Cosmic birefringence tomography and calibration-independence with reionization signals in the CMB

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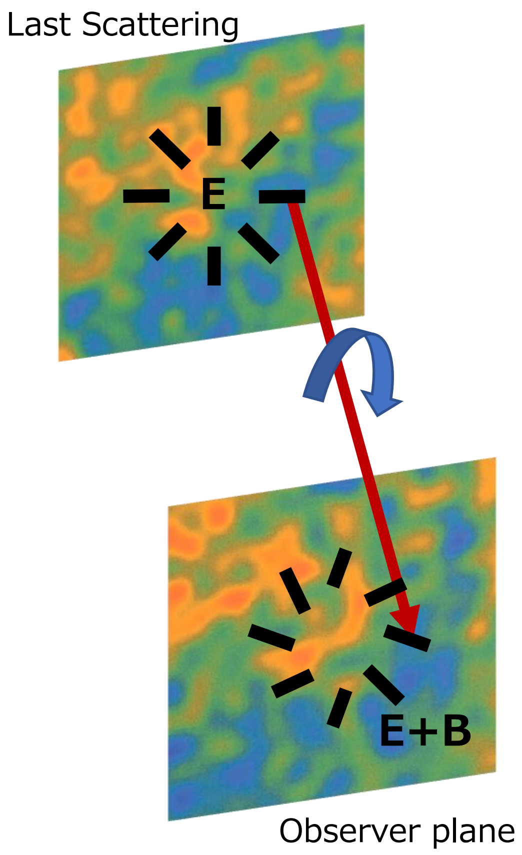
2021年11月17日 観測的宇宙論ワークショップ

B. Sherwin & T. Namikawa, 2108.09287 (arXiv)

T. Namikawa, 2105.03367 (arXiv)

Cosmic Birefringence and Axion

Cosmic Birefringence = Rotation of CMB polarization angle during the propagation



詳細は藤田氏（去年）、小幡氏の講演を参照ください

Cosmic Birefringence and Axion

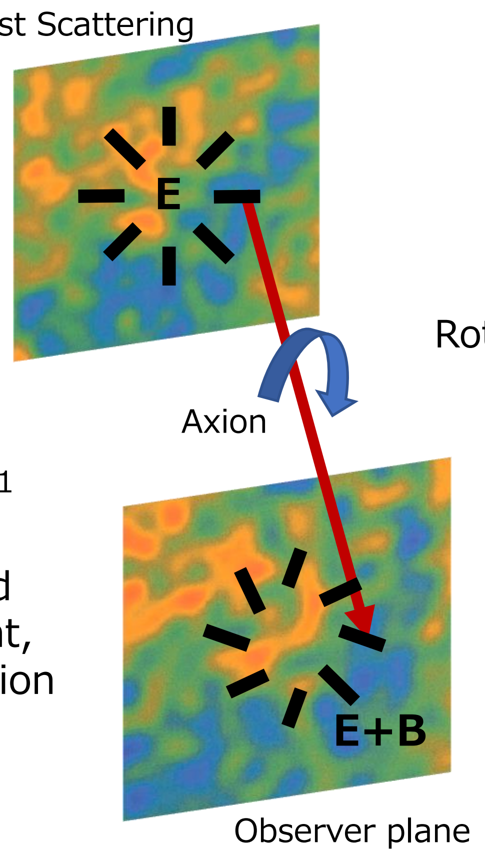
Cosmic Birefringence = Rotation of CMB polarization angle during the propagation

Coupling parameter

$$\mathcal{L} \supset \frac{g\phi}{4} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

See e.g. Caroll’98, Li&Zhang’08, Pospelov+’09, Caldwell+’11

This term makes the phase velocities of right- and left-handed polarization states of photons different, leading to rotation of the linear polarization direction



Difference between $\phi_{\rm LSS}$ and $\phi_{\rm obs}$

Rotation angle

$$\beta(n) = \frac{g\Delta\phi(n)}{2}$$

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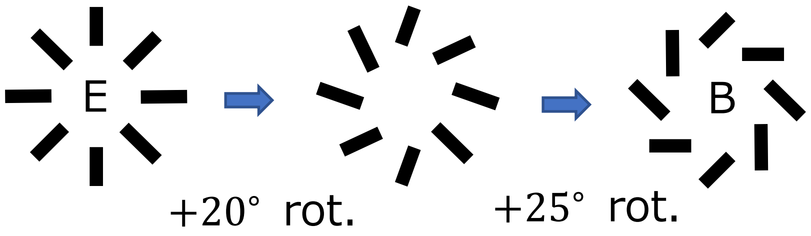
Isotropic cosmic birefringence measurement

- Isotropic birefringence converts part of E to B:



$$E^{\mathrm{CMB}} \to B^{\mathrm{obs}}$$

$$C_L^{EB} = \frac{(C_L^{EE} - C_L^{BB})\sin 4\beta}{2}$$

$\rightarrow$ β

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Problems in measuring isotropic cosmic birefringence

$$\theta = \alpha + \beta$$

Measured angle

Instrumental angle error $\Delta\alpha \sim O(0.1)\mathrm{deg}$

Birefringence signal

- How to break degeneracy between α and β

Minami et al. (2019) proposed to use FGs to constrain α: FGs are not rotated by β EE ≠ BB

