Quantifying the bias on the inferred tensor-to-scalar ratio arising from `patchy' reionization

Jain et al. (in prep)

@ Cosmology from Home 2022

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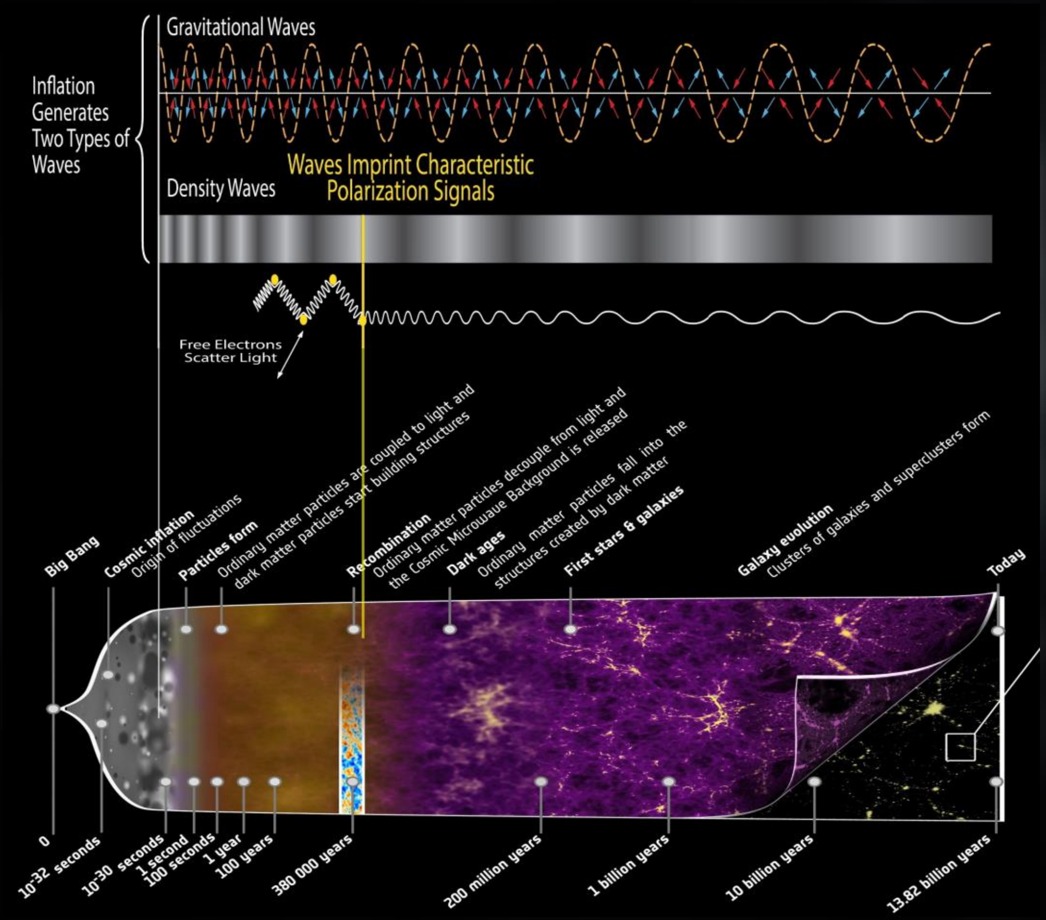
Primordial Gravitational Waves : Signature of Inflation in CMB



