Galactic foreground bias in CMB lensing reconstruction

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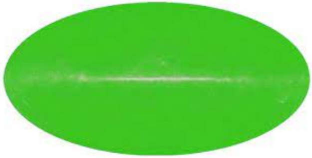
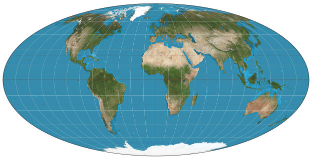
Cosmic Microwave Background (CMB)

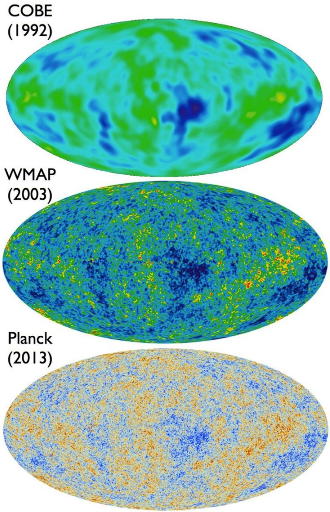
- Penzias and Wilson first measured the CMB in 1964.



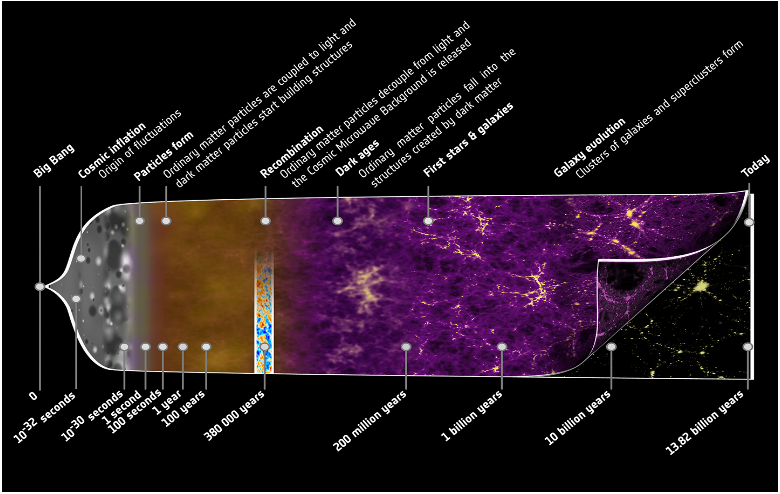
Penzias & Wilson



Mollweide projection

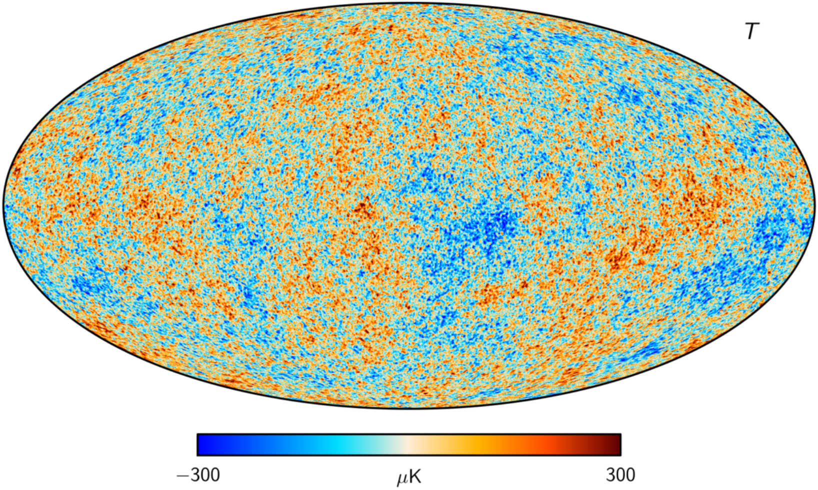


Big Bang model



Planck team(ESA)

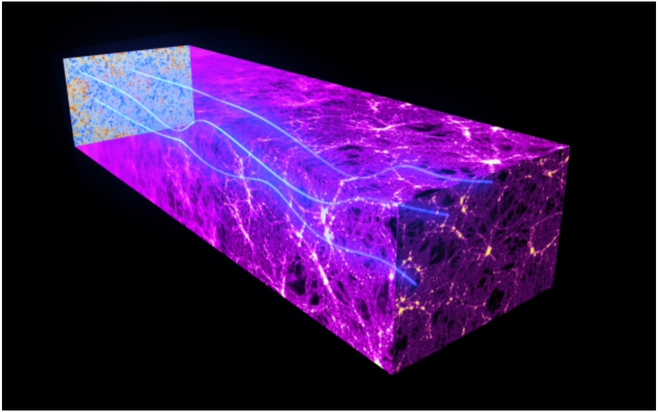
Planck full-sky survey



Planck (2018)

CMB is weakly lensed

- CMB photons experience lensing by the intervening matter distribution.



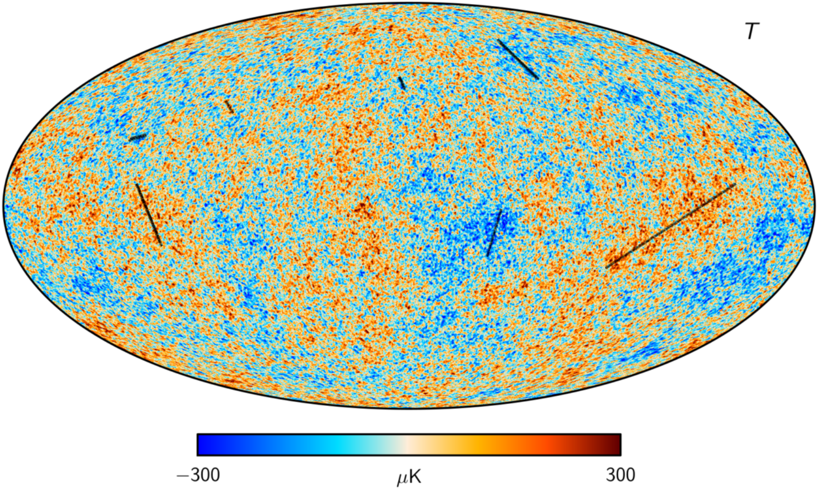
Planck (EAS)

