Cosmic birefringence tomography with polarized Sunyaev-Zel'dovich effect

Toshiya Namikawa

(Kavli IPMU, University of Tokyo)

Cosmic birefringence tomography

- Planck (+WMAP) data suggests a hint of cosmic birefringence

0.35 ± 0.14 deg	Minami & Komatsu (2020)
0.36 ± 0.11 deg	Diego-Palazuelos et al. (2022)
$0.34^{+0.094}_{-0.091}$ deg	Eskilt & Komatsu (2022)

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$$C_\ell^{EB} \simeq 2\beta C_\ell^{EE} \qquad \beta = \frac{g\Delta\phi}{2}$$

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Axion-like particles (Nakatsuka et al. 2022, Naokawa et al. in prep.)
Early dark energy (Murai et al. 2022, Galaverni et al. 2023)

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(+ Break degeneracies between birefringence signals and miscalibration angle (Sherwin & Namikawa 2022))

cosmic birefringence tomography

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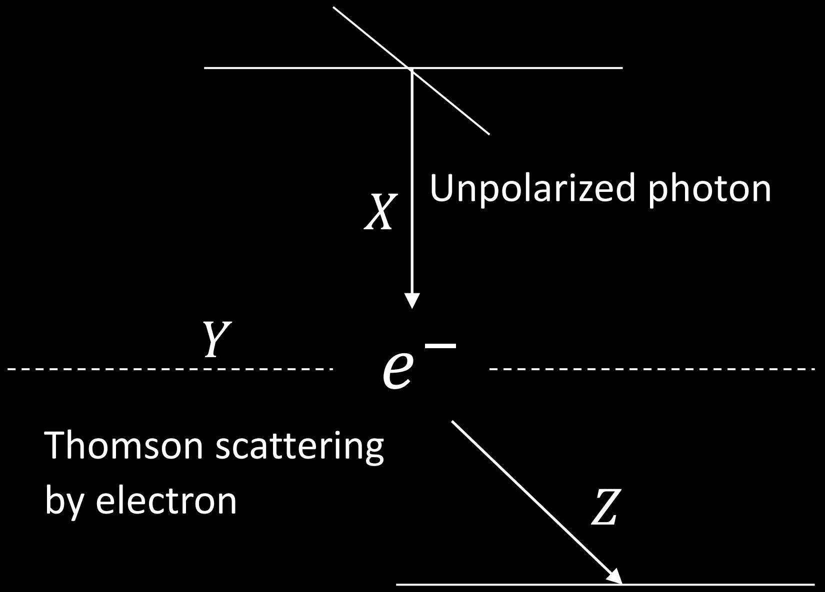
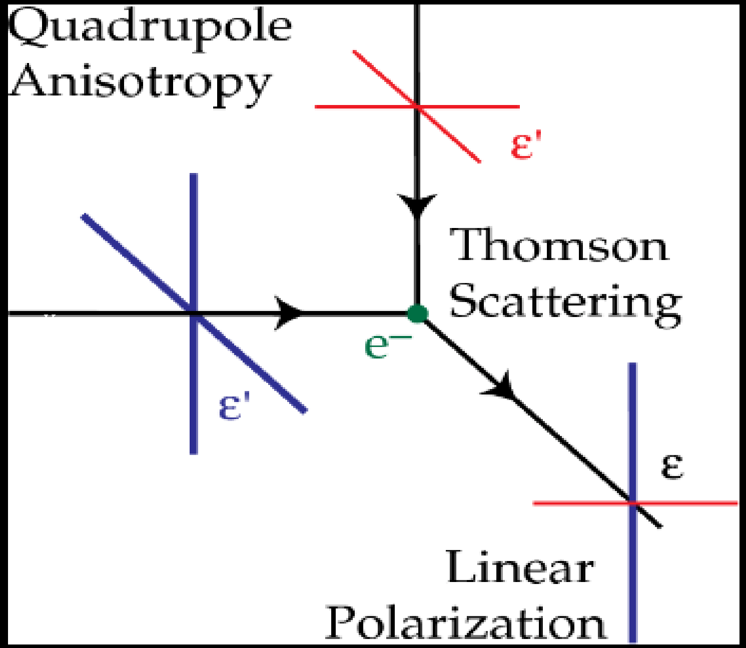
cosmic birefringence tomography

In this talk, I discuss new tomographic sources; the polarized Sunyaev Zel'dovich (pSZ) effect ($z \ll 10$)