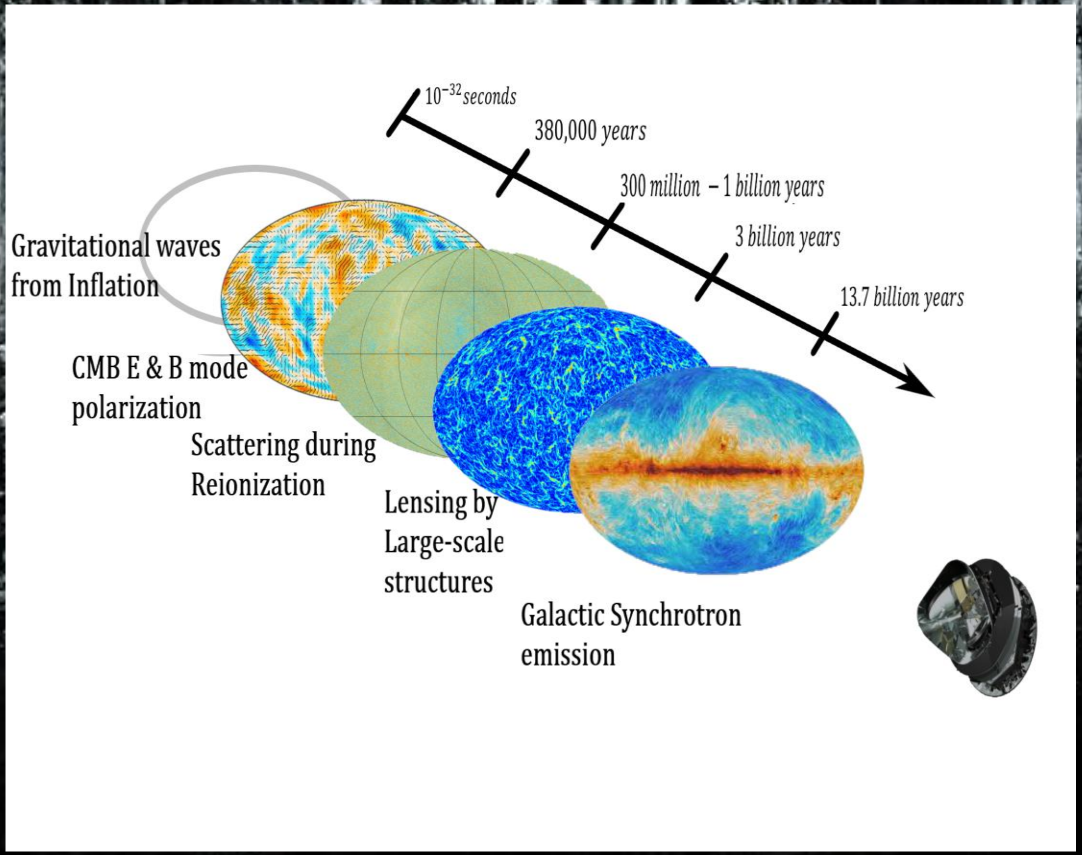
- Inflationary models predict gravitational waves (tensor metric perturbations) . [Liddle & Lyth 2000]
- Detection of Primordial Gravitational Wave (PGW) is tied to constraining the parameter r
- Defined as $\frac{P_{tensor}(k)}{P_{scalar}(k)} = r$
- PGW waves imprint E and B mode polarization on CMB [Sejlak & Zaldarriga 1997]
- Only source of perturbation to cause B mode polarization prior to reionization
- Latest constraint:

$$r < 0.036\ (95\%\ C.L.)$$

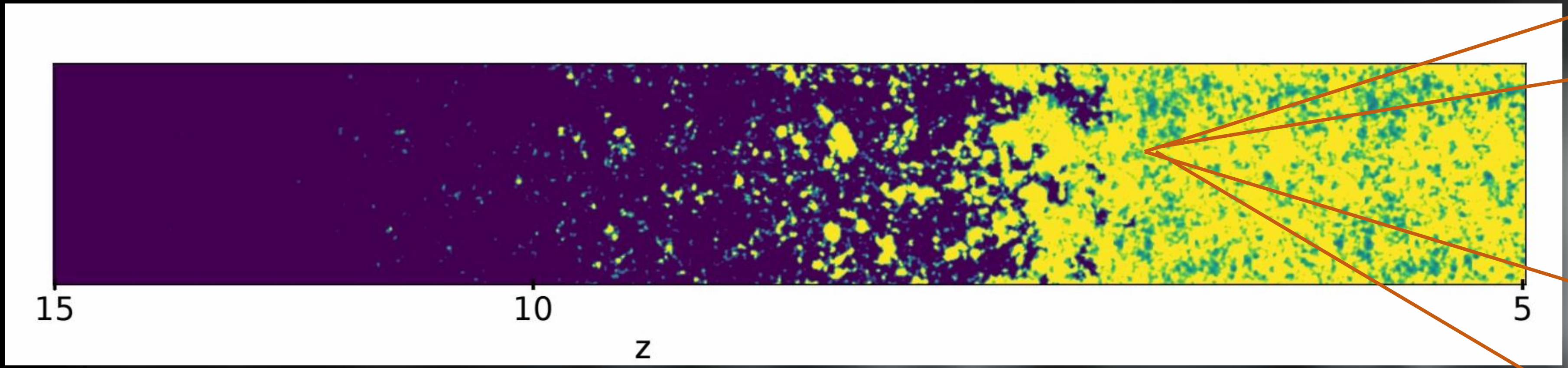
(Keck Collaboration 2022)