Motivation

To probe primordial anisotropies :

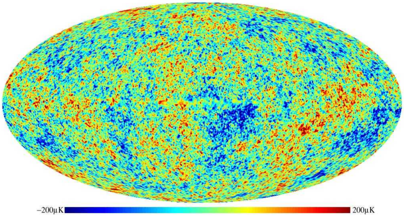
1. Retrace the lensing
   $\Longrightarrow$ reconstruct the lensing field.
2. De-lense the observed CMB maps

CMB anisotropies



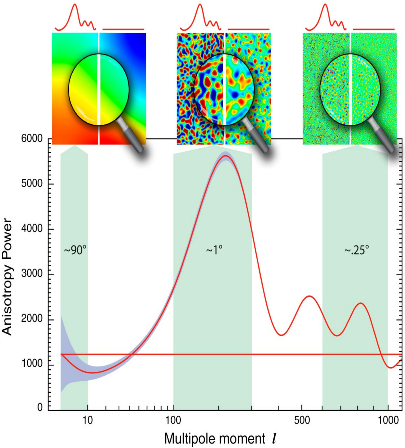
Planck (2018)

Statistics of the anisotropies



Tegmark et. al. (WMAP)

- Anisotropies as a function of angular size
- Multipole moment,
  $$l \sim \pi/\theta$$

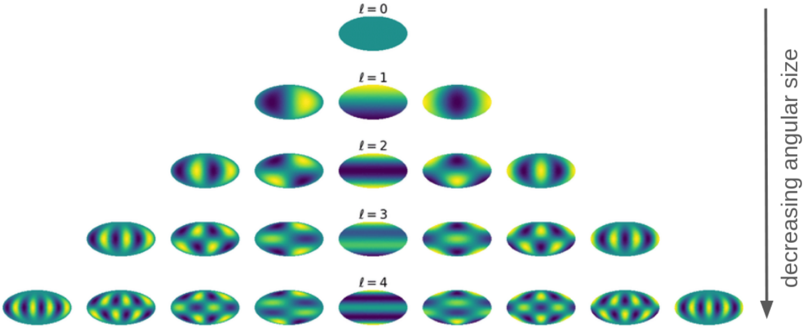


WMAP (NASA)

Spherical harmonics

- Temperature fluctuations are decomposed in spherical harmonic basis :

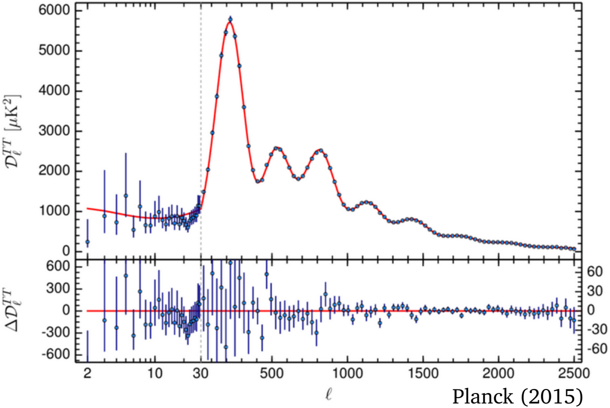
$$\frac{\Delta T}{T} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm}^{T} Y_l^m$$



Angular power spectra

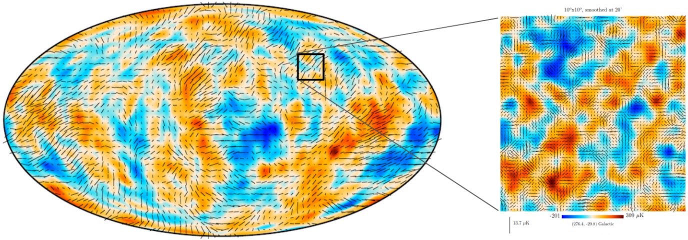
- **Power spectra** : Fluctuations as a function of angular size.

$$C_l^{TT} = \frac{1}{2l+1} \sum_{m=-l}^{l} a_{lm}^{T*} a_{lm}^{T}$$

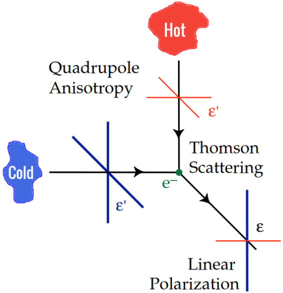


Planck (2015)

Polarisation in CMB



- Thomson scattering by electrons
- Hot and cold patches at 90°



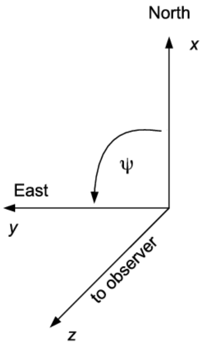
W. Hu (1997)

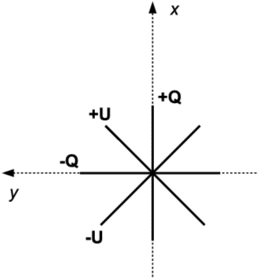
Measuring polarisation

Stokes parameters are measured as,

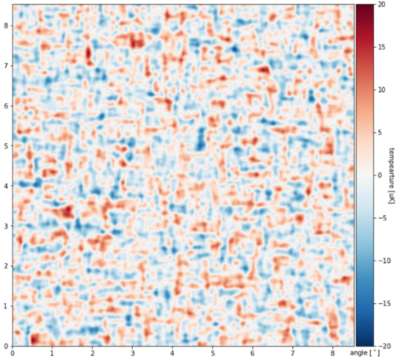
$$Q \propto E_x^2 - E_y^2$$
$$U \propto E_{45^\circ}^2 - E_{-45^\circ}^2$$

Q and U are rotationally **not** invariant.

