Impact of galactic foregrounds on delensing of CMB B-modes

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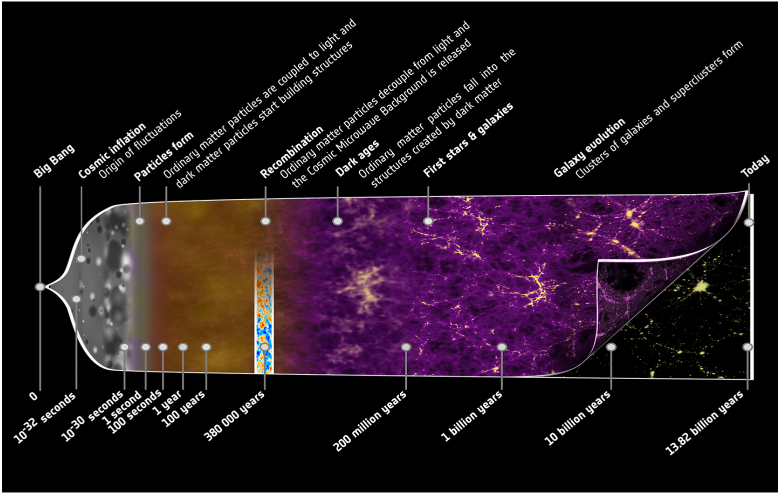
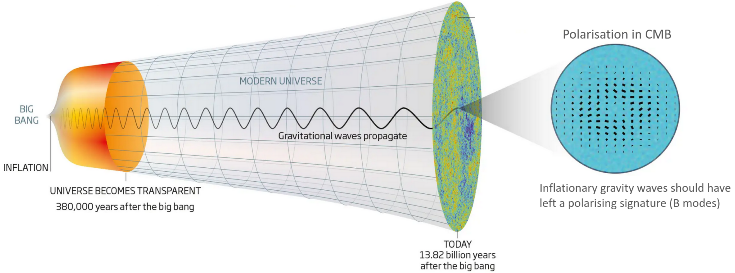
ANOMALIES & TENSIONS IN COSMOLOGY · COSMOVERSE

Evolution of the Universe



Planck team(ESA)

Tensor fluctuations



Inflation predicts tensor fluctuations which creates B-mode polarisation patterns $\implies C_l^{BB,prim}$ is non-zero

Detection of primordial gravitational waves (**PGWs**)

Hunt for tensor B modes

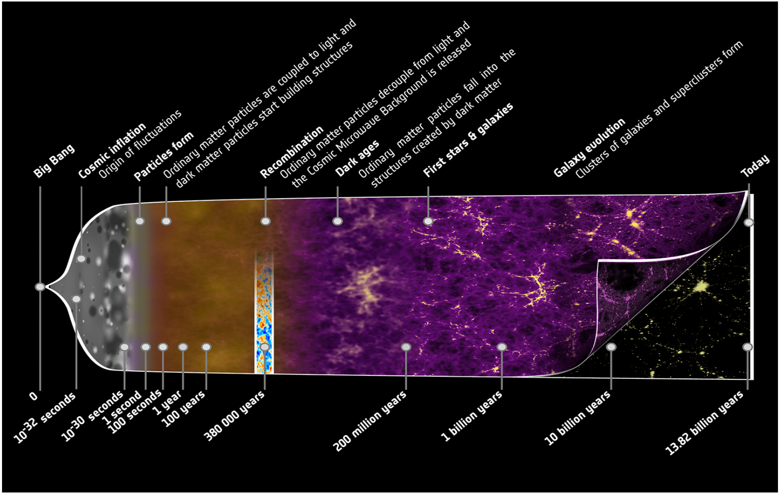
Constraining the primordial GW amplitude $\rightarrow$

Tensor-to-Scalar ratio

$$r = \frac{\text{amplitude of tensor fluctuations}}{\text{amplitude of scalar fluctuations}}$$

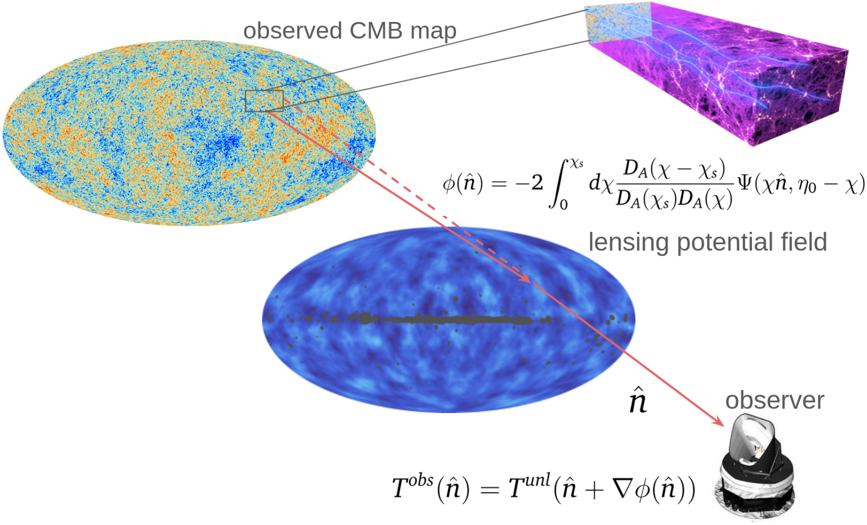
... in the early universe.