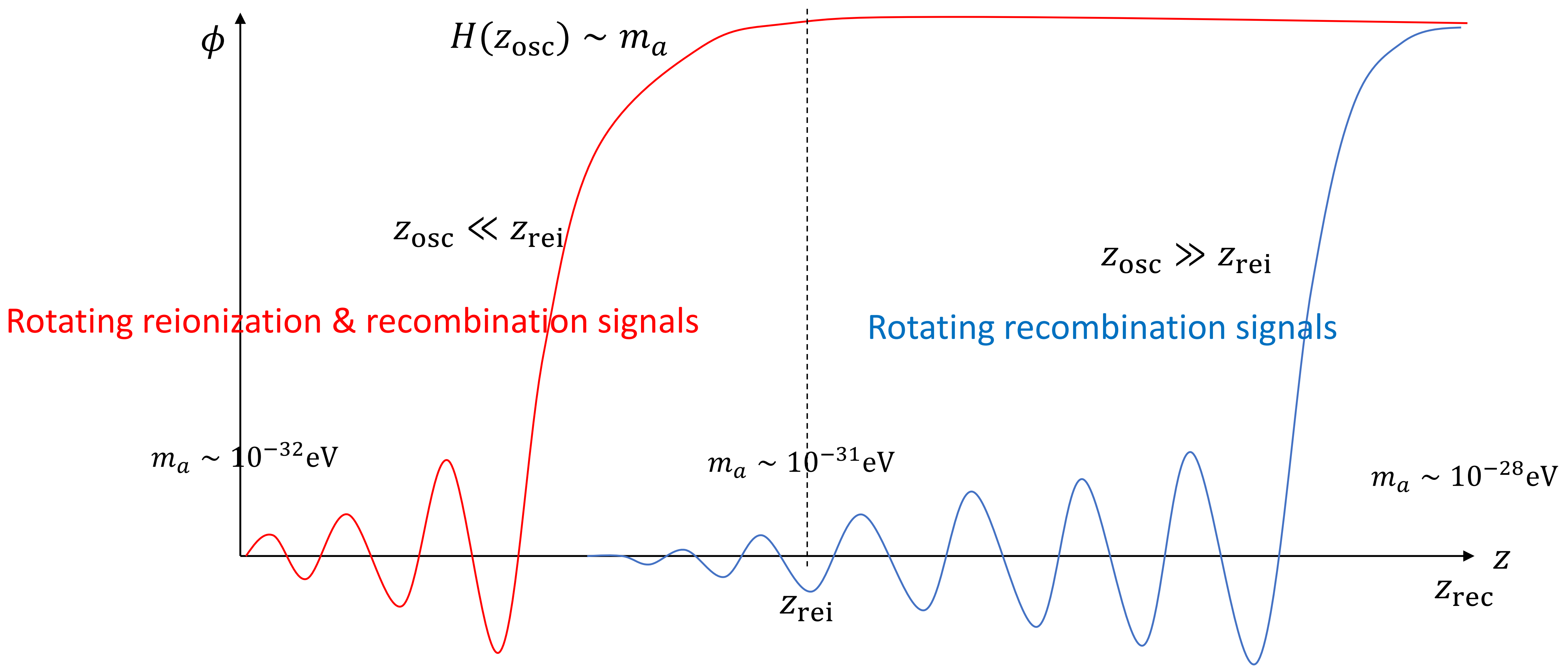
Planck Collaboration (2017)	$0.31 \pm 0.05\ (\mathrm{stat}) \pm 0.28\ (\mathrm{sys})$
Minami & Komatsu (2020)	0.35 ± 0.14 (angle calibration by foreground)