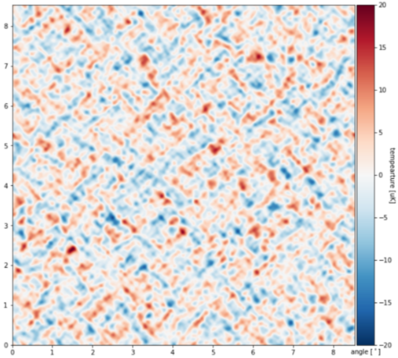




Q and U maps



Q

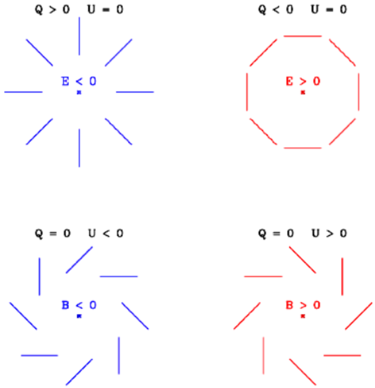


U

Planck (2015)

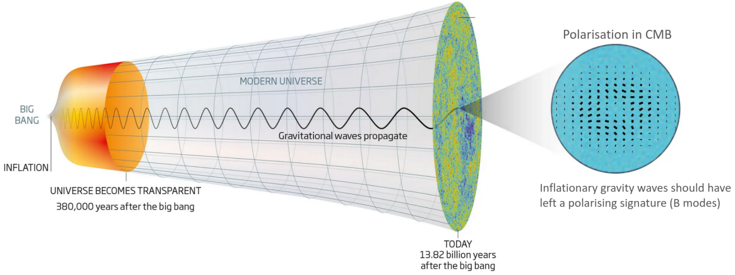
E and B modes

- **E modes** :
  "Gradient-like",
  parity even.
- **B modes** :
  "Curl-like",
  parity odd.



Density perturbations (scalar) generate only *E modes*.
Gravity waves (tensor) generate both *E* and *B modes*.

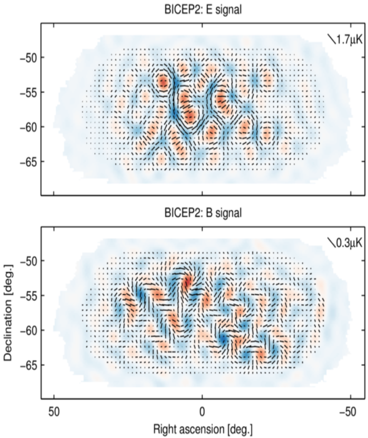
Evidence of inflation



- Primordial gravity waves (tensor modes) creates B modes $\implies$ C_l^{BB} is non-zero
  Smoking gun evidence for inflation.

Measuring E and B modes

Recent and future experiments targets detection of primordial B modes.



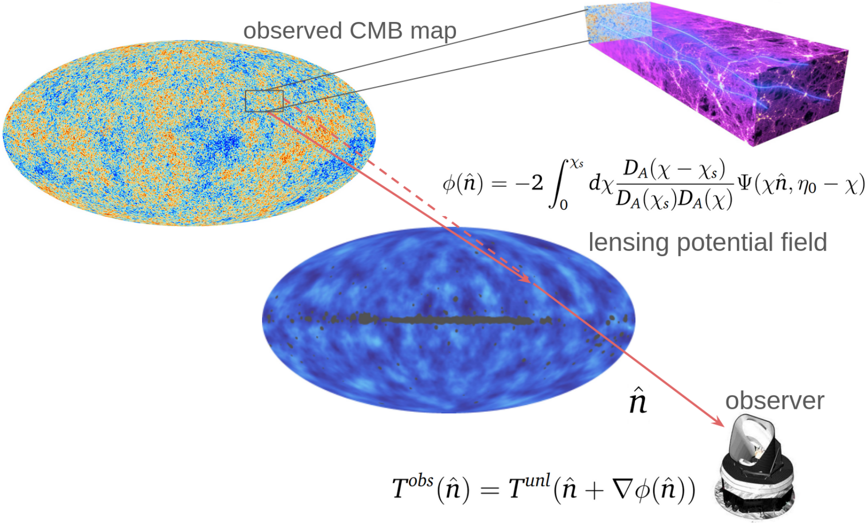
BICEP2 (2013)

UWAGA!!!

There is a catch...actually two.

1. CMB lensing
2. Foregrounds

CMB Lensing

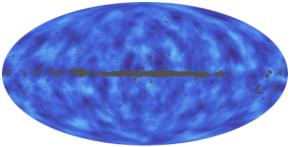


$$\phi(\hat{n}) = -2\int_0^{\chi_s} d\chi \frac{D_A(\chi - \chi_s)}{D_A(\chi_s)D_A(\chi)}\Psi(\chi\hat{n}, \eta_0 - \chi)$$

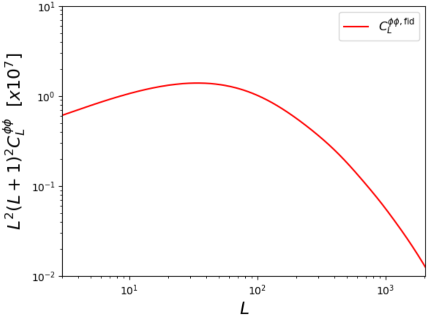
$$T^{obs}(\hat{n}) = T^{unl}(\hat{n} + \nabla\phi(\hat{n}))$$

Lensing potential

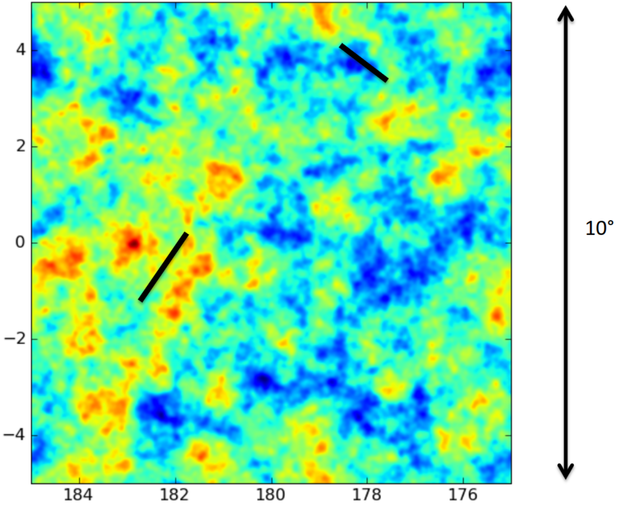
- Lensing field is characterised by lensing power spectra.
- Lensing amplitude is maximum at degree scale.



