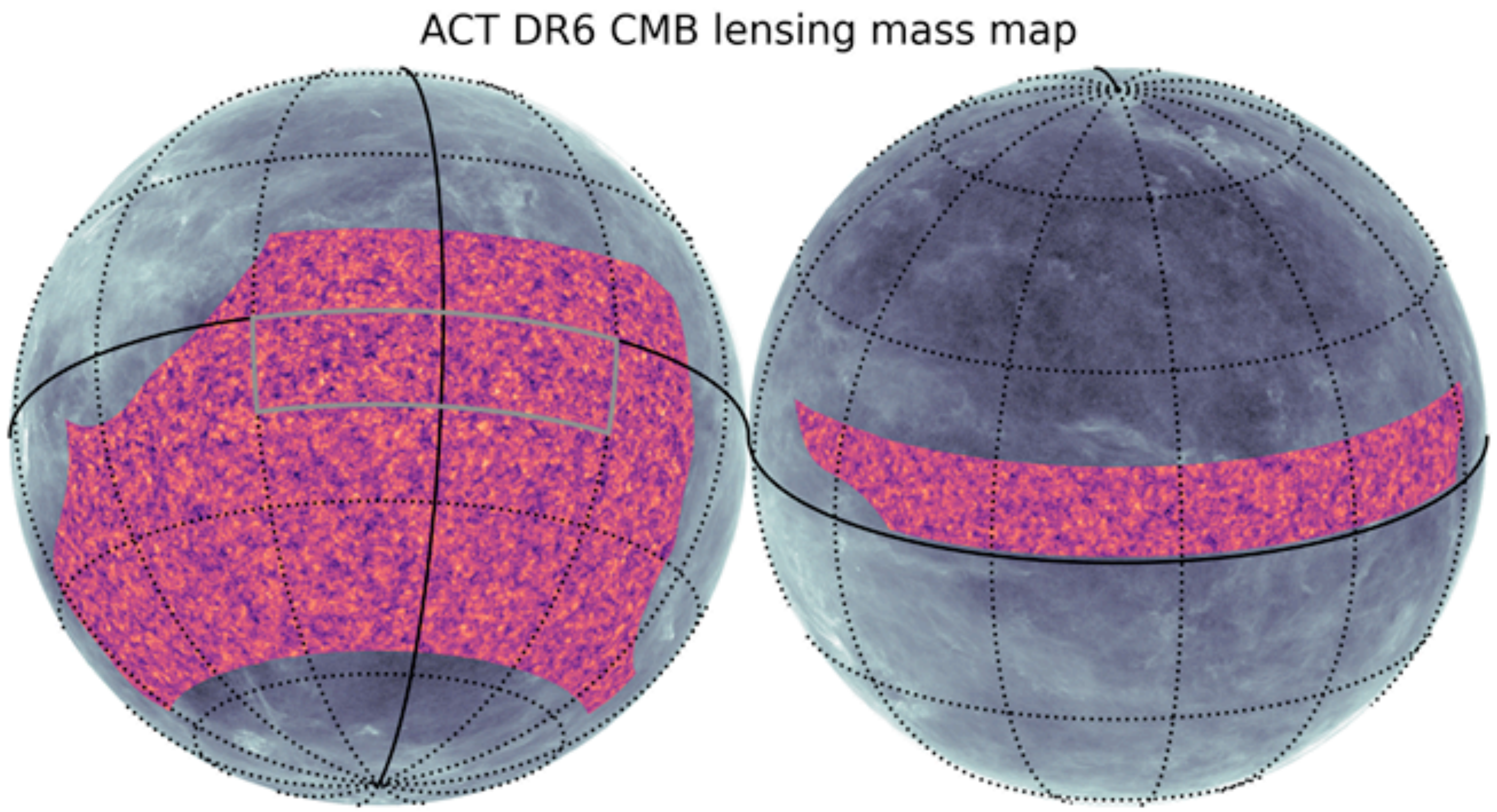
Planck PR4 and ACT DR6 public lensing maps



Planck PR4 lensing
(JC, Mirmelstein & Lewis 2022)

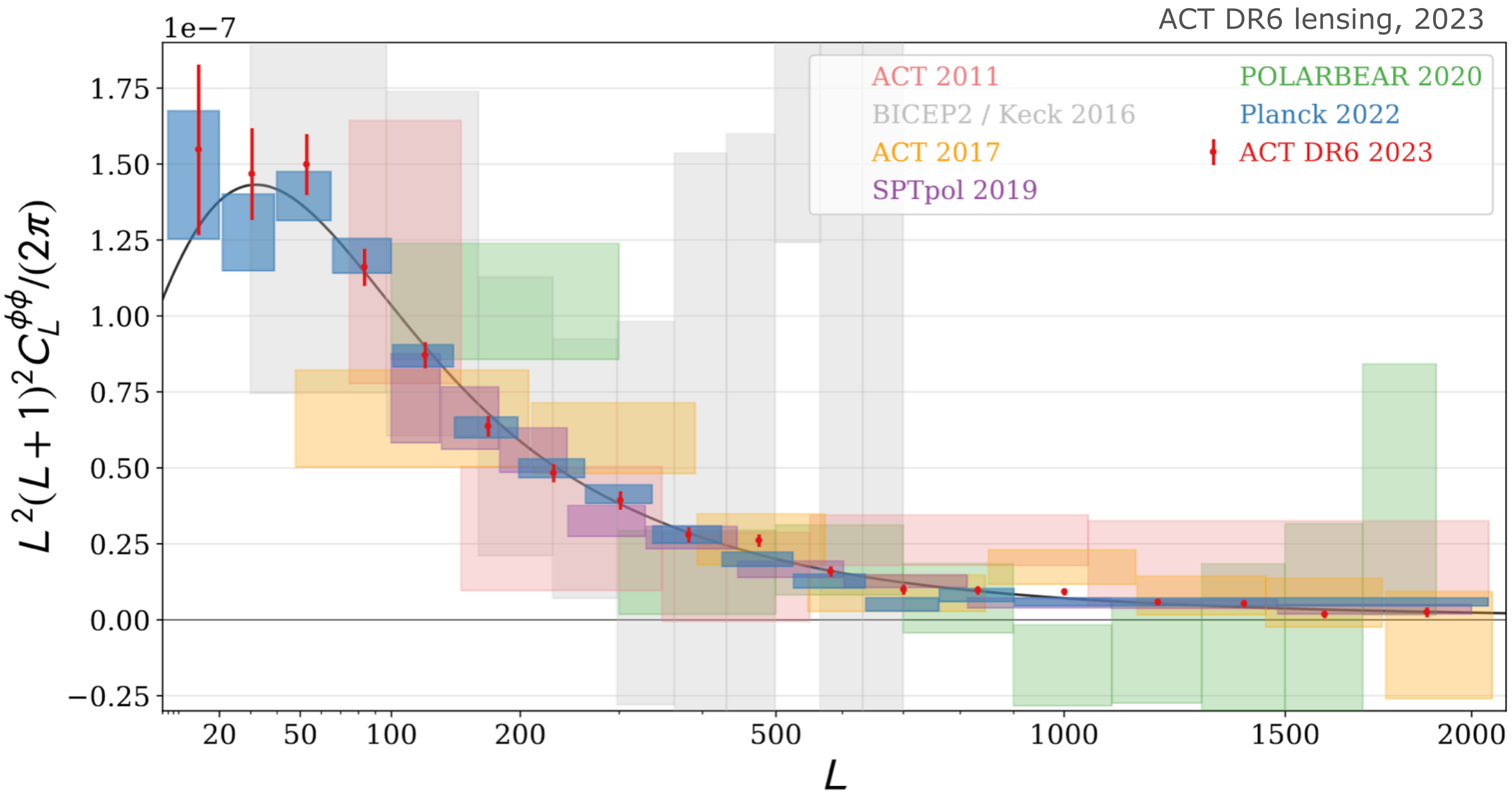
'Boosted' Planck PR3 lensing map

(Qu et al 2023)