Polarized Sunyaev Zel'dovich (pSZ) effect

Temperature quadrupole anisotropies -> linear polarization

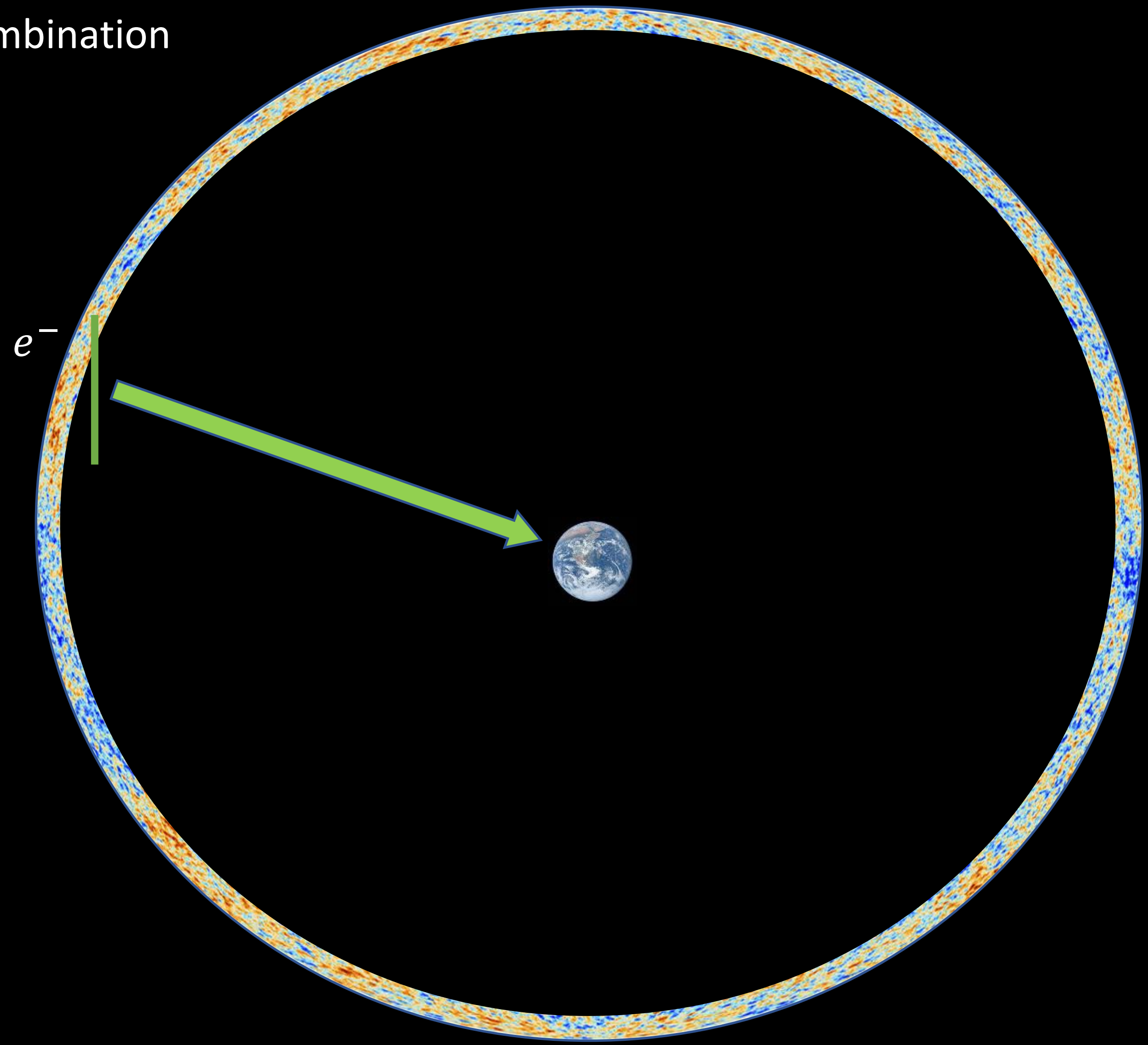




Wayne Hu's Tutorial
(http://background.uchicago.edu/~whu)

Polarized Sunyaev Zel'dovich (pSZ) effect

CMB polarization from recombination



Polarized Sunyaev Zel'dovich (pSZ) effect

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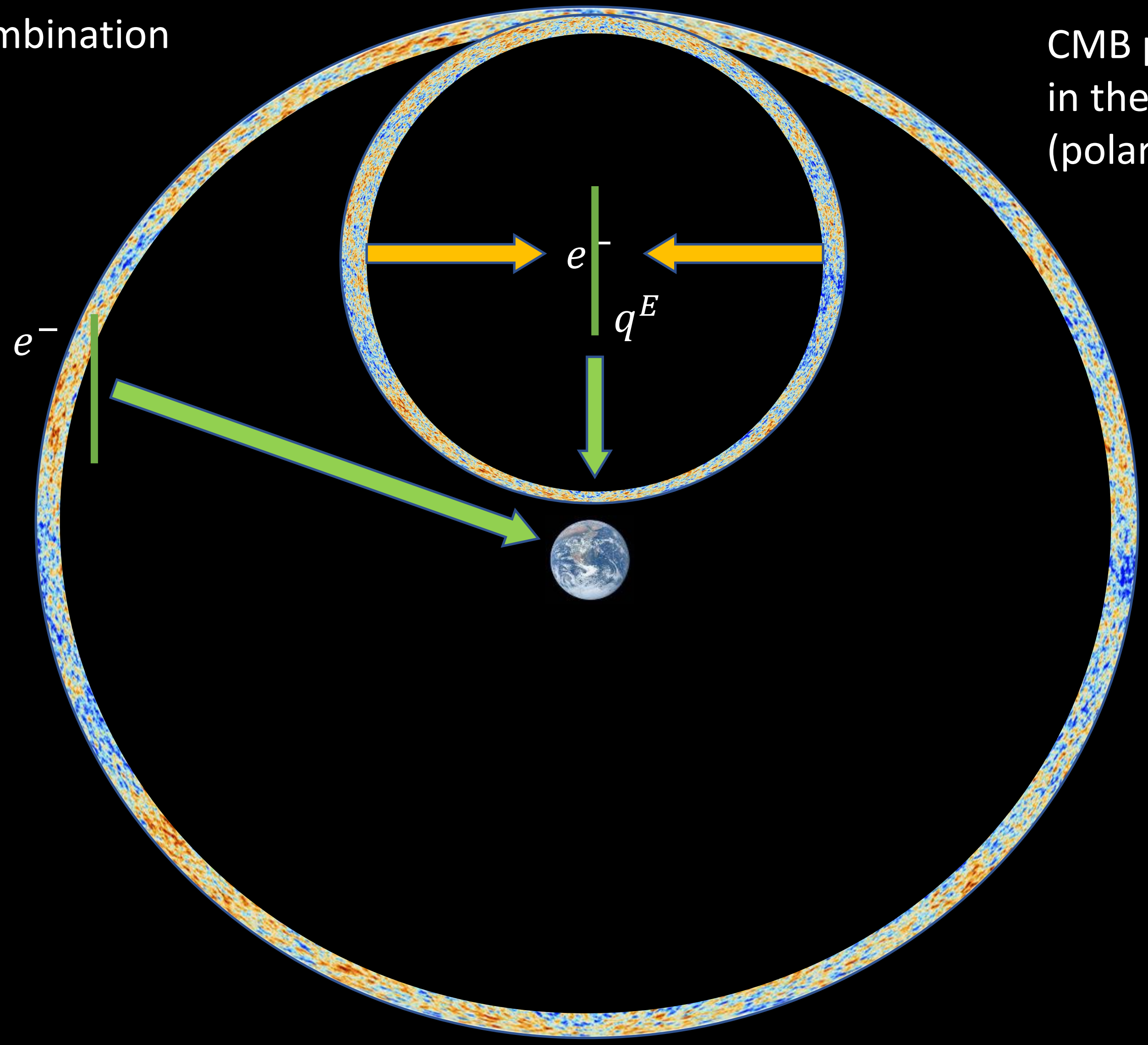


CMB polarization generated in the late-time universe (polarized Sunyaev Zel'dovich effect)

