Challenges in optimal de-lensing of CMB B-modes and constraining primordial gravity waves

Thesis Defense v.1

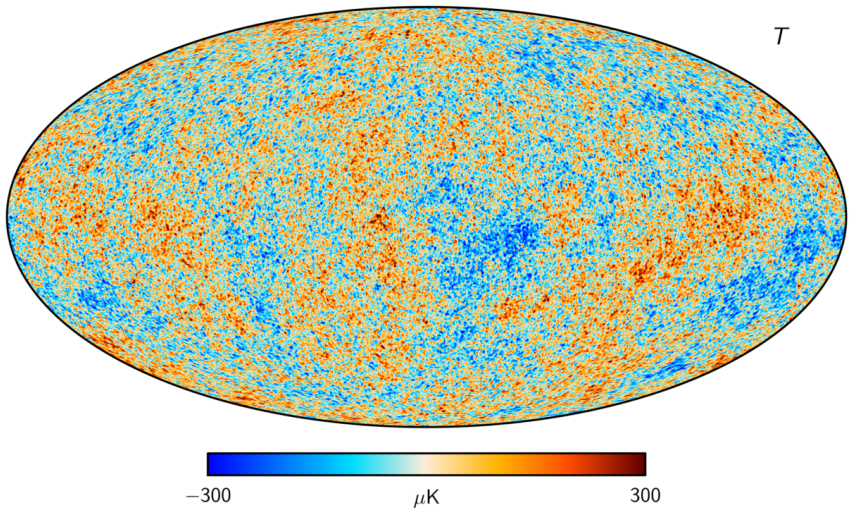
KISHAN DEKA

Advisor : Paweł Bielewicz

National Centre for Nuclear Research (NCBJ)
Warsaw, Poland

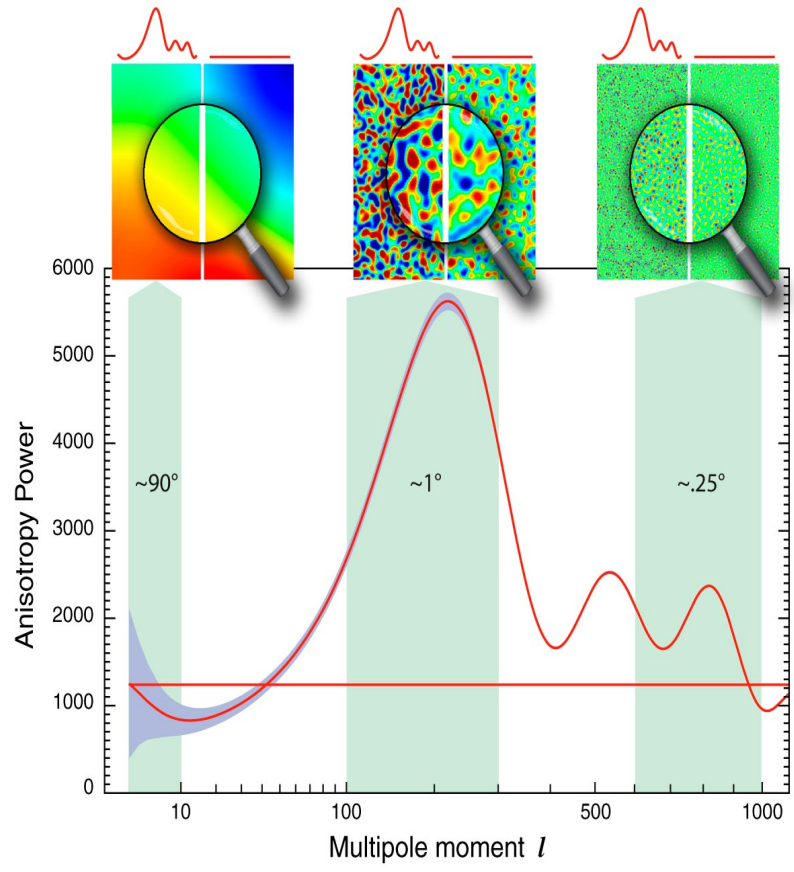
Contents

Cosmic Microwave Background



Planck survey

- "Afterglow" of the Big Bang
- Anisotropies as a function of angular size multipole : $l \sim \pi/\theta$
- Good fit to the standard model : ΛCDM



WMAP (NASA)

CMB Polarisation : E and B modes

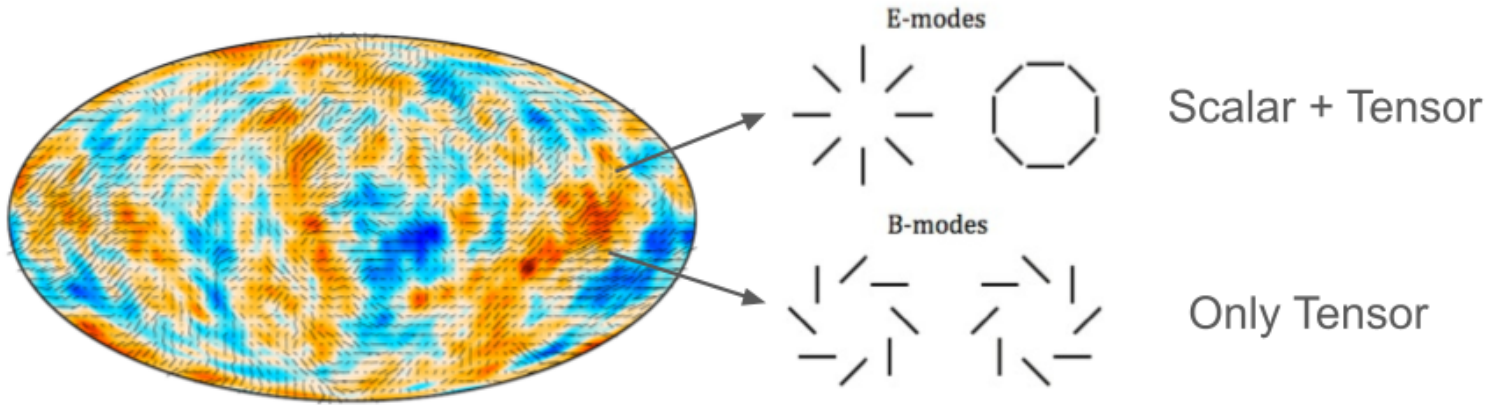


Figure: CMB polarisation

CMB Polarisation : E and B modes

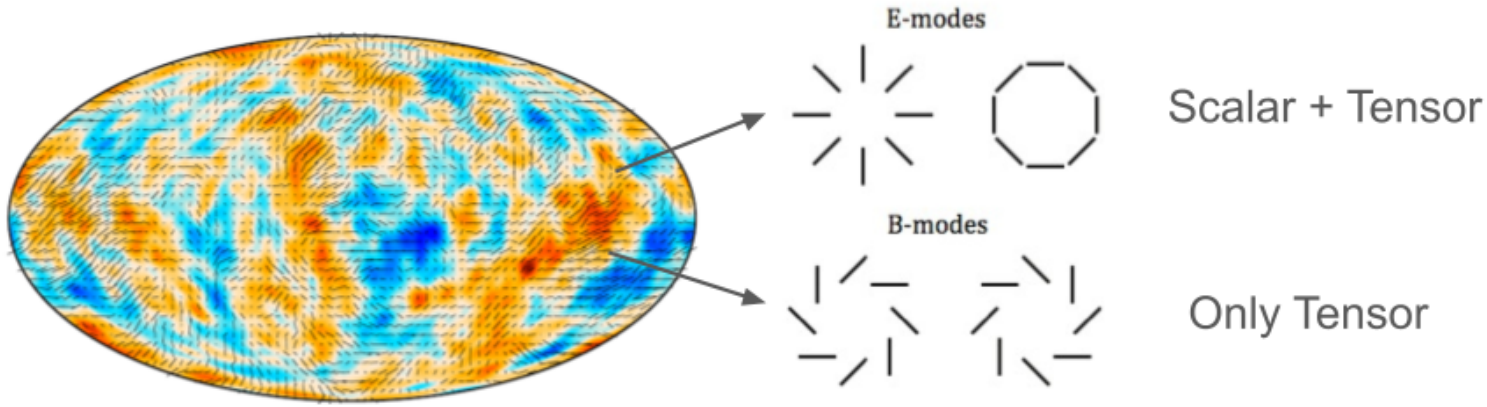


Figure: CMB polarisation

Prediction of ΛCDM :

Inflationary gravity waves(**GW**) imprints Primordial B modes.