Atacama Cosmology Telescope DR6: deeper, less sky area

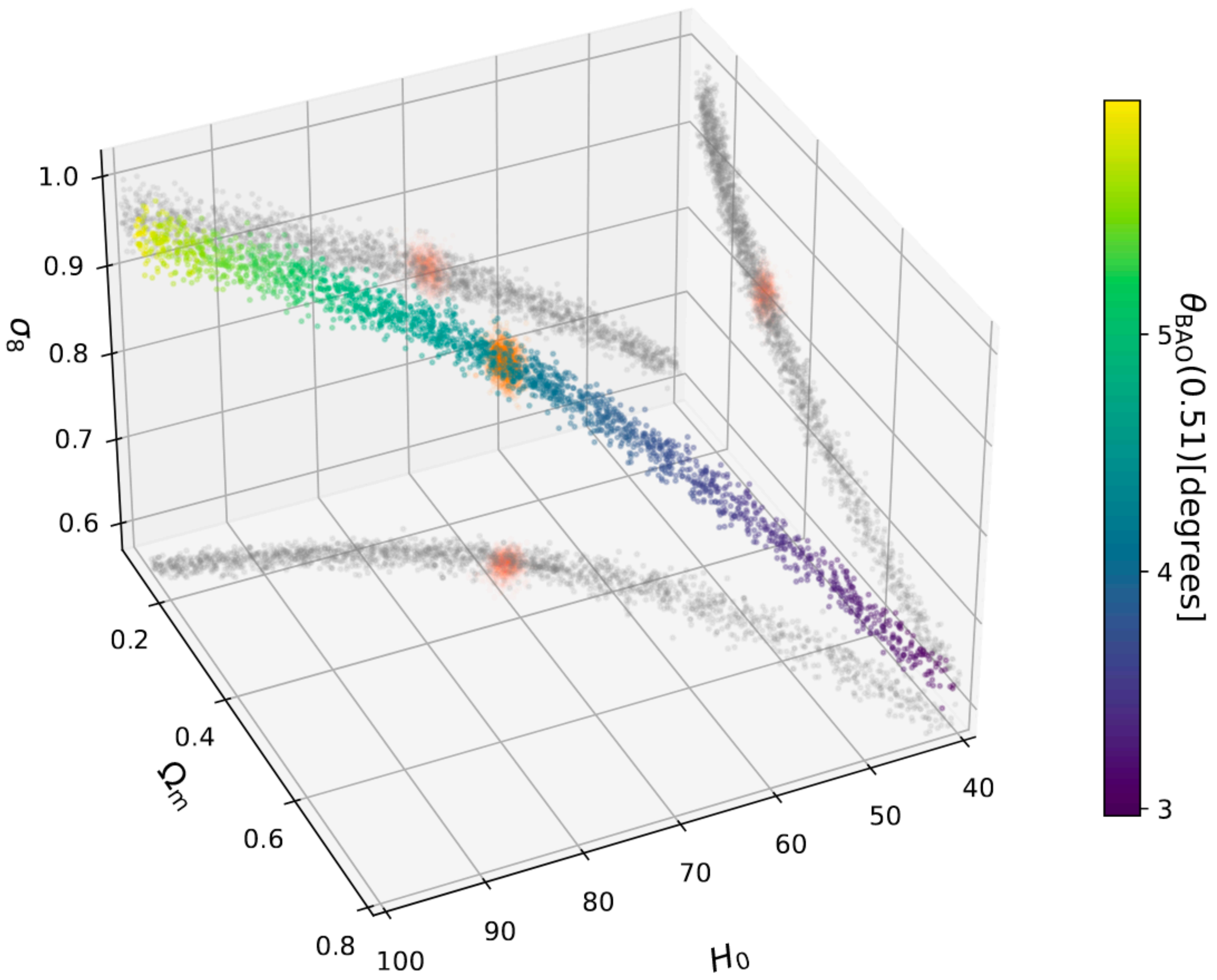
Lensing spectra



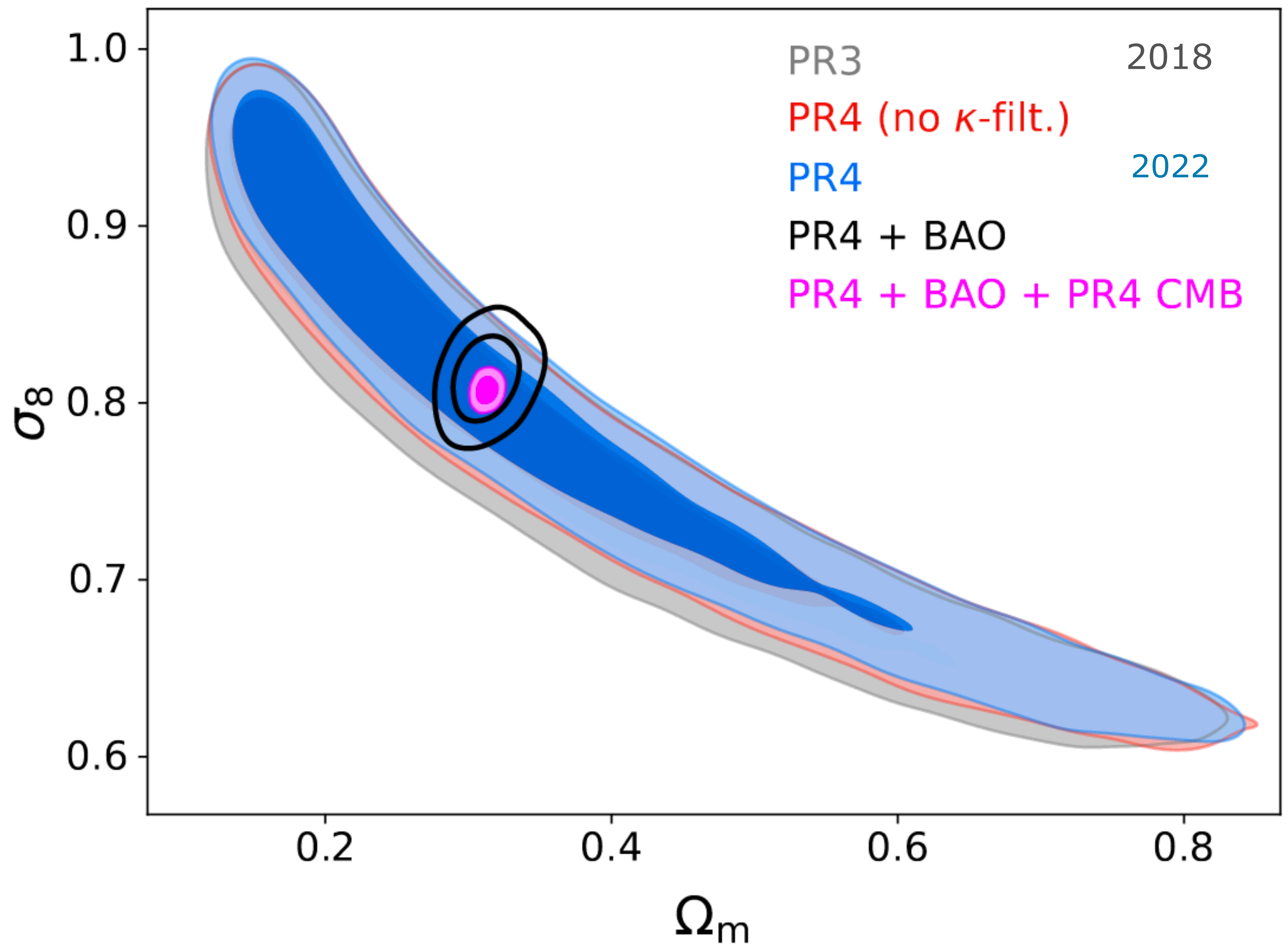
- Planck and ACT DR6 now of comparable statistical power (~40σ)

Planck PR4 CMB lensing-only constraints:

JC, Mirmelstein & Lewis 2206.07773



(With BBN prior on baryon density)

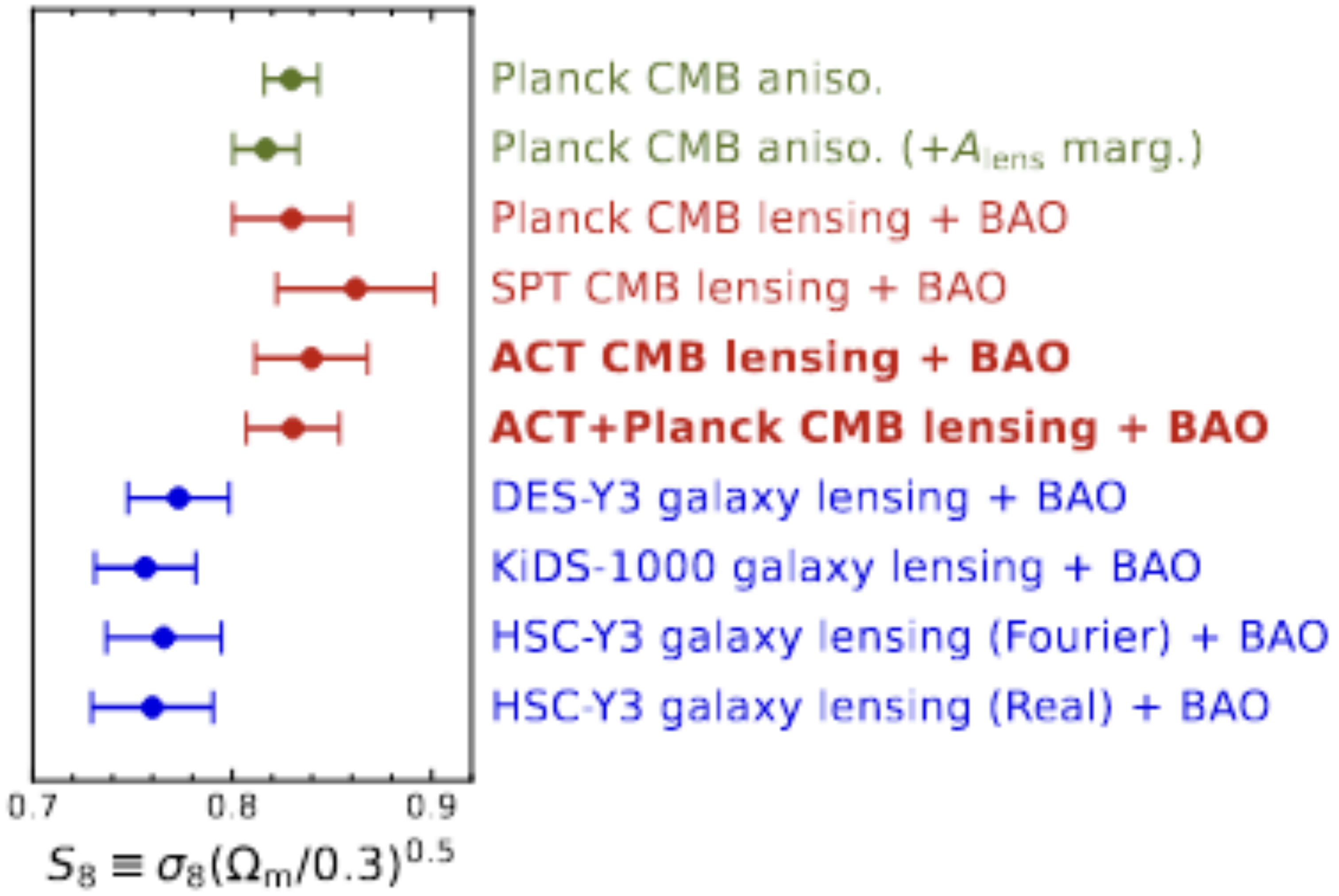


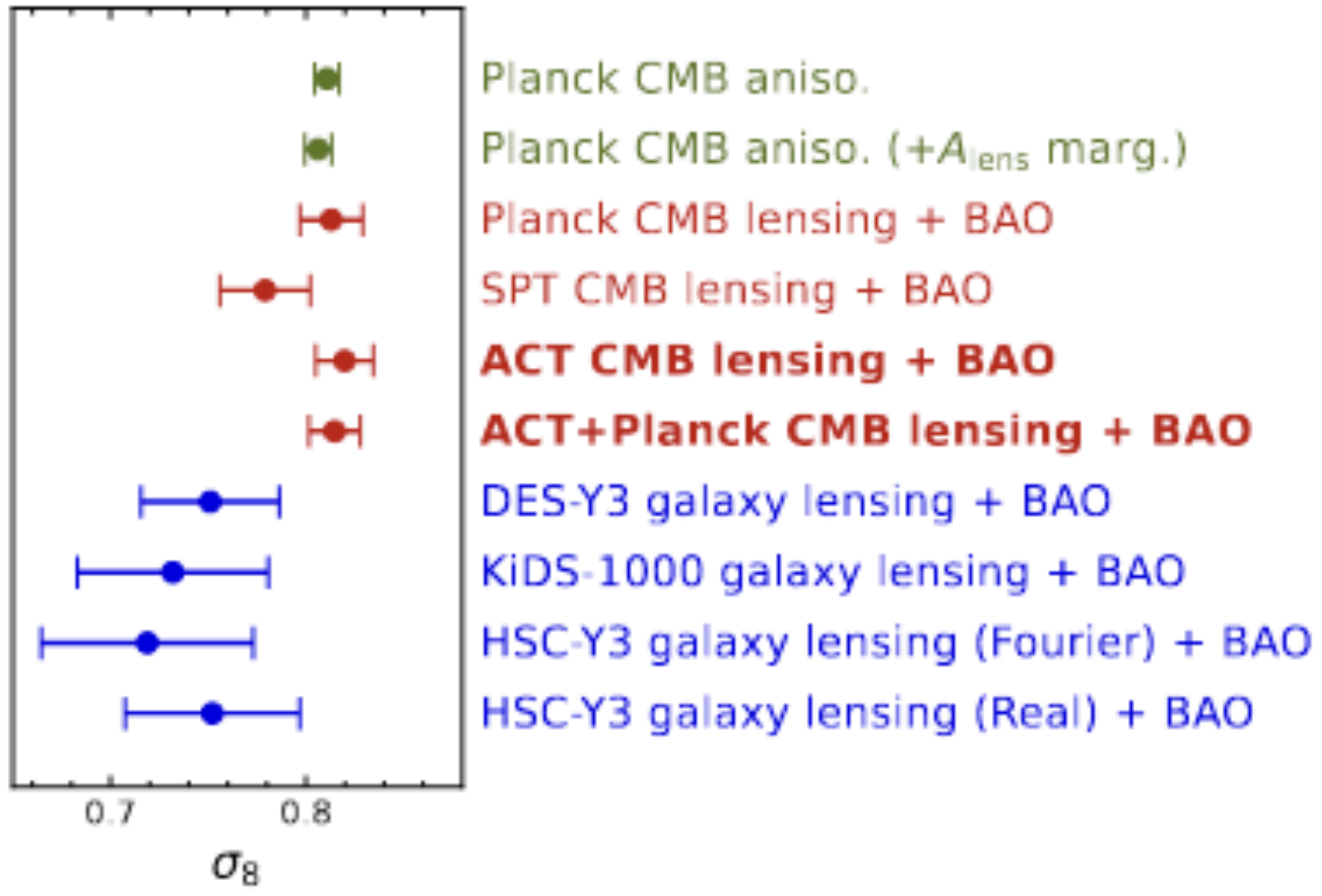
Constraints independent from CMB spectra