Sunyaev & Zel'dovich 1980, Kamionkowski & Loeb 1997, Portsmouth 2004

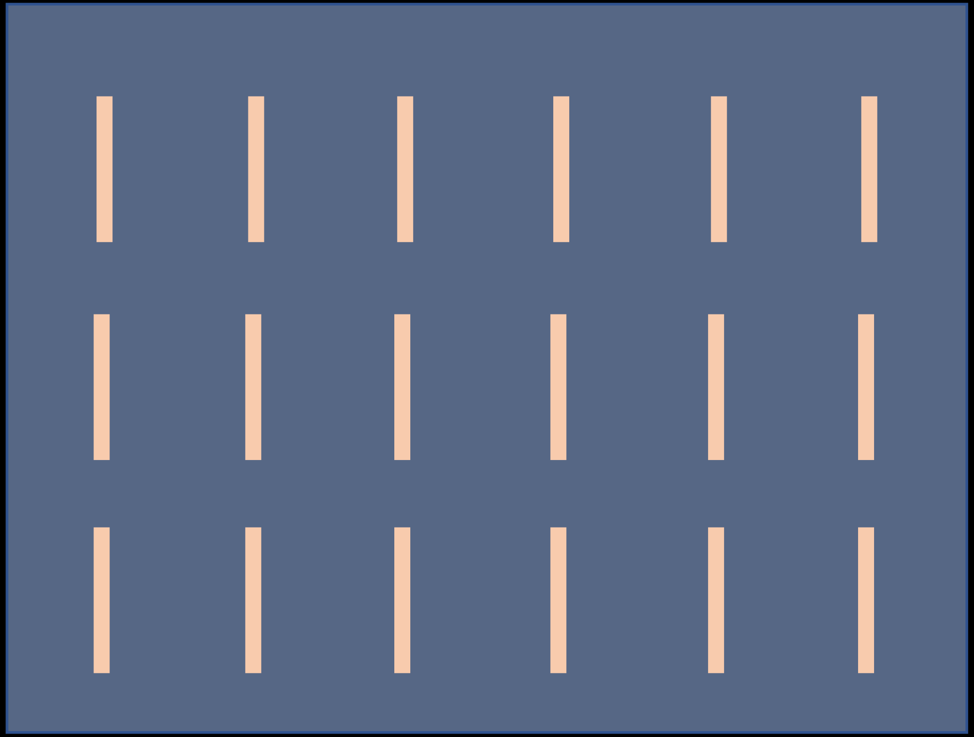
pSZ can be used to probe time evolution of ϕ in the late-time universe

Polarized Sunyaev Zel'dovich (pSZ) effect

- $Q^{\mathrm{pSZ}} \pm iU^{\mathrm{pSZ}} = \int \mathrm{d}z$ (local polarization) $\times$ (electron number density)

  q^E $\qquad\qquad\qquad$ $\bar{n}_e$

Polarization pattern with homogeneous n_e



(Local polarization has only E-modes, q^E)

pSZ contributions in observed E/B modes:

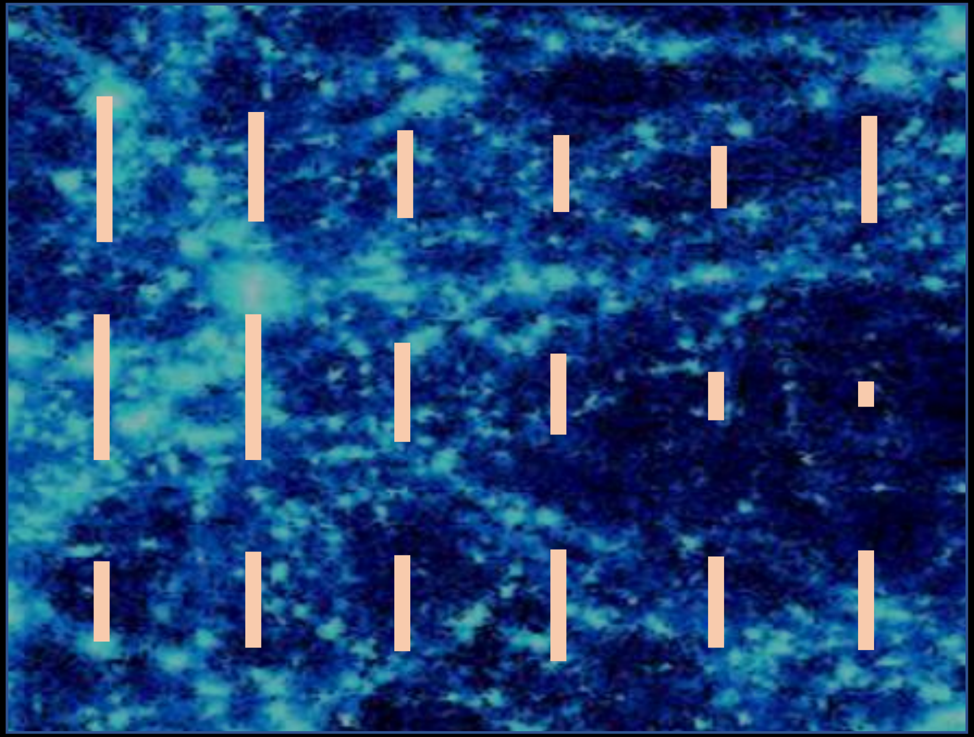
$$\begin{cases} \bar{E}^{\mathrm{pSZ}} \sim \int \mathrm{d}z\ \bar{n}_e w^E q^E \\ \bar{B}^{\mathrm{pSZ}} = 0 \end{cases}$$

Polarized Sunyaev Zel'dovich (pSZ) effect

- $Q^{\mathrm{pSZ}} \pm iU^{\mathrm{pSZ}} = \int \mathrm{d}z$ (local polarization) $\times$ (electron number density)

$$q^E \qquad\qquad n_e = \bar{n}_e(1+\delta_e)$$

Polarization pattern with inhomogeneous n_e



(Local polarization has only E-modes, q^E)

pSZ contributions in observed E/B modes:

