UNIVERSITÉ DE GENÈVE

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

LOUIS LEGRAND

Julien Carron

Legrand and Carron 2021

arXiv:2112.05764

Phys. Rev. D 105, 12351

CMB LENSING WITH NEXT GENERATION SURVEYS

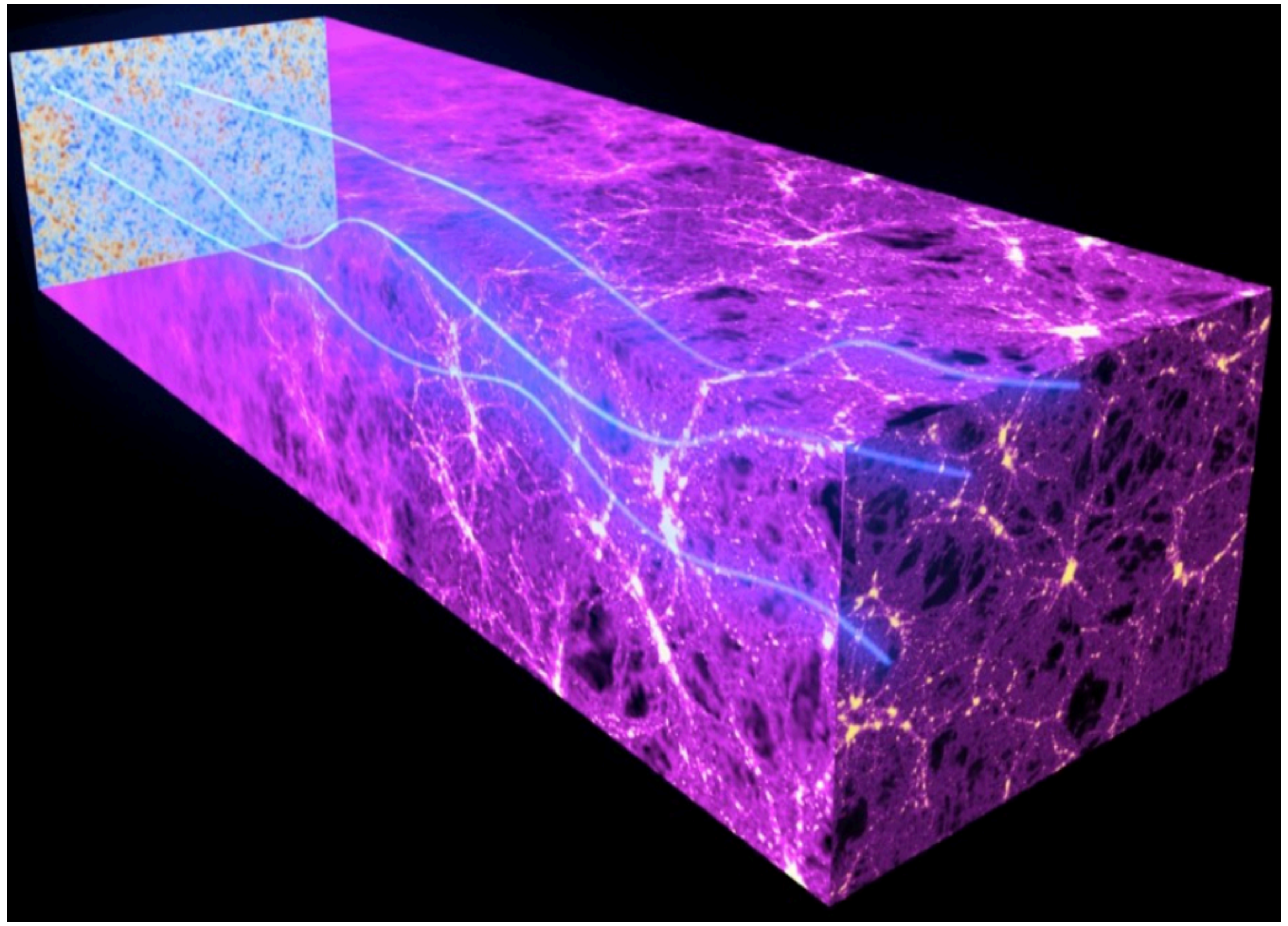
CMB E modes lensed - unlensed

CMB GRAVITATIONAL LENSING

- CMB is an extended light source at z=1100
- CMB photons are lensed by the large scale structures created by gravitational evolution of matter

$$\boldsymbol{\alpha} = \overrightarrow{\nabla} \phi$$

$$\phi(\boldsymbol{n}) = -2 \int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} \Psi \left(\chi \boldsymbol{n}; \eta_0 - \chi\right)$$

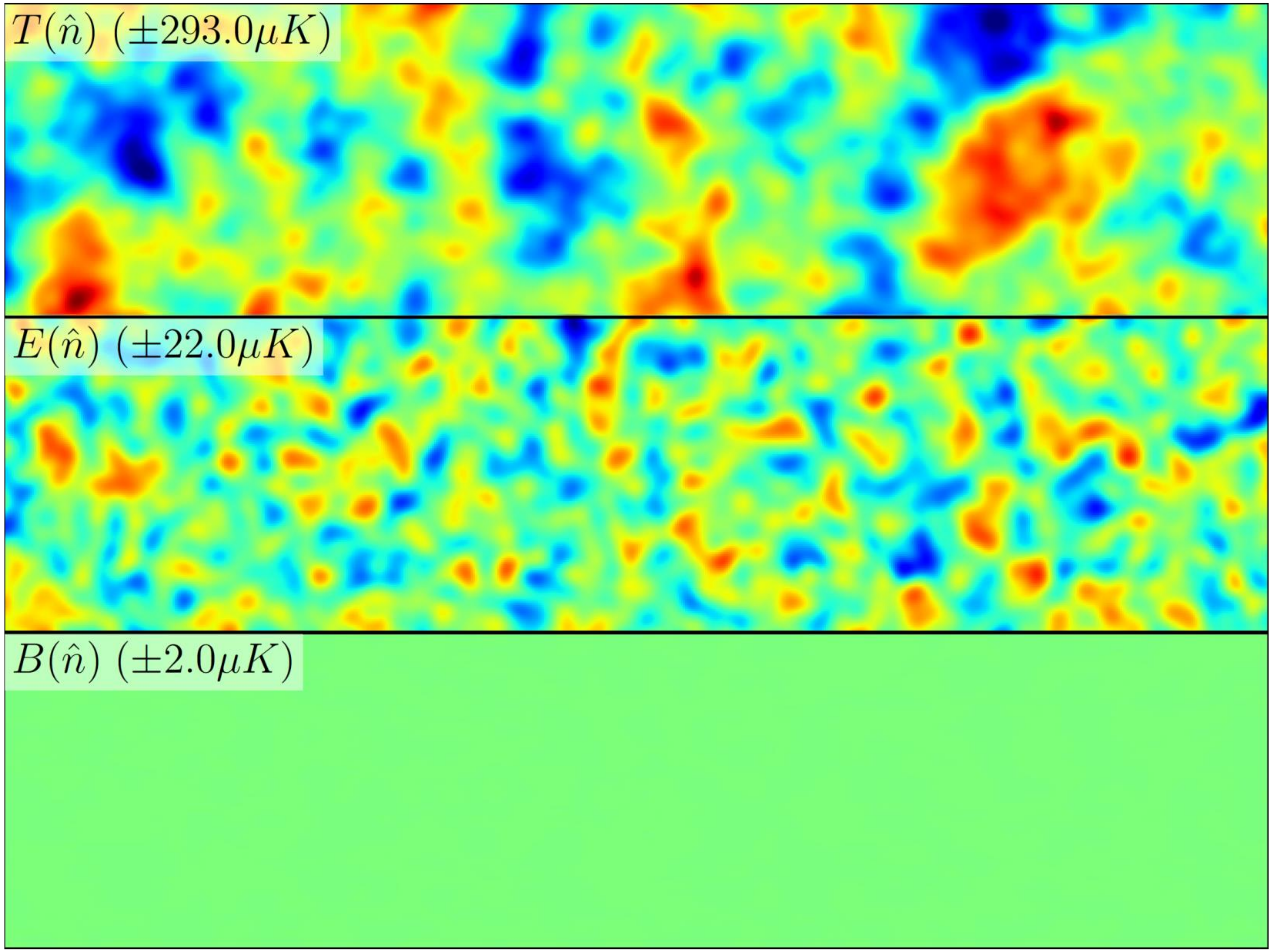


CMB LENSING

- Lensing acts as a remapping of the primordial CMB fields

$$X^{\mathrm{len}}(\boldsymbol{n}) = X^{\mathrm{unl}}(\boldsymbol{n} + \boldsymbol{\alpha}(\boldsymbol{n}))$$

