Cosmic birefringence tomography

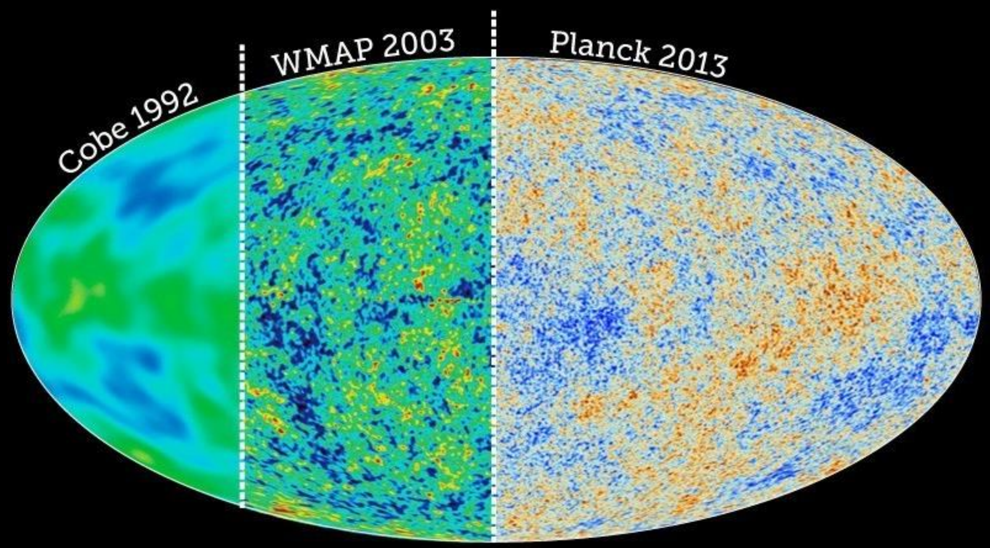
Toshiya Namikawa

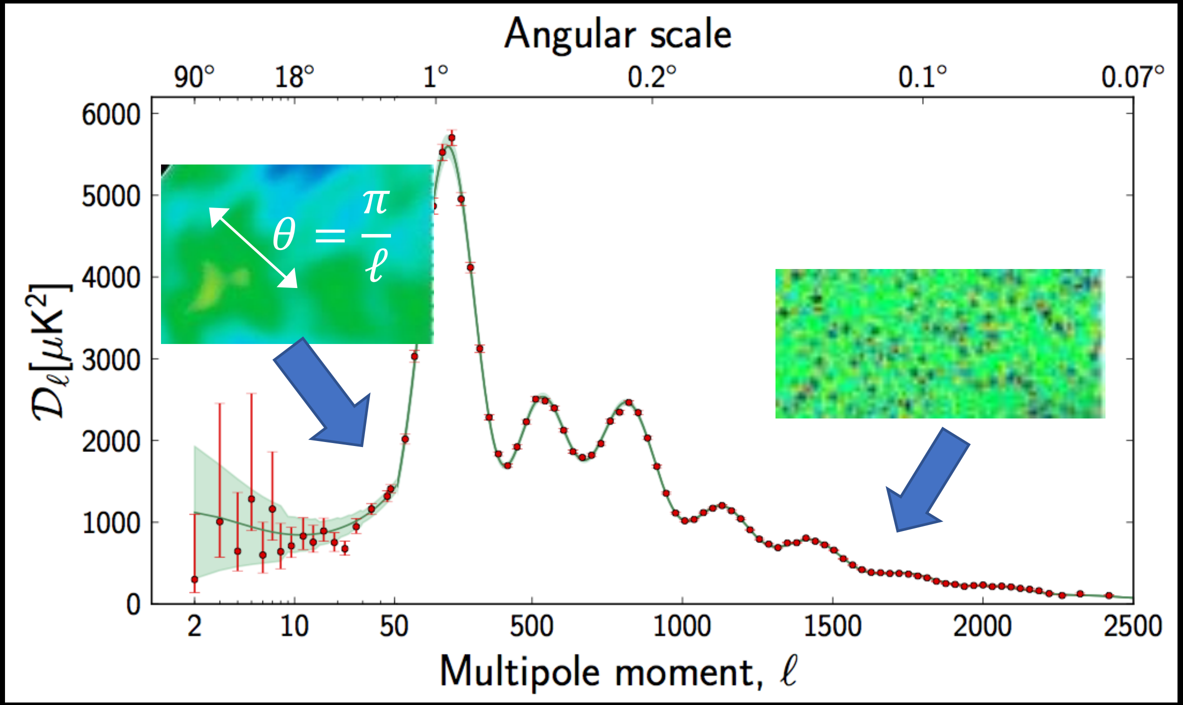
(Kavli IPMU, University of Tokyo)

iTHEMS Cosmology Forum @ RIKEN, 5/14/2024

CMB measurements and cosmology

- Anisotropies of CMB temperature have been measured very precisely



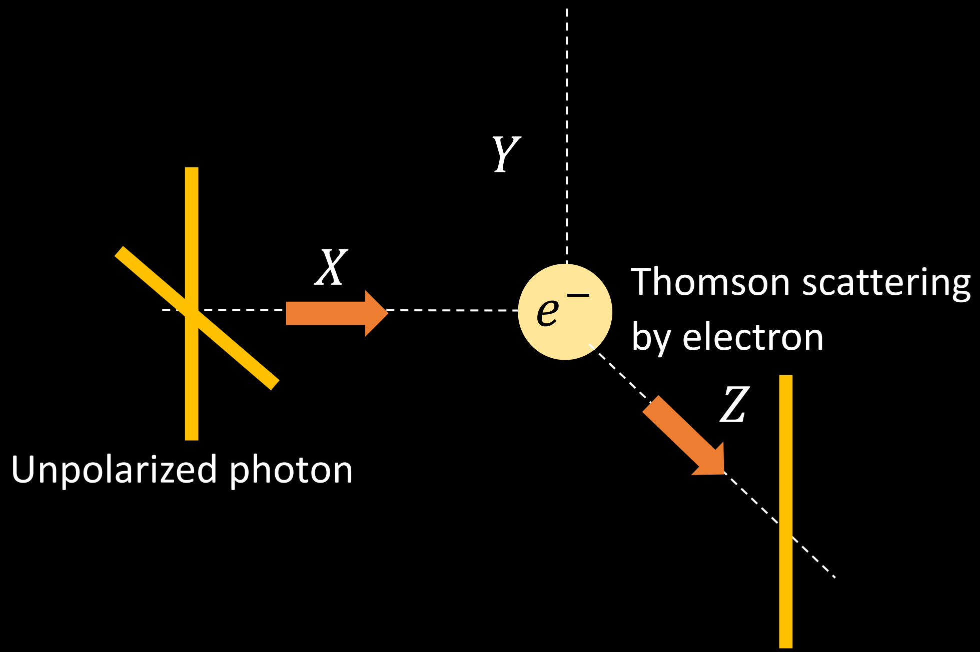


- Establish the standard cosmological model by combining CMB + SNeIa + Large-scale-structure
  - ✓ Constrain composition of the universe
  - ✓ Accelerated expansion of the recent universe
  - ✓ Spatially flat universe
  - ✓ Gaussian primordial fluctuations

CMB polarization is a key observable in observational cosmology in the coming decades

CMB polarization

Temperature quadrupole anisotropies generates linear polarization



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

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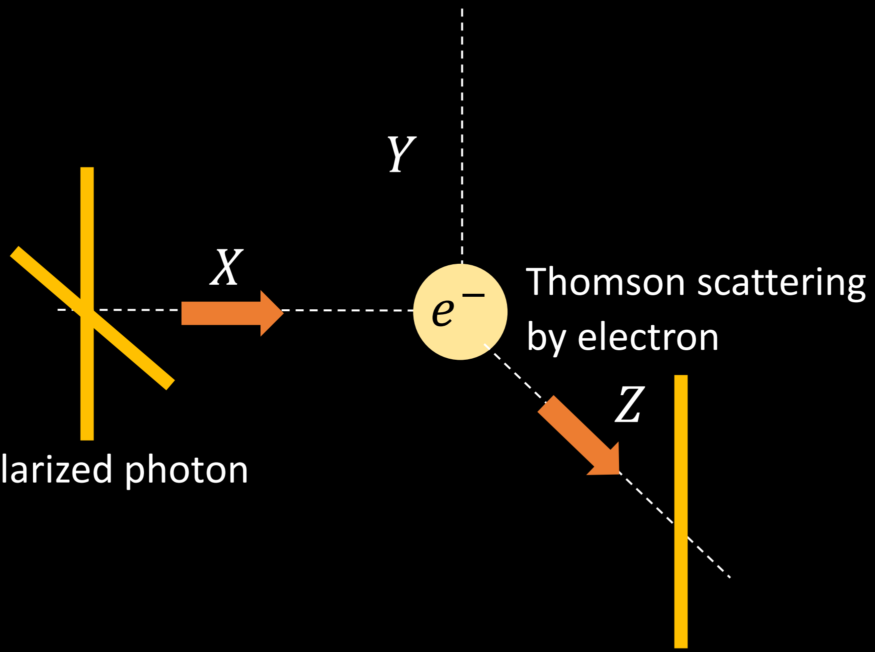

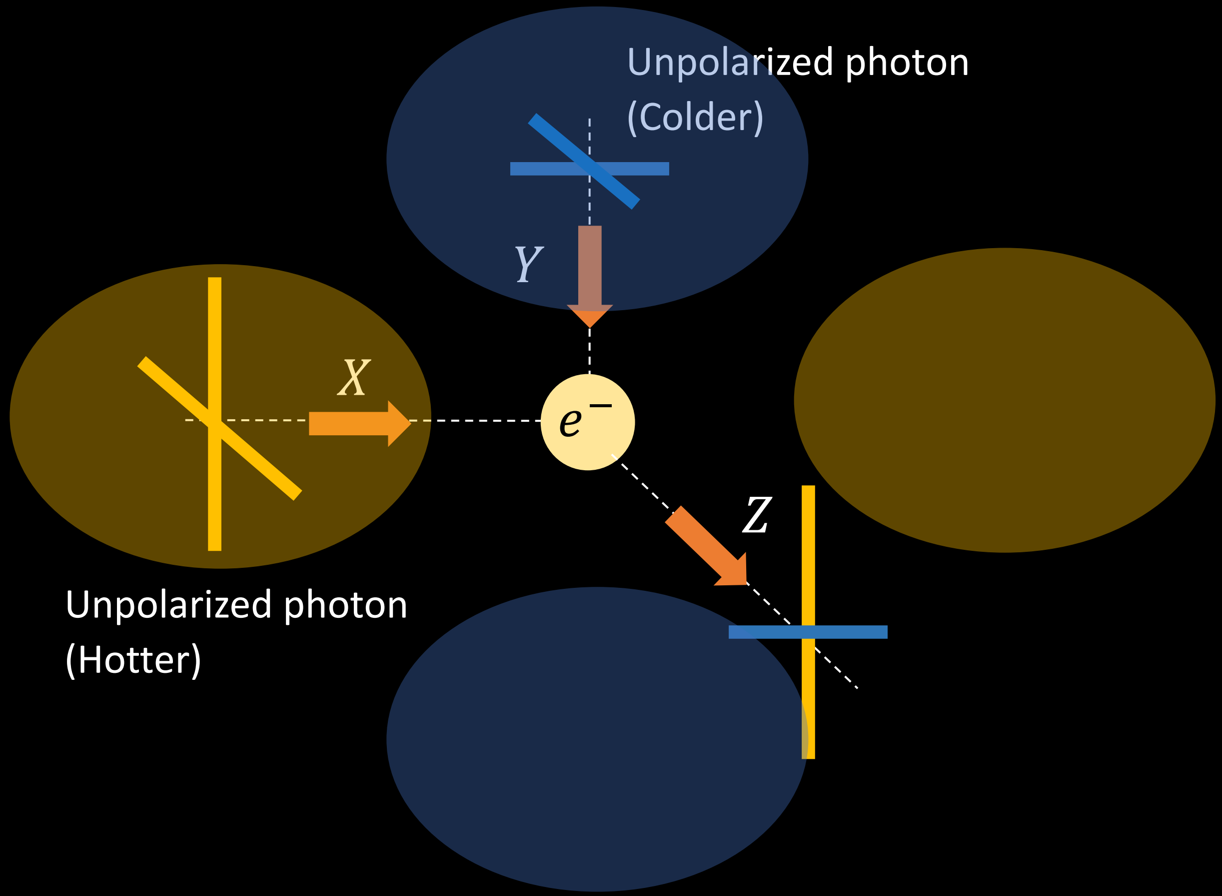

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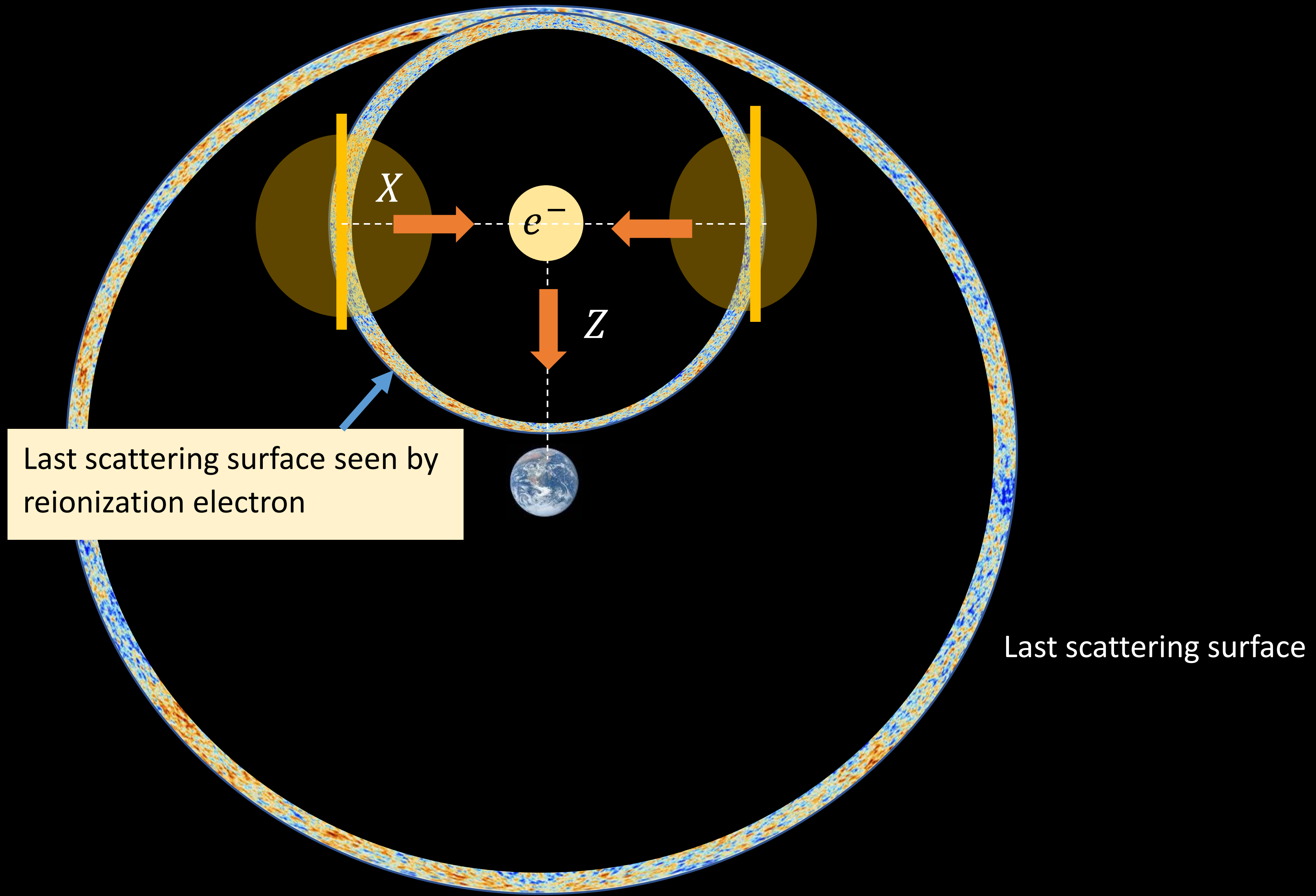
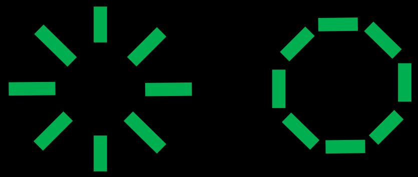