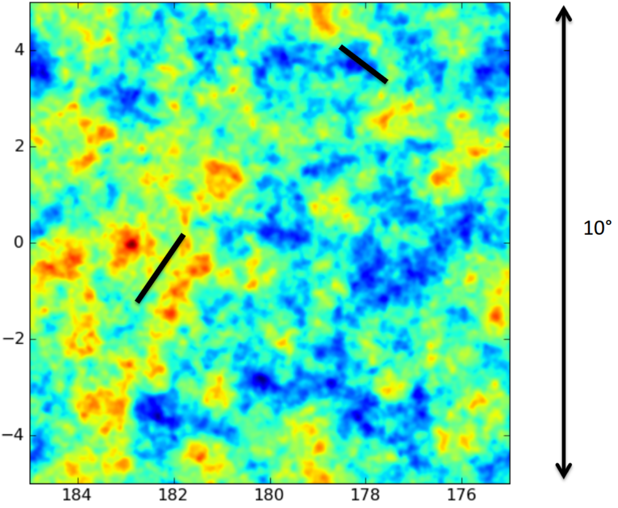
Planck (2015)



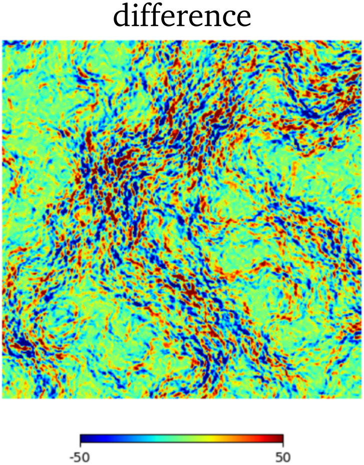
Unlensed T map

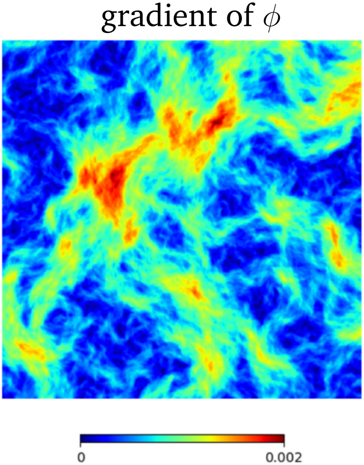


Lensed T map



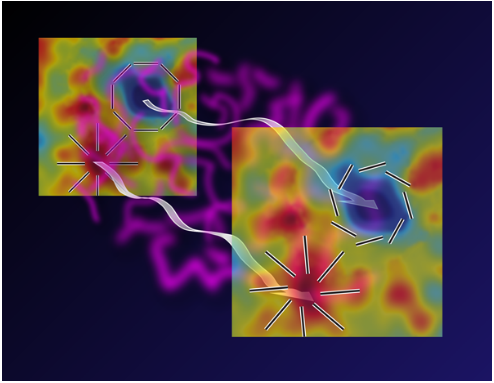
Difference map





Lensing B modes

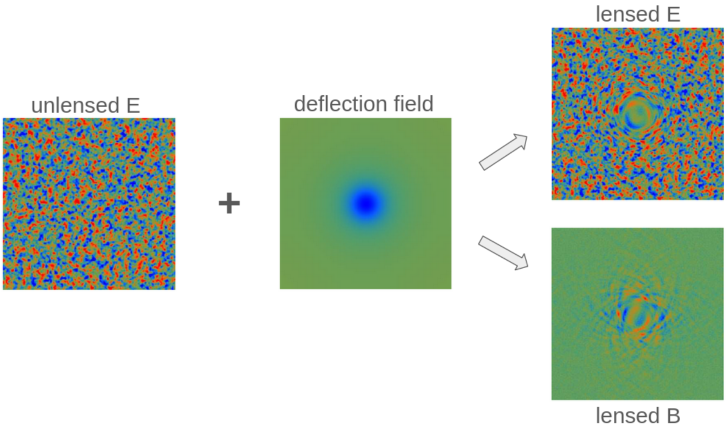
- Lensing twists primordial E modes
  $\Longrightarrow$ generates lensing B modes



APS / Alan Stonebrake

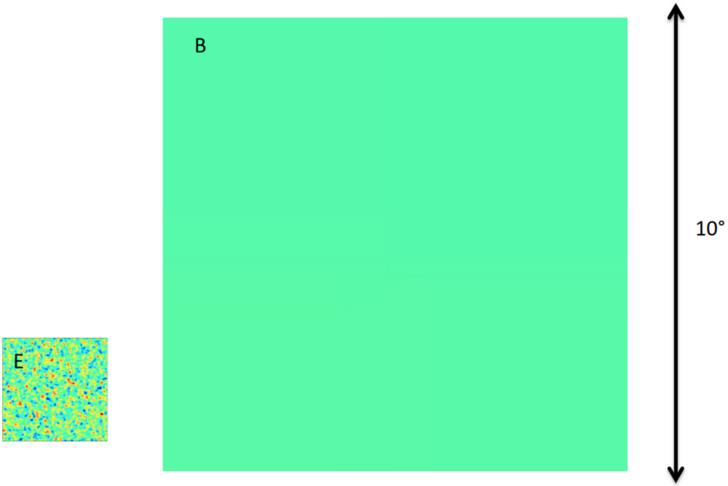
An illustrative example

Here is an exaggerated example of lensing by a Gaussian deflection field.