- It creates statistical anisotropies and correlation between different scales



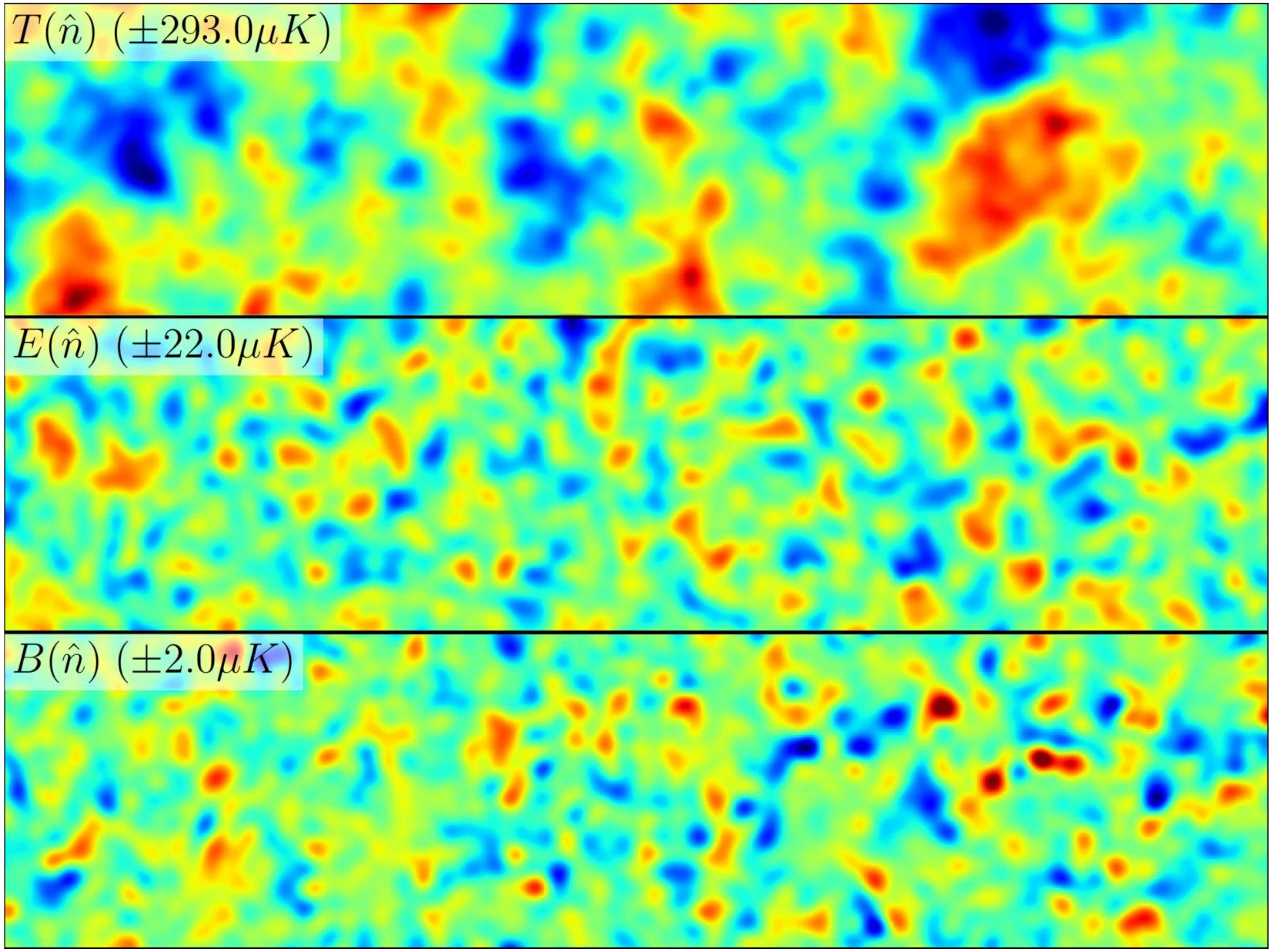
from J. Carron

CMB LENSING

- Lensing acts as a remapping of the primordial CMB fields

$$X^{\mathrm{len}}(\boldsymbol{n}) = X^{\mathrm{unl}}(\boldsymbol{n} + \boldsymbol{\alpha}(\boldsymbol{n}))$$

- It creates statistical anisotropies and correlation between different scales



from J. Carron

HOW CAN WE MEASURE THE CMB LENSING POTENTIAL?

QUADRATIC ESTIMATOR (QE)

- Lensing creates correlations between different multipole moments

$$\left\langle X^{\mathrm{len}}(\boldsymbol{l}) Y^{\mathrm{len}\,*}(\boldsymbol{l}') \right\rangle_{\substack{\text{fixed lensed} \\ \boldsymbol{l} \neq \boldsymbol{l}',\, \boldsymbol{L} = \boldsymbol{l} + \boldsymbol{l}'}} = f_{XY}(\boldsymbol{l}, \boldsymbol{l}')\, \phi(\boldsymbol{L})$$

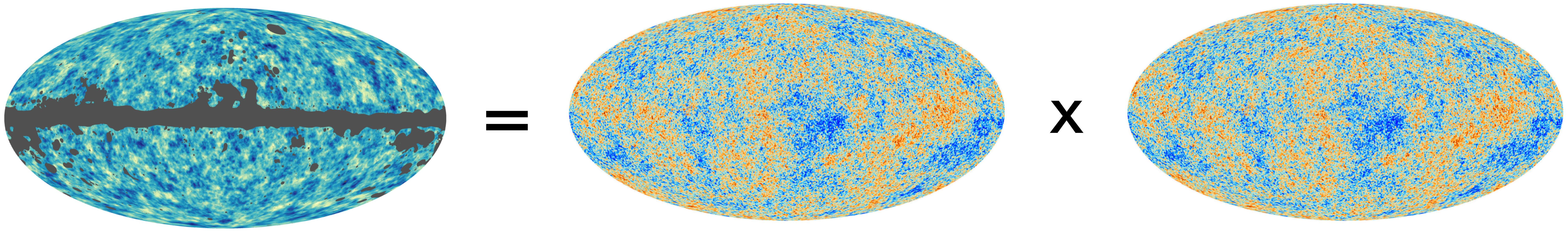
Lensing induced correlations

- The QE combines scales of two CMB fields (Hu & Okamoto 2002)

$$\hat{\phi}(\boldsymbol{L}) = \frac{1}{R_L^{XY}} \int \frac{d^2\boldsymbol{l}}{2\pi}\, f^{XY}(\boldsymbol{l}, \boldsymbol{L})\, \bar{X}(\boldsymbol{l})\, \bar{Y}^*(\boldsymbol{l} - \boldsymbol{L})$$

Normalisation (response of the estimator)

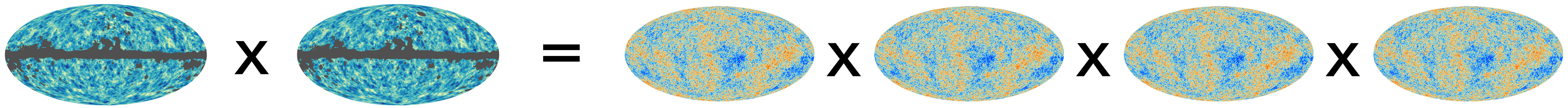
Inverse variance filtered CMB fields



NOISY RECONSTRUCTION

- The power spectrum of the estimated lensing potential is a 4 point functions of the maps

$$C_L^{\hat{\phi}\hat{\phi}} =$$



- Chance correlations between different scales can mimic the lensing effect

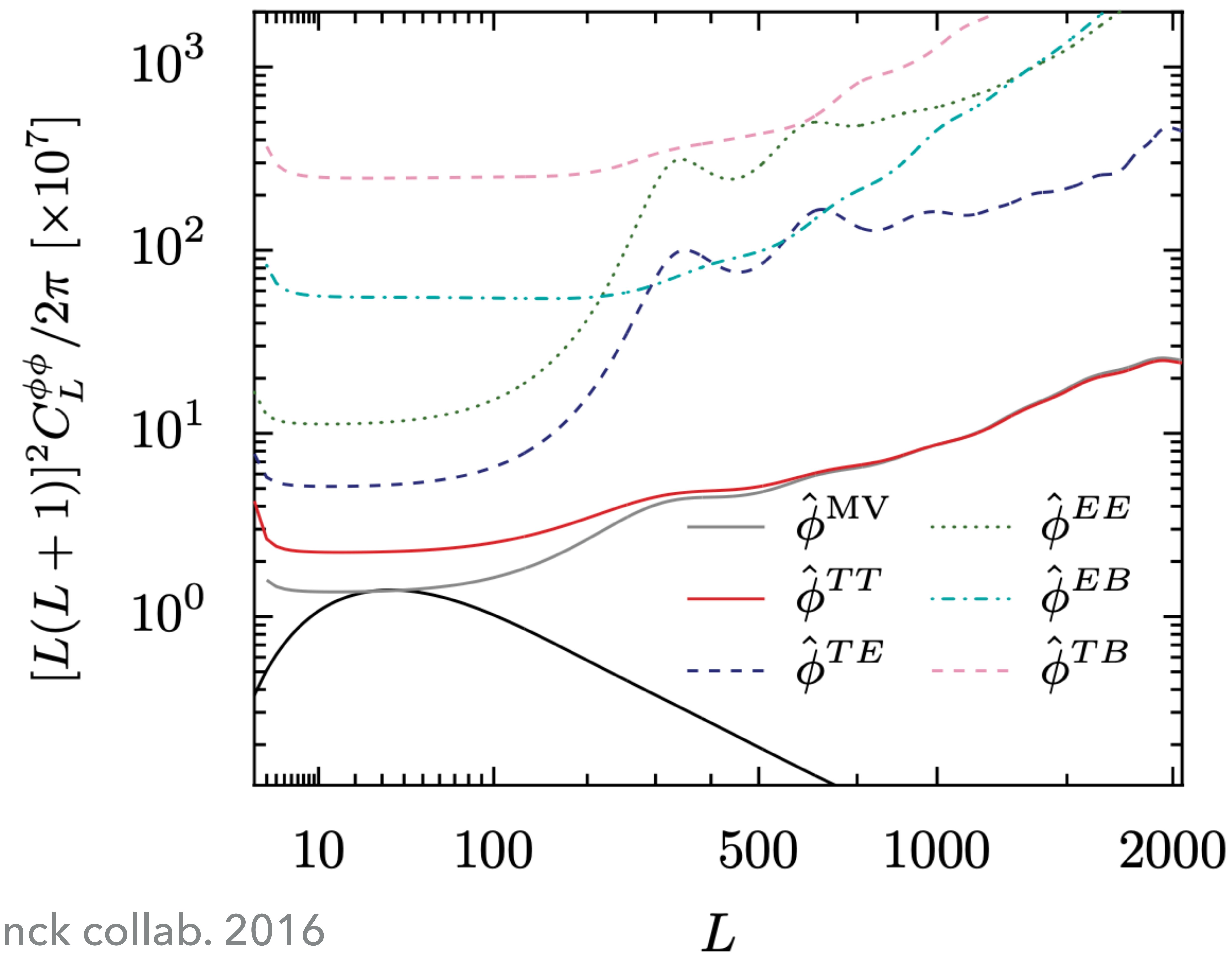
The signal we want

$$C_L^{\hat{\phi}\hat{\phi}} = C_L^{\phi\phi} + N_L^0 + N_L^1 + \dots$$

Disconnected (gaussian) contractions of the lensed CMB fields

Non gaussian secondary contractions created by lensing (proportional to $C^{\phi\phi}$)