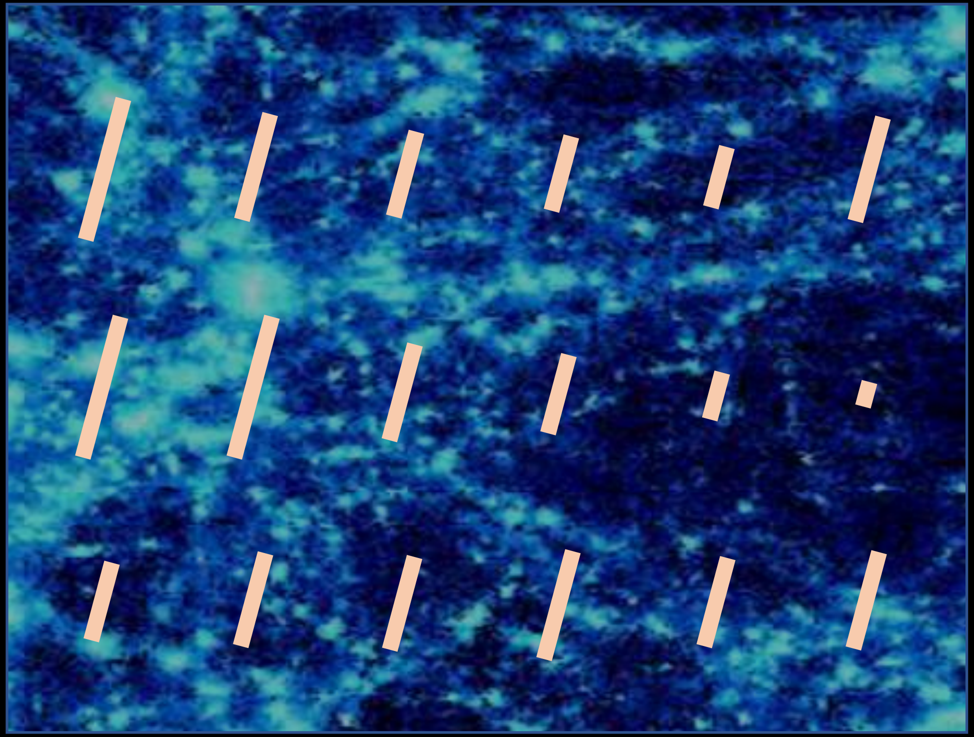
$$\begin{cases} E^{\mathrm{pSZ}} \sim \bar{E}^{\mathrm{pSZ}} + \int \mathrm{d}z\, w^E \bar{n}_e \delta_e\, q^E \\ B^{\mathrm{pSZ}} \sim \int \mathrm{d}z\, w^B \bar{n}_e \delta_e q^E \end{cases}$$

Polarized Sunyaev Zel'dovich (pSZ) effect + cosmic birefringence

- $Q^{\mathrm{pSZ}} \pm iU^{\mathrm{pSZ}}$ = $\int \mathrm{d}z$ (local polarization) × (rotation) × (electron number density)

$$q^E, \quad q^B = 2\beta q^E \qquad\qquad n_e = \bar{n}_e(1+\delta_e)$$

Polarization pattern with inhomogeneous n_e + rotation 2β



(Local polarization has both E- and B-modes, q^E, q^B)

pSZ contributions in observed E/B modes:

$$\begin{cases} E'^{\mathrm{pSZ}} \sim E^{\mathrm{pSZ}} + \mathcal{O}(\beta^2) \\ B'^{\mathrm{pSZ}} \sim B^{\mathrm{pSZ}} + \int dz\, \bar{n}_e w^E (1+\delta_e) q^B + \mathcal{O}(\beta^2) \end{cases}$$

Polarized Sunyaev Zel'dovich (pSZ) effect **+ cosmic birefringence**

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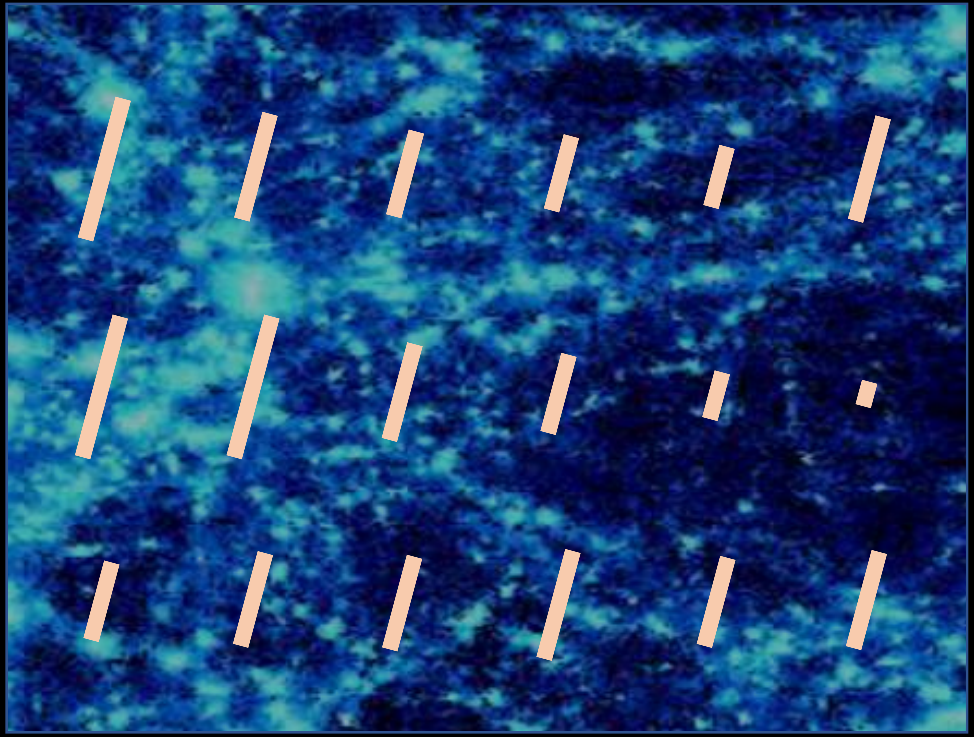

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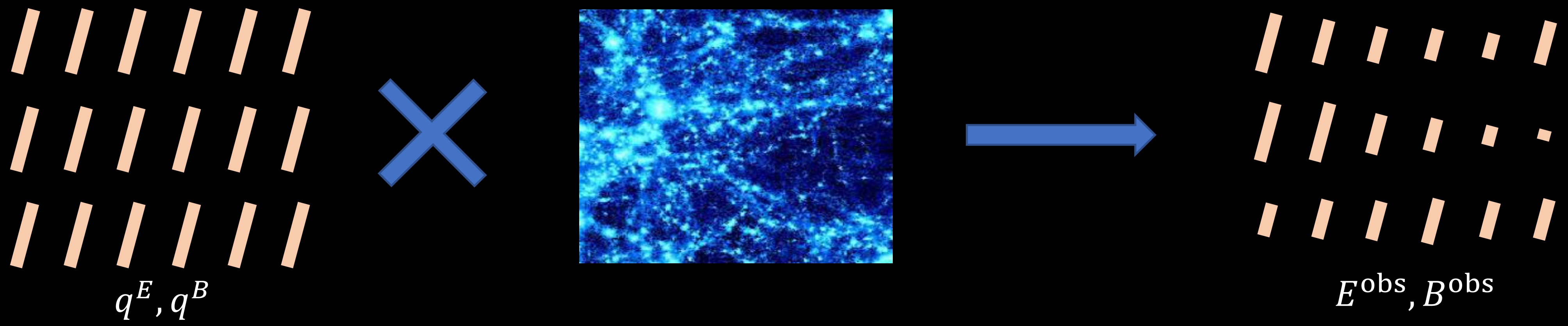
We can reconstruct the local polarization q^E, q^B at each z-bin with the fact that the polarization is distorted by δ_e