今回は、これとは異なる等方的宇宙複屈折効果の検証方法を考案した（以降のスライド）

1. Cosmic birefringence from reionization

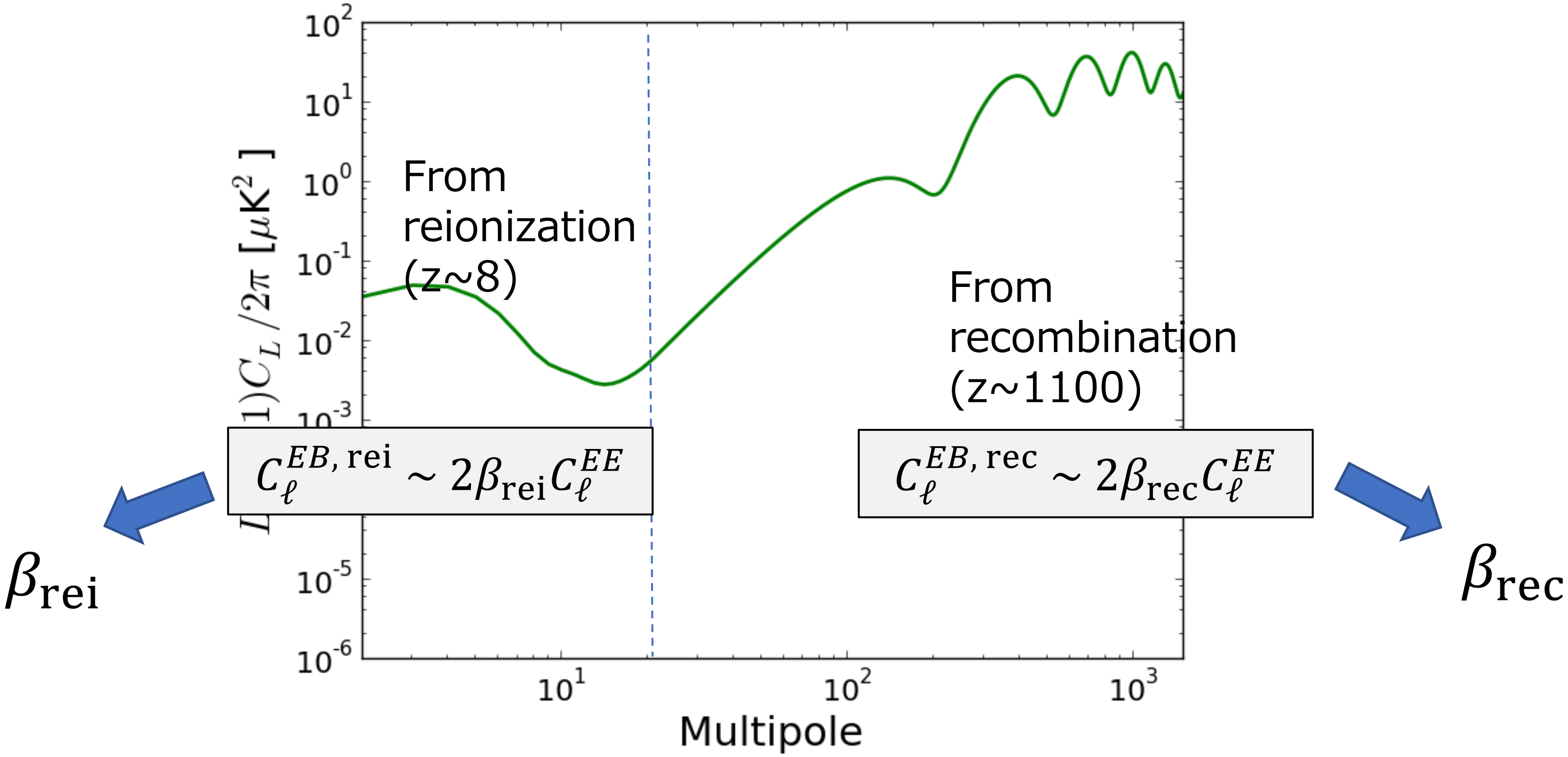
Tomography

- Tomographic info of axion fields



Polarization from reionization and recombination could be differently rotated depending on details of axion dynamics (or any other new physics)