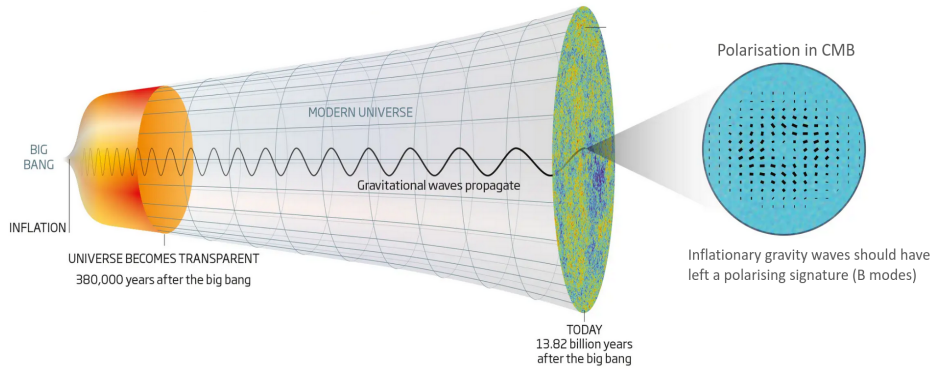


Figure: Primordial B mode pattern

Primary CMB : Tensor B-mode

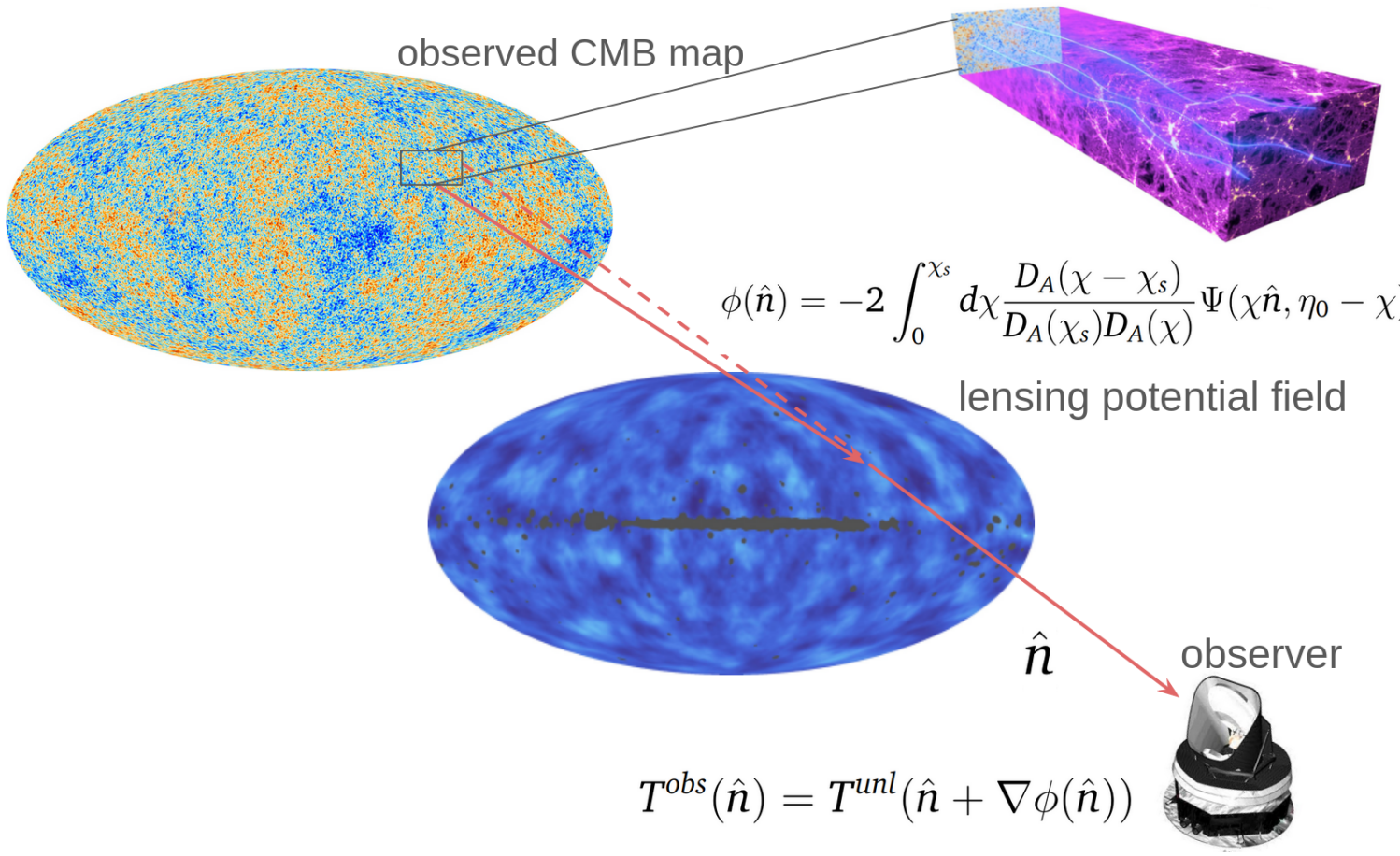
Ongoing and upcoming CMB experiments targets **Constraining the primordial gravity wave (PGW) amplitude** $\rightarrow$

Tensor-to-Scalar ratio

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

Next generation survey targets to achieve $r < 0.003$.
One order higher than current constraint $r < 0.032$ (BICEP/Keck + Planck).

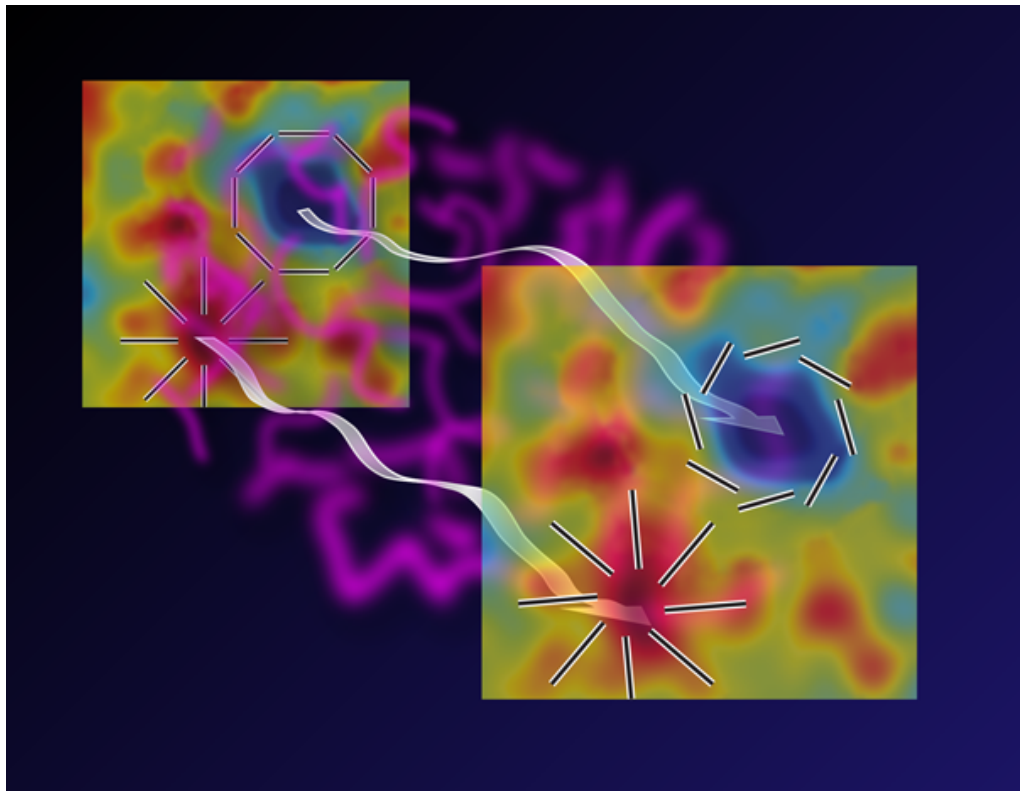
Secondary effects : CMB weak lensing



Lensing field traces the integrated line-of-sight dark matter distribution and large-scale structures (LSS).