- Planck survey + BICEP-Keck survey joint analysis gives upper limit $r < 0.032$.
- Next generation survey targets to achieve $r < 0.003$.



Planck team(ESA)

CMB weak lensing



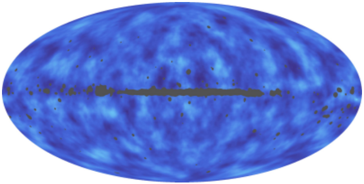
$$\phi(\hat{n}) = -2 \int_0^{\chi_s} d\chi \frac{D_A(\chi - \chi_s)}{D_A(\chi_s) D_A(\chi)} \Psi(\chi \hat{n}, \eta_0 - \chi)$$

$$\hat{n}$$

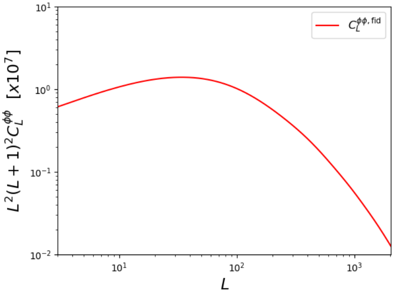
$$T^{obs}(\hat{n}) = T^{unl}(\hat{n} + \nabla \phi(\hat{n}))$$

Lensing potential

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

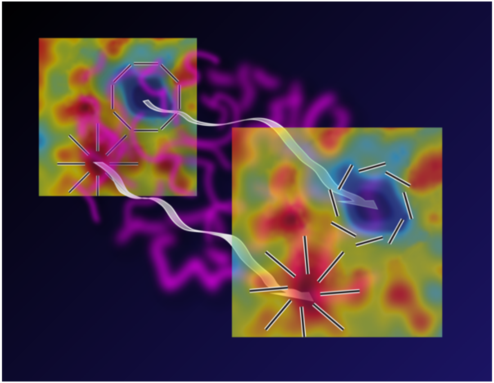


Planck (2015)



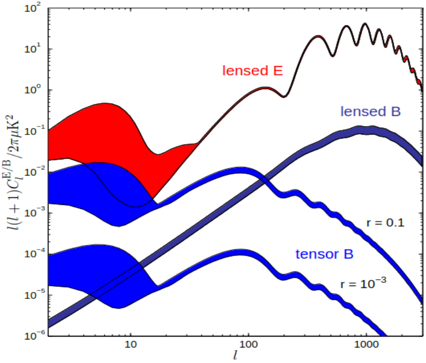
Lensing B modes

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



APS / Alan Stonebrake

Motivation



Lewis, Challinor (2006)

- Lensing reconstruction of the deflection field.
- Subtract lensed B modes to probe primordial B modes.
- Improved constrains on tensor-to-scalar ratio (r).

CMB Stage-4 survey

- Next generation ground-based CMB survey : targets to achieve $r < 0.003$.

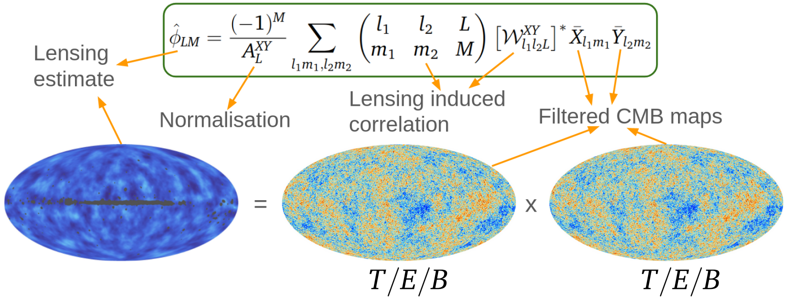
Atacama, Chile

- Angular resolution $(FWHM) = 2.5$ arcminute
- Noise level in Polarisation $(\sigma_P) = 1.5\ \mu K$-arcminute
- Comparing with Planck survey :
  Angular resolution $(FWHM) = 10$ arcminute (pol.)
  Noise level in Temperature $(\sigma_T) = 35\ \mu K$-arcminute

Lensing reconstruction

Quadratic combination of CMB fields provides a noisy lensing estimate.

