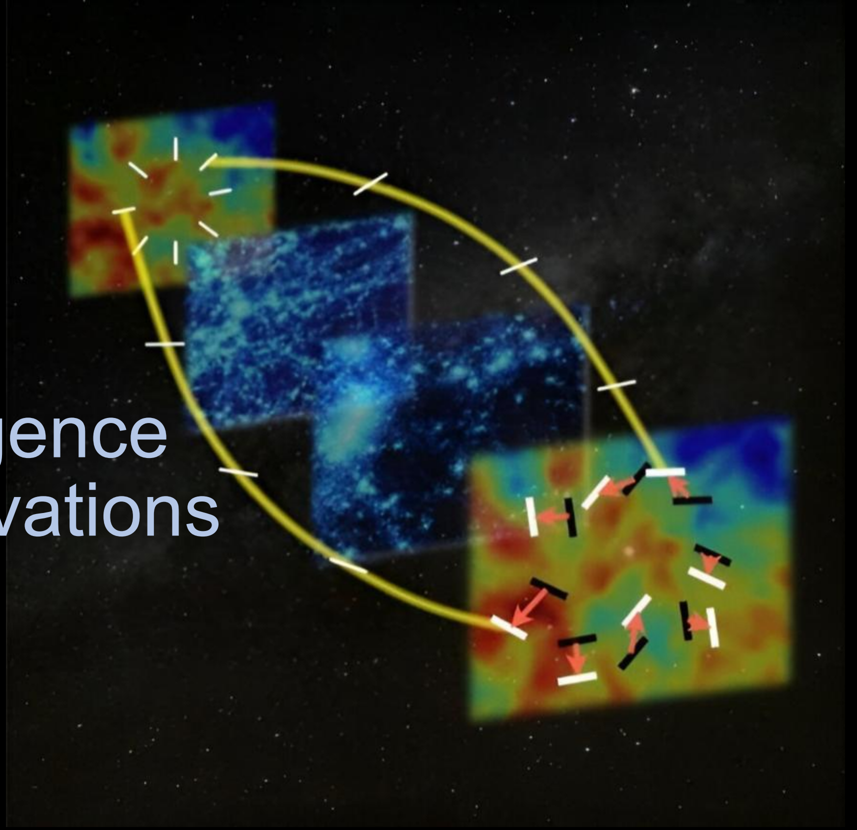

Implications for Cosmic Birefringence from Recent Cosmological Observations

Toshiya Namikawa

This talk is based on arXiv:2506.20824, arXiv:2506.22999

KAVLI IPMU
東京大学 国際高等研究所 カブリ数物連携宇宙研究機構
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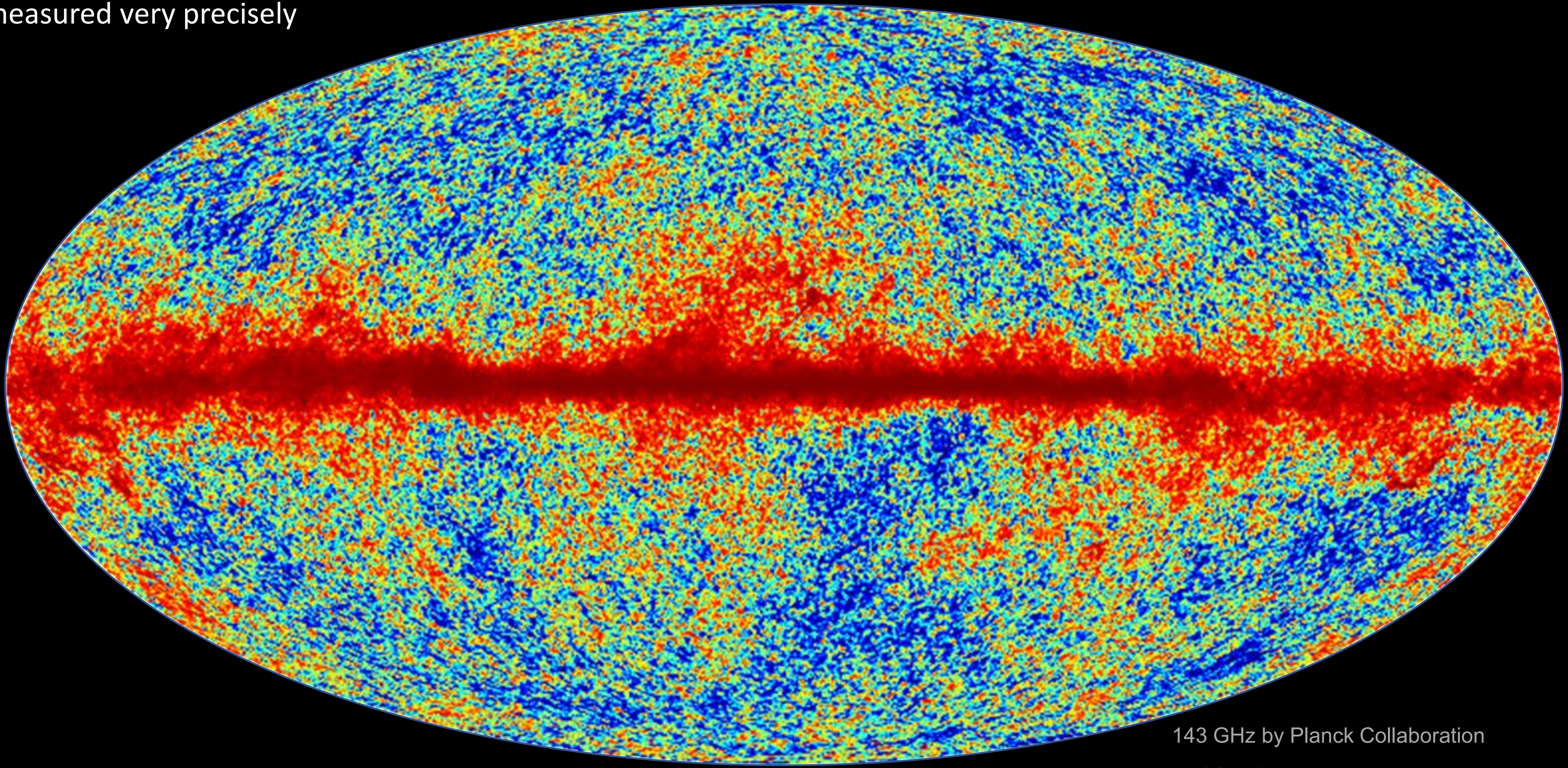
UNIVERSITY OF CAMBRIDGE
Kavli Institute for Cosmology Cambridge

0. CMB polarization and cosmic birefringence

1. Testing signature of cosmic birefringence with the shape of CMB power spectra

2. A possible resolution of some tensions in cosmology with cosmic birefringence

Anisotropies of CMB temperature have been measured very precisely

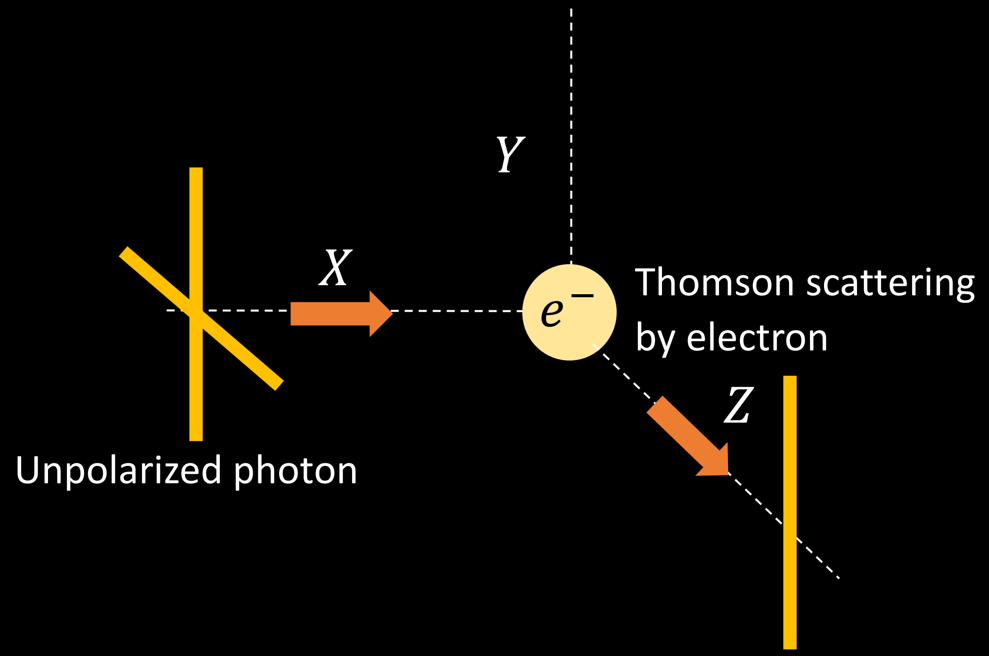


143 GHz by Planck Collaboration

~ $10\mu K$

CMB polarization

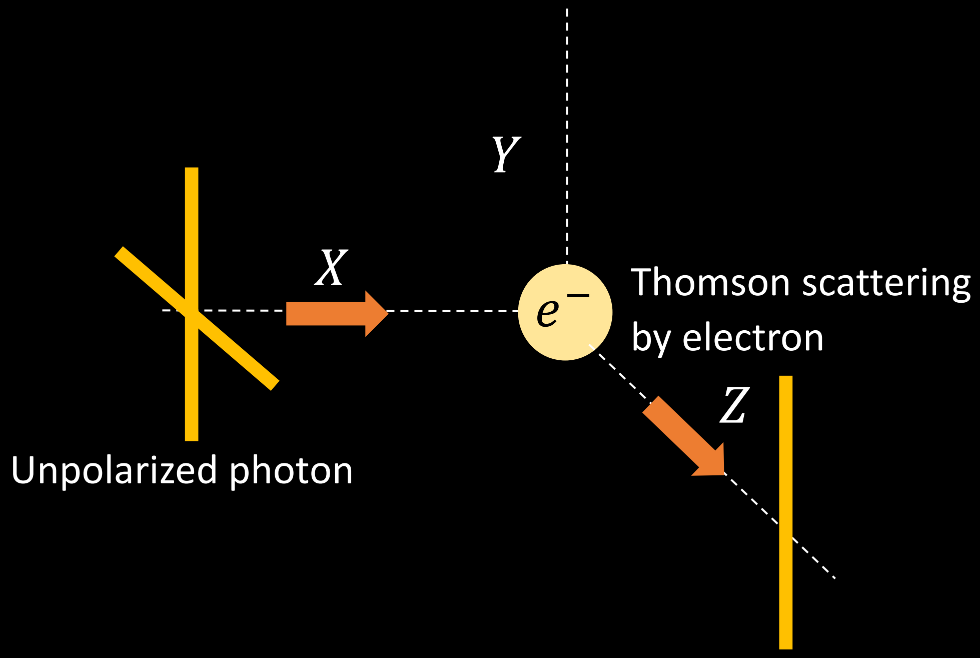
Temperature quadrupole anisotropies generates linear polarization

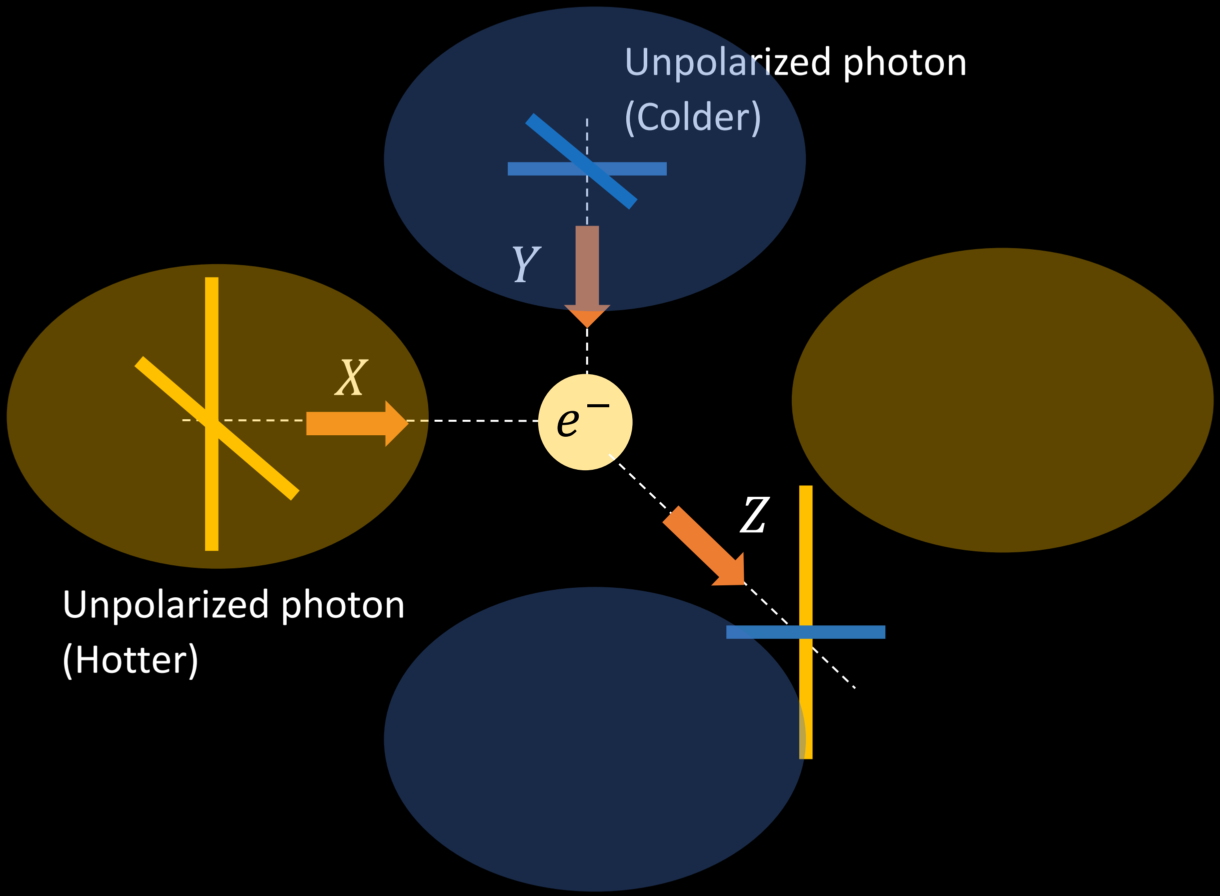


Wayne Hu's Tutorial (http://background.uchicago.edu/~whu)

CMB polarization

Temperature quadrupole anisotropies generates linear polarization

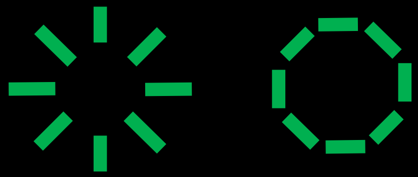




Wayne Hu’s Tutorial (http://background.uchicago.edu/~whu)

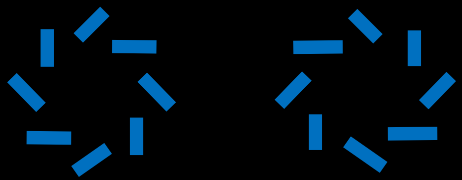
CMB polarization from reionization

E modes (even parity)