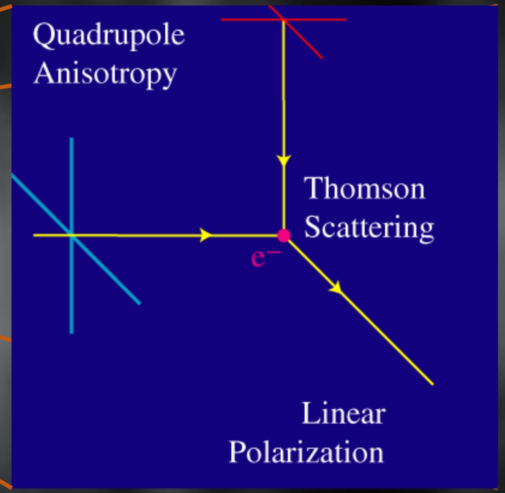
Challenges in observing signature PGWs

- Foregrounds to B-modes from PGWs:
  - Polarized thermal and Synchrotron emission B-modes from our Galaxy [P. Ade et al. 2014]
    - Foreground resolution: Multi frequency observation of CMB
  - Lensed E modes by large-scale structures [P. Ade et al. 2014]
    - Foreground resolution: Observation of tracers of large-scale structure
  - B-modes from re-scattering during patchy reionization [Wayne Hu 2000]



The CMB-“patchy” Reionization connection : Secondary Polarization anisotropy





Lightcone on evolution of Δ_e

- Reionization produces secondary polarization due to inhomogeneous scattering of local CMB quadrupole temperature anisotropy.

Associated with Reionization

- $C_\ell^{BB,reion} = \frac{6\bar{n}_H^2\sigma_T^2}{100}\int d\chi \frac{e^{-2\tau(\chi)}}{a^4\chi^2} P_{ee}(k = \frac{\ell + 1/2}{\chi}, \chi) \frac{Q_{RMS}^2}{2}$
  - Electron density fluctuation: $\Delta_e = x_e(1+\delta)$ where x_e: free electron fraction
  - Power spectrum of electron density fluctuation : $P_{ee}(k,\chi)\delta(k-k') =< \Delta_e(k,\chi)\Delta_e^*(k',\chi) >$

Reionization-CMB connection

Optical Depth τ:

- When CMB photons from last-scattering surface re-scatters off the free electrons from the reionization era it impacts both temperature and polarization anisotropies.
- CMB photons are sensitive to the reionization optical depth τ.

Kinetic-Sunyaev Zeldovich effect:

- kSZ effect : Doppler shift in CMB photons as a result scattering off ionized bubbles with non-zero bulk velocity at lower redshifts (z<30)
- $\frac{\Delta T(\hat{n})}{T_0} = -\sigma_T \bar{n}_H \int \frac{d\chi}{a^2} e^{-\tau(\chi)} \boldsymbol{q} \cdot \hat{n}$
  - Momentum field : $\boldsymbol{q} = \boldsymbol{\Delta_e}(\boldsymbol{v}/c)$
  - $\boldsymbol{v}$: Peculiar Velocity field
  - $\Delta_e = x_e(1+\delta)$
- Total kSZ= Patchy kSZ + Homogeneous kSZ
  (sourced by Δ_e) (sourced by δ)

Bayesian Inference on r from CMB observations:

- CMB observables of reionization: $\tau, D_{\ell=3000}^{kSZ}, D_{\ell}^{BB,reion}$
- Polarization experiments can probe D_{ℓ}^{BB} within $\ell \in [\ell_{min}, \ell_{max}]$
  - Space based Observatories probe $\ell = [2{,}250]$
  - Ground based Observatories probe $\ell = [50{,}250]$

$$-2L \propto \left(\frac{\tau - \tau^{obs}}{\sigma_{\tau}^{obs}}\right)^2 + \left(\frac{D_{\ell=3000}^{kSZ,tot} - D_{\ell=3000}^{kSZ,obs}}{\sigma_{\ell=3000}^{kSZ,obs}}\right)^2$$

$$+ \sum_{\ell,\ell'=\ell_{\min}}^{\ell_{max}} \left(\widetilde{D}_{\ell}^{BB} - D_{\ell}^{BB}\right) \Sigma_{\ell,\ell'}^{-1} \left(\widetilde{D}_{\ell'}^{BB} - D_{\ell'}^{BB}\right)$$

- $\widetilde{D}_{\ell}^{BB}$: Mock B-mode Power Spectra D_{ℓ}^{BB}: Model B-mode Power Spectra
- $\Sigma_{\ell,\ell'}^{-1}$: Noise Covariance matrix (function of $\widetilde{D}_{\ell}^{BB}$ and instrument noise spectra)

Modelling of Reionization via SCRIPT:

