Galactic foreground bias in CMB lensing convergence reconstruction

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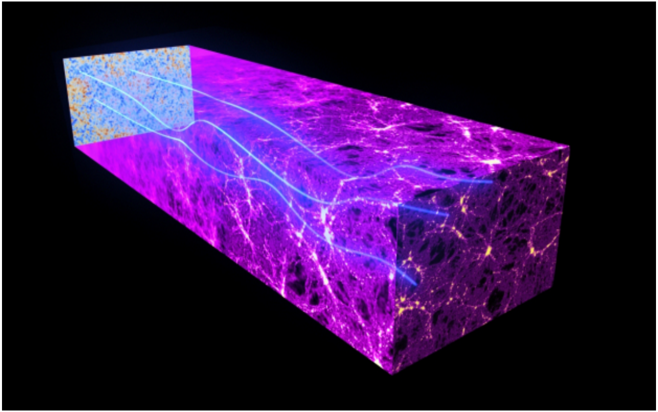
Outline

Weak lensing of CMB

- CMB photons experience lensing by the intervening matter distribution.



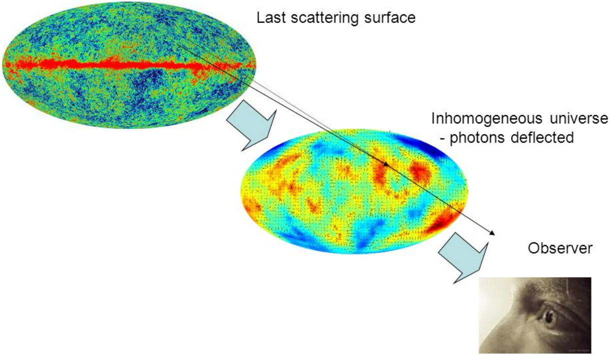
Credits - EAS

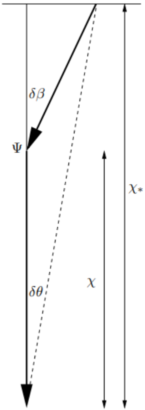
Deflection angle

- Lensing remaps the primordial CMB signal on the sky.

$$\begin{aligned} T(\hat{n}) &= T^{unl}(\hat{n} + \nabla\phi(\hat{n})) \\ [Q + iU](\hat{n}) &= [Q^{unl} + iU^{unl}](\hat{n} + \nabla\phi(\hat{n})) \end{aligned} \quad (1)$$

- The deflection angle depends on the gradiant of lensing potential, ϕ.


Last scattering surface
Inhomogeneous universe
- photons deflected
Observer


$\delta\beta$
Ψ
χ_*
$\delta\theta$
χ

A. Lewis (2016)

Lensing potential

- Integrated effect of intervening large scale structure.
- Line-of-sight projection of Weyl gravitational potential.

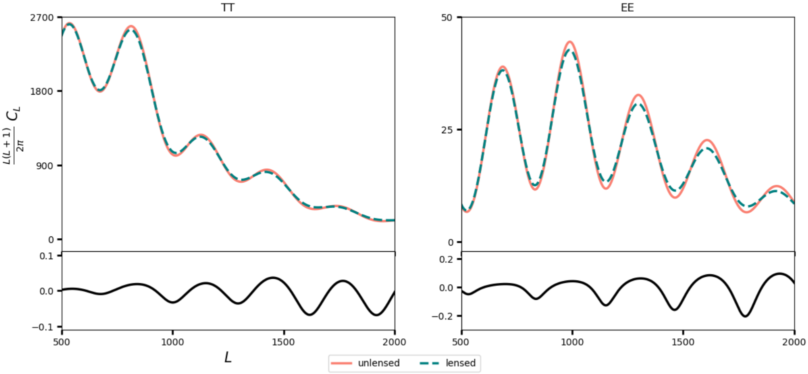
$$\phi(\hat{n}) = -2\int_0^{\chi_s} d\chi \frac{D_A(\chi - \chi_s)}{D_A(\chi_s)D_A(\chi)}\Psi(\chi\hat{n}, \eta_0 - \chi) \tag{2}$$

- Gaussain random field characterised by lensing power spectra.
- Lensing power is maximum at degree scale.