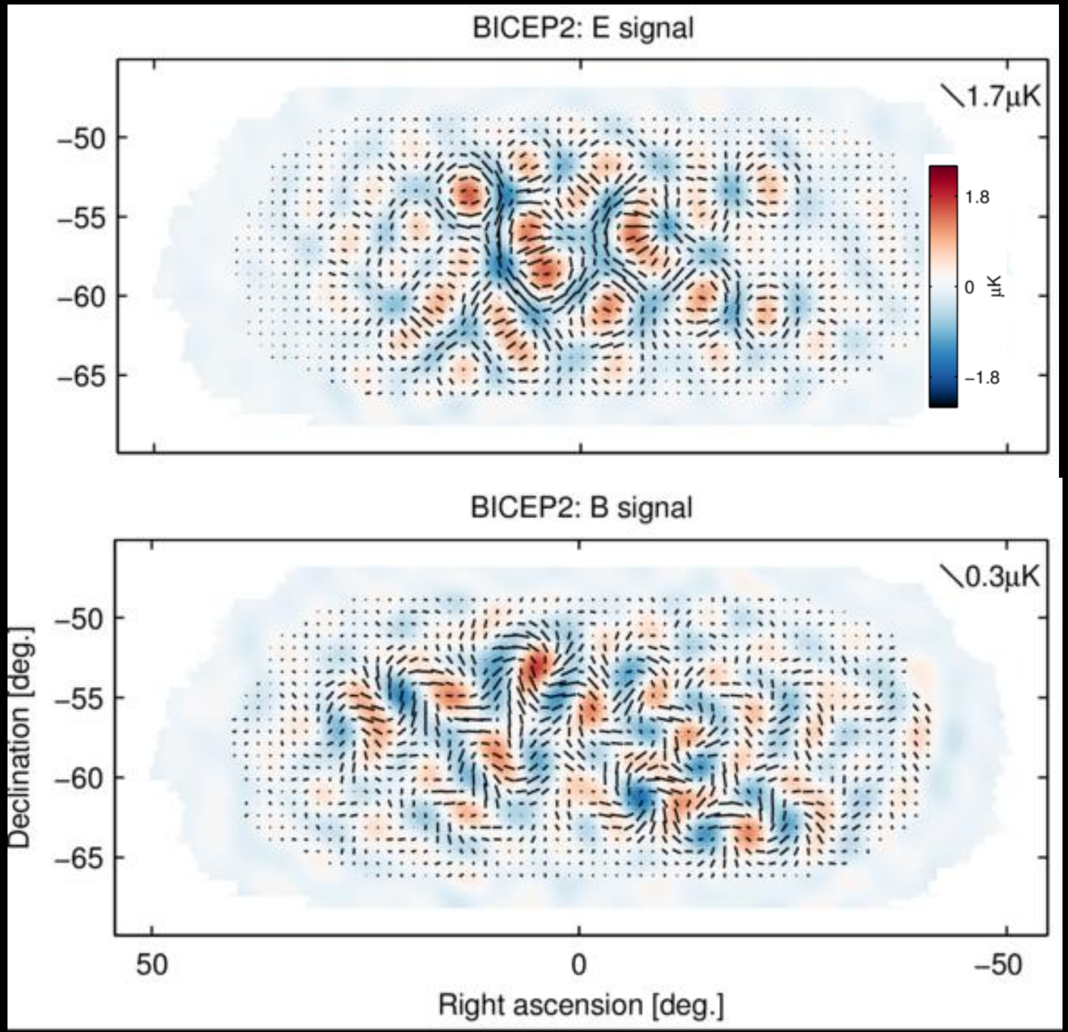


Density fluctuations generate **only** E-modes

B modes (odd parity)



Primordial GWs generate **not only** E modes **but also** B modes



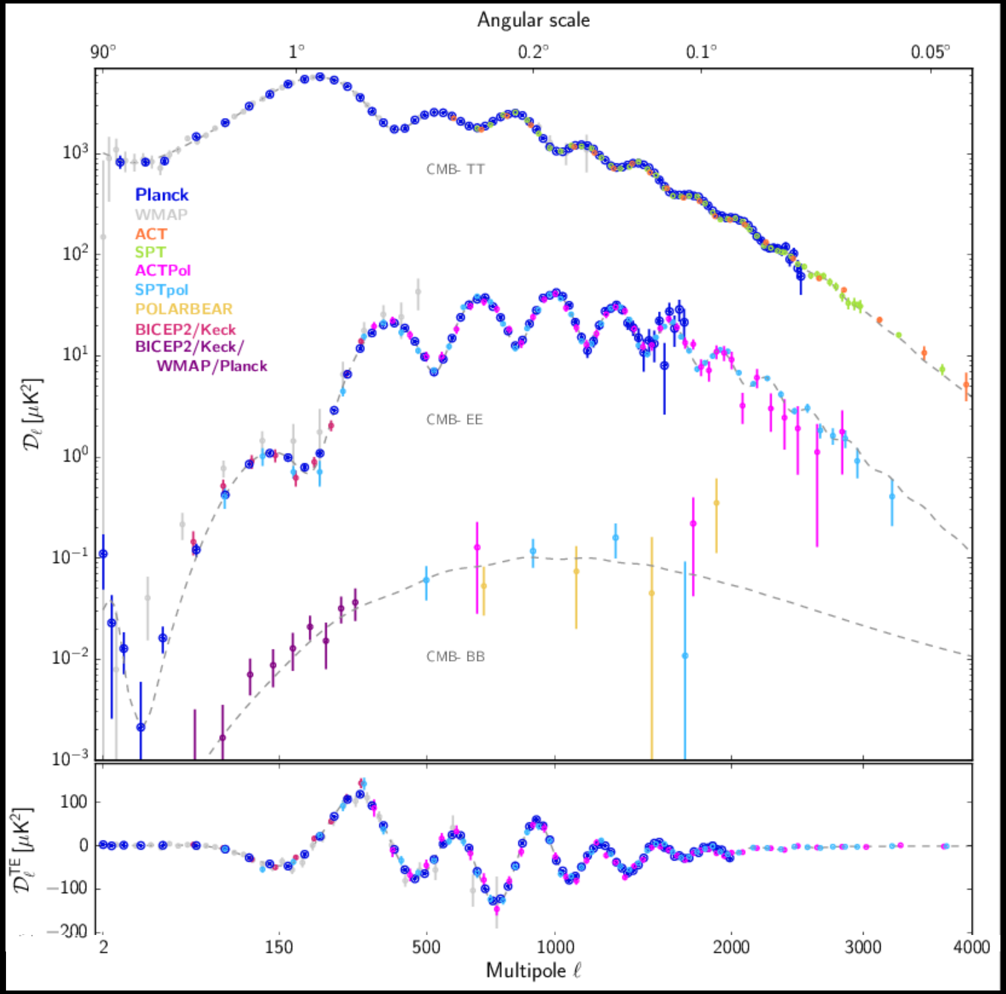
BICEP Collaboration (2014)

CMB polarization from reionization

- CMB observations have constrained cosmology very precisely with

C_ℓ^{TT} C_ℓ^{TE} C_ℓ^{EE} C_ℓ^{BB}

Parity even



Planck Collaboration (2020)

CMB polarization from reionization

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C_ℓ^{TT} C_ℓ^{TE} C_ℓ^{EE} C_ℓ^{BB}

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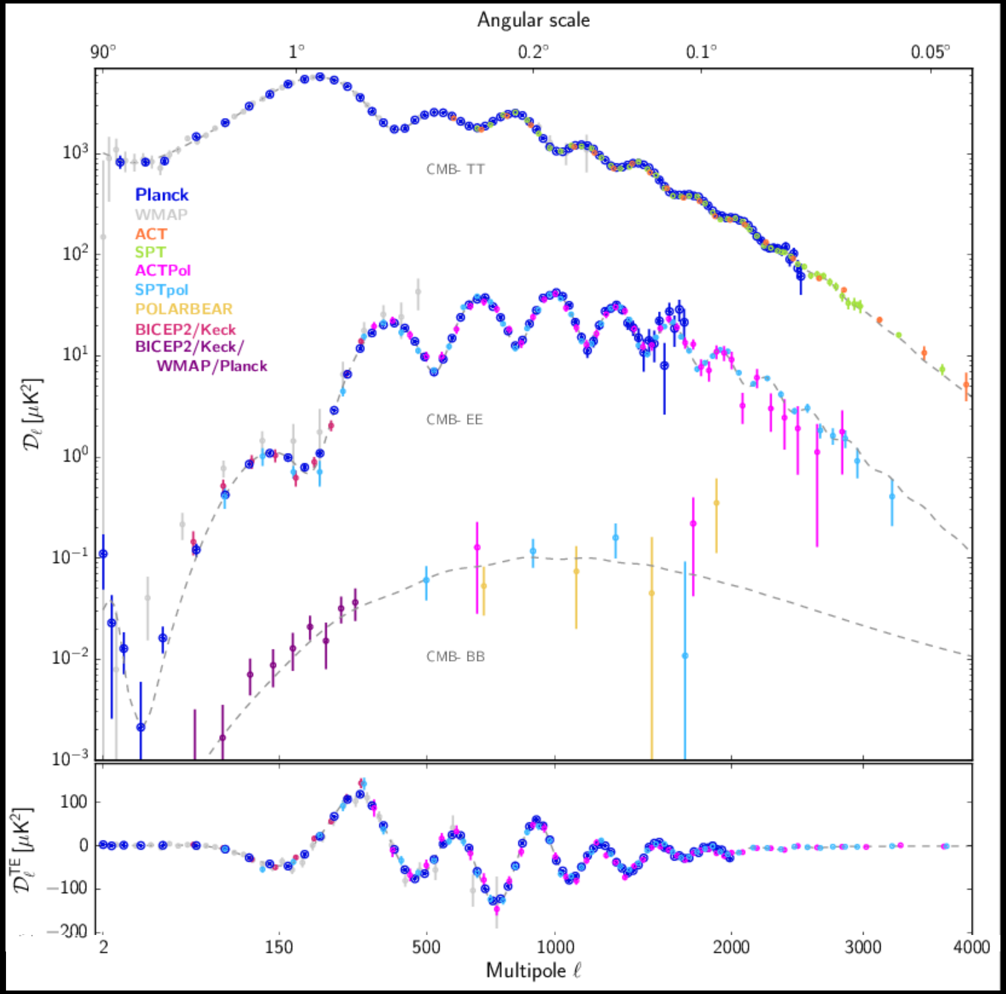


Planck Collaboration (2020)

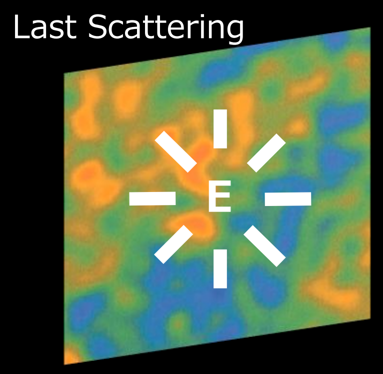
- But, there are other spectra that can constrain cosmology

C_ℓ^{TB} C_ℓ^{EB}

Parity odd

EB correlation by cosmic birefringence

Cosmic Birefringence = A phenomena that rotates polarization plane of photons



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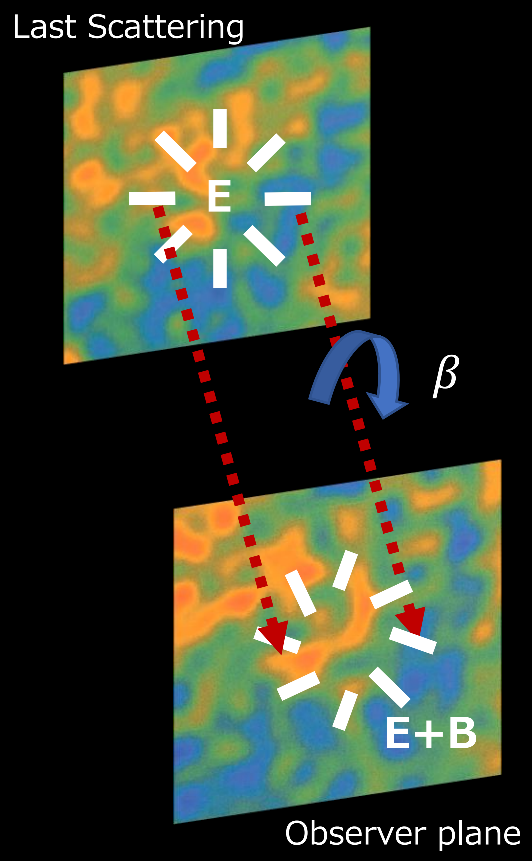
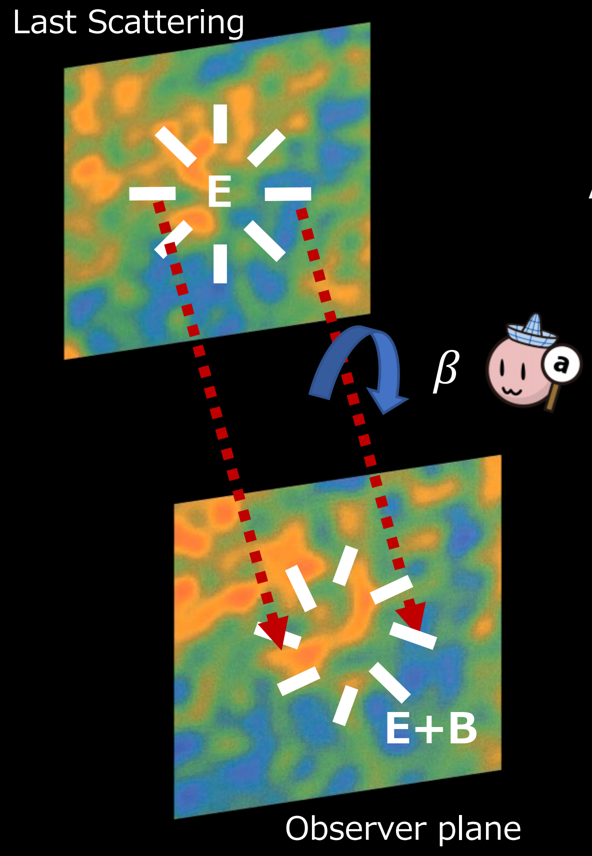


$$C_\ell^{EB\,\mathrm{obs}} = \frac{\sin(4\beta)}{2}\, C_\ell^{EE} \neq 0$$

EB correlation by cosmic birefringence

Cosmic Birefringence = A phenomena that rotates polarization plane of photons



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

Ni (1977), Turner & Widrow (1988)

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

wide range of mass (m_ϕ) and coupling (g)

Arvanitaki et al. (2010)