CMB polarization is generated not only from recombination but also from reionization

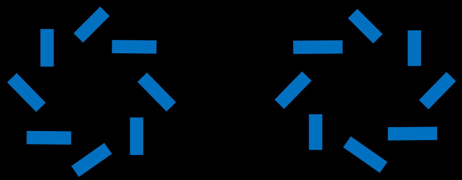
CMB polarization

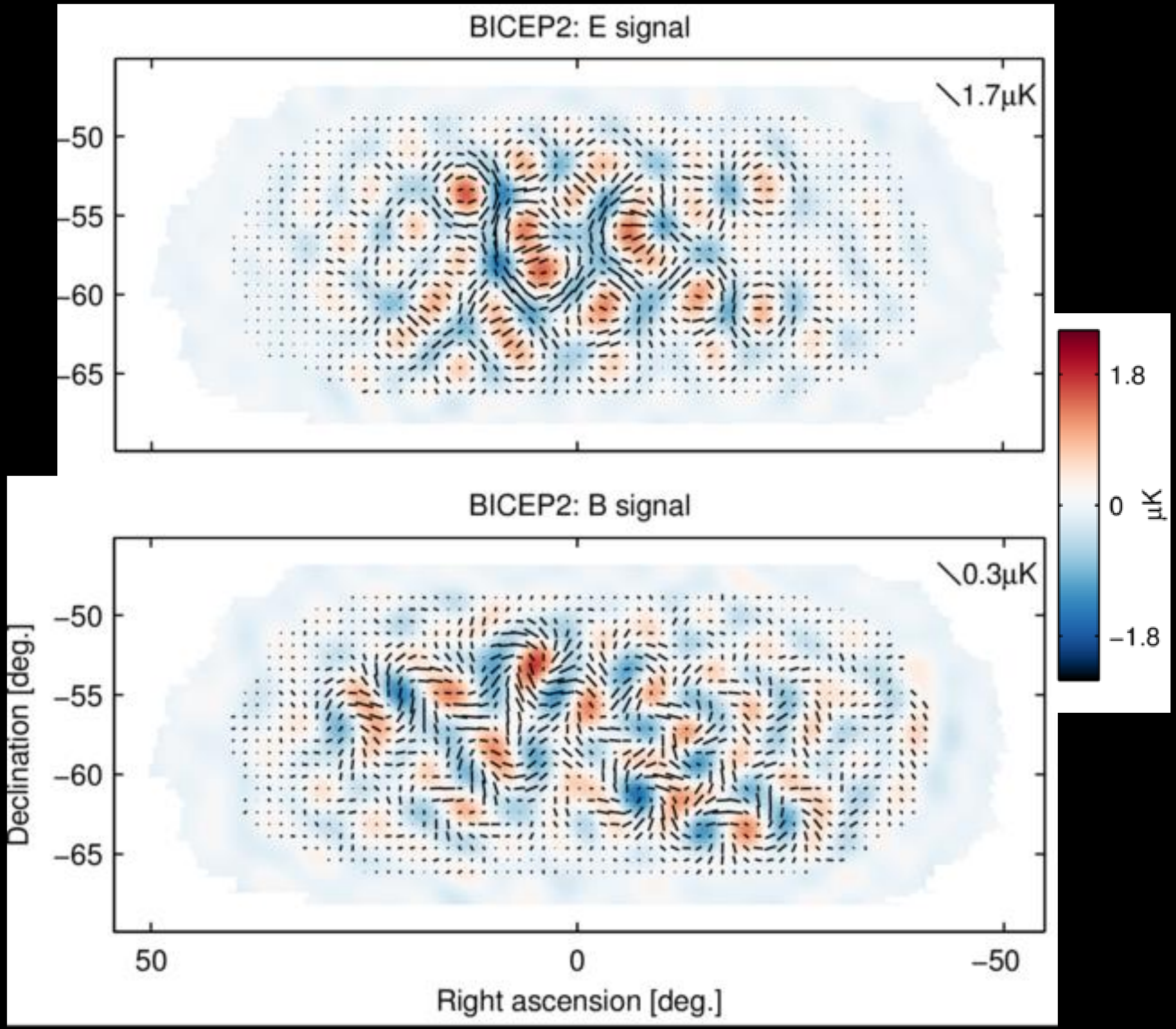
E modes (even parity)



Density fluctuations generate **only** E-modes

B modes (odd parity)





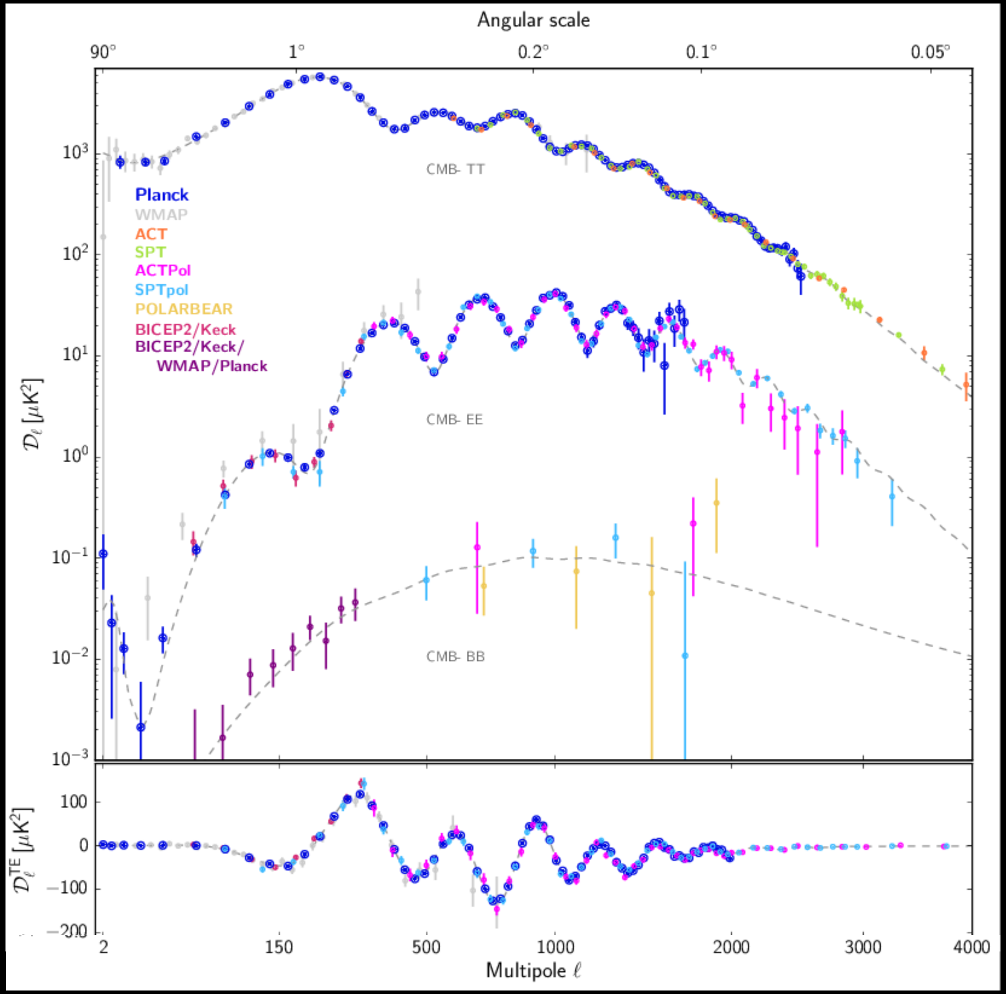
Primordial GWs generate **not only** E modes **but also** B modes

CMB power spectra and parity

- Correlations between CMB temperature, E-mode, and B-mode

C_ℓ^{TT} C_ℓ^{TE} C_ℓ^{EE} C_ℓ^{BB}

Parity even



Planck Collaboration (2020)

CMB power spectra and parity

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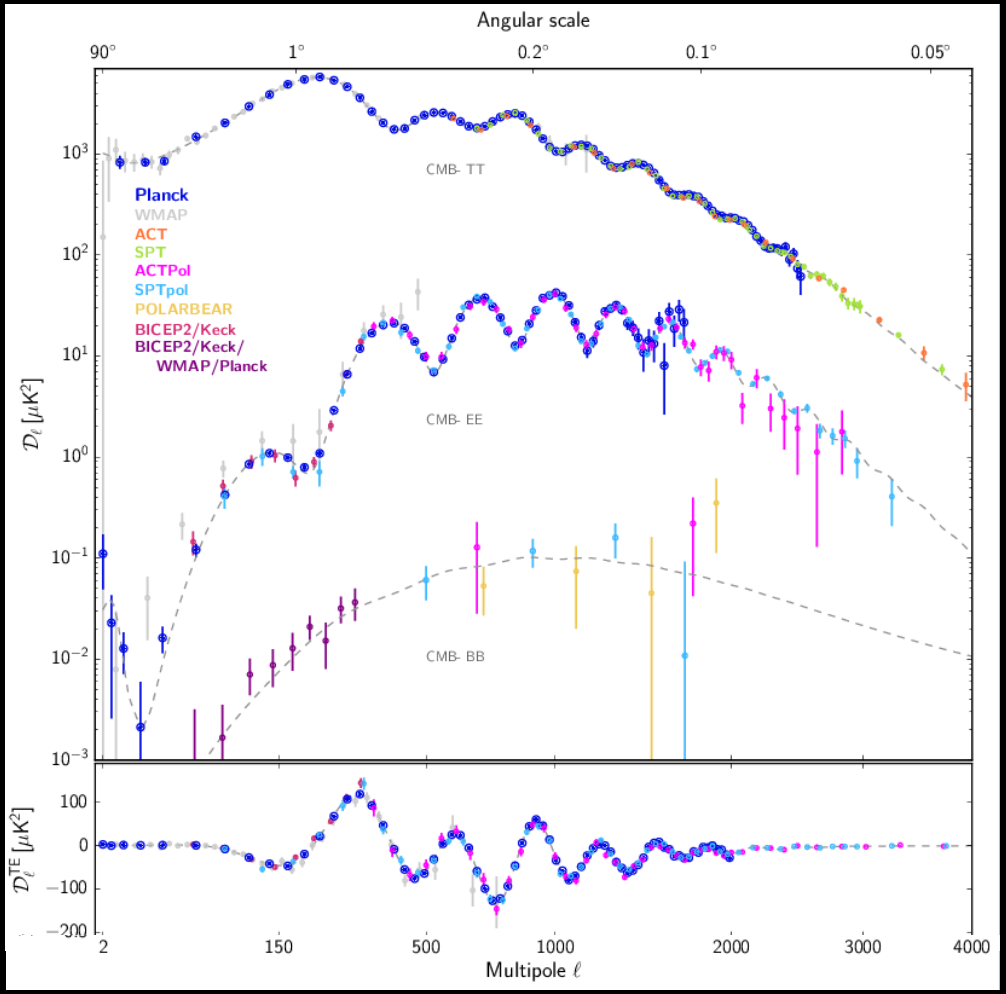
C_ℓ^{TT} C_ℓ^{TE} C_ℓ^{EE} C_ℓ^{BB}

Parity even

C_ℓ^{TB} C_ℓ^{EB}

Parity odd

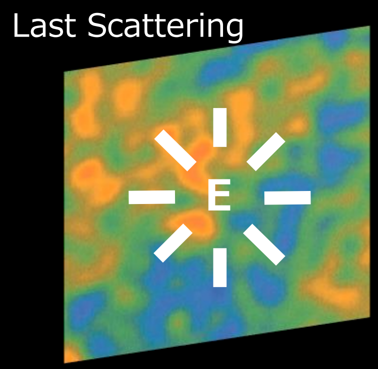
We can prove parity violation by observing C_ℓ^{TB} and C_ℓ^{EB}



Planck Collaboration (2020)

Cosmic birefringence

Cosmic Birefringence = A phenomena which rotates polarization plane of CMB during the propagation



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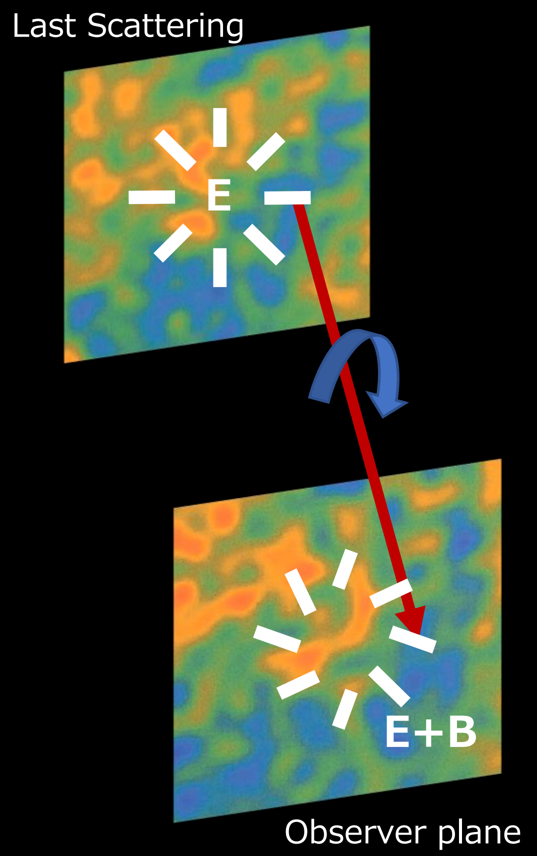

$$E^{\mathrm{obs}} = E\cos(2\beta)$$
$$B^{\mathrm{obs}} = E\sin(2\beta)$$
$$\Rightarrow \quad C_\ell^{EB\ \mathrm{obs}} = \frac{\sin(4\beta)}{2}\, C_\ell^{EE}$$