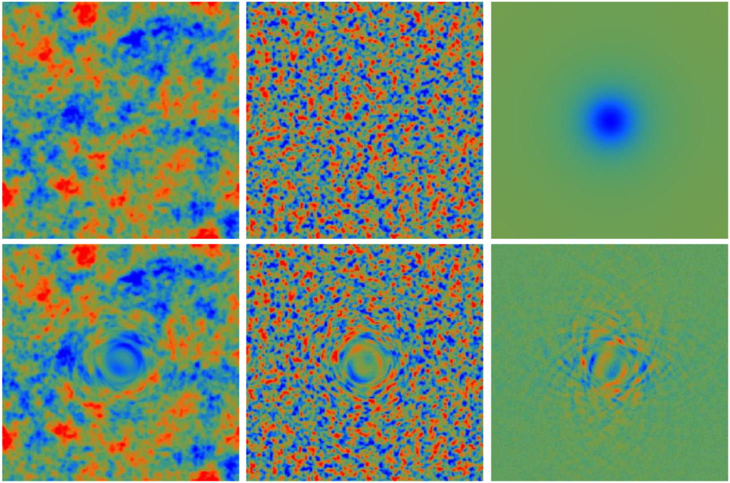
Lensing effects

- Lensing smooths out the angular power spectra.
- **Interesting** : Lensing mixes the power between large scales and small scales.
- **Important** : It generates lensing B-modes from primordial E-modes.

Angular power spectra



Lensing example



Hu & Okamoto (2002)

Lensing reconstruction

- Mode-coupling between multipoles in fourier space.

$$\delta T(\mathbf{l}) = \int \frac{d^2\mathbf{l}_1}{2\pi}(\mathbf{l}_1 - \mathbf{l}).\mathbf{l}_1 \tilde{T}(\mathbf{l}_1)\phi(\mathbf{l} - \mathbf{l}_1) \quad (3)$$

- Ensemble average of random Gaussian CMB realisations for a fixed potential field $\implies$

$$\langle T(\mathbf{l})T(\mathbf{l}')\rangle_{CMB} = f_{\alpha}^{TT}(\mathbf{l}, \mathbf{l}')\phi(L) \quad (4)$$

where, $L = \mathbf{l} + \mathbf{l}'$, assuming $\mathbf{l} \neq -\mathbf{l}'$

- The factor f_{α}^{TT} is fixed combination of unlensed power spectra.

Quadratic Estimators

- Generalised estimate of ϕ :

$$\langle x(\mathbf{l})x(\mathbf{l}')\rangle_{CMB} = f_\alpha(\mathbf{l},\mathbf{l}')\phi(L) \tag{5}$$

where, $x, x' = T, E, B$.

- ϕ is statistically isotropic $\implies \langle\phi(L)\rangle = 0$.
- Okamoto & Hu estimator :

$$d_\alpha(L) = \frac{A_\alpha(L)}{L}\int \frac{d^2\mathbf{l}_1}{(2\pi)^2} x(\mathbf{l}_1)x'(\mathbf{l}_2)g_\alpha(\mathbf{l}_1,\mathbf{l}_2) \tag{6}$$

where, $\mathbf{l}_2 = L - \mathbf{l}_1$ and the normlaization satisfies,
$\langle d_\alpha(L)\rangle_{CMB} = L\phi(L)$