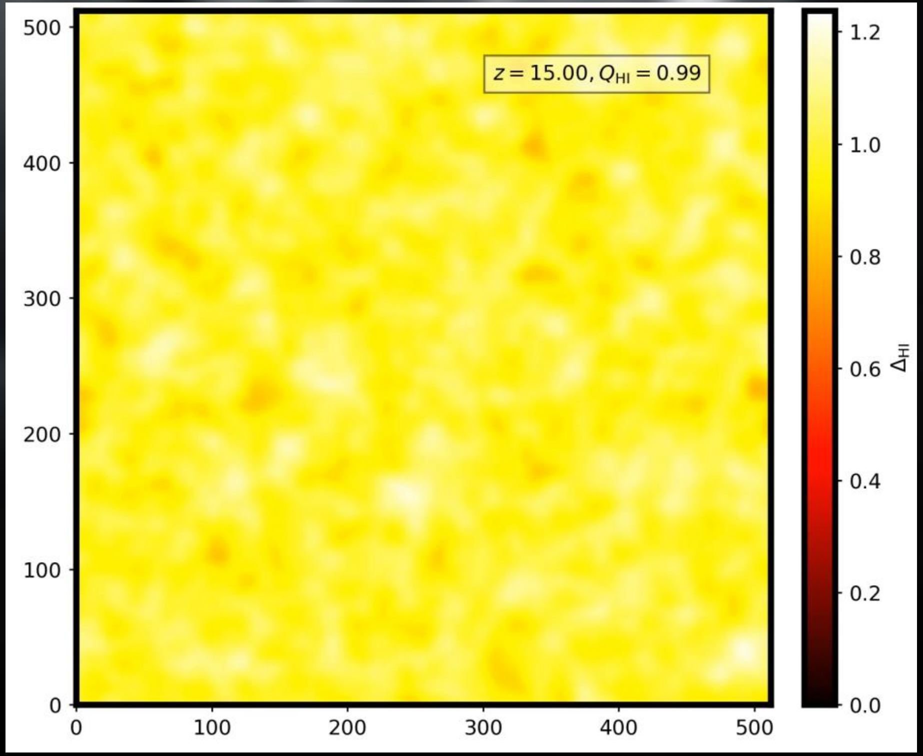
SCRIPT is an explicitly photon-conserving semi-numerical scheme (Choudhury & Paranjape 2018) The ionization maps are generated with the

The key point advantage in using SCRIPT is its explicitly photon conserving

Advantage: SCRIPT produces a large-scale ionization field that is independent of the resolution.

Semi-numerical nature of SCRIPT makes it indespensable for parameter estimation studies

- SCRIPT Bootcamp I:
  - Input : Dark Matter snapshot at redshift z
  - Output : Ionization fraction $x_{HII}(\boldsymbol{x}, z)$
  - Required parameters : $\log M_{min}$, ζ
  - Parameters of interest:
    - $x_e(\boldsymbol{x}, z) = \chi_{He} x_{HII}(\boldsymbol{x}, z)$
    - $Q_{HII}(z) =< x_{HII}(\boldsymbol{x}, z)(1 + \delta_{dm}) >$
    - $\Delta_e = x_e(1 + \delta)$
    - $\boldsymbol{q} = \boldsymbol{\Delta_e}(\boldsymbol{v}/c)$
  - Derive optical depth τ, patchy kSZ power and patchy B mode power



Specifications of modelling:

We use MUSIC (Hahn et al. 2011) to generate dark matter snapshots of side 512 $Mpc\ h^{-1}$ with 512^3 particles over redshift $z = 20$ to $z = 5$ at redshift spacing of $dz = 0.1$.

Model of Reionization:

- Evolution of minimum halo mass M_{min}:

$$M_{min} = M_{min,0} \left(\frac{1+z}{9}\right)^{\alpha_M}$$

- Evolution of ionizing efficiency ζ:

$$\zeta = \zeta_0 \left(\frac{1+z}{9}\right)^{\alpha_\zeta}$$

Here, ζ_0 , $M_{min,0}$ are defined at redshift $z = 8$

- Additional Prior : All reionization histories should end by redshift 5. (Mc Greer 2011, Kulkarni 2014)

Free parameter	**Prior**
$\log \zeta_0$	$(0, \infty)$
$\log M_{min,0}$	$[7.0,11.0]$
α_ζ	$(-\infty, \infty)$
α_M	$(-\infty, 0)$

Specifications of modelling:

- We use the MCMC sampler part of Cobaya package (Torrado & Lewis 2021) to sample the parameter space of free parameters $\left[\log \zeta_0 , \log M_{min,0} , \alpha_\zeta, \alpha_M, r\ \right]$.