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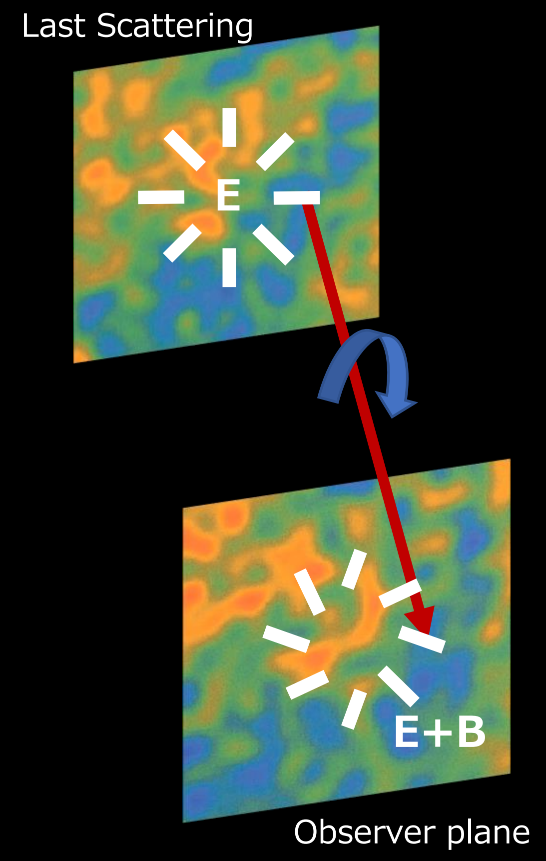

- Axion-like particles (ALPs; ϕ) coupled with photons

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

Ni (1977), Turner & Widrow (1988)

Wide range of mass (m_ϕ) and coupling (g) Arvanitaki et al. (2010)

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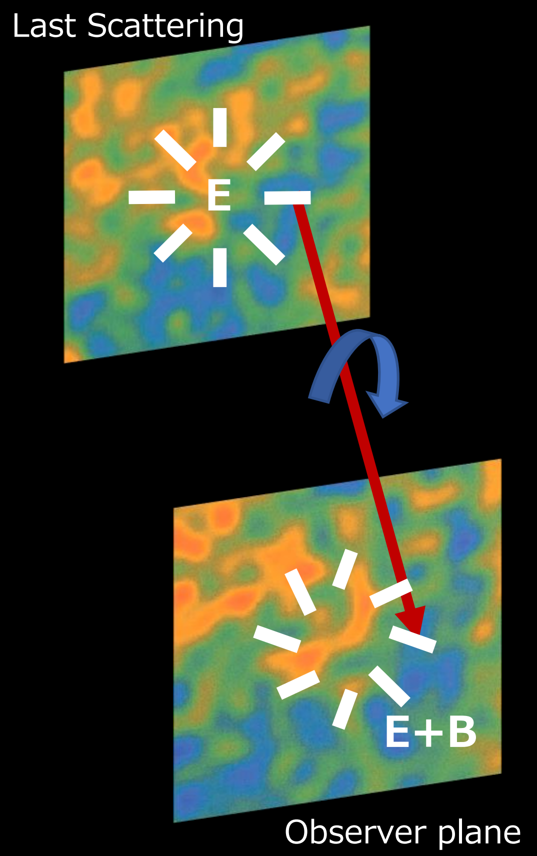

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This term makes the phase velocities of right- and left-handed polarization states of photons different, leading to rotation of the polarization plane

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

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

Independent of photon frequency (c.f. Faraday rotation by magnetic fields)

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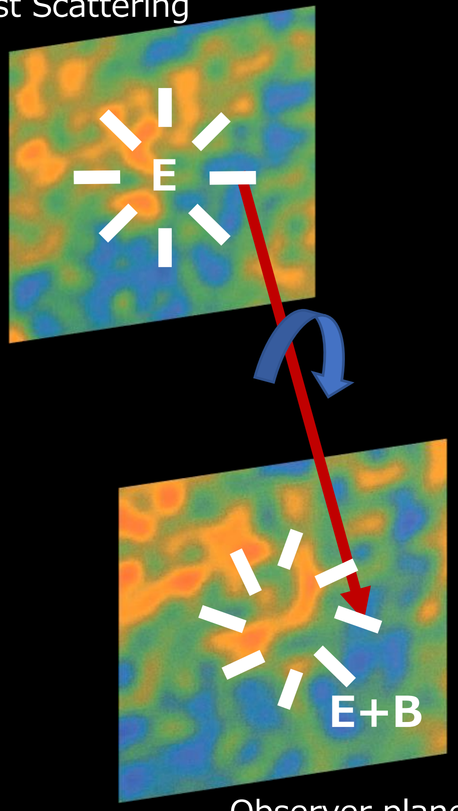

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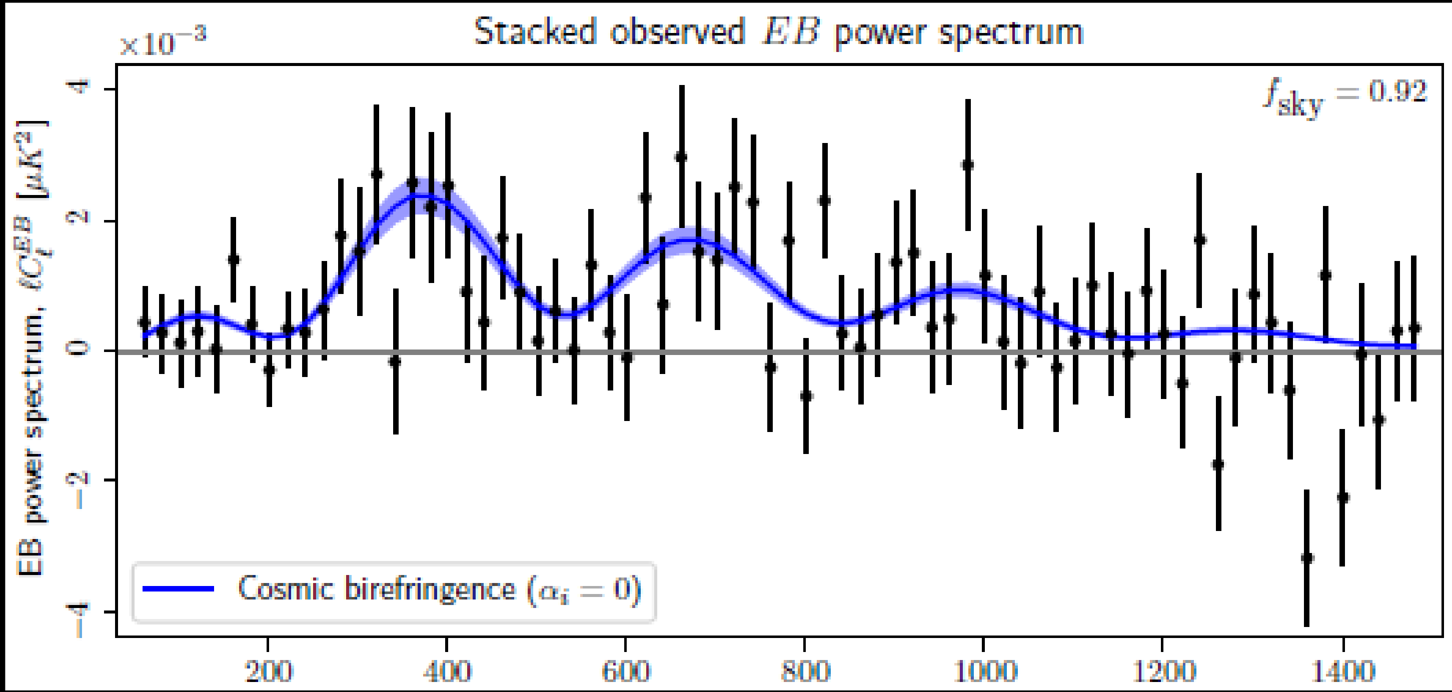
We can make implications for ALPs by observing β (C_ℓ^{EB})

(see Takahashi-san's talk)

Observation of Cosmic birefringence

- WMAP + Planck EB power spectrum



Eskilt & Komatsu (2022)

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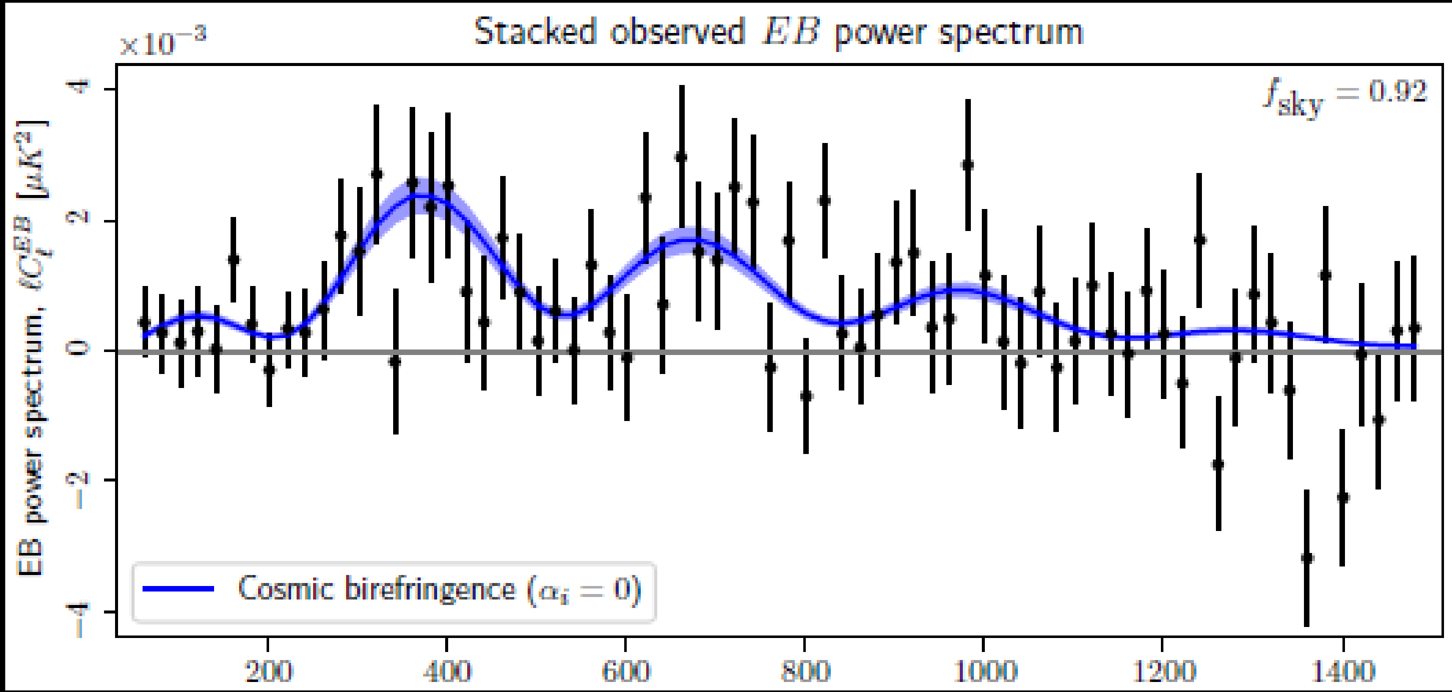
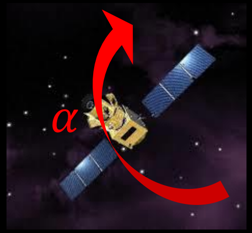


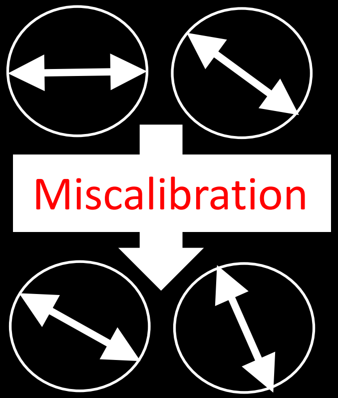
Eskilt & Komatsu (2022)

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

Observed CMB polarization can be rotated simply because polarization directions of detectors are rotated with respect to the sky coordinates