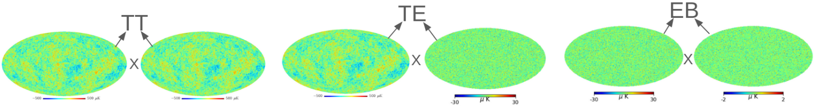
$$\hat{\phi}_{LM} = \frac{(-1)^M}{A_L^{XY}} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & M \end{pmatrix} \left[\mathcal{W}^{XY}_{l_1 l_2 L}\right]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2}$$

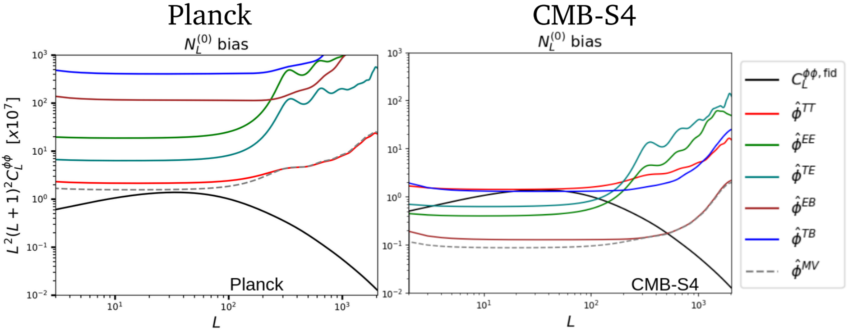


$$\hat{C}_L^{\phi\phi} = \langle \phi^*_{LM} \phi_{L'M'} \rangle = (2\pi)^2 \delta(L - L') \left[C_L^{\phi\phi} + N_L^{\phi\phi} \right]$$

Quadratic Estimator

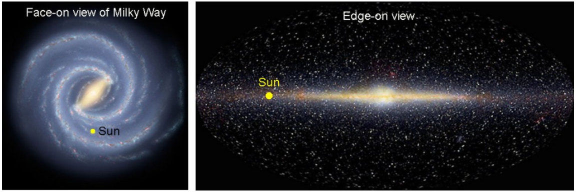
Quadratic Estimator (QE) can be build from a pair of any two fields.



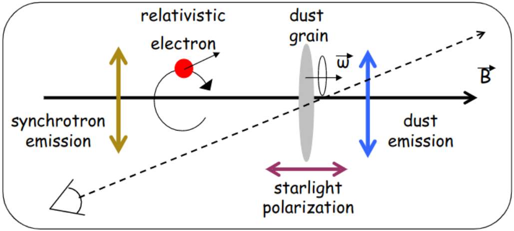


Galactic emissions

Galactic dust emissions contaminates CMB radiation.



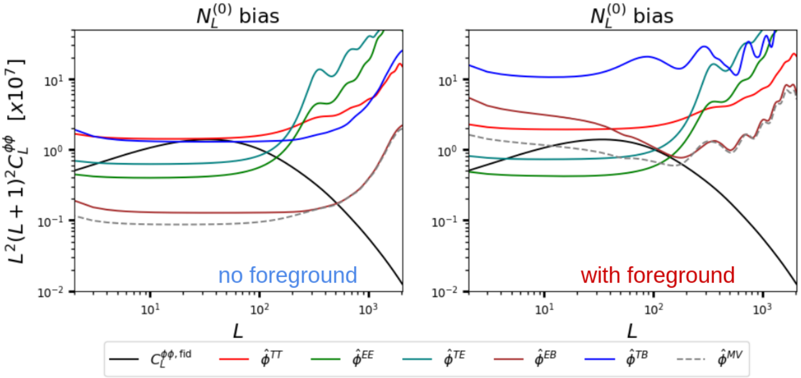
our location in Milkyway



Dust and Synchrotron emission. (L. Fauvet)

Foreground bias

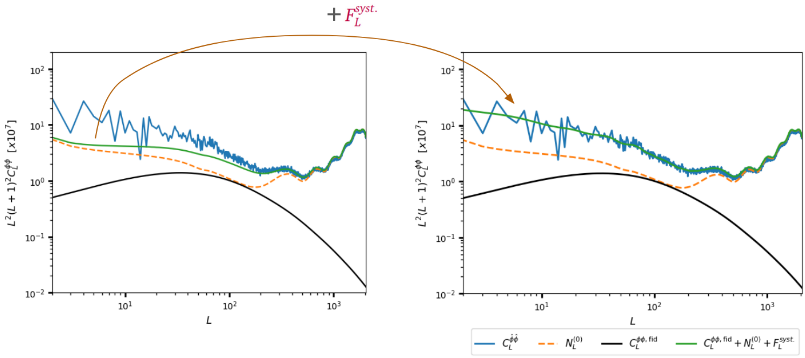
Reconstruction noise increases in presence of foreground.
We use 80% of the sky for lensing reconstruction.



$F_L^{syst.}$ bias : additional bias

$$\hat{C}_L^{\phi\phi} = \frac{1}{2L+1}\sum_M \langle \phi_{LM}^* \phi_{LM} \rangle = C_L^{\phi\phi} + N_L^{\phi\phi} + F_L^{syst.} \quad (1)$$

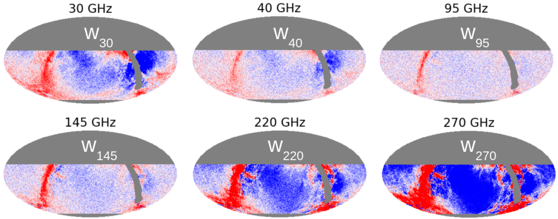
- The $F_L^{syst.}$ term is computed using lensing reconstruction estimate on foreground only maps.
- $F_L^{syst.}$ term corrects the bias in low multipole.