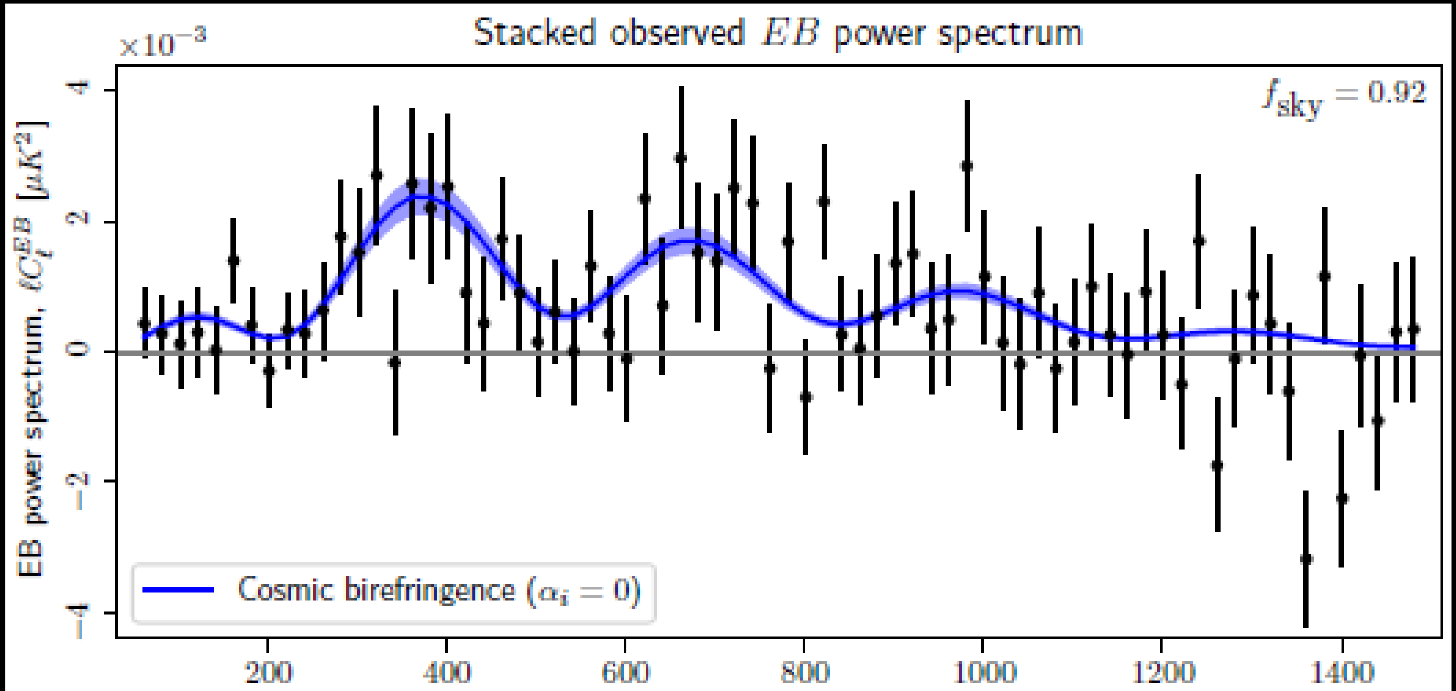
$$\beta = \frac{g}{2}(\phi_{\rm obs} - \phi_{\rm source})$$

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

$$C_\ell^{EB\,\rm obs} = \frac{\sin(4\beta)}{2}\,C_\ell^{EE} \neq 0$$

Observation of Cosmic birefringence

- WMAP + Planck EB power spectrum



Eskilt & Komatsu (2022)

Observation of Cosmic birefringence

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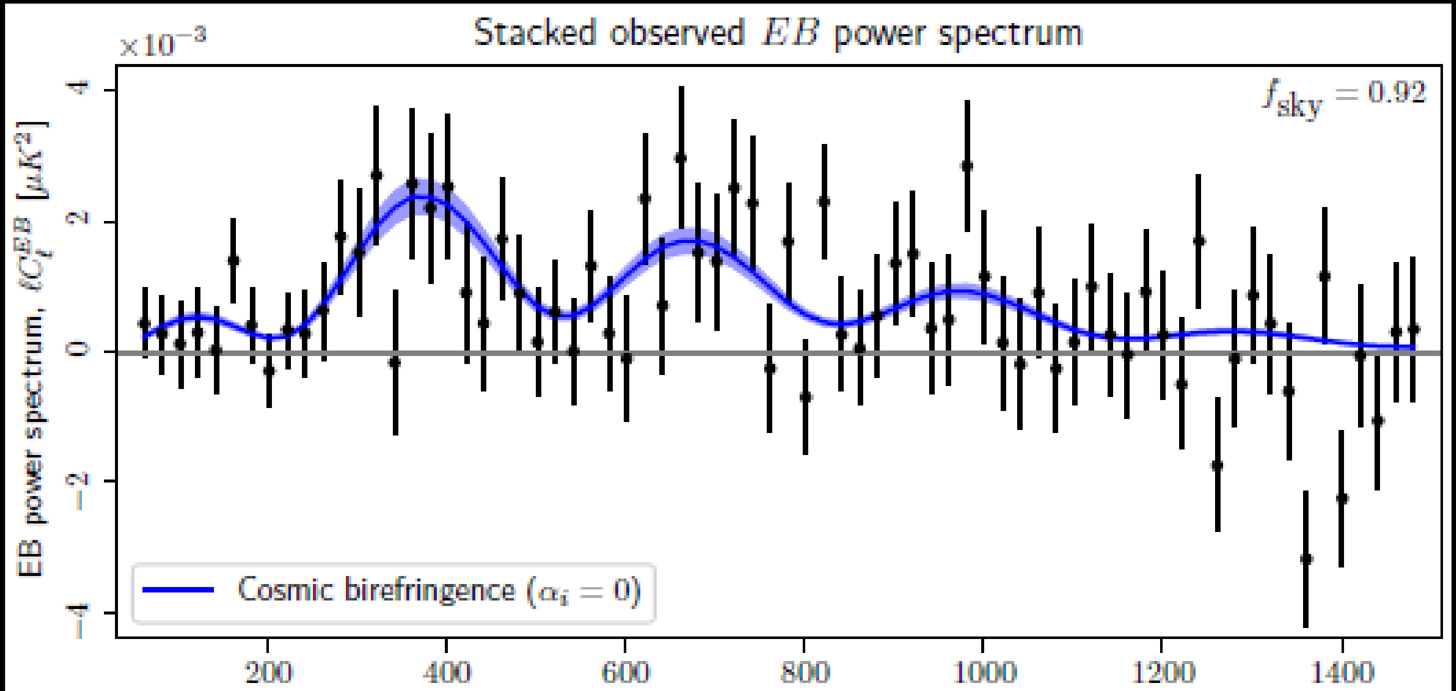


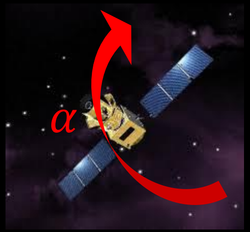
Eskilt & Komatsu (2022)

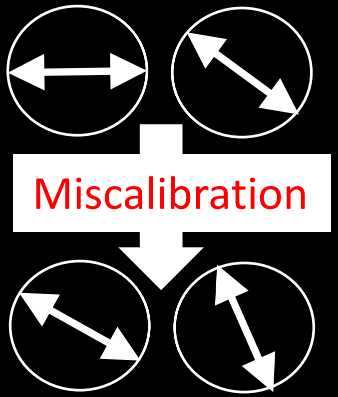
- However, miscalibration angle, α, limits observation of cosmic birefringence from CMB

rotation by ALPs

$$\beta^{\rm obs} = \beta + \alpha$$

rotation by an instrument



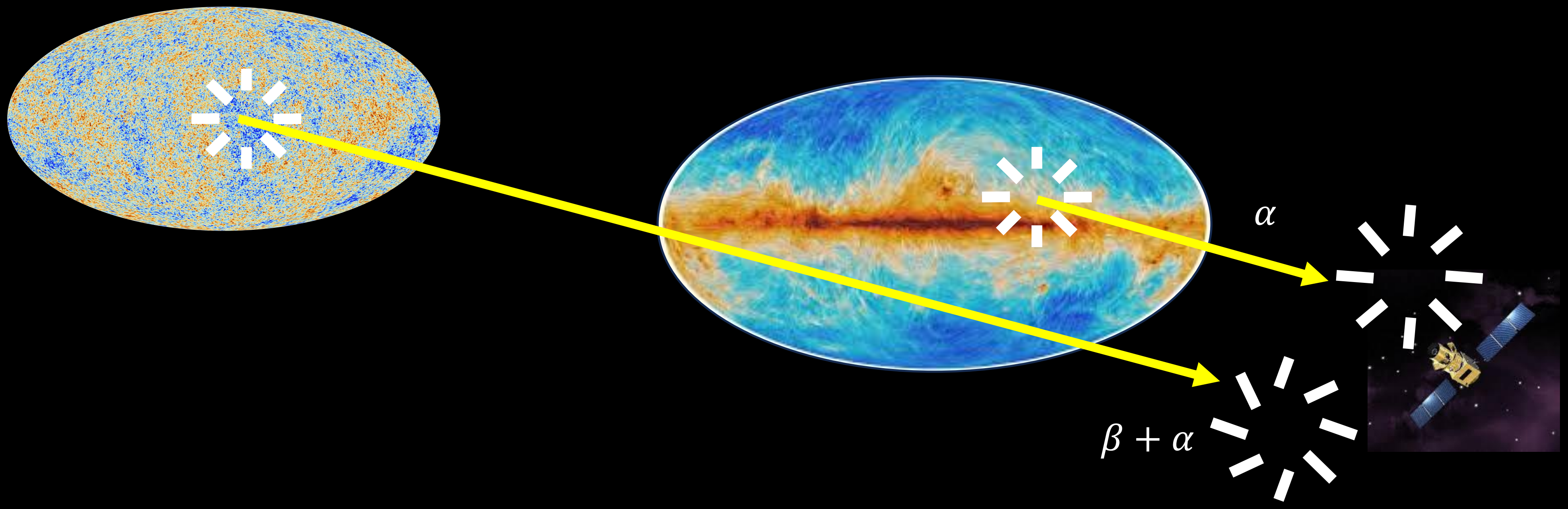


Observation of Cosmic birefringence

- New Idea by Minami et al. (2019)

CMB polarization is rotated by both cosmic birefringence and miscalibration angle

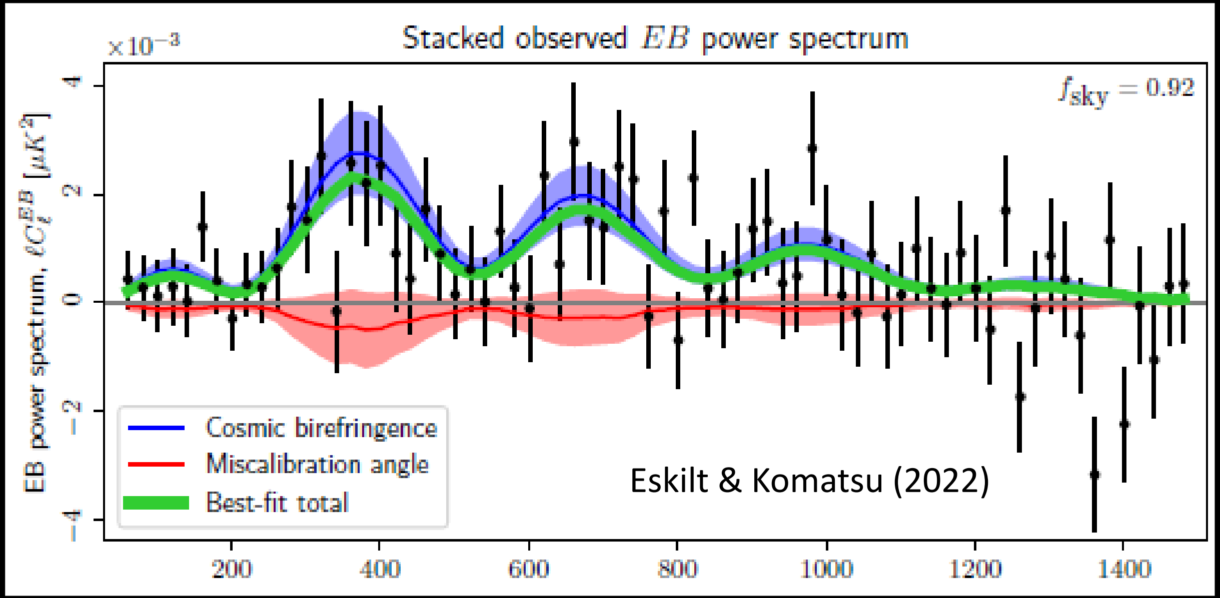
Galactic foreground is rotated by only miscalibration angle



We can calibrate α with Galactic foreground and then extract β

Current status of cosmic birefringence measurements

- WMAP+Planck data constraint: $\beta = 0.34^{+0.094}_{-0.091}$ deg



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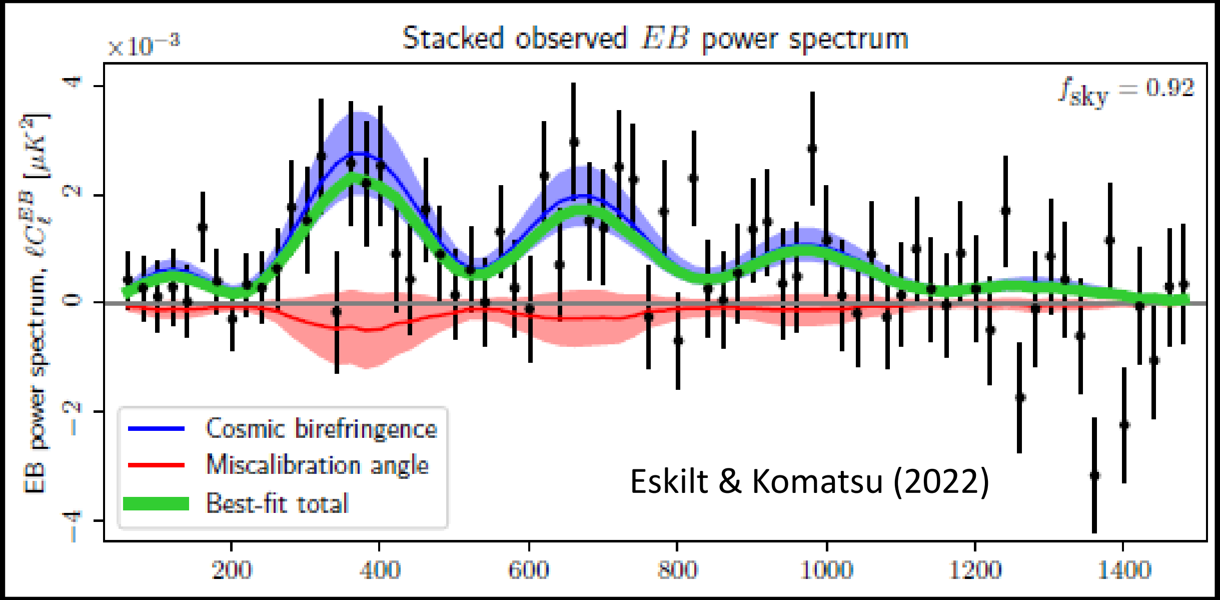
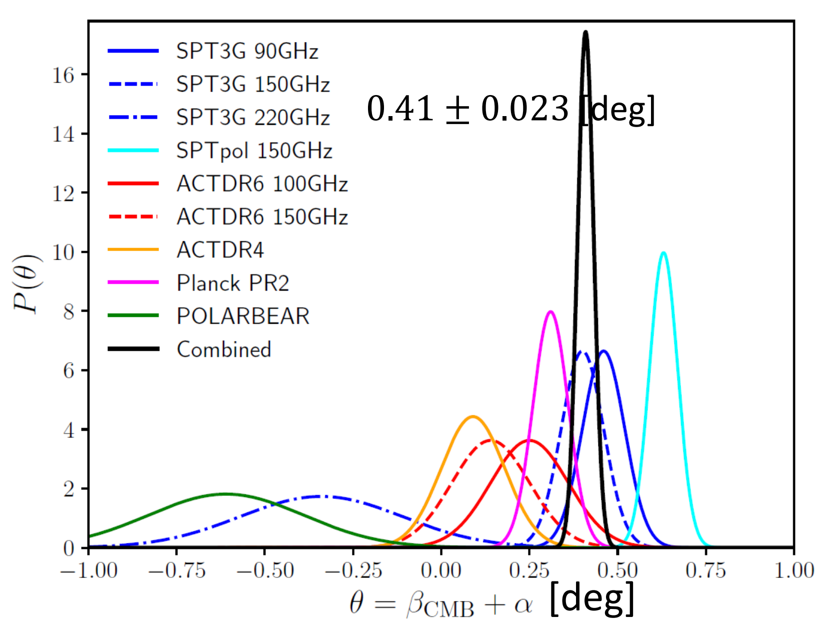


