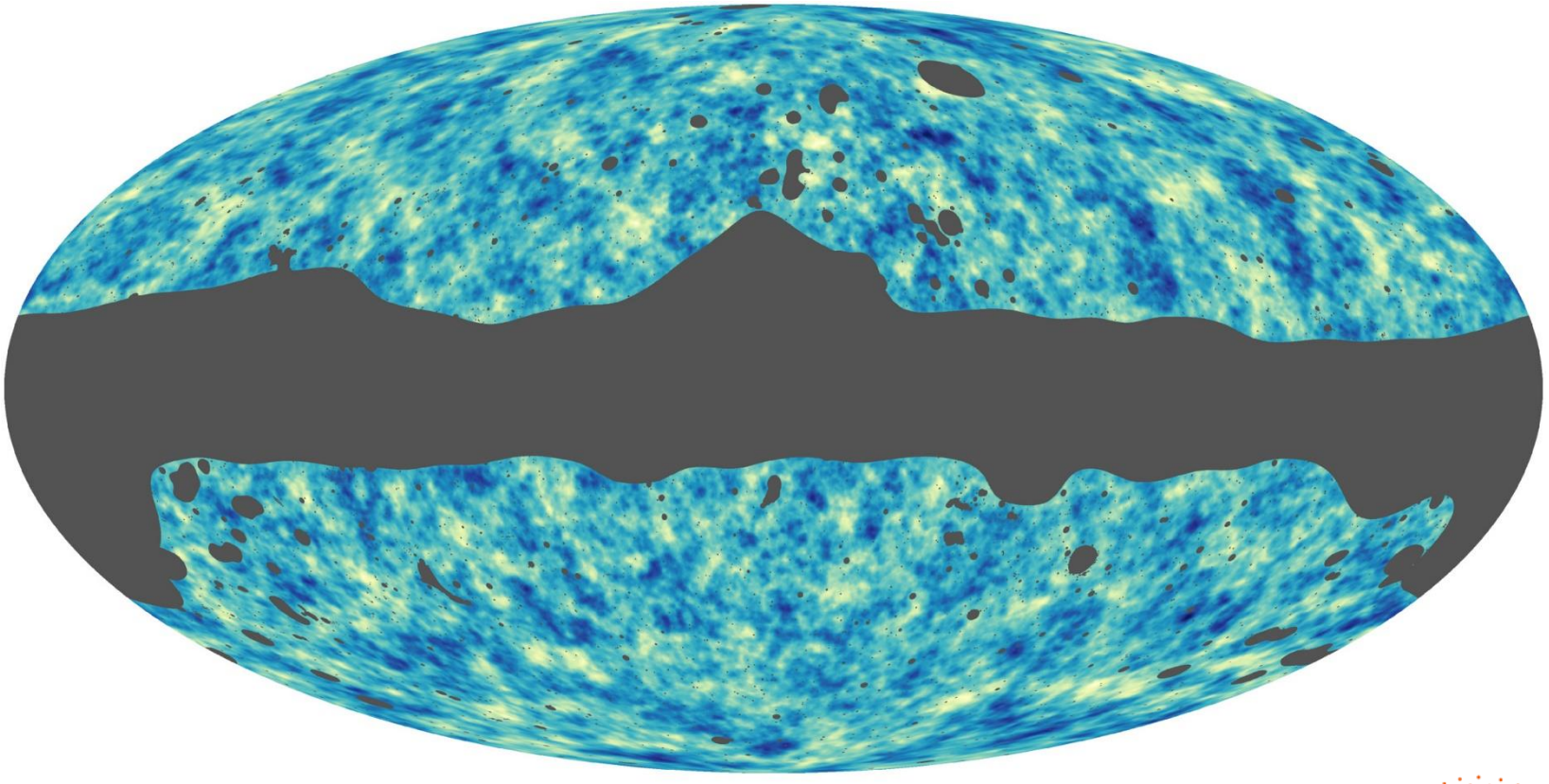
CMB lensing, delensing and correlations



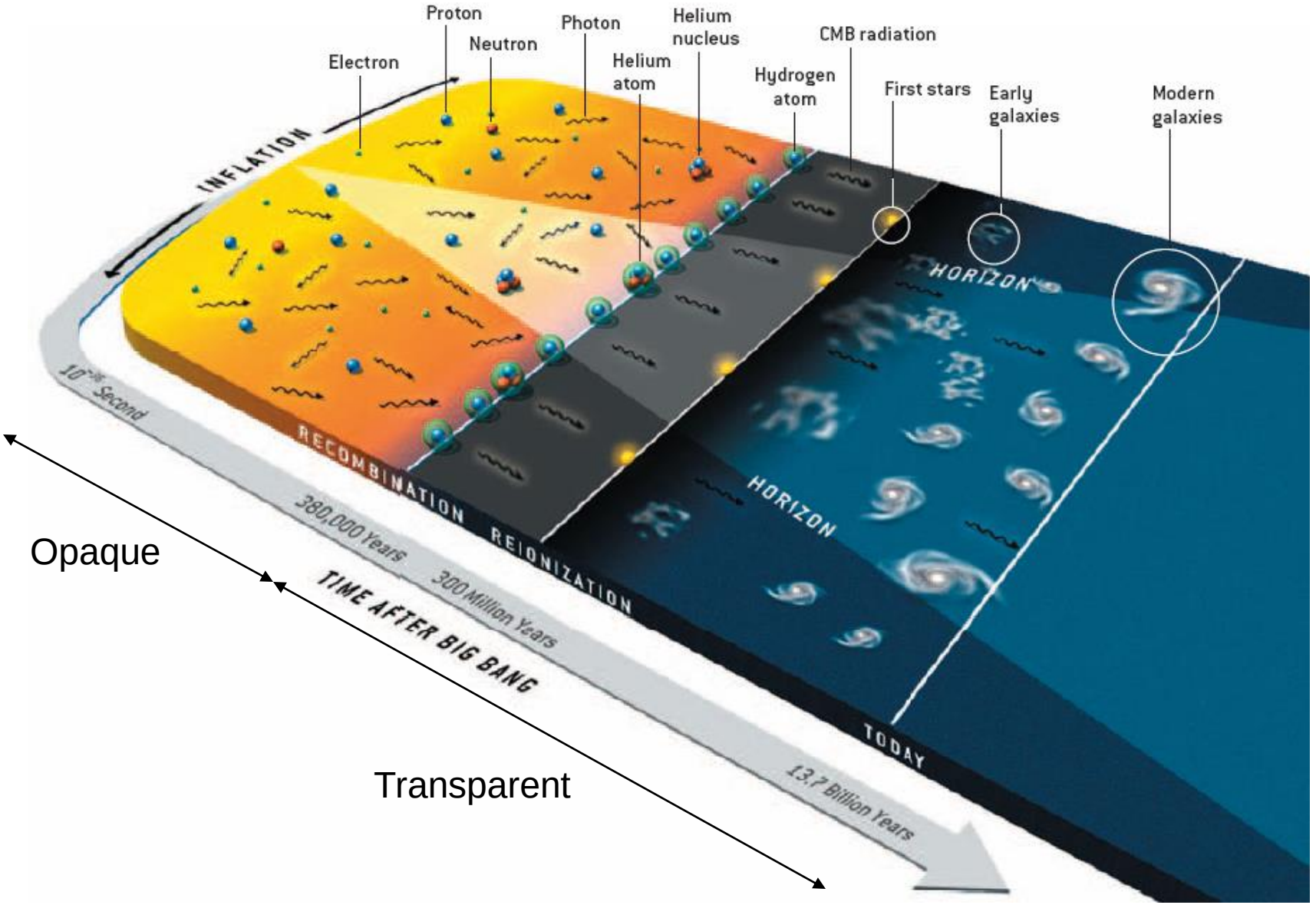
Antony Lewis
http://cosmologist.info/

UNIVERSITY OF SUSSEX

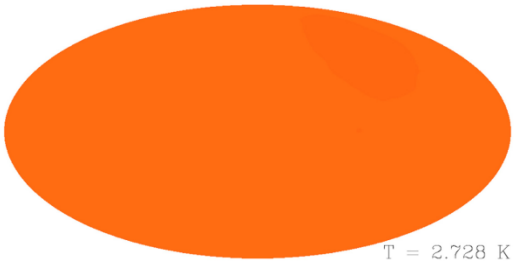
European Research Council
Established by the European Commission

Science & Technology Facilities Council

Evolution of the universe

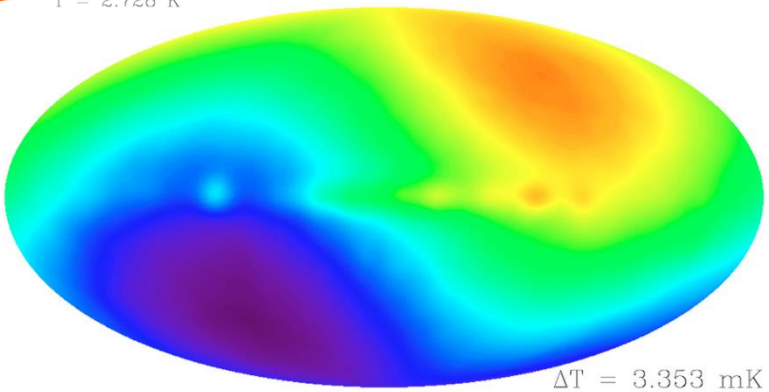


Hu & White, Sci. Am., 290 44 (2004)



(almost) uniform 2.726K blackbody

T = 2.728 K

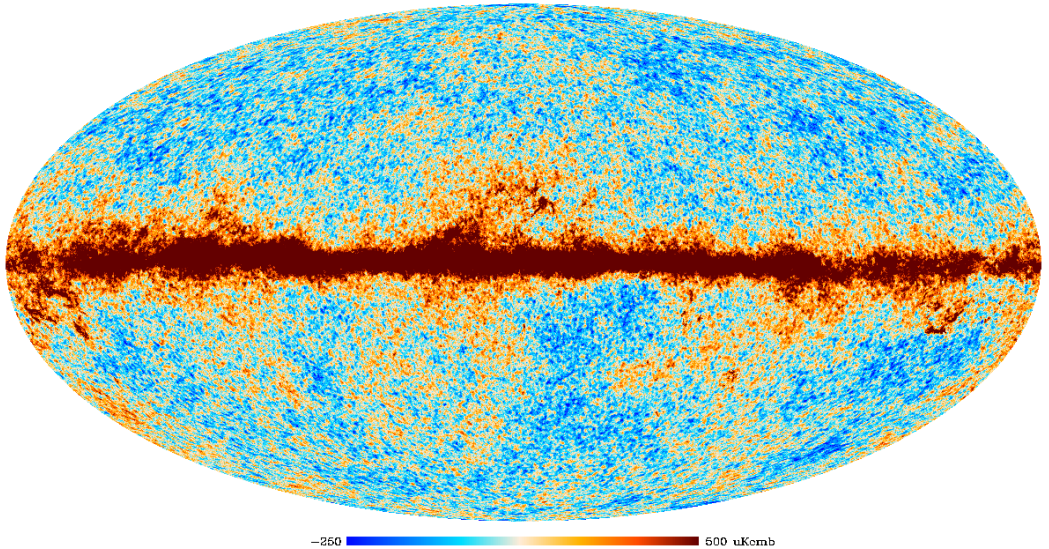


ΔT = 3.353 mK

Dipole (local motion)

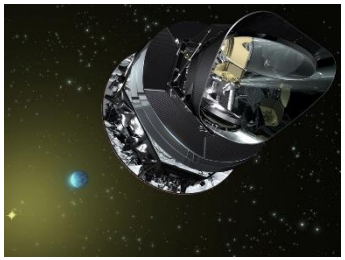
O(10^{-5}) perturbations (+galaxy)

Nominal mission 143GHz



−250 500 uKcmb

Observations:
the microwave sky today

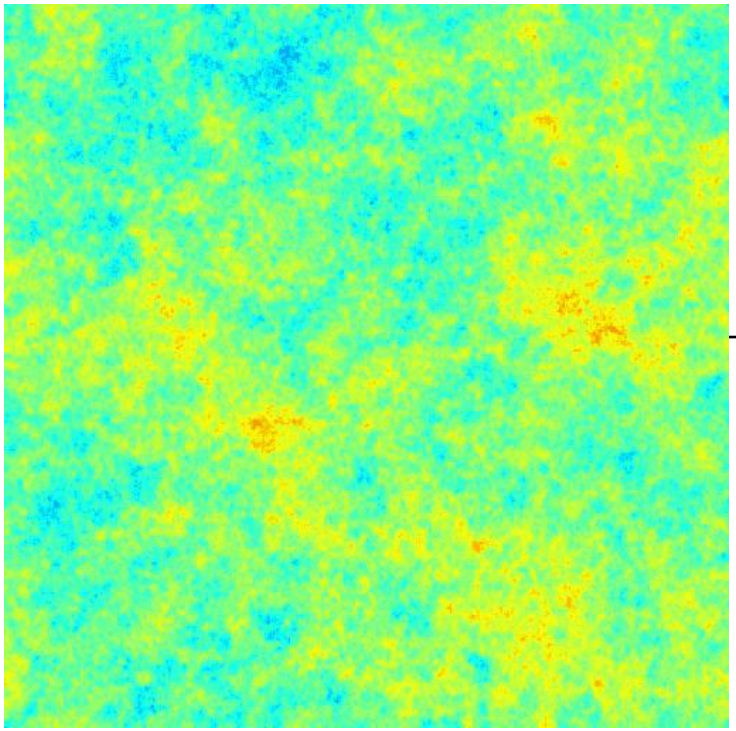


Planck Satellite

0^{th} order (uniform 2.726K) + 1^{st} order perturbations (anisotropies)

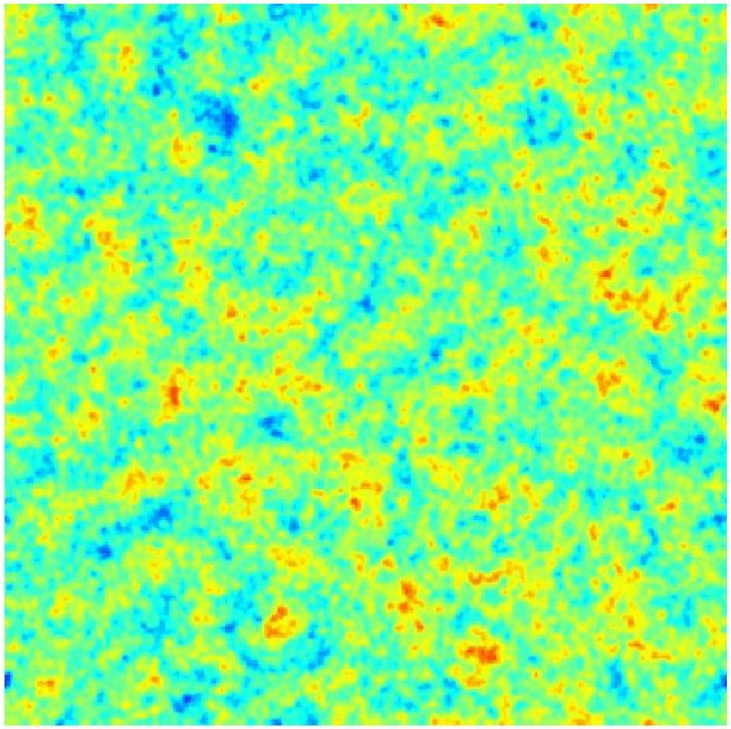
Perturbation evolution

Perturbations: End of inflation

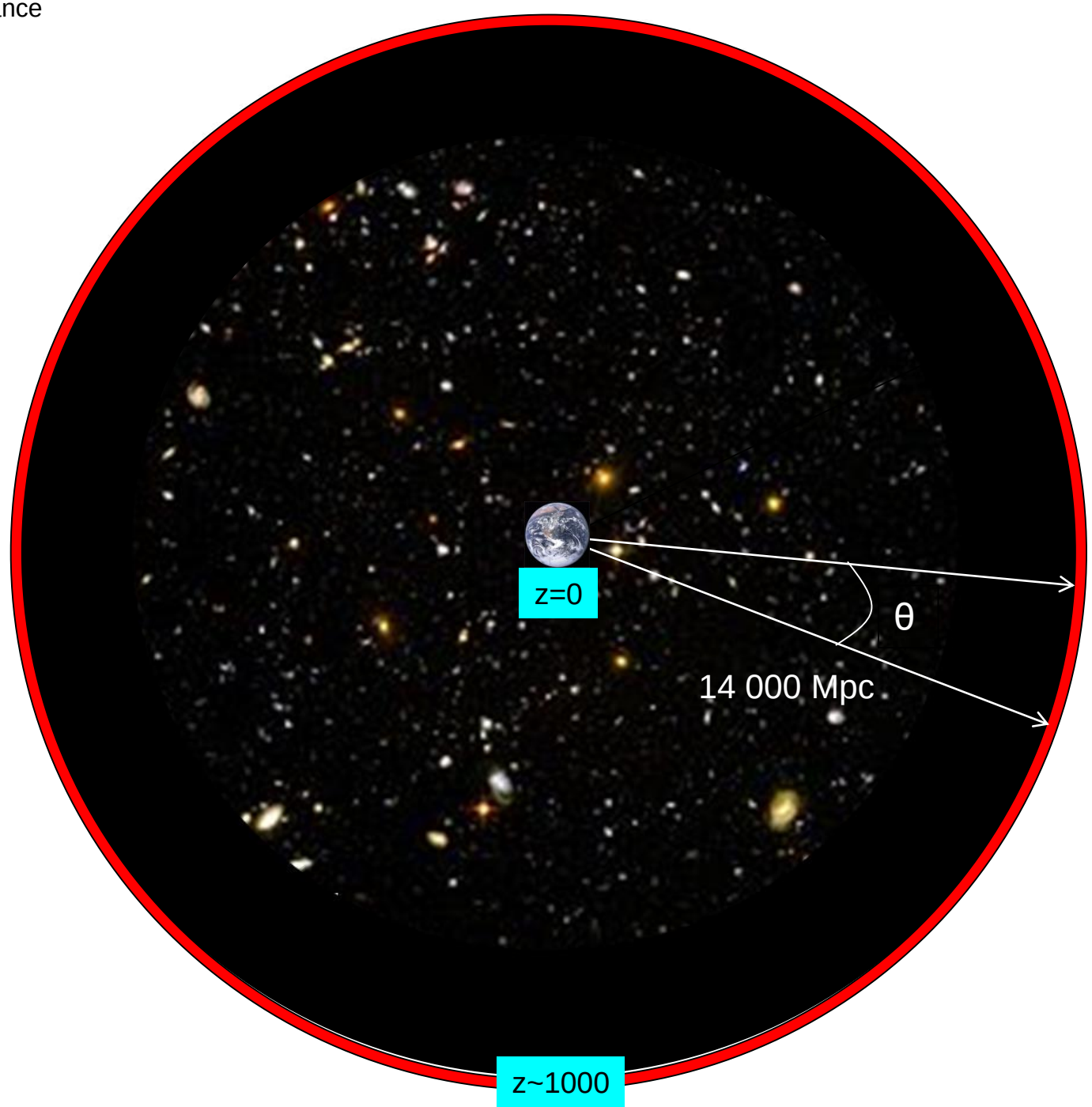


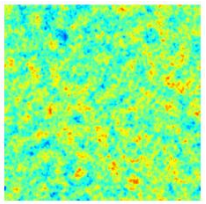
gravity+
pressure+
diffusion

Perturbations: Last scattering surface

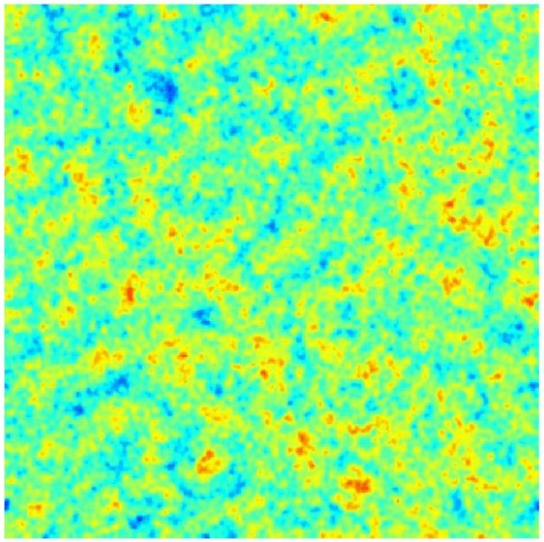


In comoving distance

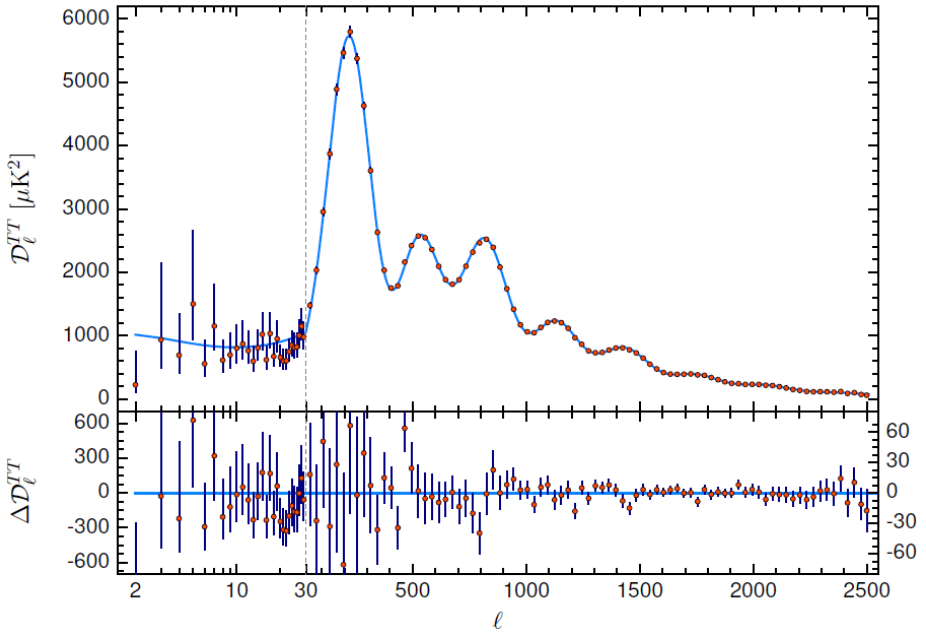




Observed CMB power spectrum



Planck 2018 arXiv:1807.06209



Observations

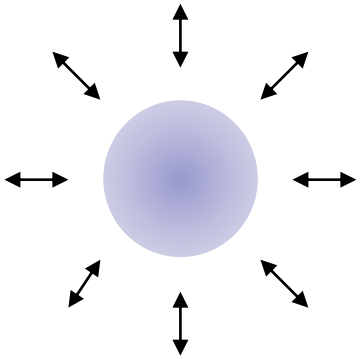
Constrain theory of early universe
+ evolution parameters and geometry