Component Separation

For CMB-S4, we have 20, 30, 40, 95, 145, 220, 270 GHz channels.
We combine the multi-frequency observed map with noise, D^i,

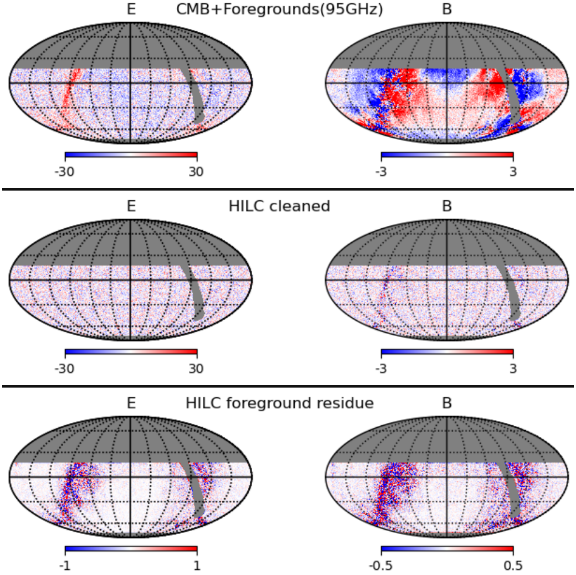
$$T^{CMB}(\hat{n}) = \sum_i w_i D^i(\hat{n}) \quad \text{for} \quad i \in \{1, \ldots, N_c\}$$



Minimize variance of T^{CMB} under the constraint,

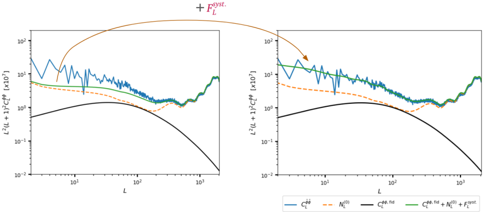
$$\sum_i w_i = 1$$

Foreground cleaned maps

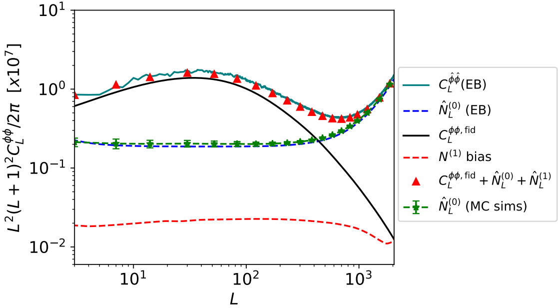


$F_L^{syst.}$ bias is no more !

Before foreground removal :



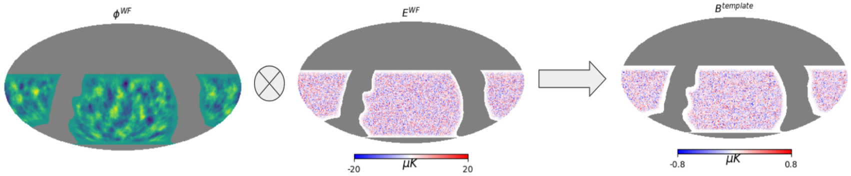
After foreground removal (HILC) :



Delensing of B modes

Lensing B-mode template :

$$B^{template} = E^{obs} \circ \phi^{QE}$$



Weiner Filtering : Inverse weighted by noise spectra to supress noisy modes.

Delensing : $\quad B^{del} = B^{obs} - B^{template}(E^{obs} \circ \phi^{QE})$

B^{obs} and E^{obs} are observed (or simulated observation) maps.

CMB-S4 sky coverage

CMB-S4 observations with :

- Large Aperature Telescopes (LATs) : wide field but high noise levels.
- Small Aperature Telescopes (SATs) : small field but low noise levels.

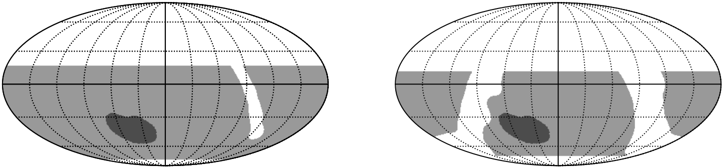


Figure: Sky coverage of LAT and SAT.