Four-point correlation

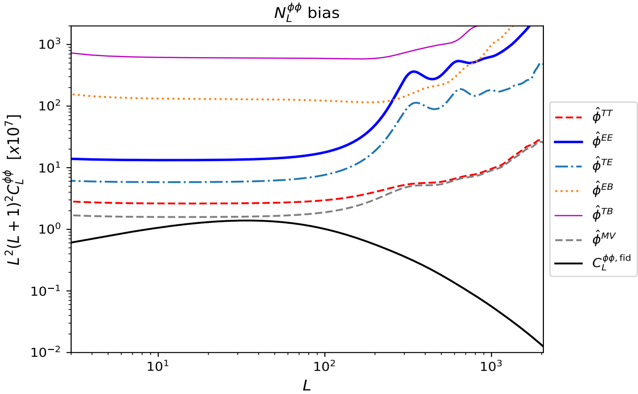
- Minimize $\langle d^*_\alpha(L) d_\alpha(L') \rangle \implies$ mimimum variance weights $g_\alpha(\mathrm{l}_1, \mathrm{l}_2)$.
- The lensing power spectra reconstruction is,

$$\langle d^*_\alpha(L) d_\beta(L') \rangle = (2\pi)^2 \delta(L - L') \left[C_L^{\phi\phi} + N_L^{\alpha\beta} \right] \tag{7}$$

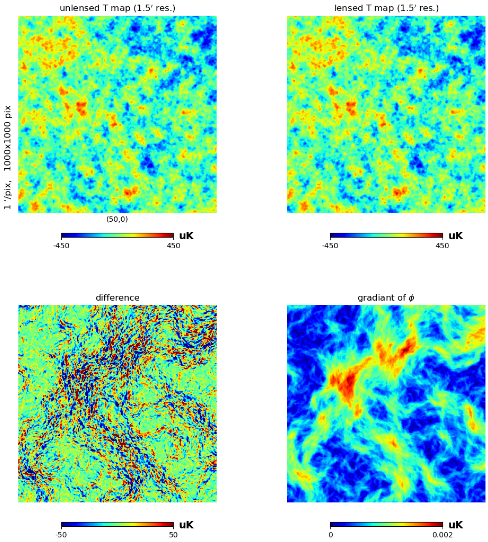
  with noise covarince $N_L^{\alpha\beta}$.
- Quadratic estimators (QE) $\implies$ determine 4-point correlation function.

Reconstruction noise

- The noise is dominated by $N_L^{(0)}$ bias from disconnected part of QE.



Lensing simulations



CMB-S4 survey

- Next generation ground-based CMB survey.

South-Pole

Chile

- Targets galactic polar regions $\implies$ both small and large scales.

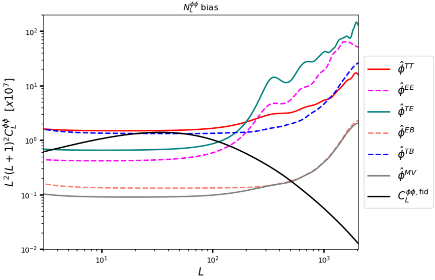
Noise properties

- Isotropic Gaussian noise with power spectra,

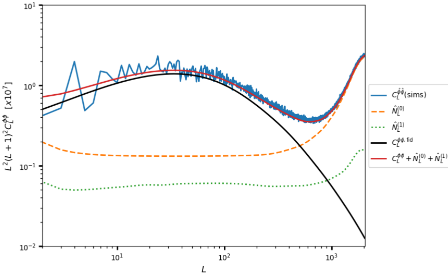
$$N_l^{TT} = (\sigma_T)^2 \exp\left(\frac{[l(l+1)\theta_{\mathrm{FWHM}}]^2}{8\log 2}\right) \tag{8}$$

- For large aperture telescopes :
  - Angular resolution $(\theta_{\mathrm{FWHM}}) = 1.5$ arcminute
  - Noise level in T $(\sigma_T) = 2.0$ μK-arcminute
- For polarization : $\sigma_P = \sqrt{2}\sigma_T$