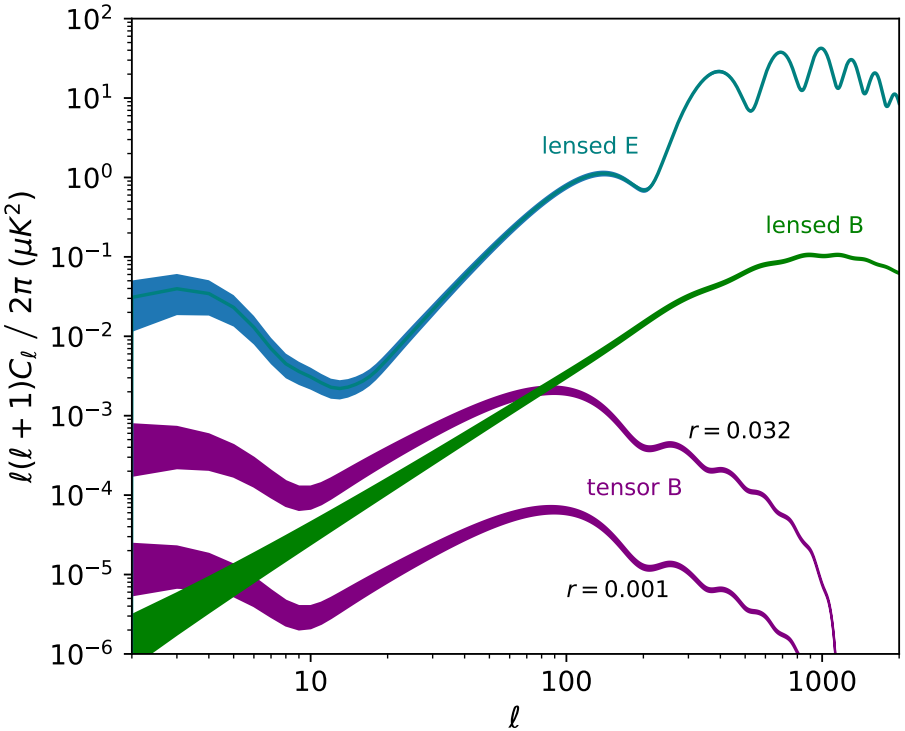
Secondary effects : Lensing B modes

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



APS / Alan Stonebrake

Lensing B-mode vs. Tensor B-mode



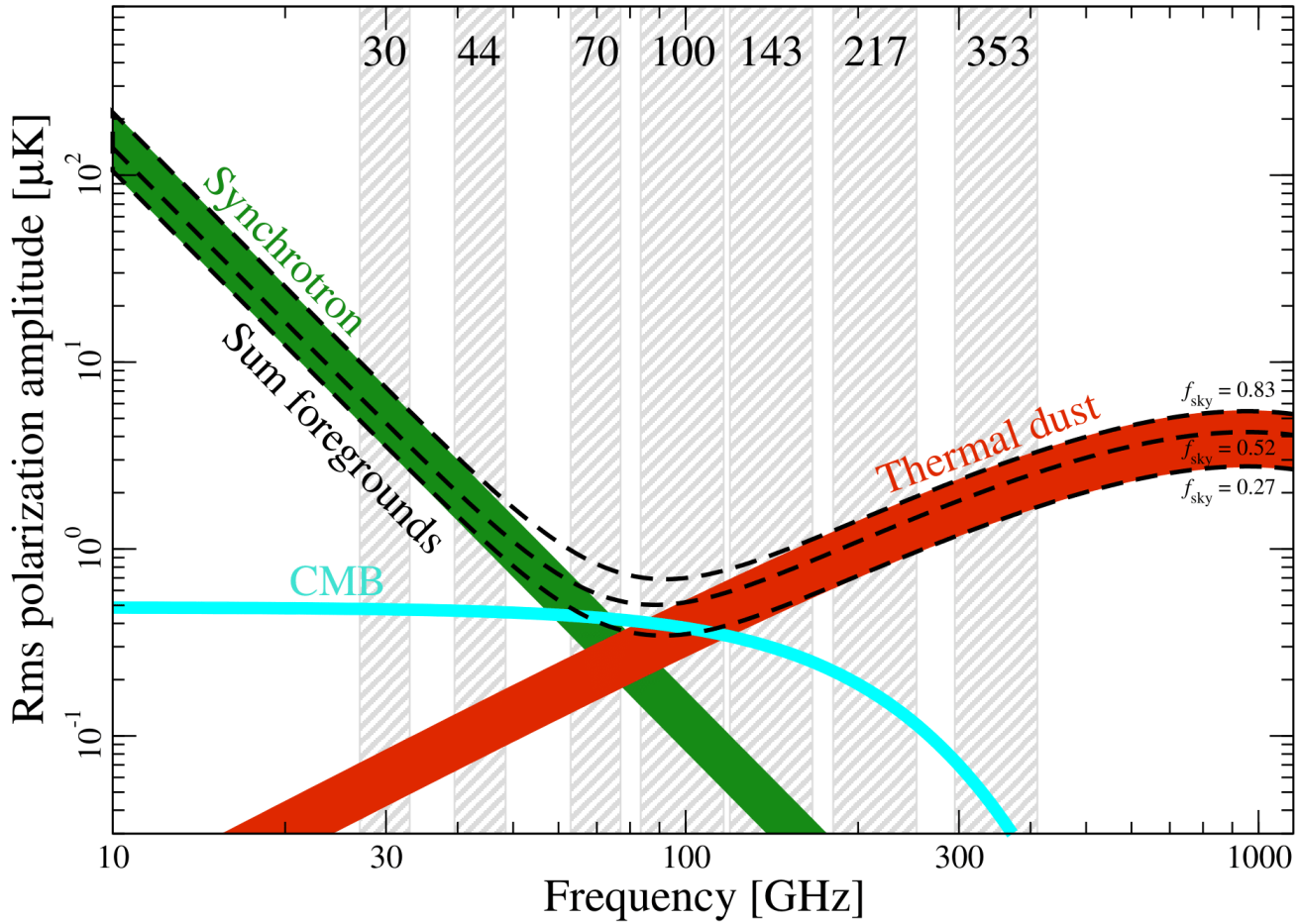
Lensing B modes dominates over tensor B modes ($r \sim 10^{-3}$).

Motivation

- Reconstruction of the lensing potential field.
- Subtract lensed B-mode template from observed signal.
- Improve constraints on tensor-to-scalar ratio, r.

CMB contaminants : Galactic foregrounds

Polarised Galactic emissions : dust and synchrotron



Planck 2018 results IV

Problems to solve : Project-1

What is the impact of Galactic foregrounds on the lensing reconstruction and on the delensed B modes?

in the context of CMB-S4–like experiment.

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A&A, 708, A188 (2026)
https://doi.org/10.1051/0004-6361/202557977

Astronomy & Astrophysics

Galactic foreground residue biases in cosmic-microwave-background lensing-convergence reconstruction and delensing of *B*-mode maps

Kishan Deka* and Paweł Bielewicz

National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland

Received 4 November 2025 / Accepted 23 February 2026

Methods : Lensing reconstruction

Quadratic Estimator [Hu & Okamoto (2002)]

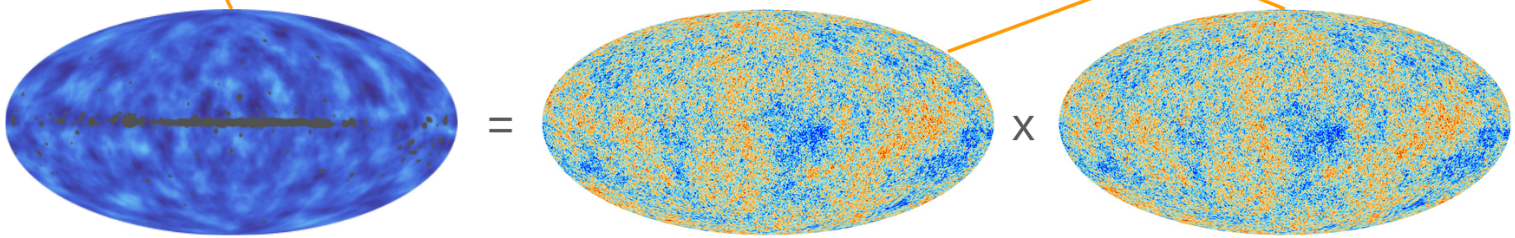
$$\hat{\phi}_{LM} = \frac{(-1)^M}{A_L^{XY}} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & M \end{pmatrix} \left[\mathcal{W}_{l_1 l_2 L}^{XY}\right]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2}$$