Delensed B-mode

Delensing : $B^{del} = B^{obs} - B^{template}(E^{obs} \circ \phi^{QE})$

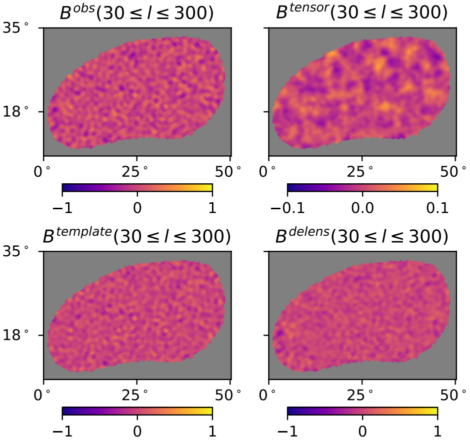
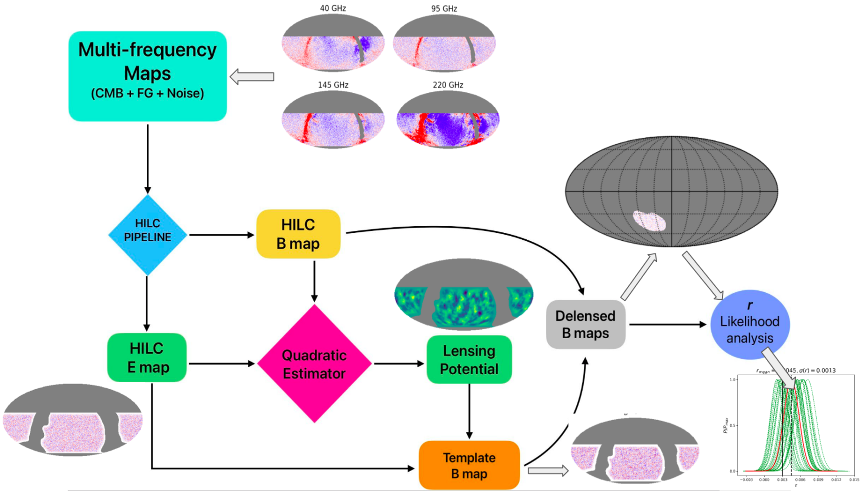


Figure: Delensed B-mode for SAT maps.

Pipeline Schematic



Constrain on tensor-to-scalar ratio, r

$$C_l^{del} = rC_l^{prim.,r=1} + C_l^{res} + C_l^{noise} + F_l^{res}$$

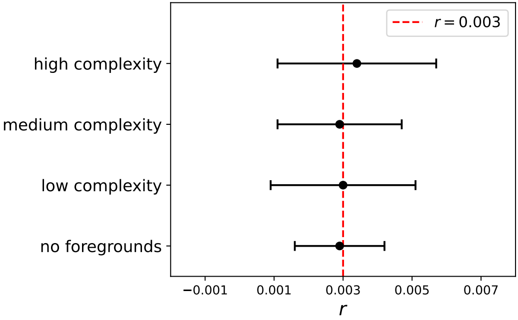


Figure: Mean value of r from 100 simulations and error on the mean for different galactic emission models of varying complexity.

Contribution to $\sigma(r)$

Lensing residue signal dominates the constrain on r.

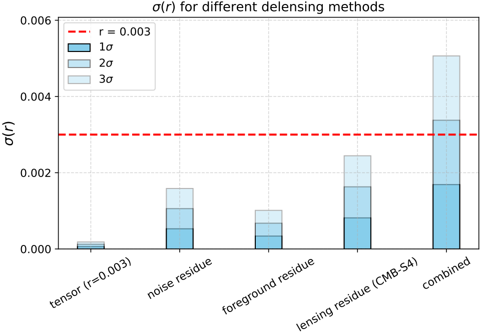


Figure: Contribution of different signals to the r constrain.

It is shown that iterative delensing method reduces the lensing residue further $\rightarrow$ tightning the constrain.

In summary

- Lensing reconstruction is crucial to remove lensing B modes.
- Foreground contamination will impact lensing reconstruction and delensing efficiency.
- Component separation reduces the biases in reconstruction and delensing.
- Constrain on r is lensing residual limited. Iterative methods of delensing can improve the constrain.
- Accurate modeling of non-gaussianity in galactic foreground signal is important.

Thank You!

Questions?

Backup slides ...

HILC spectra

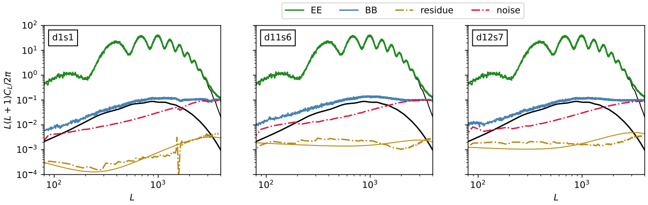


Figure: LATs HILC results.

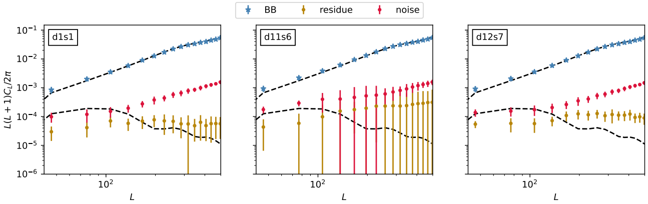


Figure: LATs HILC results.