E and B polarization

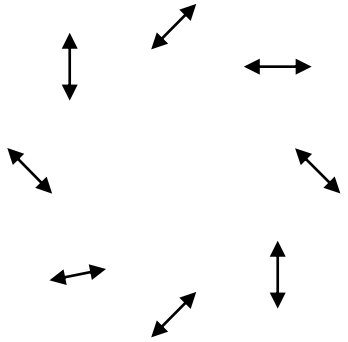
Trace free gradient:
E polarization

Curl:
B polarization

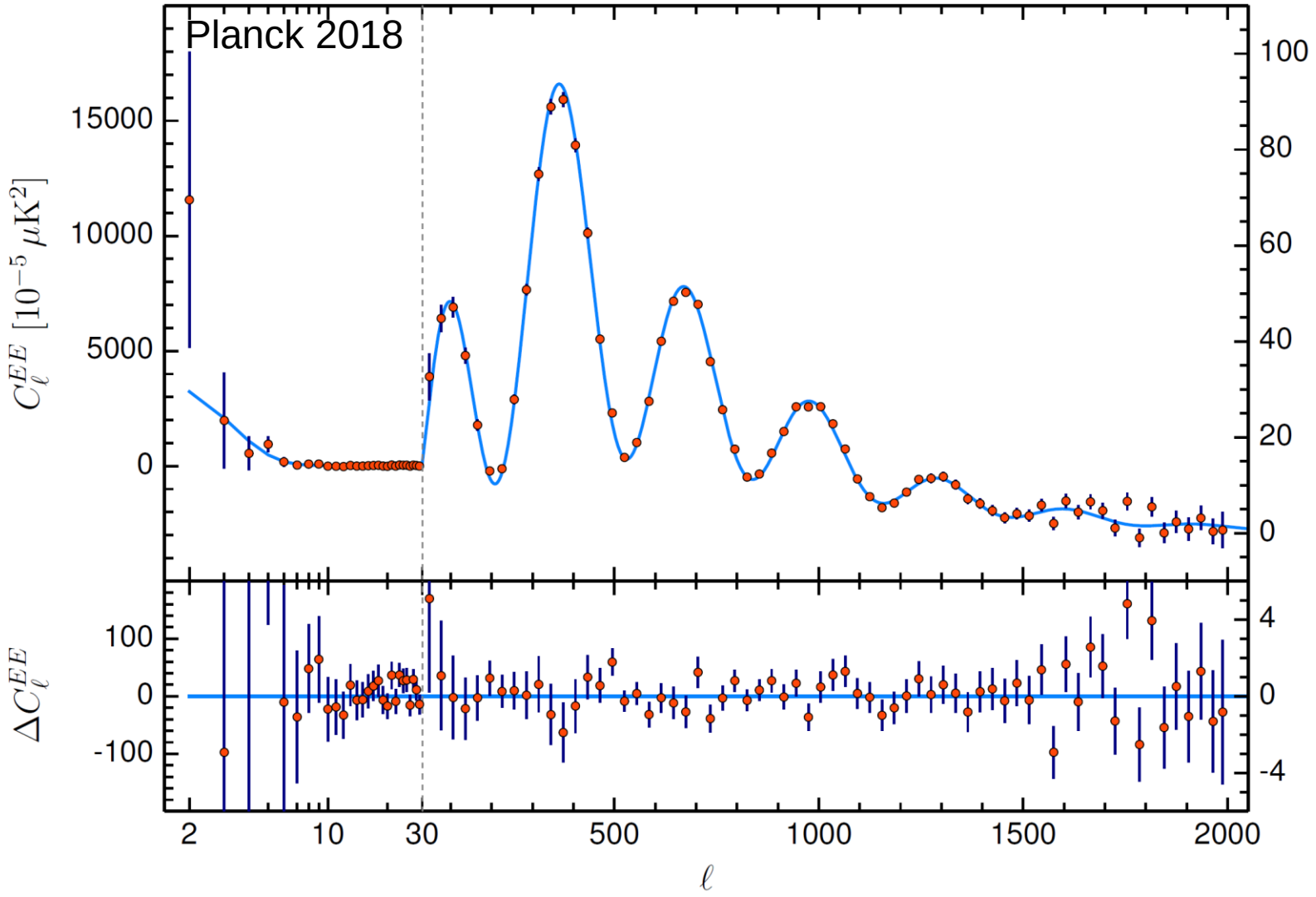
e.g.



e.g. cold spot

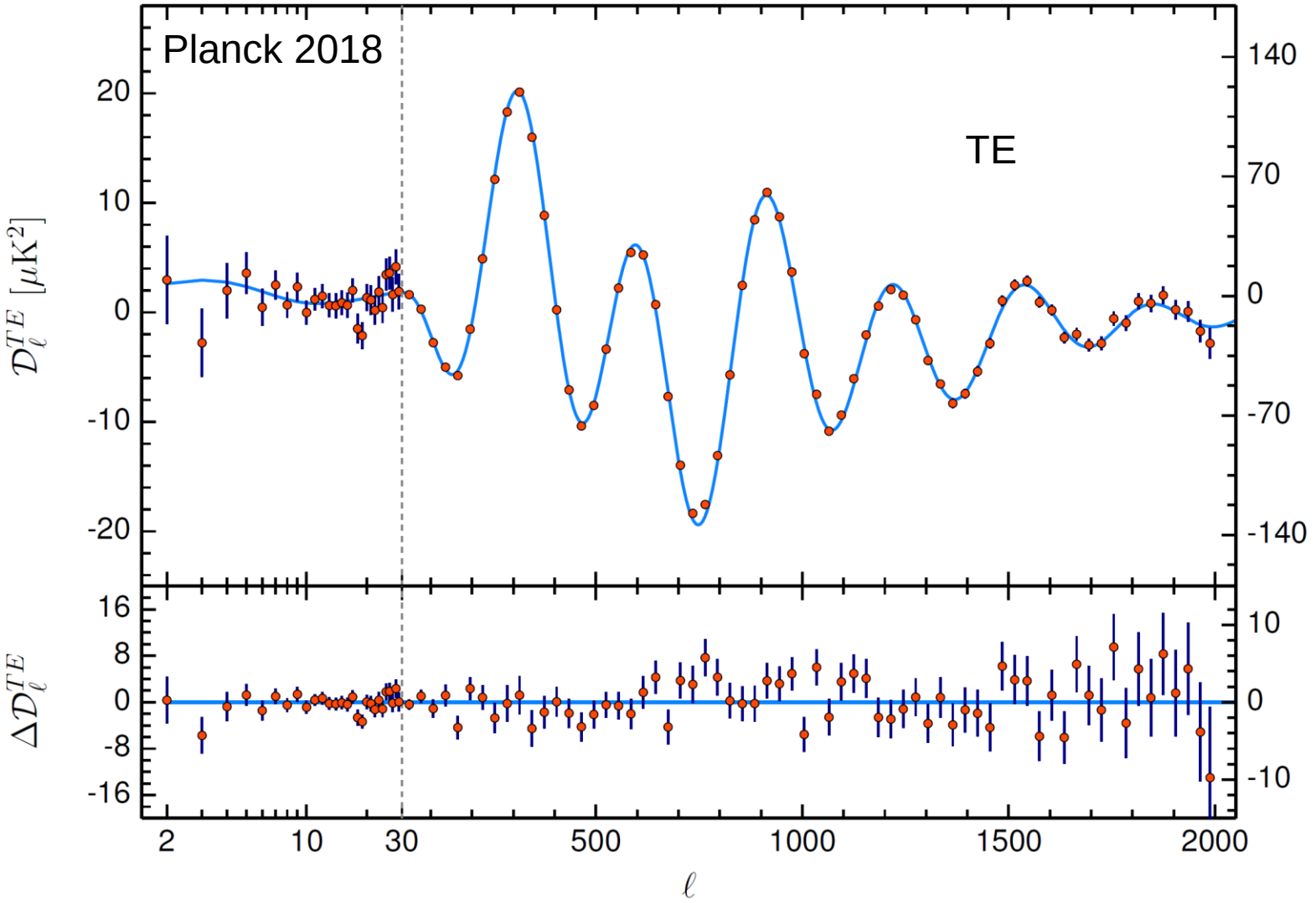


E-mode polarization

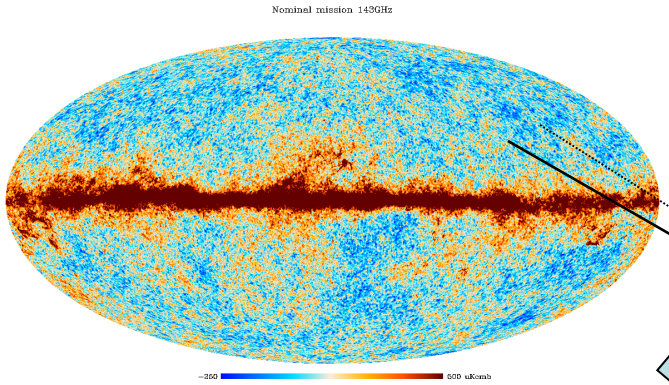


+ ACT/SPT/ACTpol/SPTpol ground-based in progress
Forthcoming ground-based: Simons Observatory, S4

and cross-correlation with temperature

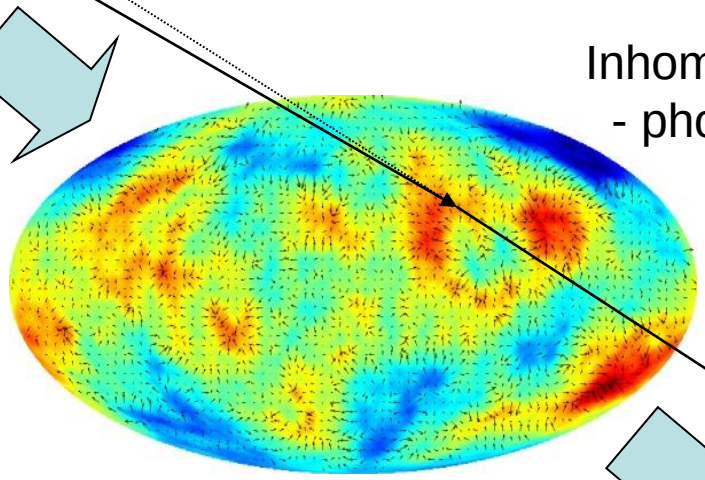


Weak lensing of the CMB perturbations



Last scattering surface

Inhomogeneous universe
- photons deflected



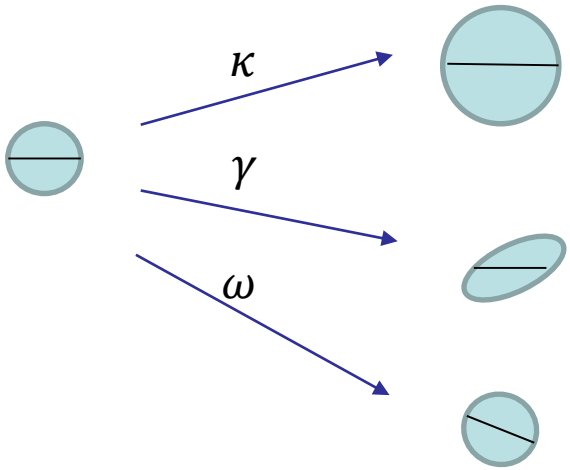
Observer

Lens remapping approximation: deflection angle $\boldsymbol{\alpha}$

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

Deflection related to shear γ_i , convergence κ , and rotation ω

$$A_{ij} \equiv \delta_{ij} + \frac{\partial}{\partial\theta_i}\alpha_j = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2+\omega \\ -\gamma_2-\omega & 1-\kappa+\gamma_1 \end{pmatrix}$$



Convergence

$$\kappa = -\tfrac{1}{2}\nabla\cdot\boldsymbol{\alpha}$$

Shear

Rotation

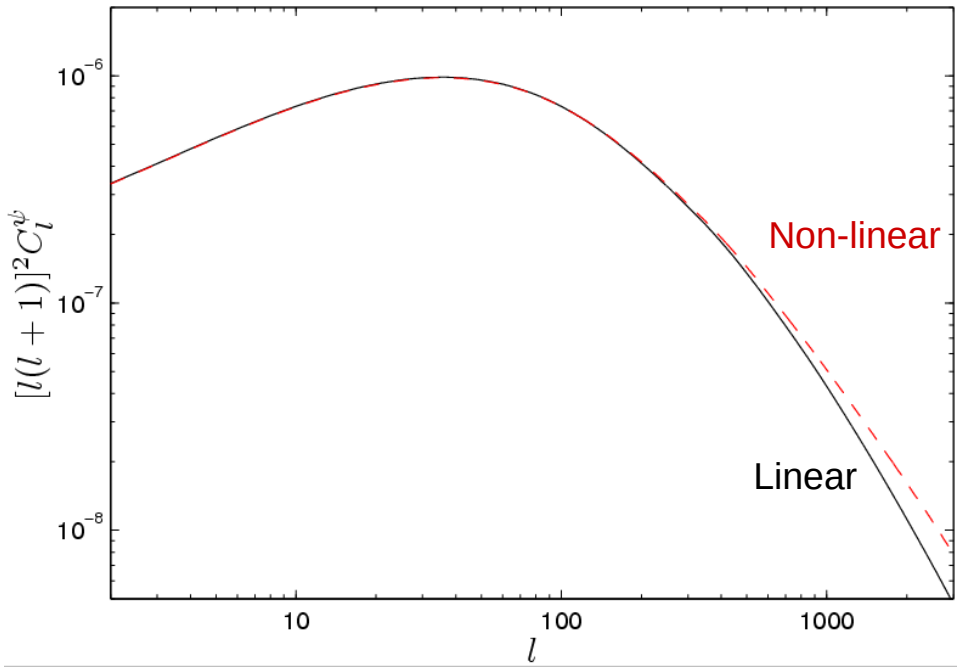
Rotation $\omega = 0$ from scalar perturbations in linear perturbation theory

$$\omega = 0 \Rightarrow \ \alpha = \nabla\psi$$

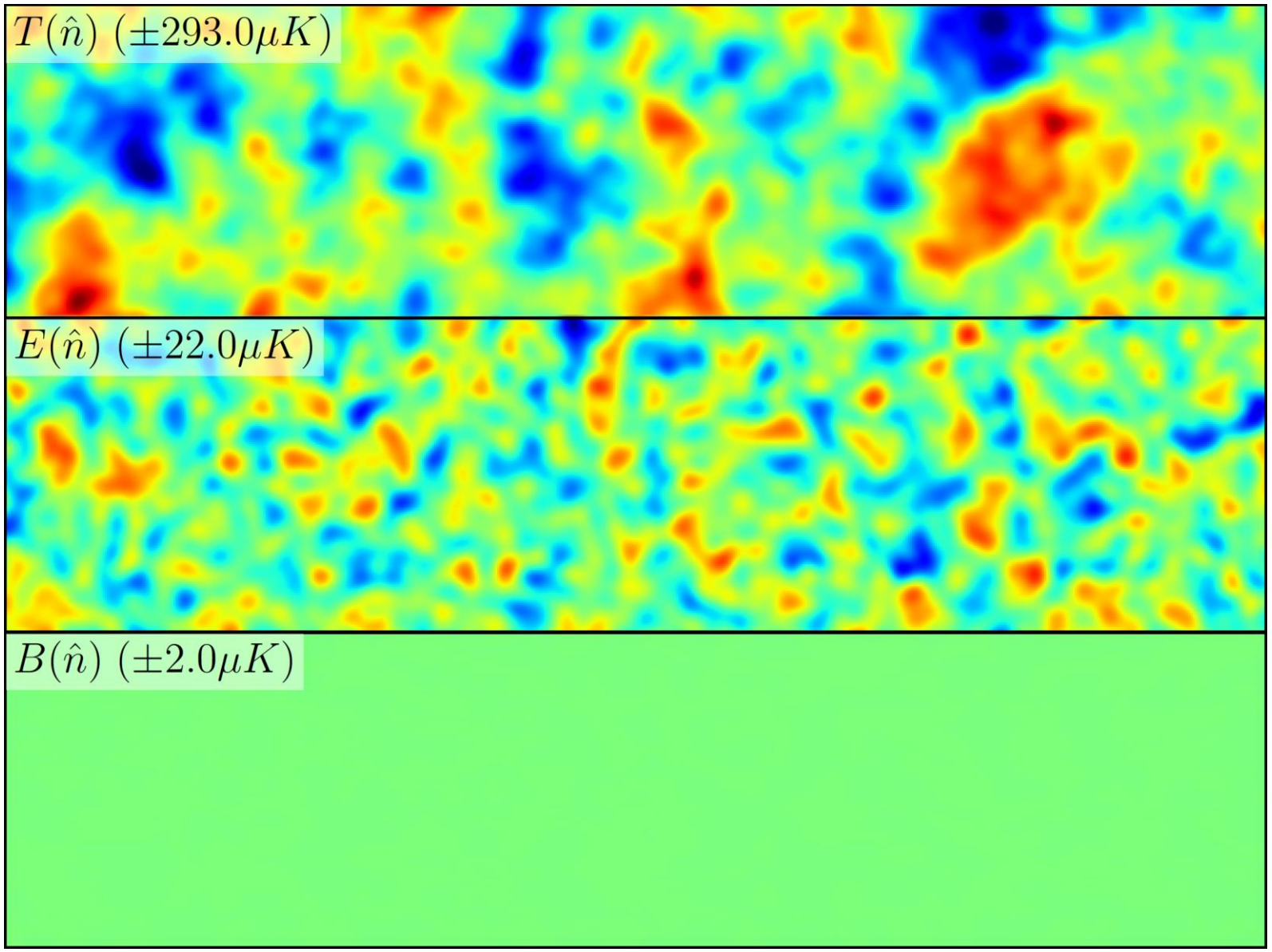
Deflection angle power spectrum

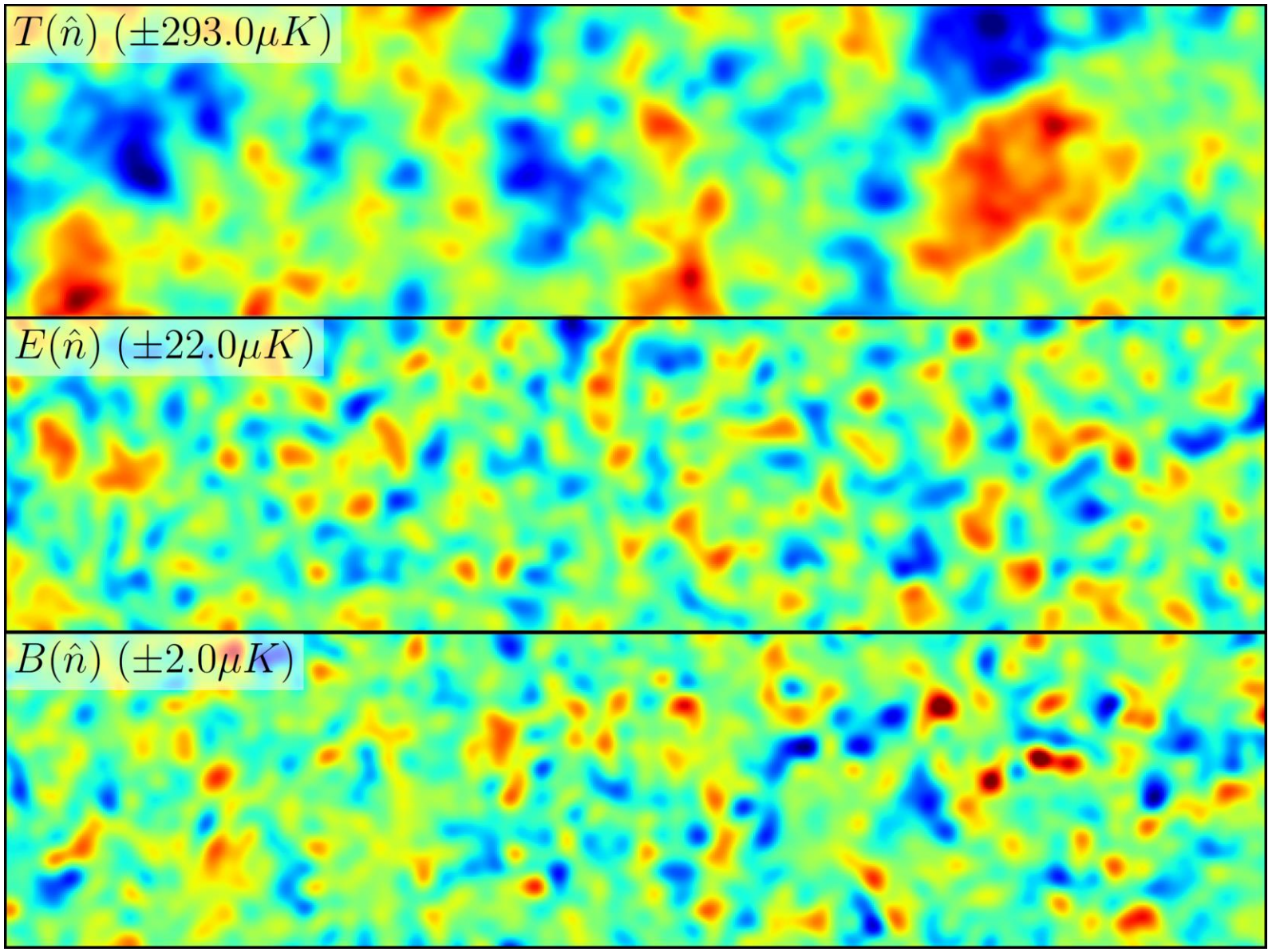
On small scales
(Limber approx. $k\chi \sim l$)

$$C_l^{\psi} \approx \frac{8\pi^2}{l^3} \int_0^{\chi_*} \chi \mathrm{d}\chi \, \mathcal{P}_{\Psi}(l/\chi; \eta_0 - \chi) \left(\frac{\chi_* - \chi}{\chi_* \chi} \right)^2$$



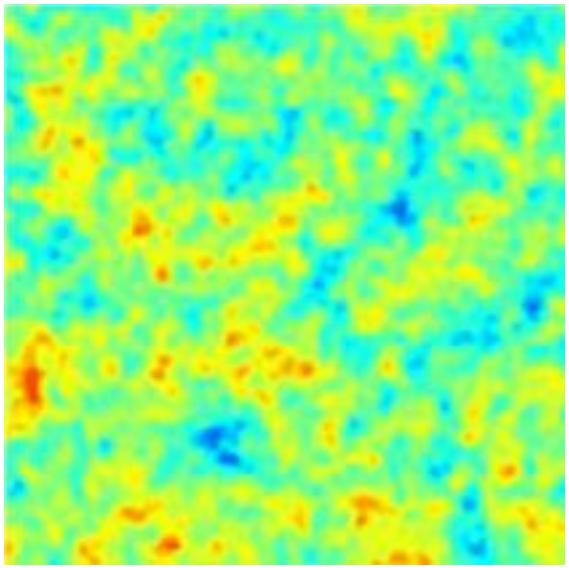
Deflections O(10^{-3}), but coherent on degree scales → important!