- Other measurements "without" calibration



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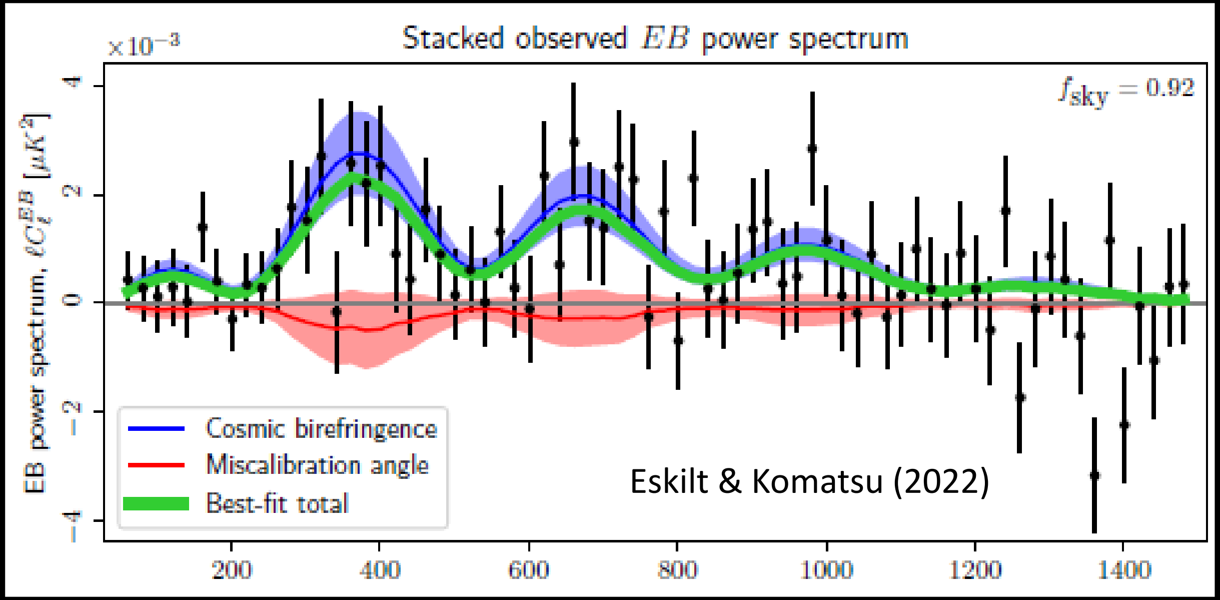
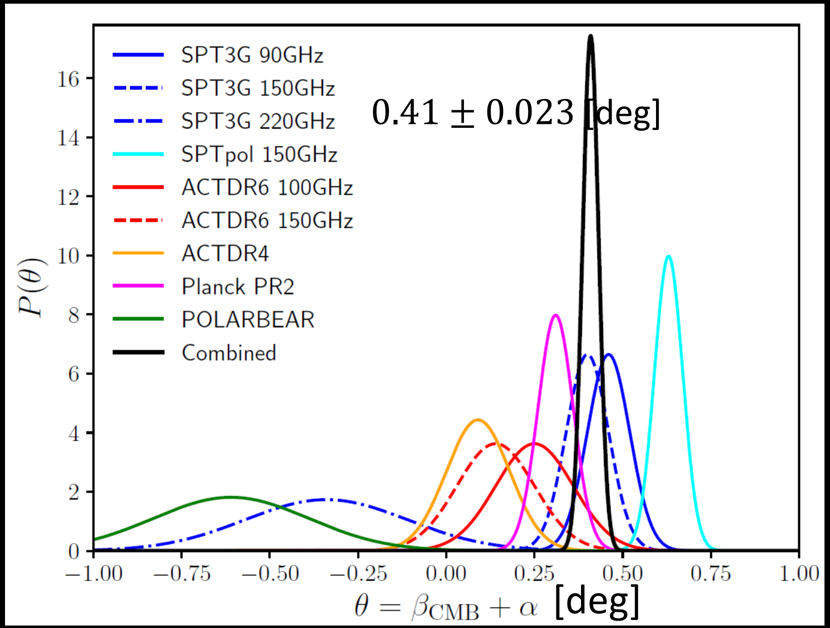


- Other measurements "without" calibration



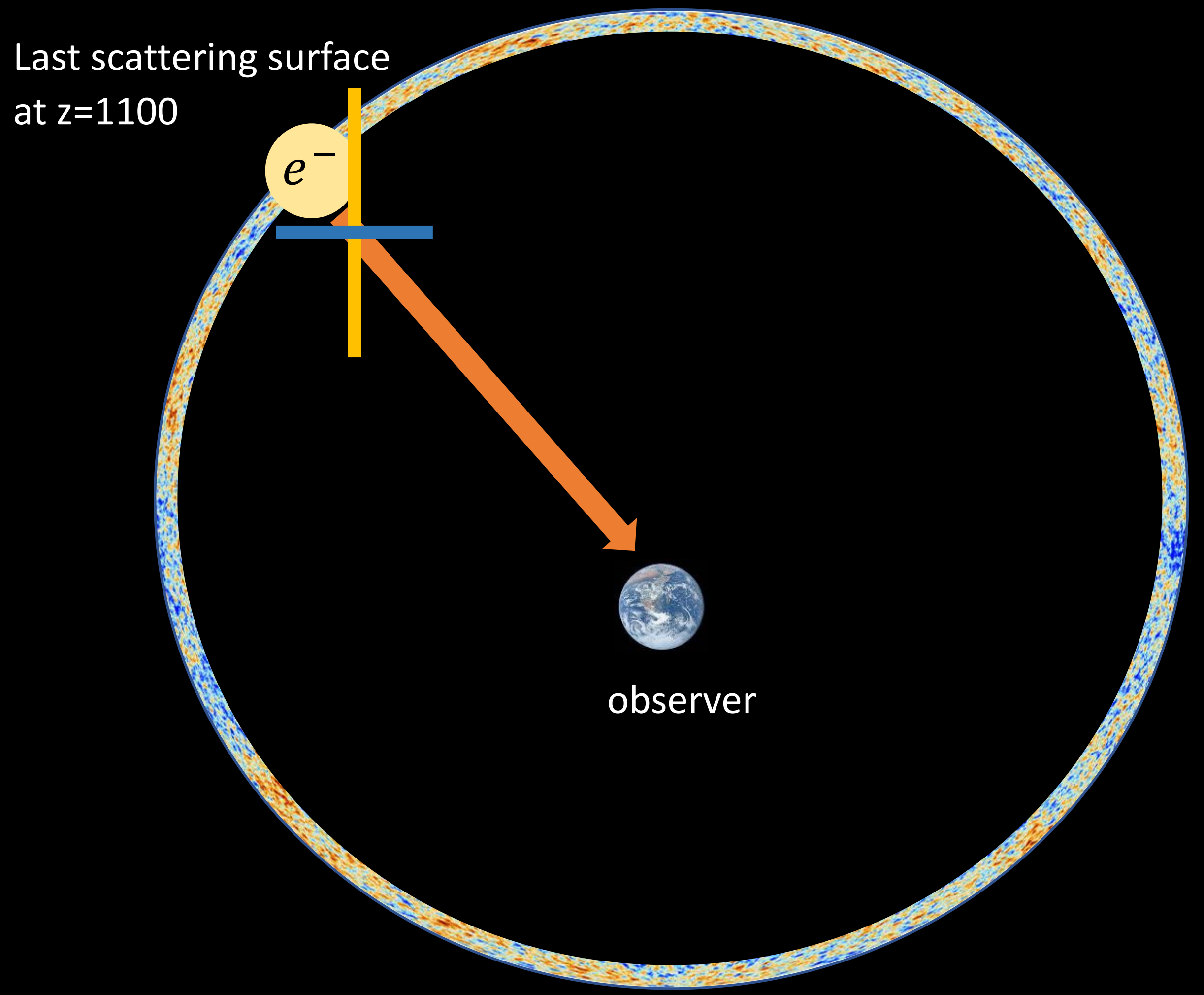
- Further investigations are important to confirm the signal
  - Reducing uncertainties on α with improved hardware calibrators — Wiregrid: SO-SAT targets $\sigma(\alpha) < 0.1$ deg
  - Measuring other observables: **shape of the CMB power spectra**

0. CMB polarization and cosmic birefringence

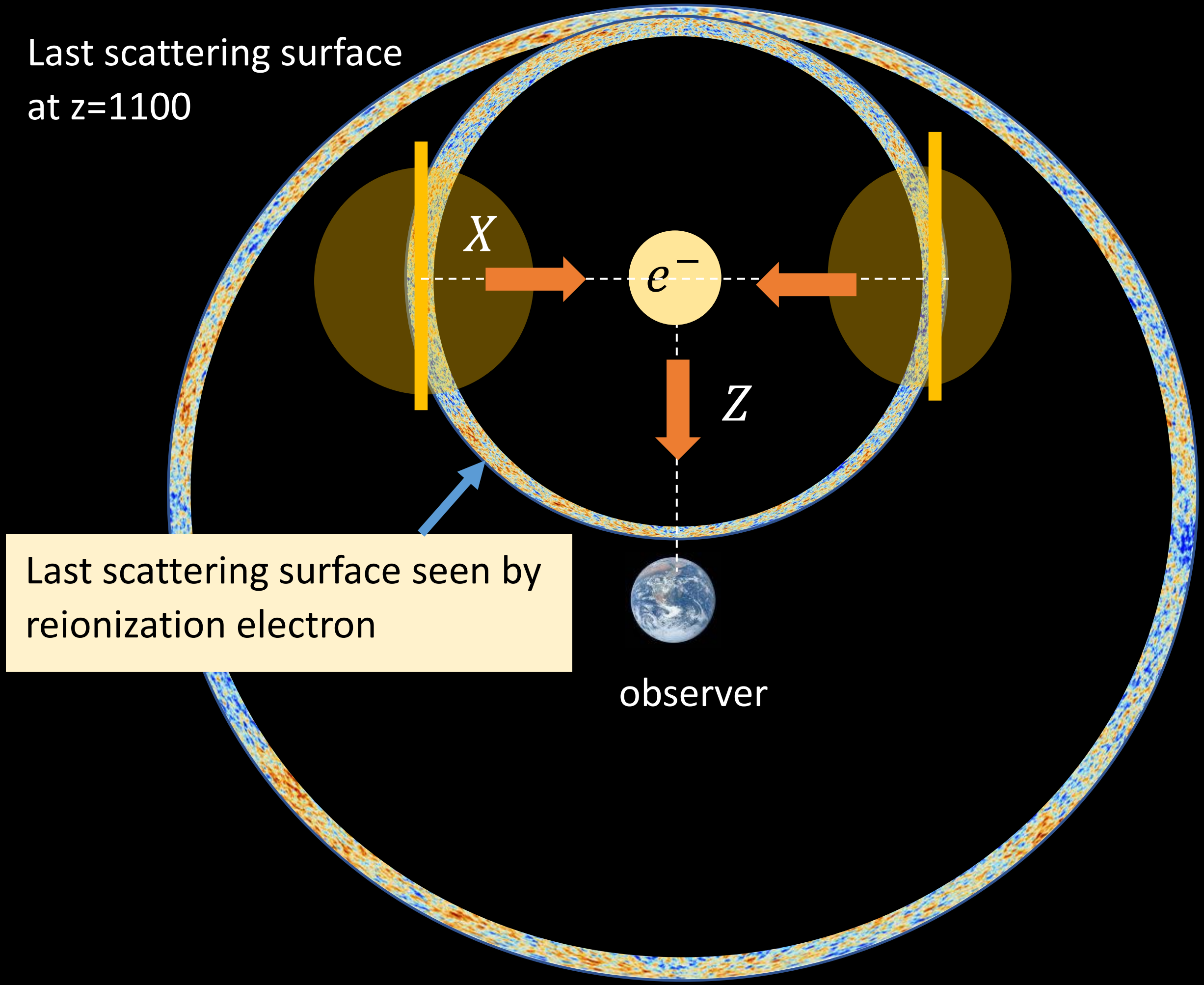
1. Testing signature of cosmic birefringence with the shape of CMB power spectra