Lensing + BAO	σ_8	H_0	Ω_m
PR3 2018	0.811 ± 0.019	$67.9^{+1.2}_{-1.3}$	$0.303^{+0.016}_{-0.018}$
PR4 2022	0.814 ± 0.016	$68.14^{+0.99}_{-1.10}$	$0.313^{+0.014}_{-0.016}$

ACT DR6 lensing

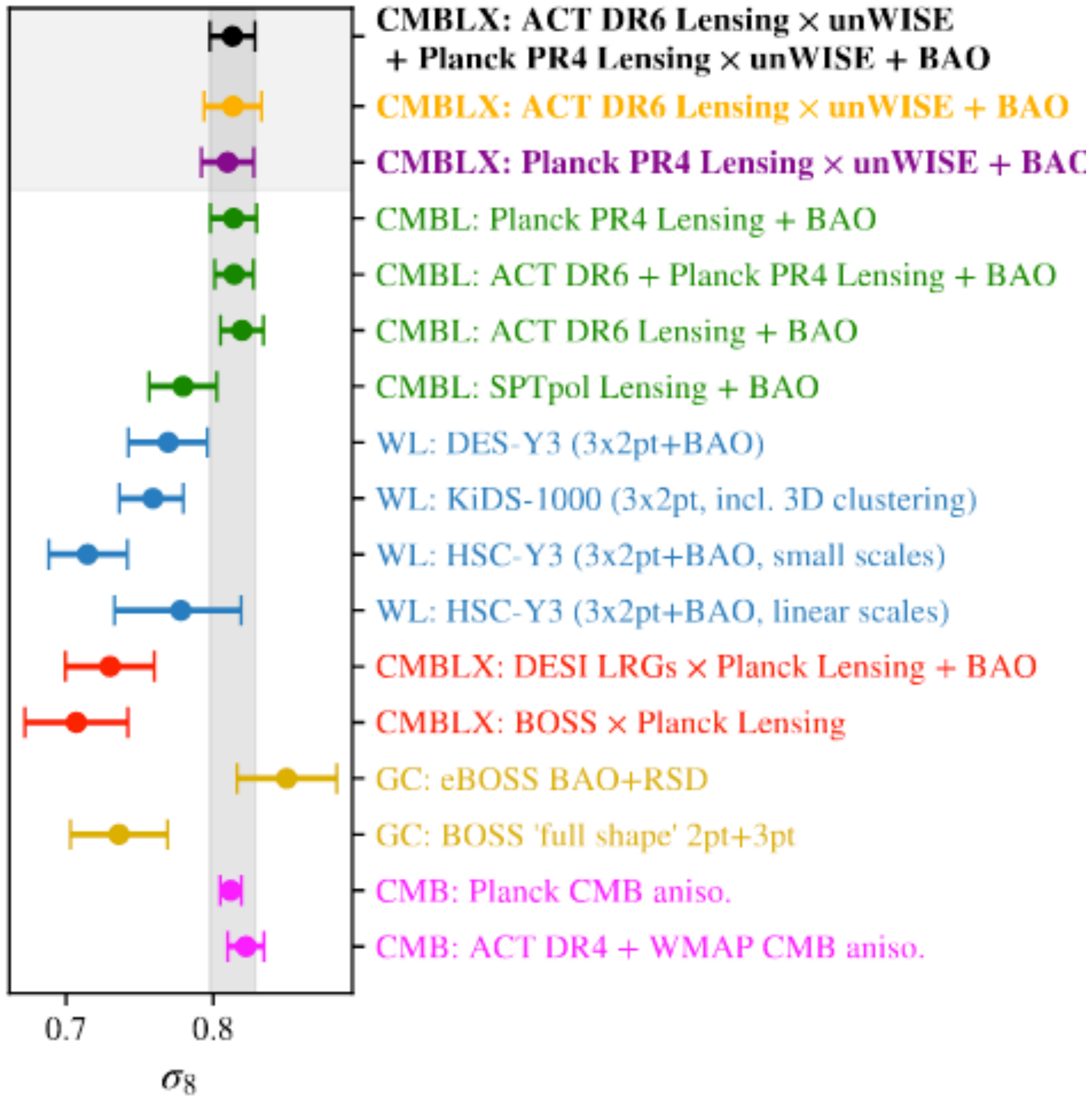
Qu et al; Madhavacheril et al; MacCrann et al 2023





Farren et al 2023, x unWISE galaxies

z~1, linear scales, CMBL x to galaxies very consistent to CMB



Planck and ACT lensing almost independent and very consistent!

CMB-S4 major science targets and lensing

Planck

Lensing SNR 40

Simons Observatory

Lensing SNR > 140

CMB-S4

Lensing SNR ~ 400 from L < 1500?

New methodology for S4 is a must!

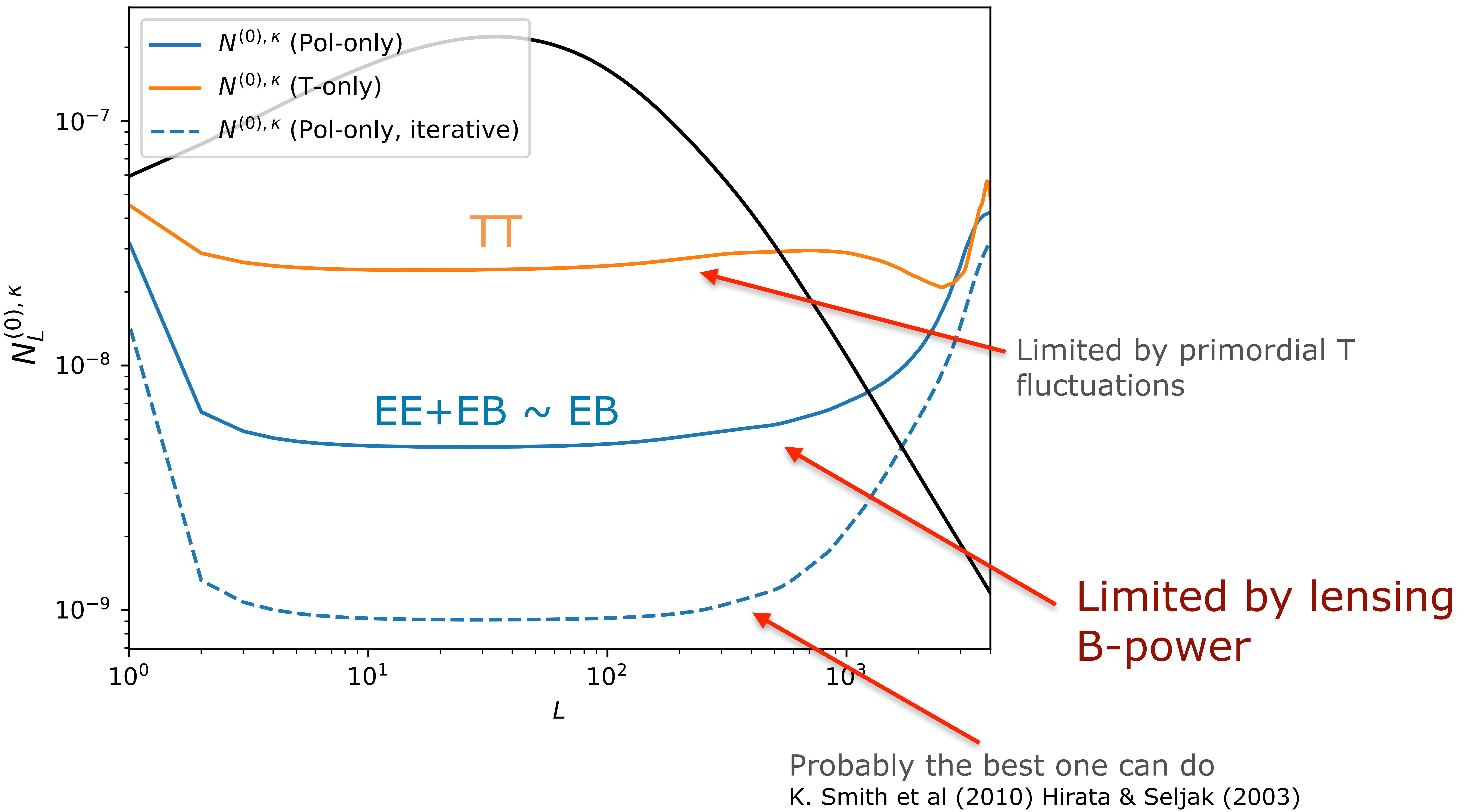
	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	Boss BAO prior 0.15eV	DES+BOSS SPT clusters ~180
Stage 3 10,000 detectors	10^{-6}	0.006	0.06	Boss BAO prior 0.06eV	DES + DESI SZ Clusters ~300-600
Stage 4 CMB-S4 ~500,000 detectors	**10^{-8}**	**0.0005**	**0.027**	DESI BAO +Te prior **0.015eV**	DESI +LSST S4 Clusters **1250**

Delensing (points to $\sigma(r)$ = 0.0005)

Structure growth (points to $\sigma(\Sigma m_\nu)$ = 0.015eV and F.O.M 1250)