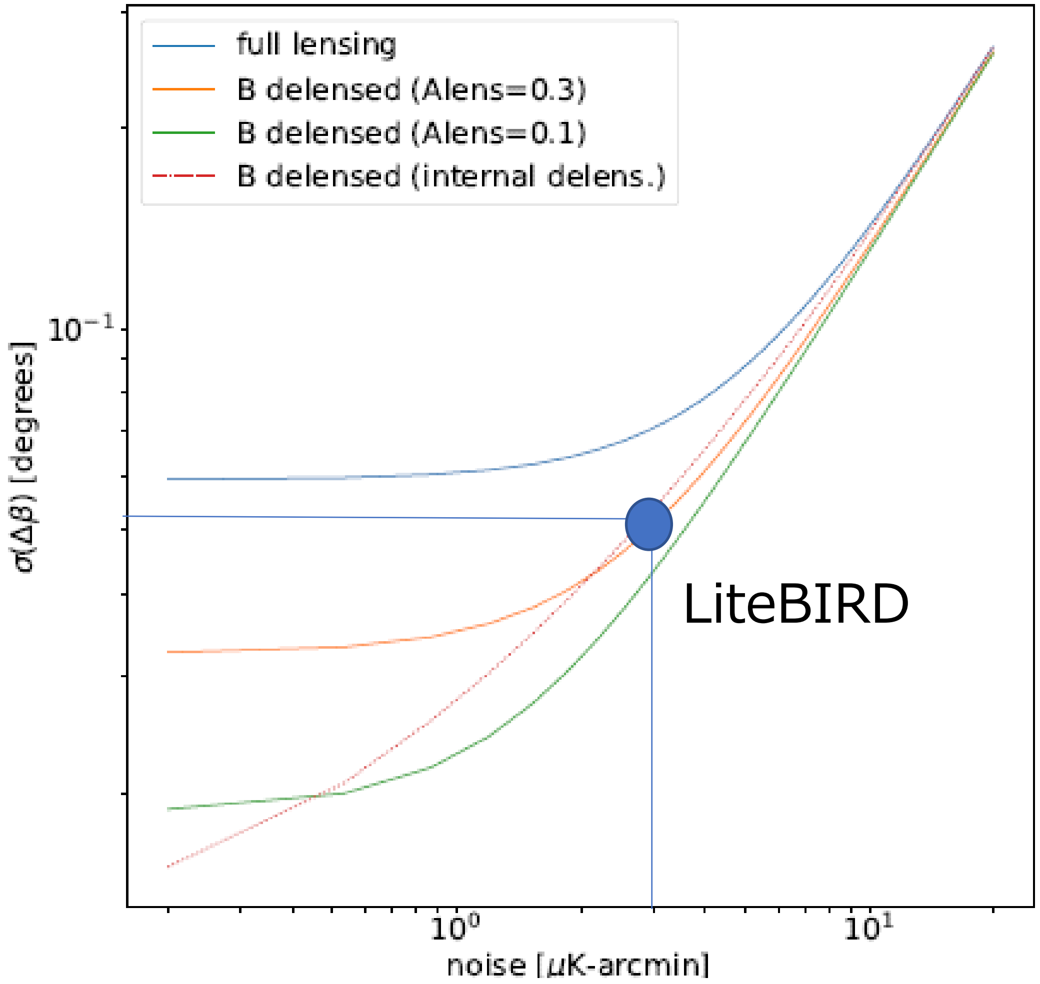
Our idea



- Difference could be measured without angle errors

$$\theta_{\mathrm{rec}} - \theta_{\mathrm{rei}} = (\alpha + \beta_{\mathrm{rec}}) - (\alpha + \beta_{\mathrm{rei}}) = \beta_{\mathrm{rec}} - \beta_{\mathrm{rei}} \equiv \Delta\beta$$

Forecast



$$\mathbf{F}_{ij} = \sum_l f_{\rm sky} \frac{2l+1}{2} \mathrm{Tr}\left(\mathbf{C}_l^{-1} \frac{\partial \mathbf{C}_l}{\partial p_i} \mathbf{C}_l^{-1} \frac{\partial \mathbf{C}_l}{\partial p_j} \right) \Bigg|_{p_i = p_{i,\rm fid}} \qquad \mathbf{C}_l \equiv \begin{pmatrix} \widehat{C}_l^{EE} & \widehat{C}_l^{EB} \\ \widehat{C}_l^{EB} & \widehat{C}_l^{BB} \end{pmatrix}$$

$$\frac{\partial C^{EE}}{\partial p_i} = \frac{\partial C^{BB}}{\partial p_i} = 0 \quad \Downarrow \quad p_i^{fid} = 0$$

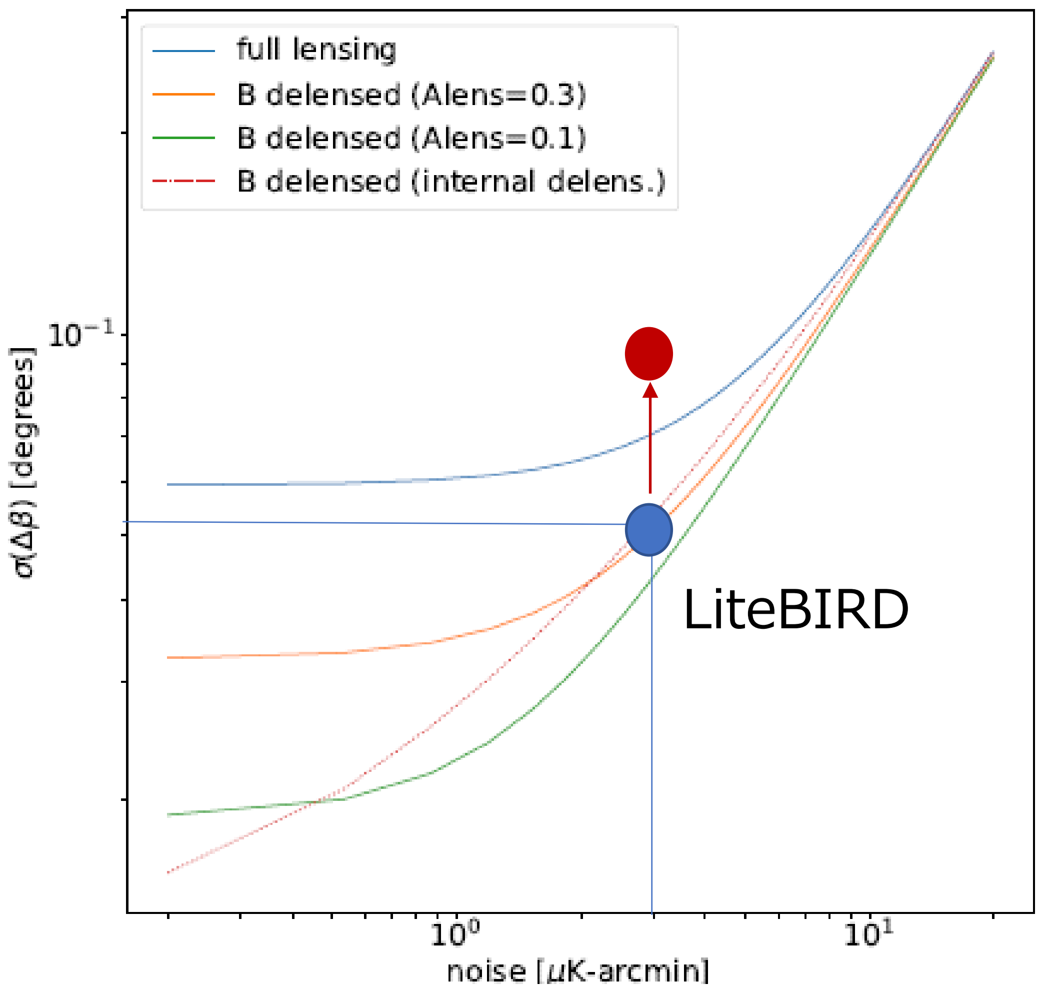
$$\mathbf{F}_{\theta_x \theta_y} = \sum_l f_{\rm sky} (2l+1) \frac{4(C_l^{EE,x} - C_l^{BB,x})(C_l^{EE,y} - C_l^{BB,y})}{\widehat{C}_l^{EE} \widehat{C}_l^{BB}}$$

Figure 1. Constraints on the birefringence angle difference as a function of CMB polarization noise level, with different delensing efficiencies assumed (we also assume $f_{\rm sky} = 0.7$.) Solid lines of different colours assume different constant delensing efficiencies; the dotted line labelled 'internal delens.' assumes delensing using lensing measurements by the same experiment. These results show that for future CMB satellites reaching noise levels of a few μK-arcmin, competitive constraints on the birefringence angle difference of order 0.05 degrees can be achieved. Note that here any Galactic foreground residuals are not included in the forecasts.