Likelihood function : $-2L \propto \chi^2 = \left(\frac{\tau - \tau^{obs}}{\sigma_\tau^{obs}}\right)^2 + \left(\frac{D_{\ell=3000}^{ksz,tot} - D_{\ell=3000}^{kSZ,obs}}{\sigma_{\rm kSZ}^{obs}}\right)^2$

$$+ \sum_{\ell,\ell'=\ell_{\rm min}}^{\ell_{max}} (\widetilde{D}_\ell^{BB} - D_\ell^{BB})\Sigma_{\ell,\ell'}^{-1}(\widetilde{D}_{\ell'}^{BB} - D_{\ell'}^{BB})$$

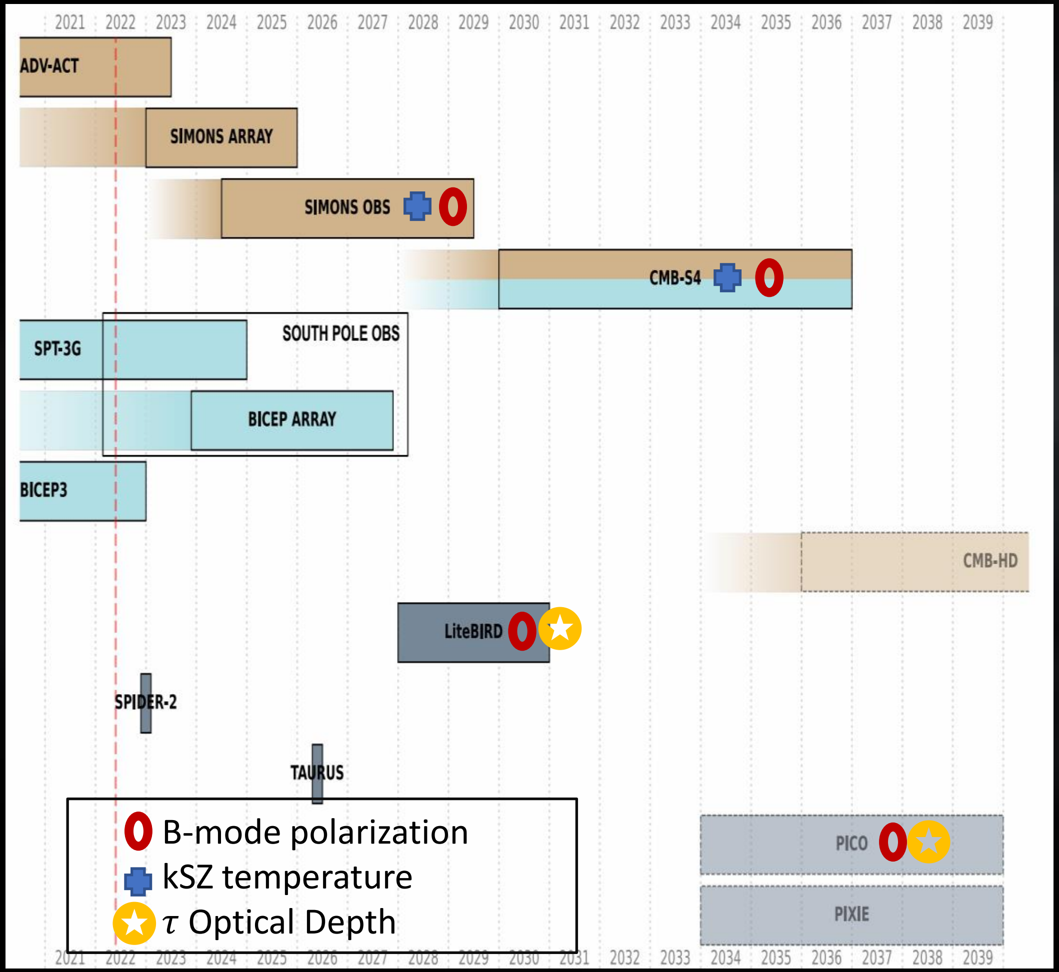
- As $D_{\ell=3000}^{kSZ,tot} = D_{\ell=3000}^{kSZ,reion} + D_{\ell=3000}^{kSZ,h}$
- We use scaling relations by Shaw et al. 2012 to calculate the $D_{\ell=3000}^{kSZ,h}$

How to test for bias?

- $\widetilde{D}_\ell^{BB} = \mathrm{D}_\ell^{\mathrm{BB,prim}}(r) + A_{lens} D_\ell^{BB,lens} + \mathrm{D}_\ell^{\mathrm{BB},reion}$
  - Calculated with CAMB modified to have reionization history from SCRIPT as input
  - A_{lens} is the lensing amplitude
  - Input r : $[5 \times 10^{-4}, 1 \times 10^{-3}]$
- Model
  - Template : $D_\ell^{BB} = D_\ell^{BB,prim}(r) + A_{lens} D_\ell^{BB,lens} + D_\ell^{BB,reion}$
  - Template $w/o\ D_\ell^{BB,reion}$: $D_\ell^{BB} = D_\ell^{BB,prim}(r) + A_{lens} D_\ell^{BB,lens}$

  [Choice of model of Reionization : input model for kSZ forecasting]
- Free parameters : $[\log M_{min,0}\,, \log \zeta_0\,, \alpha_M, \alpha_\zeta, r]$
- Bias : $\Delta\, r = r_{Template}^{inf,mean} - r_{Template\ w/o\ D_\ell^{BB,reion}}^{inf,mean}$
- Bias estimate : $\Delta r / \sigma_r$
- If $\frac{\Delta r}{\sigma_r} \sim 1$, B-mode from patchy reionization is a contaminant to primordial B-modes