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



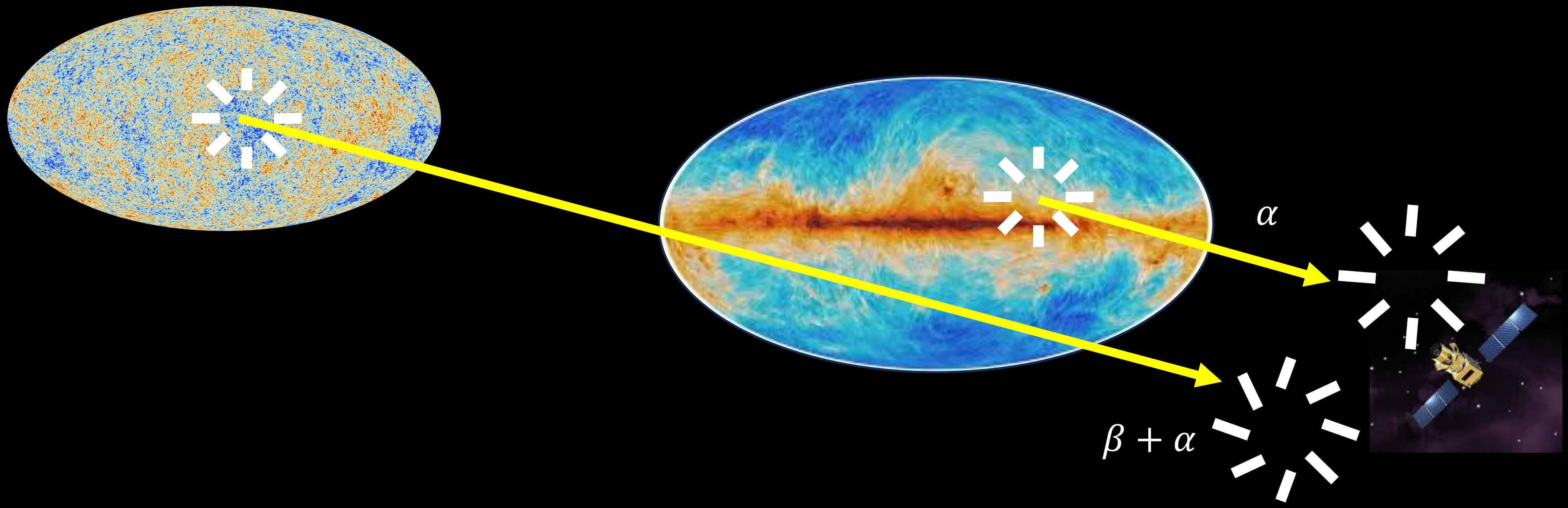


Observation of Cosmic birefringence

- 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

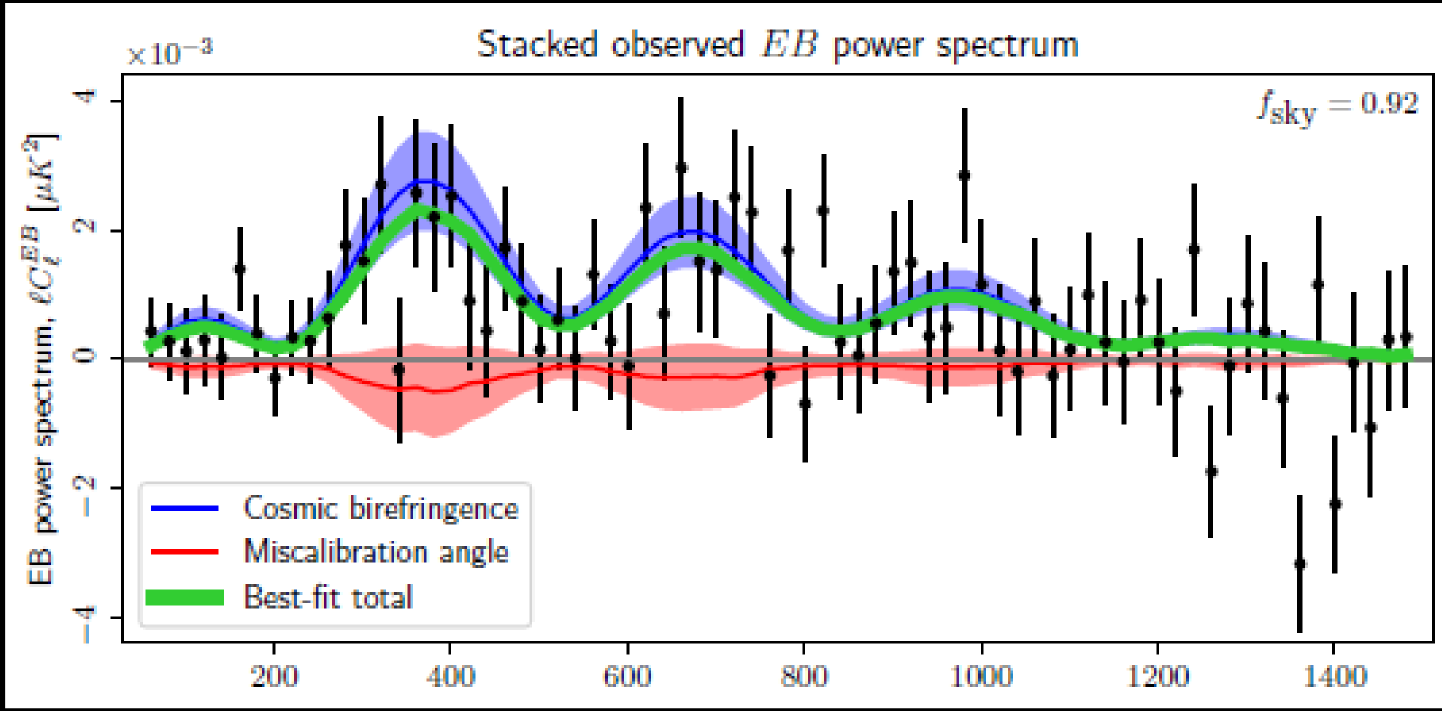


We can calibrate α with Galactic foreground and then extract β

Observation of Cosmic birefringence

- Minami & Komatsu (2020) applied this technique and obtained $\beta = 0.35 \pm 0.14$ deg
- With WMAP and a lower-noise Planck data, the current constraint is $\beta = 0.34^{+0.094}_{-0.091}$ deg

Eskilt & Komatsu (2022)



- Further investigations are needed to confirm the signal

  Intrinsic EB correlation of foregrounds

  Reducing uncertainties on α with improved hardware calibrators

Probing time-evolution of isotropic cosmic birefringence by ALPs

This part is based on the following works:

Sherwin & TN (2023)

Nakatsuka, TN, Komatsu (2022)

Murai, Nakatsuka, TN, Komatsu (2022)

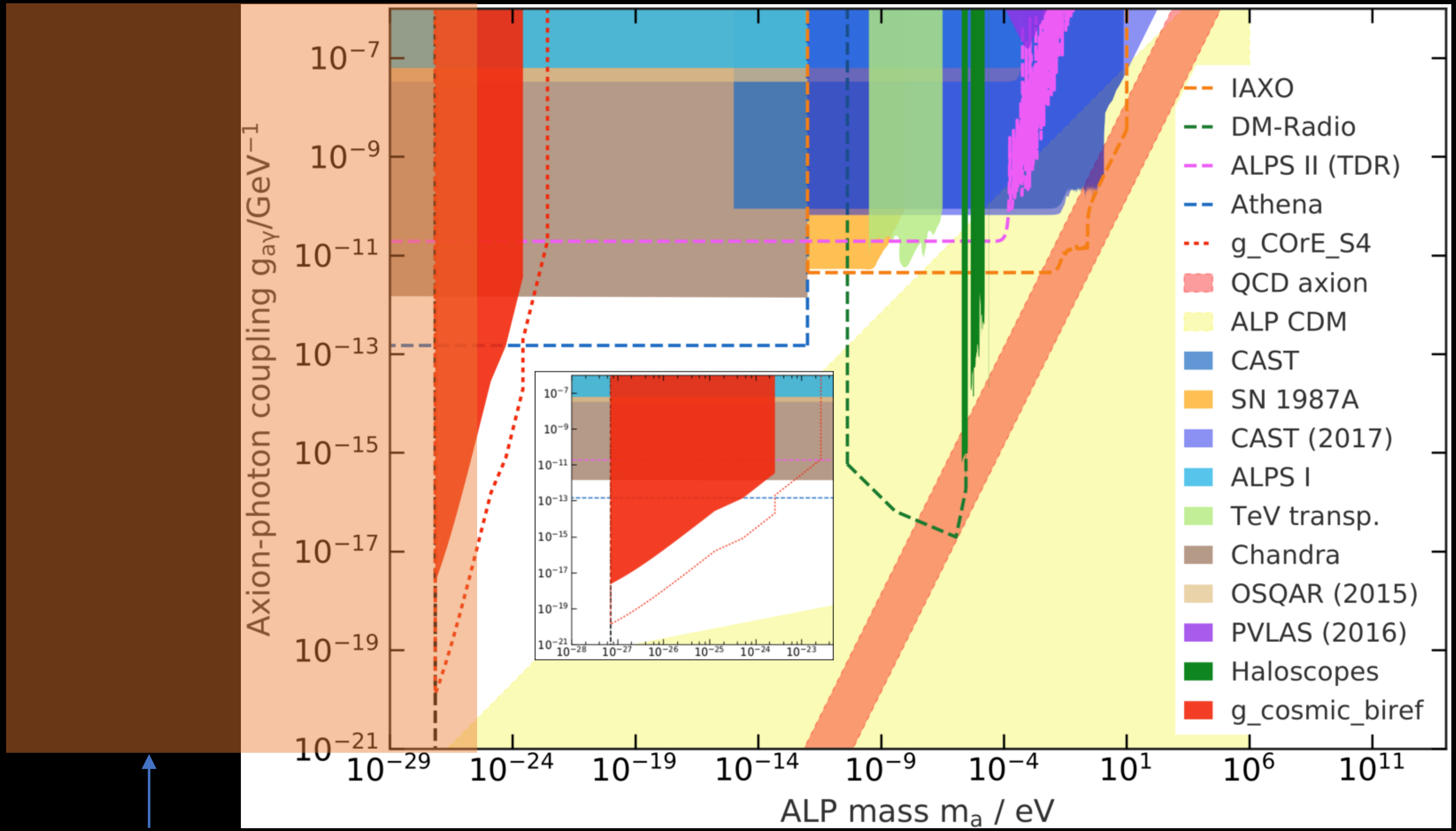
Naokawa & TN (2023)

TN & Obata (2023)

Naokawa, TN, et al. (2024) in prep.

Implications for ALPs from cosmic birefringence

- Multiple experiments have constrained ALP mass and coupling

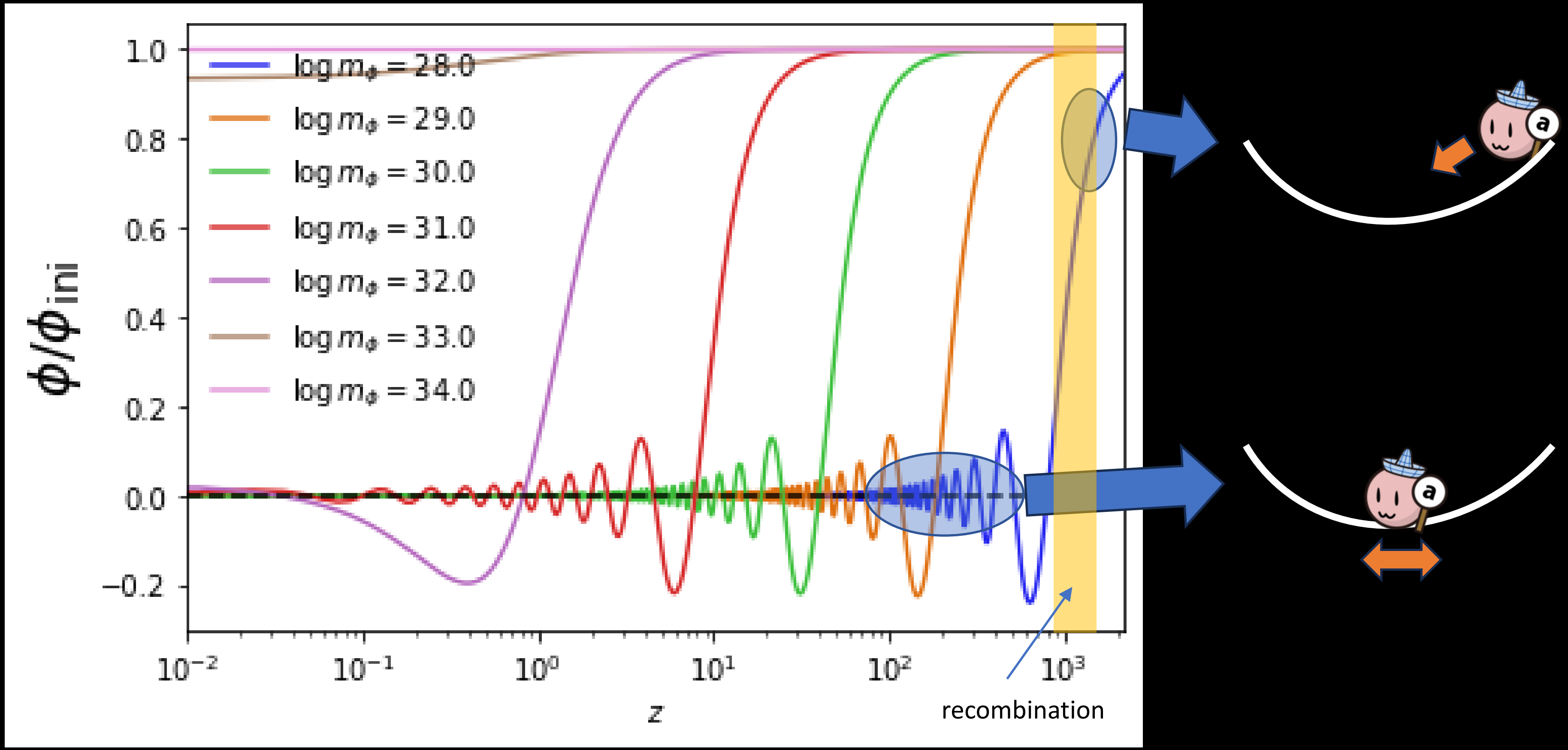


(Sigl et al., 2018)

Mass range probed by CMB cosmic birefringence

Implications for ALPs from cosmic birefringence

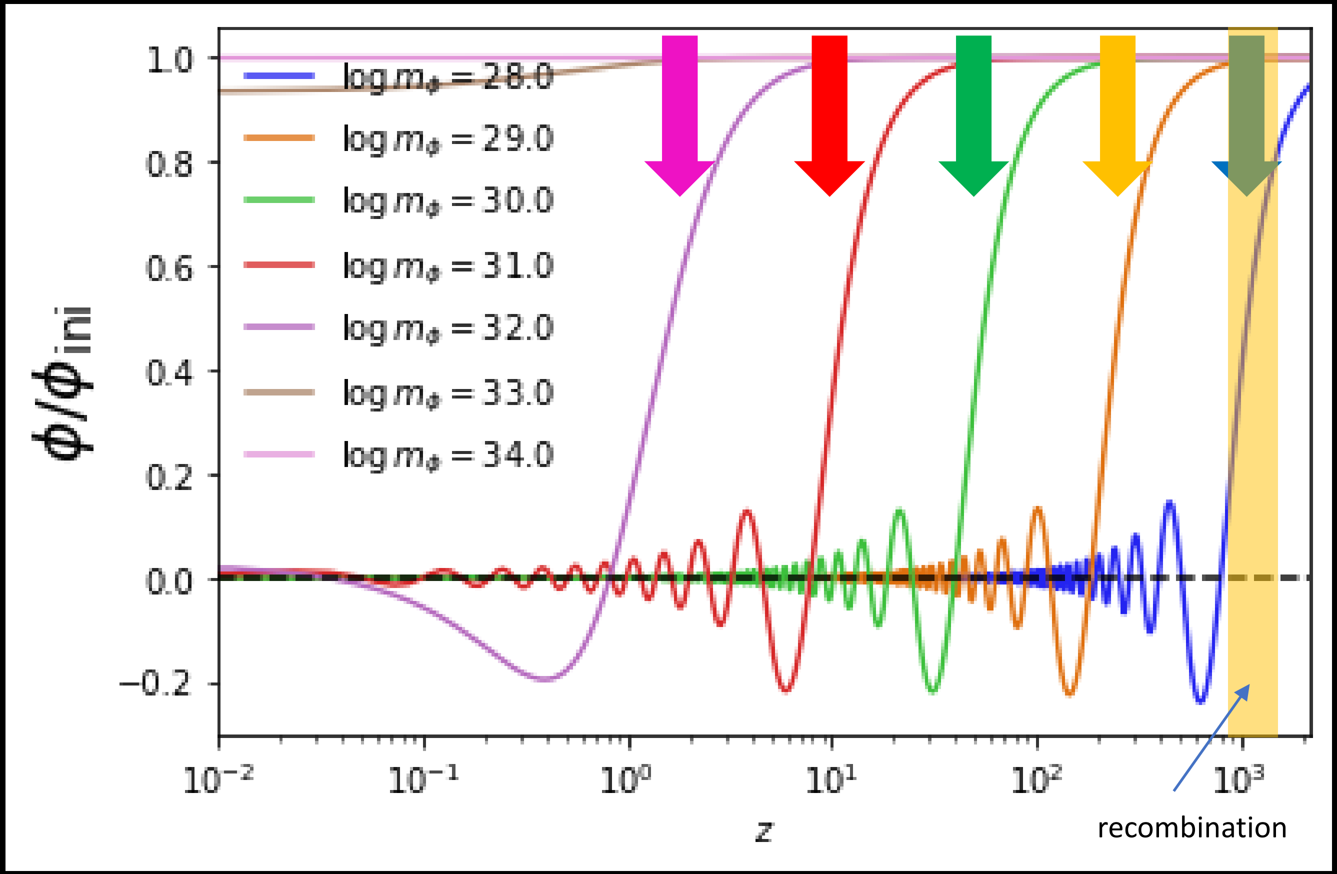
- Implications for ALPs from observed birefringence angle (Fujita, Murai, Nakatsuka & Tsujikawa 2021)