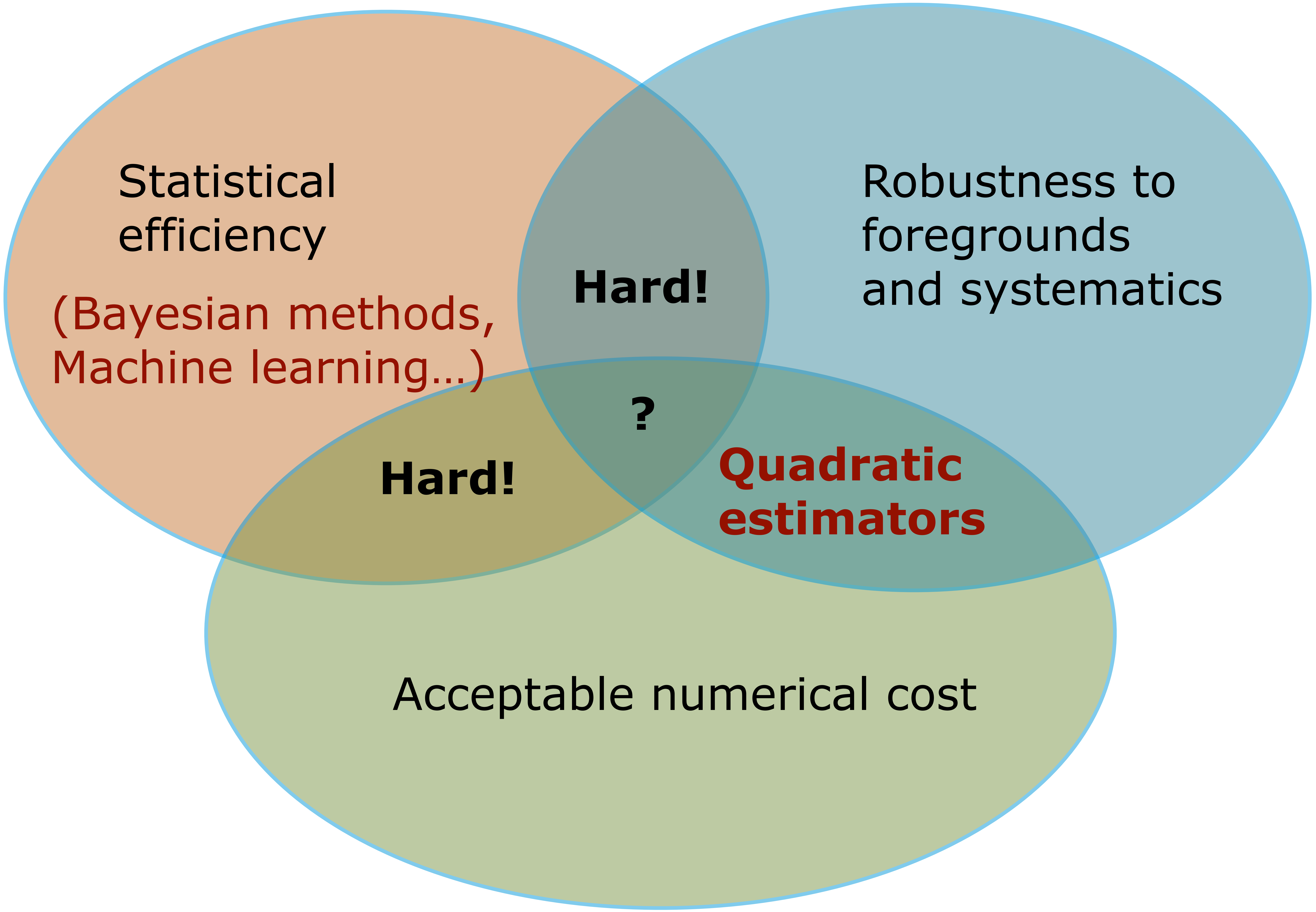
CMB-S4 *science book 1610.02743*

CMB-S4 deep field lensing reconstruction noise



- Signal comes from polarization, and is of shear-only type → less foregrounds, less systematics, great!

Desiderata for next-generation CMB lensing estimators

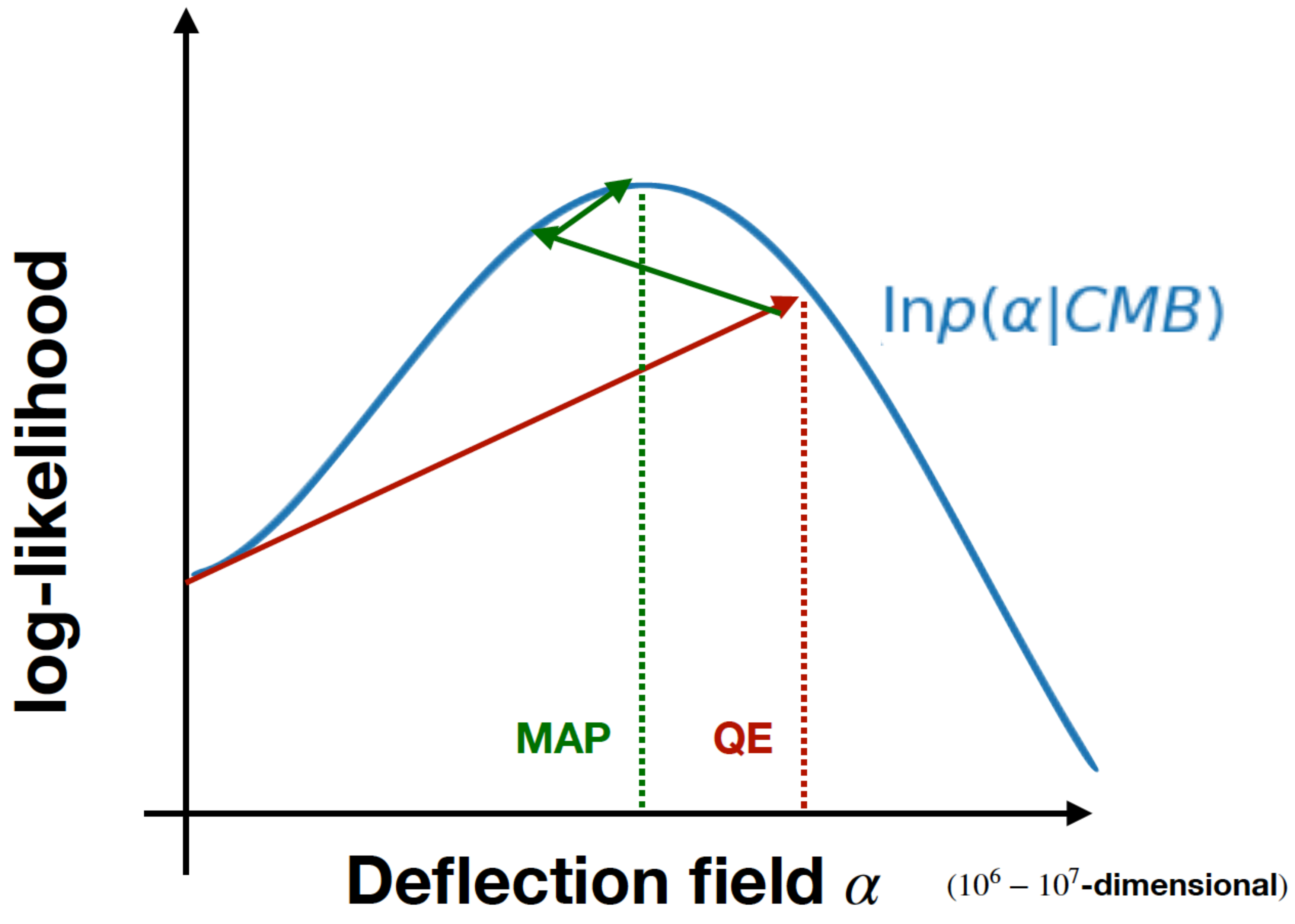


Maximum A Posteriori (MAP) reconstruction:

Hirata & Seljak 2003, JC & Lewis 2017, Legrand & JC 2021, 2023, Belkner, JC et al 2023

Demonstration on a small POLARBEAR data patch in 1909.13832

- Probably the minimally complex but efficient beyond-the QE method ?
- Uses a CMB likelihood model and search for maximum point of the posterior



- Sort of iterative QE estimation. (Build QE, delens, build new QE, delens…)

Challenges (on the ling side of things…)

- Computational cost
- Foregrounds and foregrounds non-Gaussianities?
- Mean-fields
- non-Gaussianity of lensing field?
- Importance of lensing curl modes ?
- Internal delensing biases
- …

Challenges (on the lensing side of things…)

- Computational cost

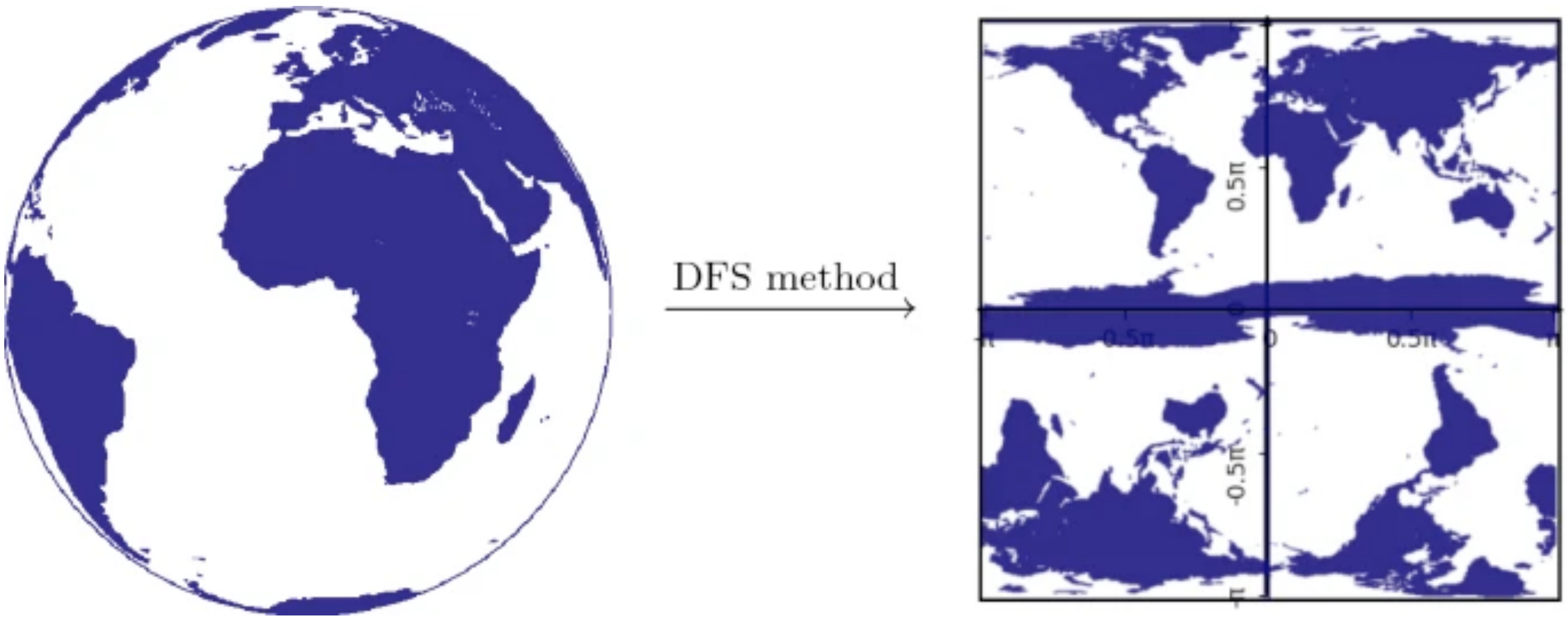
$$T^{\text{lensed}}(\boldsymbol{x}) = T^{\text{unlensed}}(\boldsymbol{x} + \boldsymbol{\alpha}(x))$$

- Lots and lots of spherical harmonic transforms on sphere pixelisation’s without any symmetries.

- They must be fast and accurate.
  (e.g. well-know lenspix (Lewis 2005 or similar algorithms not sufficient)

Doubled Fourier Sphere (DFS) method.