Lensing estimate

Normalisation

Lensing induced correlation

Filtered CMB maps



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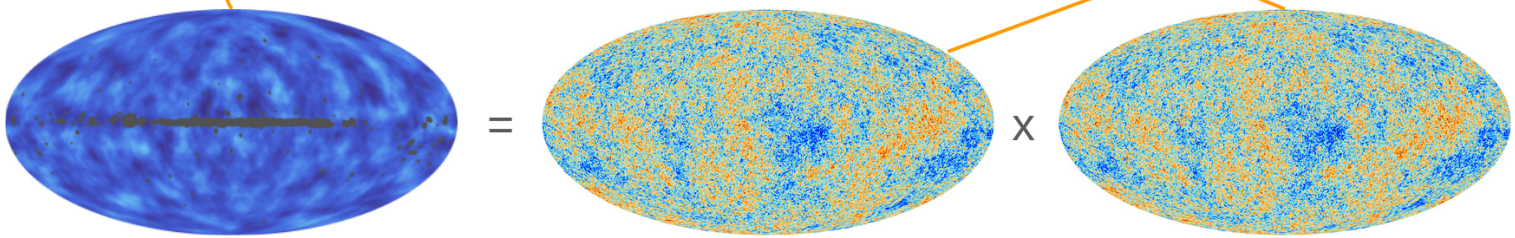
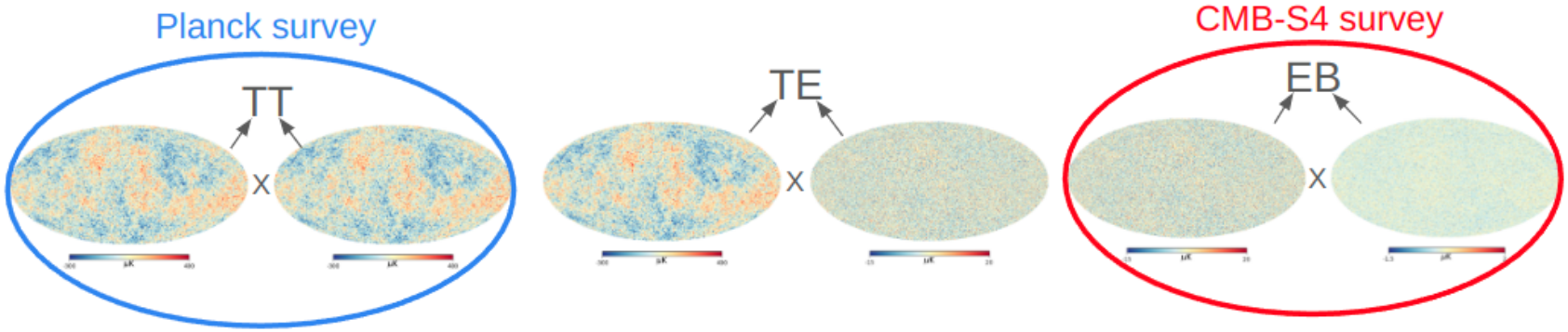


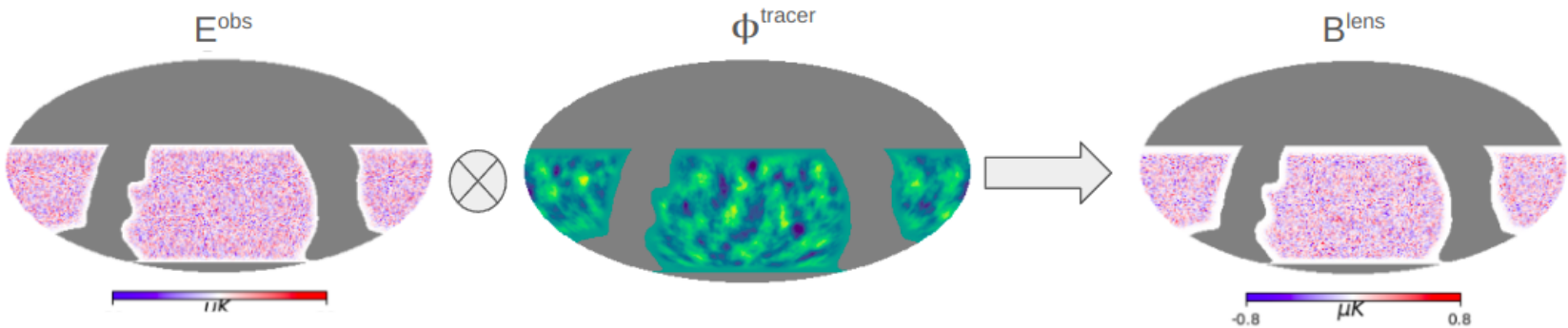
Different pairs of CMB observations



Methods : Delensing of B-mode

Template-based delensing

Lensed B-mode template: $B^{template} = E^{obs} \circ \phi^{recon.}$



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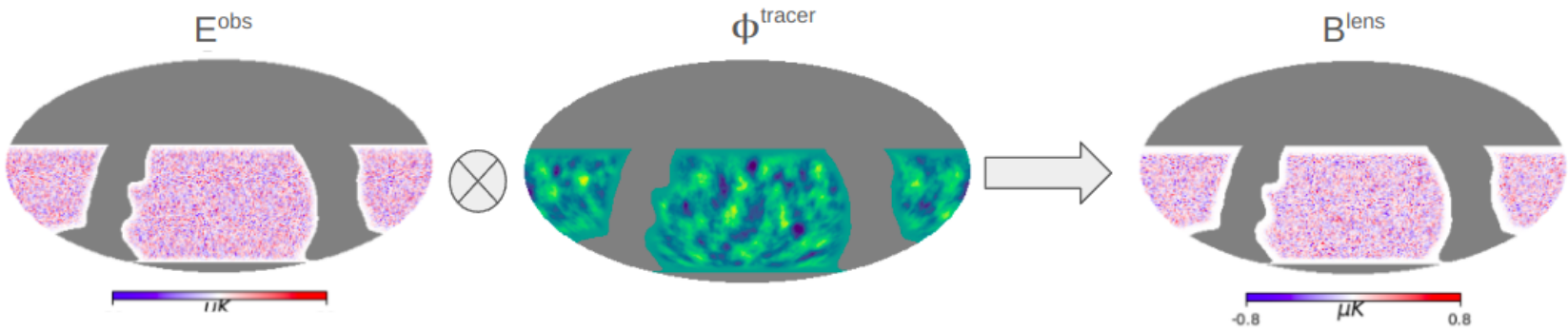

Delensing : $B^{del} = B^{obs} - B^{template}$

[Smith et al. (2012)]

Methods : Foreground cleaning

Internal Linear Combination (ILC) of multi-frequency observations, D^i,

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

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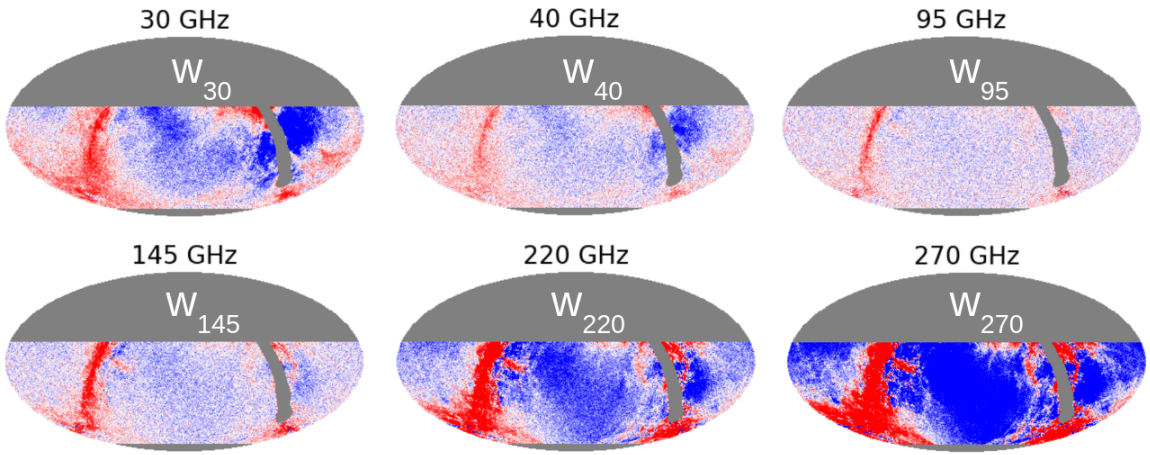