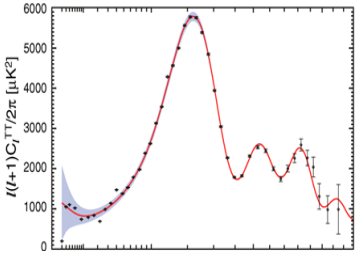

$T(\hat{n})$ $(\pm 293.0 \mu K)$
$E(\hat{n})$ $(\pm 22.0 \mu K)$
$B(\hat{n})$ $(\pm 2.0 \mu K)$


$T(\hat{n})$ $(\pm 293.0 \mu K)$
$E(\hat{n})$ $(\pm 22.0 \mu K)$
$B(\hat{n})$ $(\pm 2.0 \mu K)$

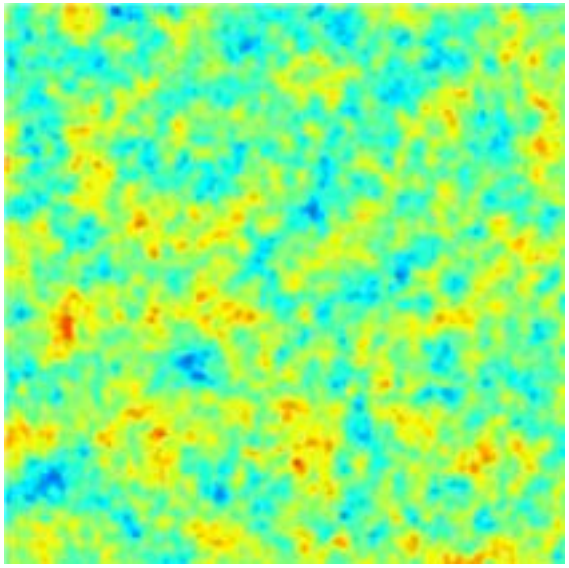
Local effect of lensing on the power spectrum

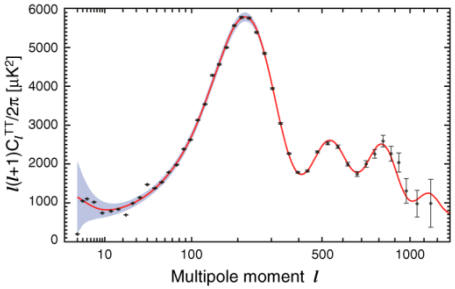
Magnified



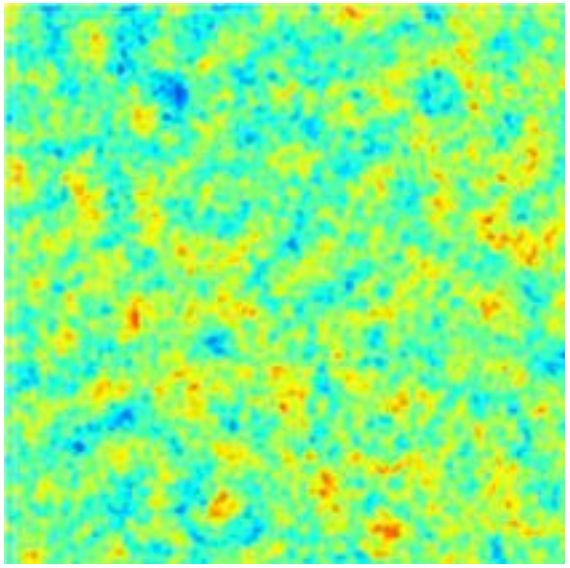


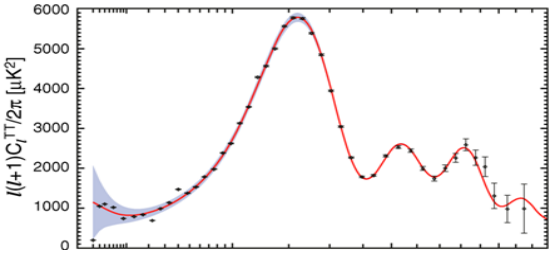
Unlensed



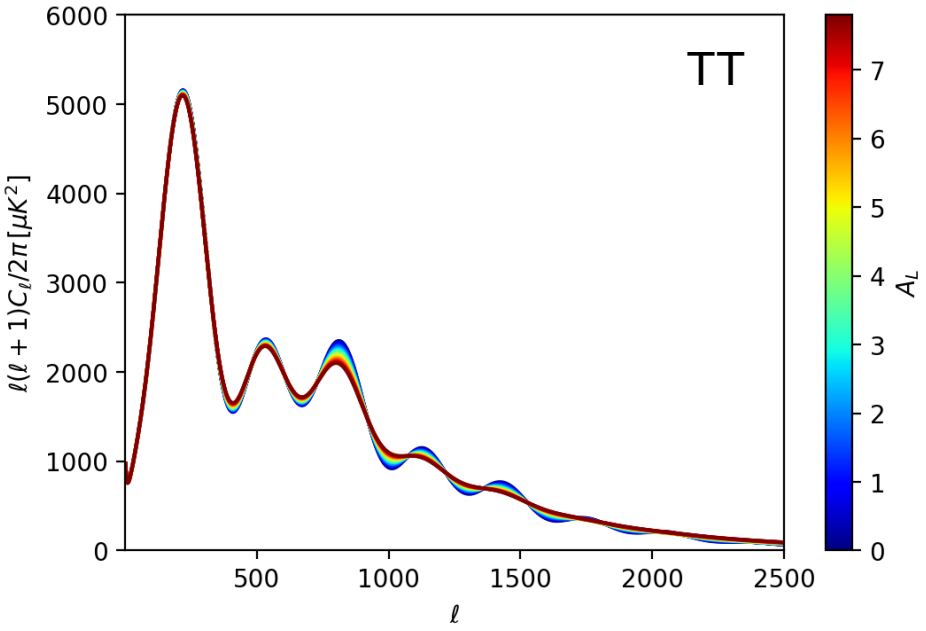


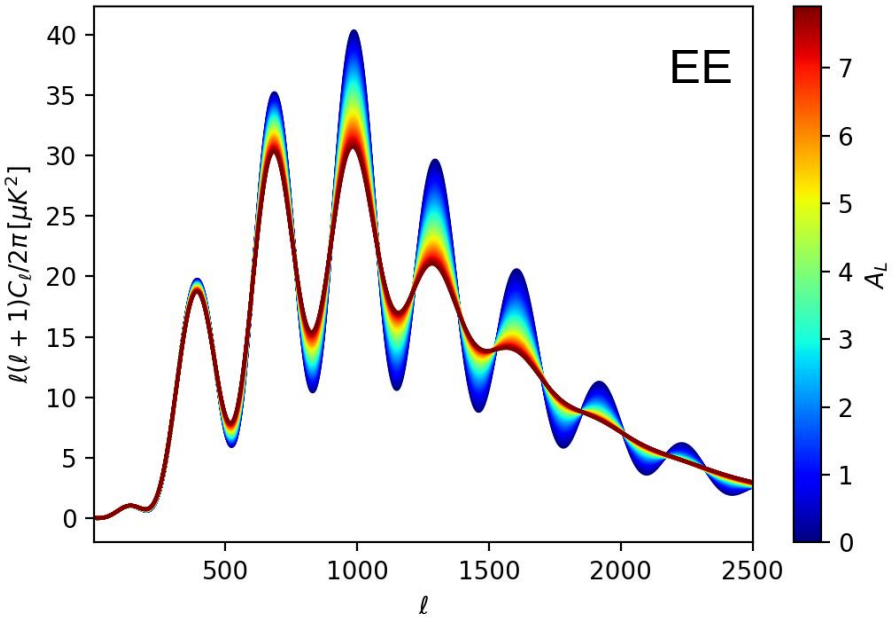
Demagnified





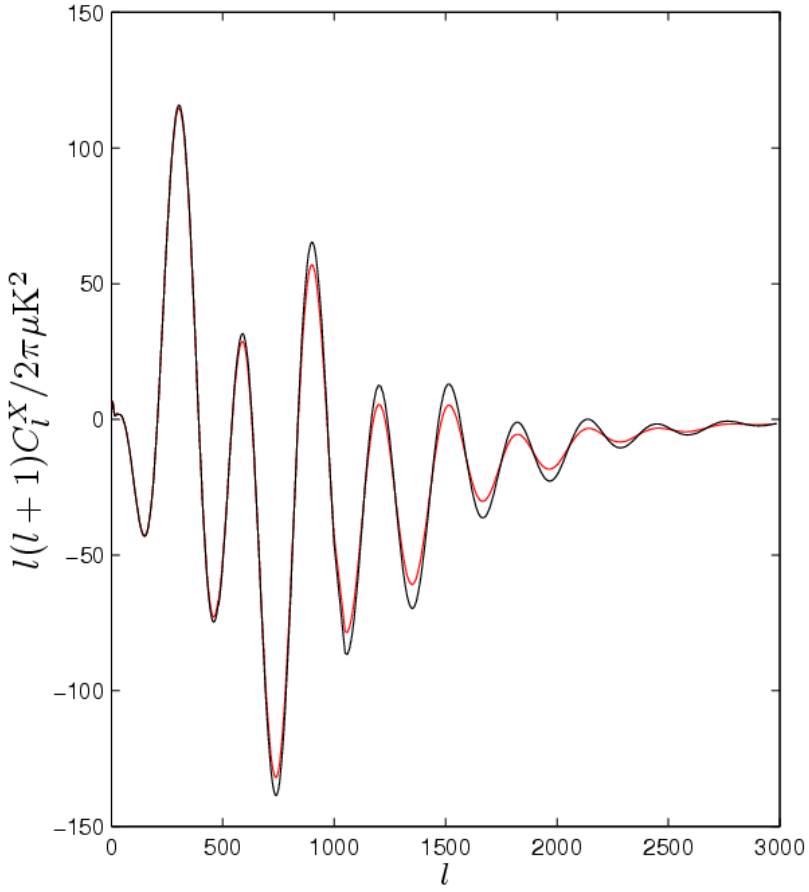
Averaged over the sky, lensing smooths out the power spectrum

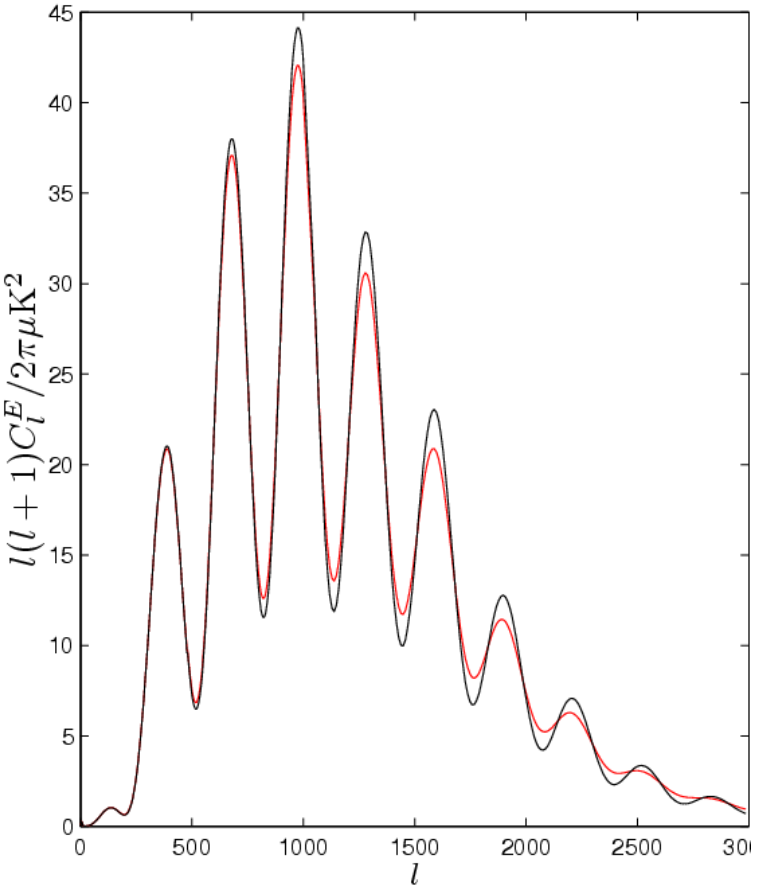




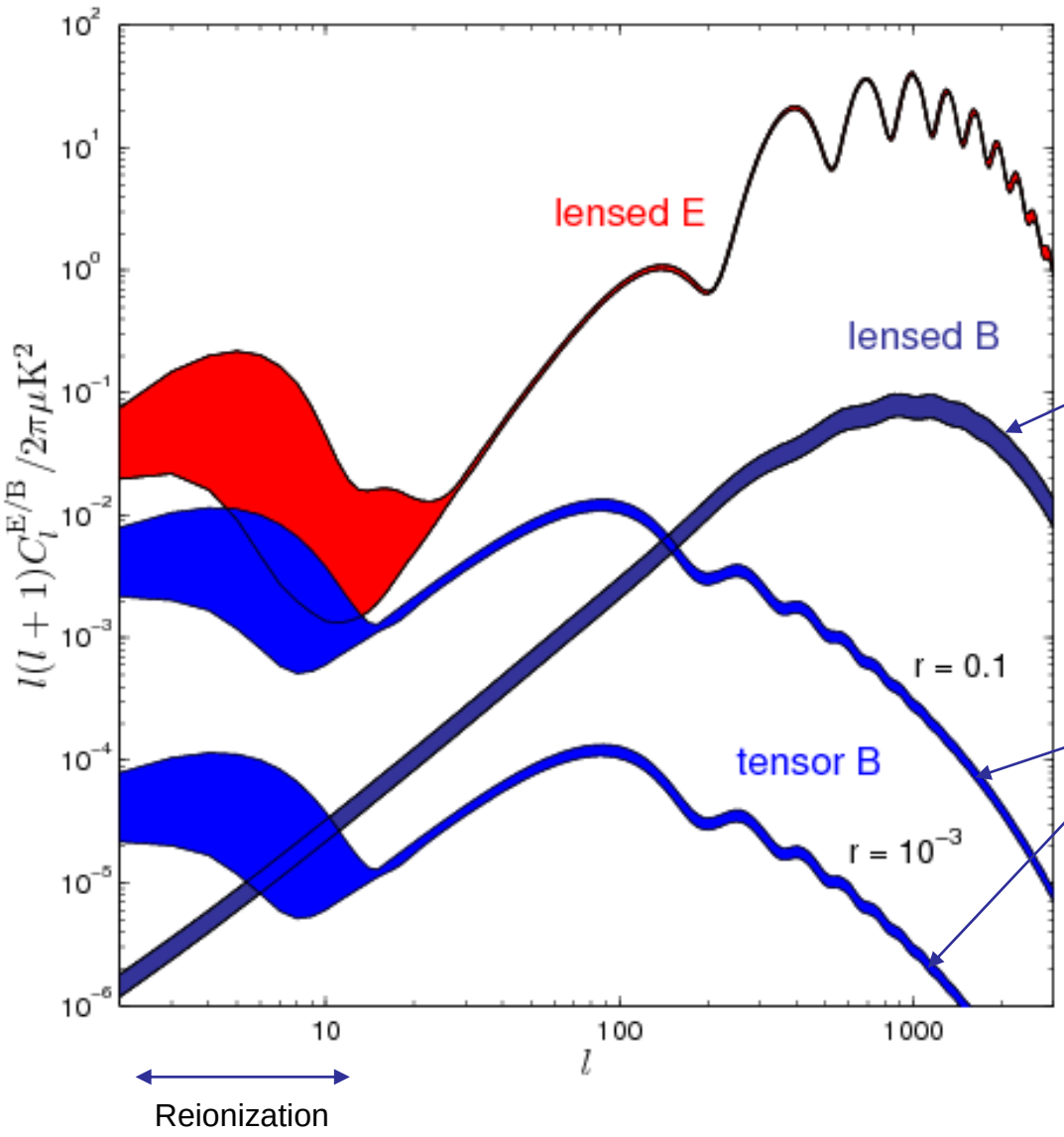
Amount of lensing
($A_L = 1$ is actual level)

Effect on TE and EE polarization spectra





Polarization power spectra



B from lensing of E

Possible primordial gravitational wave signals

Outline

1. How can we reconstruct the lensing?

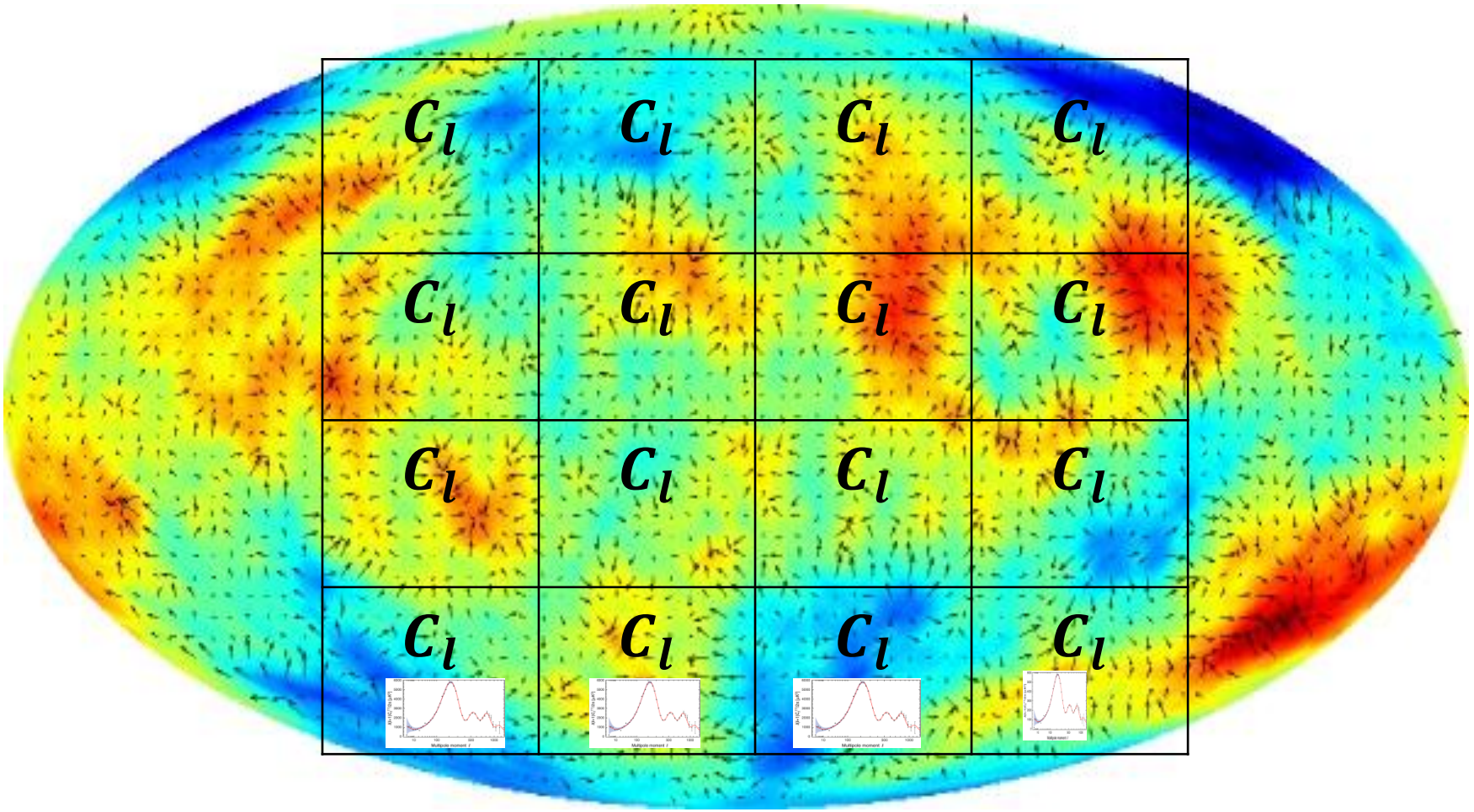
   - gives a powerful cosmological probe
     (z~2 peak; constraints on LCDM, dark energy, massive neutrinos, etc.)