- Double latitude θ range to get a doubly-periodic flat map



- Flat and spherical sky band-limits are the same
- Can use very efficient non-uniform FFT methods to interpolate (Barnett et al 2019)

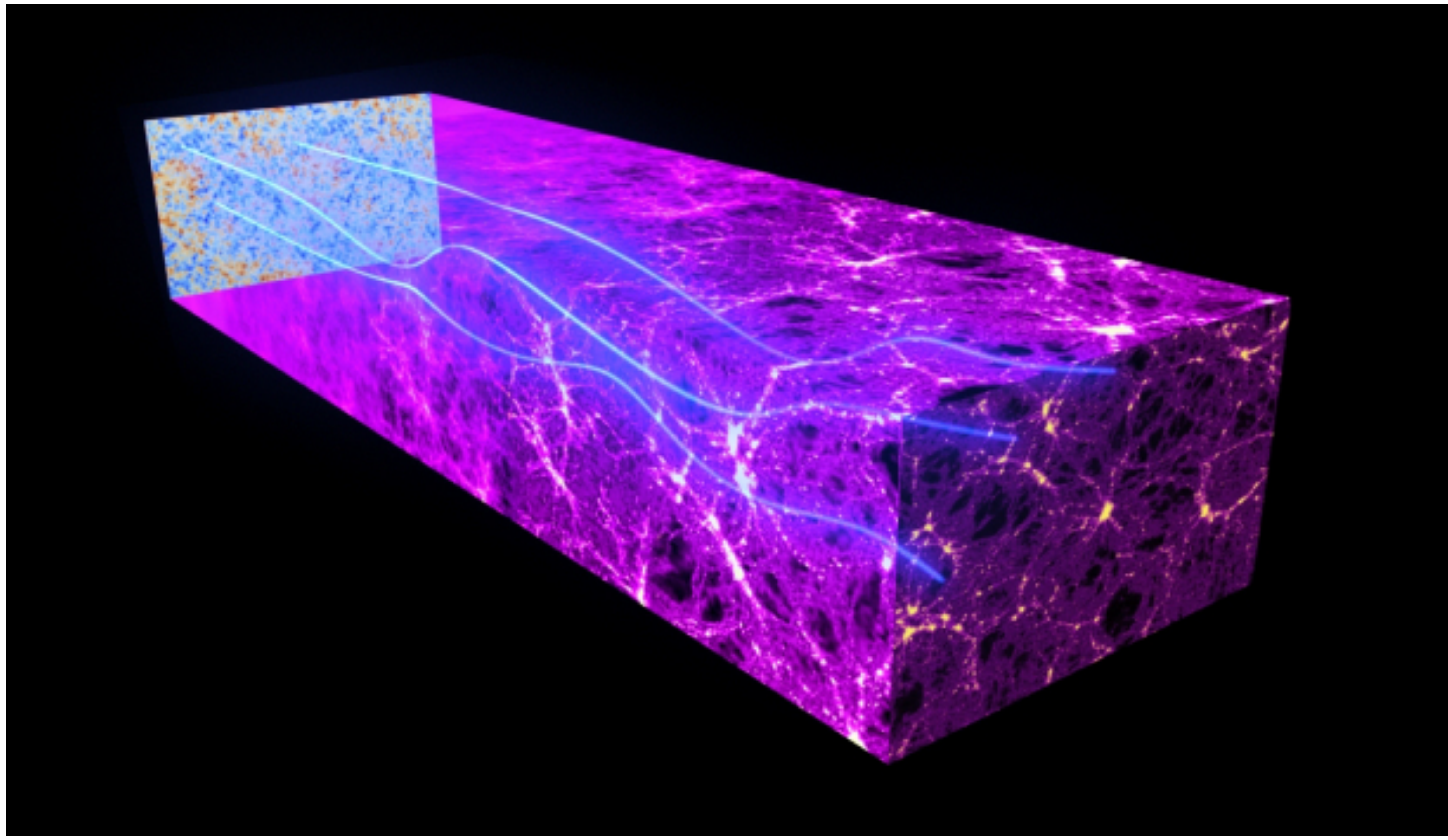
→ « Fast » spherical harmonic transforms for any pixelization

Factor of 10 and more in speed-up and in accuracy

Reinecke, Belkner et JC 2023

Non-Gaussian deflections in CMB lensing:

$$T^{\text{lensed}}(x) = T^{\text{unlensed}}(x + \alpha(x))$$



!Non-Gaussianities in the deflection field

$$C_L^{\hat{\phi}\delta} = C_L^{\phi\delta} + N_L^{(3/2)} + \cdots$$ (in x spectra to LSS)

New biases terms proportional to bispectrum

Beck et al 2018
Böhm et al 2016

$$C_L^{\hat{\phi}\hat{\phi}} = C_L^{\phi\phi} + N_L^{(0)} + N_L^{(1)} + N_L^{(3/2)} + \cdots$$ (in lensing auto-spectrum)

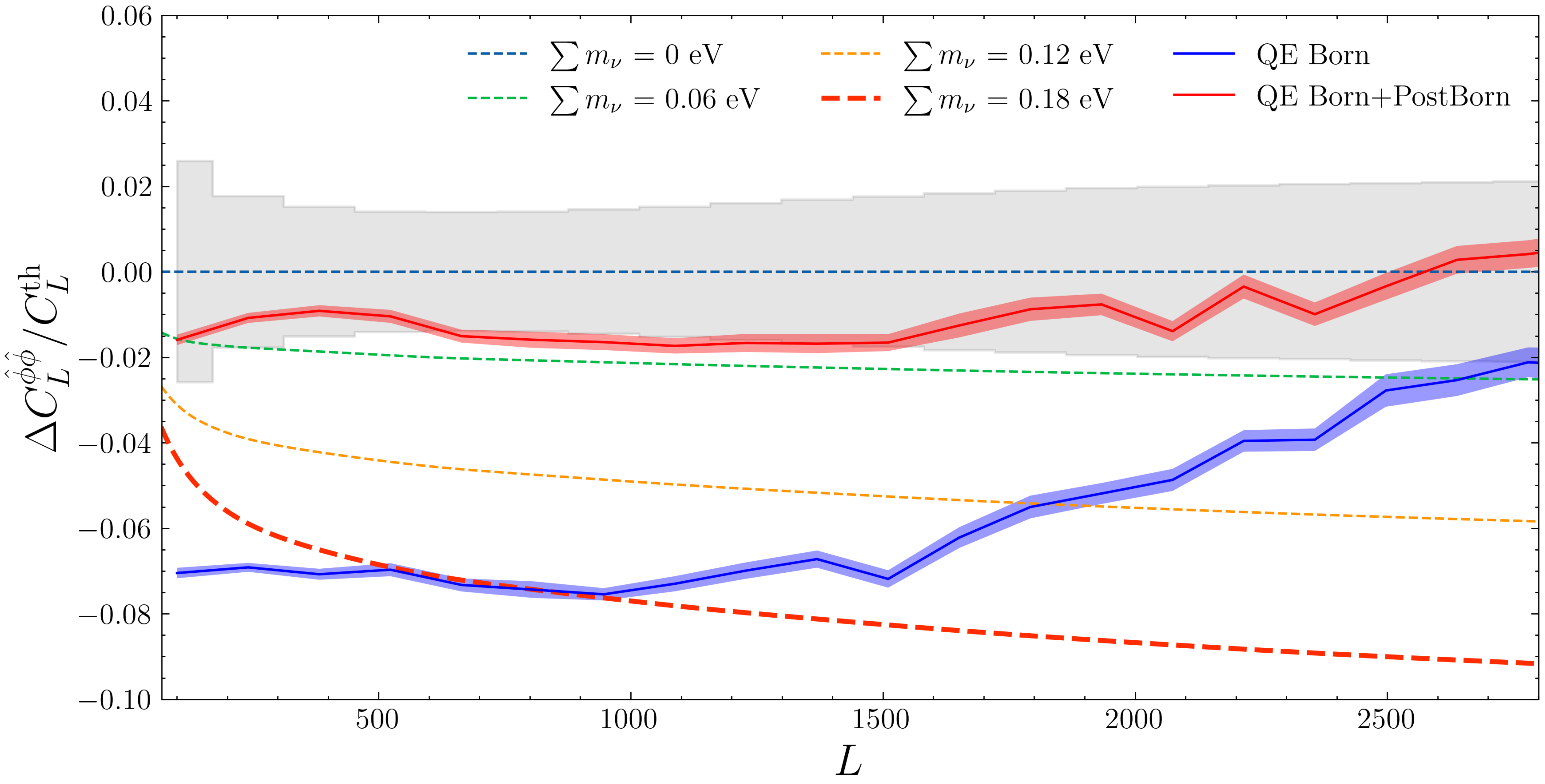
Full bispectrum $B^{\phi\phi\phi}_{Ll_1l_2}$ include:

- LSS bispectrum (non-linear growth) B^{LSS}
- « Post-Born » bispectrum (more than one deflection along the line of sight B^{PB})

Post-born effects also induce a lensing rotation

$$\omega(\hat{n}) = -4\int_0^{\chi_*} d\chi \left(\frac{\chi_* - \chi}{\chi\chi_*}\right)\int_0^{\chi} d\chi' \left(\frac{\chi - \chi'}{\chi'\chi}\right) \cdot [\gamma_1(\hat{n},\chi)\gamma_2(\hat{n},\chi') - \gamma_2(\hat{n},\chi)\gamma_1(\hat{n},\chi')]$$

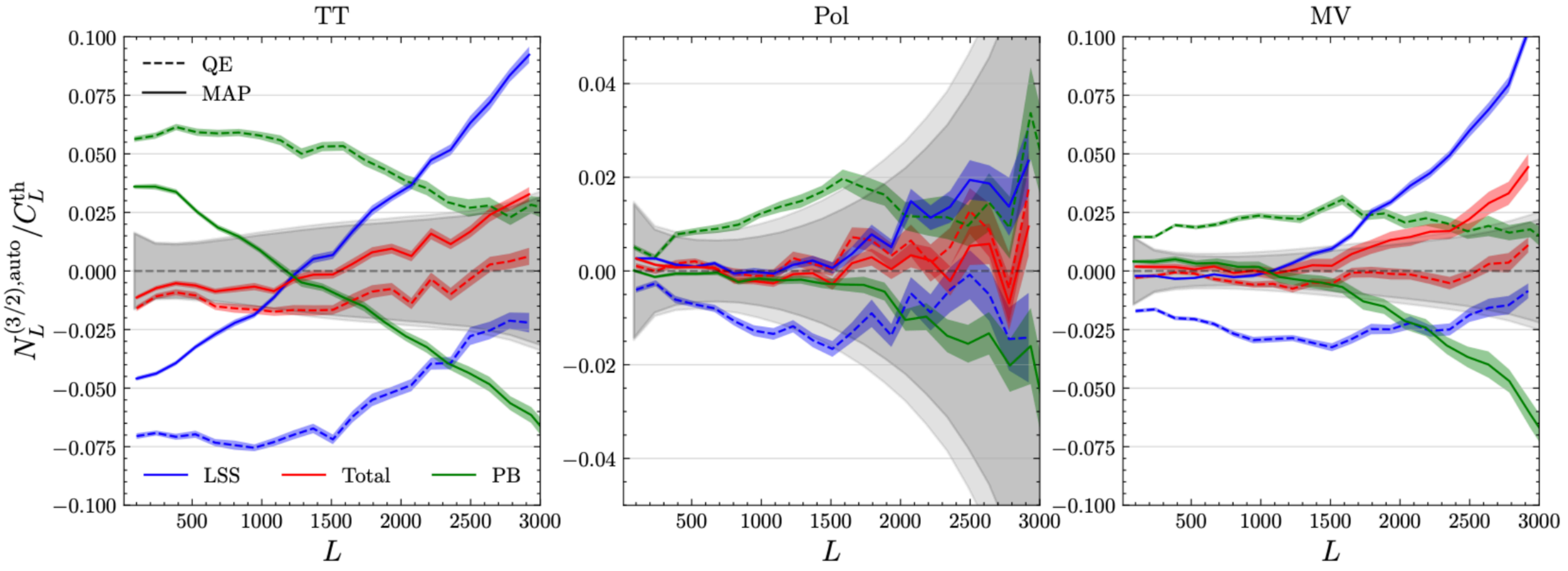
Quadratic estimator $N_L^{(3/2)}$ bias



Large cancellations between LSS and Post-Born bispectra
(only for « CMB » lensing!)