Minimize variance of T^{CMB} under the constraint $\sum_i w_i = 1$

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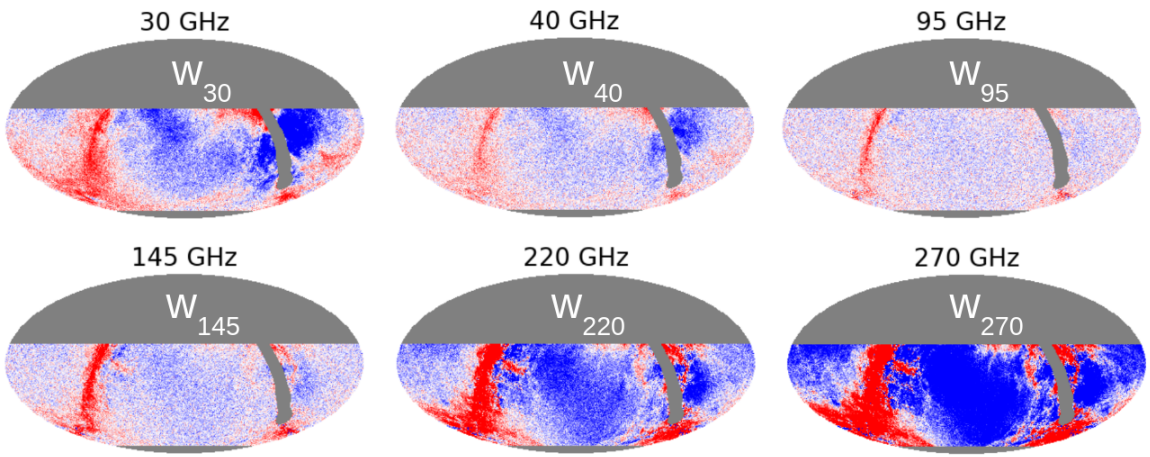
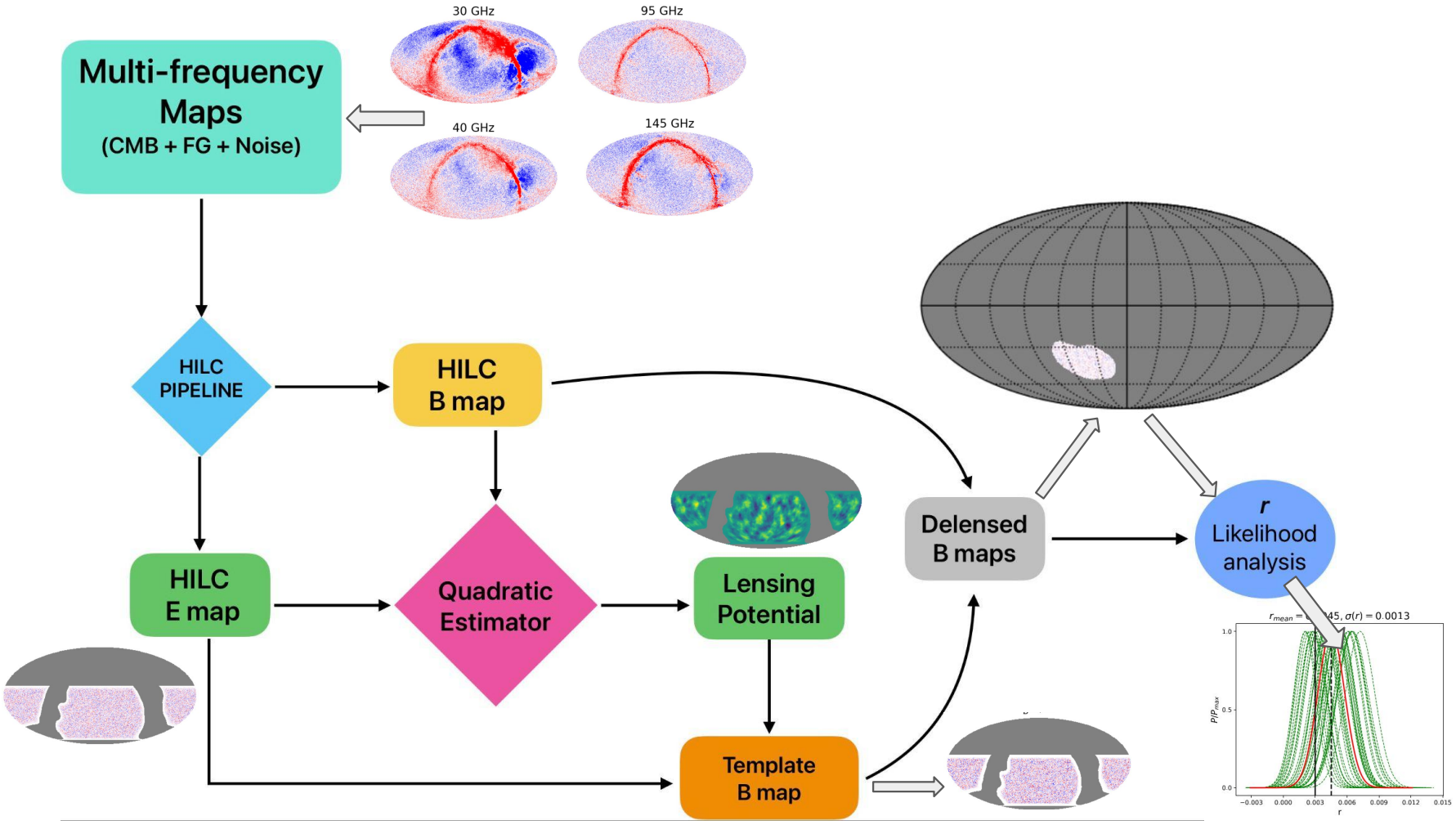


Minimize variance of T^{CMB} under the constraint $\sum_i w_i = 1$

We do it in Harmonic (Fourier) space,
so we call it Harmonic ILC (HILC).

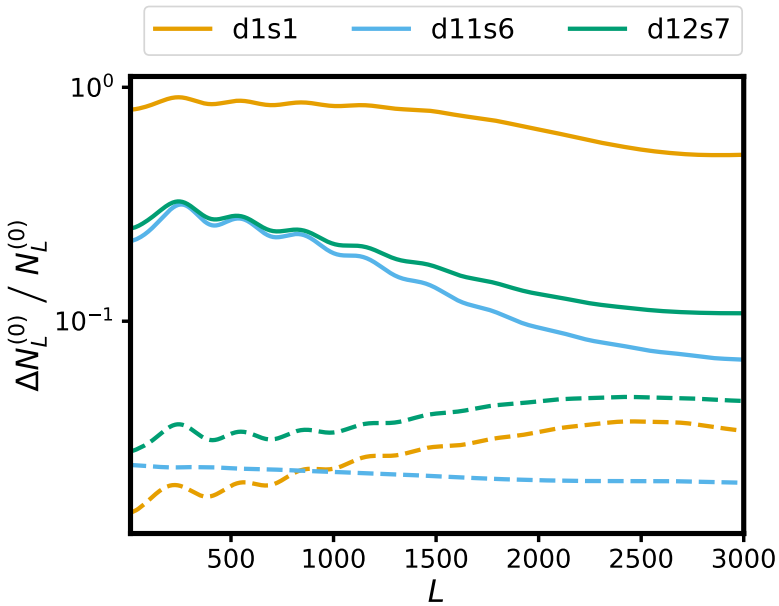
Project-1 : The workflow



Bias in reconstruction noise

$$C_L^{\phi\phi,\ \text{recon.}} = r\, C_L^{\phi\phi,\ \text{input}} + \left[\mathbf{N_L^{\phi\phi,(0)}} + N_L^{\phi\phi,(1)}\right] + F_L^{\phi\phi,\ \text{syst.}}$$

$\Delta N_L^{(0)}$ is the relative increase in reconstruction noise, $N_L^{(0)}$, due to presence of foregrounds or its residue.

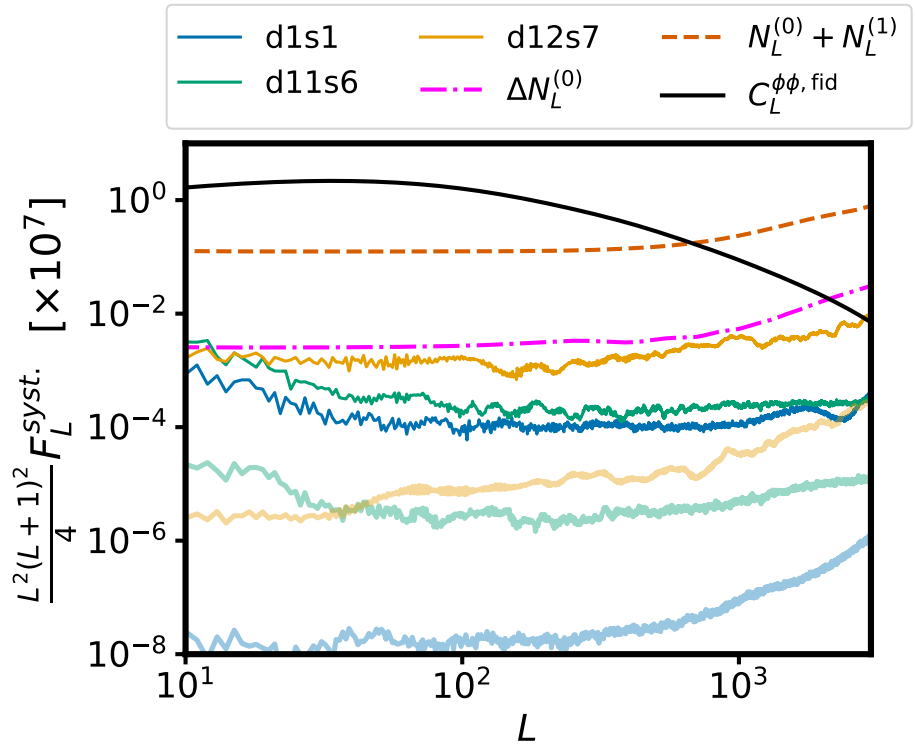


Solid : Before foreground cleaning, **Dahsed** : After cleaning.