Inferring bias for upcoming CMB experiments



Combination of Experiments:

- SO+ : Planck (τ) + SO (kSZ) +SO (BB)

[70 % delensing]

- LiteBIRD+ : Planck (τ) + SO (kSZ) + LiteBIRD (BB)

[70 % delensing]

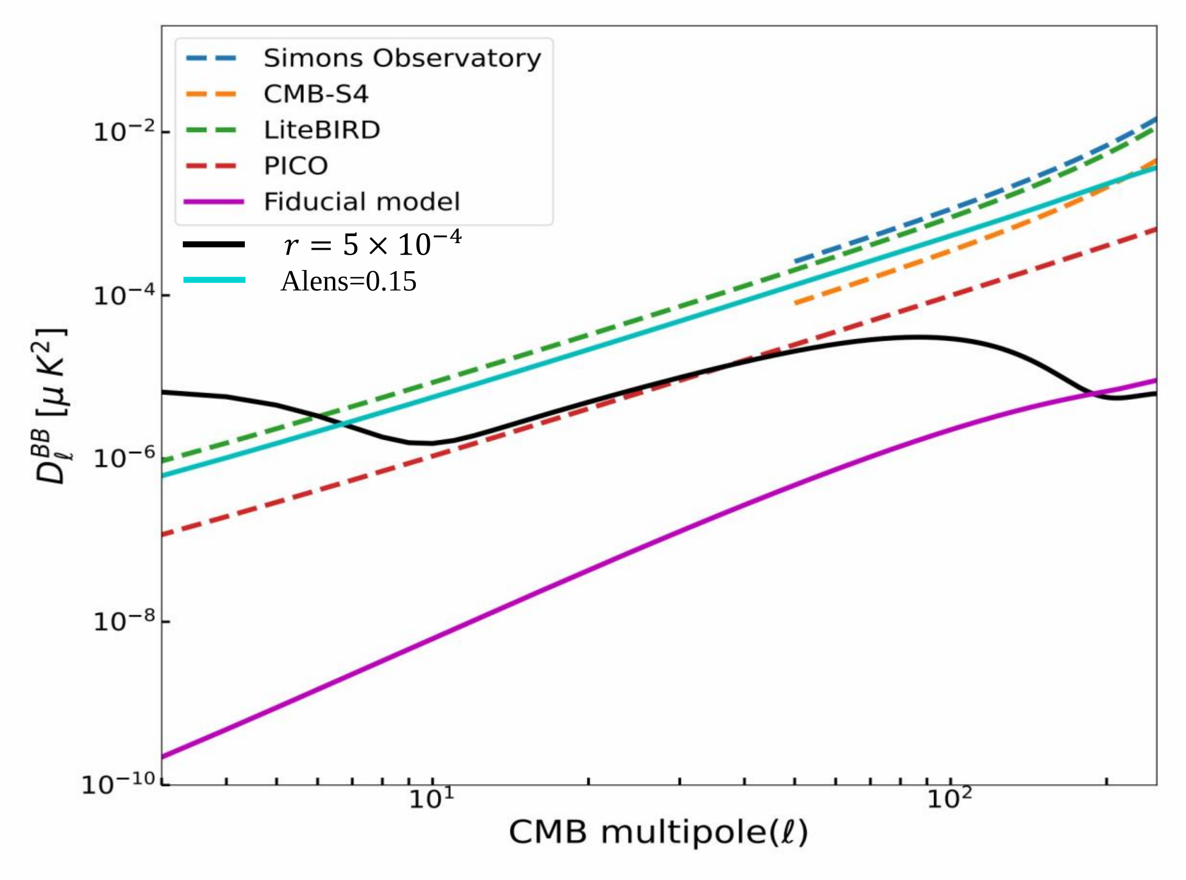
- CMB-S4+ : LiteBIRD (τ) + CMB-S4 (kSZ) + CMB-S4 (BB)

[85 % delensing]

- PICO + : LiteBIRD (τ) + CMB-S4 (kSZ) + PICO (BB)

[85 % delensing]

Inferring bias for upcoming CMB experiments



The fiducial model of reionization is obtained using the model $[\log M_{min,0}, \log \zeta_0, \alpha_M, \alpha_\zeta]$