Findings on N-body sims

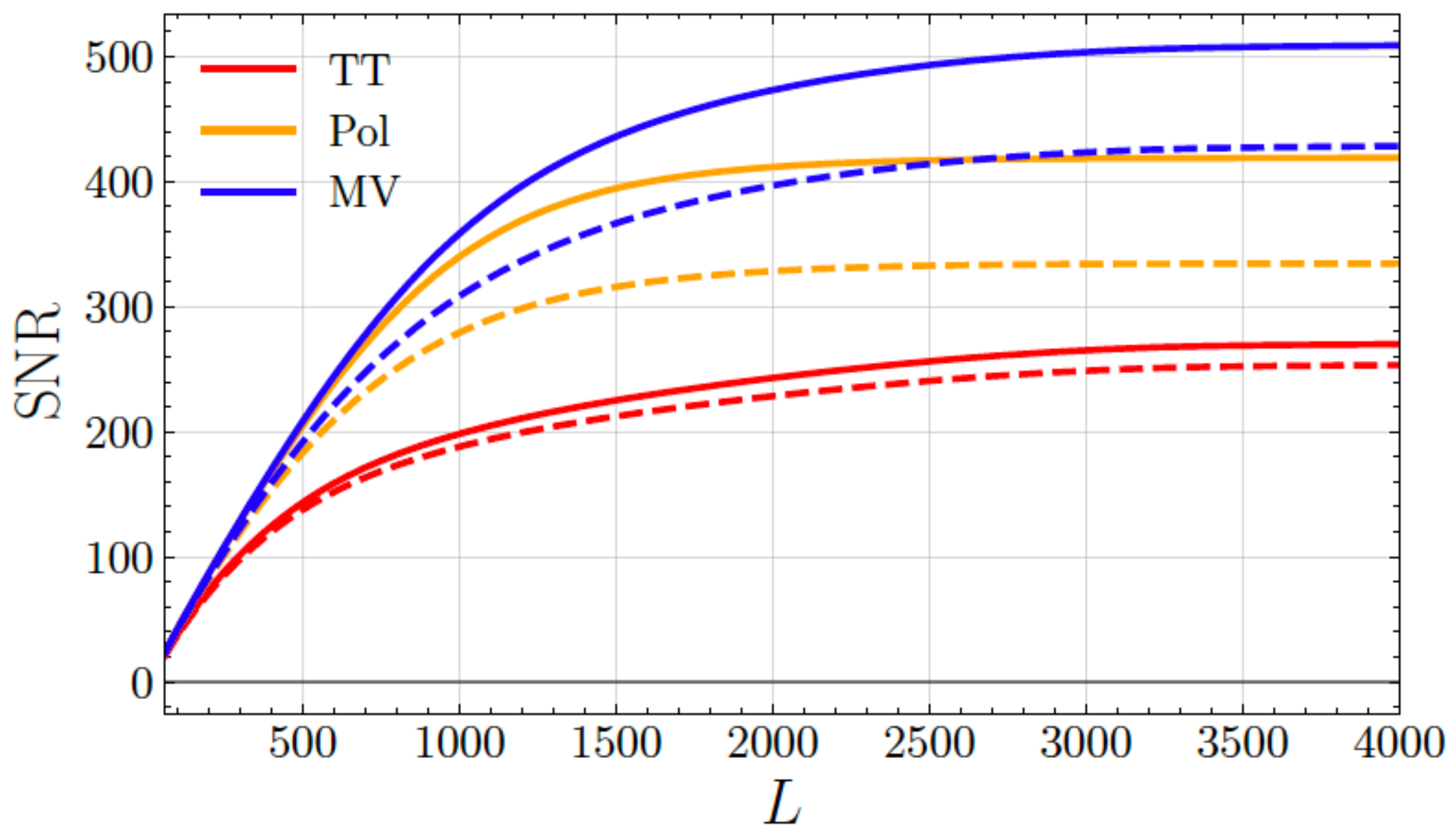
(Darwish, Belkner et al in prep.)



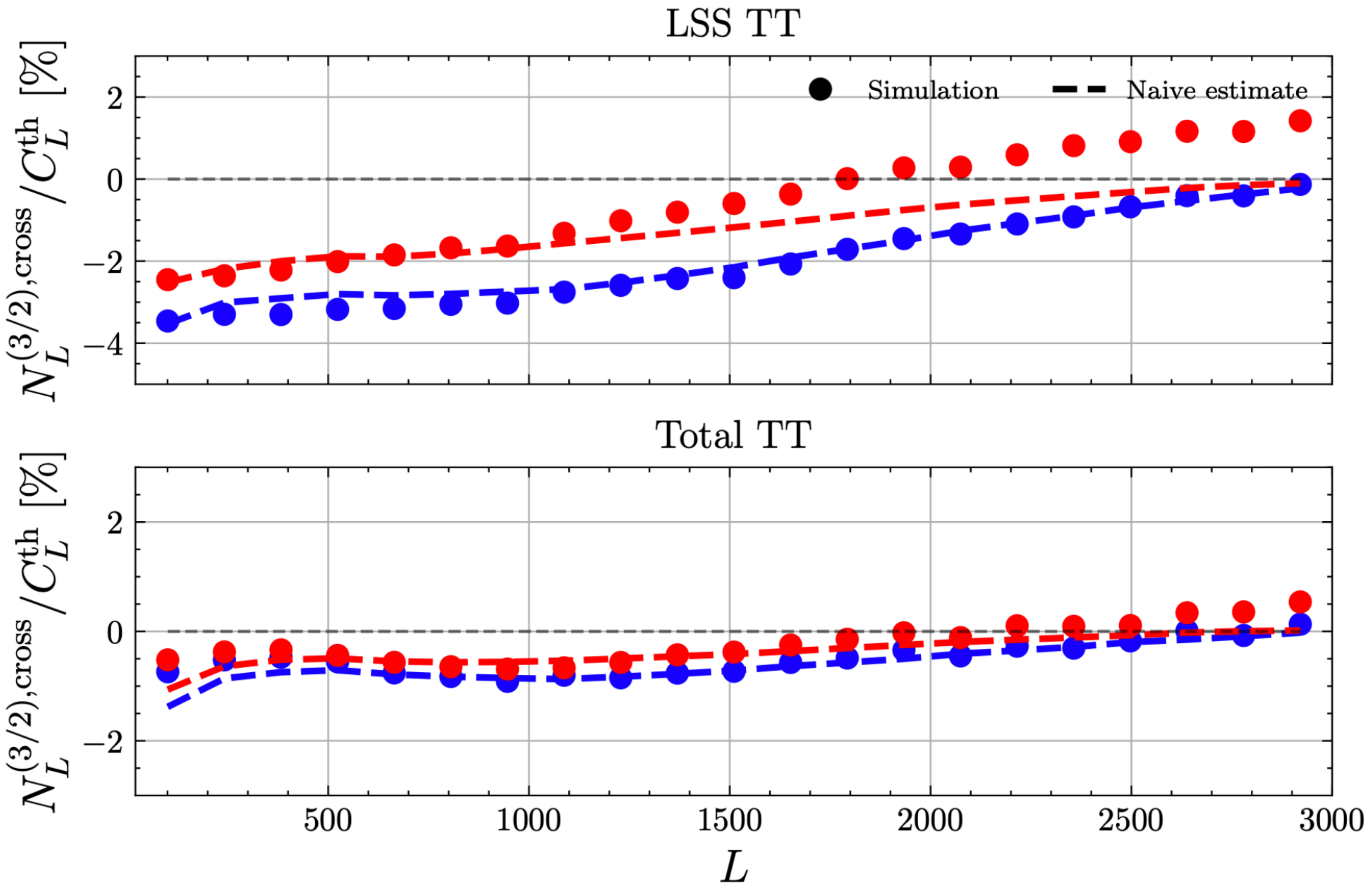
$$\mathrm{Total}: N_L^{(3/2)} = \langle \hat{C}_L^{\hat{\phi}^{XY}\phi^{\mathrm{ext}}}[\kappa^{\mathrm{tot}}] - \hat{C}_L^{\hat{\phi}^{XY}\phi^{\mathrm{ext}}}[\kappa^{\mathrm{tot,R}}]\rangle_{\mathrm{CMB}}$$

$$\mathrm{LSS}: N_L^{(3/2)} = \langle \hat{C}_L^{\hat{\phi}^{XY}\phi^{\mathrm{ext}}}[\kappa^{\mathrm{LSS}}] - \hat{C}_L^{\hat{\phi}^{XY}\phi^{\mathrm{ext}}}[\kappa^{\mathrm{LSS,R}}]\rangle_{\mathrm{CMB}}$$

$$\mathrm{PB}: N_L^{(3/2)} = \langle \hat{C}_L^{\hat{\phi}^{XY}\phi^{\mathrm{ext}}}[\kappa^{\mathrm{tot}}] - \hat{C}_L^{\hat{\phi}^{XY}\phi^{\mathrm{ext}}}[\kappa^{\mathrm{LSS,R}}]\rangle_{\mathrm{CMB}}$$



Predictions for cross-spectrum

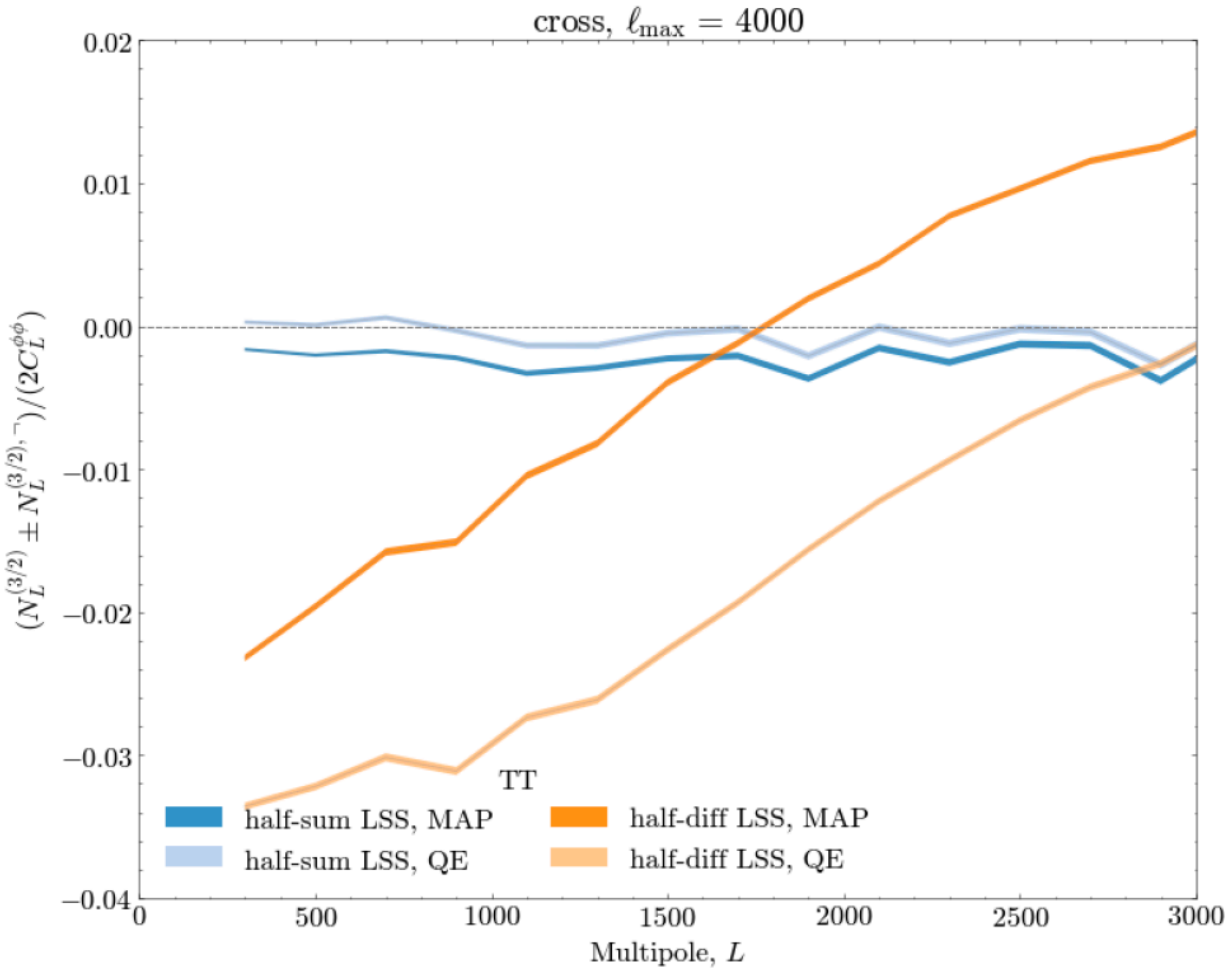


- Analytic predictions for optimal reconstruction intractable
- Naive prediction recipe:

  replace lensing field in CMB legs with residual lensing field:

$$B^{\phi\phi\phi}(L, l_1, l_3) \to B^{\phi\phi\phi}(L, l_1, l_3)(1 - \mathcal{W}_{l_1})(1 - \mathcal{W}_{l_3}).$$