Bias in reconstructed signal

$$C_L^{\phi\phi,\ \text{recon.}} = r\, C_L^{\phi\phi,\ \text{input}} + \left[N_L^{\phi\phi,(0)} + N_L^{\phi\phi,(1)}\right] + \mathbf{F_L}^{\phi\phi,\ \text{syst.}}$$

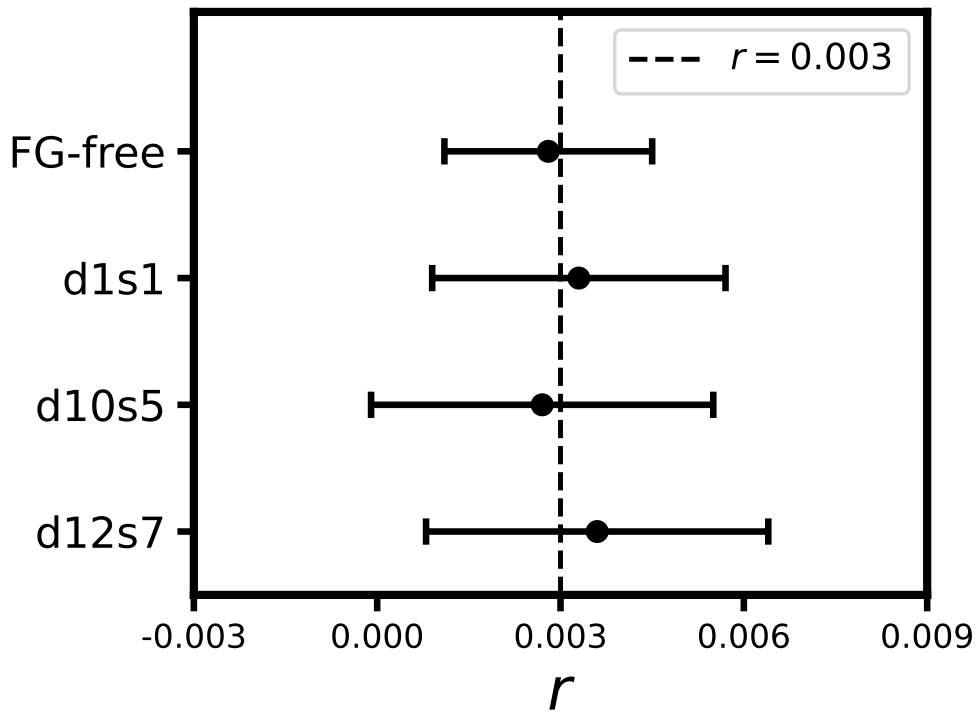
$F_L^{\text{syst.}}$ is the systematic bias in reconstructed lensing power spectra due to foregrounds or its residue.



Dark : Before foreground cleaning, **Light** : After cleaning.

Impact on r constraint

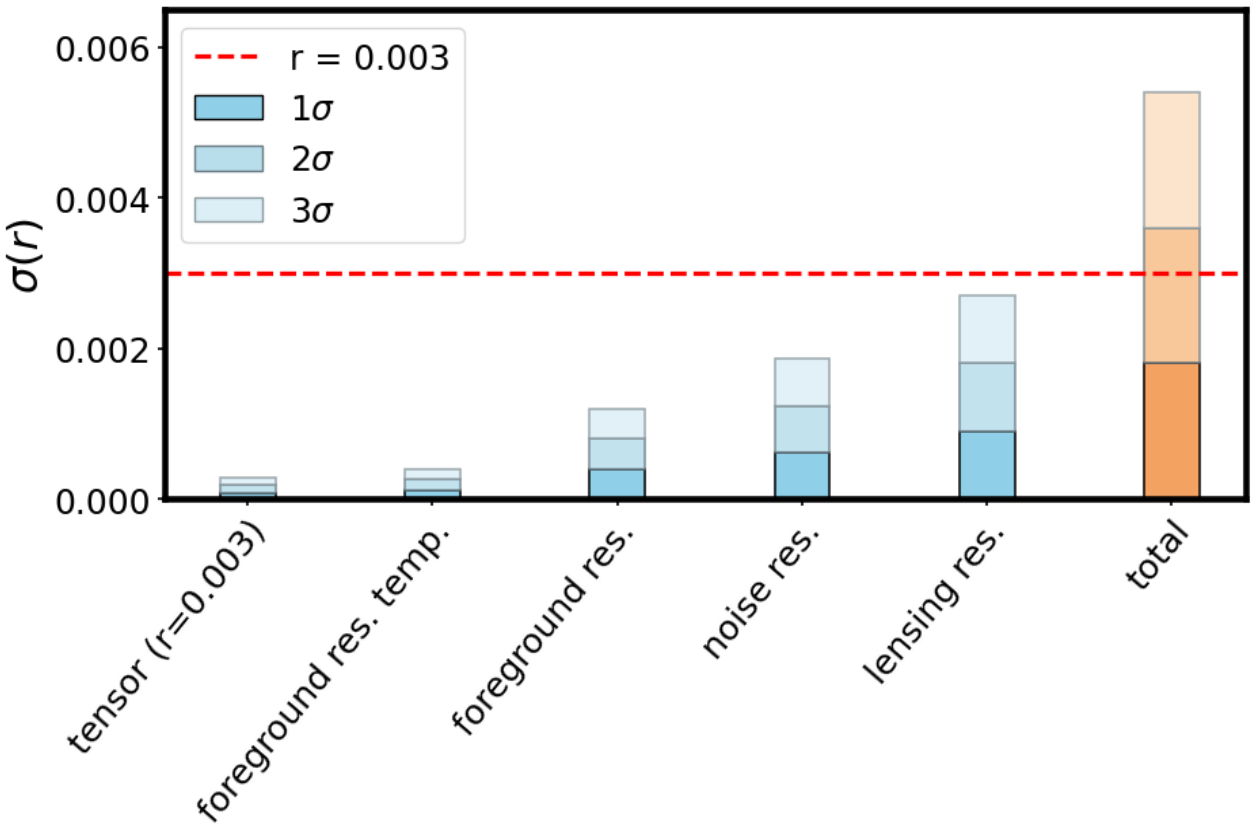
$$C_l^{BB,\,\mathrm{del}} = r\,C_l^{BB,\,\mathrm{tens}} + C_l^{BB,\,\mathrm{lens.\ res}} + C_l^{BB,\,\mathrm{fg\ res}} + C_l^{BB,\,\mathrm{noise}}$$



Mean r and $\sigma(r)$.

Impact on r constraint

$$C_l^{BB,\ \mathrm{del}} = r\, C_l^{BB,\ \mathrm{tens}} + C_l^{BB,\ \mathrm{lens.\ res}} + C_l^{BB,\ \mathrm{fg\ res}} + C_l^{BB,\ \mathrm{noise}}$$



Contribution to $\sigma(r)$.

Problems to solve : Project-2

How to get optimal delensing efficiency using cross-correlations between CMB and galaxy surveys?

in the context of Simons Observatory (CMB) and LSST (galaxy).

In preparation : KD et. al., 2026

Astronomy & Astrophysics manuscript no. output
May 12, 2026

Impact of photometric redshift error on primordial gravity wave amplitude constraints

SO × LSST forecast

Kishan Deka[1]⋆, Chandra Shekhar Saraf[2], and Pawel Bielewicz[1]

[1] National Centre for Nuclear Research, Pasteura 7, 02-093, Warsaw, Poland
[2] Korea Astronomy and Space Science Institute, 776 Daedeok-daero, Yuseong-gu, Daejeon 34055, Republic of Korea

Delensing with CMB$\times$LSS

Large-scale structure(LSS) tracers : galaxy overdensity maps

$$\delta_i = \frac{n_g - \bar{n}_g}{\bar{n}_g}$$

where, n_g is the galaxy count in a pixel and $\bar{n}_g$ is the mean galaxy count.