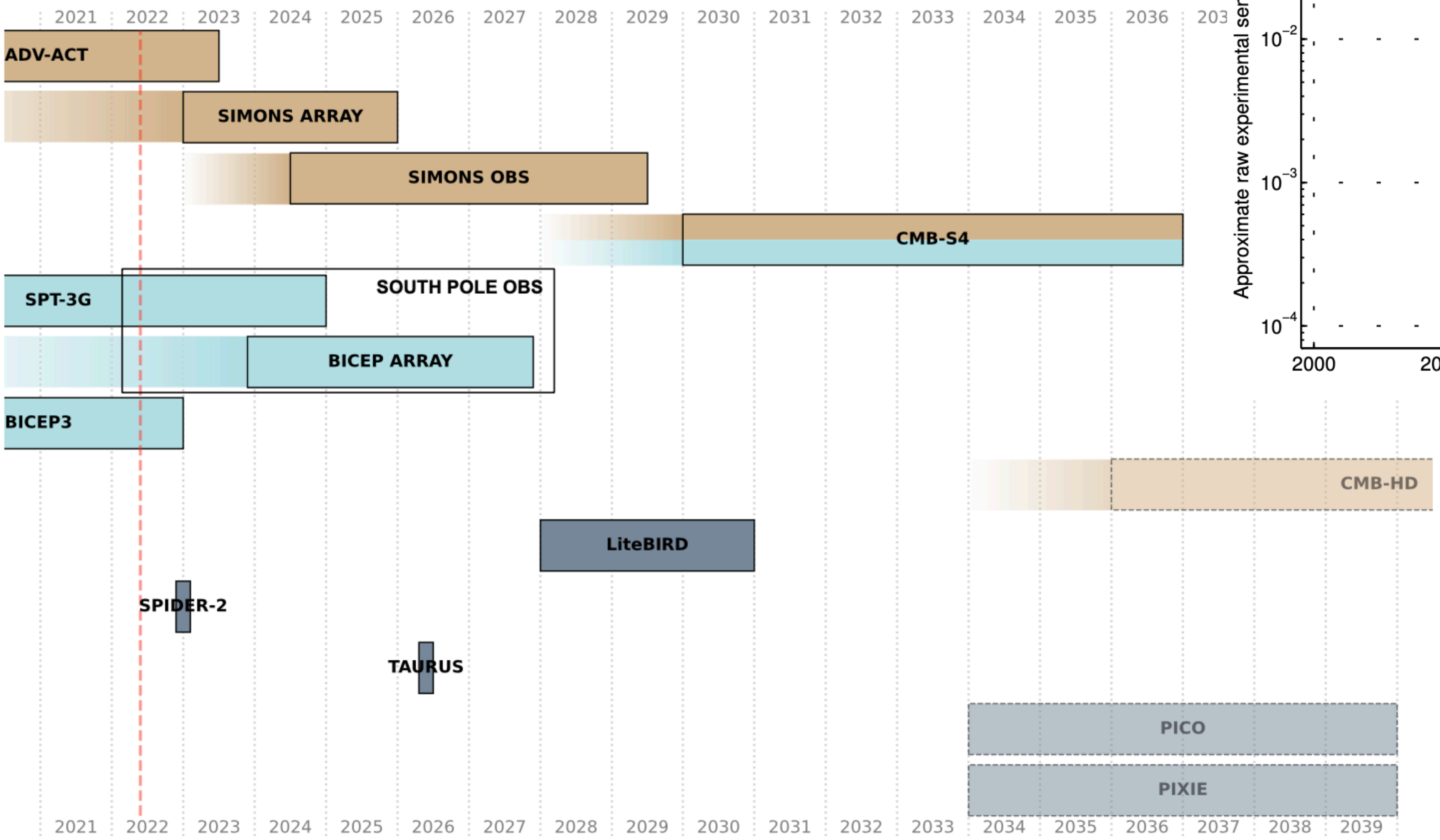
NOISY RECONSTRUCTION

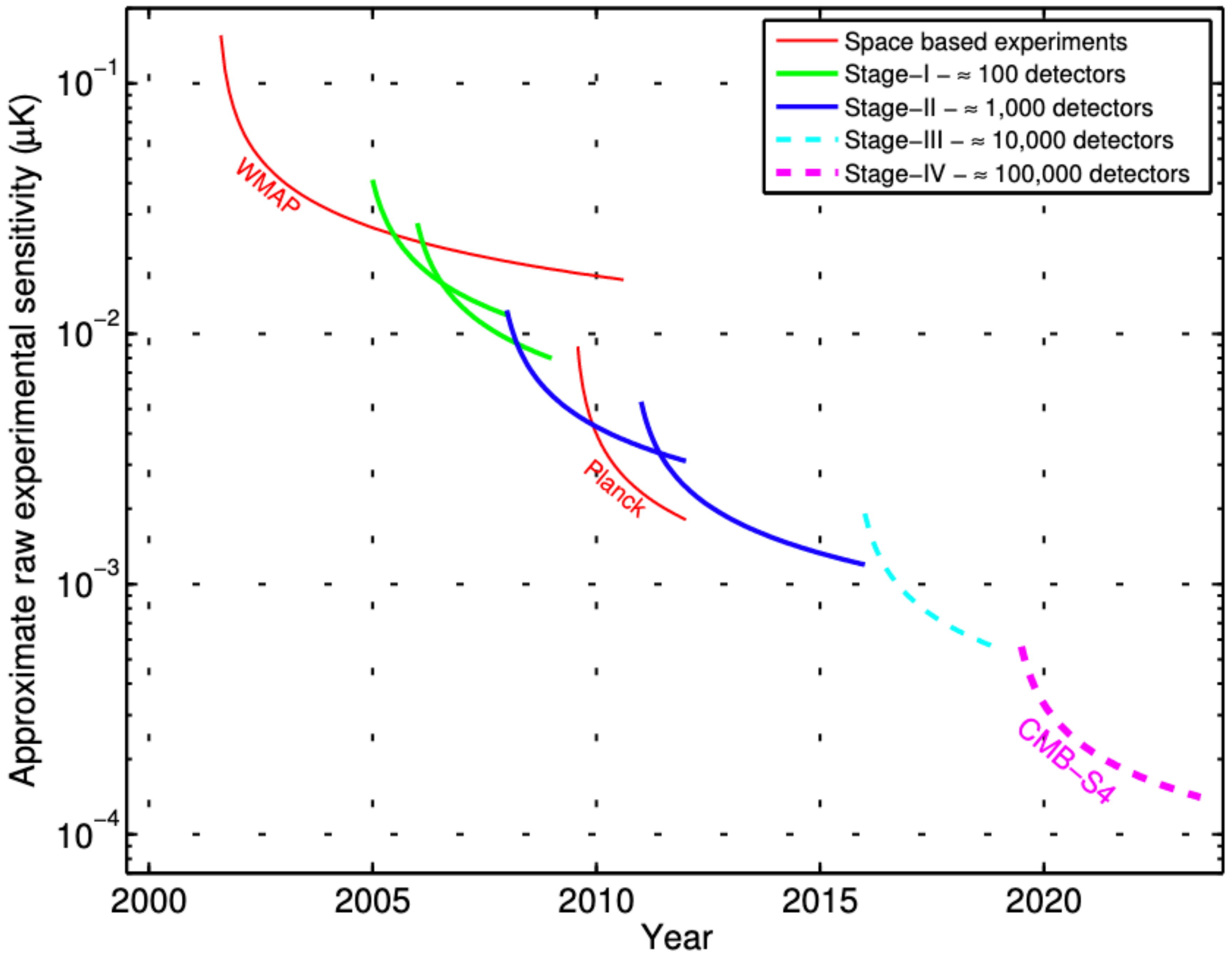


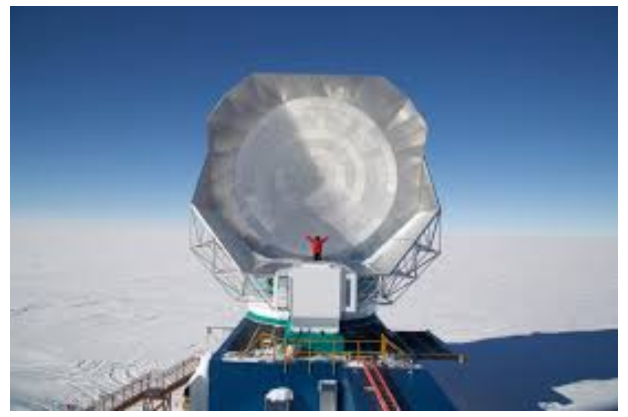
Planck collab. 2016

- Planck lensing power spectrum is dominated by the N0 bias at all scales
- Combining all pairs of maps into a minimum variance estimator
- TT estimator is dominating in Planck