LiteBIRD like experiment

$$\sigma(\Delta\beta) \simeq 0.05 \text{ degs}$$

Forecast



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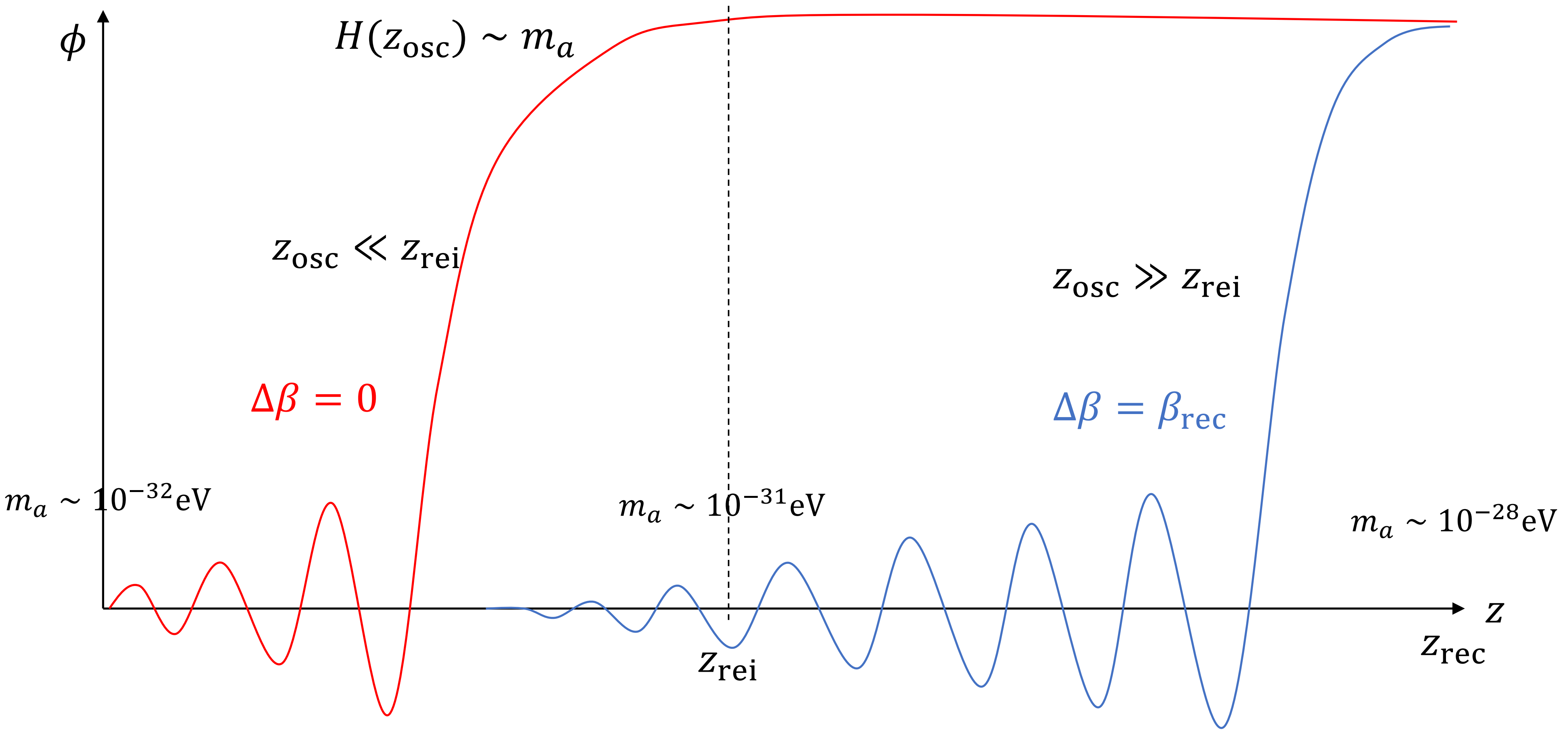
worse a bit w/ FG residuals

$$\sigma(\Delta\beta) \simeq 0.09\ \mathrm{degs}$$

c.f. $\sigma(\beta) \simeq 0.06$ deg with the FG-based method of Minami et al. (2019)