Implications for ALPs from cosmic birefringence

- Implications for ALPs from observed birefringence angle (Fujita, Murai, Nakatsuka & Tsujikawa 2021)

$\Delta\phi \simeq \phi_{\rm ini}$ if $10^{-32}\ \mathrm{eV} < m_\phi < 10^{-28}\ \mathrm{eV}$ and we need a similar g to explain $\beta = 0.3$ deg

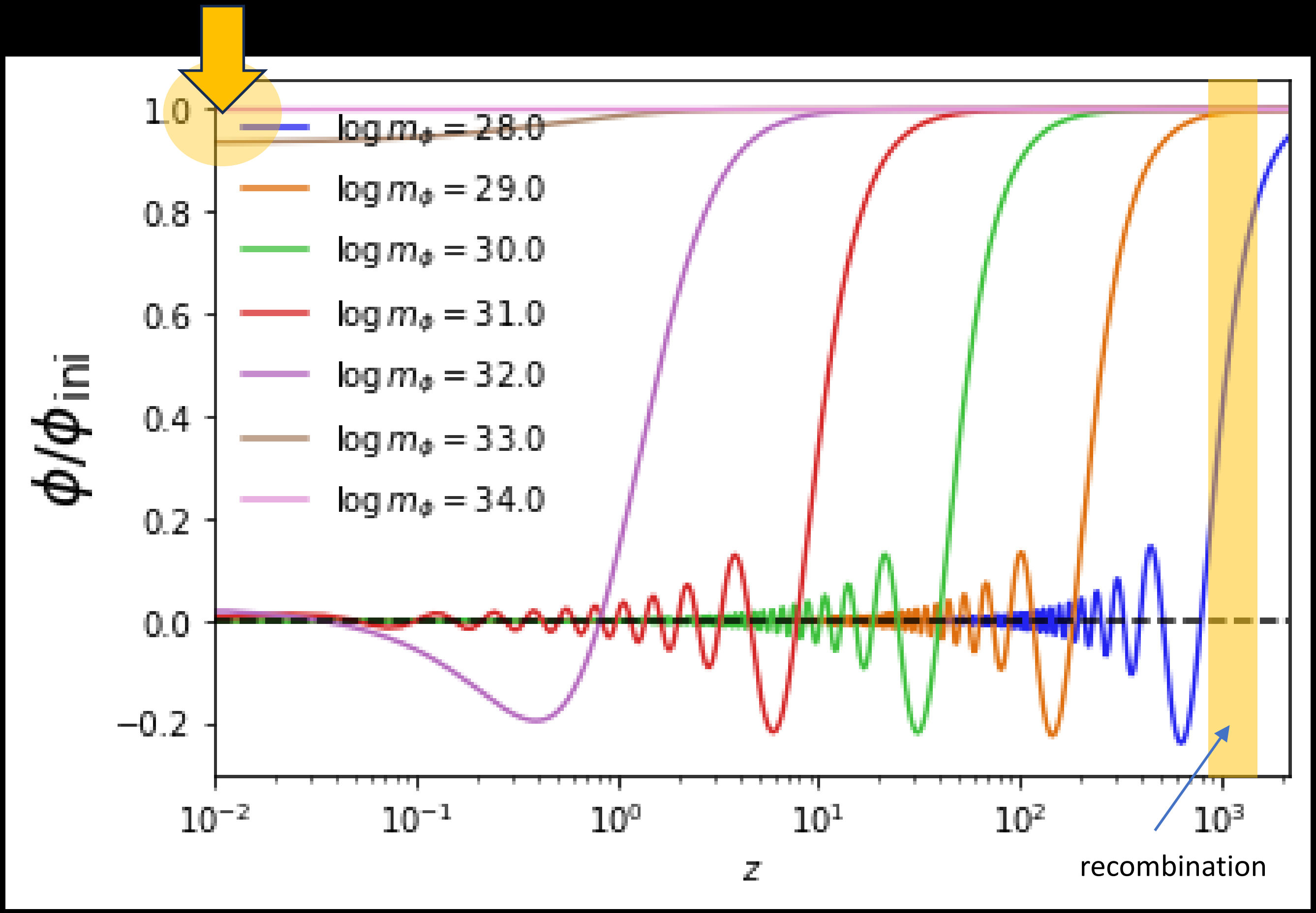


$$\beta = \frac{g}{2}(\phi_{\rm obs} - \phi_{\rm source})$$

Implications for ALPs from cosmic birefringence

- Implications for ALPs from observed birefringence angle (Fujita, Murai, Nakatsuka & Tsujikawa 2021)

$\Delta\phi \ll \phi_{\rm ini}$ if $m_\phi \ll 10^{-33}$ eV and we need a large g to explain $\beta = 0.3$ deg



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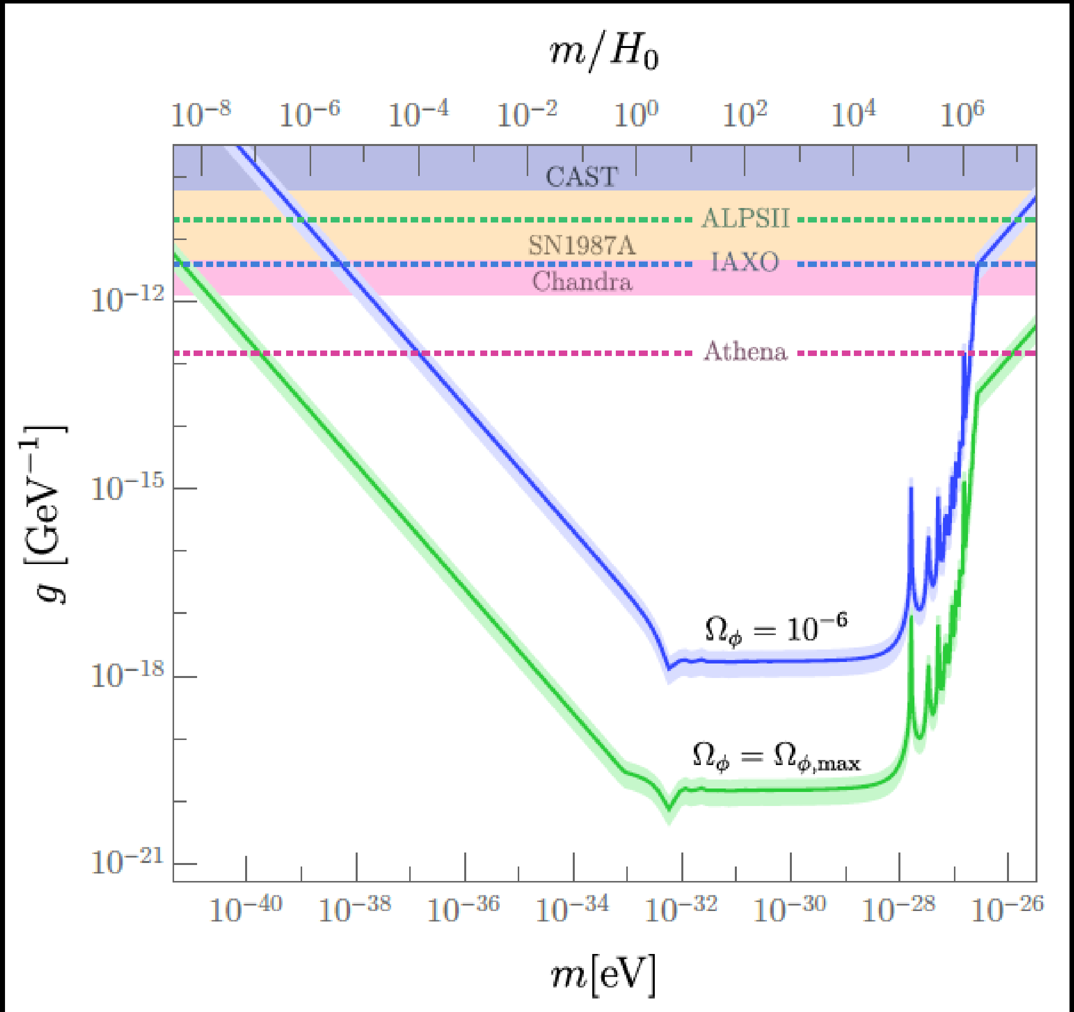


Cosmic birefringence tomography

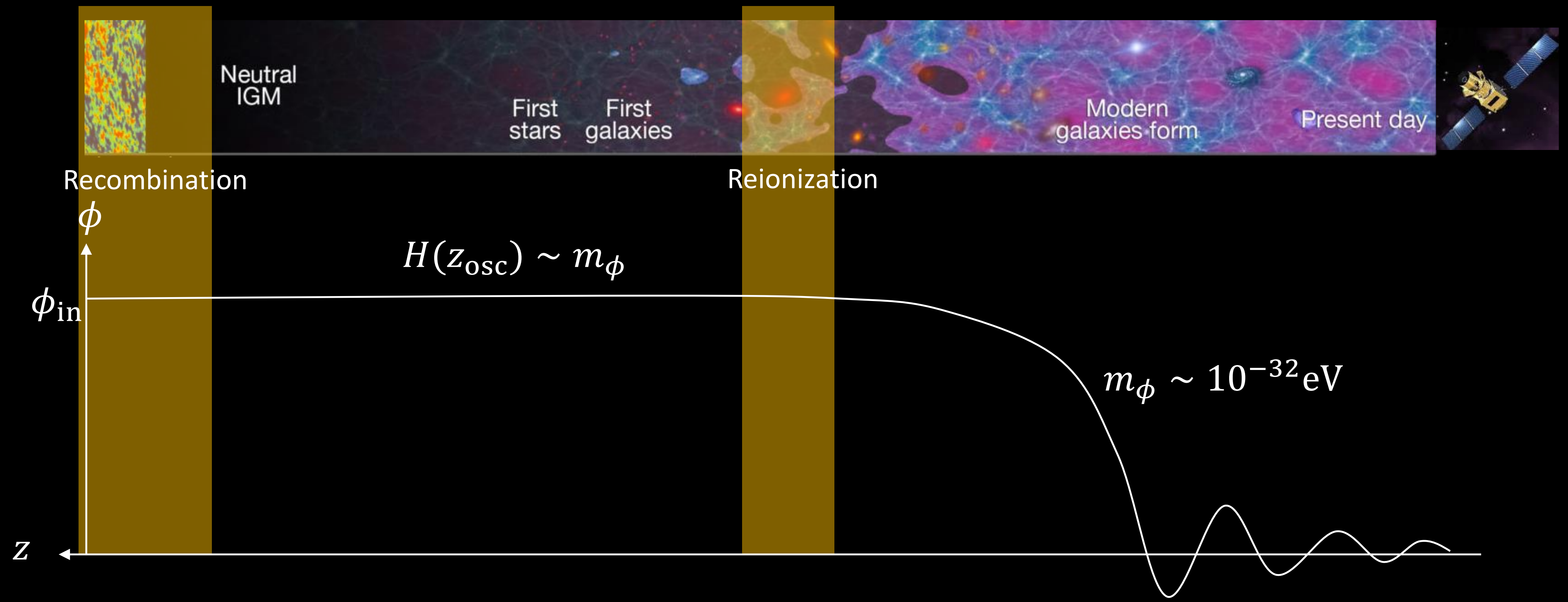
C_ℓ^{EB} has been assumed to have the simple form: $C_\ell^{EB} \simeq 2\beta C_\ell^{EE}$

However, shape of EB significantly depends on ALP mass: $C_\ell^{EB} \neq 2\beta C_\ell^{EE}$

We can probe tomographic information on ALPs

Rotation of CMB photons and dynamics of ϕ

Sherwin & TN (2023)



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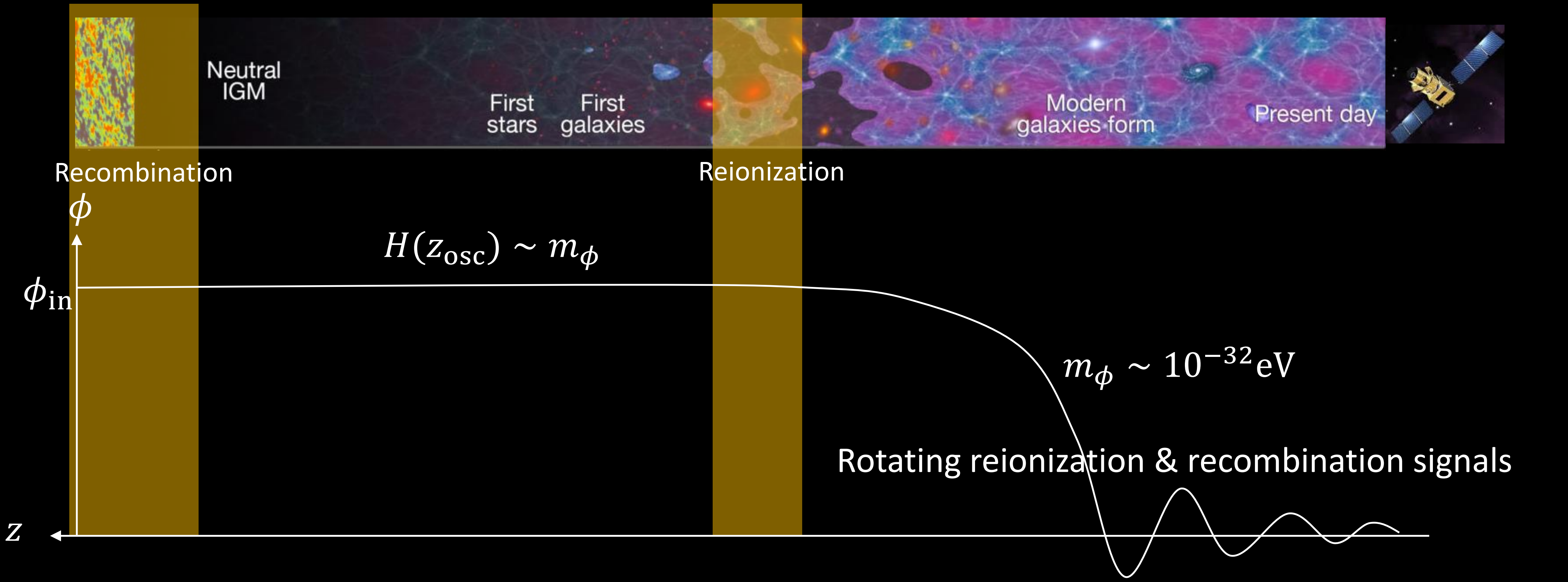