2. A possible resolution of some tensions in cosmology with cosmic birefringence

CMB polarization from reionization



CMB polarization from reionization

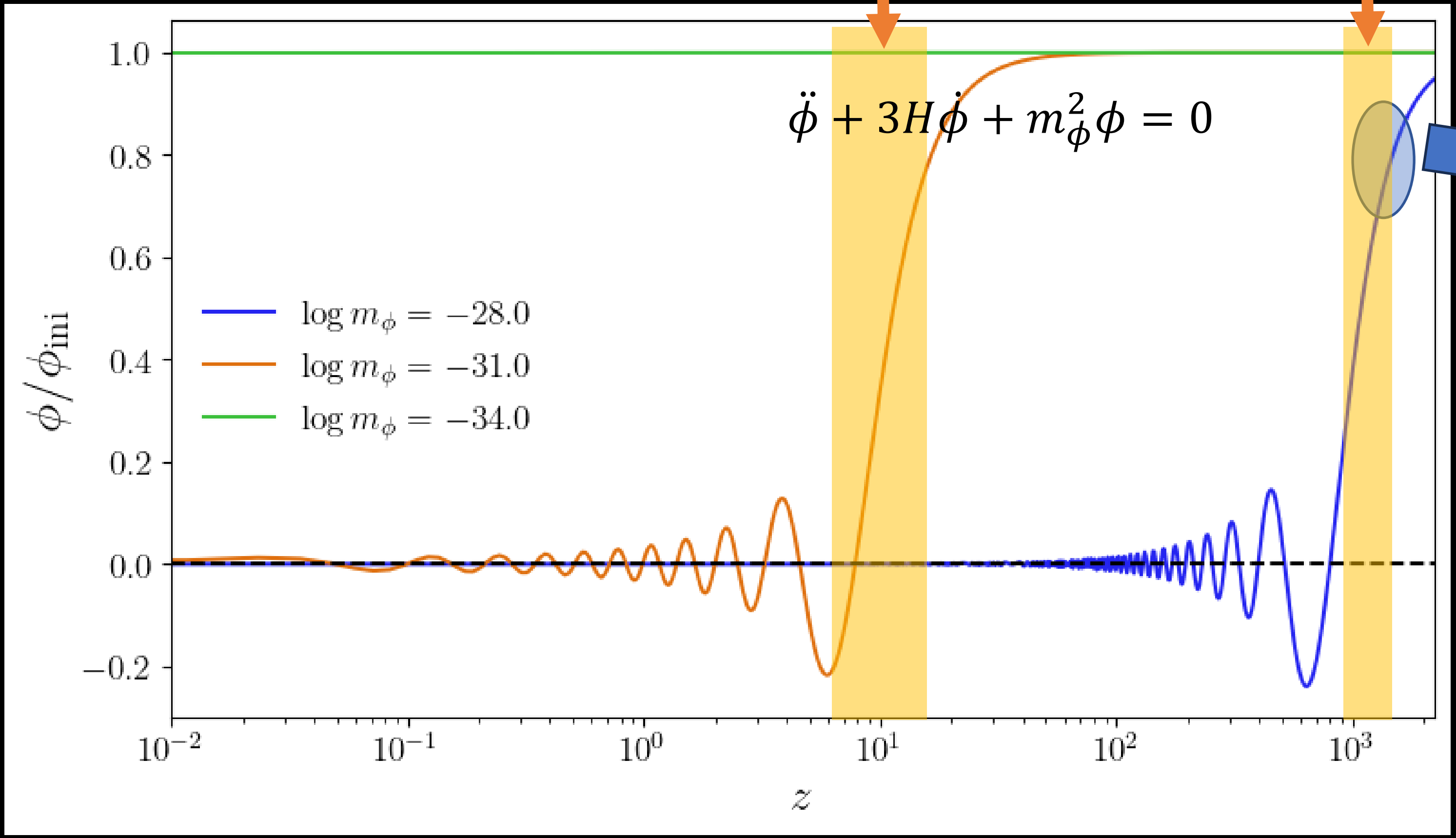


CMB polarization is generated at 1) recombination ($z \sim 1100$) and 2) reionization ($z \sim 10$)

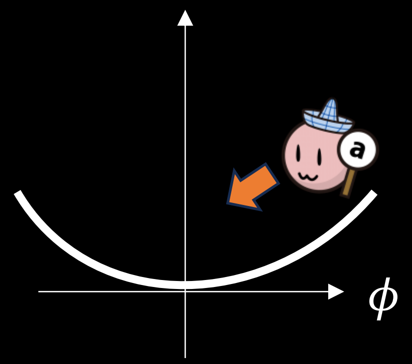
- Time evolution of ALP fields depends on mass (m_ϕ)

Reionization era

Recombination era



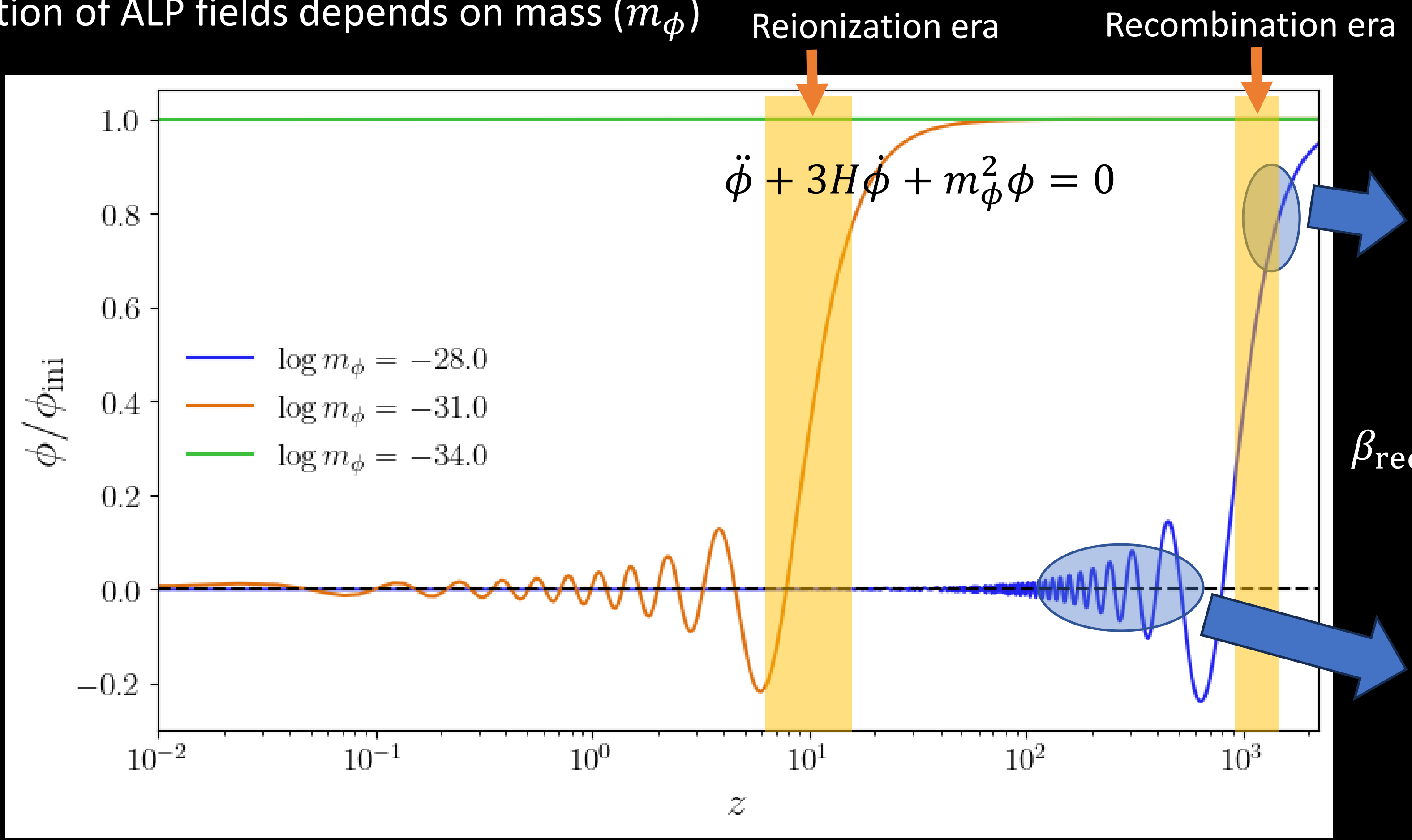
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

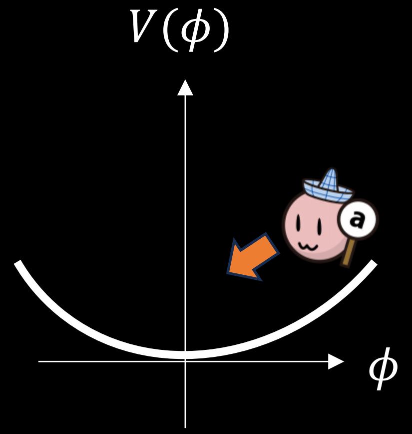


$$\beta_{\rm rec} \simeq \frac{g}{2}(\phi_{\rm ini} - \phi_{\rm obs}) \sim \frac{g}{2}\phi_{\rm ini}$$

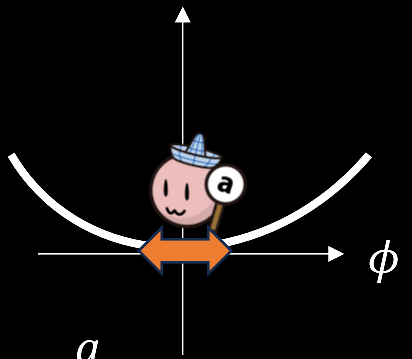
Implications for ALPs from cosmic birefringence

- Time evolution of ALP fields depends on mass (m_ϕ)





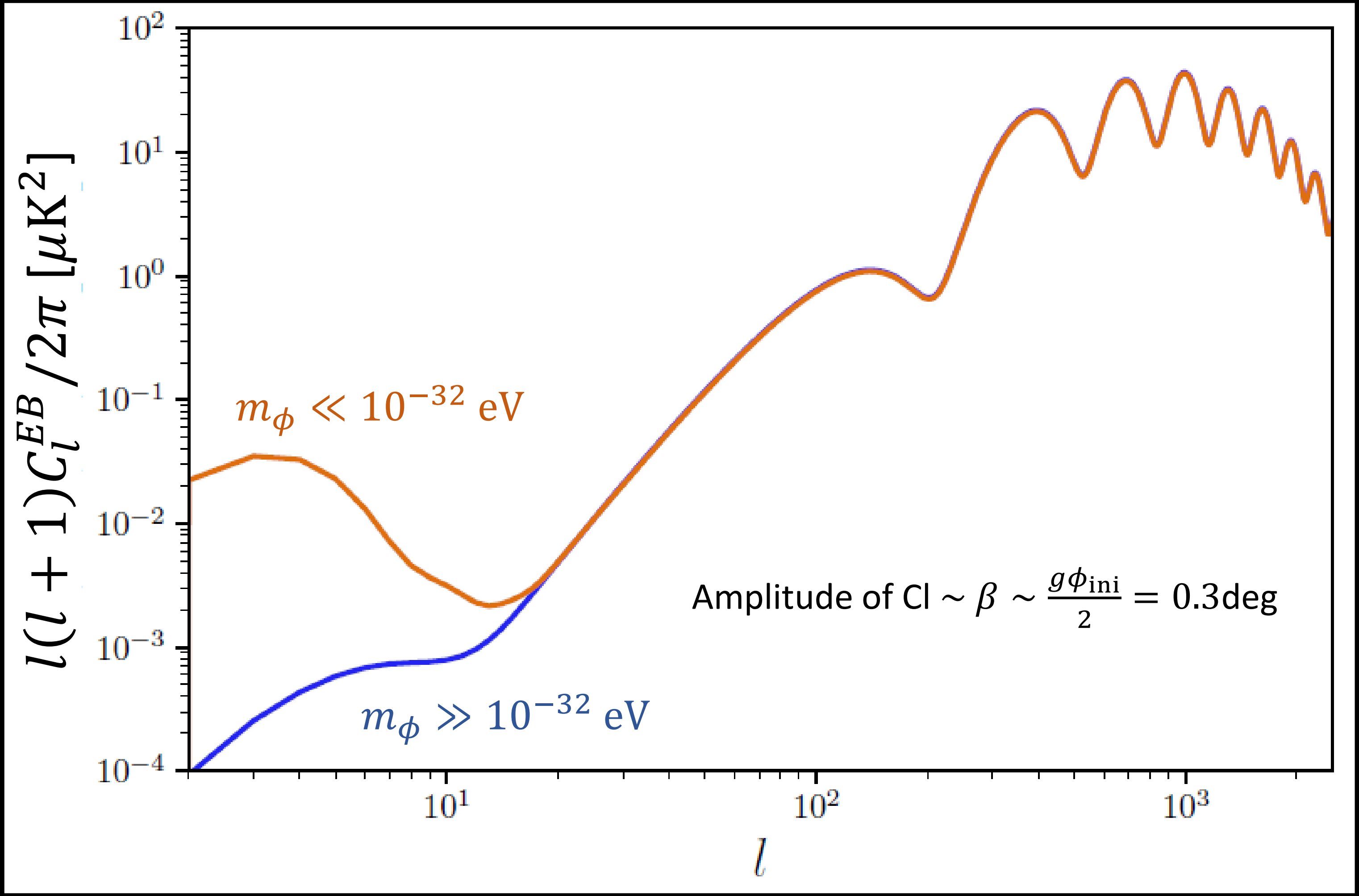
$$\beta_{\rm rec} \simeq \frac{g}{2}(\phi_{\rm ini} - \phi_{\rm obs}) \sim \frac{g}{2}\phi_{\rm ini}$$



$$\beta_{\rm rei} = \frac{g}{2}(\phi_{\rm ini} - \phi_{\rm obs}) \sim 0$$

In general, rotation angle is not constant, depends on time (redshift)

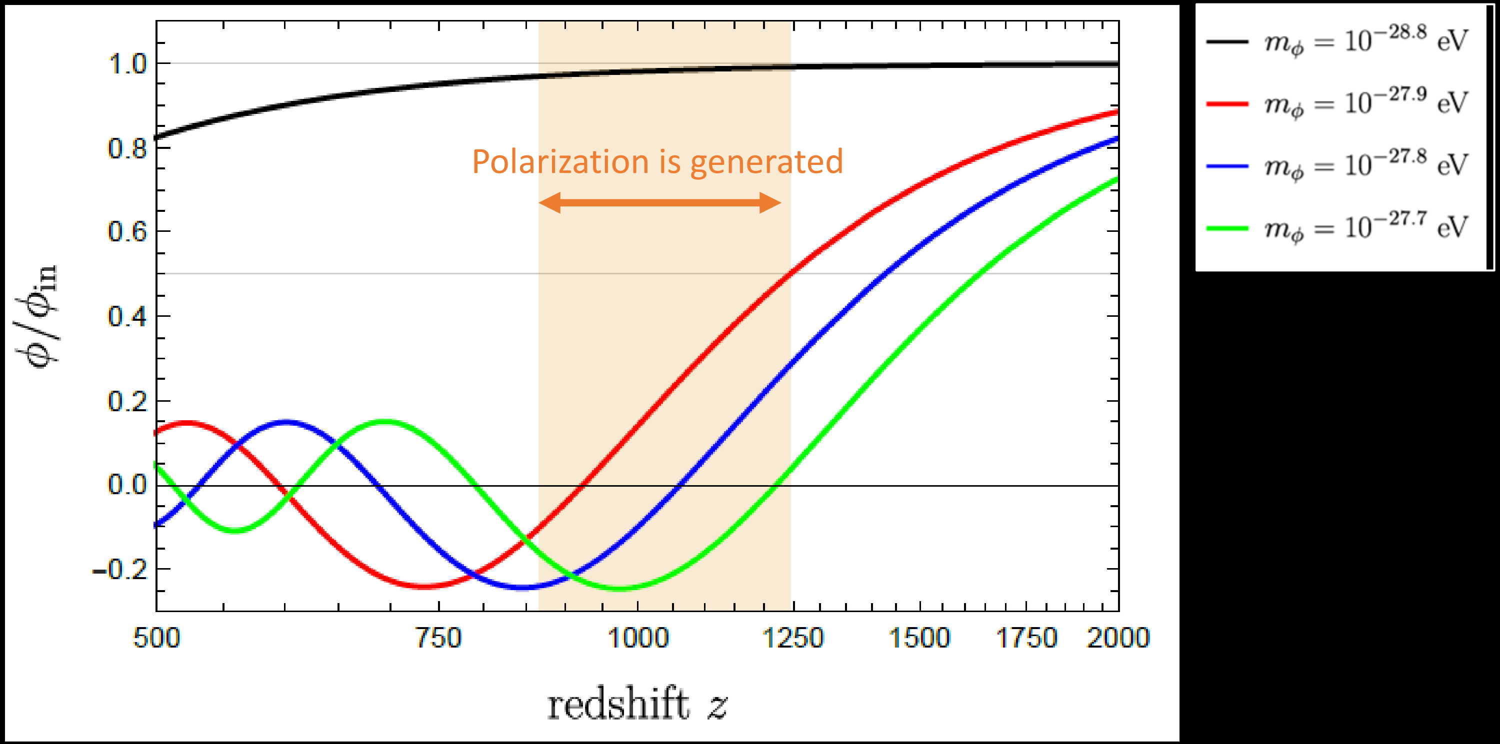
Mass dependence of C_ℓ^{EB} $(m_\phi \ll 10^{-28}\mathrm{eV})$