(next slides)

Measuring pSZ signals

- pSZ $\sim$ (local E-modes) $\times$ (matter density fluctuations)



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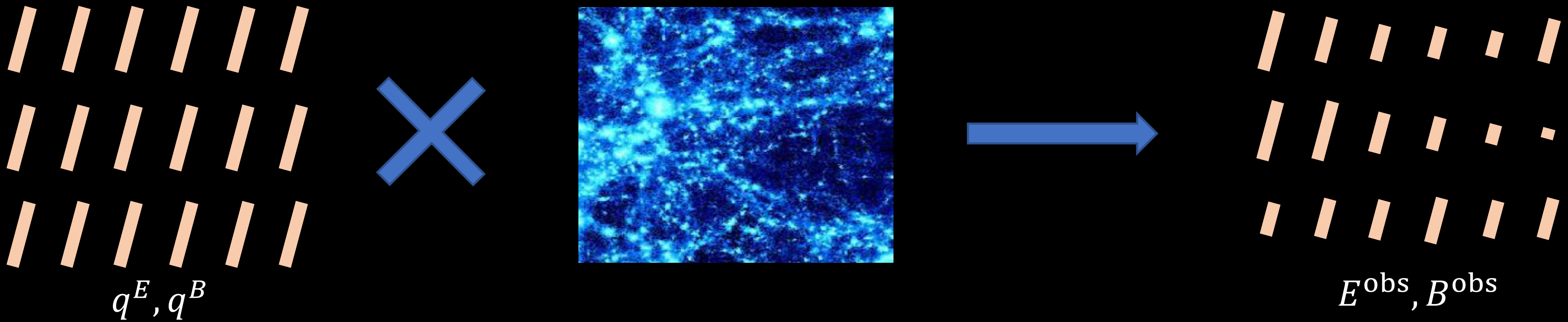

- pSZ estimator $\sim$ (observed E/B-modes) $\times$ (galaxy number density fluctuations)

(Deutsch et al. 2018)

$$\hat{q}^{E,i} = E^{\text{obs}} \odot \delta_{g,i}^{\text{obs}}$$

Measuring pSZ signals

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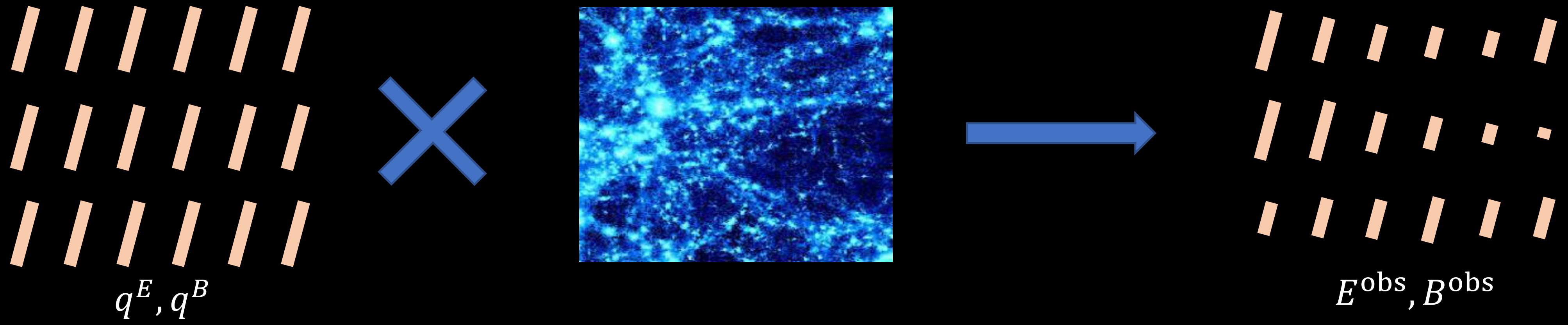

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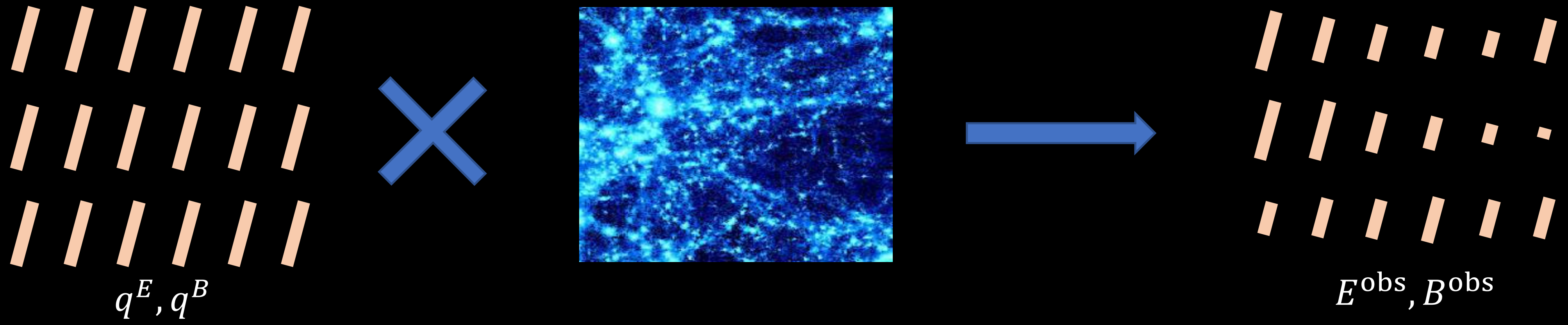
$$\hat{q}^{E,i} = E^{\mathrm{obs}} \odot \delta_{g,i}^{\mathrm{obs}} \sim E^{\mathrm{pSZ}} \odot \delta_{m,i} \sim q^{E,i} \delta_{m,i}^2$$

Measuring pSZ signals

- pSZ $\sim$ (local E-modes) $\times$ (matter density fluctuations)