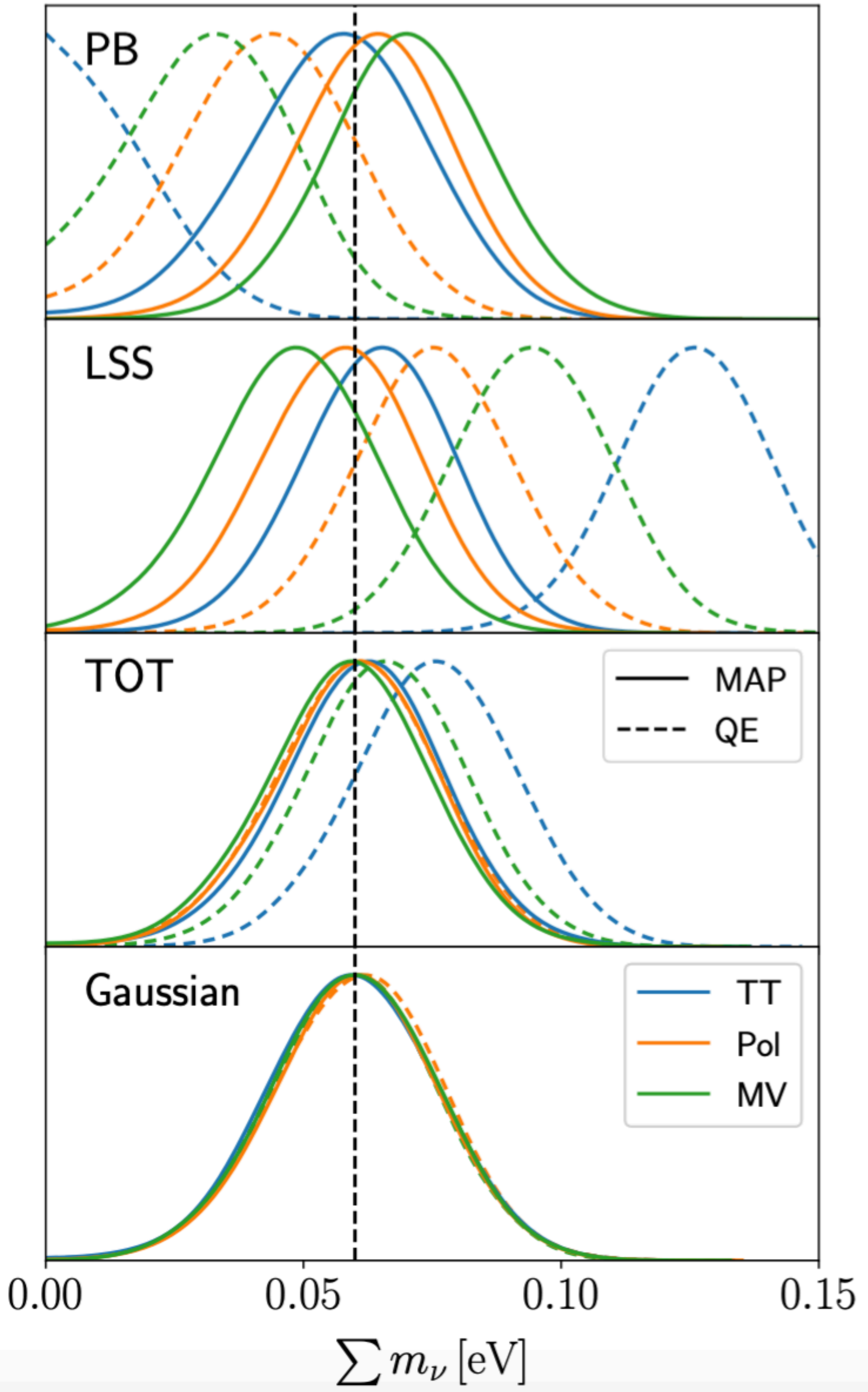
Still almost pure bispectrum effect



$$\Delta_{\pm}^{XY} = \left\langle \frac{1}{2}\left(N_L^{(3/2)}[\kappa_{LM}^{\rm in}] \pm N_L^{(3/2)}[\kappa_{LM}^{\rm in,\neg}]\right)\right\rangle_{\rm sims}$$

CMB-S4 + DESI BAO + τ
MCMC forecast constraints

(Ignoring $N_L^{(3/2)}$ completely)



Summary:

- CMB lensing powerful cosmological probe
  High significance, and robust, probe of LSS.
  Ground-based experiments now taking over from Planck (ACT…)

- For several important science targets of next-generation experiments (Simons Observatory, CMB-S4), precise lensing map reconstruction from CMB polarisation will be essential.

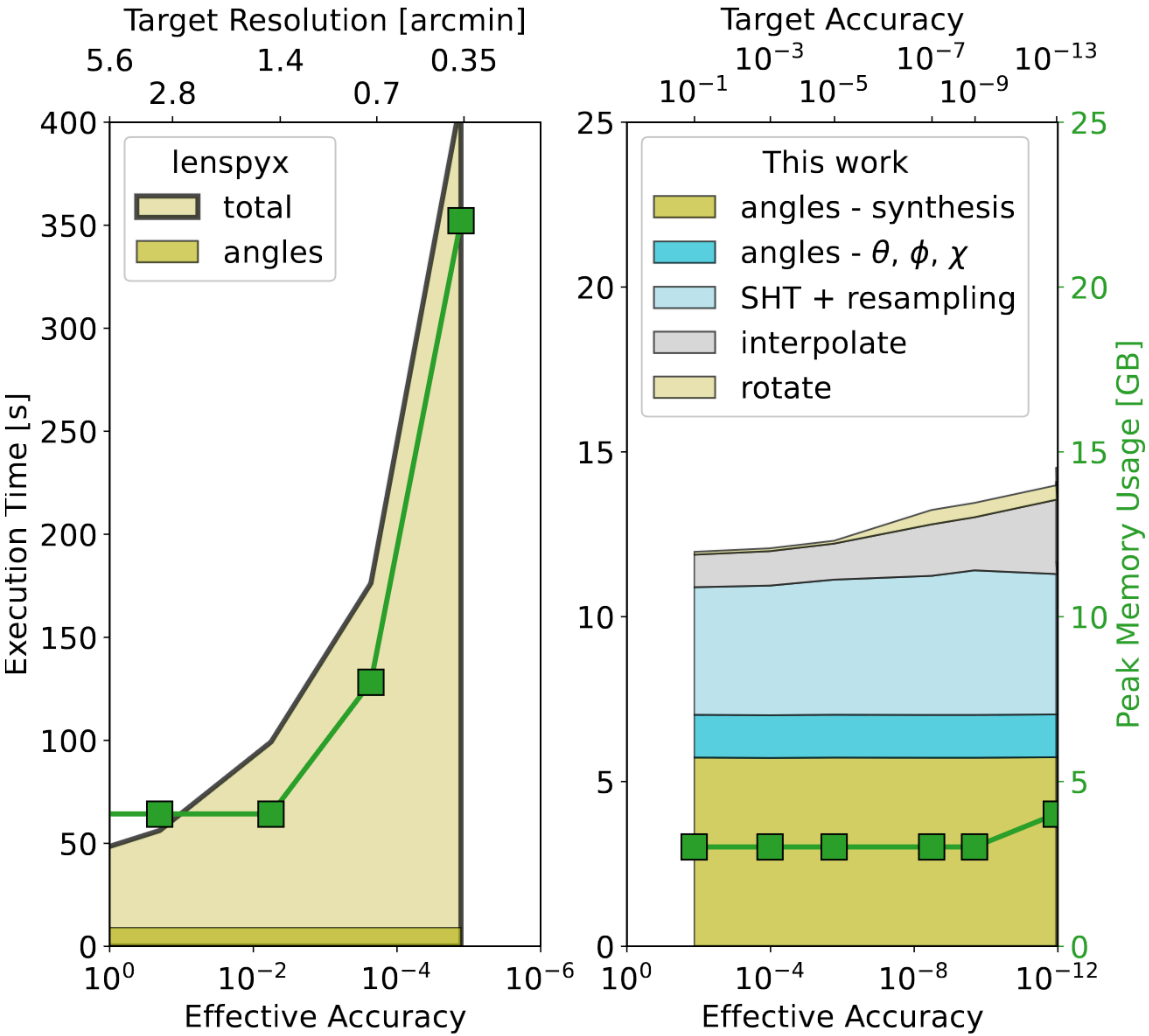
- We proposed an estimator and its likelihood for the optimal lensing reconstruction, gaining the expected signal to noise. This likely is the simplest and most economical way for beyond-the-QE reconstruction, capitalising on well-understood QE theory and techniques.

- The optimal estimator makes non-Gaussianity of the lensing deflections essentially irrelevant for CMB lensing

- Our tools for iterative delensing to get $\sigma(r) \sim 5 \cdot 10^{-4}$ to achieve their goals so far, inclusive of foregrounds, noise inhomogeneities, and non-linear lensing gradient and curl potentials.