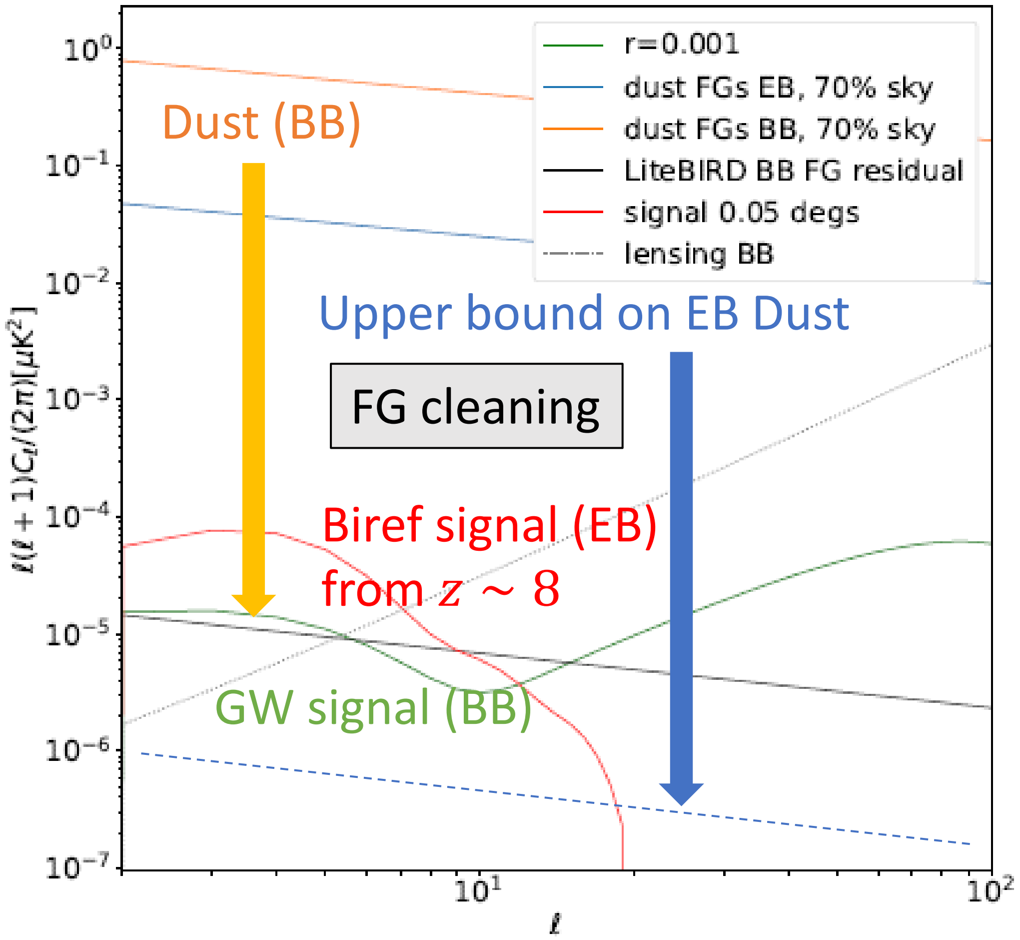
Tomography

- Tomographic info of axion fields



If $\beta_{\rm rec} = 0.35$ deg and $z_{\rm osc} \gg z_{\rm rei}$, a LiteBIRD like experiment can detect $\Delta\beta = 0.35$ deg

Main Challenge: Foregrounds



EB brief signal is much larger than EB dust FG with a FG cleaning method which realizes a detection of inflationary BB (r=0.001, a main goal of LiteBIRD)

Frequency dependence of mis-calibration angle can lead to e.g. anisotropic and/or ell-dependent α, depending on FG cleaning methods, more work required.

2. CMB mode-coupling as an alternative way of measuring isotropic birefringence

Isotropic cosmic birefringence measurement

- Frequently used statistics in cosmology

Power spectrum: $\langle X_{\ell m} Y^*_{\ell,m} \rangle = C_\ell$

Mode mixing: $\langle X_{\ell m} Y_{\ell' m'} \rangle \neq 0$ $(\ell, m \neq \ell', -m')$ (Statistical anisotropy)

- EB correlations are usually ignored in computing CMB mode coupling
  - How does it affect formulation of lensing (and other mode-mixing) estimators?
  - Can we use this effect to constrain isotropic birefringence?

Standard no isotropic birefringence case

Let first recall lensing effects on CMB polarization and later generalize it to include non-zero birefringence:

$$P'(n) = P(n + \nabla\phi) \simeq P(n) + \nabla\phi(n) \cdot \nabla P(n) \qquad\qquad P = Q + iU$$

$$E'_{\ell m} = E_{\ell m} + \sum_{LM\ell' m'} (-1)^m \begin{pmatrix} \ell & L & \ell' \\ -m & M & m' \end{pmatrix} \phi_{LM} \left(E_{\ell' m'} W^{+}_{\ell L \ell'} + B_{\ell' m'} W^{-}_{\ell L \ell'} \right)$$

$$B'_{\ell m} = B_{\ell m} + \sum_{LM\ell' m'} (-1)^m \begin{pmatrix} \ell & L & \ell' \\ -m & M & m' \end{pmatrix} \phi_{LM} \left(-E_{\ell' m'} W^{-}_{\ell L \ell'} + B_{\ell' m'} W^{+}_{\ell L \ell'} \right)$$

E/B is mixed

Off diagonal correlation (i.e., $\ell, m \neq \ell', -m'$) of $X, Y = E, B$ is non-zero:

$$\langle X_{\ell m} Y_{\ell' m'} \rangle_{cmb} = \sum_{LM} \begin{pmatrix} \ell & \ell' & L \\ m & m' & M \end{pmatrix} f^{XY}_{\ell L \ell'} \phi^{*}_{LM}$$