NEXT GENERATION SURVEYS



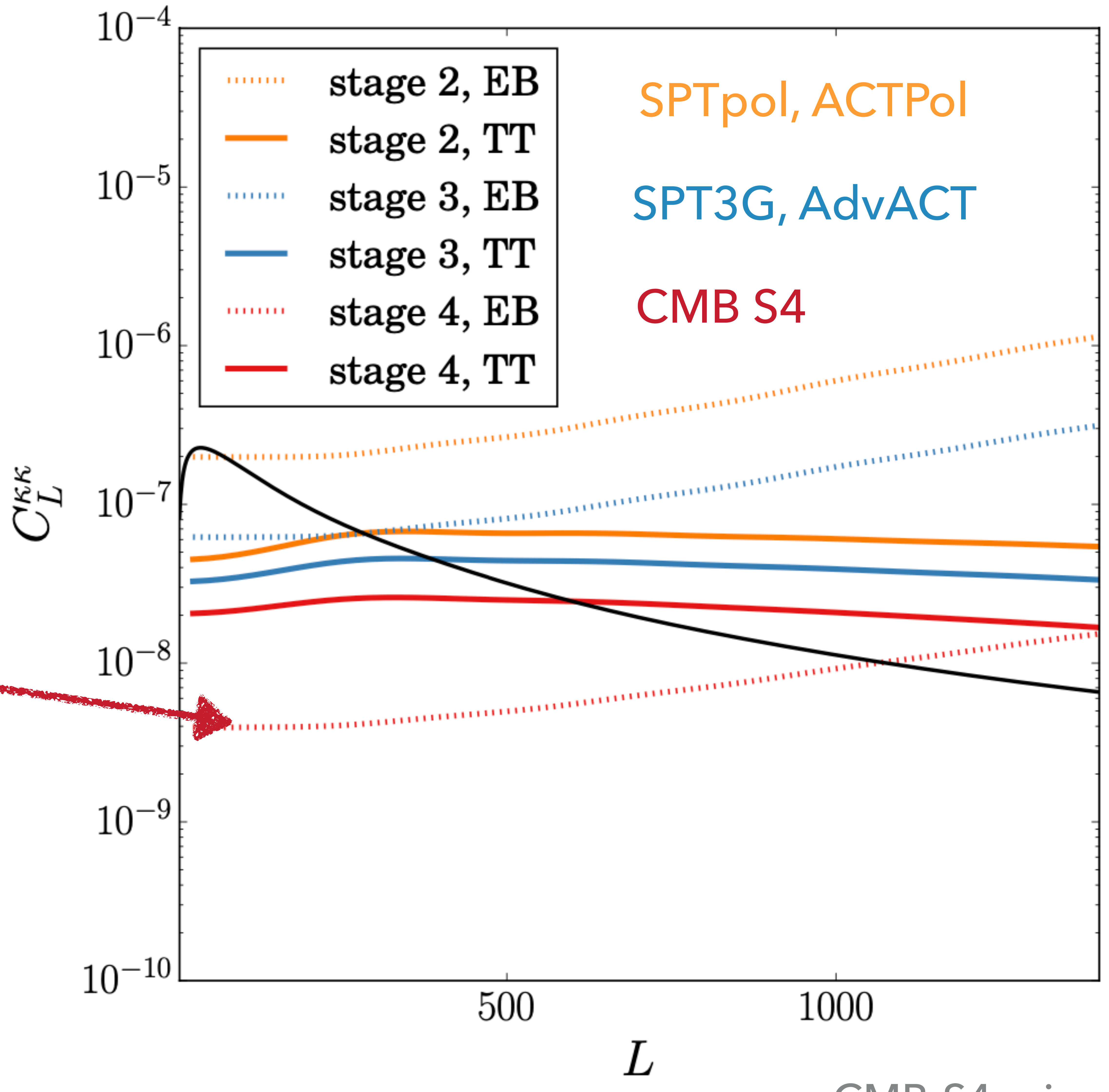




Chang et al 2022

NEXT GENERATION CMB SURVEYS

EB (polarisation) estimator
will be dominant for CMB S4



CMB-S4 science book 2016

MORE OPTIMAL ESTIMATORS

- Neglecting primordial B modes, one could reconstruct perfectly the lensing field

Lensed E + Lensed B   Lensing potential + Unlensed E

No primordial B
<=>

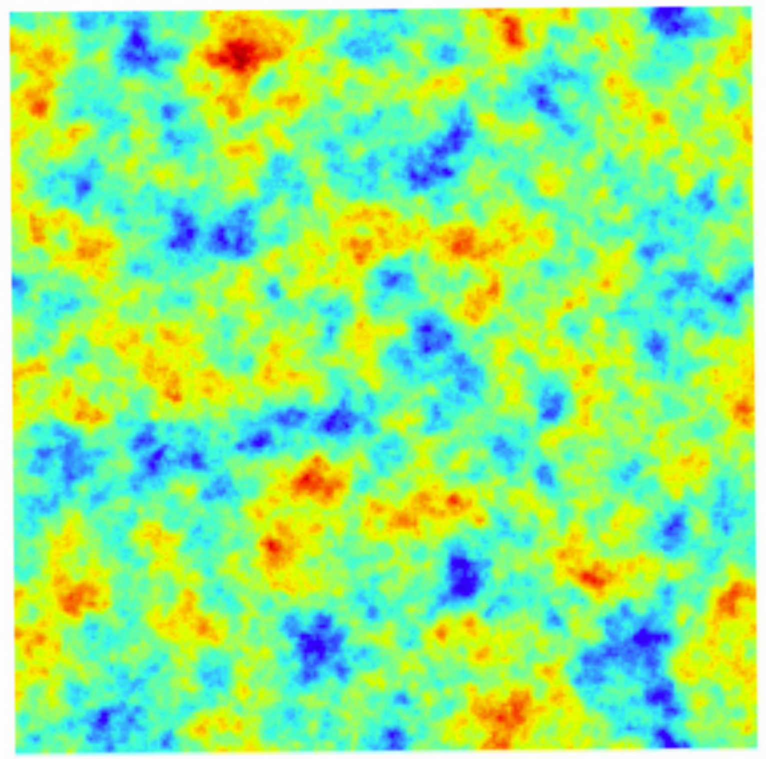
- Likelihood based approach, first introduced in Hirata & Seljak 2003 $P(\phi \,|\, \mathrm{data})$
- How can we find the maximum of this likelihood ?
  - Sampling-based approach -> Millea et al 2020
  - Iterative approach -> Carron & Lewis 2017

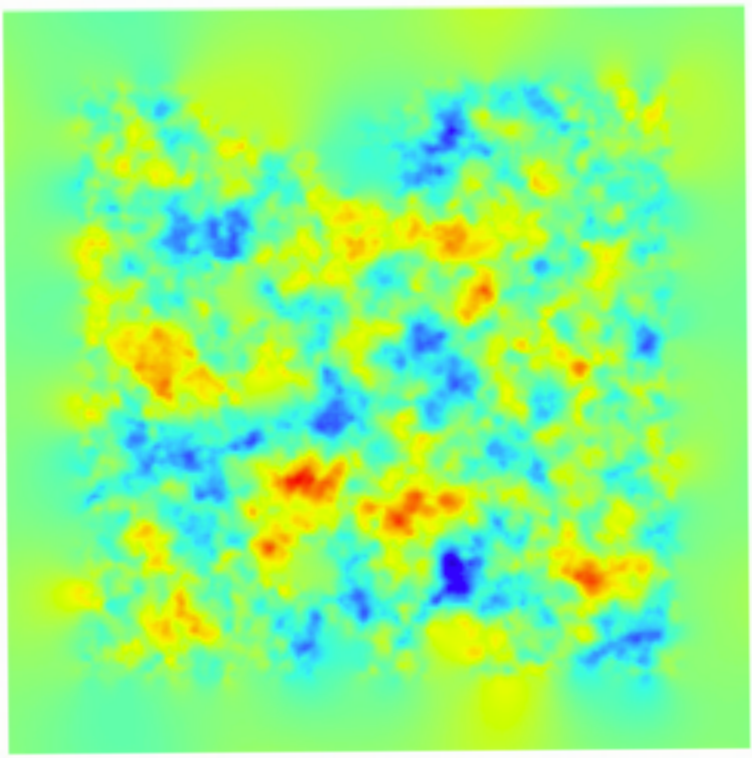
ITERATIVE APPROACH

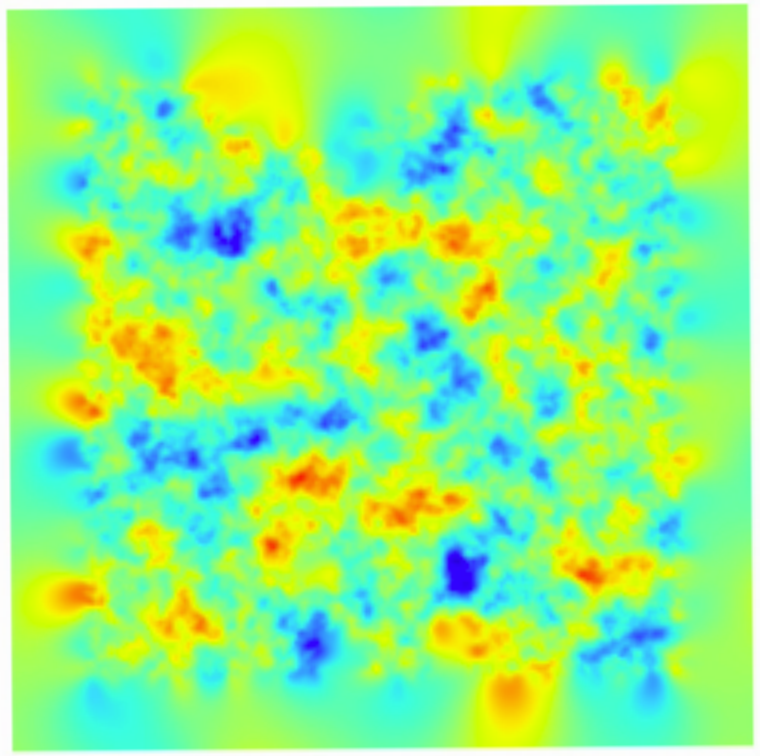
- Newton-Raphson iterations on the likelihood
- At each step we get an estimate of the maximum a posteriori lensing field, obtained with a QE