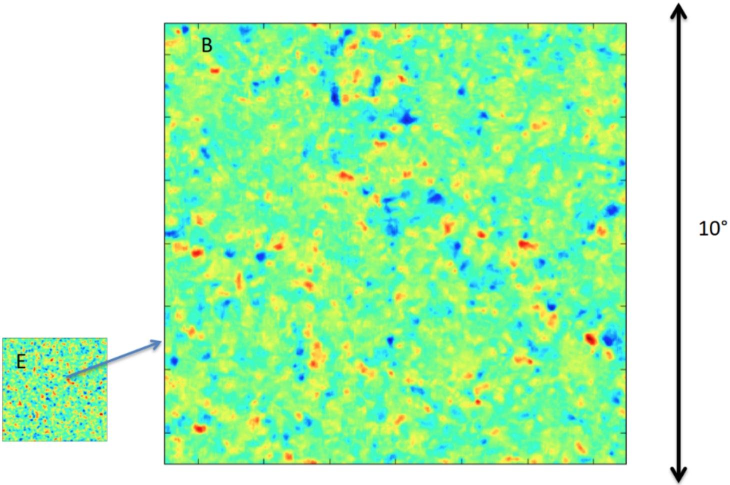


W. Hu (2000)

Unlensed B map

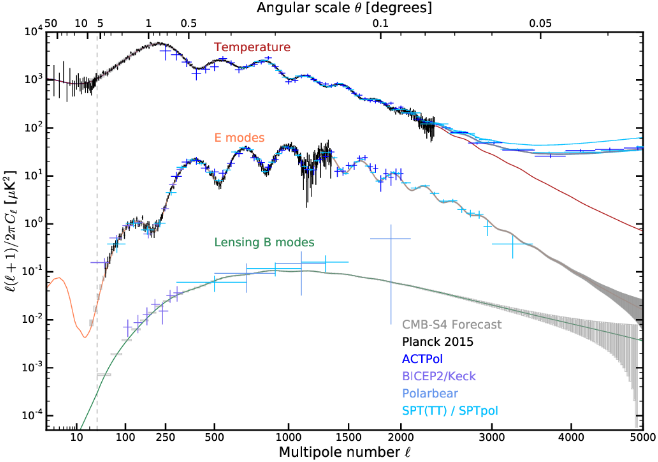


Lensed B map



Observational evidence

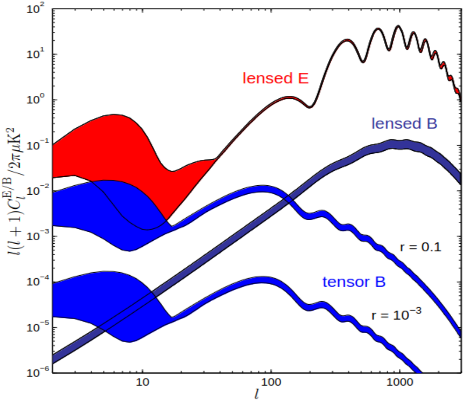
- E modes and lensing B modes have been detected by different observations.



CMB-S4 Science Book

Primordial B modes

- Lensing B modes dominates primordial B modes.
- Tensor-to-scalar ratio (r) : amplitude of tensor perturbation to amplitude of scalar perturbation.



Lewis, Challinor (2006)

Why lensing reconstruction?

Lensing reconstruction of the deflection field is important :

- Subtract lensed B modes to probe primordial B modes.
- Improved constrains on cosmological parameters.
- Probe matter distribution of the universe.

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CMB-S4 survey

- Next generation ground-based CMB survey.

South-Pole

Chile

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

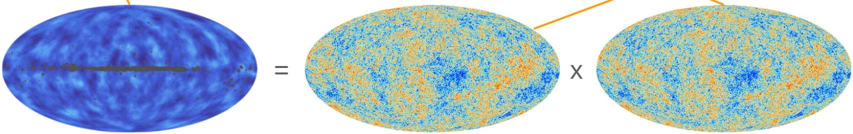
CMB-S4 specifications

- For large aperature telescopes :
  - Angular resolution $(FWHM)$ = 1.5 arcminute
  - Noise level in T (σ_T) = 2 μK-arcminute
- For comparison, Planck satellite had :
  - Angular resolution $(FWHM)$ = 5 arcminute (temperature)
  - Angular resolution $(FWHM)$ = 10 arcminute (polarisation)
  - Noise level in T (σ_T) = 35 μK-arcminute

Lensing reconstruction

- Lensing generates correlated statistical anisotropies.
- Quadratic combination of two CMB observations provides a noisy lensing estimate.

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



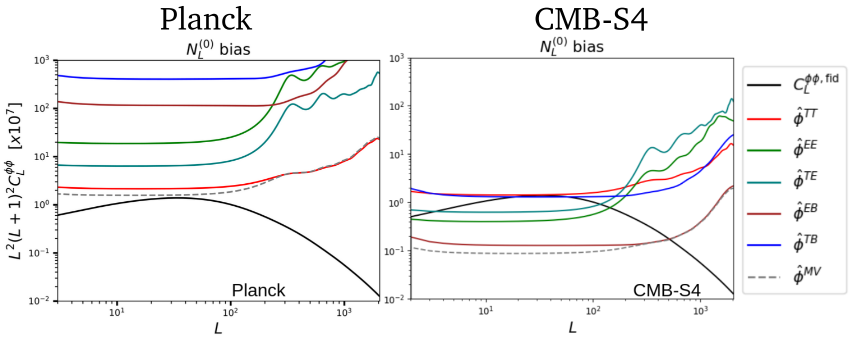
Quadratic Estimator

- The lensing power spectra is reconstructed,

$$\langle \phi^*_{LM} \phi_{L'M'} \rangle = (2\pi)^2 \delta(L - L') \left[C_L^{\phi\phi} + N_L^{\phi\phi} \right]$$

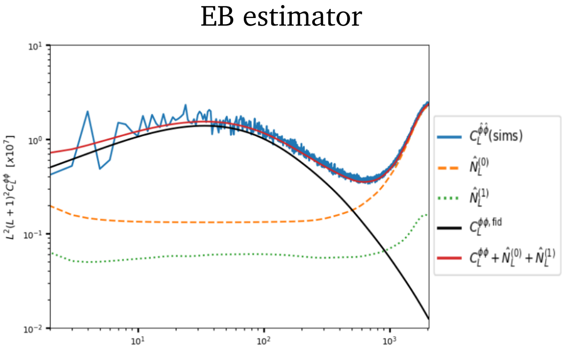
  accompanied by a noise covarince $N_L^{\phi\phi}$.
- Quadratic estimation (QE) $\implies$ determine 4-point correlation function.
- The noise ($N_L^{\phi\phi}$) is dominated by $N_L^{(0)}$ bias from disconnected part of QE.