$\beta_{\rm rec} \simeq \frac{g}{2}\phi_{\rm in}$

$\beta_{\rm rei} \simeq \frac{g}{2}\phi_{\rm in}$

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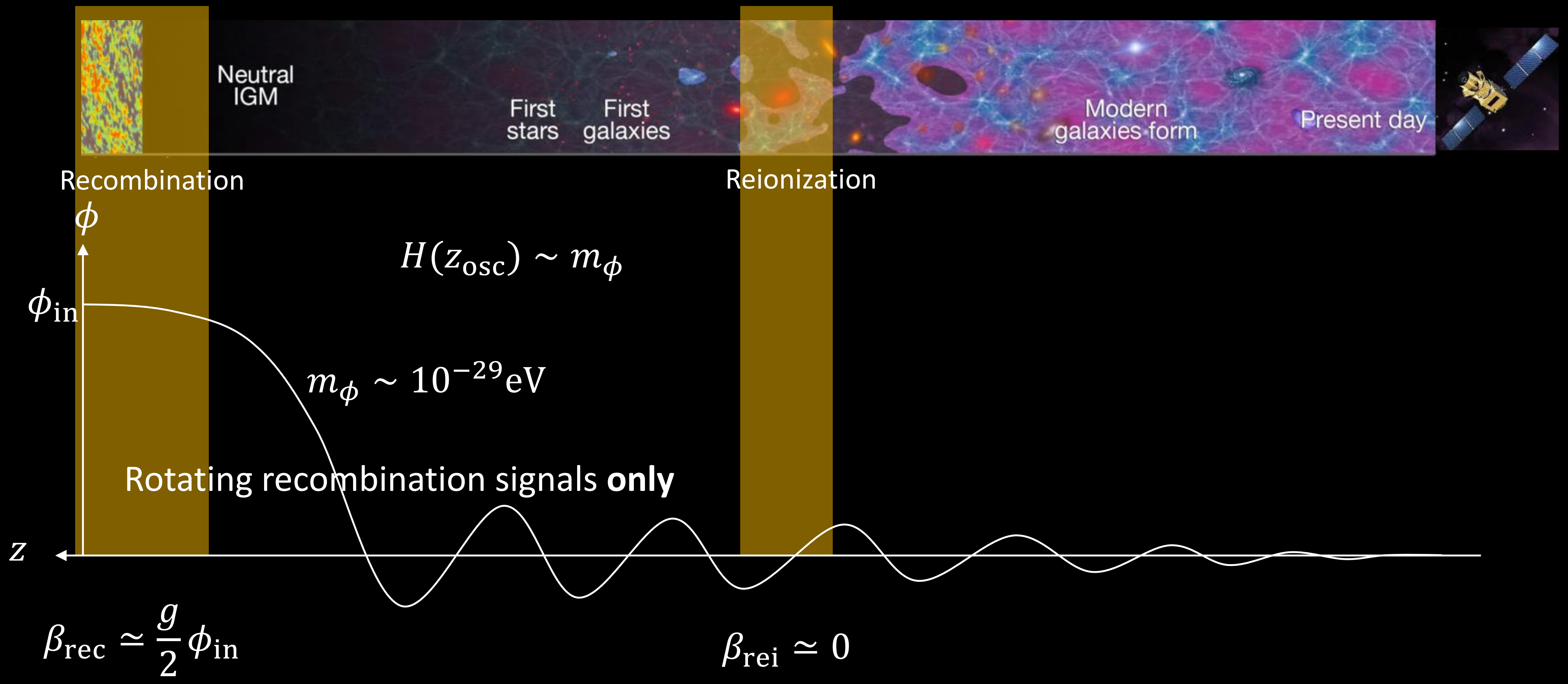

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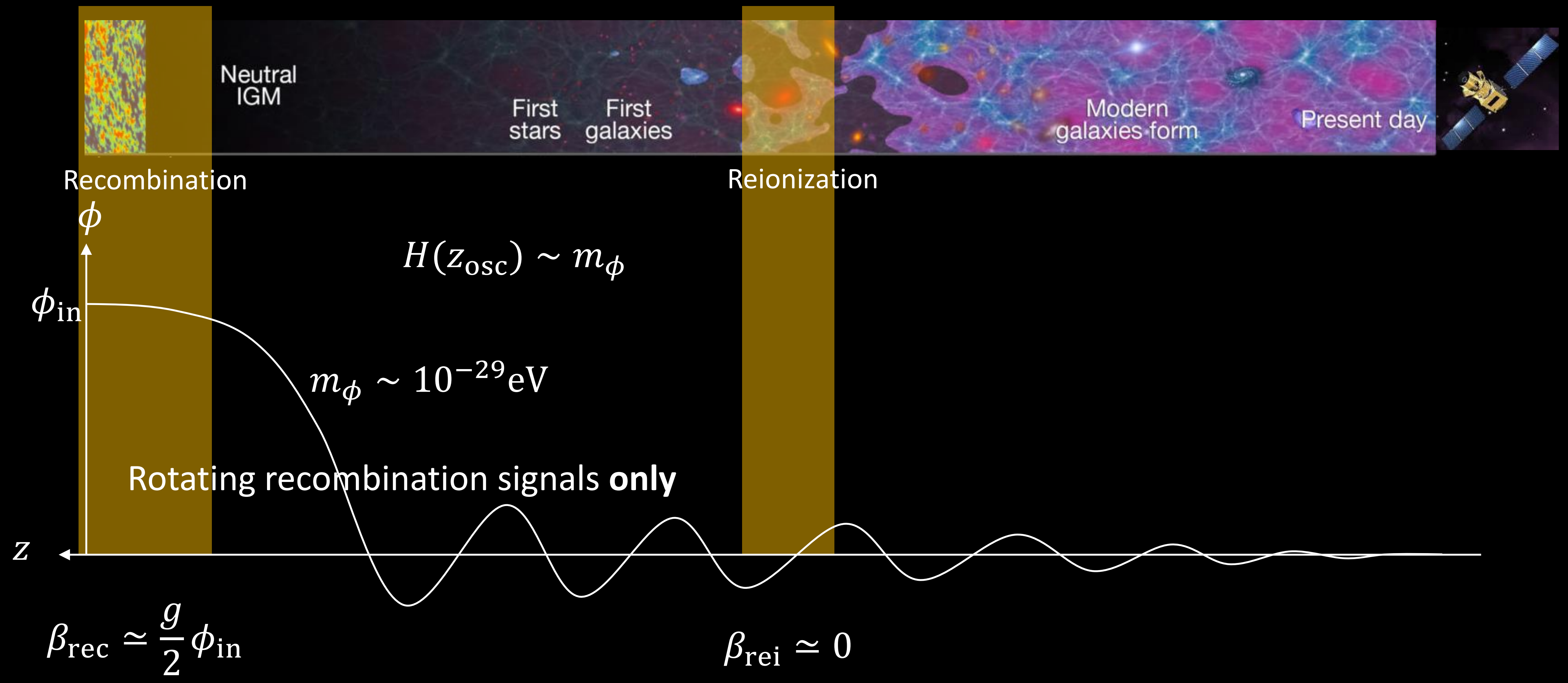
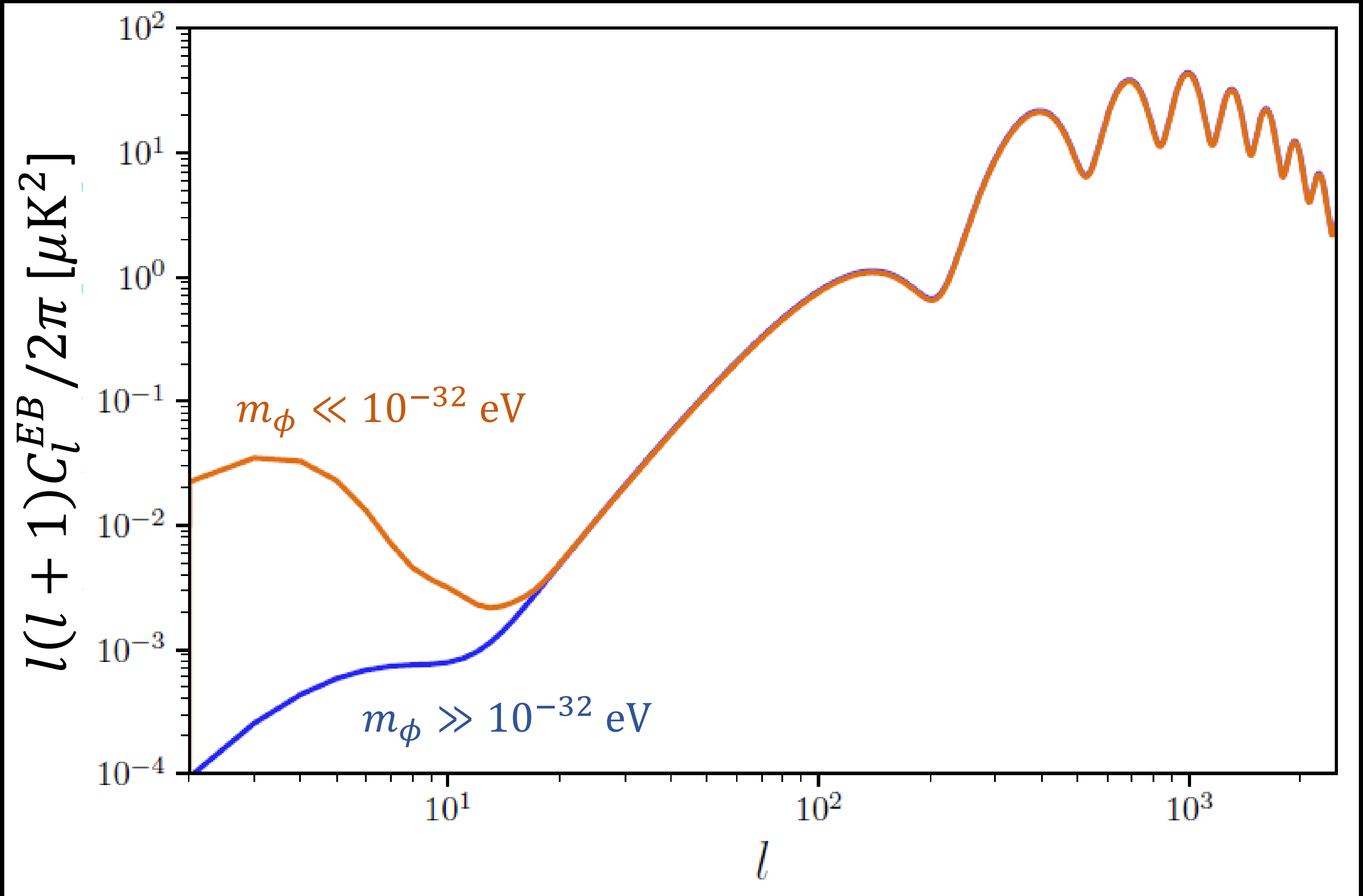


Polarization from reionization and recombination could be differently rotated depending on m_ϕ

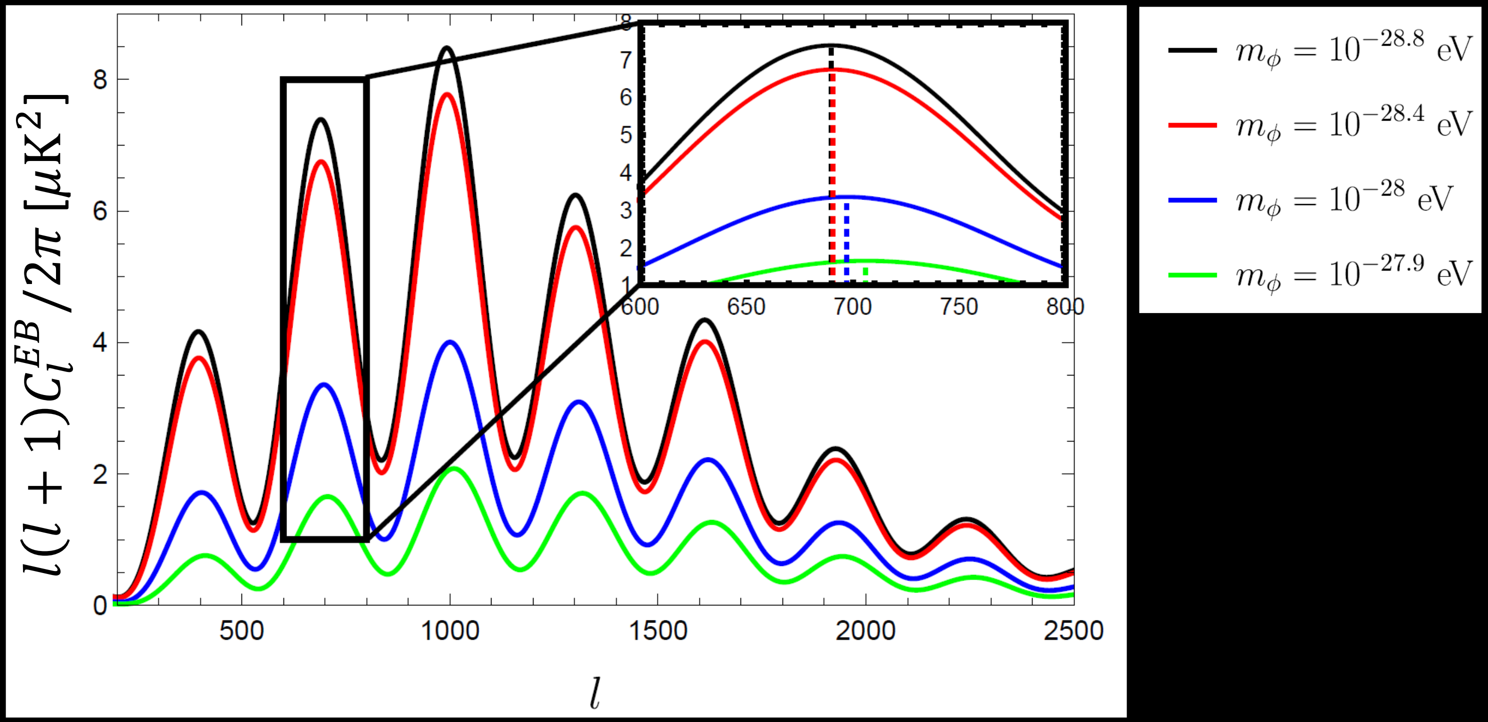
Mass dependence of C_ℓ^{EB} $m_\phi \ll 10^{-28}\mathrm{eV}$ Nakatsuka, ***TN***, Komatsu (2022)