Sherwin & *Namikawa* (2023)

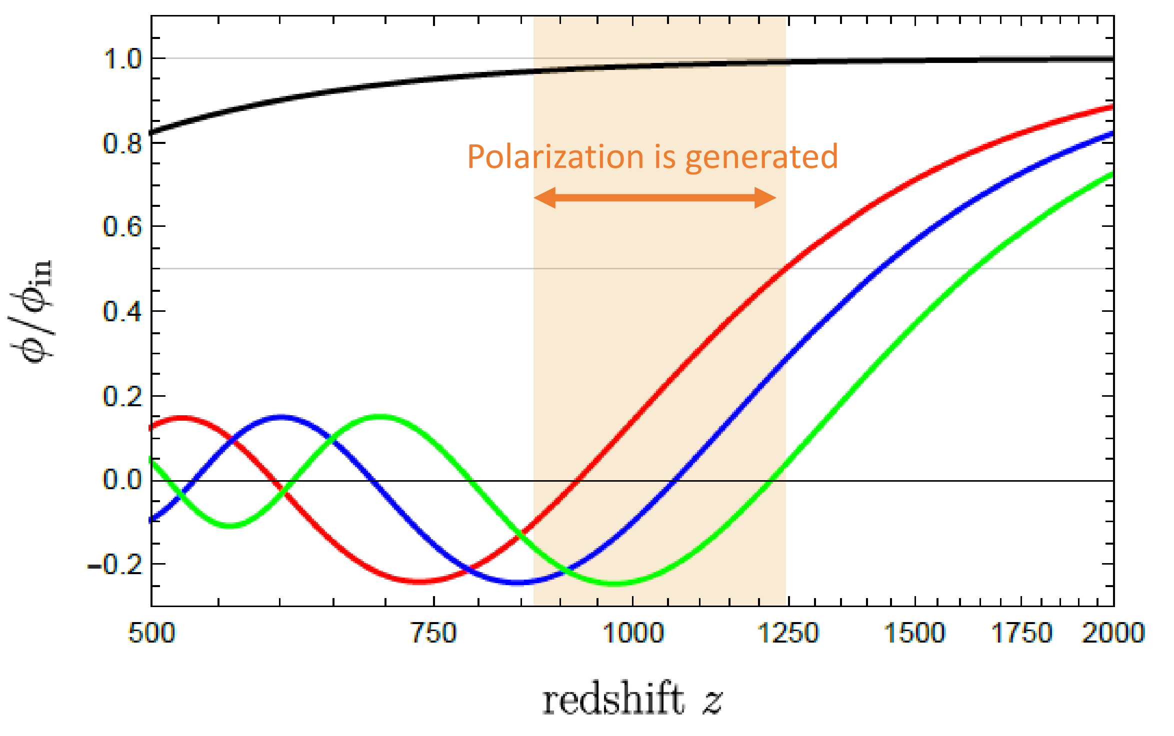
Reionization bump significantly depends on m_ϕ

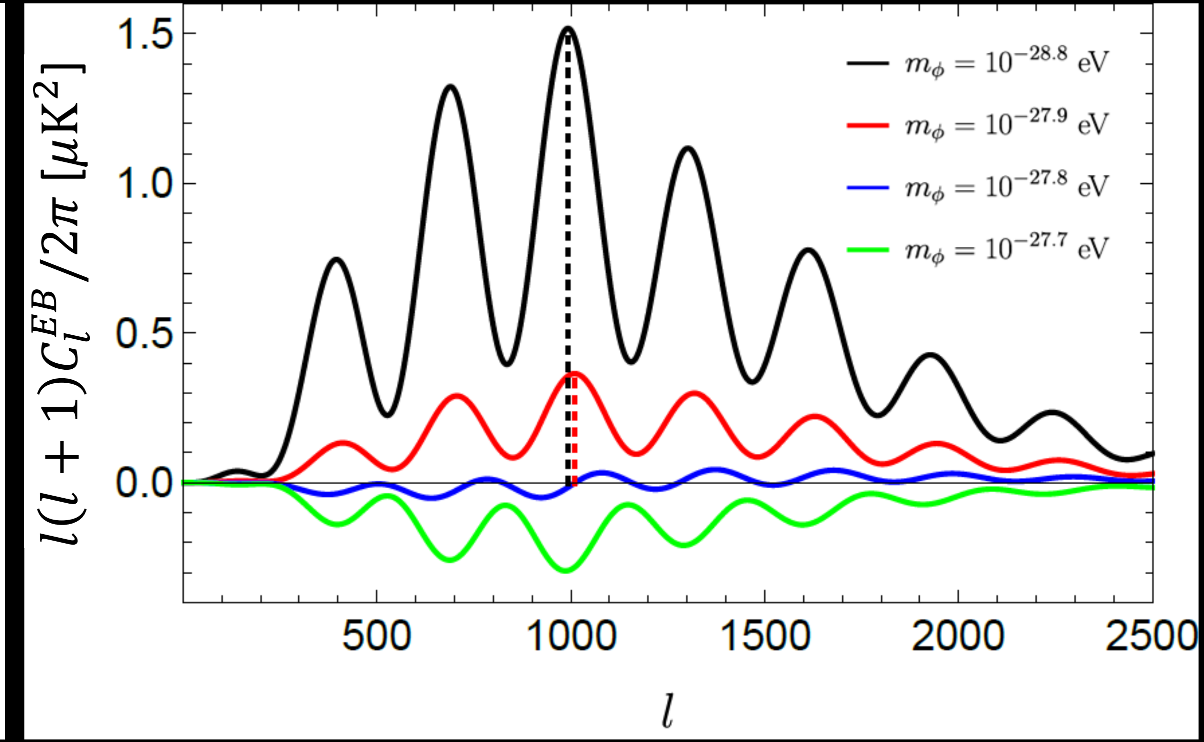
Constraining ALP parameters with Planck C_ℓ^{EB}



Nakatsuka, *Namikawa*, Komatsu (2022)

Constraining ALP parameters with Planck C_ℓ^{EB}





Nakatsuka, *Namikawa*, Komatsu (2022)

- Shifting scales of acoustic peaks
- Suppressing C_l^{EB} amplitude
- Sign of C_l^{EB} becomes negative as m_ϕ increases

Constraining ALP parameters with Planck C_ℓ^{EB}

- Basic equation for fitting

Single-frequency:
$$\hat{C}_l^{EB} = \frac{\hat{C}_l^{EE} - \hat{C}_l^{BB}}{2}\tan 4\alpha + \frac{1}{\cos 4\alpha}\frac{\sin 4\beta}{2}\left(C_l^{EE,\mathrm{lss}} - C_l^{BB,\mathrm{lss}}\right)$$

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Multi-frequency:
$$\hat{C}_l^{E_iB_j} = \vec{R}_{ij}(0)\mathrm{R}_{ij}^{-1}(0)\begin{pmatrix}\hat{C}_l^{E_iE_j}\\ \hat{C}_l^{B_iB_j}\end{pmatrix} + \left[\vec{R}_{ij}^{T}(\beta) - \vec{R}_{ij}(0)\mathrm{R}_{ij}^{-1}(0)\mathrm{R}(\beta)\right]\begin{pmatrix}C_l^{EE,\mathrm{lss}}\\ C_l^{BB,\mathrm{lss}}\end{pmatrix}$$

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Namikawa, et al. (2025)

Simplified equation:

$$\hat{C}_l^{E_iB_j} = \frac{\hat{C}_l^{E_iE_j}\sin 4\alpha_j - \hat{C}_l^{B_iB_j}\sin 4\alpha_i}{\cos 4\alpha_i + \cos 4\alpha_j} + \frac{1}{\cos 2(\alpha_i + \alpha_j)}\frac{\sin 4\beta}{2}\left(C_l^{EE,\mathrm{lss}} - C_l^{BB,\mathrm{lss}}\right)$$

This part constraints α_i with FGs

$= C_l^{EB}$

Constraining ALP parameters with Planck C_ℓ^{EB}

- Basic equation for fitting

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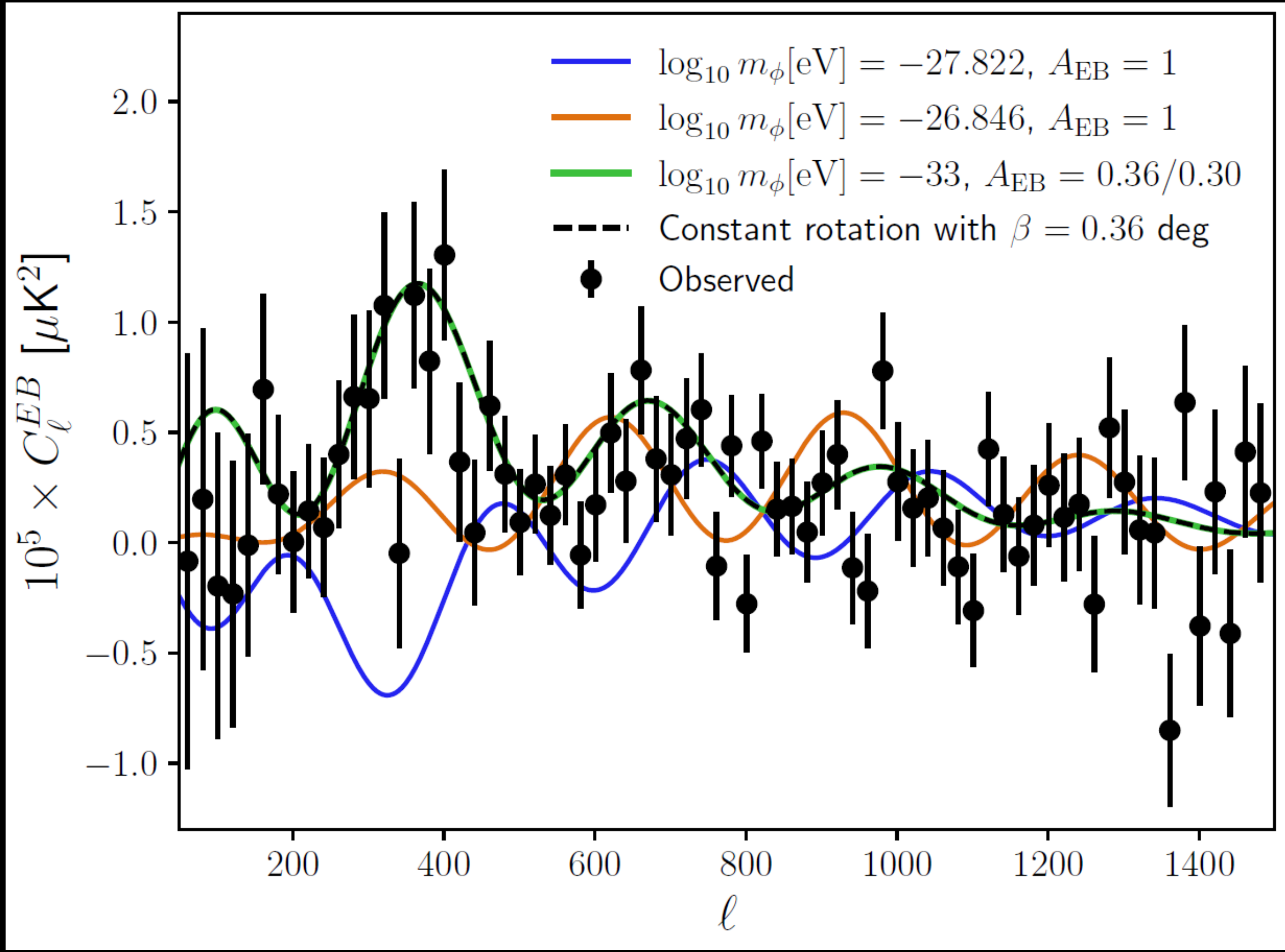
This part constraints α_i with FGs

$= C_l^{EB}$

- We use Planck PR4 HFI (100, 143, 217 353GHz)
- We constrain $\log_{10} m_\phi[\mathrm{eV}]$, $g\phi_{\mathrm{ini}}/2$, absolute pol. angles α_i, and amplitudes of an intrinsic dust EB model (Eskilt & Komatsu 2022)

$$F_l^{E_iB_j} = A_l \sin(4\psi_l)\, F_l^{E_iE_j} \qquad \tan(2\psi_l) = \frac{F_l^{TB,353}}{F_l^{TE,353}}$$

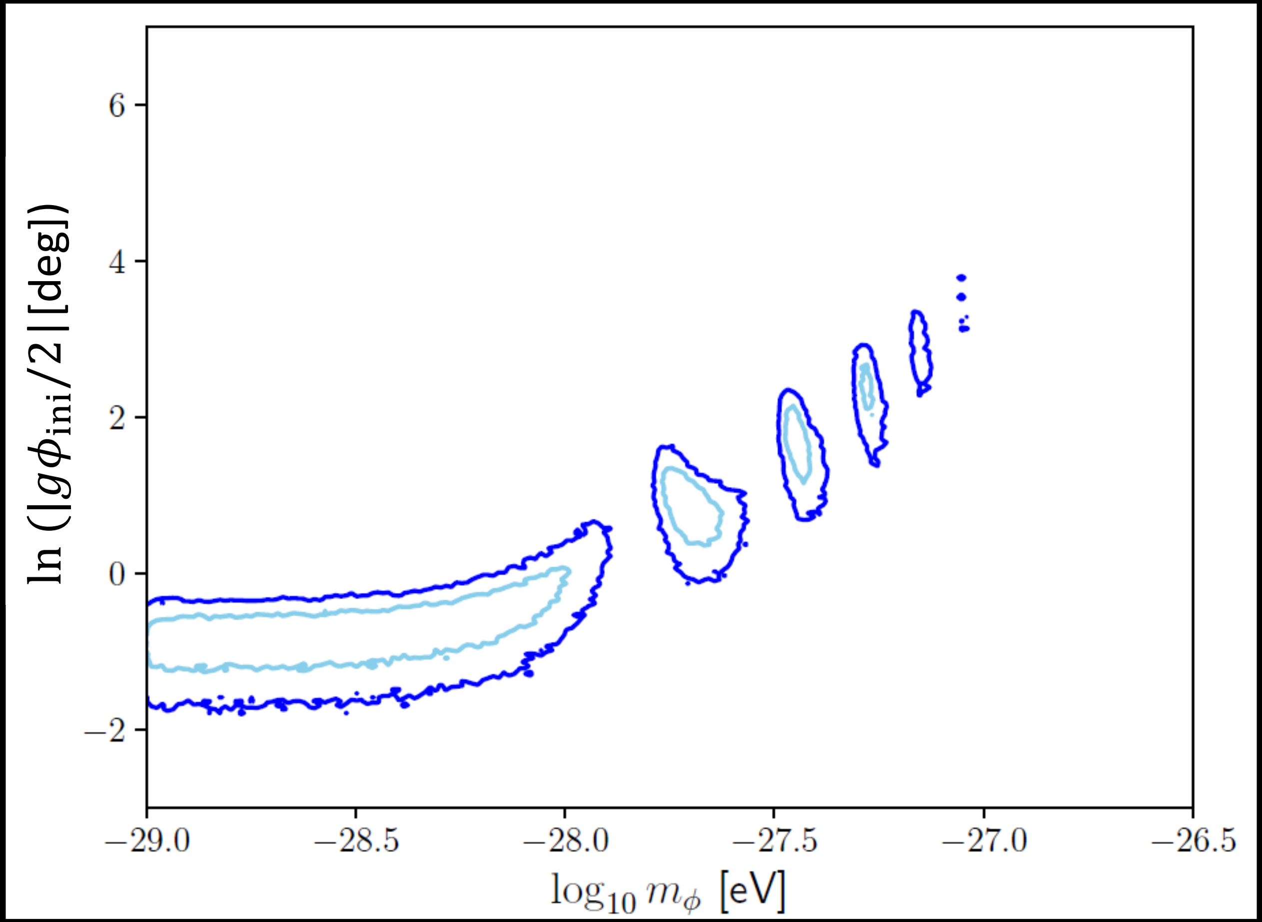
Constraining ALP parameters with Planck C_ℓ^{EB}