Reconstruction noise



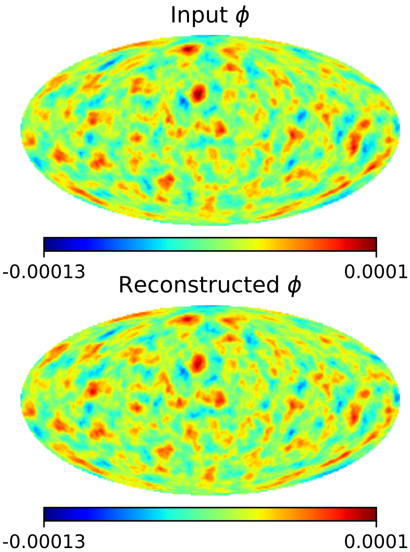
- For CMB-S4 survey, the EB estimator has the lowest reconstruction bias.
- Minimum Variance (MV) combination of all estimators has the least bias by construction.

Lensing reconstruction

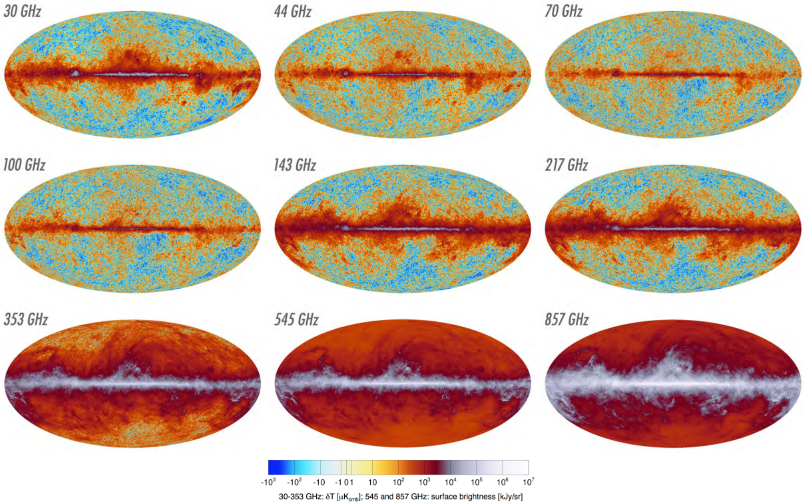


- Noise dominates at high multipoles.
- $N_L^{(1)}$ bias is very small and higher order $N_L^{(p)}$ biases are smaller.

Full-sky reconstruction

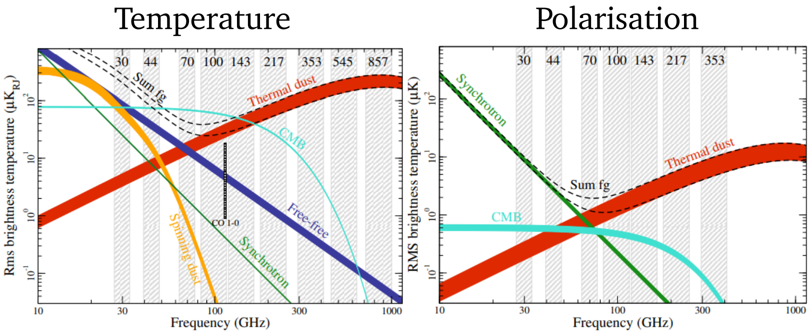


CMB Foregrounds



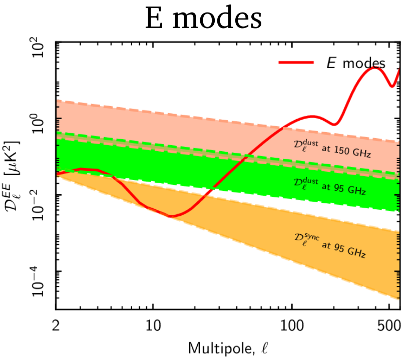
Planck (2015)

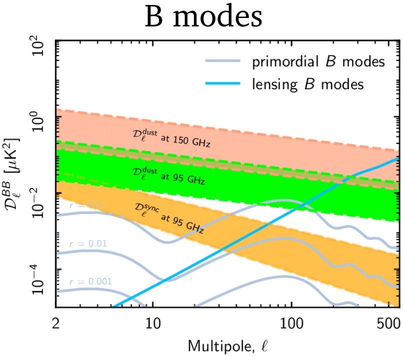
Foreground contributions



Planck (2018)

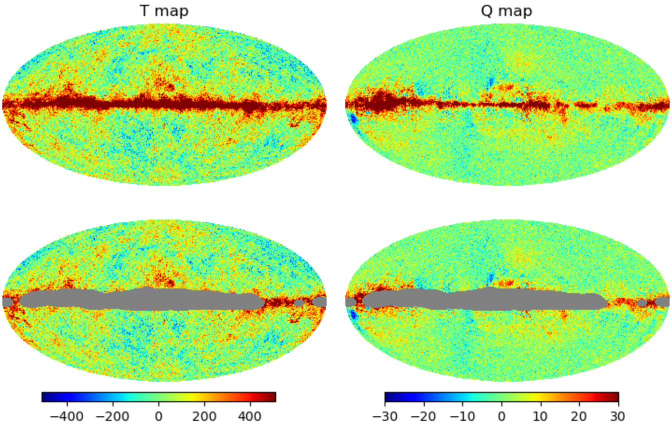
Contamination in polarisation





Planck (2018)