Lensing reconstruction

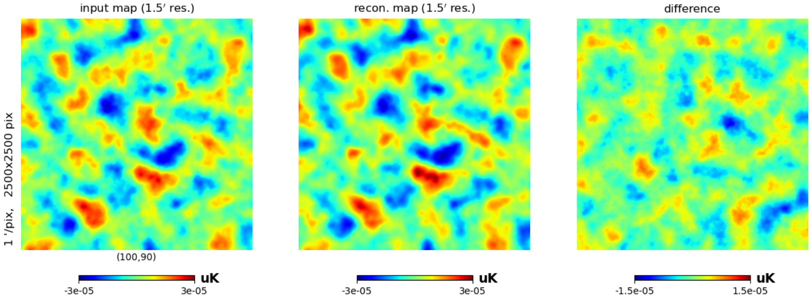


EB estimator

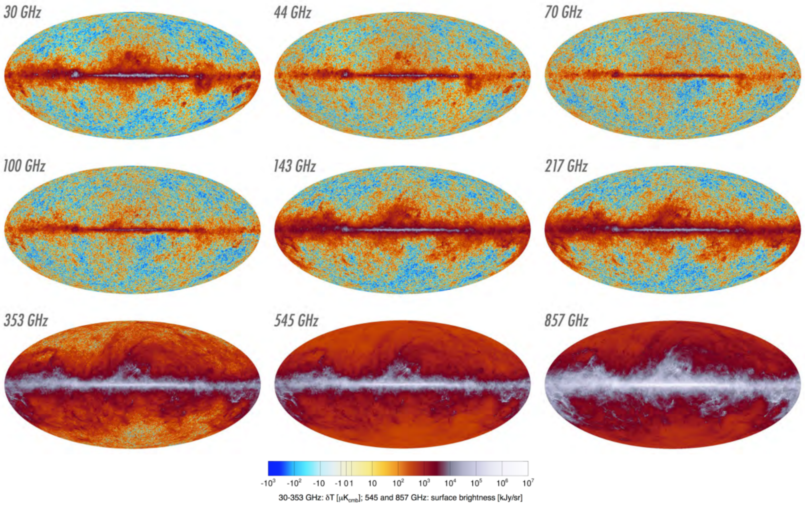


- The EB estimator has lowest reconstruction bias.
- $N_L^{(1)}$ bias is very small and higher order $N_L^{(p)}$ bias are even smaller.

Lensing potential



CMB Foregrounds



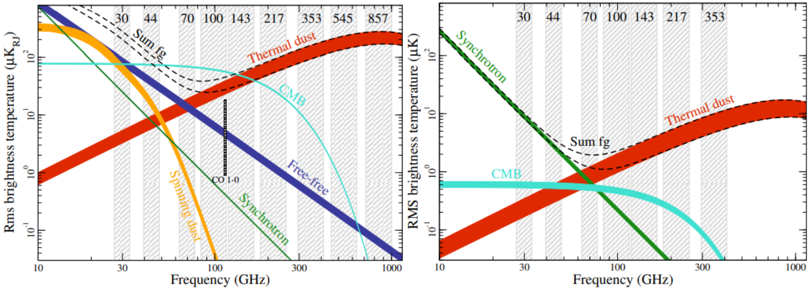
Planck 2015 results I.

Galactic Foregrounds

Different emissions dominates at different frequencies –

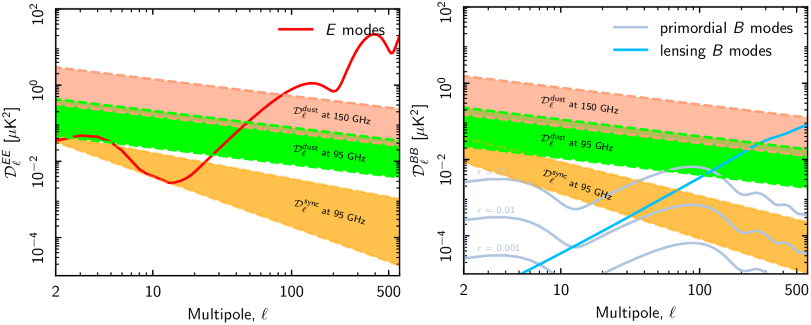
- Thermal dust emission: dust + galactic magnetic field (GMF)
- Synchrotron emission : relativistic electron accelerated by GMF
- Free-Free emission : Warm Ionized Medium
- Spinning dust : Rotating dipole radiation