2. Can we then delens?

   - unsmooth the power spectra, clean the lensing B modes

3. What does the future hold?

Lensing reconstruction (concept)



Measure spatial variations in magnification and shear

Use assumed unlensed spectrum, and unlensed statistical isotropy

Lensing Reconstruction – Quadratic Estimators

- Fixed lenses introduce statistically-anisotropic correlations:

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

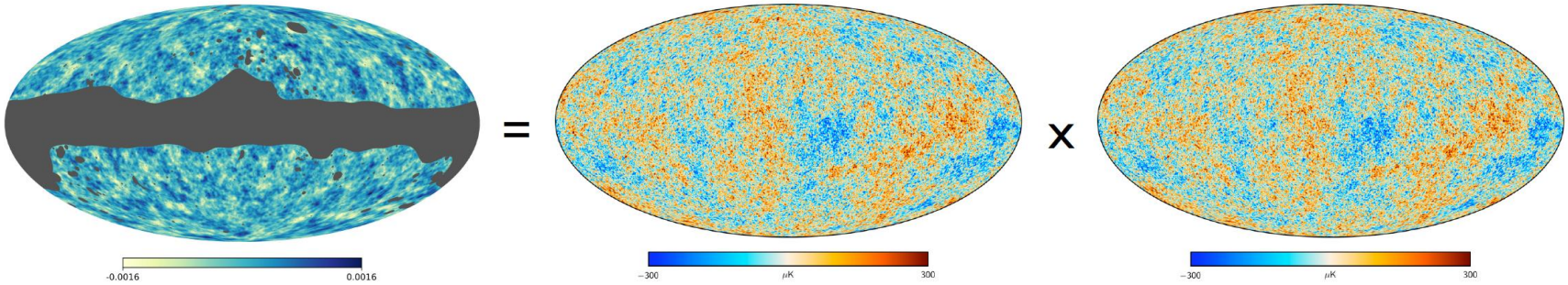
- Noisy lensing estimates from quadratic CMB combinations:

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

Normalisation

Known lensing-induced correlations

Inverse-variance-weighted CMB fields

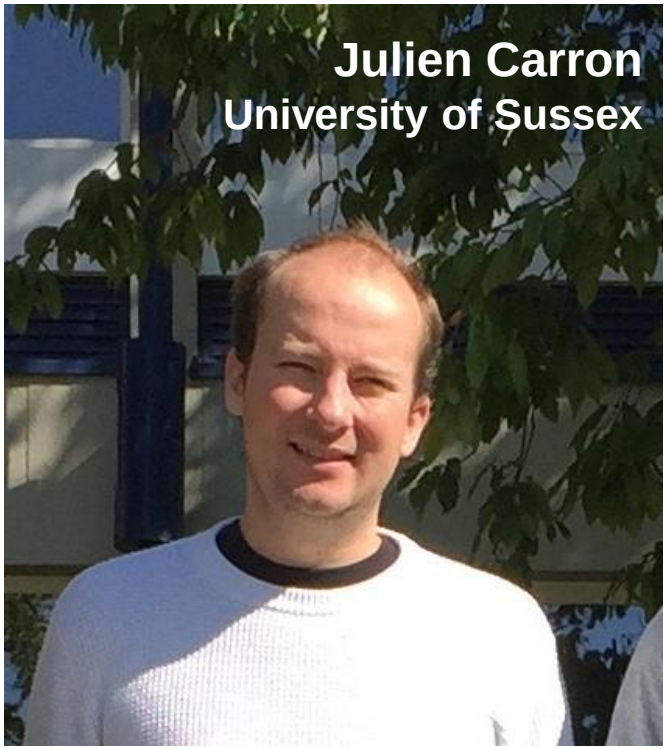


Credit: Anthony Challinor

Planck Lensing 2018 arXiv:1807.06210

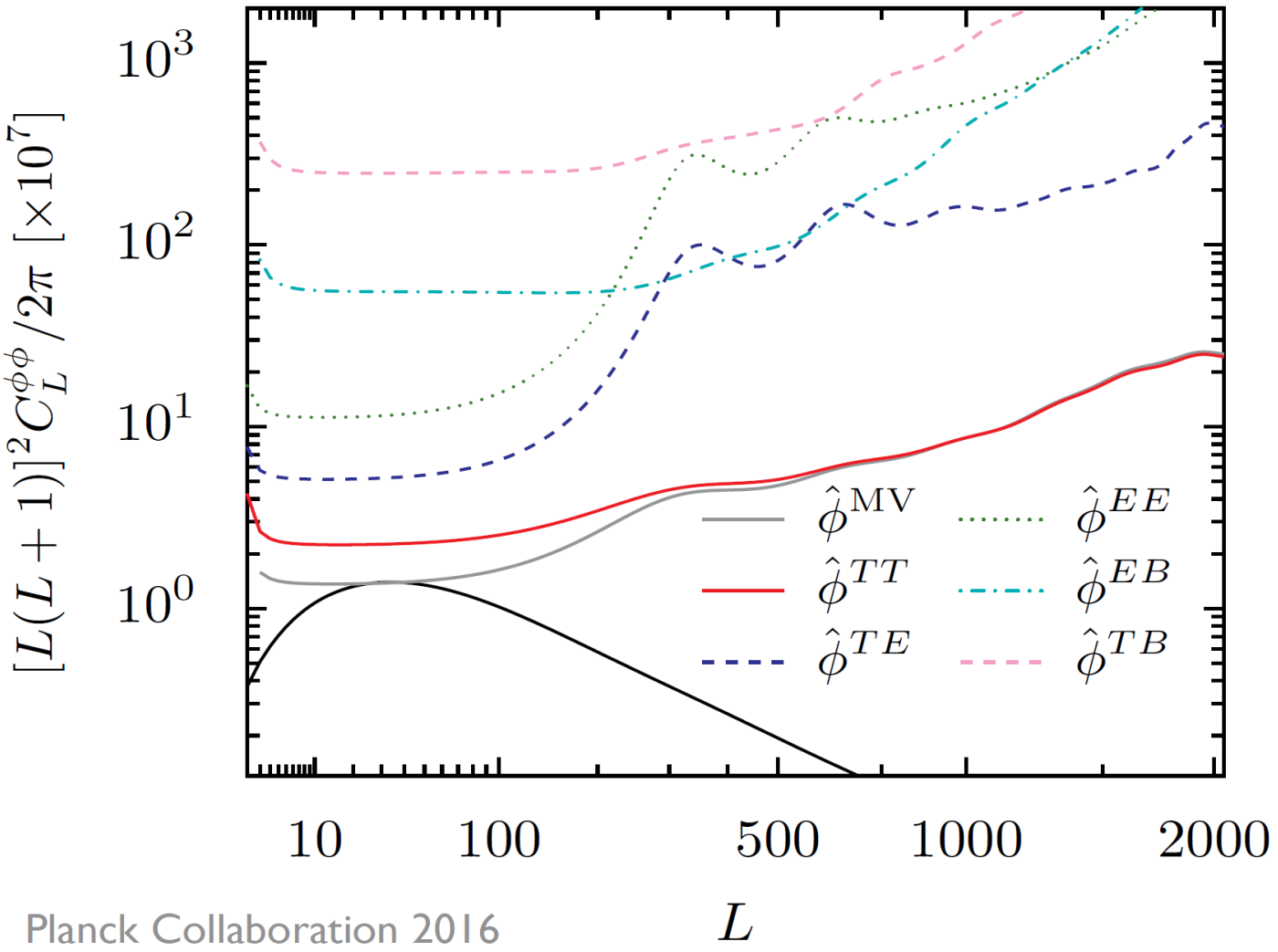
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.



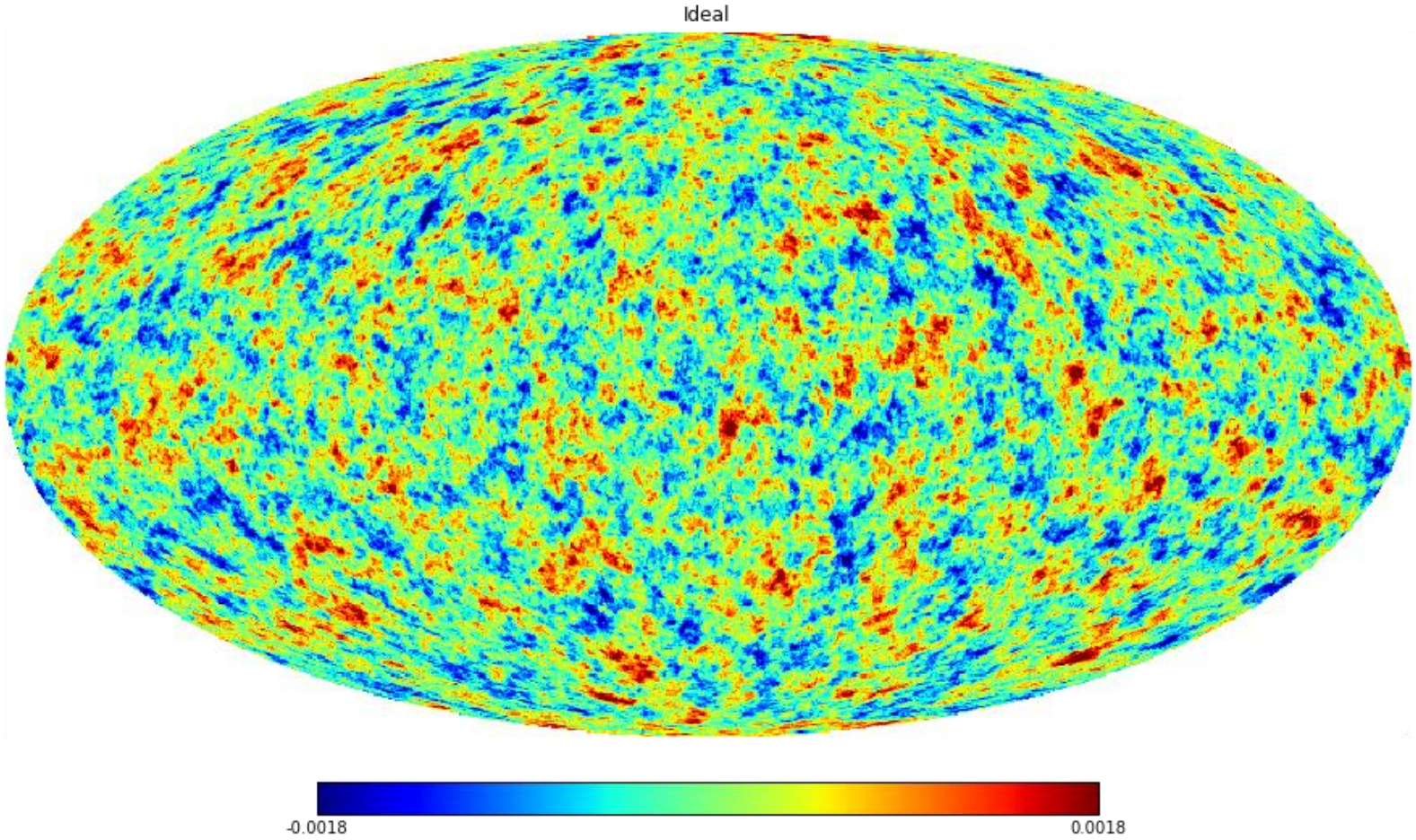
Planck lensing reconstruction noise

(instrumental noise + cosmic variance of unlensed T/E)