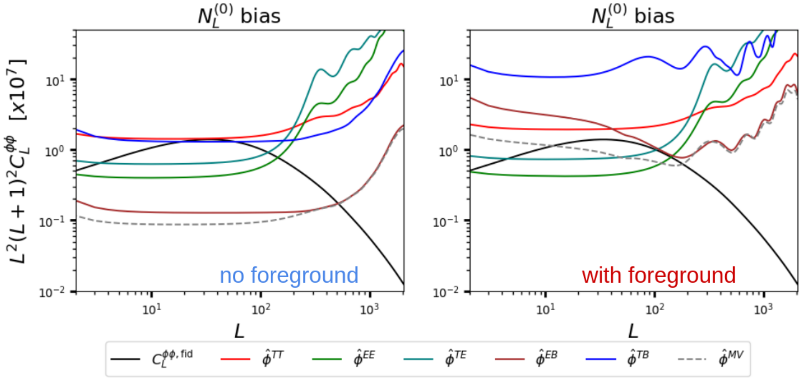
Foregrounds at 145GHz



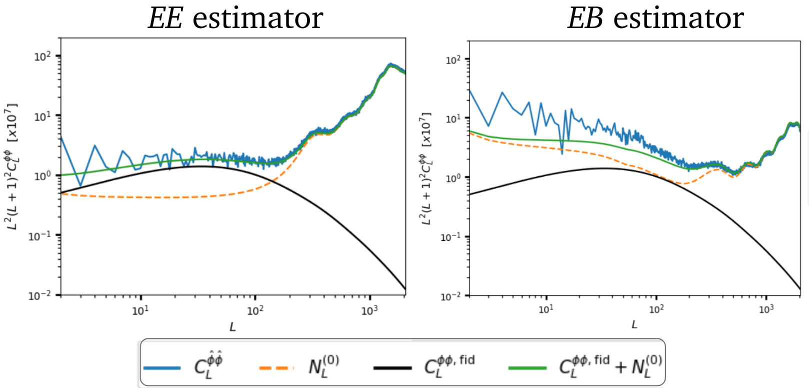
Galactic plane is masked (80% of the sky).

Foreground bias

Reconstruction noise increases in presence of foreground.
We use 80% of the sky for lensing reconstruction.



Lensing reconstruction



Lensing reconstruction on 80% of sky with foregrounds.

- EB estimator result has an extra bias.
- Higher order $N_L^{(p)}$ bias are too small to add significant deviation.

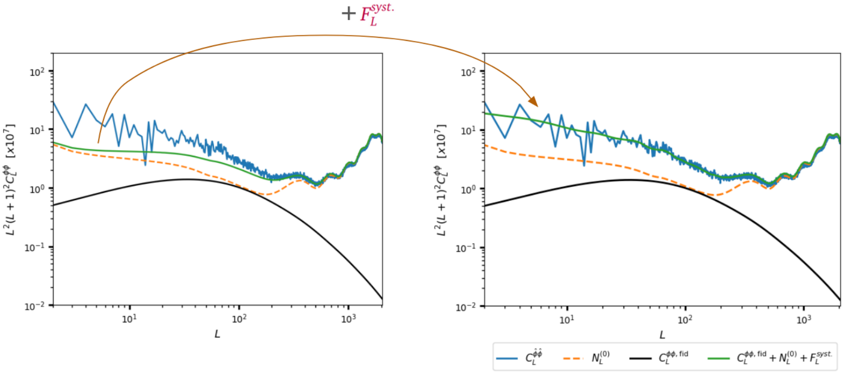
$F_L^{syst.}$ bias : another term

- Lensing power spectra estimator includes foreground power.

$$\frac{1}{2L+1}\sum_M \langle \phi_{LM}^* \phi_{LM} \rangle = C_L^{\phi\phi} + N_L^{\phi\phi} + F_L^{syst.} \tag{1}$$

- The $F_L^{syst.}$ term is computed using lensing reconstruction algorithm on foreground only maps.

The biases adds up



- $F_L^{syst.}$ term corrects the bias in low multipole.

Summary

- Lensing reconstruction is crucial to remove lensing B modes.
- Polarisation field estimators performs well for CMB-S4 experiment.
- Foreground contamination have huge impact on EB estimator (the best one).
- Foreground removal is necessary to reduce $F_L^{syst.}$ bias.
- I will study foreground residue bias on foreground removed CMB maps.

Thank You.

Backup slides ...

Minimum variance combination

- A generalised inverse variance weighting yields,

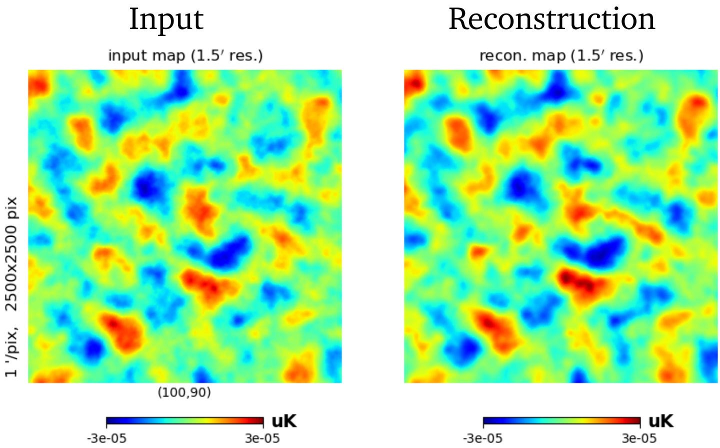
$$d_L^{mv} = \sum_\alpha w_L^\alpha d_L^\alpha \tag{2}$$

where,

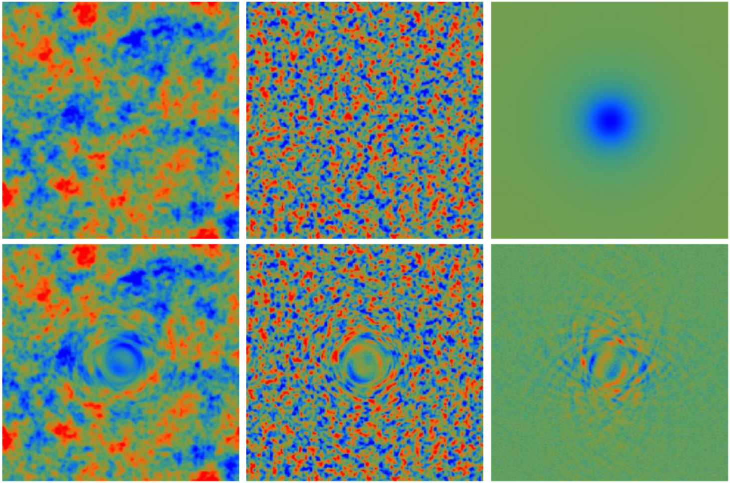
$$w_\alpha = \frac{\sum_\beta (\mathbf{N}^{-1})_\alpha \beta}{\sum_{\beta_\gamma} (\mathbf{N}^{-1})_\beta \gamma} \quad , \quad N_{mv} = \frac{1}{(\sum_{\beta_\gamma} \mathbf{N}^{-1})_\beta \gamma}$$