F_l^{syst} bias

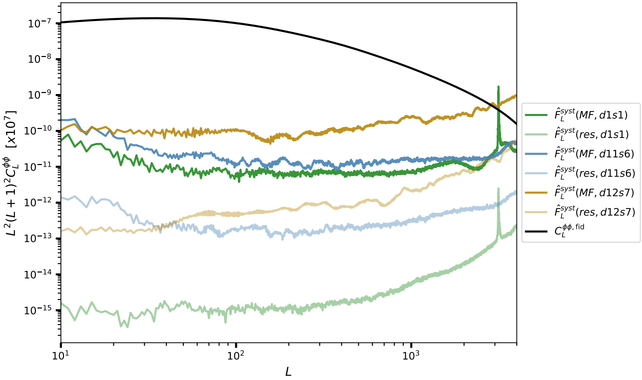
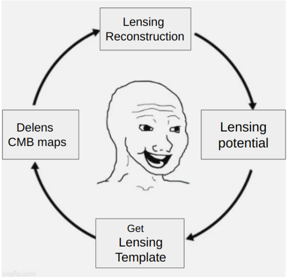
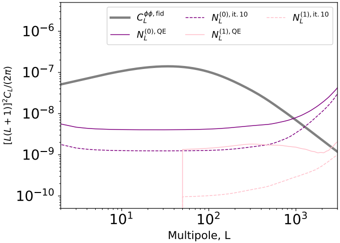


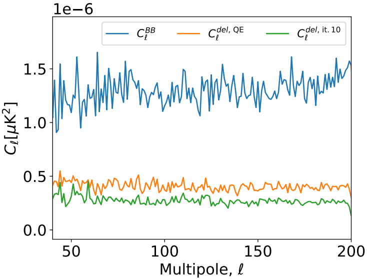
Figure: Caption

Iterative delensing



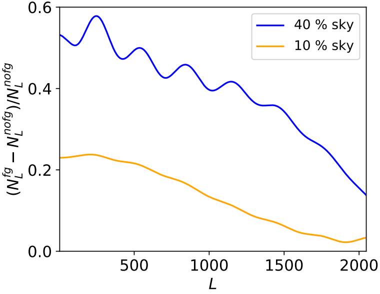


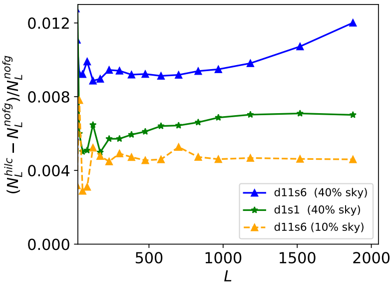
(a) Iterative methods reconstruction noise.



(b) Iterative vs QE delensing.

Reconstruction noise





Residual foreground contributes to $N_L^{(0)}$ bias in reconstruction.

Minimum variance combination

- A generalised inverse variance weighting yields,

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

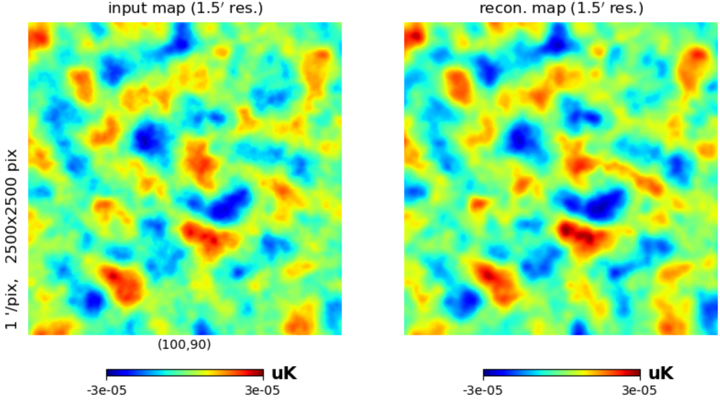
where,

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

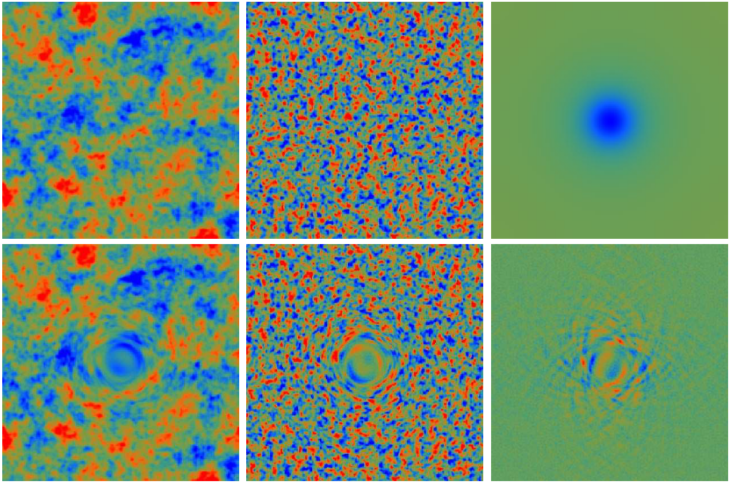
- Minimum variance estimator reduce reconstruction noise.
- BB estimator is neglected.