- In practice at each step:
  - delens the data using the deflection estimate
  - apply a quadratic estimator on the resulting maps
  - start again until convergence

- Advantage: fast and based on a well known tool, the quadratic estimator


Input phi


QE

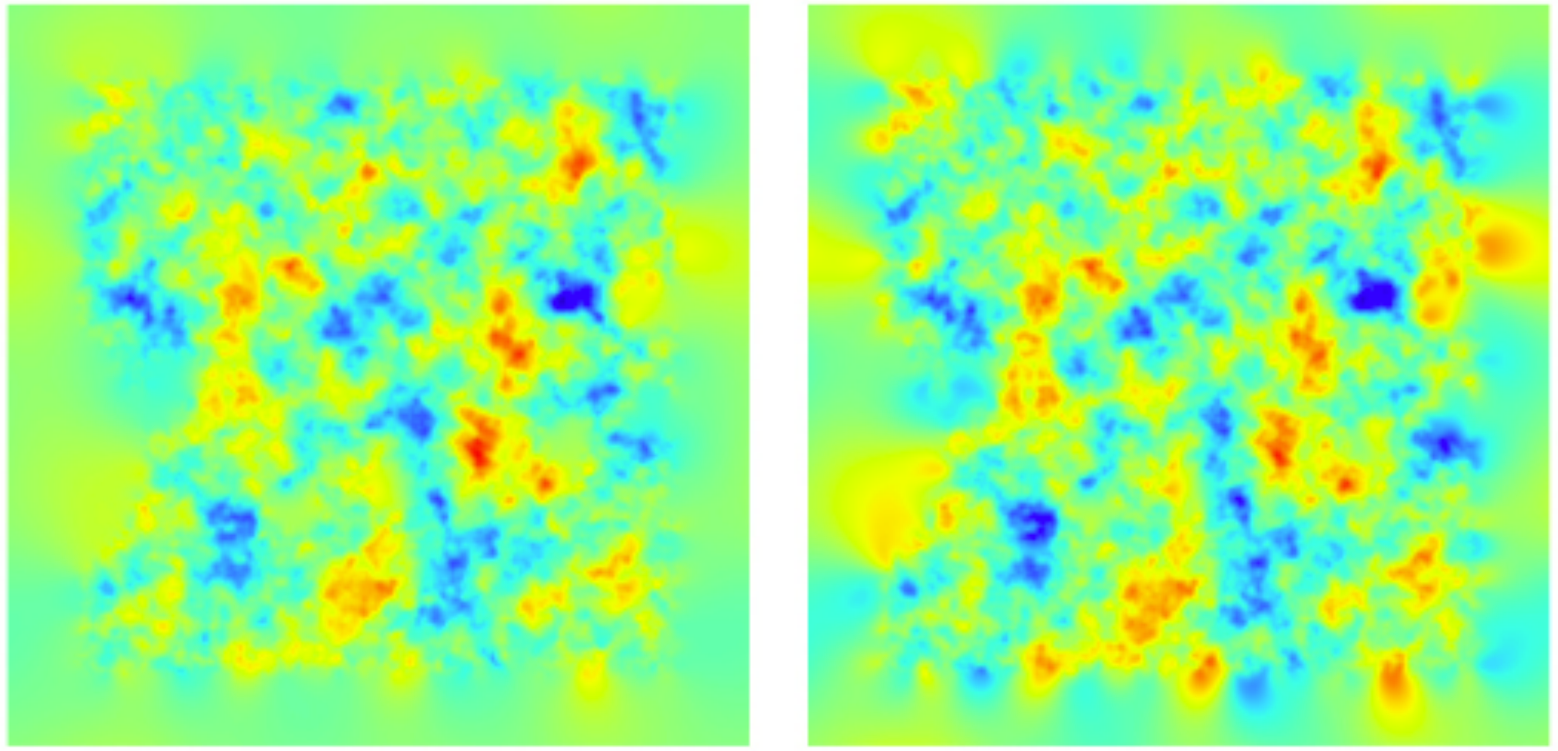

MAP

Carron&Lewis 2017

OPTIMAL LENSING POWER SPECTRUM ESTIMATION

- Problem: cannot track analytically the 4 point function of the lensing power spectrum
- How do we debias the spectrum obtained from the iterative lensing reconstruction ?

QE



MAP

$$C_L^{\hat{\phi}\hat{\phi}} = C_L^{\phi\phi} + N_L^0 + N_L^1 + \dots$$

$$C_L^{\hat{\phi}\hat{\phi}} = C_L^{\phi\phi} + N_L^{0,\mathrm{MAP}} + N_L^{1,\mathrm{MAP}} + \dots$$

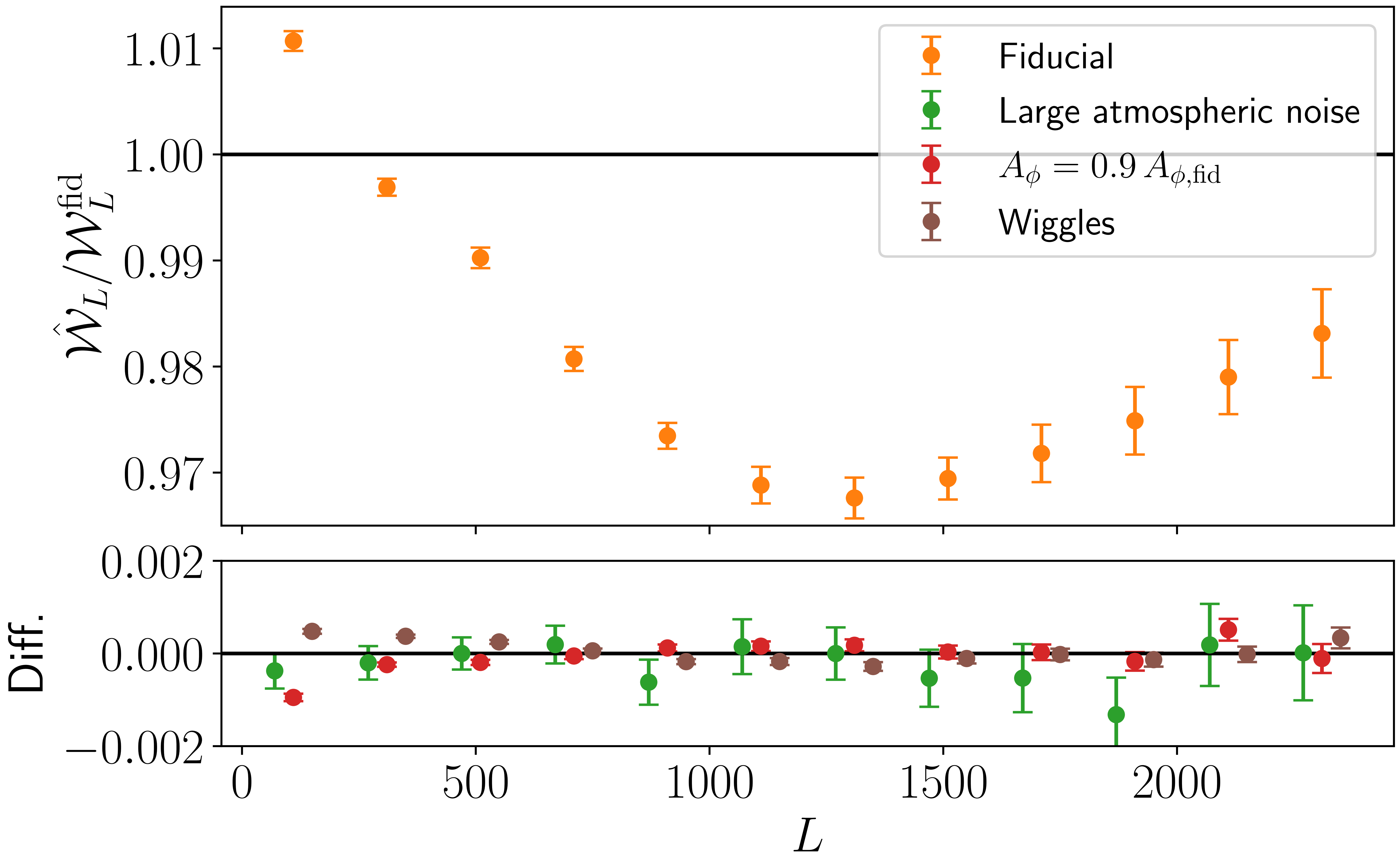
NORMALISATION

$$\hat{\phi}(\boldsymbol{L}) = \frac{1}{R_L^{XY}} \int \frac{d^2\boldsymbol{l}}{2\pi} f^{XY}(\boldsymbol{l}, \boldsymbol{L})\, \bar{X}(\boldsymbol{l})\, \bar{Y}^*(\boldsymbol{l} - \boldsymbol{L})$$