Namikawa, et al. (2025)

At higher mass, the EB power spectrum becomes disagree with data

Constraining ALP parameters with Planck C_ℓ^{EB}



Namikawa, et al. (2025)

No feature specific to ALP dynamics is detected:

Some m_ϕ is excluded by more than 2 sigma from Planck data

0. CMB polarization and cosmic birefringence

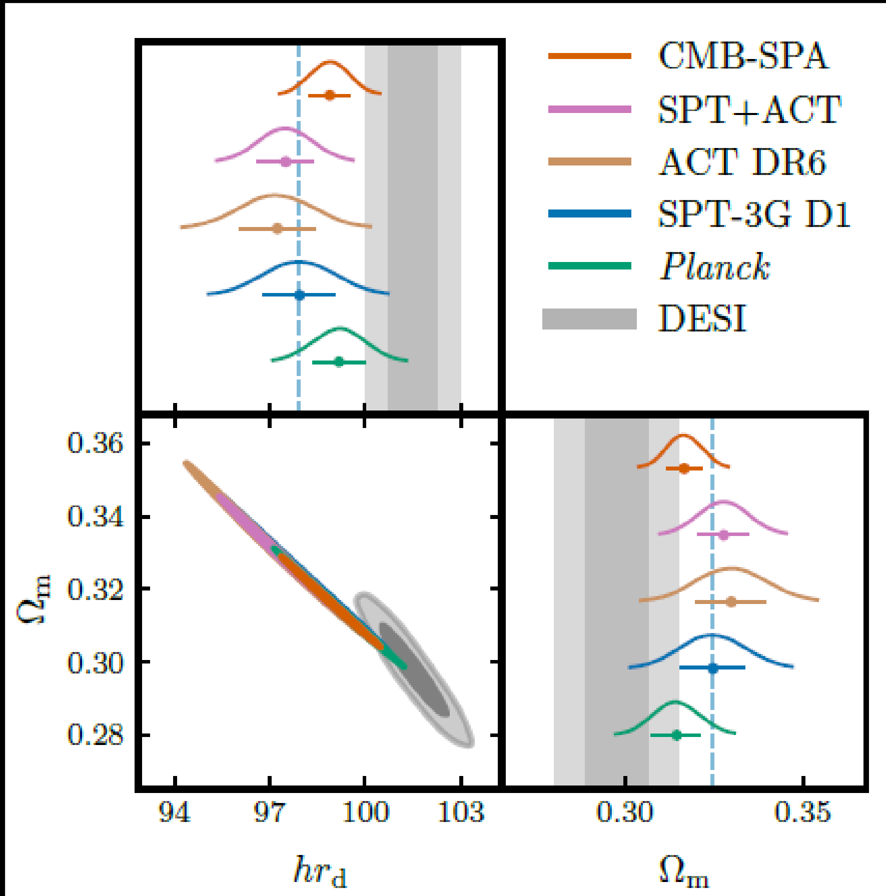
1. Testing signature of cosmic birefringence with the shape of CMB power spectra

2. A possible resolution of some tensions in cosmology with cosmic birefringence

A mild tension between DESI BAO and CMB observations

- The ΛCDM model faces a mild tension (CMB-BAO tension):

  Tension in Ω_m constraints



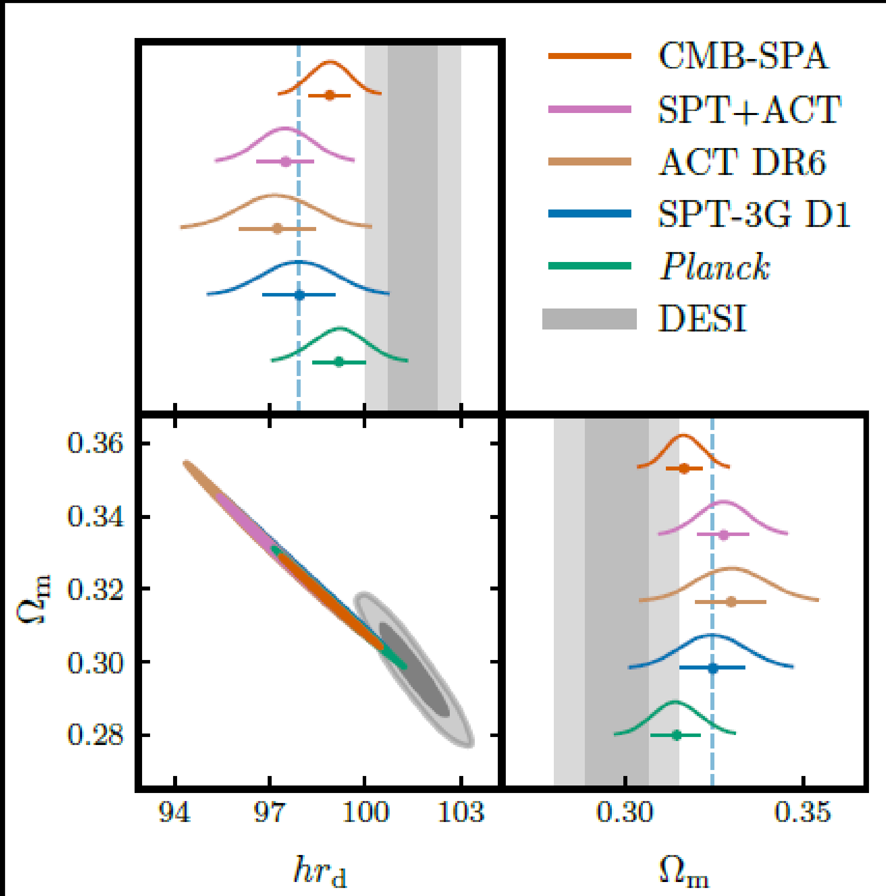
SPT-3G collaboration (2025)

A mild tension between DESI BAO and CMB observations

- The ΛCDM model faces a mild tension (CMB-BAO tension):

  Tension in Ω_m constraints

- Beyond ΛCDM, this tension turns into
  - a preference of $\sum m_\nu$ much lower than the lower bound of oscillation experiments
  - dynamical dark energy



SPT-3G collaboration (2025)

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- Beyond ΛCDM, this tension turns into
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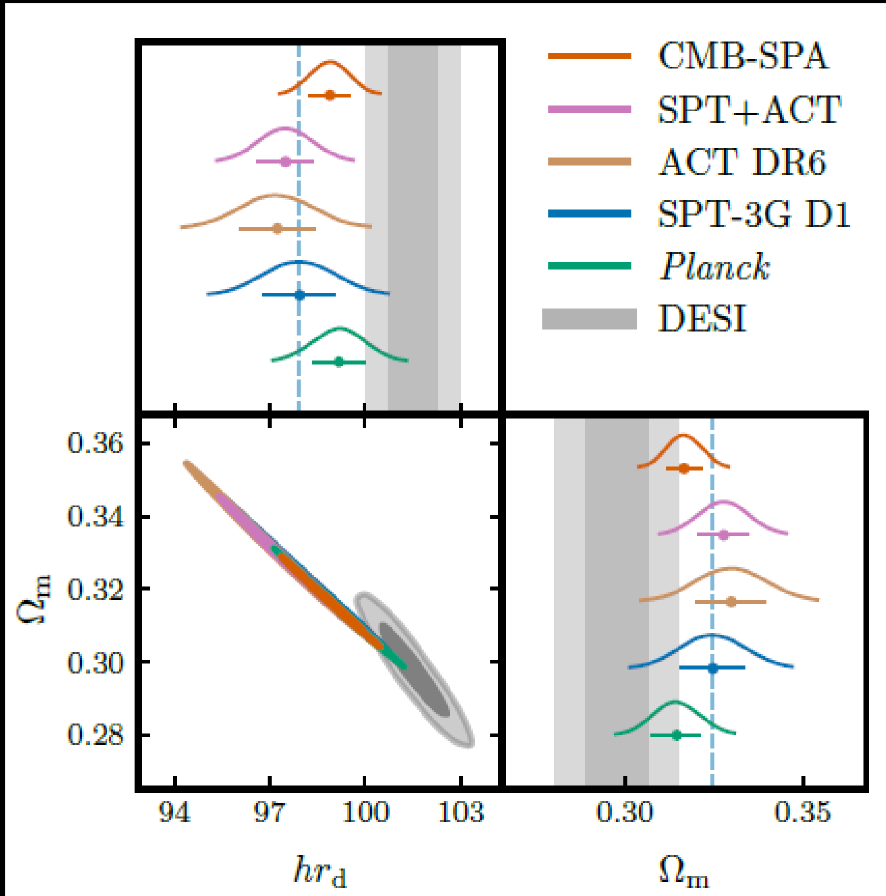
  - dynamical dark energy

- Within ΛCDM, raising optical depth $\tau \simeq 0.09$ can ease this tension (also $A_{\rm lens}$ and Ω_K anomaly)

  Sailor et al. (2025), Jhaveri et al. (2025)

  - but this conflicts with large-scale CMB polarization data that suggest $\tau \simeq 0.05$ (τ-tension)

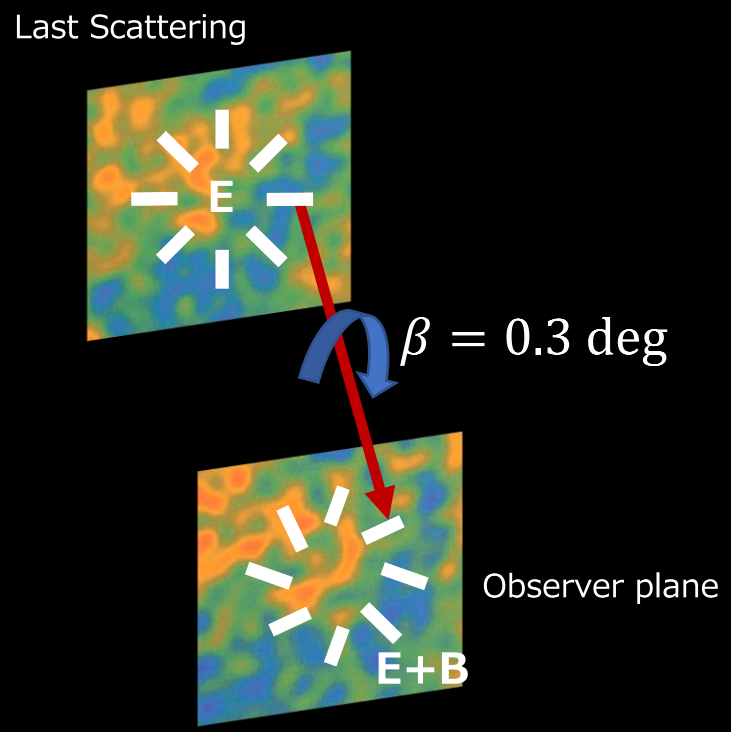


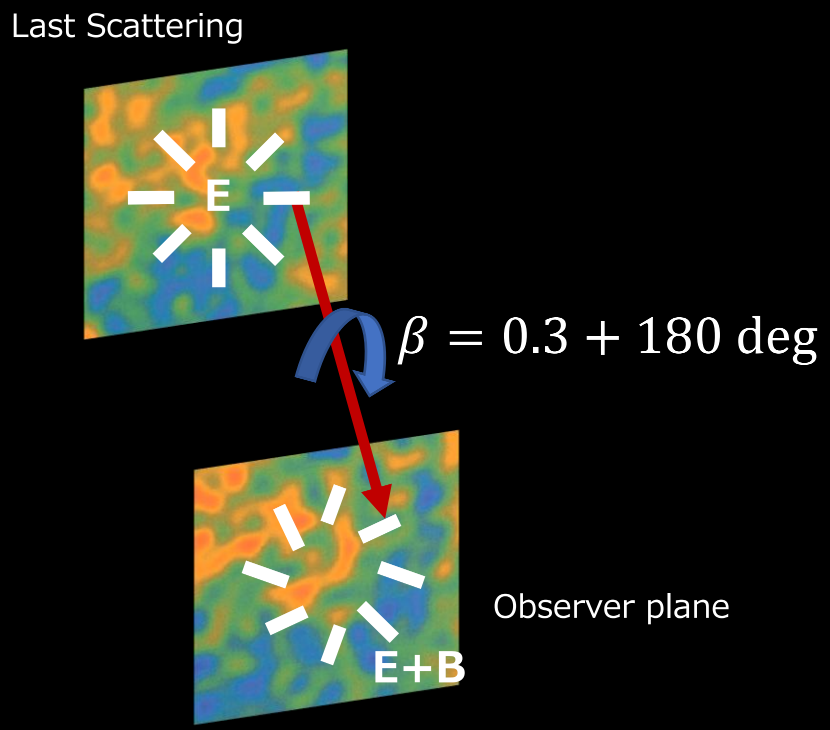
SPT-3G collaboration (2025)

We consider a possibility that cosmic birefringence helps reconcile the discrepancy in τ