Foreground contributions



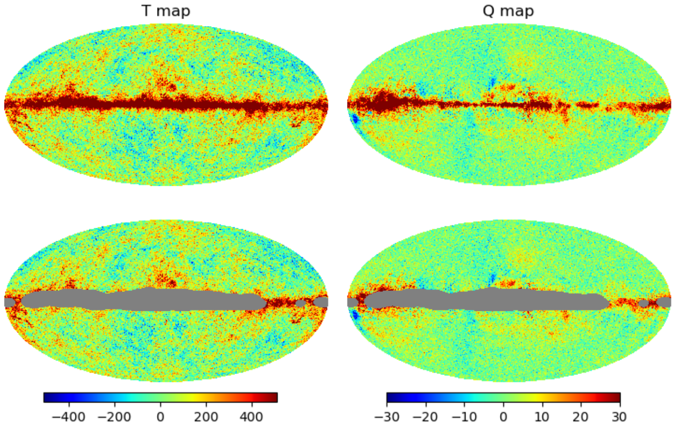
Planck results (2015 & 2018)

Contamination in polarisation

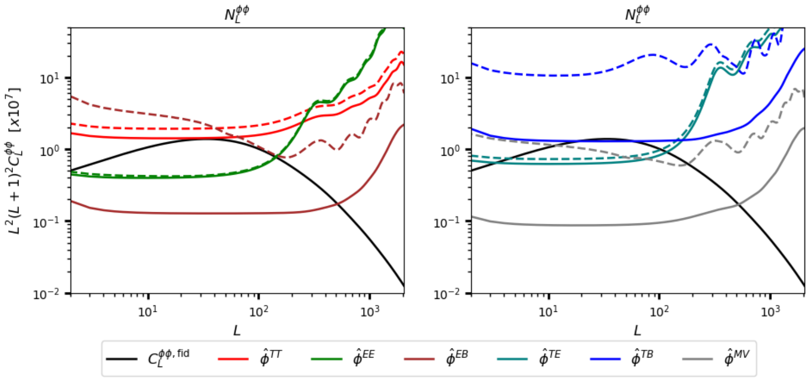


Planck 2018 results XI.