Reionization bump depends on m_ϕ

Sherwin & TN (2023)

Mass dependence of C_ℓ^{EB} $\quad m_\phi \sim 10^{-28}\mathrm{eV}$



- Shifting scales of acoustic peaks
- Suppressing C_l^{EB} amplitude

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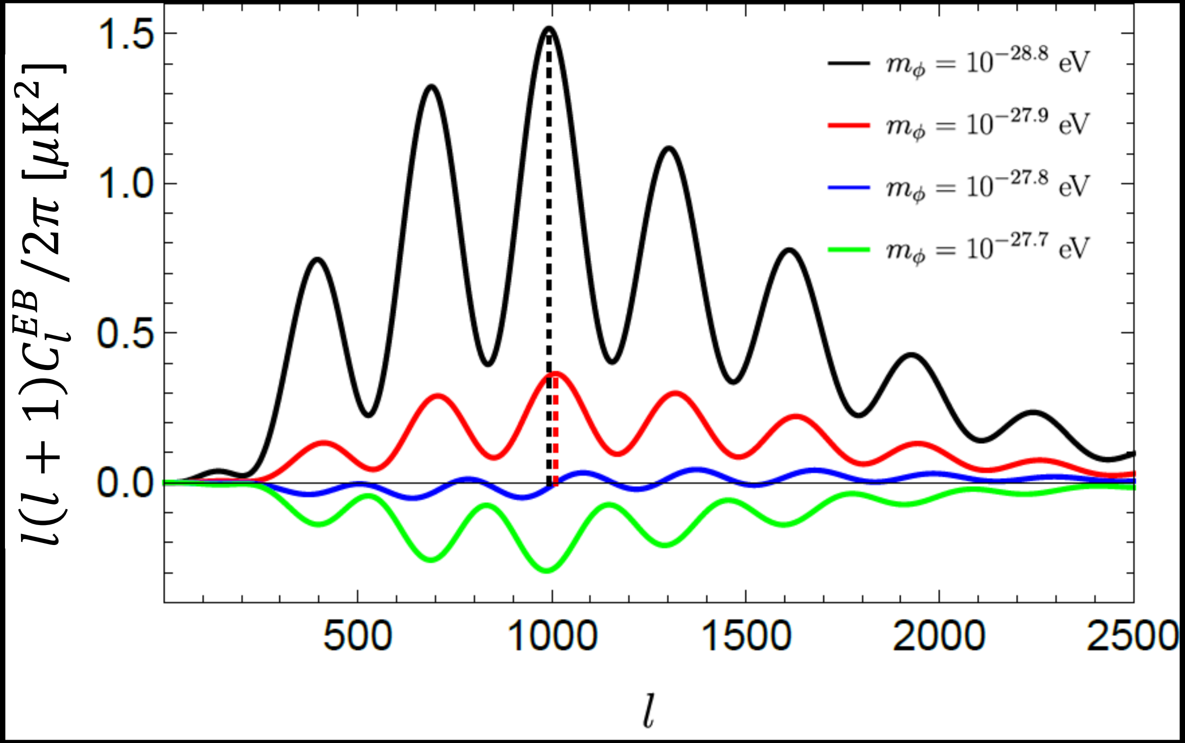
Nakatsuka, ***TN***, Komatsu (2022)



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

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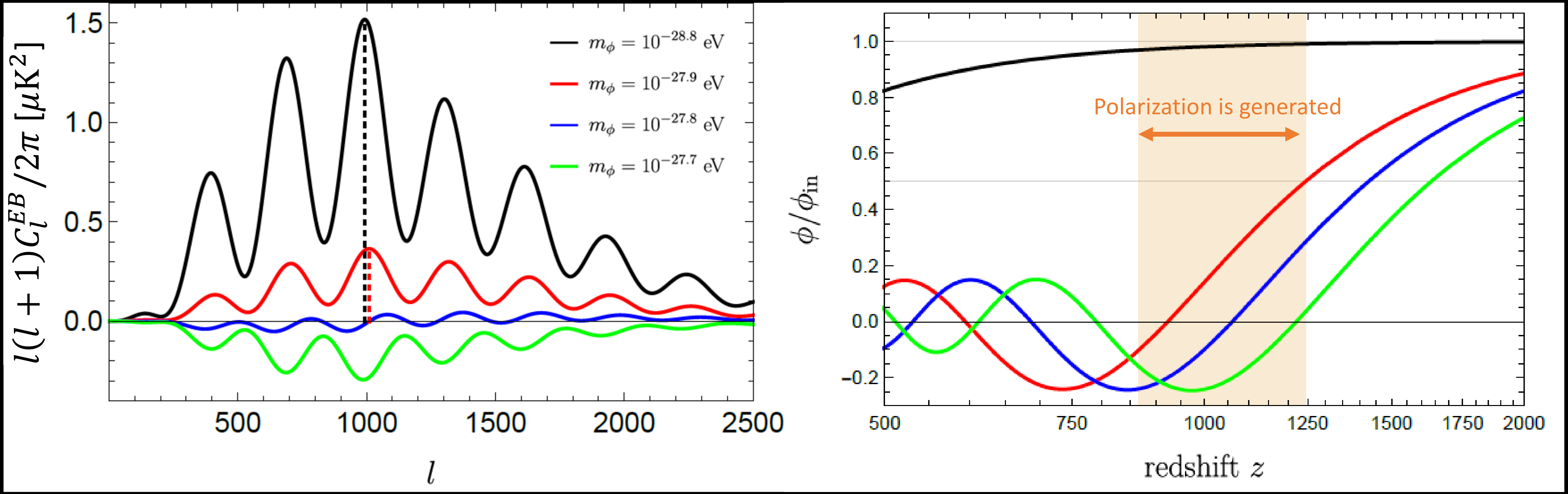

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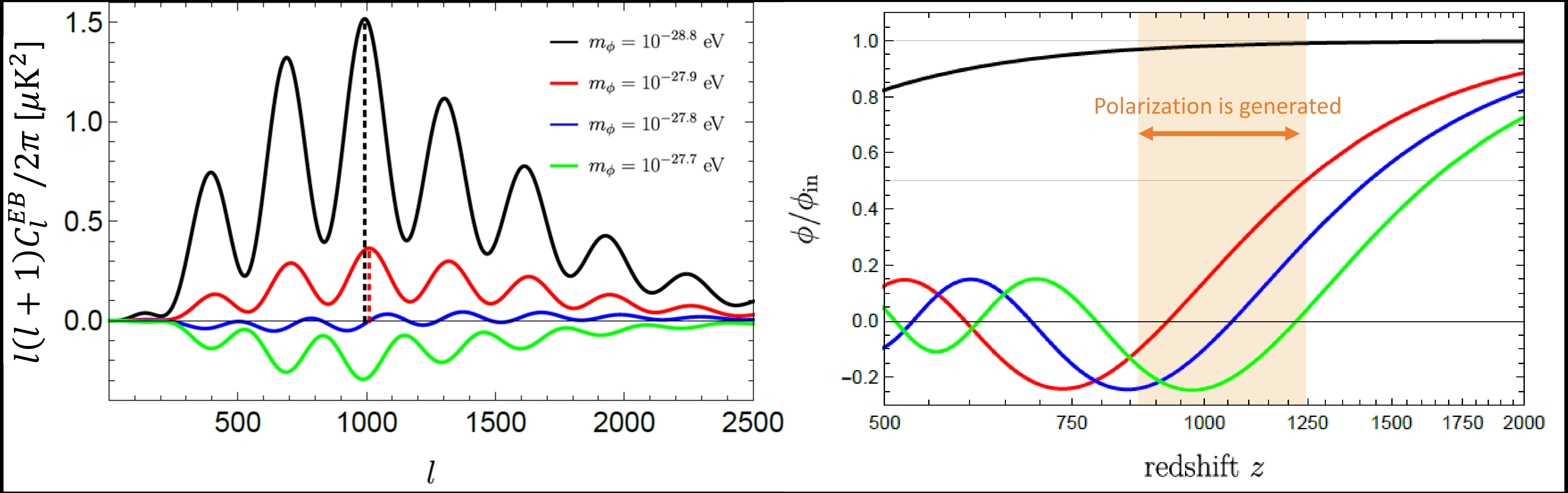

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- Sign of C_l^{EB} becomes negative as m_ϕ increases

Similar features appear for cosmic birefringence by early dark energy (Murai et al. 2022)

Implications for ALPs from C_ℓ^{EB}

- C_l^{EB} is sensitive to m_ϕ

How significantly can we constrain m_ϕ using ongoing and future experiments?

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How significantly can we constrain m_ϕ using ongoing and future experiments?

Using the full shape of C_l^{EB} breaks degeneracy between cosmic birefringence and miscalibration angle α

$$C_\ell^{EB} = \frac{\sin(4\alpha)}{2} C_\ell^{EE}$$

Ongoing and Future Large CMB Projects

POLARBEAR / SA

ACT

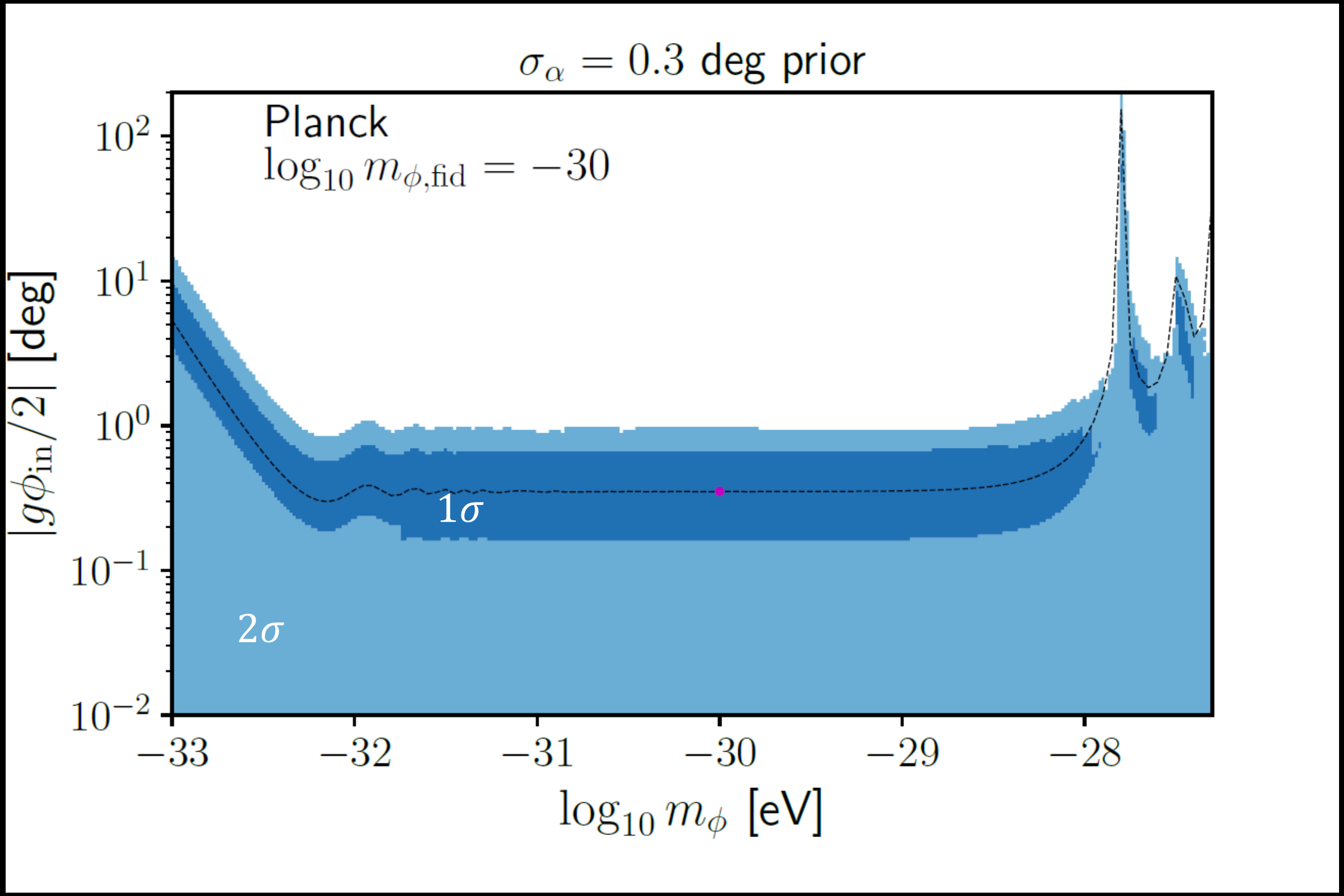
Simons Observatory (2023-)

(2030s ?)

