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Cosmic birefringence tomography and angle calibration requirement

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• Recent analysis of WMAP + Planck data: $\beta = 0.34^{+0.094}_{-0.091}$ deg Eskilt & Komatsu (2022)



However, absolute polarization angle (ψ) is calibrated with Galactic foregrounds

• To confirm the signal:

Improve understanding of Galactic foregrounds

Improve ψ calibration

Look for another signs in observables that is not so sensitive to ψ uncertainties

Full-shape of the EB angular power spectrum

Anisotropic cosmic birefringence



• Axion-like particles (ALPs; ϕ) coupled with photons

 $\mathcal{L} \supset \frac{g\phi}{4} F_{\mu
u} \widetilde{F}^{\mu
u}$ Ni (1977), Turner & Widrow (1988)

Wide range of mass (m_{ϕ}) and coupling (g) Arvanitaki et al. (2010)

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

Carroll et al. (1900), Harari & Sikivie (1992)

$$\beta = \frac{g}{2}(\phi_{\rm obs} - \phi_{\rm source})$$

We can make implications for ALPs by observing β (C_{ℓ}^{EB})

• Time evolution of ultralight ALPs



• Time evolution of ultralight ALPs



ALP mass dependence of C_{ℓ}^{EB}

Sherwin & **TN** (2023)



Reionization bump depends on m_{ϕ}

Nakatsuka, TN, Komatsu (2022)

ALP mass dependence of C_{ℓ}^{EB}



[•] Shifting scales of acoustic peaks

c.f. birefringence by early dark energy (Murai et al. 2022)

- Suppressing C_l^{EB} amplitude
- Sign of $C_l^{\overline{EB}}$ becomes negative as $\overline{m_{\phi}}$ increases

Future CMB experiments are sensitive to the above features by ALPs

+ Using the full shape of C_l^{EB} breaks degeneracy between birefringence and ψ

Naokawa, TN (2023)

Lensed C_{ℓ}^{EB}

- Birefringence rotates the polarization plane along the trajectory
- We derive the lensing correction to C_{ℓ}^{EB} by extending formula of Challinor & Lewis 2005 and implement it to CLASS

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

$$\tilde{C}_{l}^{EB} = 2\pi \sum_{l'mm'} \int_{-1}^{1} d(\cos\gamma) d_{mm'}^{l'}(\gamma)$$

$$\times C_{l'}^{EB} A_{l'}^{-}(\gamma) d_{2,-2}^{l}(\gamma),$$

$$\tilde{C}_{l}^{\Theta B} = 2\pi \sum_{l'mm'} \int_{-1}^{1} d(\cos\gamma) d_{mm'}^{l'}(\gamma)$$

$$\times C_{l'}^{\Theta B} A_{l'}^{X}(\gamma) d_{20}^{l}(\gamma).$$





Space experiments ($m_{\phi} = 10^{-30} \text{eV}$)



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Space experiments ($m_{\phi} = 10^{-28} \text{eV}$)











Observed rotation angle has ambiguity of phase of angle Last Scattering Last Scattering $\beta = 0.3 + 180 \deg$

= 0.3 deg

Observer plane

 $B^{\rm obs} = \sin(2 \times 0.3) E^{\rm CMB}$



 $B^{\rm obs} = \sin(2 \times (180 + 0.3)) E^{\rm CMB}$

E+B

Observer plane

CMB birefringence analysis could not distinguish $\beta = 0.3 + n \times 180 \text{ deg } (|n| = 0,1,...)$ \bullet

Nonzero values of n significantly change C_{ℓ}^{EB} (next slides)







The power spectrum is not changed at most of the angular scales



The reionization bump is changed significantly



The reionization bump in C_{ℓ}^{EE} is suppressed due to averaging of rotation angles

Polarized Sunyaev Zel'dovich (pSZ) effect



- pSZ signals can be reconstructed with CMB and LSS observables (see Deutsch et al. 2017)
- pSZ can be used to probe time evolution of ϕ in the late-time universe

• Constraints on birefringence angle at each z bin



c.f. Lee, Hotnli, Kamionkowski (2022) and Hotinli et al. (2022)

Constraints are O(0.1) deg at z>>2 with future CMB missions + LSST

Useful to constrain the $n\pi$ phase ambiguity

• We study in details the ALP-induced cosmic birefringence effect on CMB polarization

• We found that, in general, $C_{\ell}^{EB} \neq 2\beta C_{\ell}^{EE}$ and the shape significantly depends on m_{ϕ} (ALP dynamics) Sherwin & **TN** (2023) Nakatsuka, **TN**, Komatsu (2022) Naokawa & **TN** (2023) Naokawa, **TN**, Murai, Obata, Kamada (2024)

Breaking degeneracy between the absolute angle and birefringence signal, relaxing the requirement for the angle calibration

For example, $\Delta \alpha \sim 0.5 \text{deg}$ is enough to confirm the signal for SO/ S4 if $m_{\phi} > 10^{-28} \text{ eV}$

 Polarized SZ could provide independent constraint on cosmic birefringence at low redshift TN & Obata (2023)