For MCMC analysis with the Likelihood function

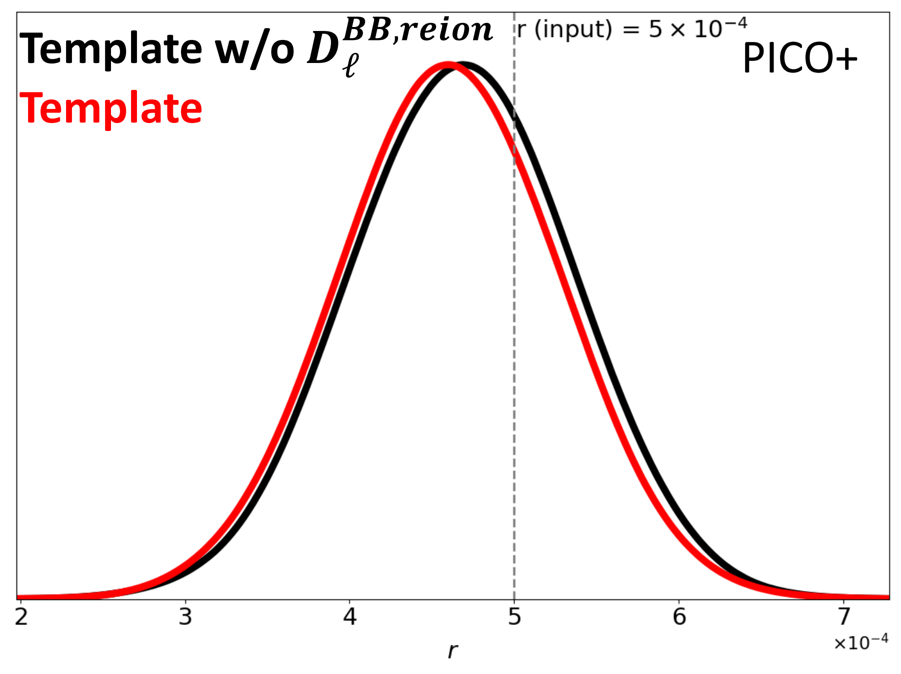
$$-2L \propto \chi^2 = \left(\frac{\tau - \tau^{obs}}{\sigma_\tau^{obs}}\right)^2 + \left(\frac{D_{\ell=3000}^{ksz,tot} - D_{\ell=3000}^{kSZ,obs}}{\sigma_{\mathrm{kSZ}}^{obs}}\right)^2$$

With observations of Planck $\tau = 0.054 \pm 0.007$ [Planck 2018] and SPT $D_{\ell=3000}^{kSZ,obs} = 3.00 \pm 1.0\ \mu K^2$[SPT 2021].

The resulting best-fit (Fiducial) model given as :

$[\log M_{min,0} = 9.73, \log \zeta_0 = 1.58, \alpha_M = -2.06, \alpha_\zeta = -2.01]$

Inferred Bias



$r_{input} \times 10^3 = 0.5$

Case	Model	68% limts	$\Delta r/\sigma$
CMB-S4+	Template	$0.50^{+0.18}_{-0.19}$	0.16
	Template $w/o\ D_\ell^{BB,reion}$	$0.53^{+0.18}_{-0.19}$	
PICO+	Template	$0.46^{+0.09}_{-0.10}$	0.21
	Template $w/o\ D_\ell^{BB,reion}$	$0.48^{+0.08}_{-0.10}$	

$r_{input} \times 10^3 = 1$

Case	Model	68% limts	$\Delta r/\sigma$
SO+	Template	< 3.53	–
	Template $w/o\ D_\ell^{BB,reion}$	< 3.54	
LiteBIRD+	Template	$0.86^{+0.39}_{-0.60}$	0.02
	Template $w/o\ D_\ell^{BB,reion}$	$0.87^{+0.43}_{-0.56}$	
CMB-S4+	Template	$0.99^{+0.21}_{-0.18}$	0.08
	Template $w/o\ D_\ell^{BB,reion}$	$1.02^{+0.18}_{-0.18}$	
PICO+	Template	$0.95^{+0.14}_{-0.99}$	0.17
	Template $w/o\ D_\ell^{BB,reion}$	$0.97^{+0.10}_{-0.10}$	