$n\pi$ phase ambiguity of rotation angle

- Observed rotation angle has ambiguity of phase of angle





$n\pi$ phase ambiguity of rotation angle

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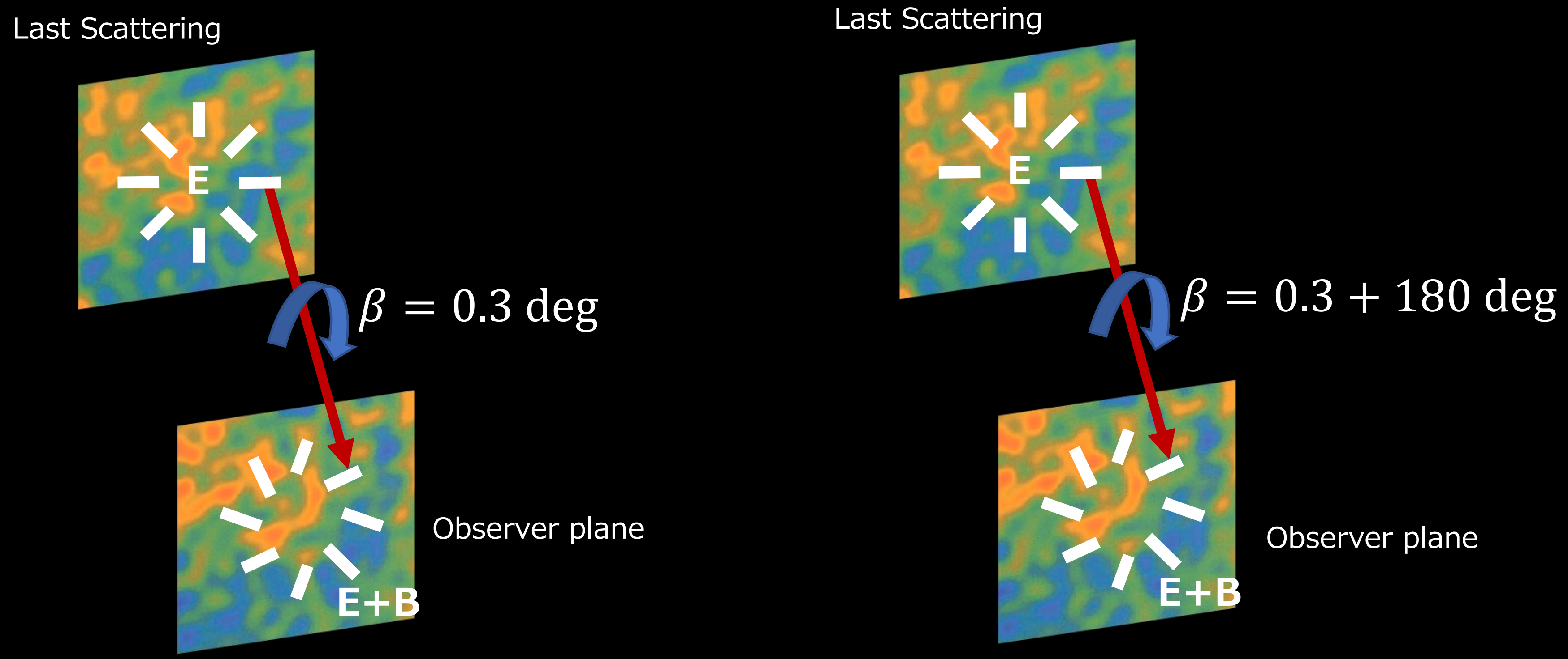
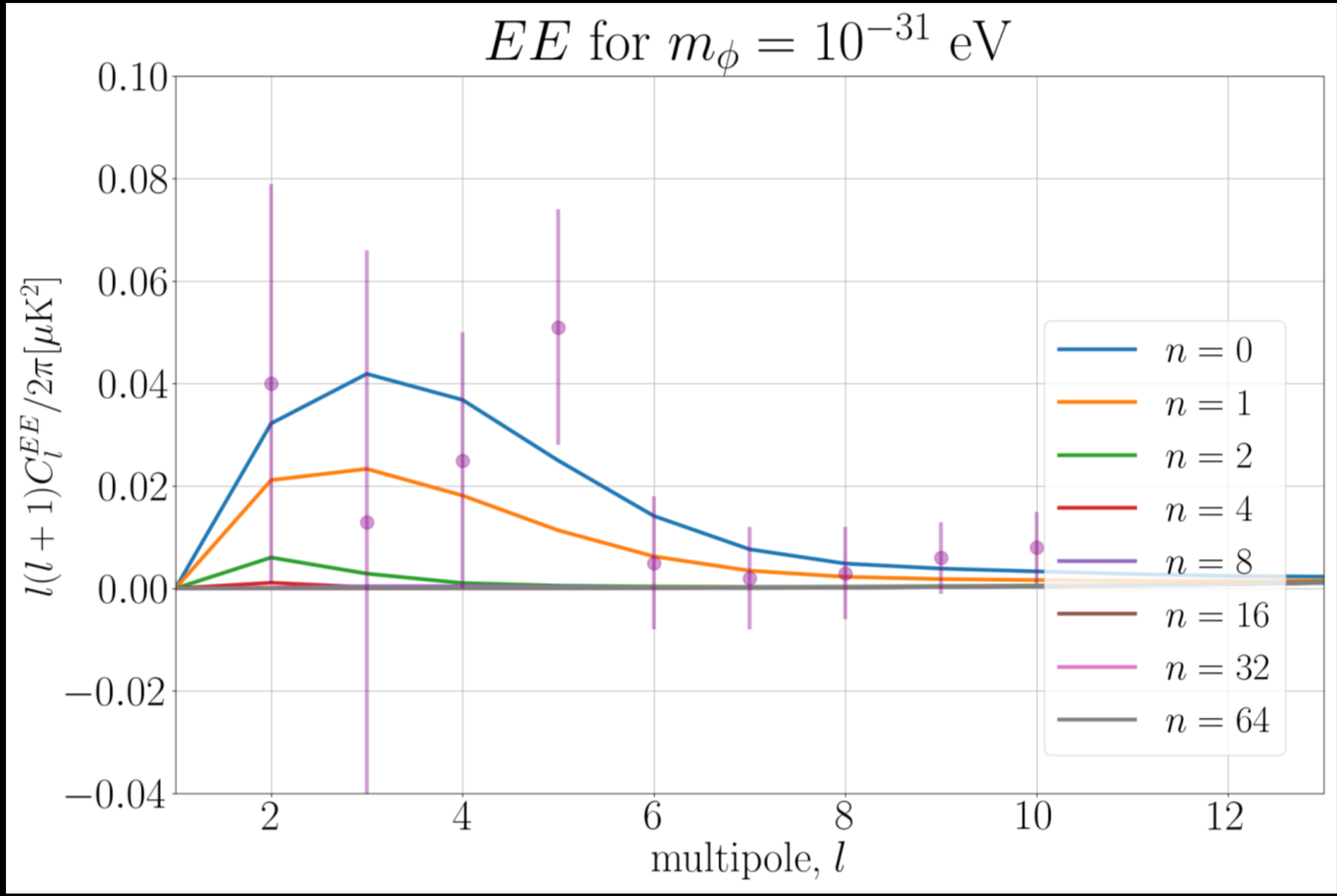


- CMB birefringence analysis could not distinguish $\beta = 0.3 + n \times 180$ deg ($|n| = 0,1, \ldots$)

Nonzero values of n significantly change C_l (next slides)

$n\pi$ phase ambiguity of rotation angle



Naokawa, *Namikawa*, Murai, Obata, Kamada (2024)

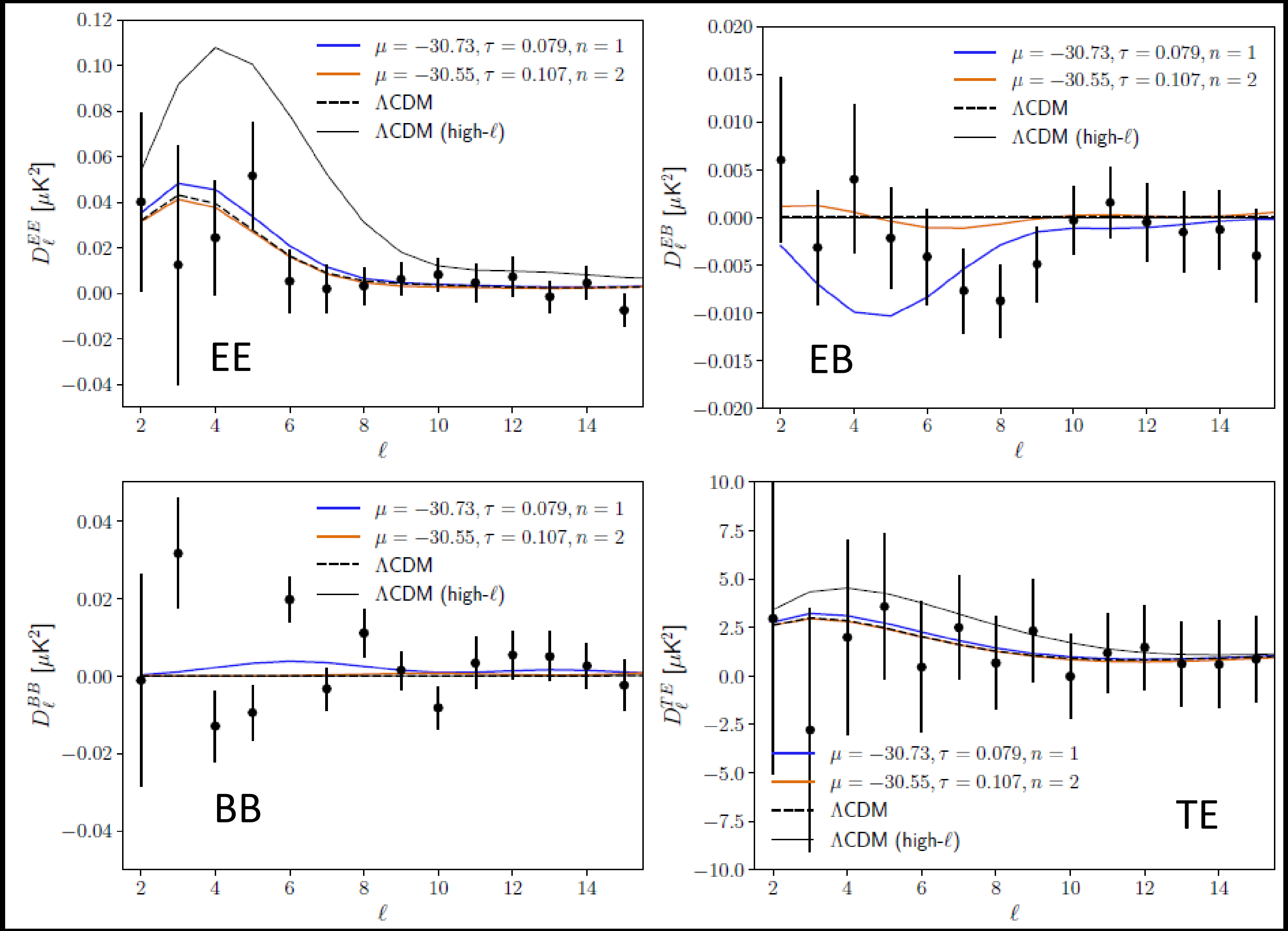
$$\beta(z_{\rm rec}) = 0.3 + n \times 180 \text{ deg}$$

$$E^{\rm rei} \sim E(z_{\rm rei}) \int_{z_{\rm start}}^{z_{\rm end}} {\rm d}z \cos[2\beta(z)]$$

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

Large CMB optical depth and cosmic birefringence

- EE, EB, BB from Planck PR4 Lollipop low-ell spectra (and TE from PR3)

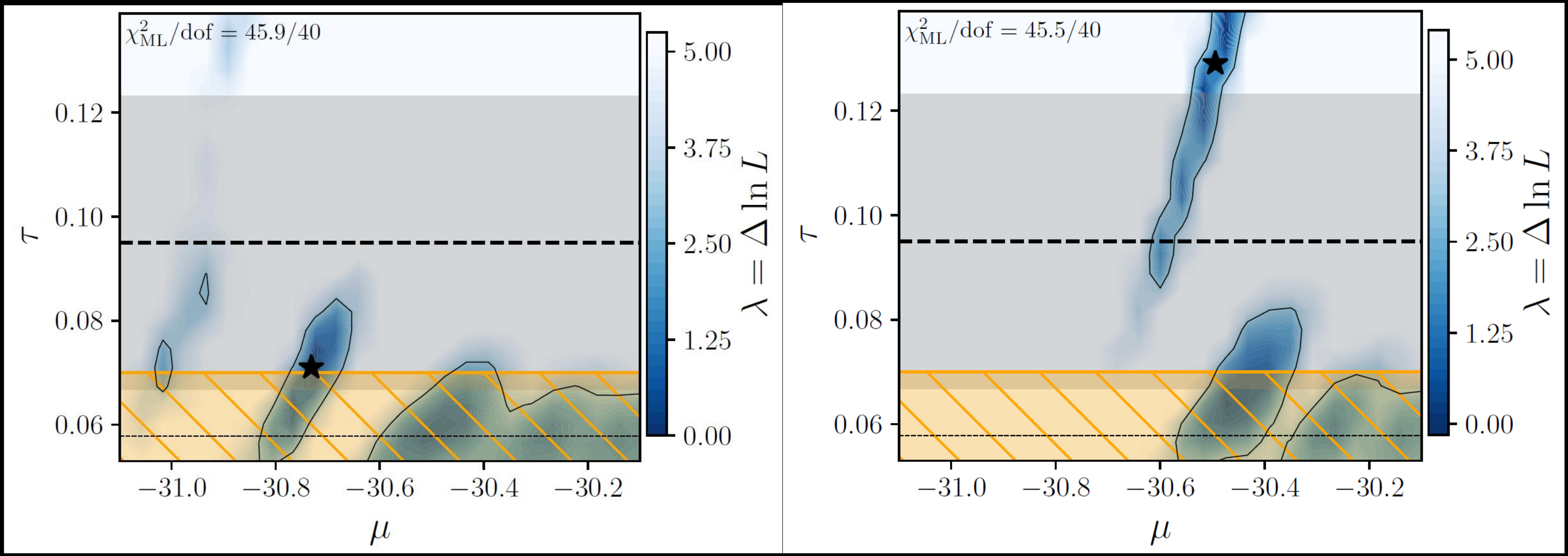


$\mu = \log_{10} m_\phi$ [eV]

Namikawa (2025)

Large CMB optical depth and cosmic birefringence

- Computing the likelihood values with varying parameters



$\mu = \log_{10} m_\phi$ [eV]

Namikawa (2025)

- There are parameters that fit the observed power spectra well
- Alternative to n, we can consider a large rotation angle ($O(10)$ deg) during reionization would be enough

Summary

- We explored cosmic birefringence scenario that explains recent several hints on beyond ΛCDM.
  - A nonzero Planck C_l^{EB}
  - CMB-BAO tension

- We first showed that the Planck EB data agrees with the constant rotation
  - Excluding ALP-induced cosmic birefringence with $m_\phi \gg 10^{-28}$ eV ($> 2\sigma$)

Namikawa, Murai, Naokawa (2025)
arXiv:2506.20824

- Cosmic birefringence is also a possible solution of the recent CMB-BAO tension by requiring a higher τ.
  - This scenario can be tested with
    - more low-z samples of radio galaxies
    - polarized SZ
    - CLASS, LiteBIRD for low-ell EE
  - Model building (e.g., avoid fine tunning)

Namikawa (2025)
arXiv:2506.22999