For the standard no-birefringence scenario, we have: $f^{XY}_{\ell L \ell'} = W^{-}_{\ell L \ell'} C^{BB}_{\ell'} - p_{\ell L \ell'} W^{-}_{\ell L \ell'} C^{EE}_{\ell}$

The above motivates the following quadratic estimator for lensing

$$\widehat{x}^{\mathrm{XY}}_{LM} = \frac{A^{x,(\mathrm{XY})}_{L}}{\Delta^{\mathrm{XY}}} \sum_{\ell\ell' mm'} (-1)^M \begin{pmatrix} \ell & \ell' & L \\ m & m' & -M \end{pmatrix} (f^{x,(\mathrm{XY})}_{\ell L \ell'})^{*} \overline{X}_{\ell m} \overline{Y}_{\ell' m'}$$

(basically, a convolution of CMB map and its gradient)

Non-zero isotropic birefringence case

- Now generalize the previous lensing mode-mixing to include non-zero birefringence:

$$P'(n) = \mathrm{e}^{2\mathrm{i}\beta} P(n + \nabla\phi) \supset P(n) + \nabla\phi(n) \cdot \nabla P(n) + \mathrm{i}\beta P(n) + \mathrm{i}\beta \nabla\phi(n) \cdot \nabla P(n)$$

- Off diagonal correlation has new terms:

$$\langle X_{\ell m} Y_{\ell' m'} \rangle_{cmb} = \sum_{LM} \begin{pmatrix} \ell & \ell' & L \\ m & m' & M \end{pmatrix} \left[f^{XY}_{\ell L \ell'} \phi^*_{LM} + \tilde{f}^{XY}_{\ell L \ell'} \tilde{\phi}^*_{LM} \right]$$

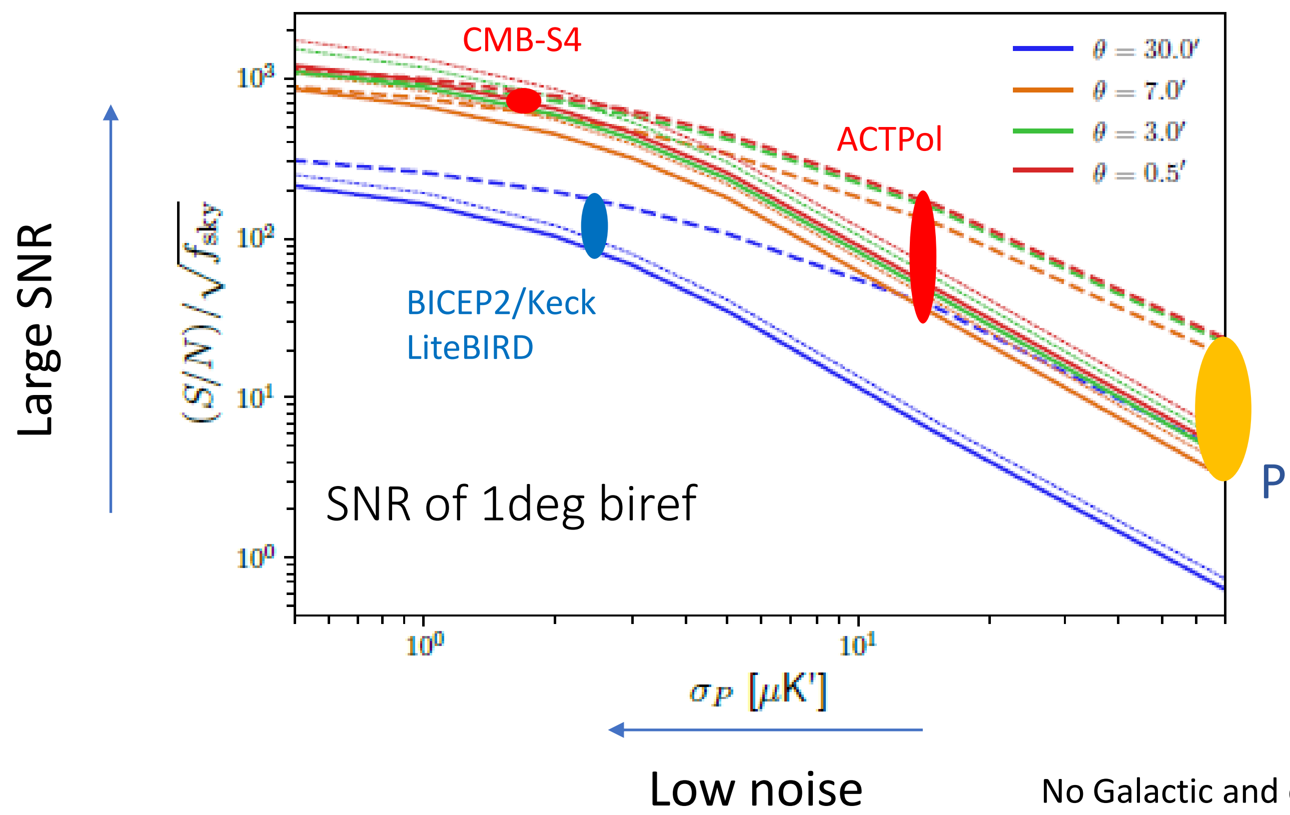
$$\tilde{f}^{XY}_{\ell L \ell'} = 2W^{+}_{\ell L \ell'} \left(C^{EE}_{\ell'} - C^{BB}_{\ell'} \right) + p_{\ell L \ell'} 2W^{+}_{\ell L \ell'} \left(C^{EE}_{\ell} - C^{BB}_{\ell} \right)$$

- The estimator to $\tilde{\phi} = \beta\phi$ becomes the same as ϕ but with a different f

- ϕ and $\tilde{\phi}$ can be estimated separately due to the parity symmetry

How efficiently can we constrain birefringence angle, β, by reconstructing $\tilde{\phi}$?