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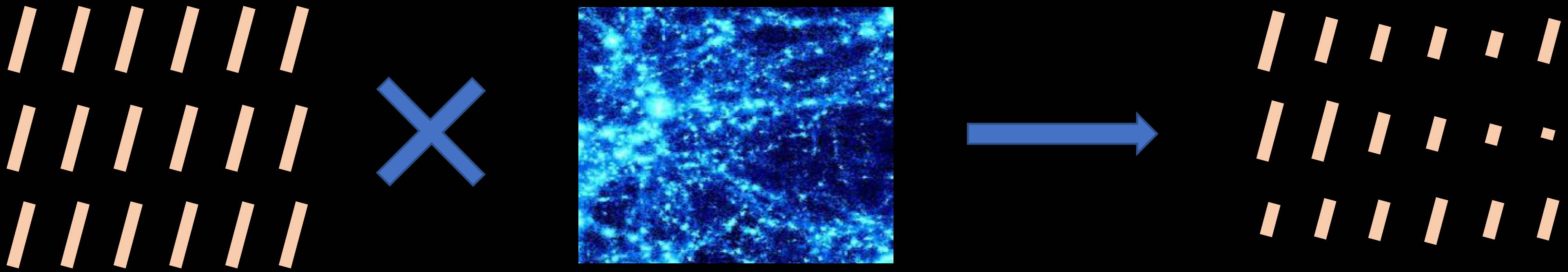
$$\hat{q}^{E,i} = E^{\rm obs} \odot \delta_{g,i}^{\rm obs} \sim E^{\rm pSZ} \odot \delta_{m,i} \sim q^{E,i}\delta_{m,i}^2$$

$$\hat{q}^{E,i} = B^{\rm obs} \otimes \delta_{g,i}^{\rm obs} \sim B^{\rm pSZ} \otimes \delta_{m,i} \sim q^{E,i}\delta_{m,i}^2$$

$$\hat{q}^{B,i} = B^{\rm obs} \odot \delta_{g,i}^{\rm obs} \sim B^{\rm pSZ} \odot \delta_{m,i} \sim 2\beta_i q^{E,i}\,\delta_{m,i}^2$$

Measuring pSZ signals

- pSZ $\sim$ (local E-modes) $\times$ (matter density fluctuations)



q^E, q^B $\qquad$ $E^{\text{obs}}, B^{\text{obs}}$

- pSZ estimator $\sim$ (observed E/B-modes) $\times$ (galaxy number density fluctuations)

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A tomographic measurement of the cosmic birefringence angle

This work

New correlations induced by polarization angle rotation (from E^{obs}, B^{obs}, $q^{E,\mathrm{obs},i}$, $q^{B,\mathrm{obs},i}$)

$$\langle E^{\mathrm{obs}} q^{B,\mathrm{obs},i} \rangle \sim 2\beta_i \langle E q^{E,i} \rangle$$

$$\langle q^{E,\mathrm{obs},i} q^{B,\mathrm{obs},j} \rangle \sim 2\beta_j \langle q^{E,i} q^{E,j} \rangle$$

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Previous study considers cosmic birefringence effect on measured pSZ signals (Lee, Hotinli, Kamionkowski 2022)

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Previous study considers cosmic birefringence effect on measured pSZ signals (Lee, Hotinli, Kamionkowski 2022)

However, we should also consider the cosmic birefringence signal in the total observed B-modes

$$B^{\rm obs} \supset B^{\rm pSZ} \sim \int dz\, w^E 2\beta(z)\, \bar{n}_e q^E \sim \sum_i 2\beta_i \underbrace{\int_{z_i-\Delta z}^{z_i+\Delta z} {\rm d}z\, w^E q^E}_{E^i} = \sum_i 2\beta_i E^i$$

This work

New correlations induced by polarization angle rotation (from $E^{\rm obs}$, $B^{\rm obs}$, $q^{E,{\rm obs},i}$, $q^{B,{\rm obs},i}$)

$$\langle E^{\rm obs} q^{B,{\rm obs},i}\rangle \sim 2\beta_i \langle E q^{E,i}\rangle$$

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$$\langle E^{\rm obs} B^{\rm obs}\rangle \sim \sum_i 2\beta_i \langle E E^i\rangle$$

These correlations are also generated

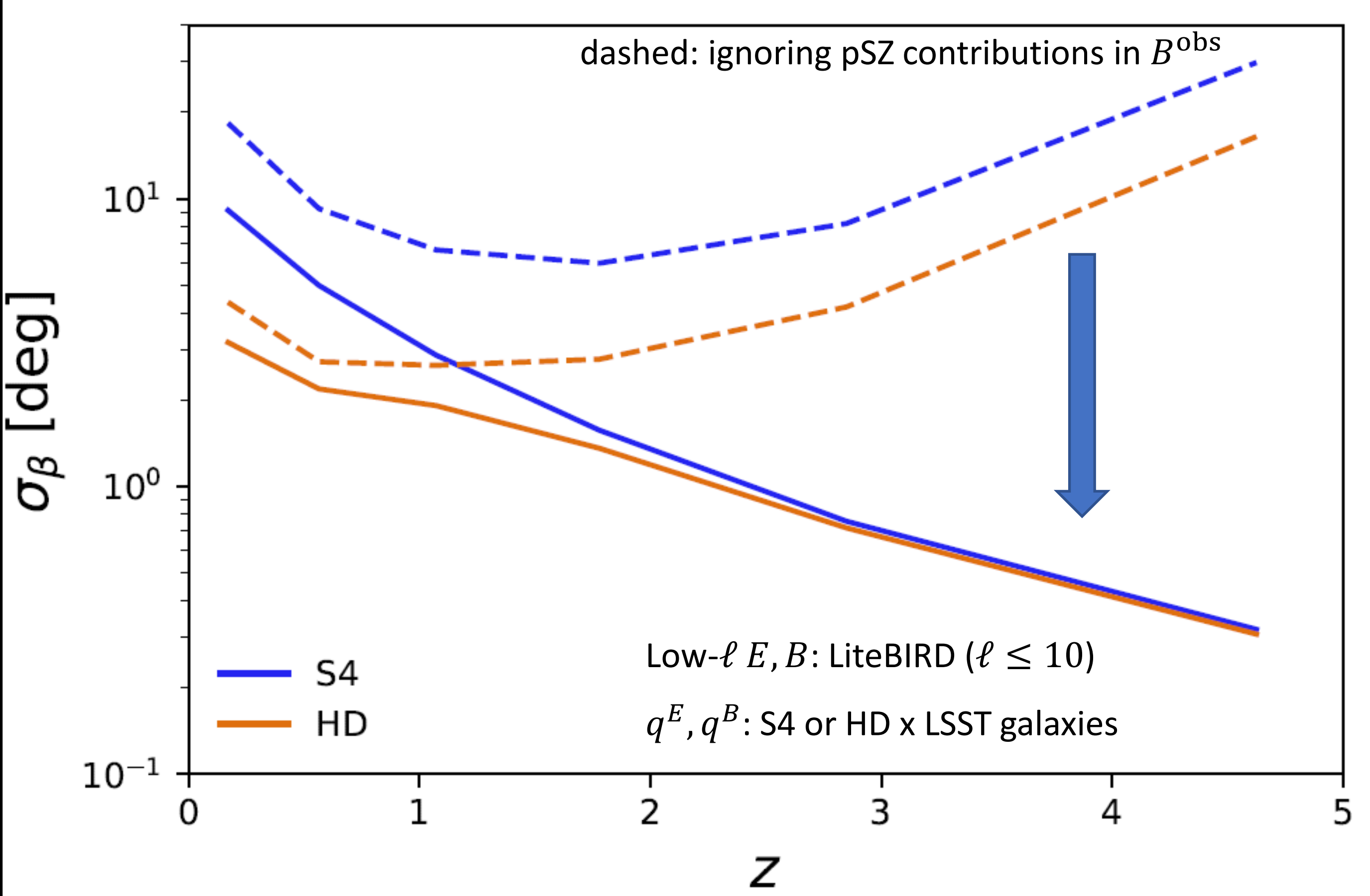
$$\langle q^{E,{\rm obs},i} B^{\rm obs}\rangle \sim \sum_j 2\beta_j \langle q^{E,i} E^j\rangle$$