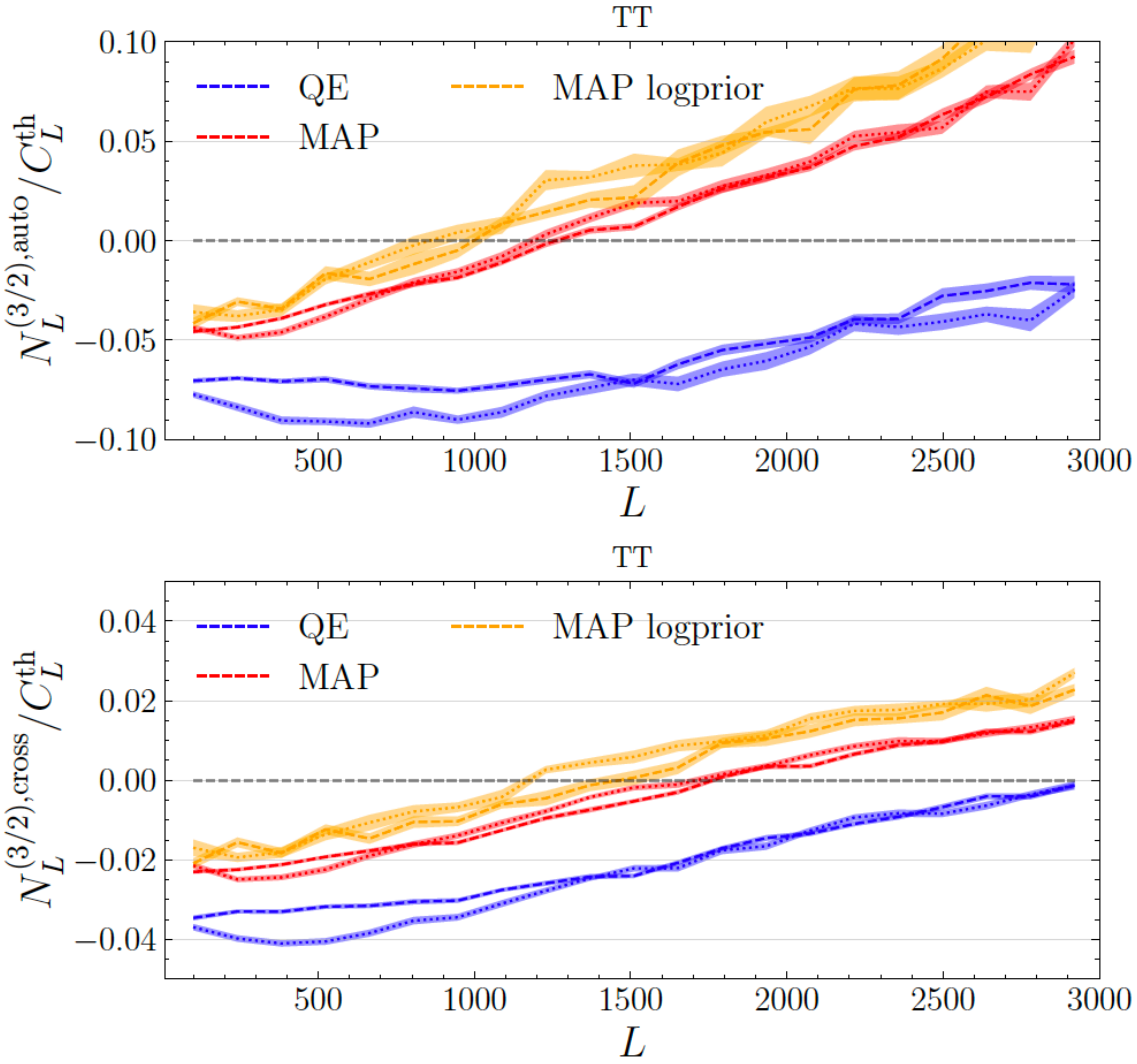
Thanks !

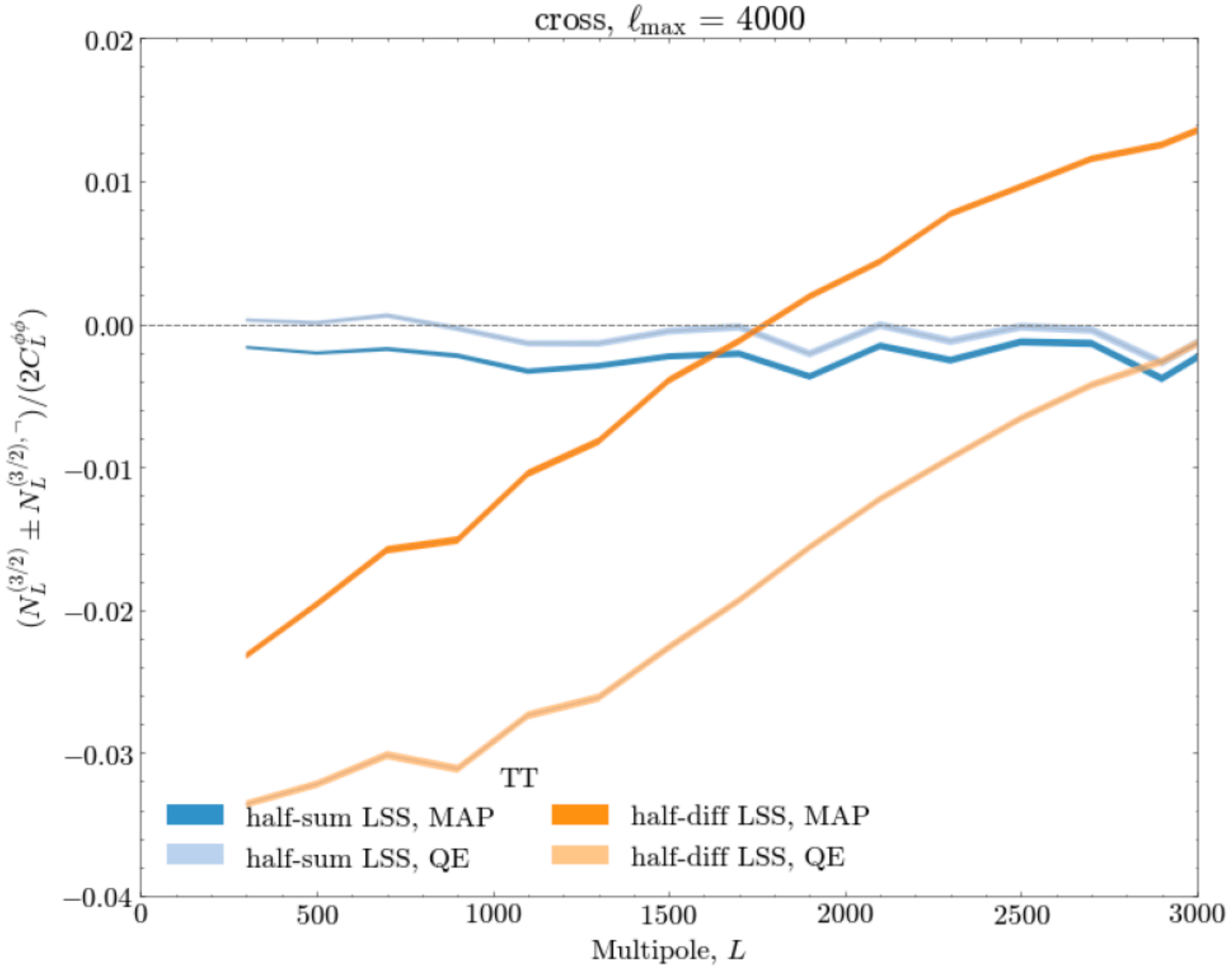
Factor of 10 and more in speed-up and in accuracy

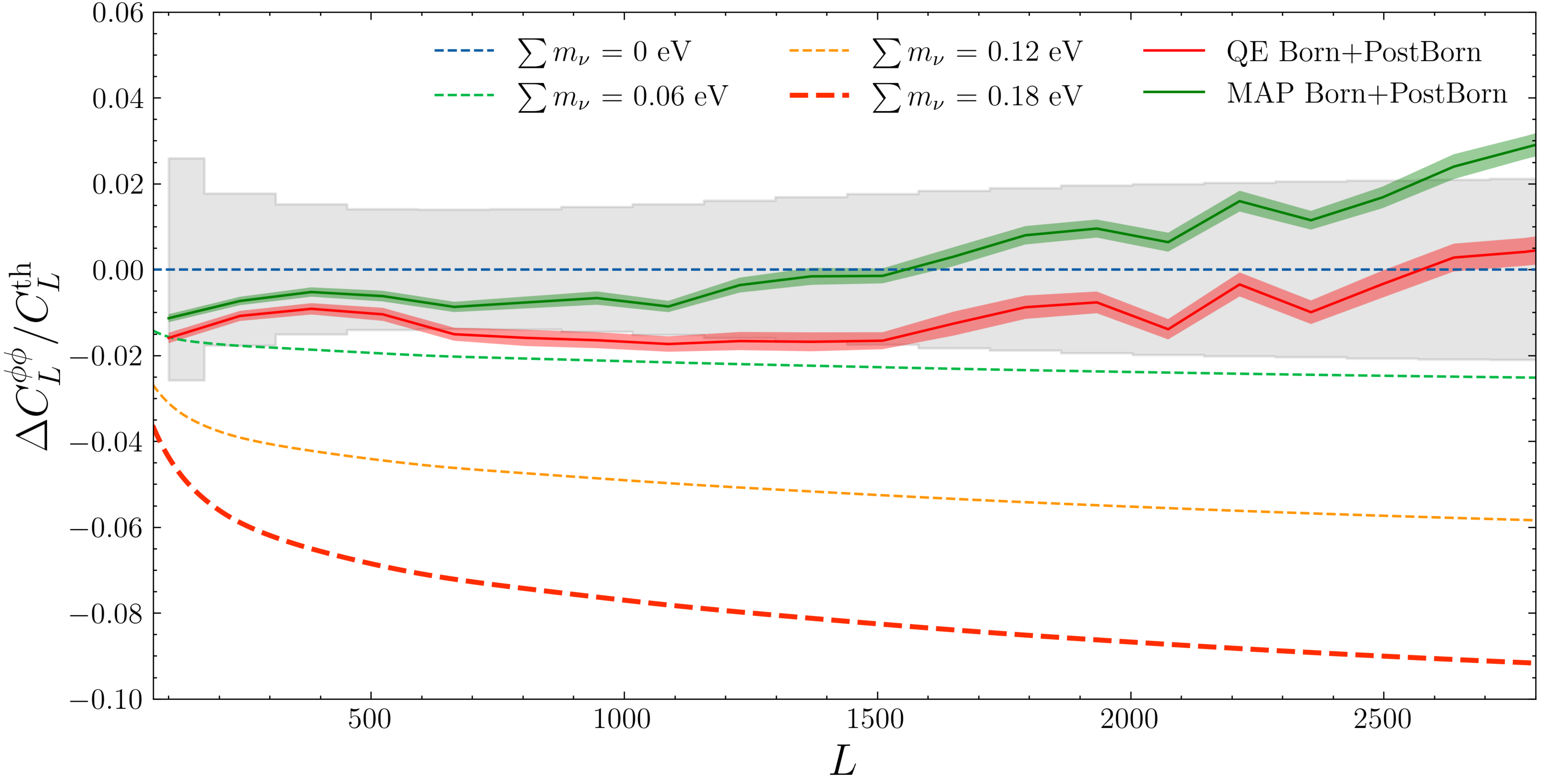


Spin-2,

$\ell_{\max} = 2048, NSIDE = 2048$


TT
QE
MAP
MAP logprior
$N_L^{(3/2),\mathrm{auto}}/C_L^{\mathrm{th}}$
L
TT
QE
MAP
MAP logprior
$N_L^{(3/2),\mathrm{cross}}/C_L^{\mathrm{th}}$
L


cross, $\ell_{\max} = 4000$
$(N_L^{(3/2)} \pm N_L^{(3/2),-})/(2C_L^{\phi\phi})$
TT
half-sum LSS, MAP
half-sum LSS, QE
half-diff LSS, MAP
half-diff LSS, QE
Multipole, L


$\sum m_\nu = 0$ eV
$\sum m_\nu = 0.06$ eV
$\sum m_\nu = 0.12$ eV
$\sum m_\nu = 0.18$ eV
QE Born+PostBorn
MAP Born+PostBorn
$\Delta C_L^{\hat{\phi}\hat{\phi}} / C_L^{\rm th}$
L
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
500
1000
1500
2000
2500