Inferred Bias: Delensing at 95%

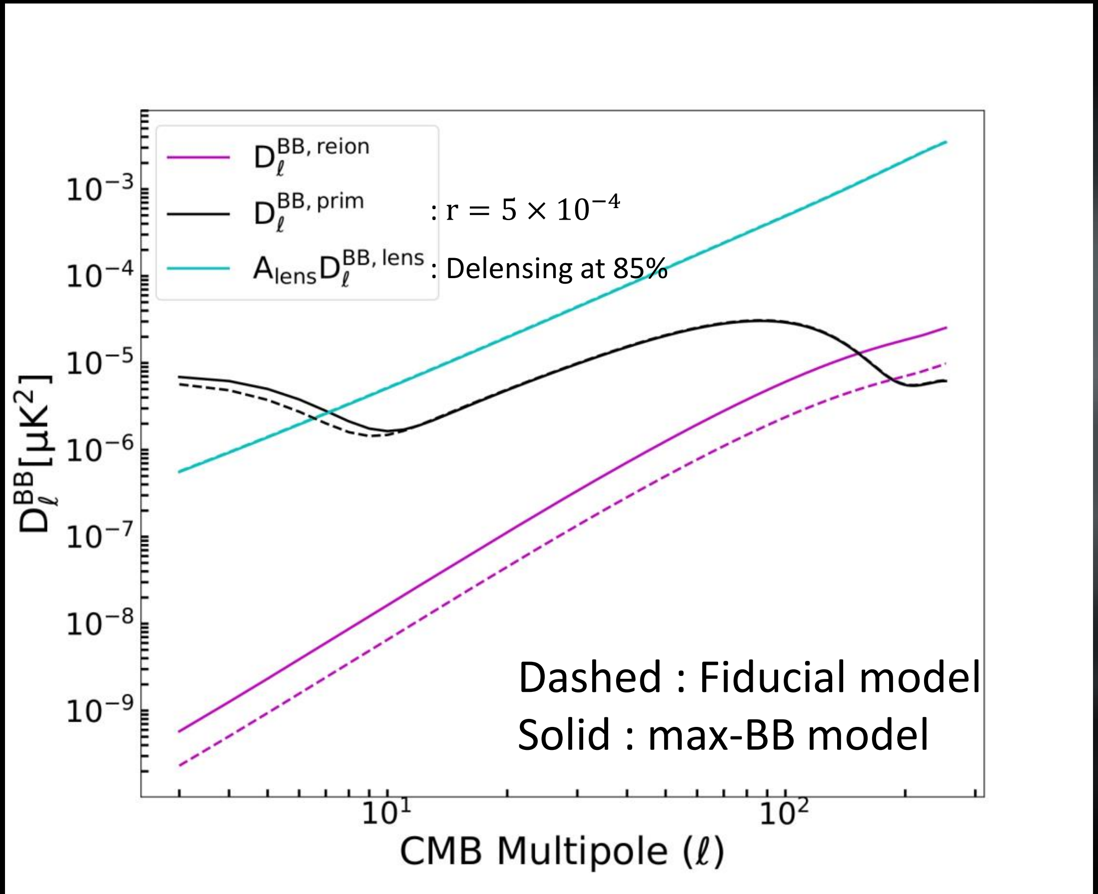
- The minimum delensing fraction (i.e., the best delensing possible) allowed by the instrumental beam and sensitivity by experiments like CMB-S4 and PICO is at 0.05 or 95% delensing

[P. Diego-Palazuelos et al. 2020]

$$r_{input} \times 10^3 = 0.5$$

Case	Model	68% limts	$\Delta r/\sigma$
PICO+ (85% delensing)	Template	$0.46^{+0.09}_{-0.10}$	0.21
	Template $w/o\ D_\ell^{BB,reion}$	$0.48^{+0.08}_{-0.10}$	
PICO+ (95% delensing)	Template	$0.47^{+0.06}_{-0.06}$	0.33
	Template $w/o\ D_\ell^{BB,reion}$	$0.49^{+0.06}_{-0.07}$	

Case of extreme bias:



Choose a model with maximum $D_{\ell=200}^{BB,reion}$ allowed by 3σ contours of Planck (τ) + SPT (kSZ) MCMC chains to study extreme bias.

max-BB: $\left[\log M_{min,0} = 10.39, \log \zeta_0 = 2.48, \alpha_M = -0.76, \alpha_\zeta = 3.58\right]$

$$r_{input} \times 10^3 = 0.5$$

Case	Model	68% limts	$\Delta r/\sigma$
PICO+ (85% delensing)	Template	$0.46^{+0.08}_{-0.09}$	0.47
	Template $w/o\ D_\ell^{BB,reion}$	$0.50^{+0.09}_{-0.09}$	
PICO+ (95% delensing)	Template	$0.47^{+0.06}_{-0.06}$	0.83
	Template $w/o\ D_\ell^{BB,reion}$	$0.52^{+0.06}_{-0.07}$	

Conclusion:

- Neglecting B-mode contribution from `patchy’ reionization will introduce a bias Δr in our inference of tensor-to-scalar power spectrum ratio r.
- Our ability to be affected by the bias Δr will depend on the sensitivity of our inference of r
- With Stage-4 CMB experiments like CMB-S4 and pico we observe Δr greater than 10% for input $r = 5 \times 10^{-4}$.
- The maximum bias we can possibly observe with PICO observations is at 0.83σ.
- Precision inference of r requires correct modelling of B-mode power spectra.
- `Patchy’ Reionization foregrounds have potential to bias our observations of r.