Equivalent to measure $\langle BB\delta_g\rangle$

We check how the missing terms change the constraint on birefringence angles

Forecast results

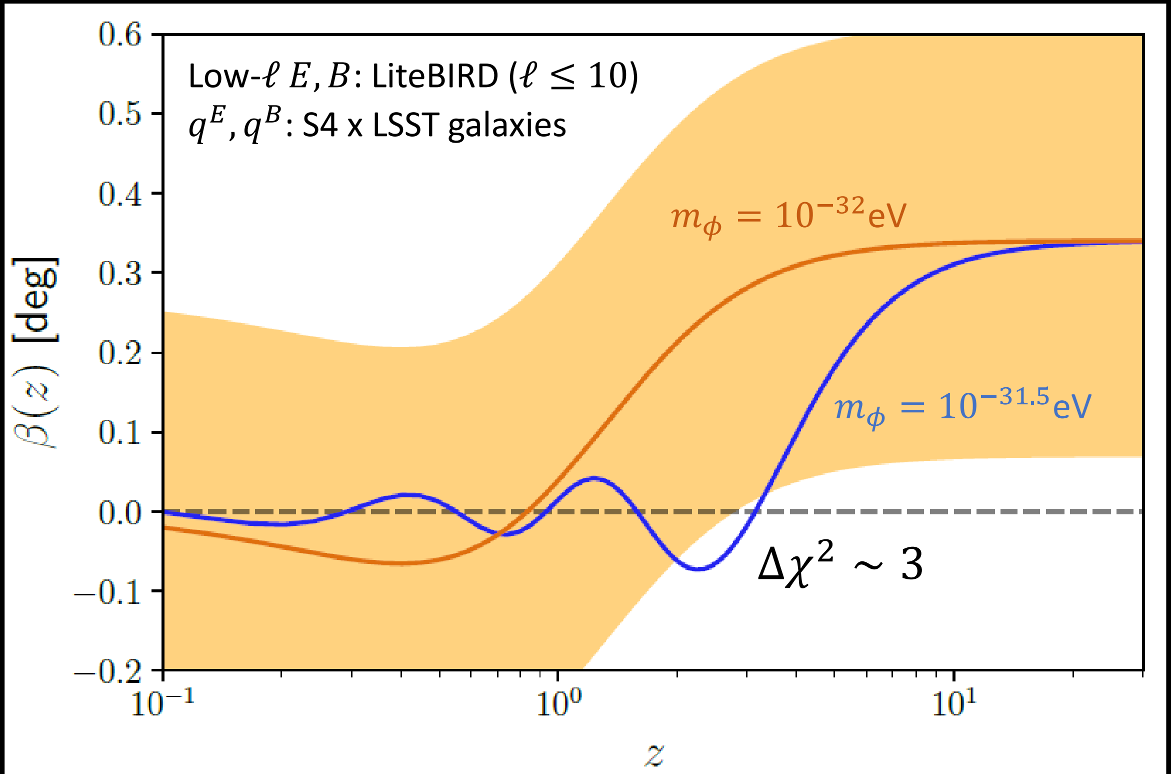
- Constraints on rotation angle at each z bin