The index, i, denotes tomographic redshift binning :

$$z_i < z_g < z_{i+1}$$

Delensing with CMB×LSS

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The index, i, denotes tomographic redshift binning :

$$z_i < z_g < z_{i+1}$$

B-mode template: $B^{template} = E^{obs} \circ \phi^{recon.} + \sum_i E^{obs} \circ (c_i \delta^i)$

with optimal weights, c_i, computed using fiducial auto and cross angular power spectra : $C_\ell^{\phi\phi}, C_\ell^{\phi\delta_i}, C_\ell^{\delta_i\delta_j}$

Delensing using LSST survey

Question : How much does multi-tracer approach improve CMB delensing?

We want to do **Simons Observatory (SO) x LSST** ?

Delensing using LSST survey

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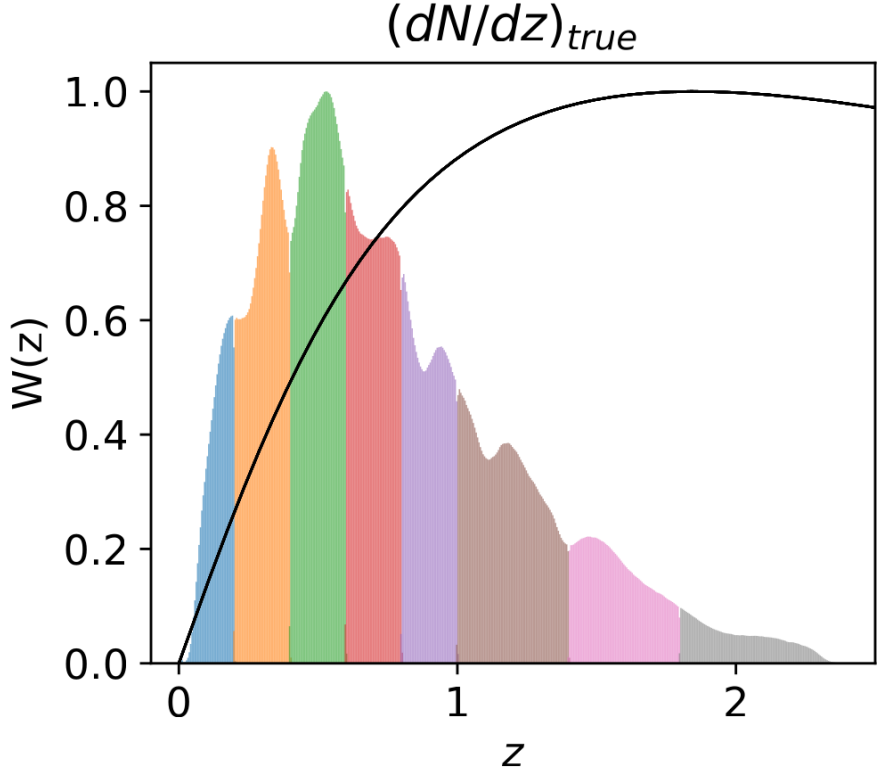
We want to do **Simons Observatory (SO) x LSST** ?

The LSST survey will catalogue 20 billion galaxies within a span of 10 years.



LSST Y10 redshift distribution from RAIL.
[RAIL Team et al. (2025)]

Delensing with SO×LSST

Lensing template: $B^{template} = E^{obs} \circ \phi^{recon.} + \sum_i E^{obs} \circ (c_i \delta^i)$

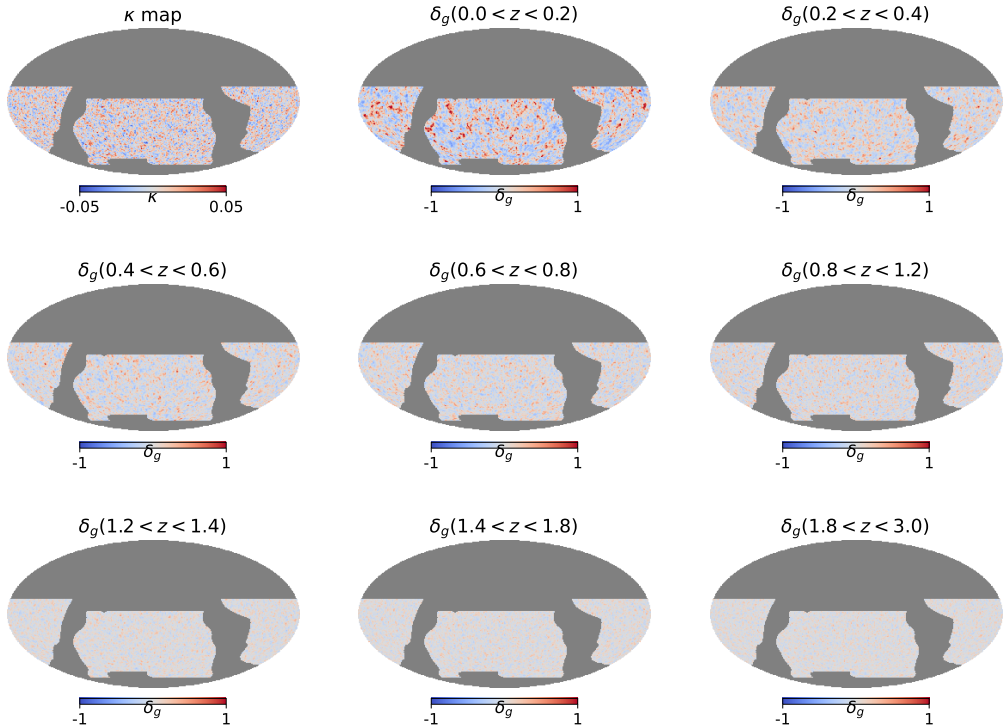


Figure: Simulation of correlated log-normal galaxy overdensity and CMB lensing field using `GLASS` code [Tessore et. al. (2023)].

Delensing with SO×LSST

$$C_l^{BB,\ \mathrm{del}} = r\, C_l^{BB,\ \mathrm{tens}} + C_l^{BB,\ \mathrm{lens.res}}\ (\downarrow) + C_l^{BB,\ \mathrm{noise}}$$

Lensing residue is reduced from 70% to 50%.