Reconstructed lensing field

Input | Reconstruction



Lensing example



Hu & Okamoto (2002)

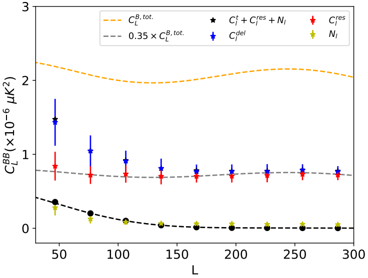
Lensing effects

- 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.

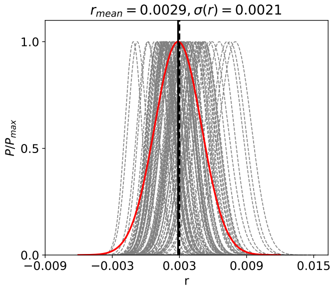
r constrain for ideal sky (no foreground)

This is a check of the pipeline for ideal case : **No foregrounds**.

Here, input tensor B modes are for $r = 0.003$.



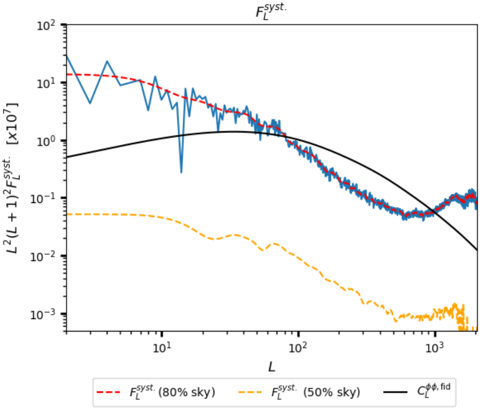
(a) Delensed B mode spectrum.



(b) Posterior of r estimate.

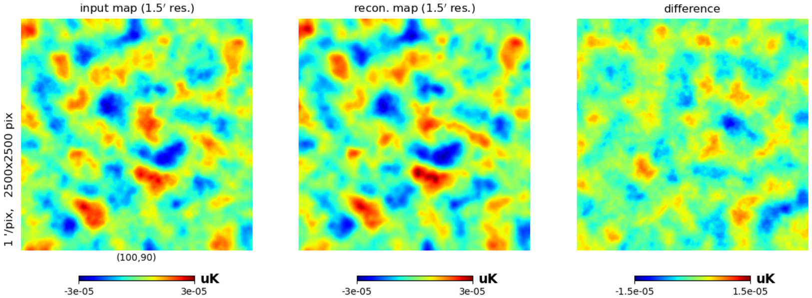
$$C_l^{del} = rC_l^{prim.,r=1} + C_l^{res} + N_l^{nois.} + N_l^{del}$$

$F_L^{syst.}$ bias

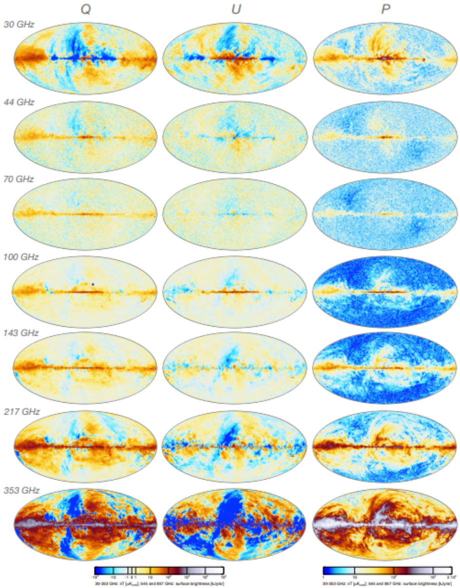


$F_L^{syst.}$
$L^2(L+1)^2 F_L^{syst.}$ [x10^7]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
L
$F_L^{syst.}$ (80% sky)
$F_L^{syst.}$ (50% sky)
$C_L^{\phi\phi, \mathrm{fid}}$

Lensing potential reconstruction

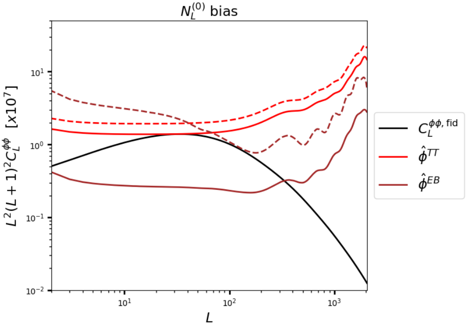


Foreground polarization (Planck 2015 resu

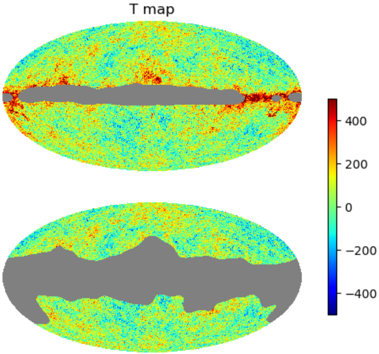


Masking

Masking larger part of galactic plane reduces bias.