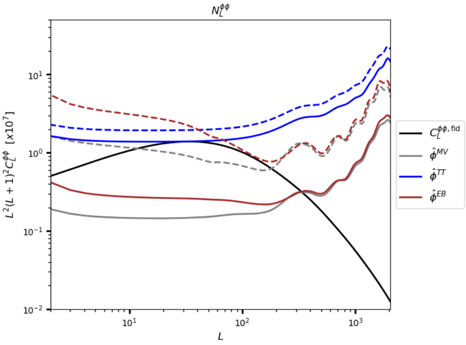
Foregrounds at 145GHz



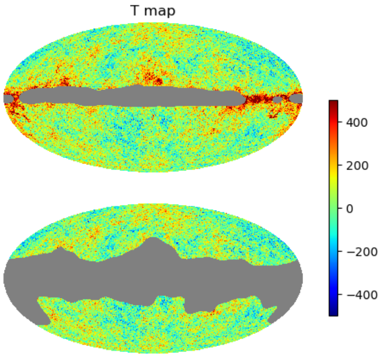
Foreground bias



Masking

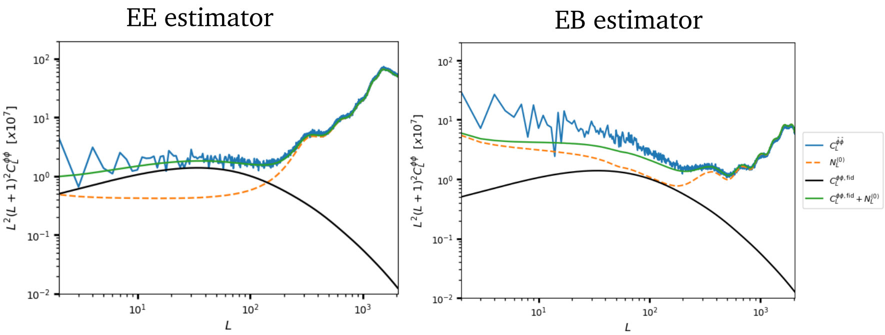


$N_L^{\phi\phi}$
$L^2(L+1)^2 C_L^{\phi\phi}$ [x10^7]
10^1
10^0
10^{-1}
10^{-2}
10^1
10^2
10^3
L
$C_L^{\phi\phi,\mathrm{fid}}$
$\hat{\phi}^{MV}$
$\hat{\phi}^{TT}$
$\hat{\phi}^{EB}$



T map
400
200
0
−200
−400

Lensing reconstruction



- EB estimator result has extra bias that can not be accounted only by reconstruction bias.
- Higher order $N_L^{(p)}$ bias is too small to add significant deviation.

$F_L^{syst.}$ bias : another term

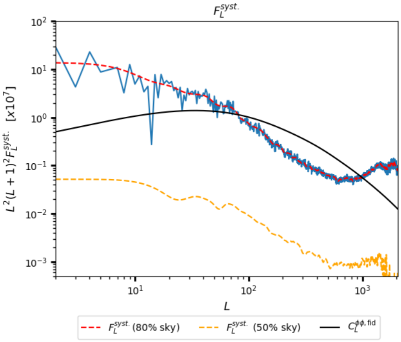
- Lensing power spectra estimator includes foreground power.

$$\hat{C}_L^{\phi\phi} = \frac{1}{2L+1} \sum_M \hat{\phi}^*_{LM} \, \hat{\phi}_{LM} - N_L(C_l) \tag{9}$$

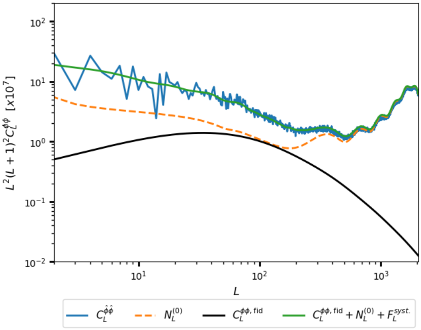
- The bias term arises as,

$$F_L^{syst.} = \frac{1}{2L+1} \sum_M \hat{f}^*_{LM} \hat{f}_{LM} - N_L^{(0)}(F_l) \tag{10}$$

Foreground bias



EB estimator



Summary

- Polarisation field estimators performs well for CMB-S4 like experiments.
- Foreground contamination have huge impact on EB polarisation field estimator.
- Component separation will reduce the $F_L^{\text{syst.}}$ bias.
- We will study residual $F_L^{\text{res.}}$ bias after component separation.

Thank You.

Minimum variance combination

- A generalised inverse variance weighting yields,

$$d_L^{mv} = \sum_\alpha w_L^\alpha d_L^\alpha \tag{11}$$

where,

$$w_\alpha = \frac{\sum_\beta (\mathbf{N}^{-1})_{\alpha\beta}}{\sum_{\beta_\gamma} (\mathbf{N}^{-1})_{\beta\gamma}} \quad , \quad N_{mv} = \frac{1}{(\sum_{\beta_\gamma} \mathbf{N}^{-1})_{\beta\gamma}}$$

- Minimum variance estimator reduce reconstruction noise.
- BB estimator is neglected.