Expected constraints on biref angle



Solid: $\tilde{\phi}\phi^{\rm CIB}$

Dashed: EB

Dotted: $\tilde{\phi}\phi^{\rm true}$

Planck:

$\sigma(\beta) \simeq 0.4$deg from $\tilde{\phi}\phi^{\rm CIB}$

No Galactic and extra galactic foregrounds

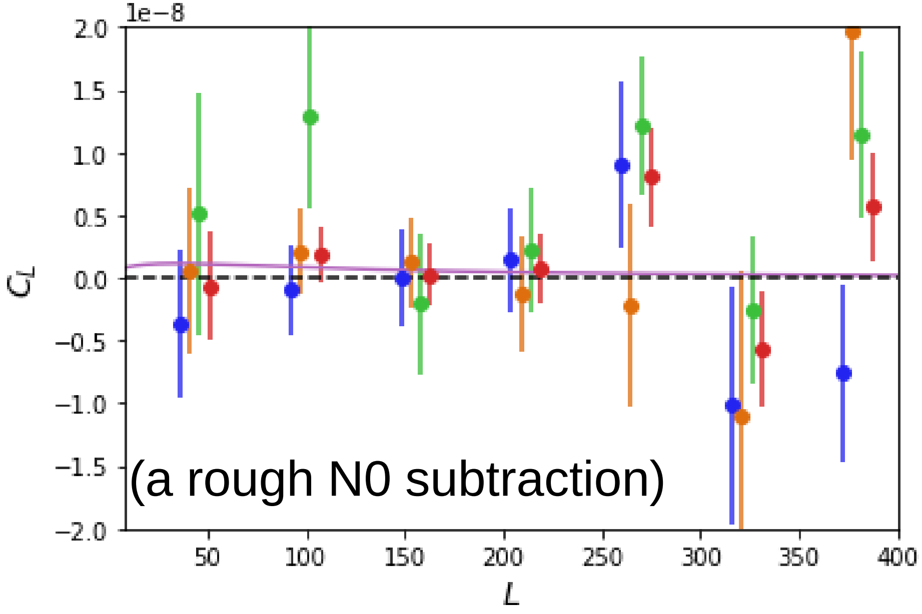
- The mode-coupling can be used as a cross check of birefringence angle measurements in low noise polarization experiments (but this method alone cannot separate α and β)

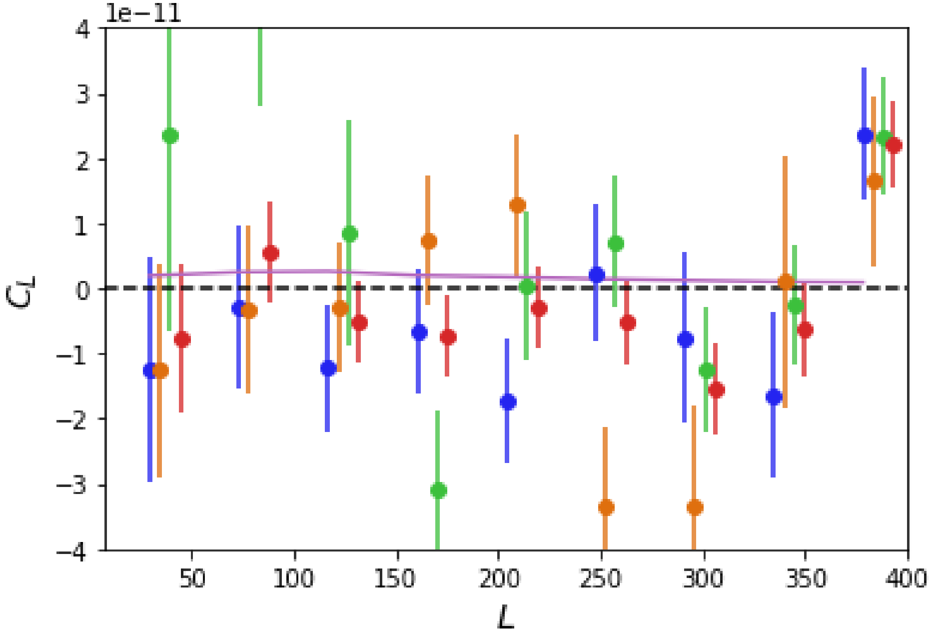
Preliminary analysis with Planck 2018 data

$\tilde{\phi}\phi$

TB, EB, BB, MV

$\tilde{\phi}T^{\mathrm{CIB}}$





SMICA (40% sky) 0.03+/-0.57 deg -0.61+/-0.45 deg

-0.35+/-0.36 deg

Summary

- EB correlation is a unique probe of parity-violating physics such as axions from CMB observations

- A precise measurement of reionization bump provides information on the axion mass (and more?)

- Isotropic birefringence measurement from the mode-coupling can be used as an alternative way of birefringence angle measurement in low noise polarization experiments