- For the MAP we assumed it is a Wiener filter

$$W_L = \frac{C_L^{\phi\phi}}{C_L^{\phi\phi} + N_L^0}$$

- Correct small bias with simulations

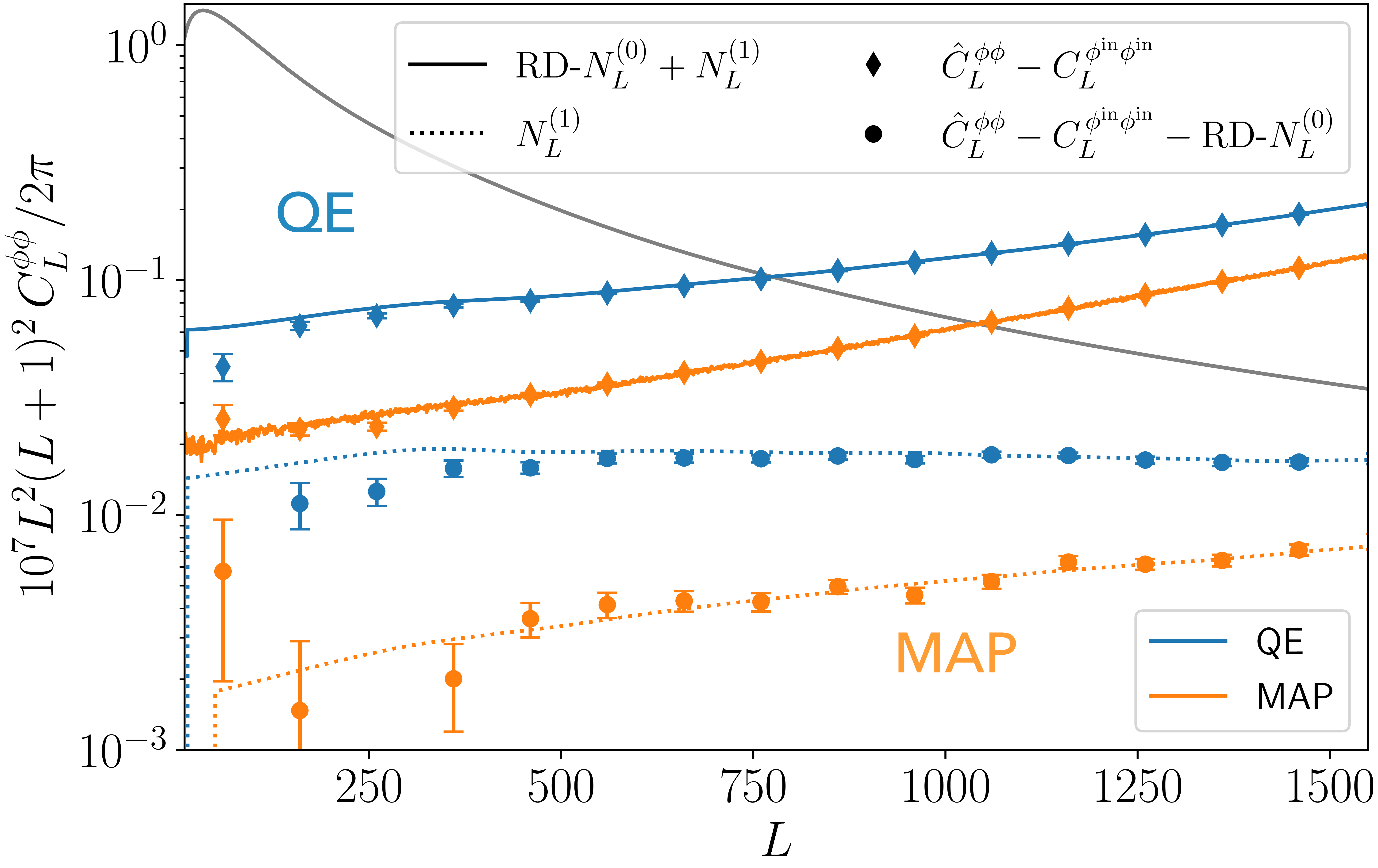


LL & Carron 2021

ITERATIVE BIASES

$$C_L^{\hat{\phi}\hat{\phi}} = C_L^{\phi\phi} + N_L^0 + N_L^1$$

- Assume N0 and N1 biases are same expression of the QE but with partially delensed CMB spectra
- We obtain them by iterateratively estimating the fiducial delensed CMB spectra and residual lensing power spectrum



LL & Carron 2021

REALISATION DEPENDENT DEBIASING

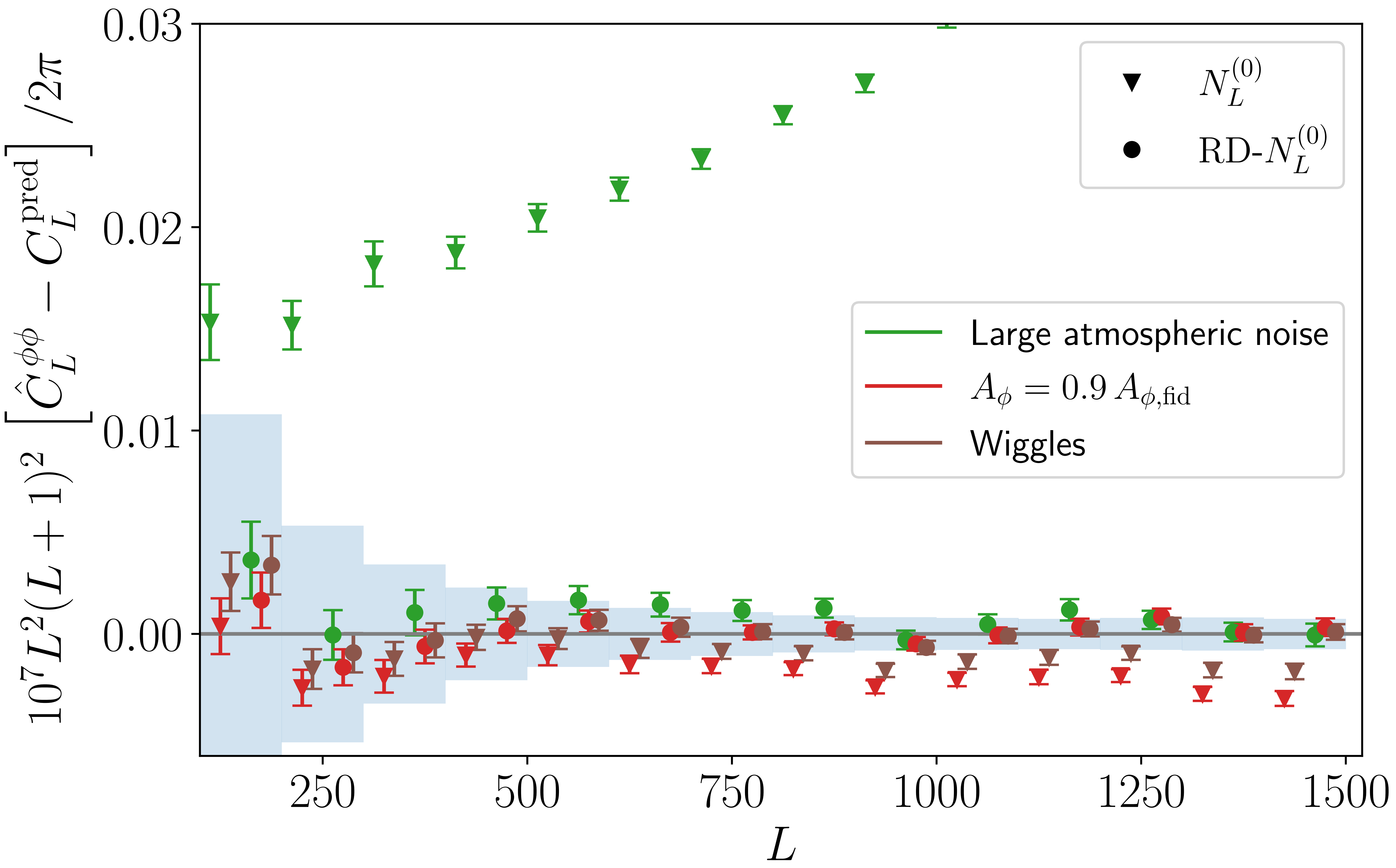
- Because N0 bias dominates the signal, it needs to be evaluated very accurately
- Very sensitive to the assumptions made on the spectra and noise of the CMB for the reconstruction
- Obtain a realisation dependant debaser with a smart combinations of the data maps with simulations in the fiducial settings:

$$\text{RD-}N_L^{(0)} \equiv \left\langle 4\hat{C}_L^{di} - 2\hat{C}_L^{ij} \right\rangle_{N_{\text{bias}}} ,$$

- This RDN0 is **insensitive at first order to mismatch** in the fiducial spectra