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



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

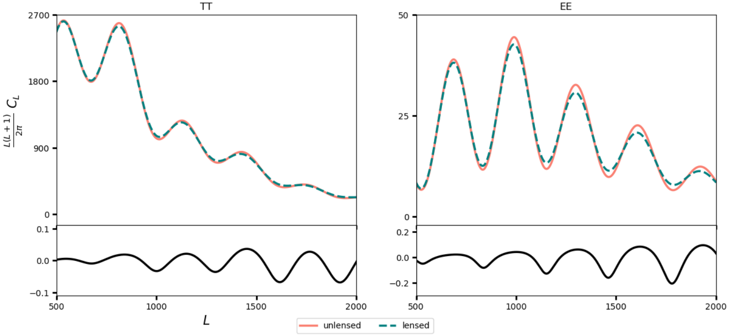
Galactic Foregrounds

Different emissions dominates at different frequencies –

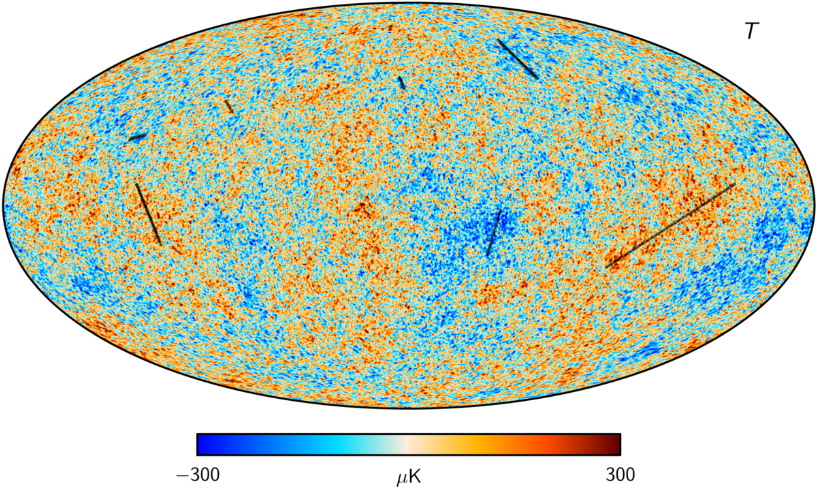
- Thermal dust emission: dust + galactic magnetic field (GMF)
- Synchrotron emission : relativistic electron accelerated by GMF
- Free-Free emission : Warm Ionized Medium
- Spinning dust : Rotating dipole radiation

Lensed power spectra

- Lensing smooths out the angular power spectra.



CMB anisotropies

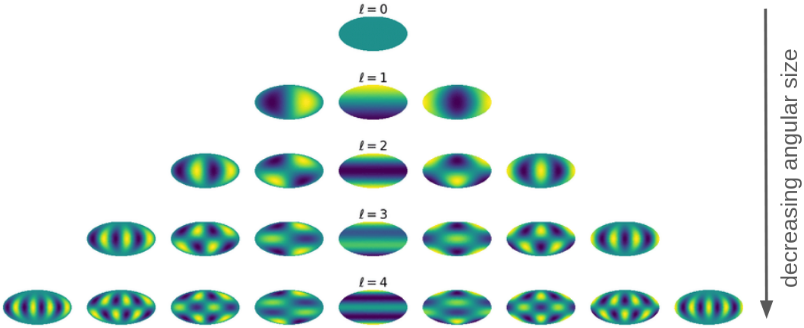


Planck (2018)

Spherical harmonics

- Temperature fluctuations are decomposed in spherical harmonic basis :

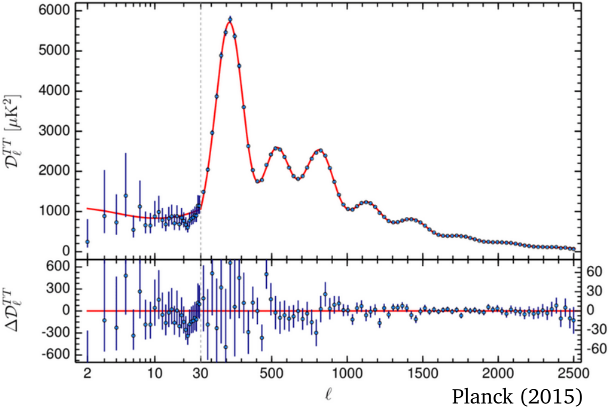
$$\frac{\Delta T}{T} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm}^{T} Y_l^m$$



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)

Lensing reconstruction

- Mode-coupling between multipoles in fourier space.

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

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

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

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 :

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

  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 normalization satisfies, $\langle d_\alpha(L)\rangle_{CMB} = L\phi(L)$

E and B modes

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

- Q and U are spin-2 fields.

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

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

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

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

Full-sky reconstruction