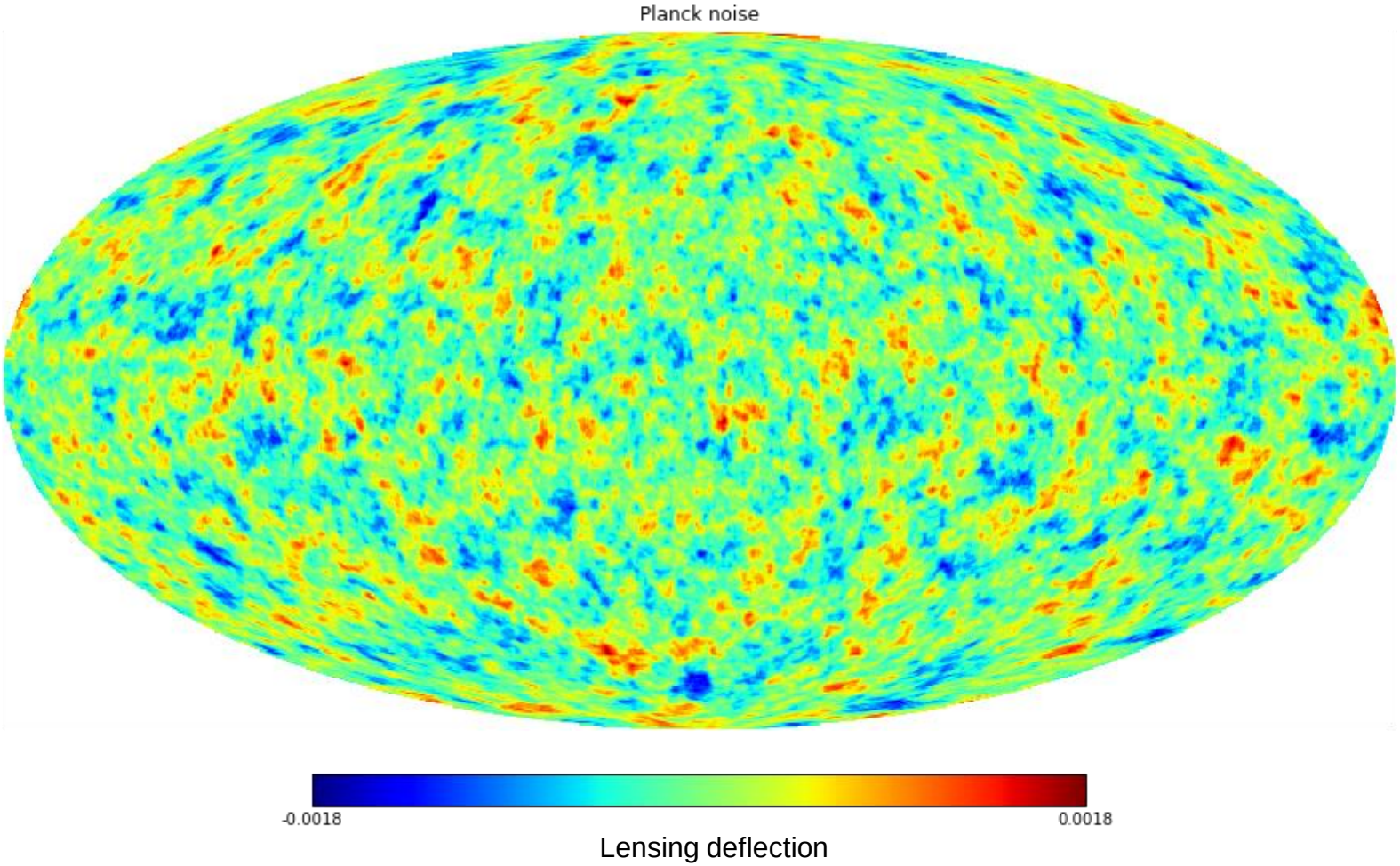


Planck Collaboration 2016

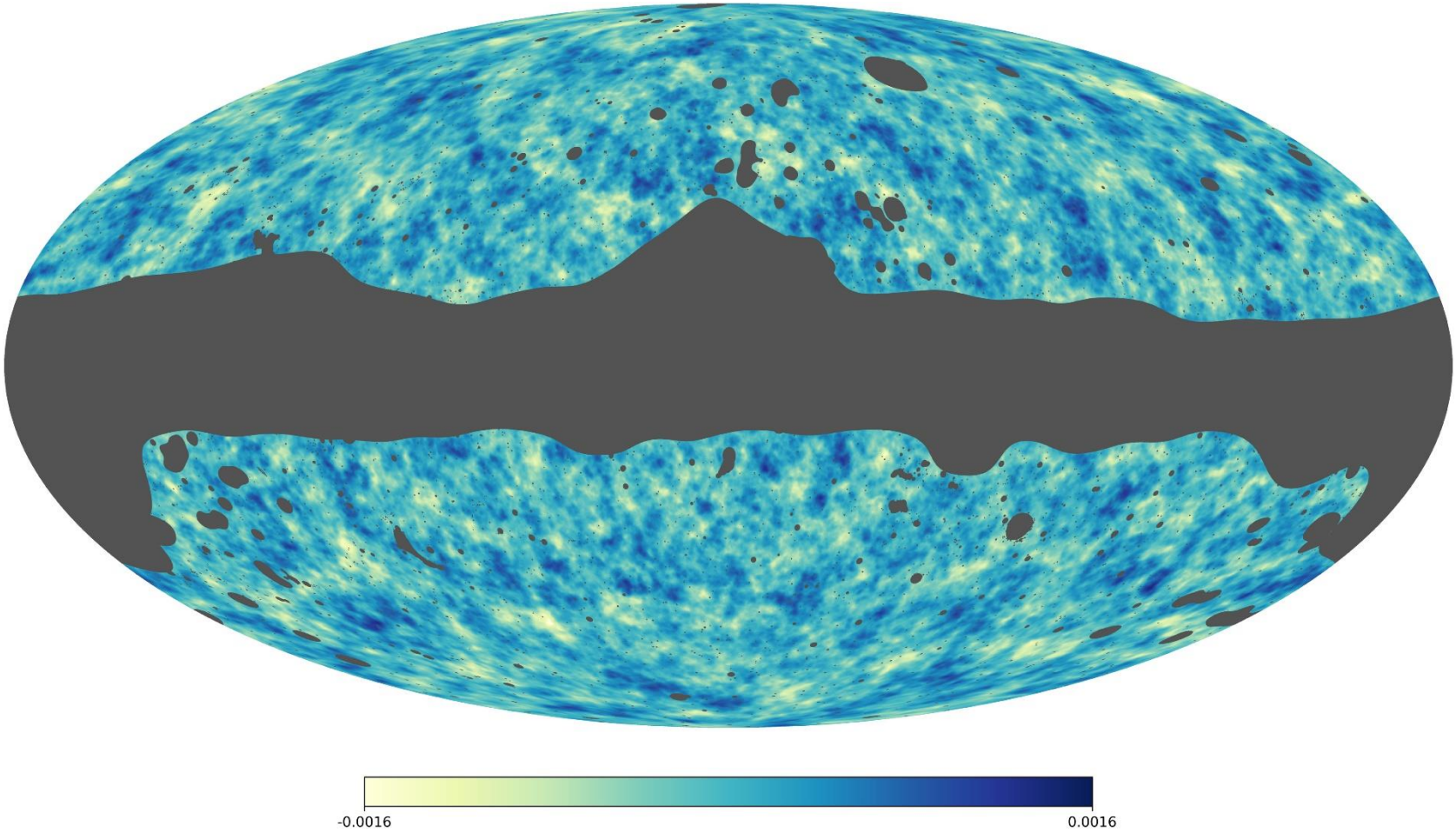
True simulation input



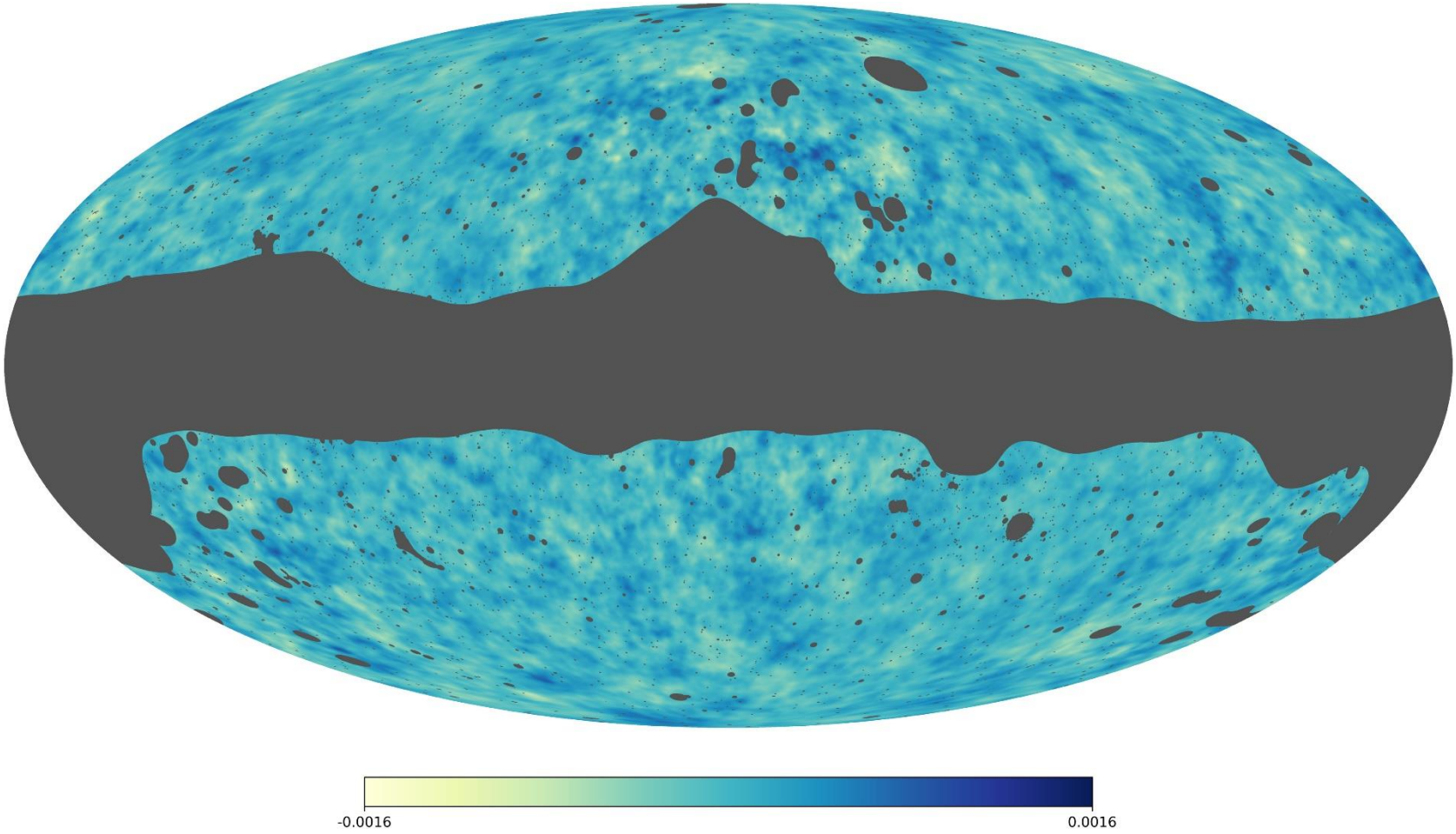
Simulated Planck lensing reconstruction



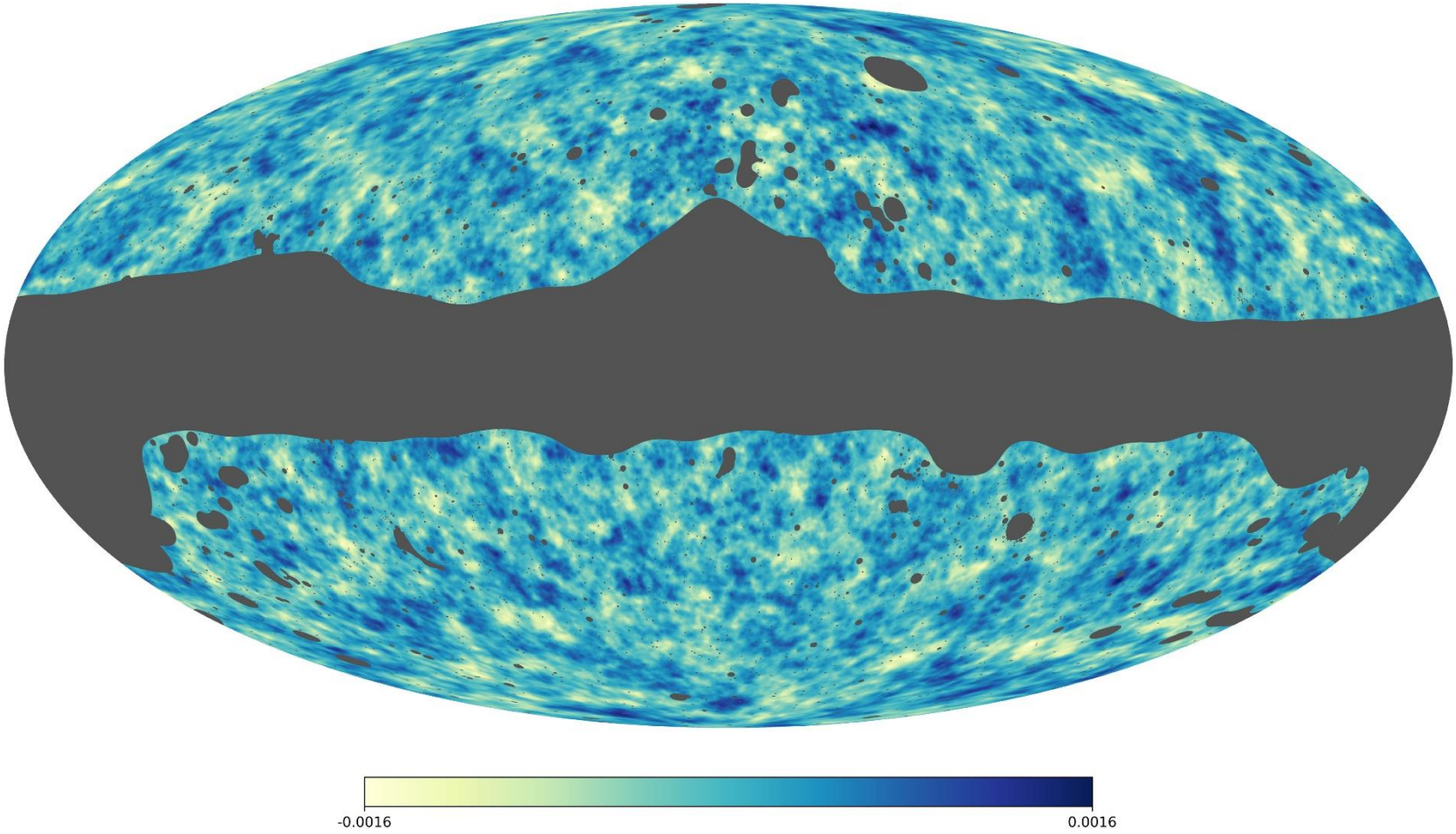
TT

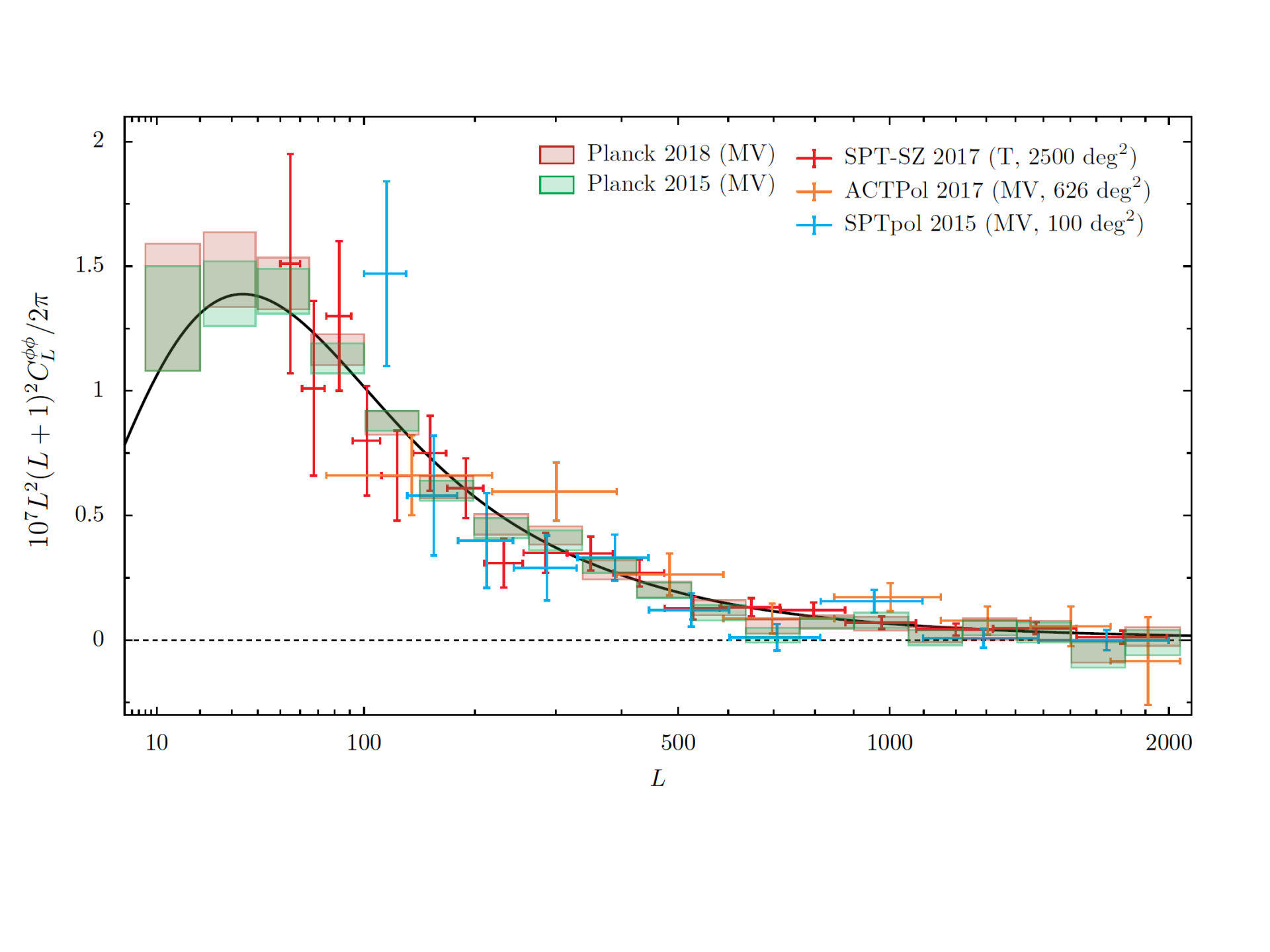


Polarization

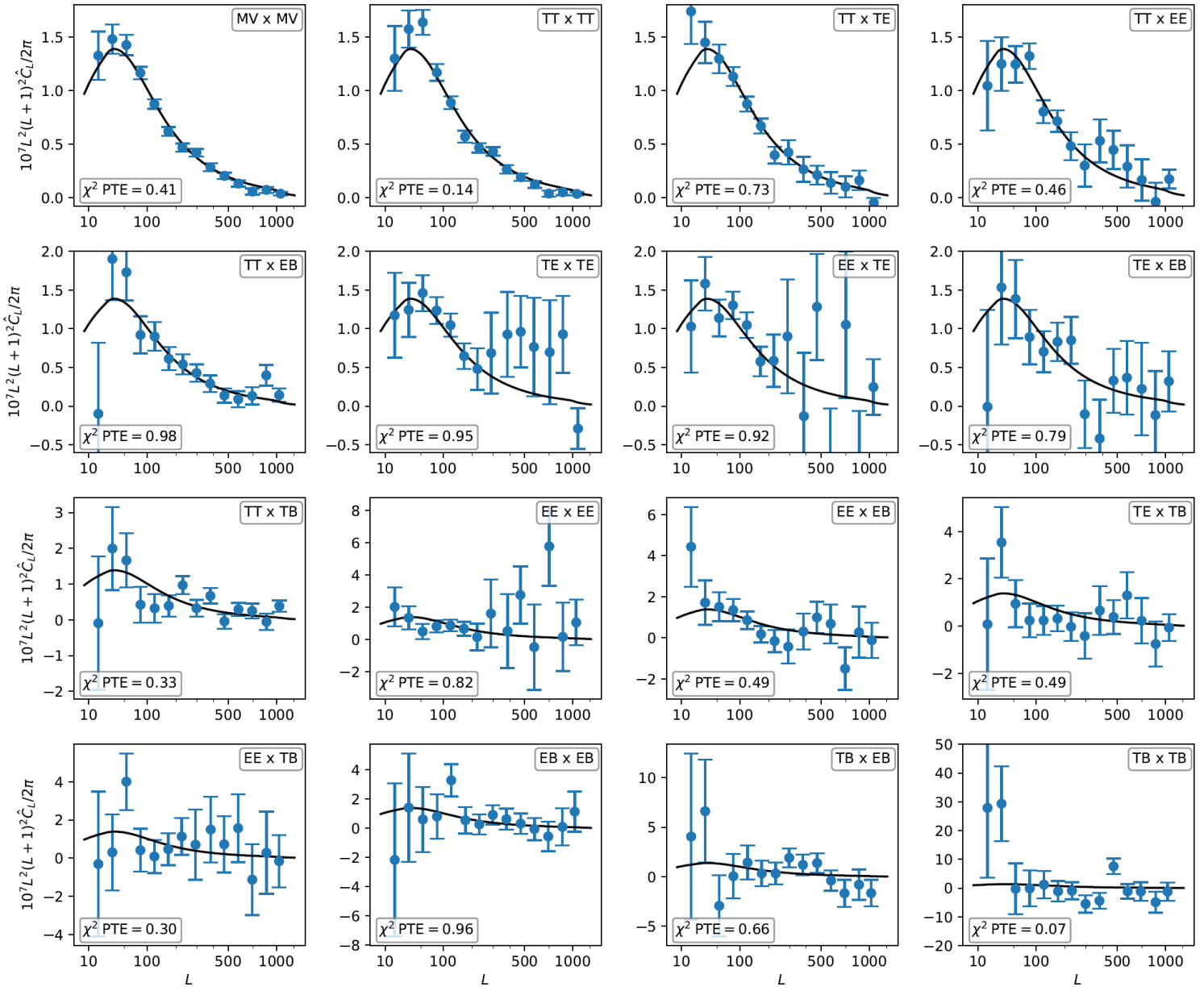


MV



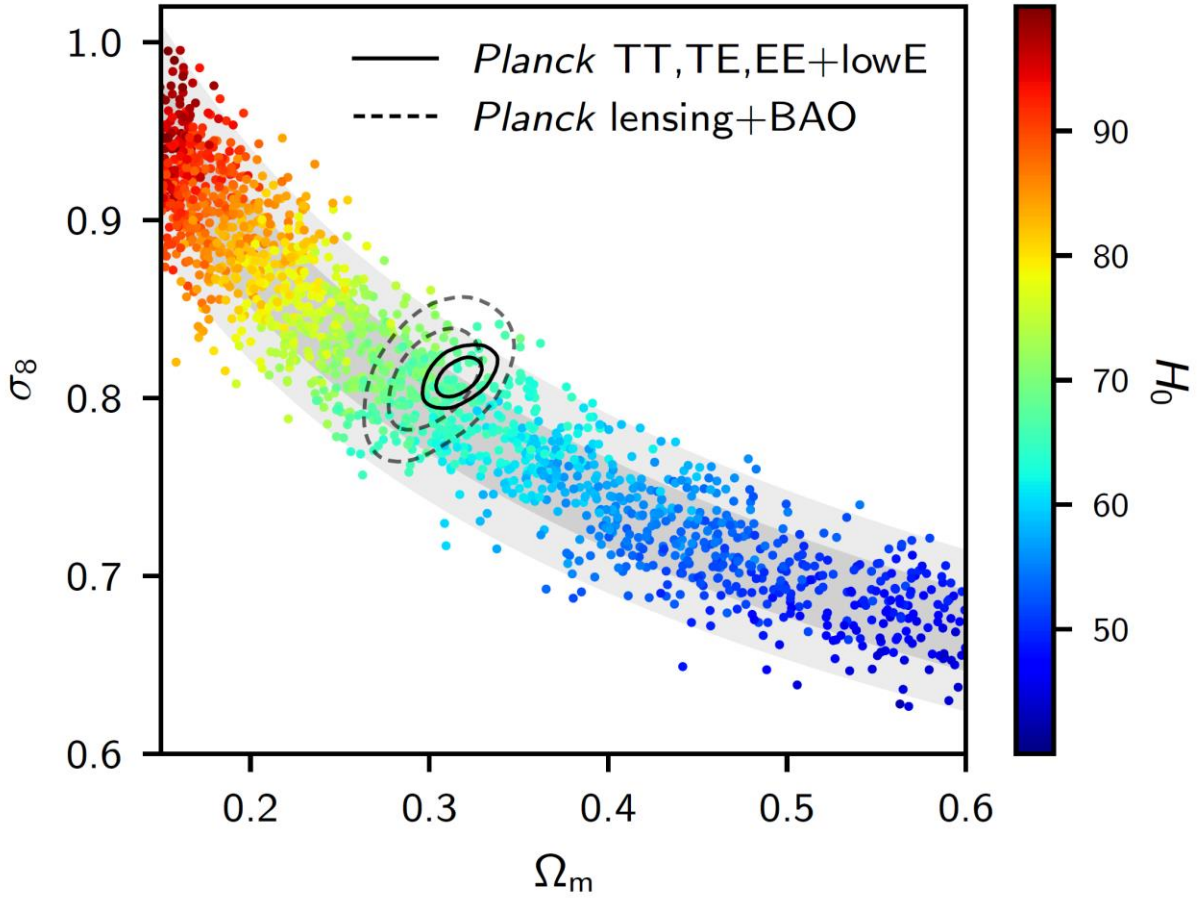

Planck 2018 (MV)
Planck 2015 (MV)
SPT-SZ 2017 (T, 2500 deg^2)
ACTPol 2017 (MV, 626 deg^2)
SPTpol 2015 (MV, 100 deg^2)
$10^7 L^2(L+1)^2 C_L^{\phi\phi}/2\pi$
L
2
1.5
1
0.5
0
10
100
500
1000
2000

Individual estimators

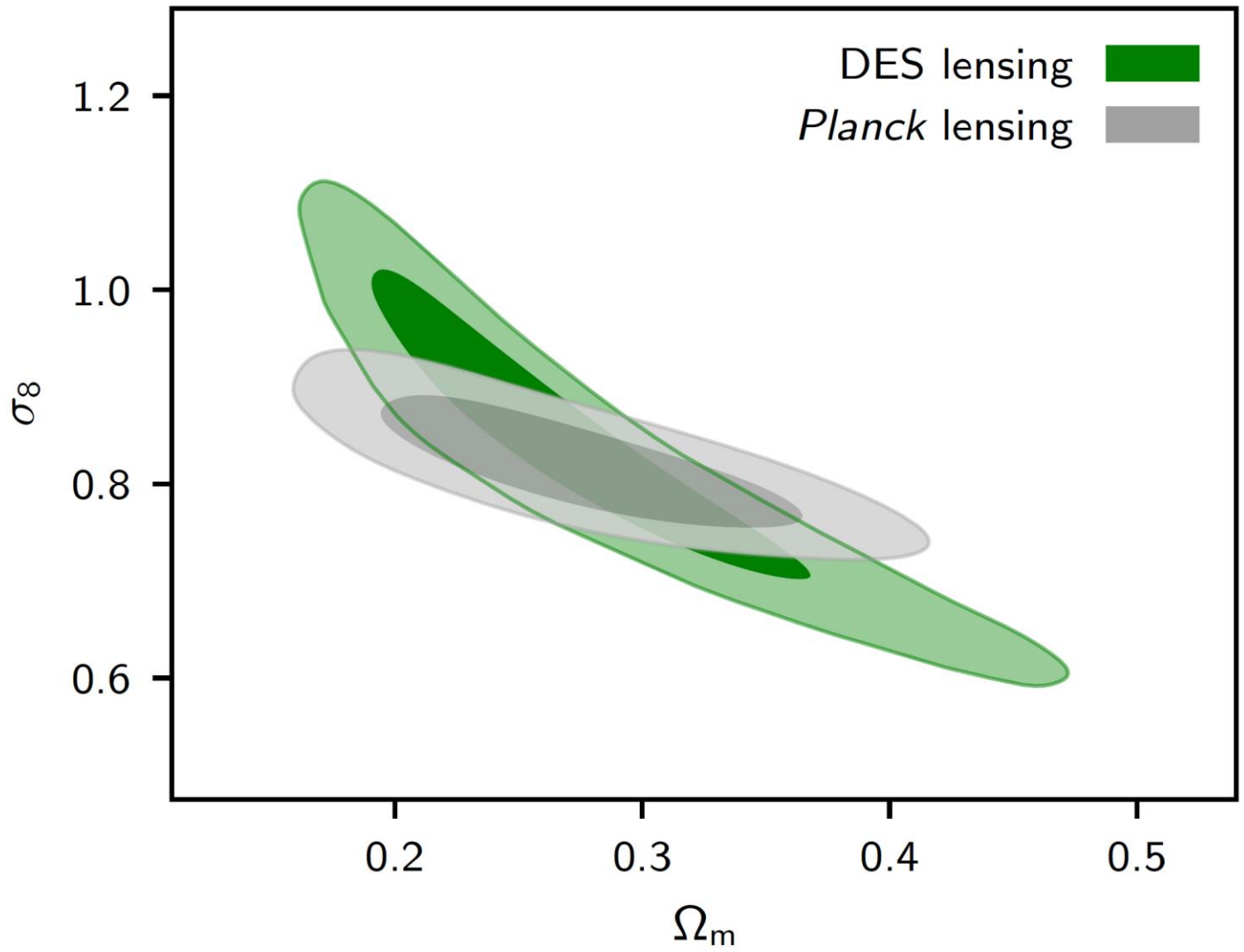


Lensing LCDM parameters

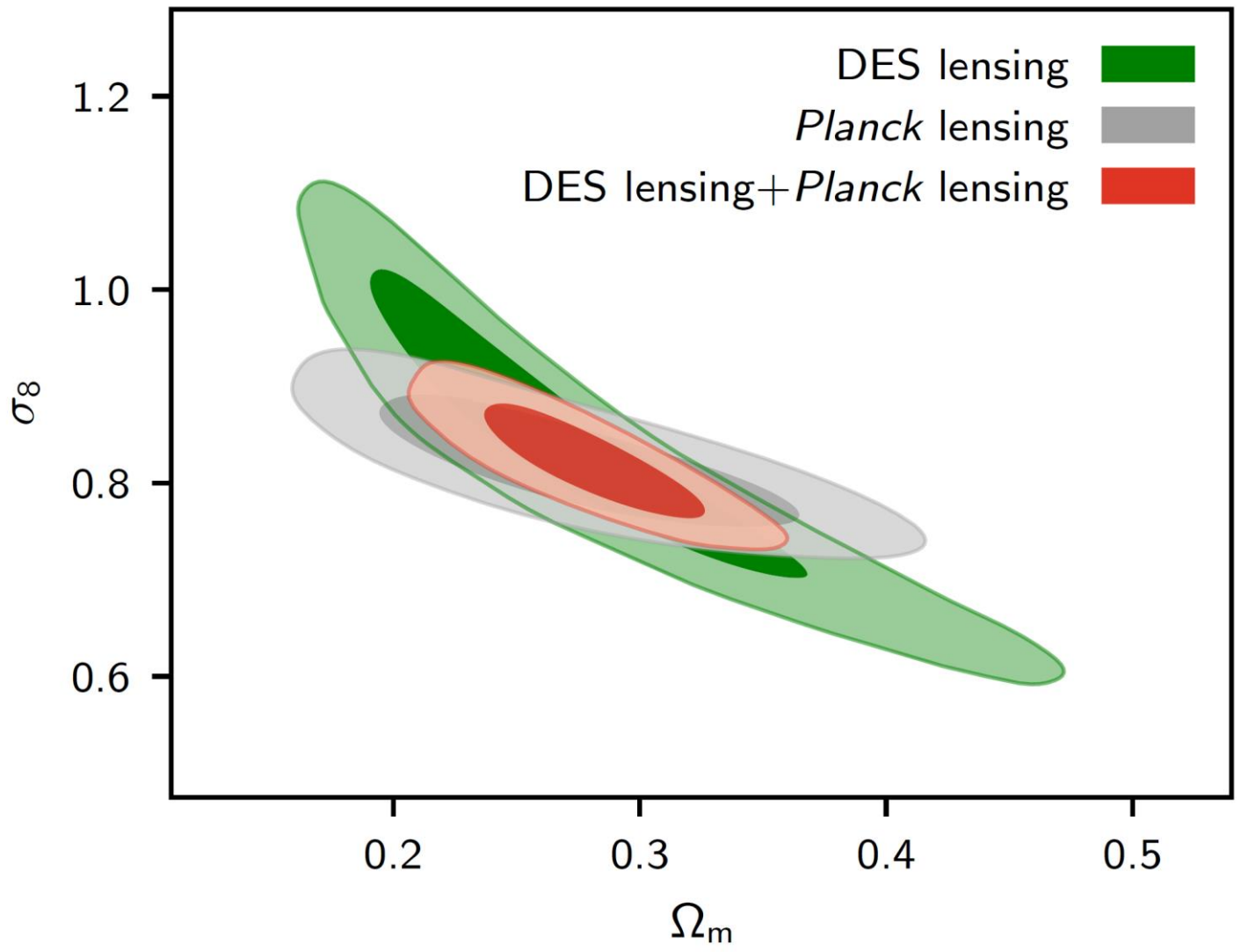
CMB lensing best measures $\sim \sigma_8 \Omega_m^{0.25} = 0.589 \pm 0.020$.