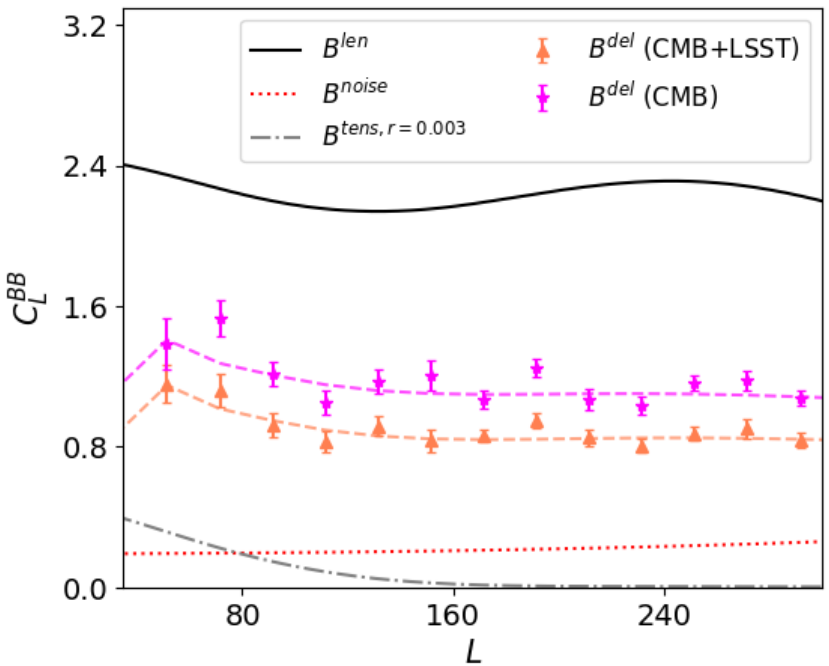
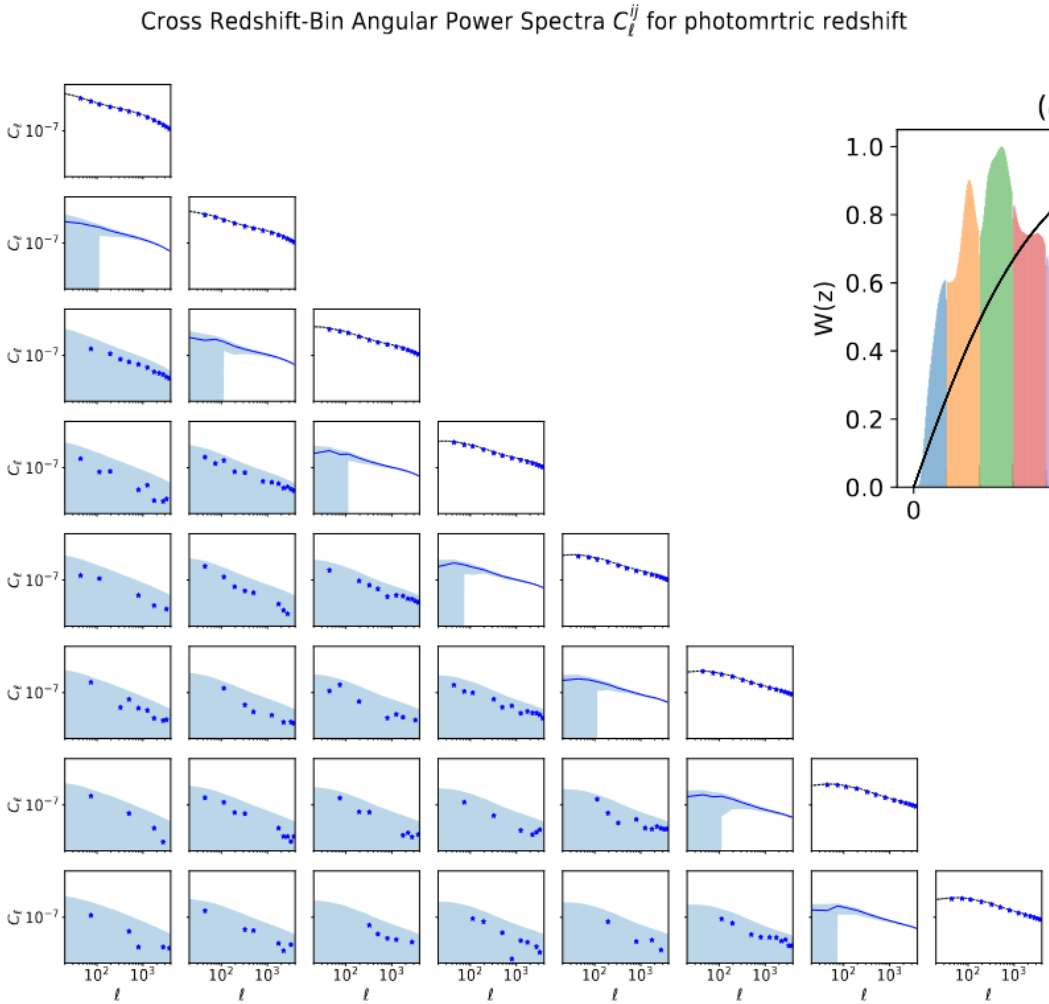
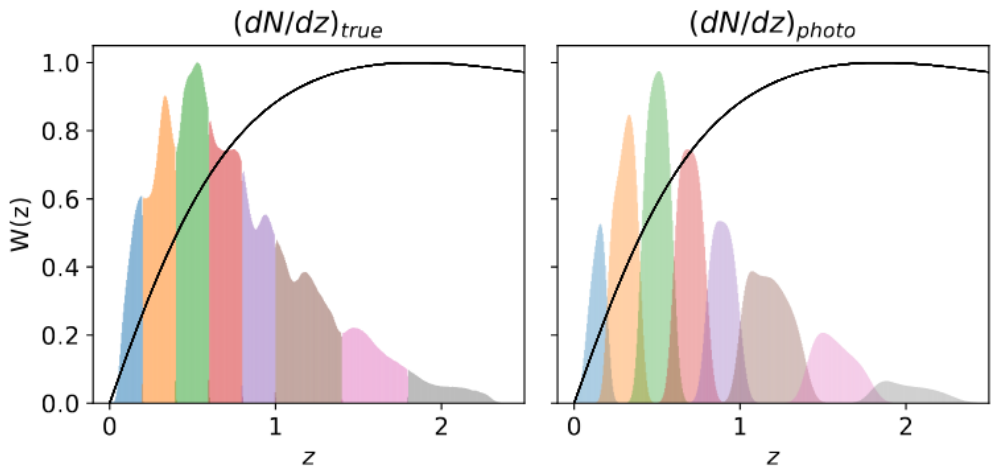


Figure: Internal vs multi-tracer delensing.

Photometric redshift distribution

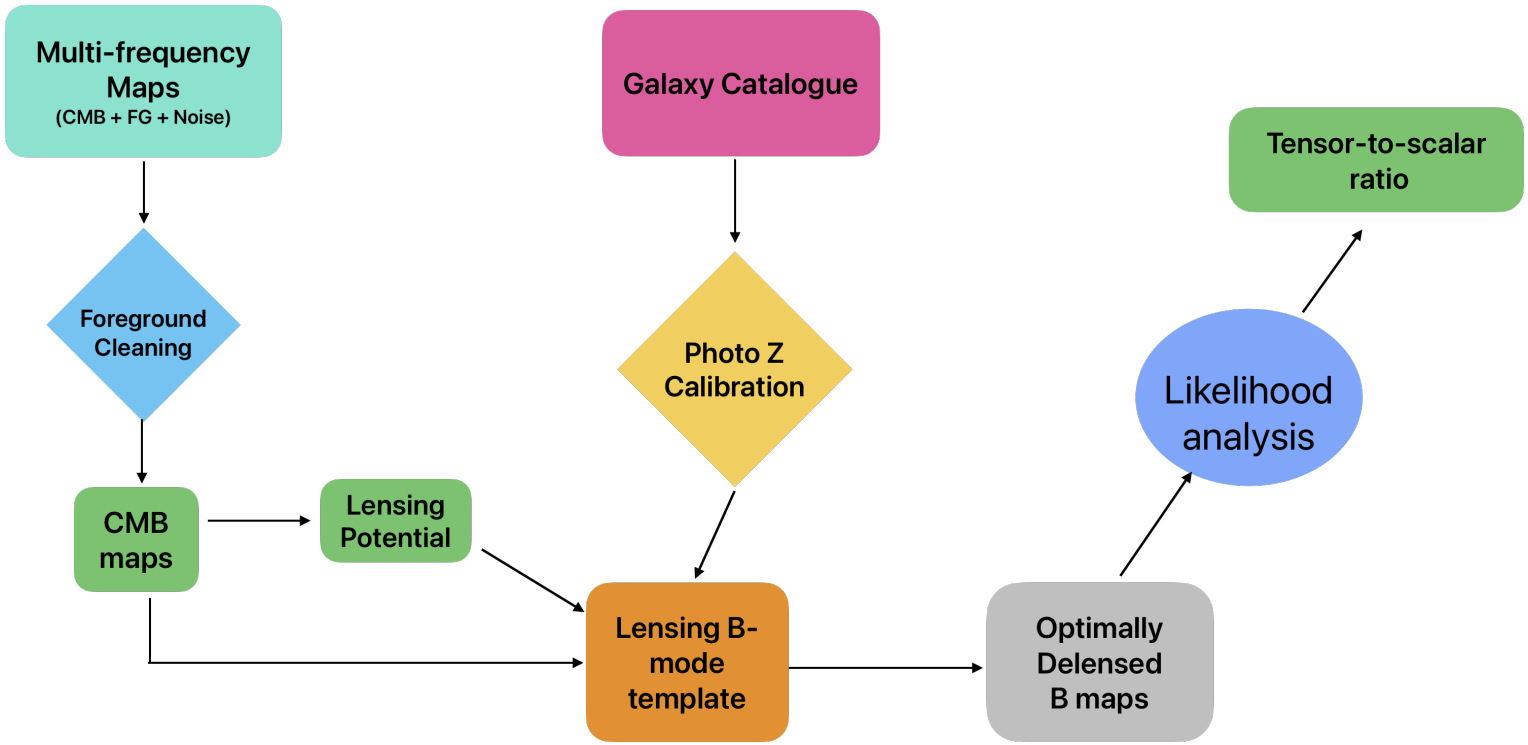
Photometric redshift error introduces correlation between redshift bins.





Optimal delensing pipeline

SO x LSST (in prep.)



Impact of photometric redshift uncertainities on tensor-to-scalar ratio contraints.

Summary and future prospects

- Constraint on r is mostly **lensing residue limited** for the case of internal delensing using QE.
- Residual foreground in delensed B-mode maps contributes to **60%** increase in uncertainty of r.
- Improved delensing with tomographic cross-correlation between CMB and galaxy survey is possible.
- Photometric redshift errors needs to be studied in details for upcoming **SO x LSST** delensing studies.
- Other external tracers such as Cosmic Infrared Background (CIB) and radio continuum survey will be added in this study.

THANK YOU!