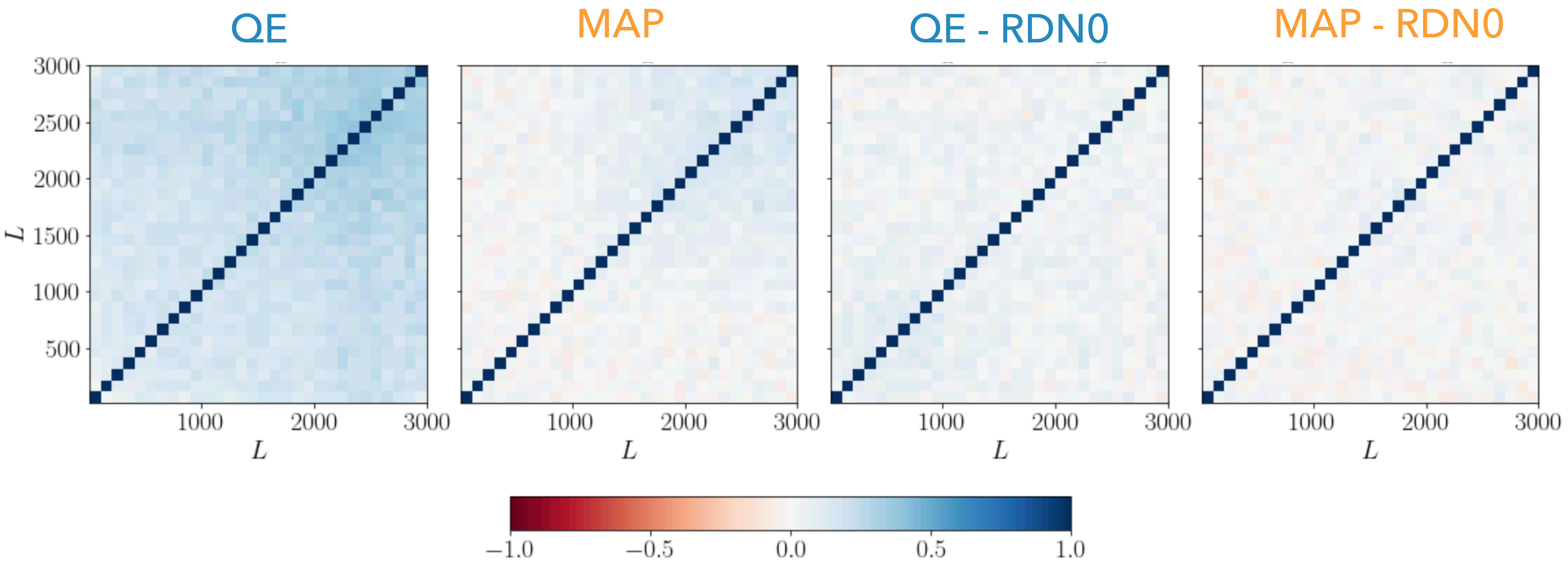
RDN0 FOR THE MAP

- Same as the QE, but simulations have the MAP lensing potential instead of being random



LL & Carron 2021

CORRELATION MATRICES

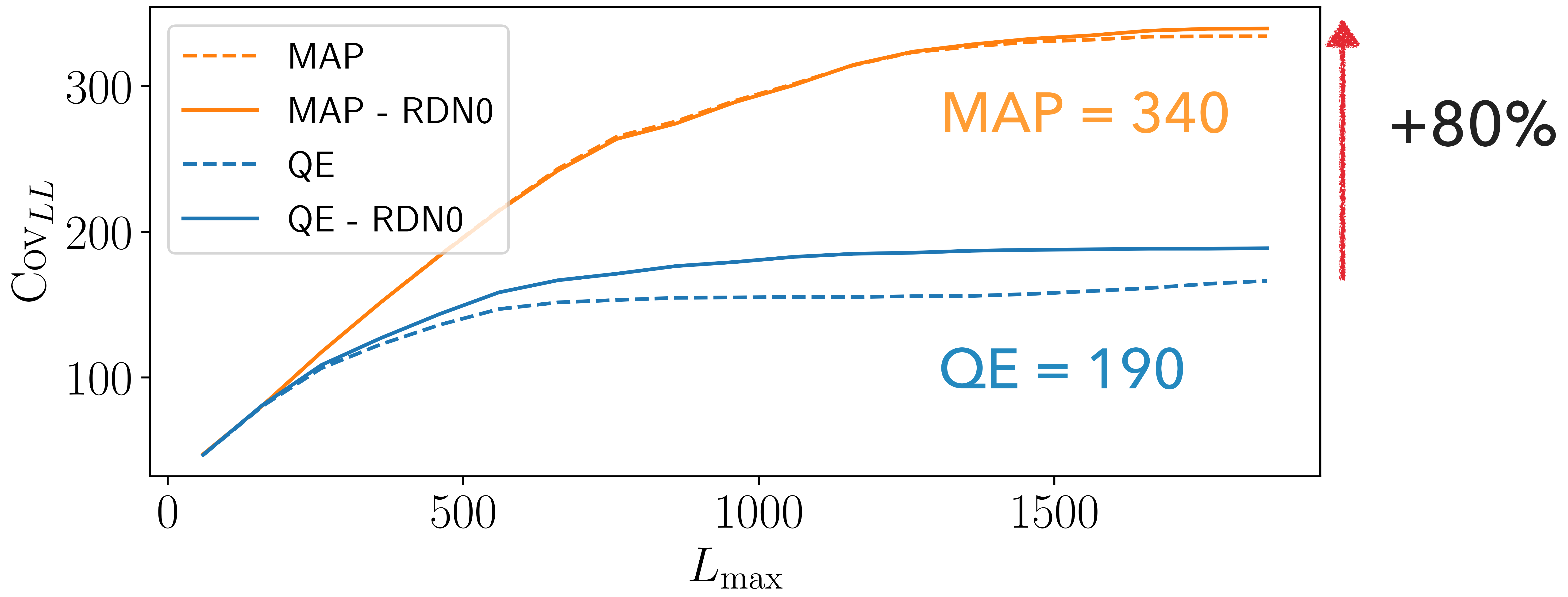


- 1024 flat sky CMB-S4 like simulations
- Covariance matrices normalised by the diagonal

LL & Carron 2021

SIGNAL TO NOISE RATIO

$$\mathrm{SNR}(L_{\max}) = \sqrt{\sum_{L_{\min}}^{L_{\max}} C_L^{\phi\phi,\mathrm{fid}} \mathrm{Cov}_{LL'}^{-1} C_L^{\phi\phi,\mathrm{fid}}} .$$



- Signal to noise ratio of the lensing power spectrum as a function of the maximum scale used in the analysis
- Information gain saturates above 1000 for QE and 1500 for MAP

LL & Carron 2021

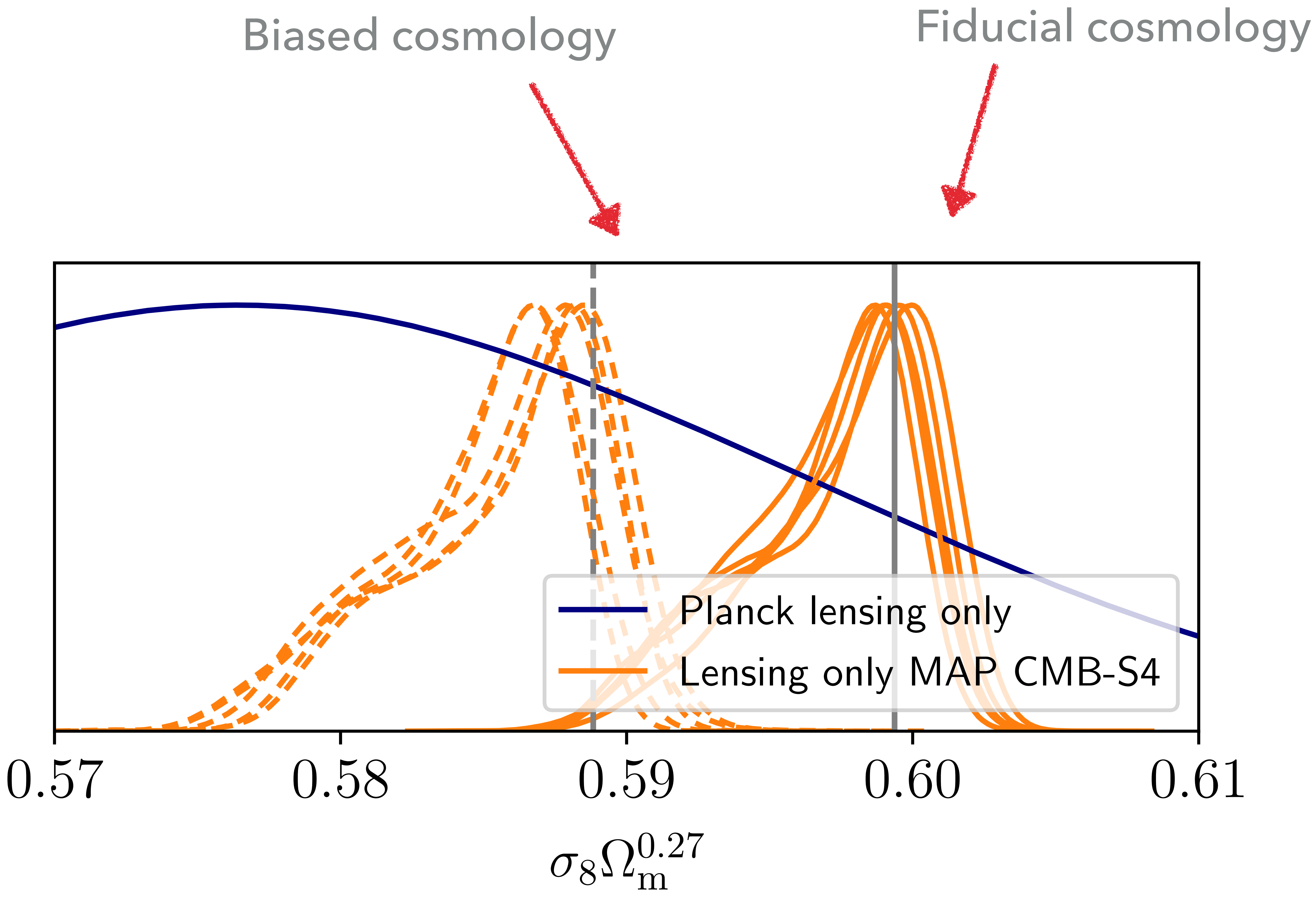
LIKELIHOOD ANALYSIS

$$\ln L(\theta\,|\,\hat{\phi}) = -\frac{1}{2}\left(C_L^{\hat{\phi}\hat{\phi}} - RD\text{-}N_L^0 - C^{\phi\phi}(\theta) - N_L^1(\theta)\right)^T \mathbf{Cov}^{-1}\left(C_L^{\hat{\phi}\hat{\phi}} - RD\text{-}N_L^0 - C^{\phi\phi}(\theta) - N_L^1(\theta)\right)$$