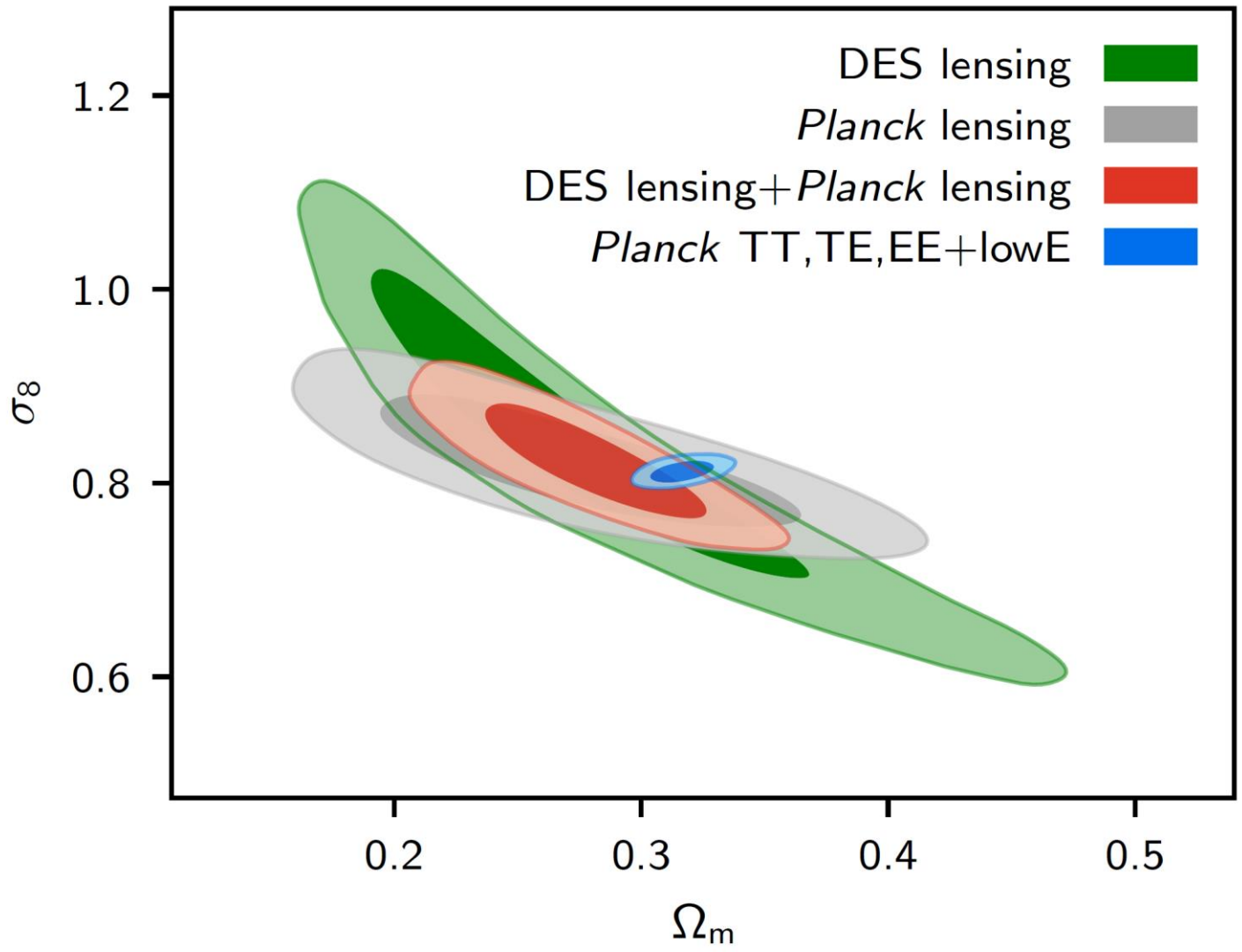


"Lensing-only" priors $\Omega_b h^2 = 0.0222 \pm 0.0005$; $n_s = 0.96 \pm 0.02$; $0.4 < h < 1$

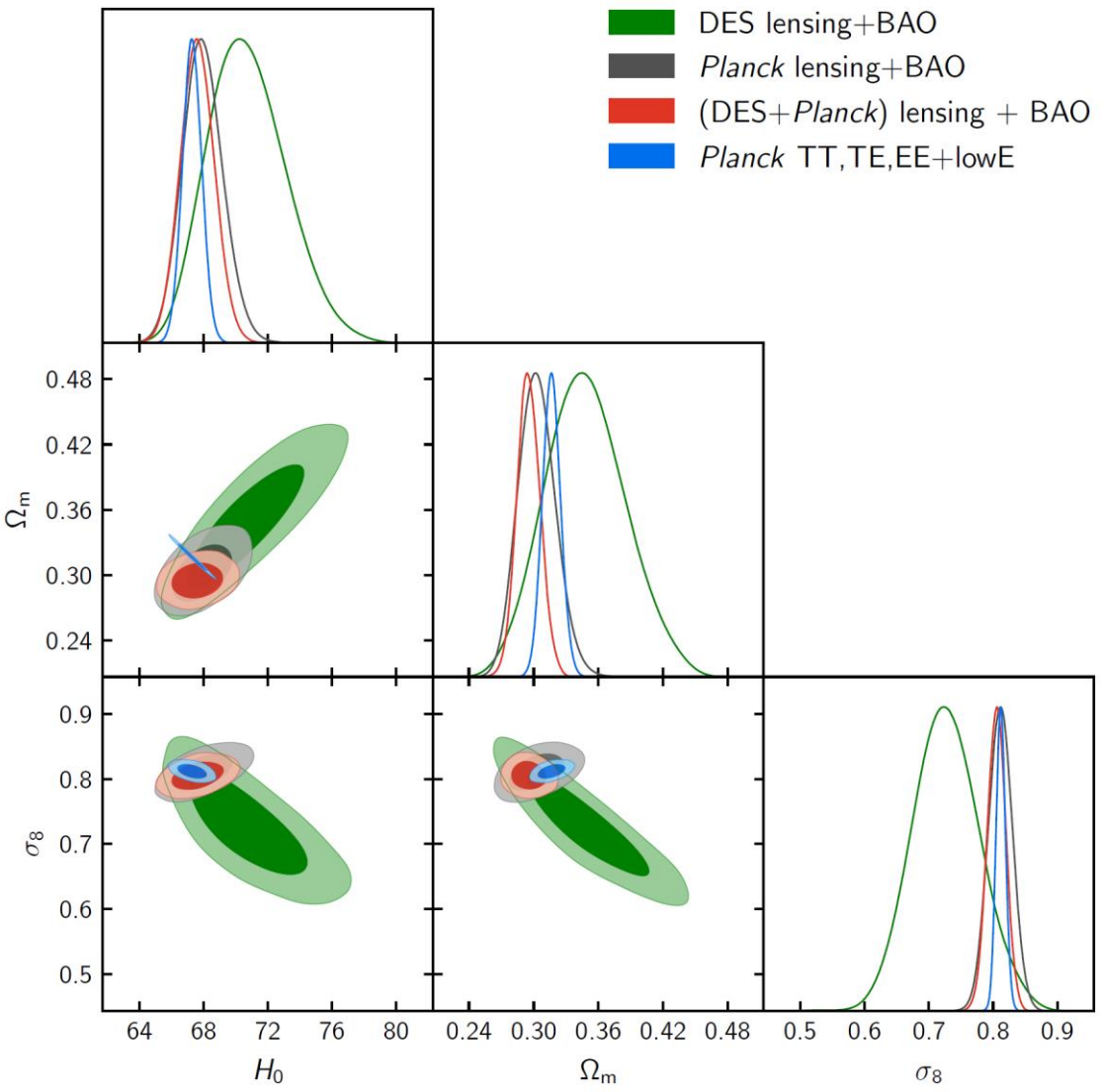


DES lensing from Troxel et al. (DES Collaboration 2017, 10 nuisance parameters marginalized)


DES lensing
Planck lensing
DES lensing+*Planck* lensing
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m


DES lensing
Planck lensing
DES lensing+*Planck* lensing
Planck TT,TE,EE+lowE
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m

Lensing + BAO + ($\Omega_b h^2 = 0.0222 \pm 0.0005$)



$H_0 = 67.9^{+1.2}_{-1.3}$ km s^{-1}Mpc^{-1},
$\sigma_8 = 0.811 \pm 0.019$,
$\Omega_m = 0.303^{+0.016}_{-0.018}$,
} 68 %, lensing+BAO

$H_0 = 70.7^{+2.1}_{-2.7}$ km s^{-1}Mpc^{-1}
$\sigma_8 = 0.727 \pm 0.052$
$\Omega_m = 0.348^{+0.033}_{-0.040}$
} 68%, DES lensing+BAO,

$H_0 = (67.6 \pm 1.1)$ km s^{-1}Mpc^{-1}
$\sigma_8 = 0.805 \pm 0.014$
$\Omega_m = 0.295 \pm 0.011$
} 68%, DES lensing +*Planck* lensing+BAO

Planck 2018 (inc. CMB)

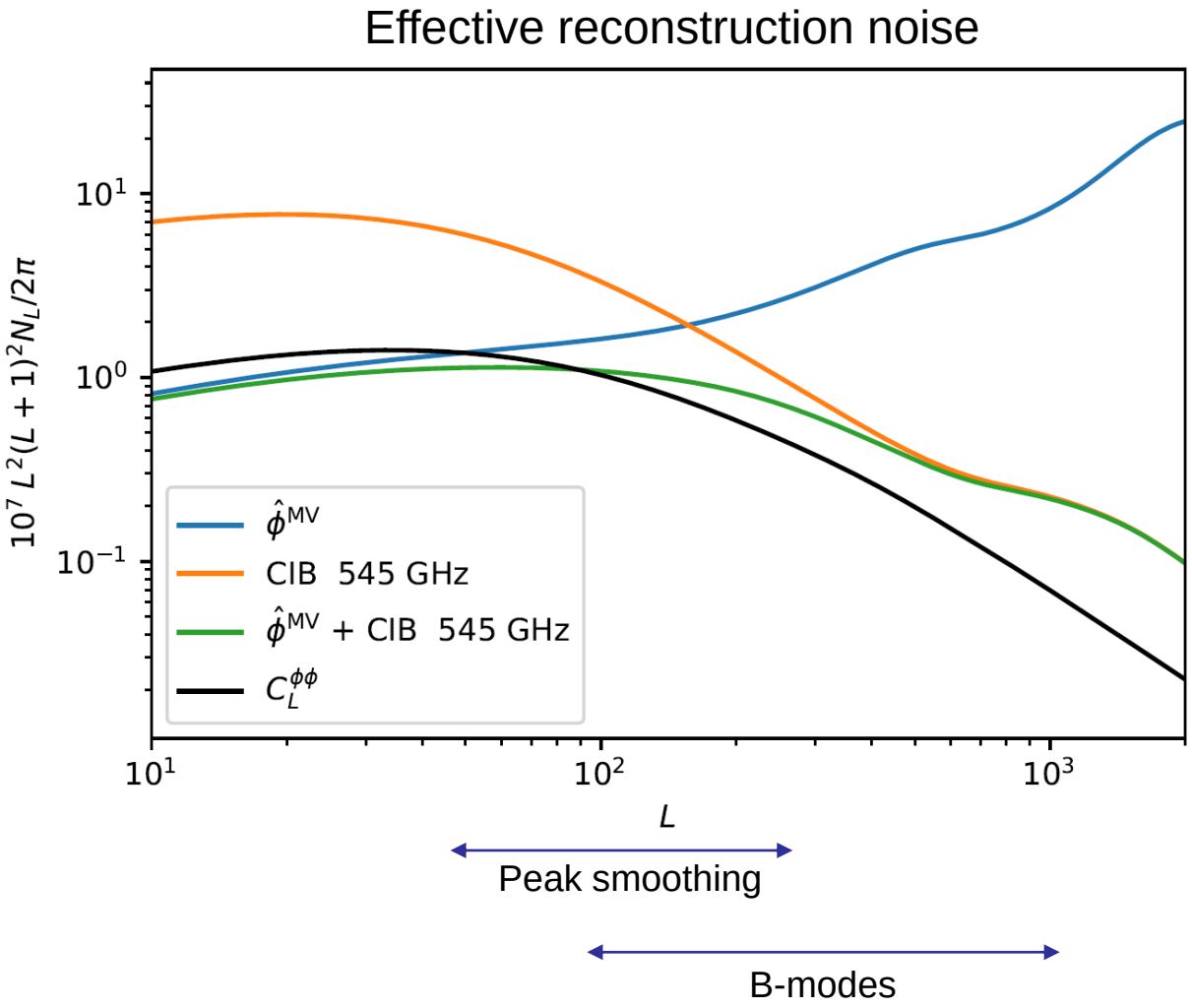
$H_0 = (67.4 \pm 0.5)$ km s^{-1}Mpc^{-1}

Riess et al. 1903.07603

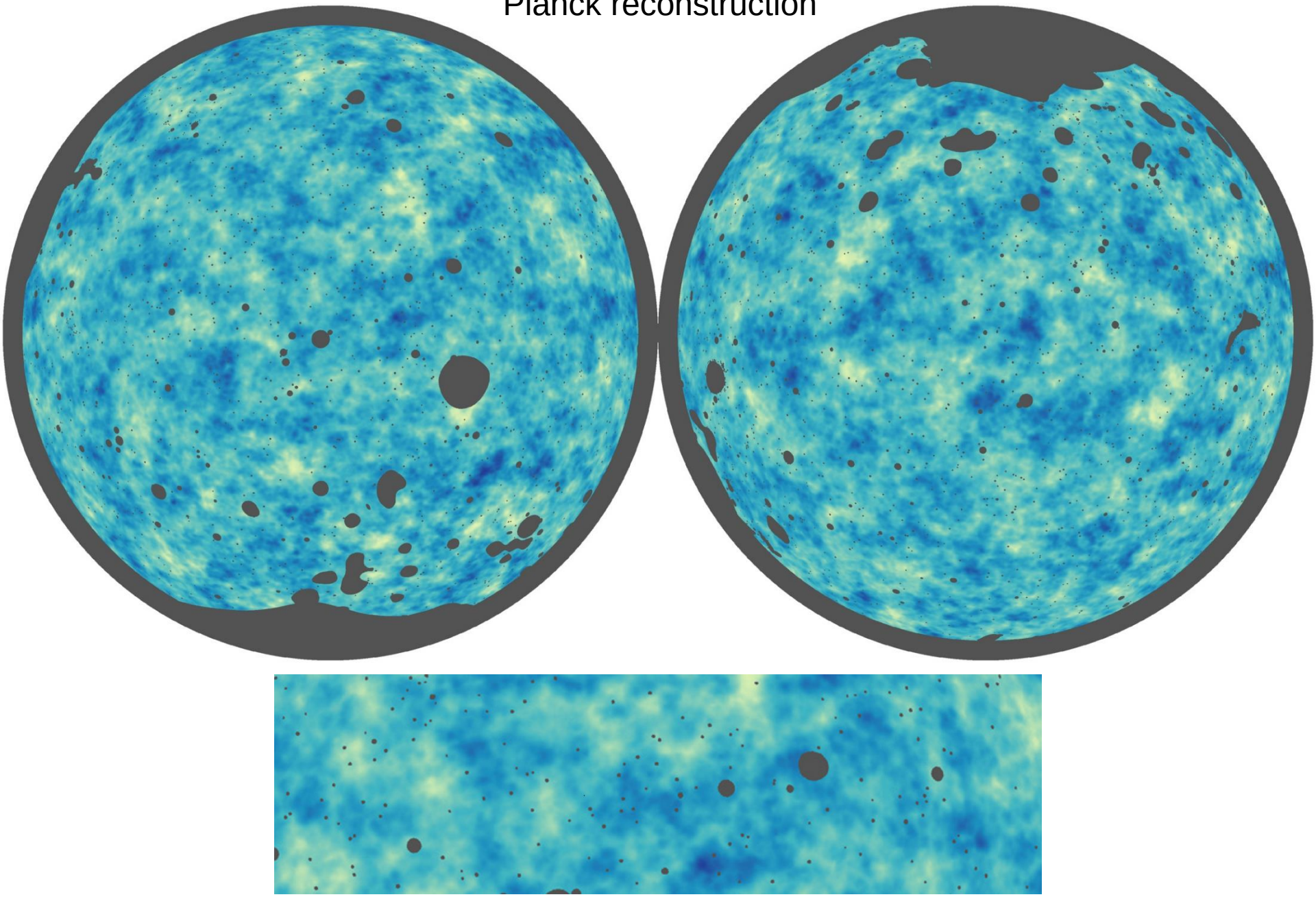
$H_0 = (74.22 \pm 1.82)$ km s^{-1}Mpc^{-1}

Improving lensing reconstruction using Cosmic Infrared Background (CIB)

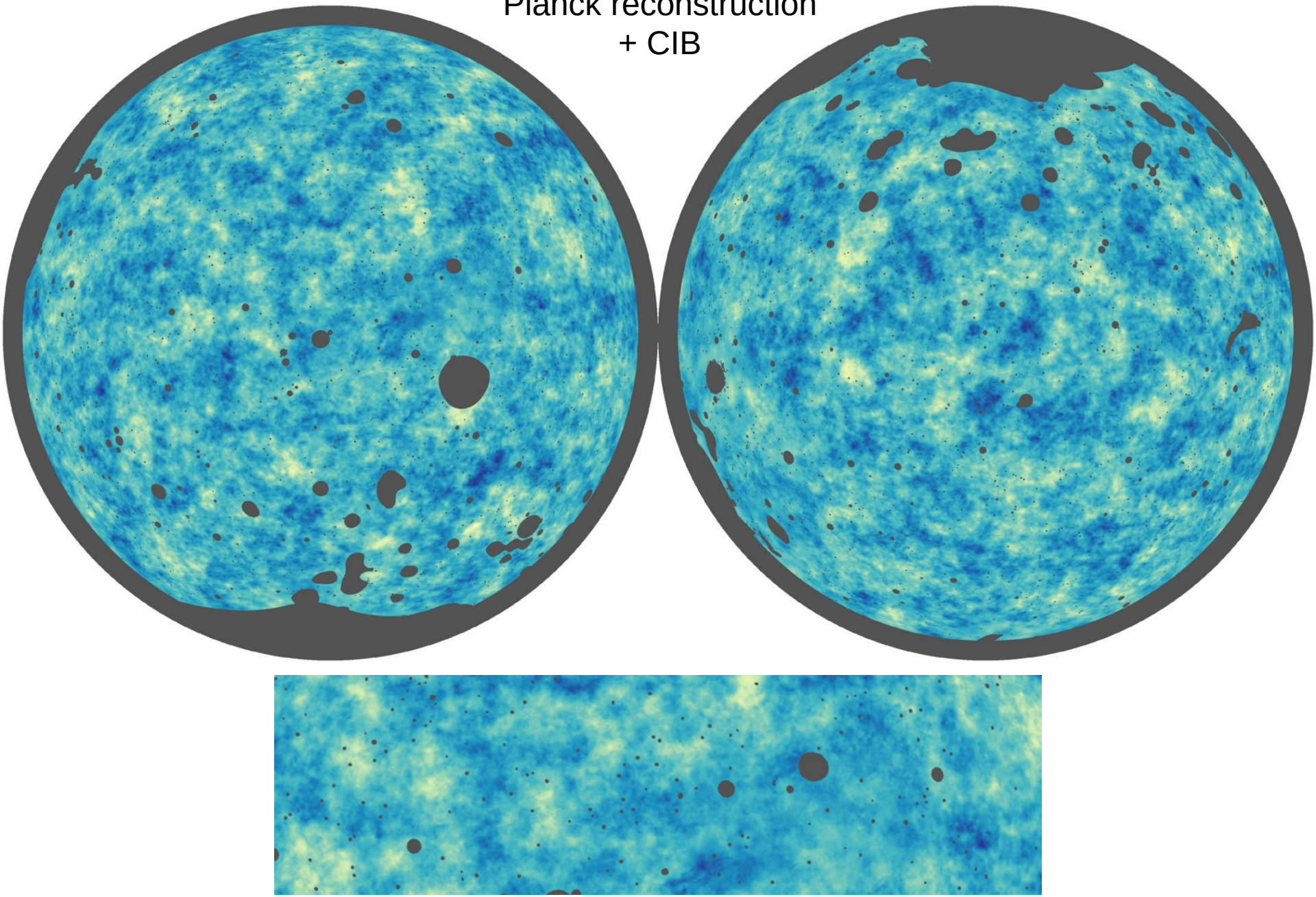
Use Planck GNILC 353, 545 GHz CIB maps as additional tracer of lensing potential