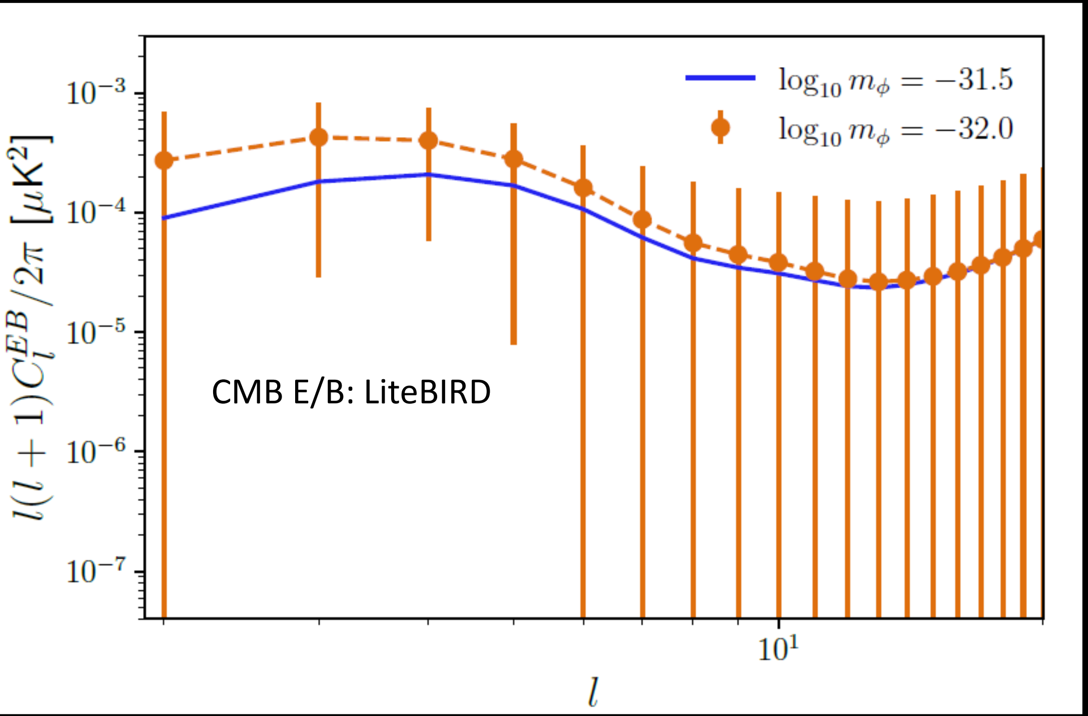


Missing terms change the constraint by an order of magnitude especially at high z

Forecast results

- 1σ constraints on overall amplitude of the rotation angle for ALPs with a specific mass (shaded region)





We would be able to distinguish different mass of ALPs even if they oscillate well after the reionization/recombination

Summary

We forecast expected constraints on cosmic birefringence with low-ell CMB (E, B) and reconstructed pSZ (q^E,q^B)

We include all relevant terms some of which are missed in the previous work
and show that these missing terms are important

1 σ constraint on the rotation angle at each z bin is roughly degree to sub-degree level

pSZ would be useful for constraining late-time cosmic birefringence

Backup

Forecast results

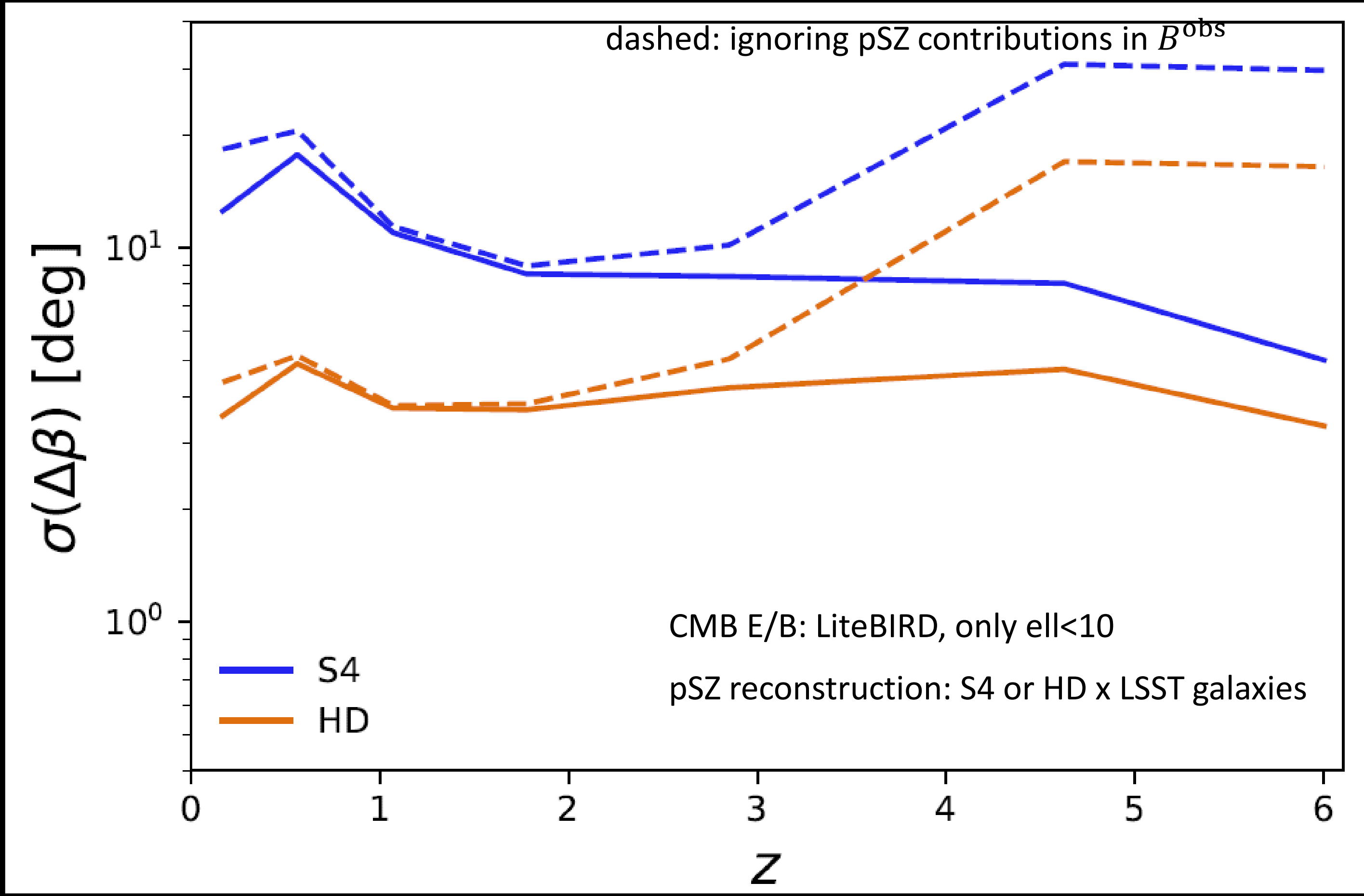
- Reconstruction of the time evolution of the rotation angle

We define the relative rotation angle which characterizes the evolution of ϕ at each z-bin:

$$\Delta\beta_i \equiv \frac{1}{2} g_{\gamma\phi}\big(\phi(z_{i+1}) - \phi(z_i)\big) = \beta(z_{i+1}) - \beta(z_i)$$

Forecast results

- Reconstruction of the time evolution of the rotation angle



Missing terms change the constraint by an order of magnitude at high z

Summary

We forecast expected constraints on cosmic birefringence with low-ell CMB (E, B) and reconstructed pSZ (q^E,q^B)

We include all relevant terms some of which are missed in the previous work
and show that these missing terms are important

1 σ constraint on the reconstructed rotation angle is more than 1deg for S4 with LSST galaxies,
while constraint at each z is sub degrees

pSZ would be useful for constraining late-time cosmic birefringence