- Estimate most likely cosmology by sampling the parameter space with a MCMC
- Do not re-estimate the lensing potential for each step of the sampling
- Introduce a possible bias (mismatch between the fiducial and the true cosmology)
- We correct this bias at first order
  - on the normalisation of the lensing potential
  - on the N1 bias

LENSING LIKELIHOOD

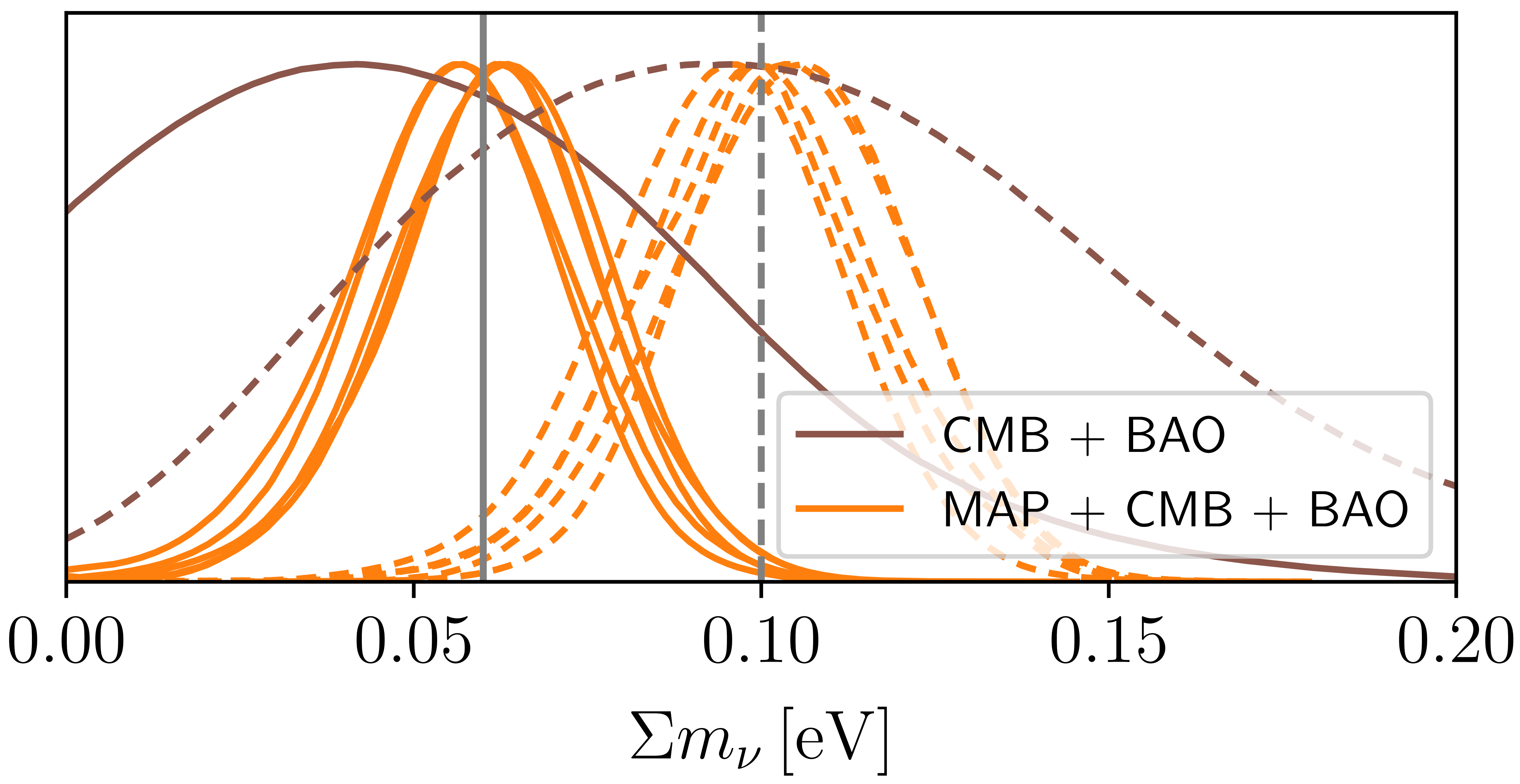
- Two datasets:
  - One in the fiducial cosmology used for the reconstruction
  - and a cosmology with less matter and more massive neutrinos
- Sampling 6 LCDM parameters
- We found unbiased estimates of the $\sigma_8 - \Omega_m$ combined parameter.



LL & Carron 2021

NEUTRINO MASS ESTIMATES

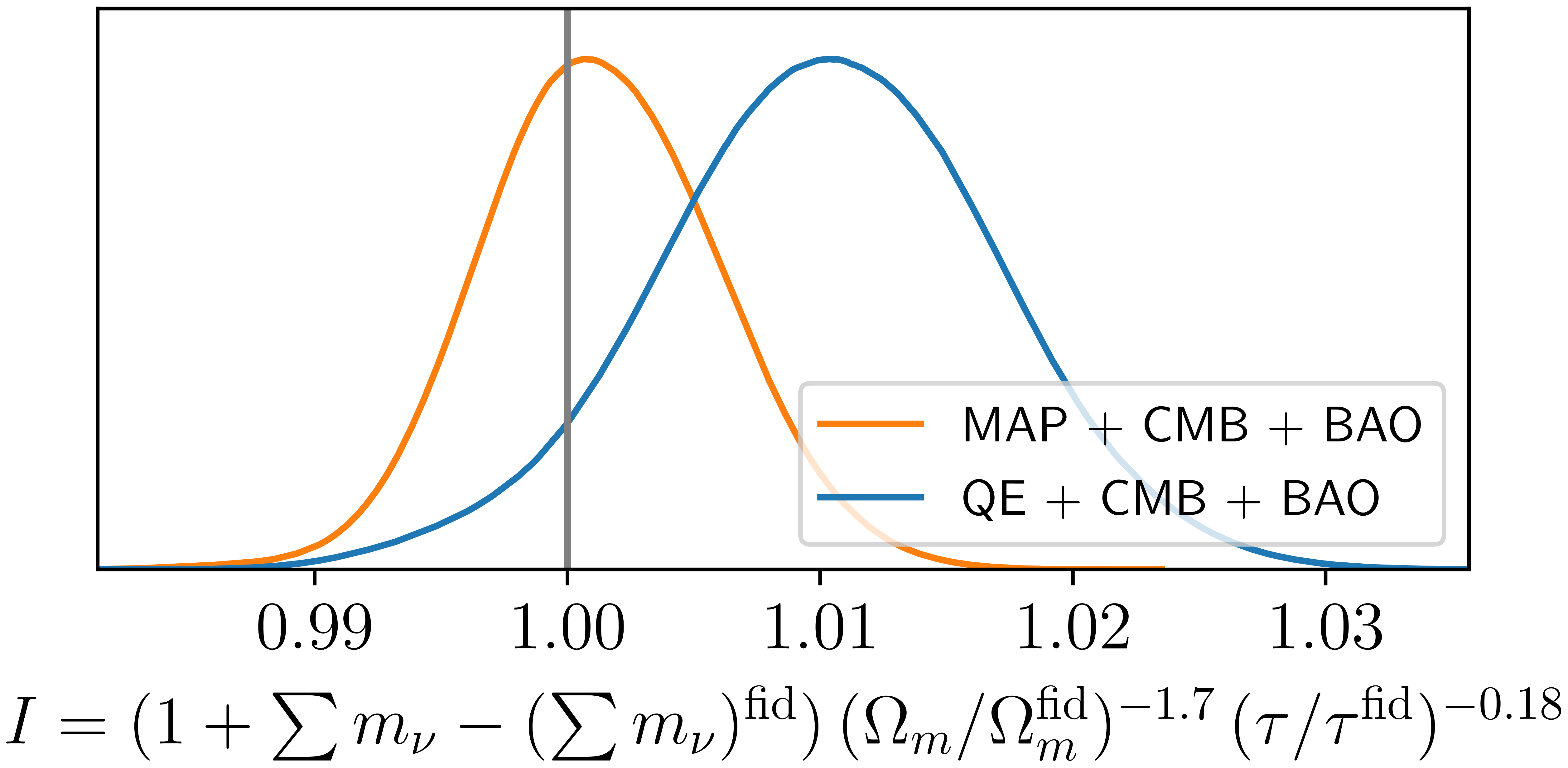
- Combining MAP likelihood with:
  - Unlensed CMB-S4 likelihood
  - DESI BAO likelihood
- Varying 6 LCDM parameters + Sum of the neutrino mass
- Fiducial $\sum m_\nu = 0.06$ eV
- Strong prior on tau: $\sigma(\tau) = 0.002$ (LiteBIRD constraints)
- CMB-S4 will allow for a 4σ detection of massive neutrinos



LL & Carron 2021

COMPARING MAP TO QE CONSTRAINTS

- Combining MAP with CMB and BAO, we get $\sigma_{M_\nu} = 0.016$
- No improvement compared to the QE spectrum
- Due to remaining degeneracies between parameters
- We perform a PCA on $\sum m_\nu, \Omega_\mathrm{m}, \tau$ combination
- Improvement of 40%



LL & Carron 2021

CONCLUSION

- Iterative methods will reconstruct optimally the lensing potential for next generation CMB surveys
- We introduced a **simple and robust** end-to-end pipeline to get an **optimal estimation of the lensing spectrum**
- Increases the signal to noise ratio of the lensing amplitude by 80%
- Robust to uncertainties in fiducial cosmology and observational noise
- Will get constraints on cosmological parameters of interest, such as the sum of neutrino mass