Planck reconstruction

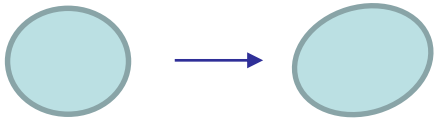


Planck reconstruction
+ CIB



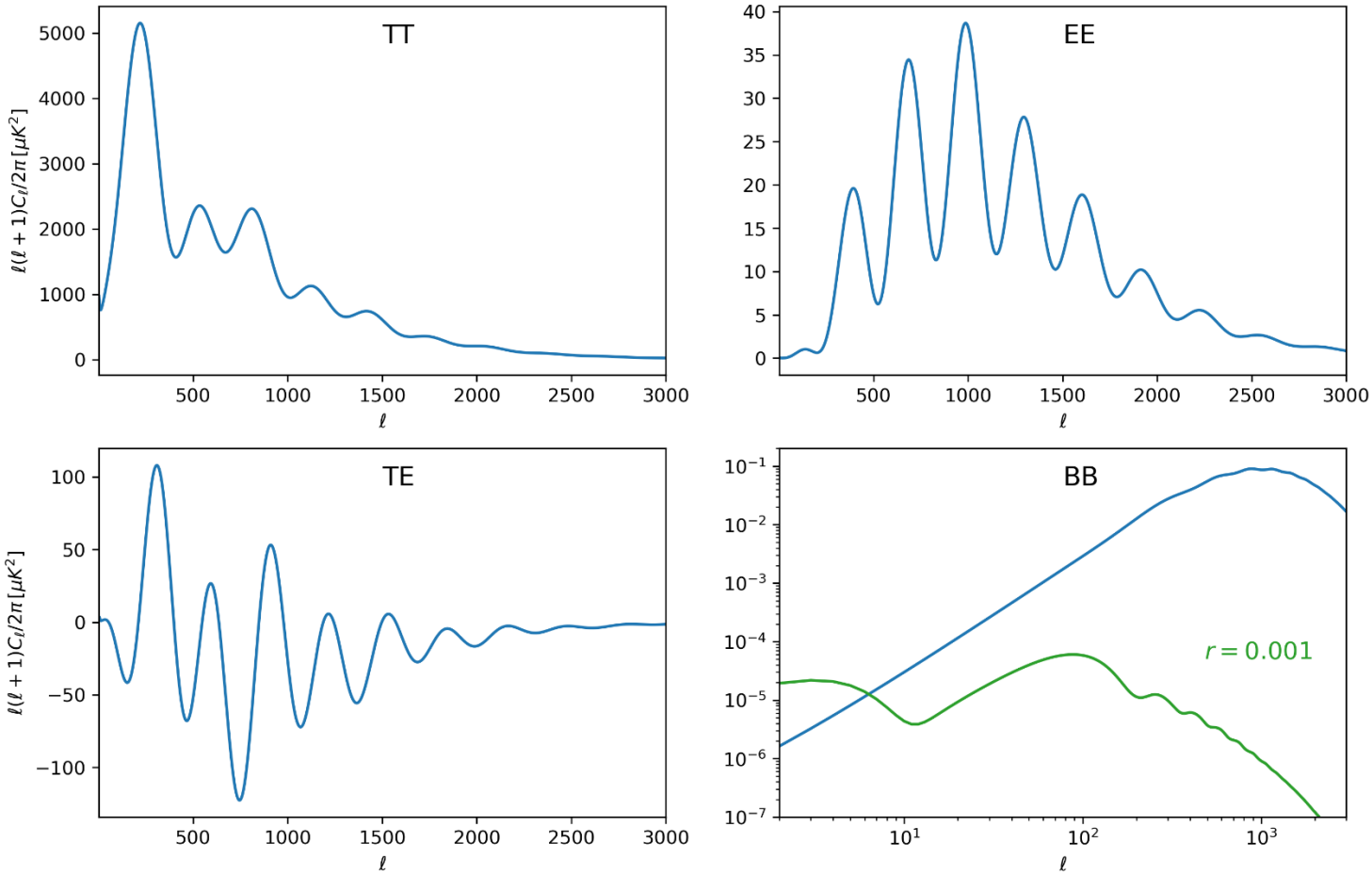
Delensing

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

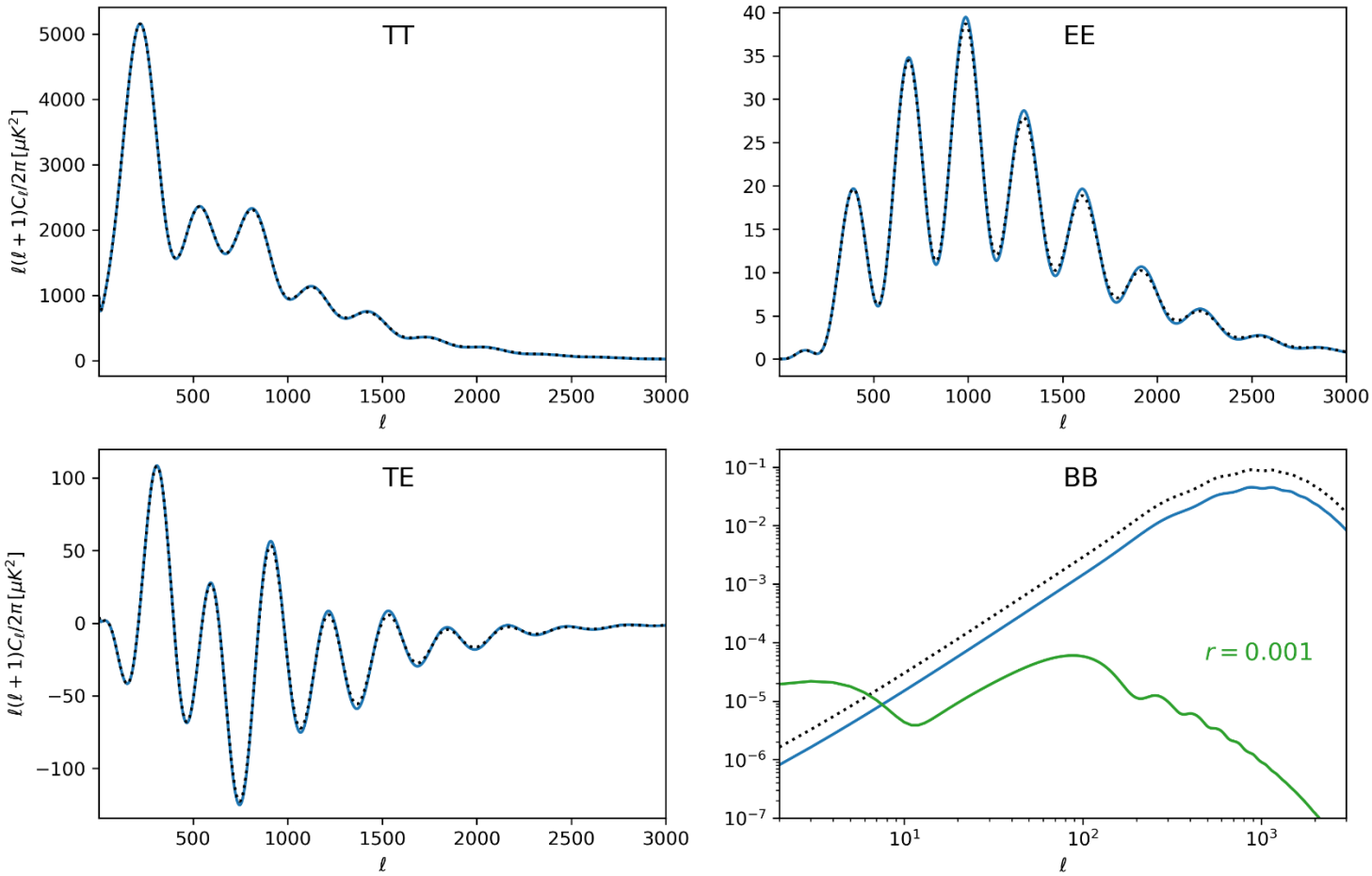


Delensing: $X^{\mathrm{delen}}(\mathbf{n}) \approx X^{\mathrm{len}}(\mathbf{n} - \boldsymbol{\alpha}(\boldsymbol{n}))$

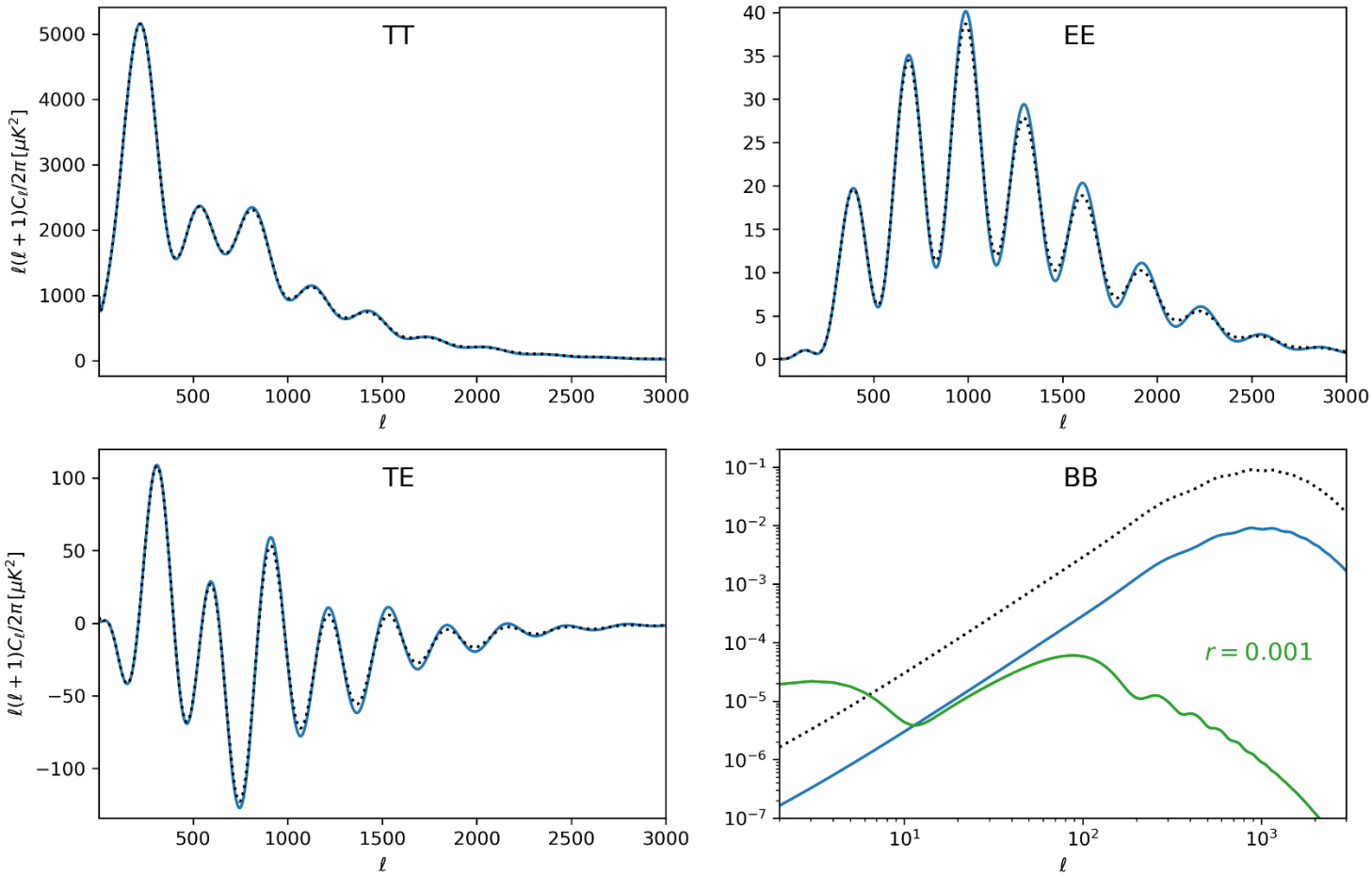
Delensing ($A_L = 1$)



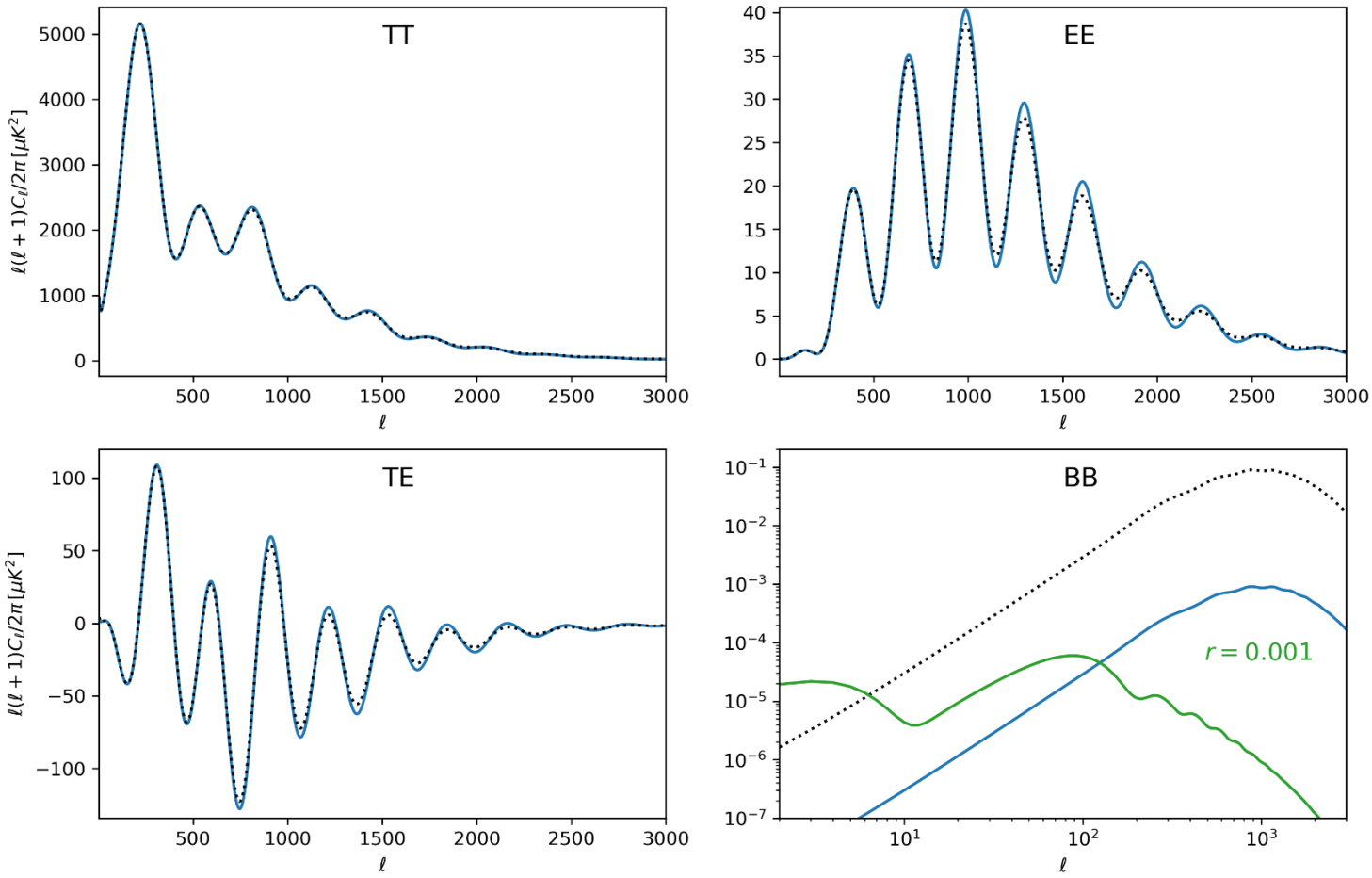
Delensing ($A_L = 0.5$)



Delensing ($A_L = 0.1$)

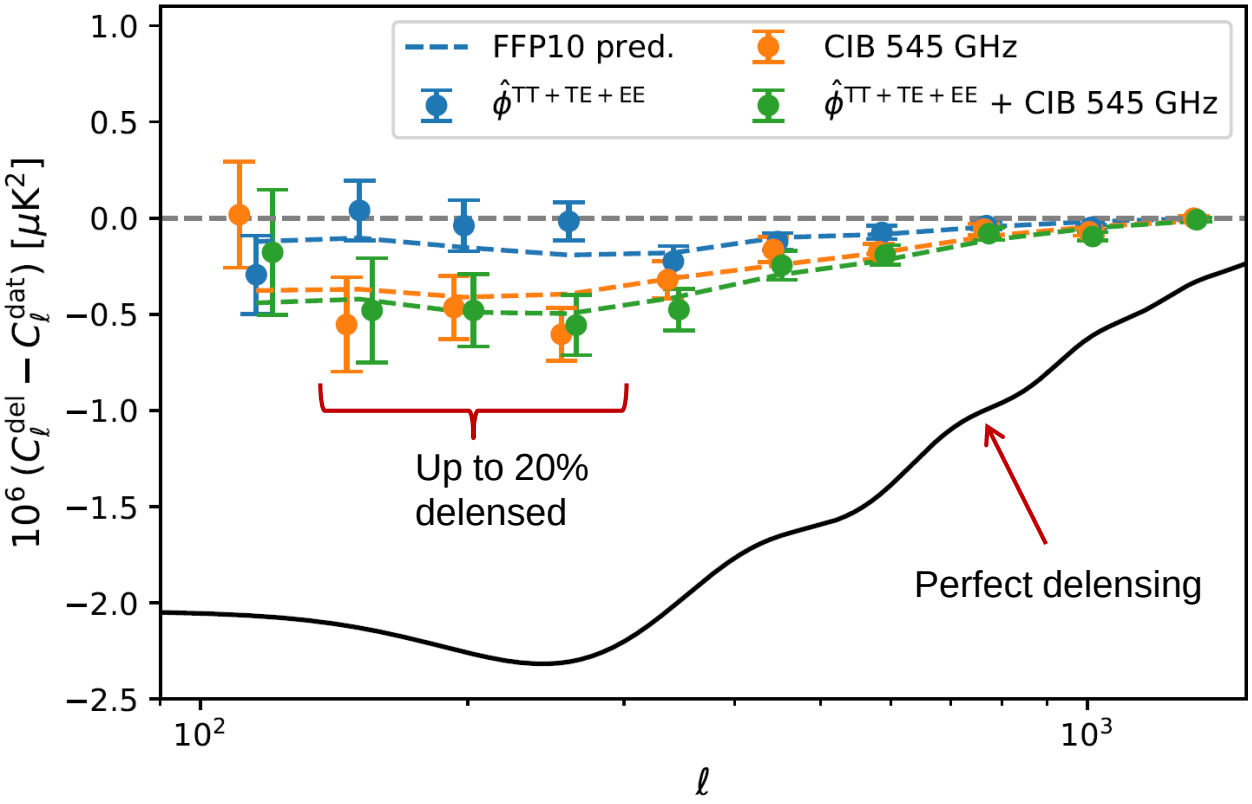


Delensing ($A_L = 0.01$)



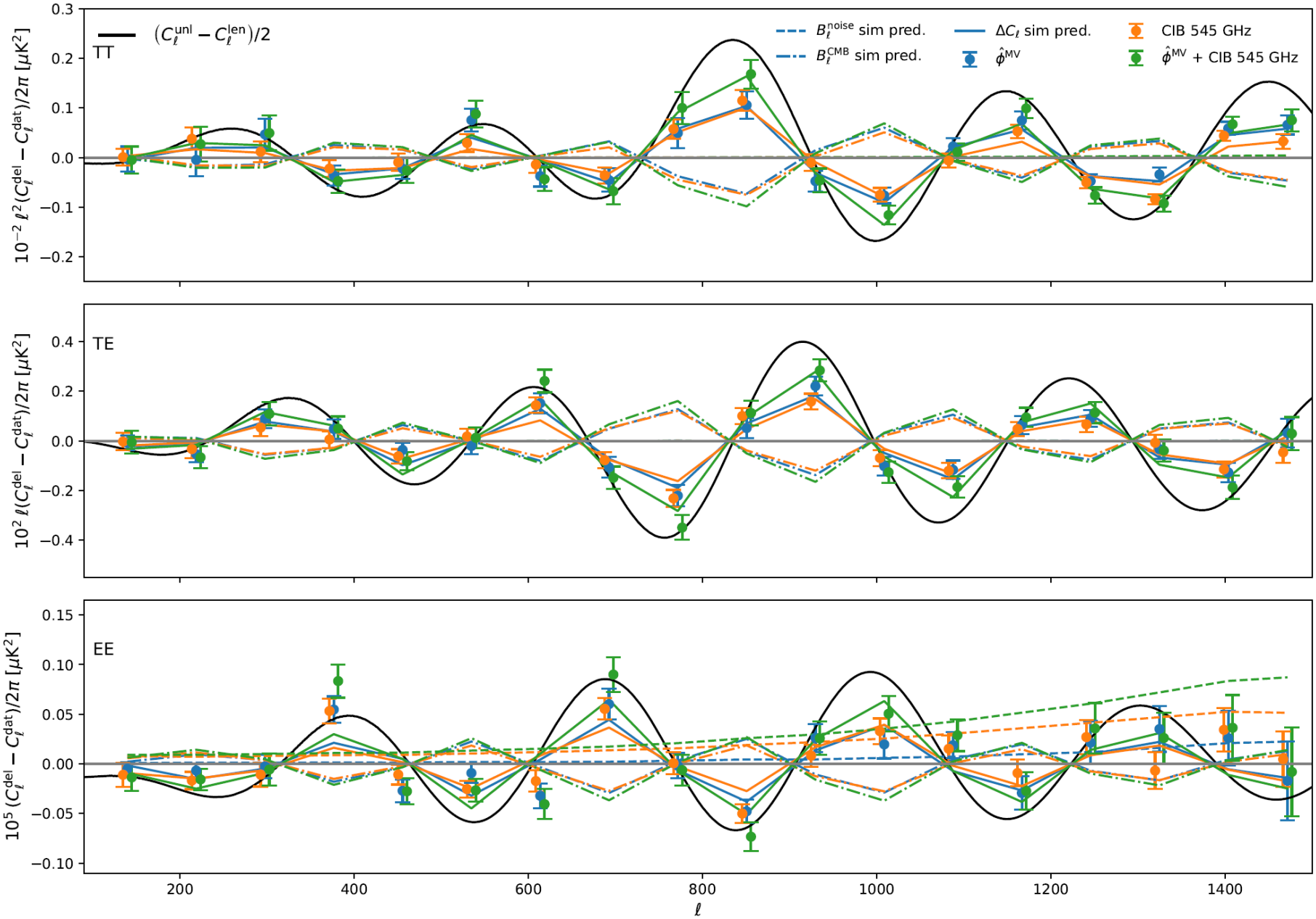
Planck B-mode delensing proof of principle

(limited delensing efficiency from Planck due to E noise)