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

Reconstructed lensing field



Lensing example

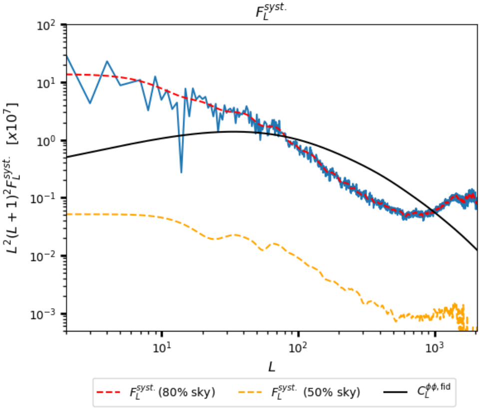


Hu & Okamoto (2002)

Lensing effects

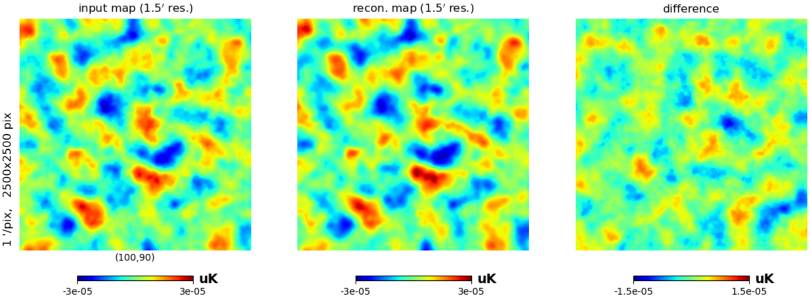
- Lensing smooths out the angular power spectra.
- **Interesting** : Lensing mixes the power between large scales and small scales.
- **Important** : It generates lensing B-modes from primordial E-modes.

$F_L^{syst.}$ bias

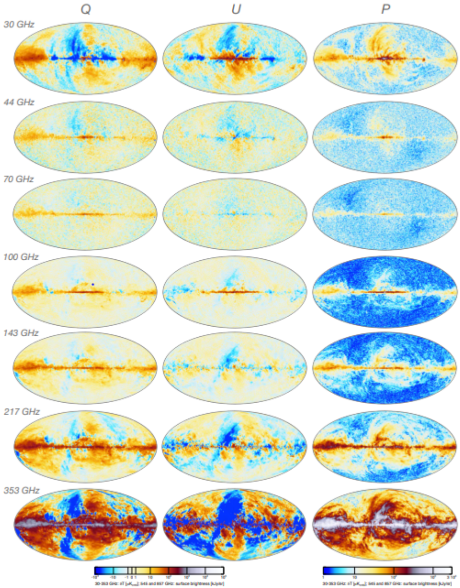


$F_L^{syst.}$
$L^2(L+1)^2 F_L^{syst.}$ [x10^7]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
L
$F_L^{syst.}$ (80% sky)
$F_L^{syst.}$ (50% sky)
$C_L^{\phi\phi,\mathrm{fid}}$

Lensing potential reconstruction

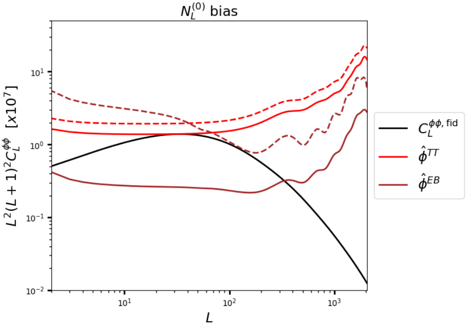


Foreground polarization (Planck 2015 resu

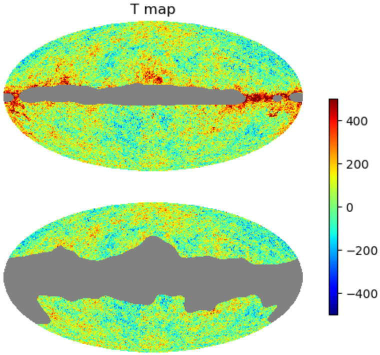


Masking

Masking larger part of galactic plane reduces bias.



solid : 50% sky, dashed : 80% sky.



top : 80% sky, bottom : 50% sky.

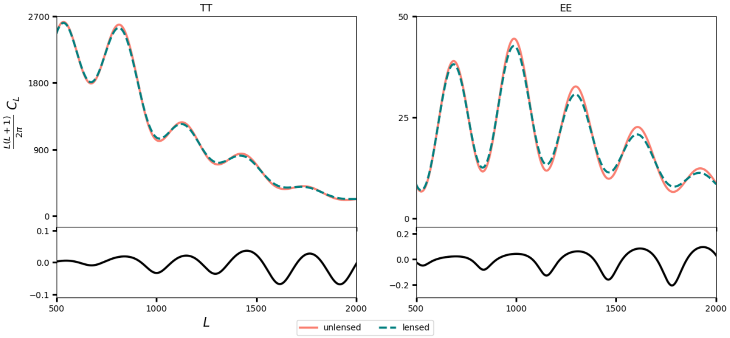
Galactic Foregrounds

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

Lensed power spectra

- Lensing smooths out the angular power spectra.



Lensing reconstruction

- Mode-coupling between multipoles in fourier space.

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

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

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

  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 :

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

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

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

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

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

E and B modes

$$\boxed{\tilde{Q} + i\tilde{U} = e^{-2i\psi}(Q + iU)}$$

- Q and U are spin-2 fields.

$$(Q \pm iU)(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm}^{\pm 2}\, {}_{\pm 2}Y_l^m = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} (a_{lm}^E \pm a_{lm}^B)\, {}_{\pm 2}Y_l^m$$

$$\boxed{a_{lm}^E = \frac{1}{2}(a_{lm}^{+2} + a_{lm}^{-2})}$$

$$\boxed{a_{lm}^B = \frac{-i}{2}(a_{lm}^{+2} - a_{lm}^{-2})}$$