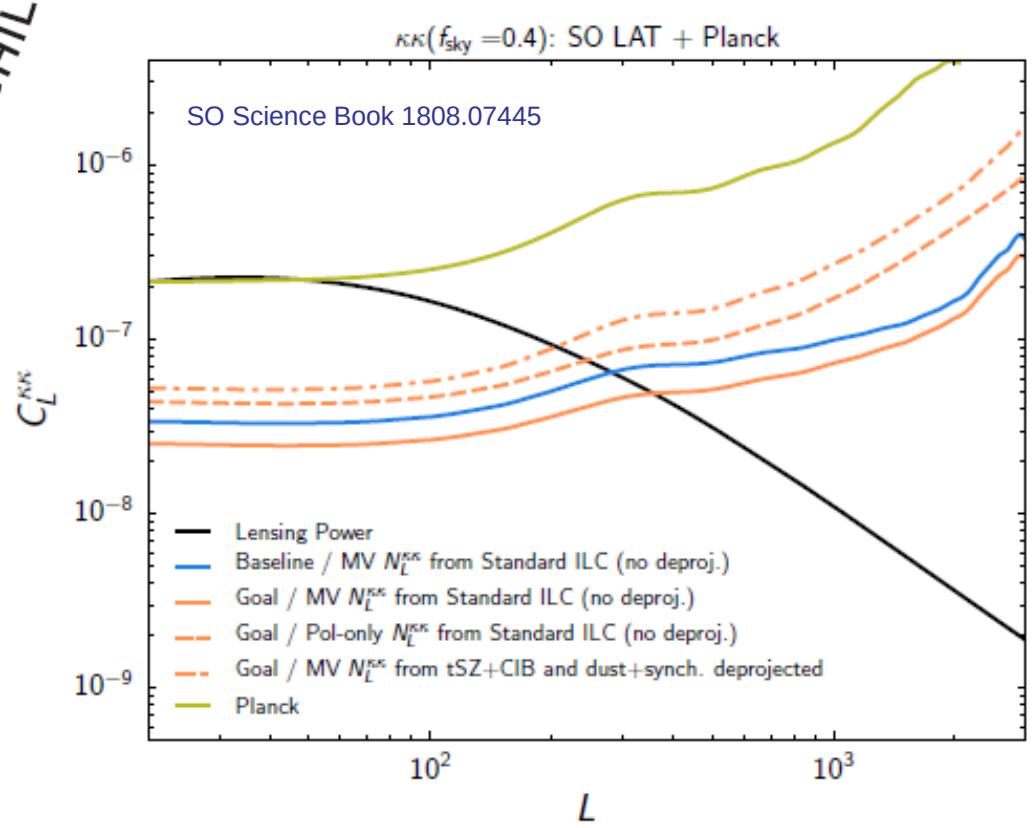
Delensing: Peak Sharpening – 40% of smoothing effect removed with MV+CIB

$$\Delta\hat{C}_{\ell,\mathrm{debias}} \equiv \hat{C}_\ell^{\mathrm{del}} - \hat{C}_\ell^{\mathrm{dat}} - B_\ell^{\mathrm{Gauss}} - B_\ell^{\mathrm{Noise}} + B_\ell^{\mathrm{CMB}}.$$



22°57'31" SOUTH, 67°47'15" WEST
ELEVATION: 5190 m
SIMONS
OBSERVATORY
PARQUE ASTRONÓMICO ATACAMA, CHILE

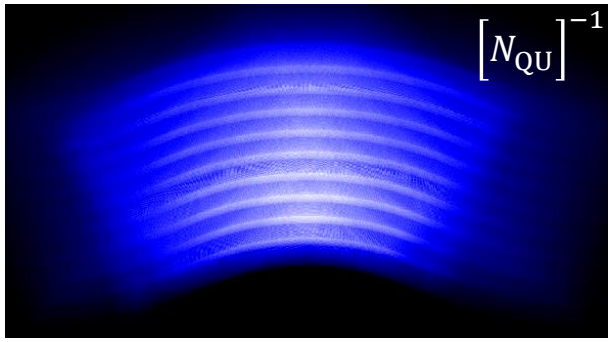
CMB Lensing


$\kappa\kappa(f_{\rm sky}=0.4)$: SO LAT + Planck
SO Science Book 1808.07445
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$C_L^{\kappa\kappa}$
10^2
10^3
L
Lensing Power
Baseline / MV $N_L^{\kappa\kappa}$ from Standard ILC (no deproj.)
Goal / MV $N_L^{\kappa\kappa}$ from Standard ILC (no deproj.)
Goal / Pol-only $N_L^{\kappa\kappa}$ from Standard ILC (no deproj.)
Goal / MV $N_L^{\kappa\kappa}$ from tSZ+CIB and dust+synch. deprojected
Planck

Optimal filtering for CMB lensing reconstruction

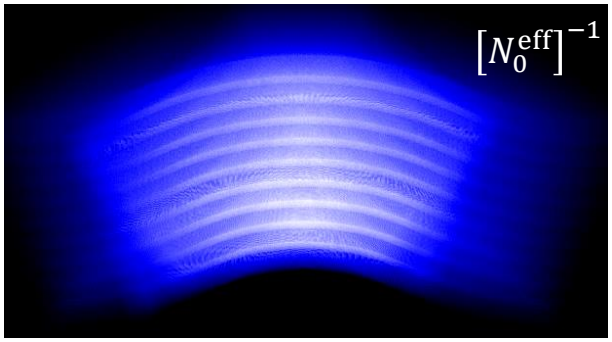
Mark Mirmelstein, Julien Carron, AL in prep.

1. Ground based: noise is very inhomogenous



⇒ Filter using $\bar{X} = S(S+N)^{-1}X$

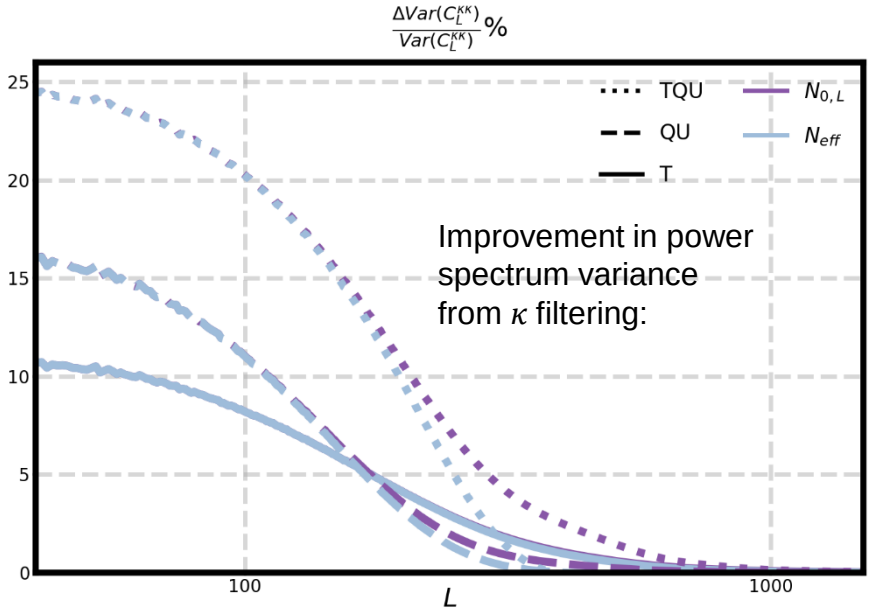
2. Lensing reconstruction noise is *also* inhomogeneous



⇒ Filter reconstruction $\bar{\kappa} = S_\kappa \left(S_\kappa + N_0^{\mathrm{eff}}\right)^{-1} \kappa$

Not quite as optimal as full maximum likelihood, but simple and still quadratic
⇒ easy to model

%



CMB lensing cross-correlations

CMB lensing

$$\hat{\phi}^{XY}(\mathbf{L}) = A_L^{XY} \int_{\mathbf{l}} g_{XY}(\mathbf{l}, \mathbf{L}) \tilde{X}_{\rm expt}(\mathbf{l}) \tilde{Y}^*_{\rm expt}(\mathbf{l} - \mathbf{L}),$$

(flat-sky approximation)

$\times$

galaxy density or lensing

$\phi^{\rm ext}$

(or CIB, 21cm, .. etc.)

- Measurements of growth of structure and bias
- Calibration of galaxy shear bias
- Improve constraints on $f_{\rm NL}$ from scale-dependent bias

Lensing potential and tracer non-Gaussian ⇒ source of bias

* Lensing auto-spectrum: Small $N^{(3/2)}$ bias Böhm et al. 1605.01392, 1806.01157

* Large-scale structure tracers lower redshift ⇒ more non-Gaussian – bigger bias?

Giulio Fabbian, AL, Dominick Beck in prep.

Cross power spectrum:

$$\langle \phi_{\rm ext}(\mathbf{L}')\hat{\phi}^{XY}(\mathbf{L})\rangle = A_L^{XY}\int_{\mathbf{l}} g_{XY}(\mathbf{l},\mathbf{L})\langle \phi_{\rm ext}(\mathbf{L}')\tilde{X}_{\rm expt}(\mathbf{l})\tilde{Y}^*_{\rm expt}(\mathbf{l}-\mathbf{L})\rangle$$

$$= A_L^{XY}\int_{\mathbf{l}} g_{XY}(\mathbf{l},\mathbf{L})\langle \phi_{\rm ext}(\mathbf{L}')\tilde{X}_{\rm expt}(\mathbf{l})\tilde{Y}^*_{\rm expt}(\mathbf{l}-\mathbf{L})\rangle_G$$

$$+\frac{A_L^{XY}}{2}\int_{\mathbf{l}} g_{XY}(\mathbf{l},\mathbf{L})\int \mathrm{d}^2\mathbf{L}''\mathrm{d}^2\mathbf{l}_1\mathrm{d}^2\mathbf{l}_3\left\langle \frac{\delta\left(\phi_{\rm ext}(\mathbf{L}')\tilde{X}(\mathbf{l})\tilde{Y}(\mathbf{L}-\mathbf{l})\right)}{\delta\phi_{\rm ext}(\mathbf{L}'')\delta\phi(\mathbf{l}_1)\delta\phi(\mathbf{l}_3)}\right\rangle_G \langle\phi_{\rm ext}(\mathbf{L}'')\phi(\mathbf{l}_1)\phi(\mathbf{l}_3)\rangle \quad + \ldots$$

$$\langle \phi_{\rm ext}(\mathbf{L}')\tilde{X}_{\rm expt}(\mathbf{l})\tilde{Y}^*_{\rm expt}(\mathbf{l}-\mathbf{L})\rangle_G = (2\pi)^2 C_{L'}^{\phi_{\rm ext}\phi}\left\langle \frac{\delta}{\delta\phi(\mathbf{L}')^*}\left(X_{\rm expt}(\mathbf{l})\tilde{Y}^*_{\rm expt}(\mathbf{l}-\mathbf{L})\right)\right\rangle_G$$
$$= (2\pi)^2\delta(\mathbf{L}+\mathbf{L}')C_L^{\phi_{\rm ext}\phi} f^{XY}(\mathbf{l},\mathbf{L}-\mathbf{l}).$$

$$\left\langle \frac{\delta}{\delta\phi(\mathbf{L})}\left(\tilde{X}(\mathbf{l}_1)\tilde{Y}(\mathbf{l}_2)\right)\right\rangle_G = \delta(\mathbf{l}_1+\mathbf{l}_2-\mathbf{L})f^{XY}(\mathbf{l}_1,\mathbf{l}_2)$$

$$\langle \phi_{\rm ext}(\mathbf{L}')\hat{\phi}^{XY}(\mathbf{L})\rangle = (2\pi)^2\delta(\mathbf{L}+\mathbf{L}')C_L^{\phi_{\rm ext}\phi}+$$

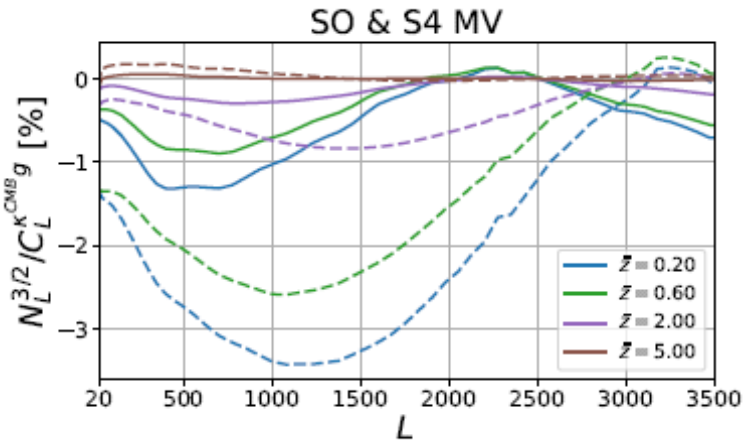
$$+(2\pi)^4\frac{A_L^{XY}}{2}\int_{\mathbf{l}_1} B^{\phi_{\rm ext}\phi\phi}(L',l_1,|\mathbf{L}'+\mathbf{l}_1|)\int_{\mathbf{l}} g_{XY}(\mathbf{l},\mathbf{L})\left\langle \frac{\delta\left(\tilde{X}(\mathbf{l})\tilde{Y}^*(\mathbf{l}-\mathbf{L})\right)}{\delta\phi(\mathbf{l}_1)\delta\phi^*(\mathbf{l}_1+\mathbf{L}')}\right\rangle_G + \ldots.$$

$N^{(3/2)}$ cross-correlation bias due to non-Gaussianity

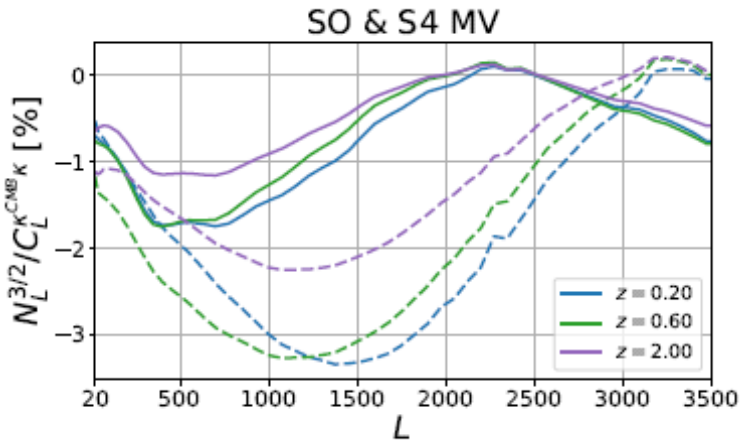
Two bispectrum contributions: Non-linear structure growth and post-Born Lensing

- partly cancel (Pratten & Lewis 1605.05662)

Fractional Non-Gaussian Bias



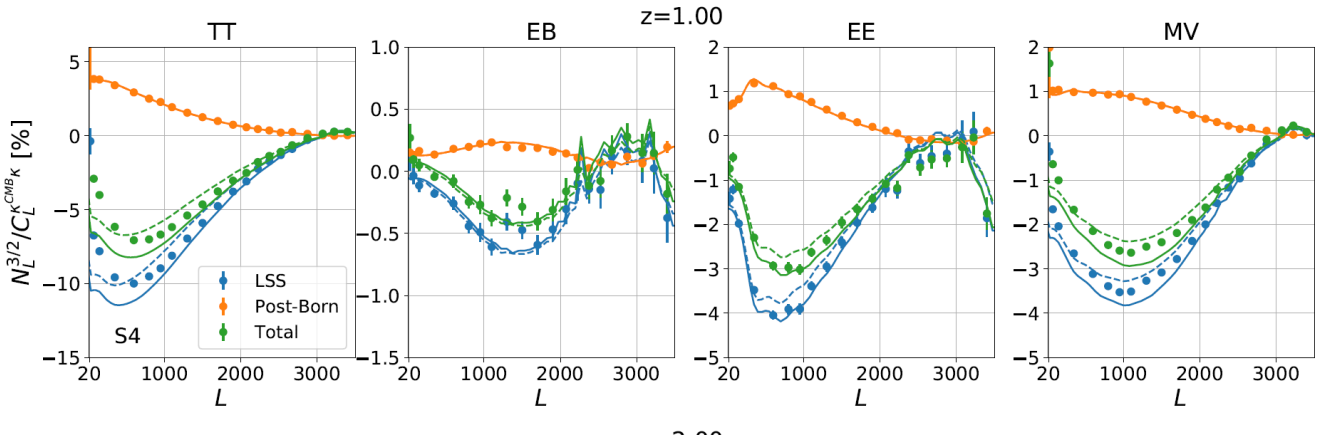
CMB lensing x galaxies



CMB lensing x galaxy lensing

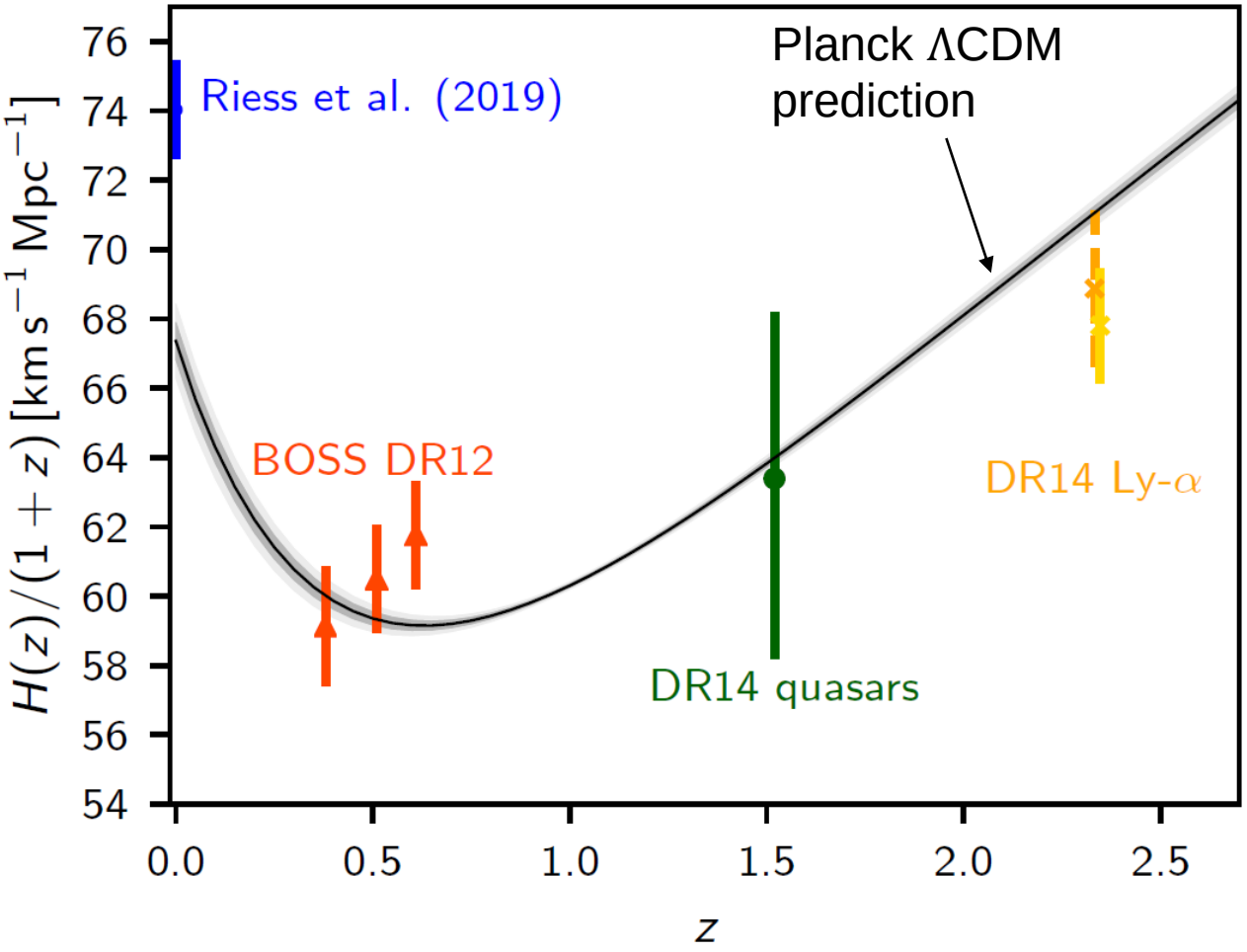
e.g.
galaxy lensing cross with S4 CMB lensing

Test with simulations



Trouble with ΛCDM?

The Hubble discrepancy assuming ΛCDM sound horizon r_d

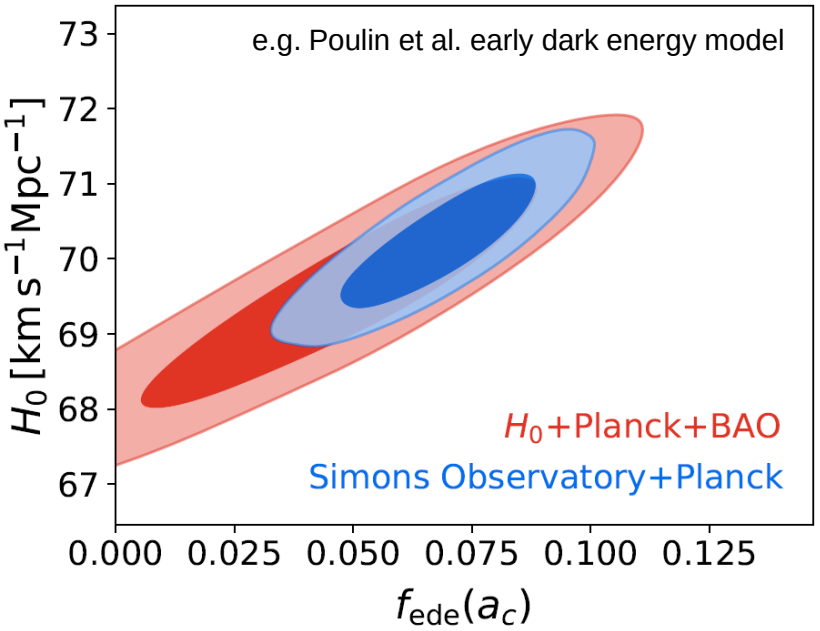


Possible solution: change sound horizon r_d by new physics before recombination

High resolution/sensitivity polarization:

precision small-scale EE, TE, TT power spectrum

If $H_0 \sim 73\ \mathrm{km\ s^{-1} Mpc^{-1}}$,
new pre-recombination physics
likely detectable at >~ 5σ



Conclusions

- CMB lensing powerful cosmological probe
  - high significance measurement with Planck
  - CMB lensing +BAO provides tight constraints on H_0, σ_8
  - complementary to galaxy lensing

- Delensing works! Planck 2018 internal delensing:
  - High significance detection of peak sharpening (T/E)
  - First detection of B-mode delensing
  - Improved delensing using Planck CIB

- Simons Observatory (and other expts.) will greatly improve the CMB lensing reconstruction to small scales
  - much more detailed modelling will be required

- If H_0 tension persists, future very interesting
  - independent $\sim 5\sigma$ internal detection of non-ΛCDM from CMB alone