LiteBIRD (will be launched in 2032)

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

Nakatsuka, ***TN***, Komatsu (2022)



$$\chi^2 = \sum_l \left| C_l^{EB,\mathrm{obs}} - \frac{g\phi_{\mathrm{in}}}{2} C_l^{EB}(m_\phi) - 2\alpha C_l^{EE} \right|^2 / \mathrm{Var}_l(C^{EB})$$

Use C_l^{EB} to simultaneously constrain m_ϕ ,amplitude and miscalibration angle (α)

Black dashed: approximate values of $|g\phi_{in}/2|$ for a given m_ϕ (to realize the Planck measurement: $\beta = 0.35$ deg)

Fiducial parameters are not ruled out by observations (Fujita, Murai, Nakatsuka & Tsujikawa 2021)

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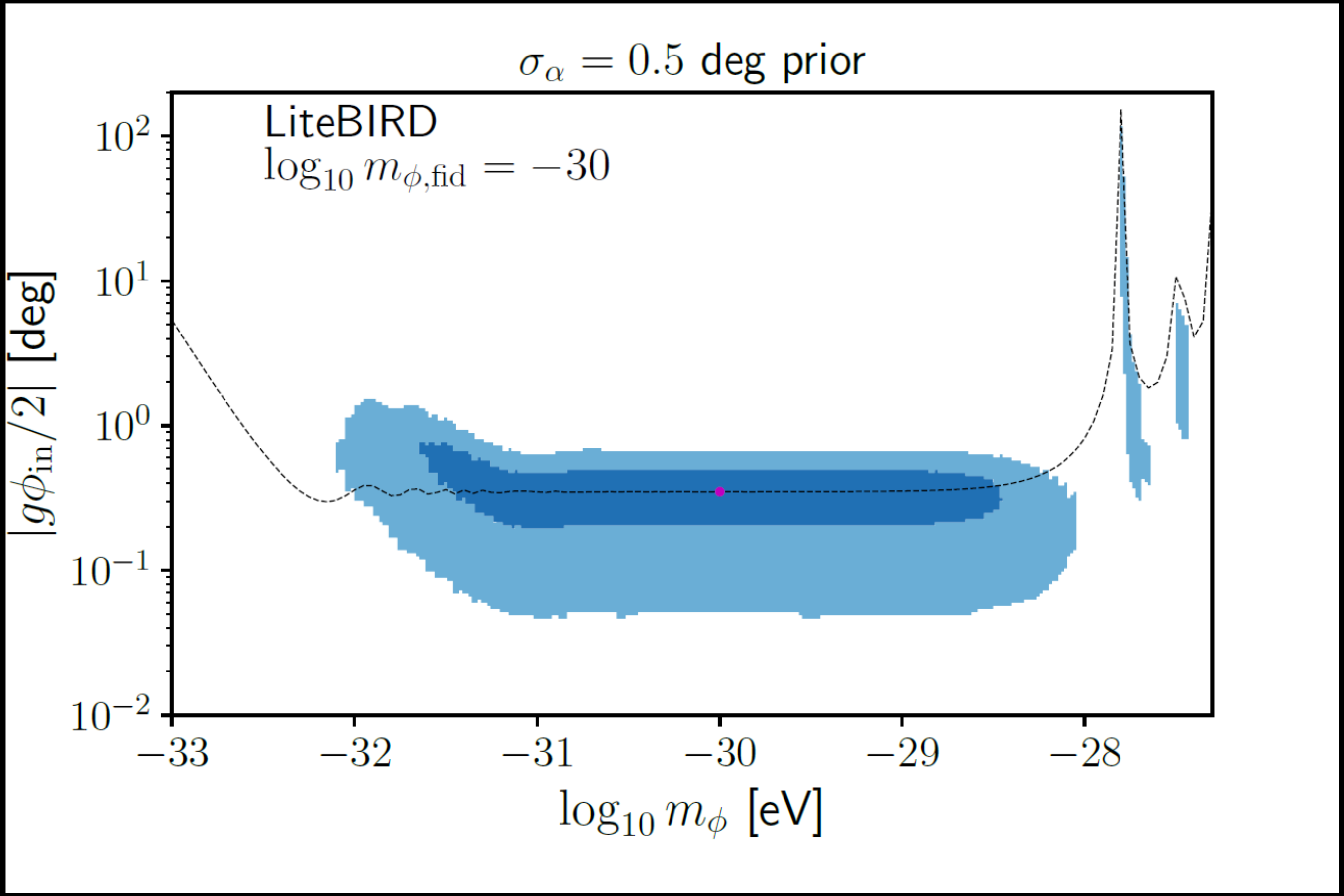

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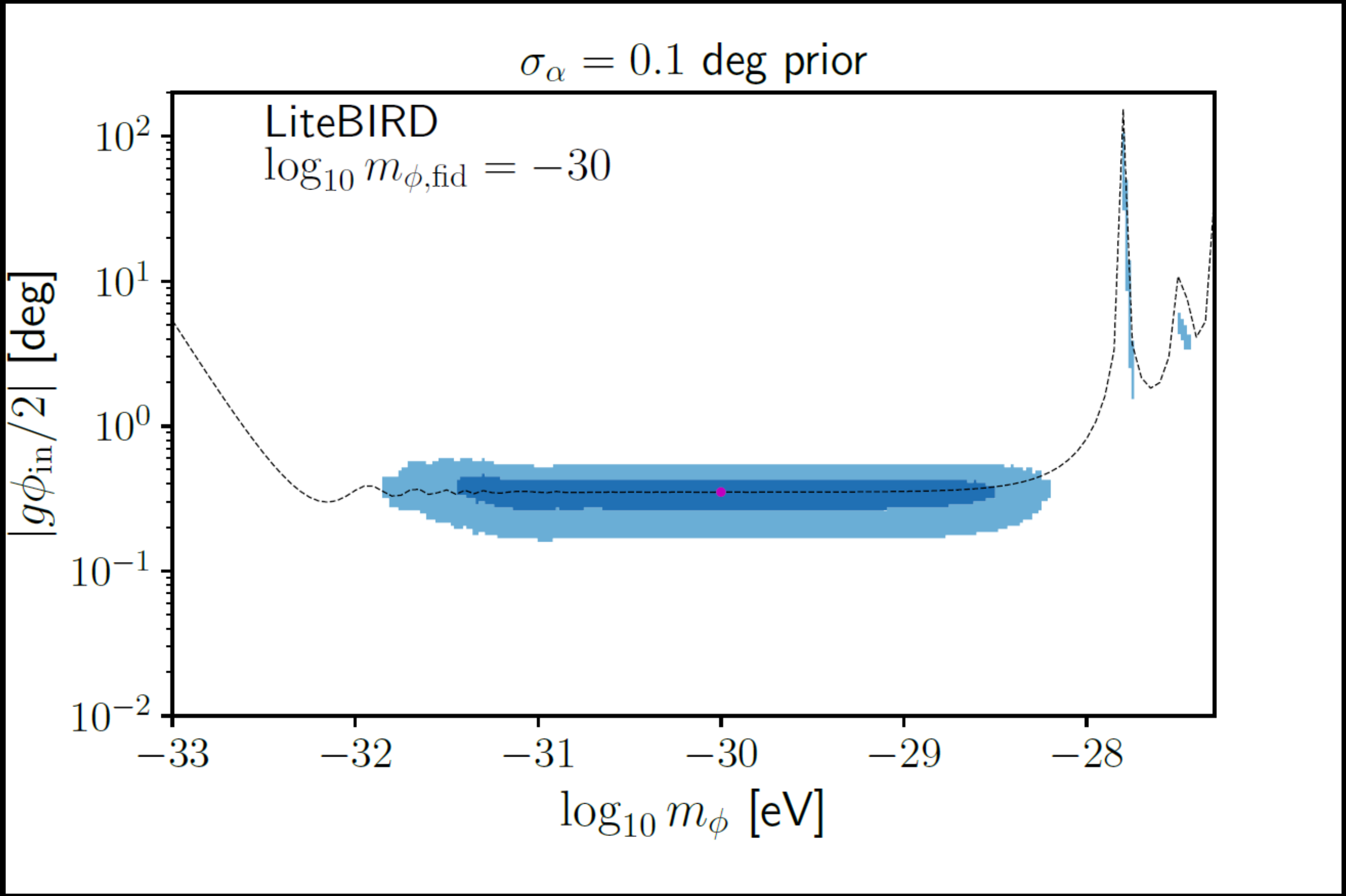

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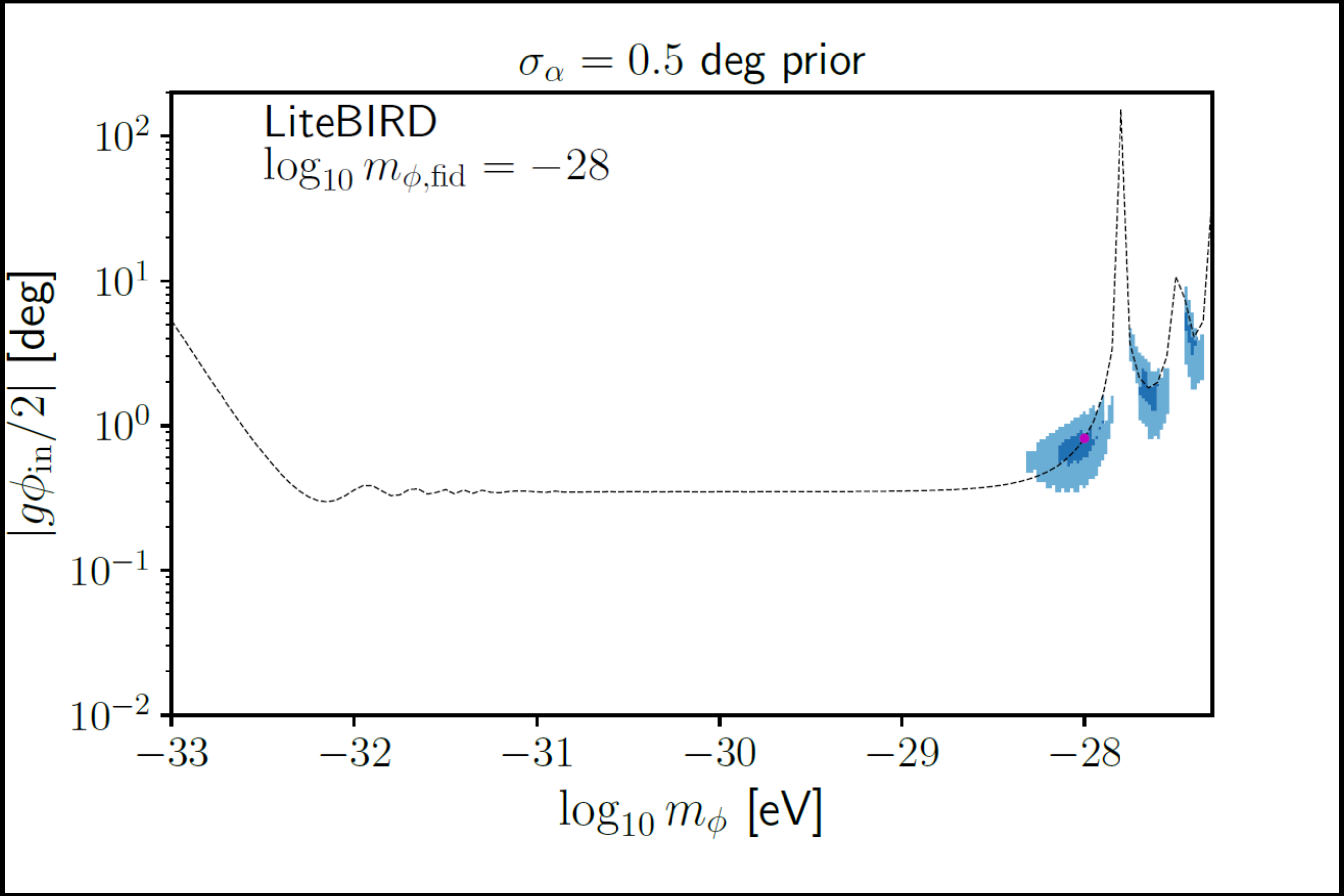

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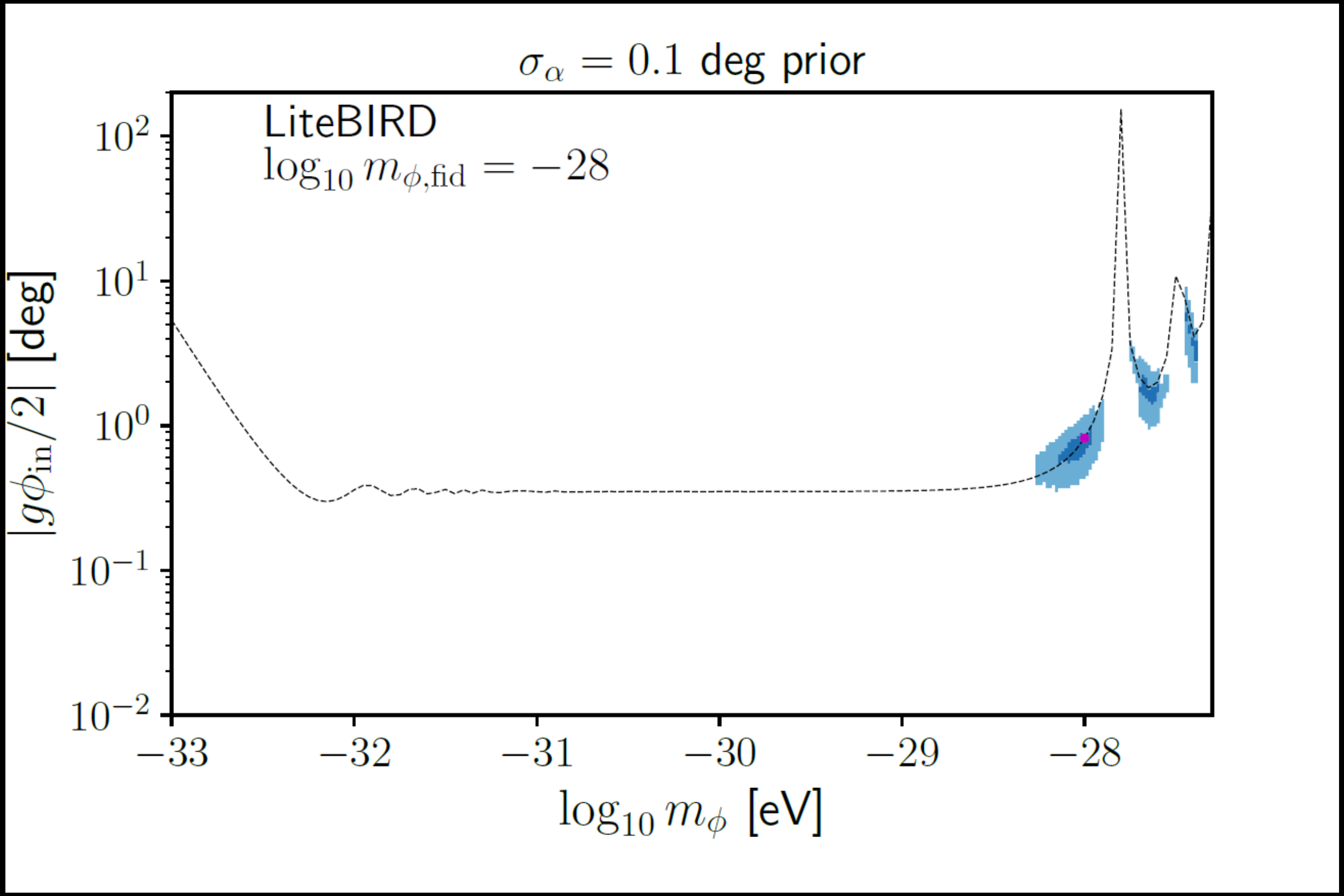


$$\chi^2 = \sum_l \left| C_l^{EB,\mathrm{obs}} - \frac{g\phi_{\mathrm{in}}}{2} C_l^{EB}(m_\phi) - \frac{\sin(4\alpha)}{2} C_l^{EE} \right|^2 / \mathrm{Var}_l(C^{EB})$$

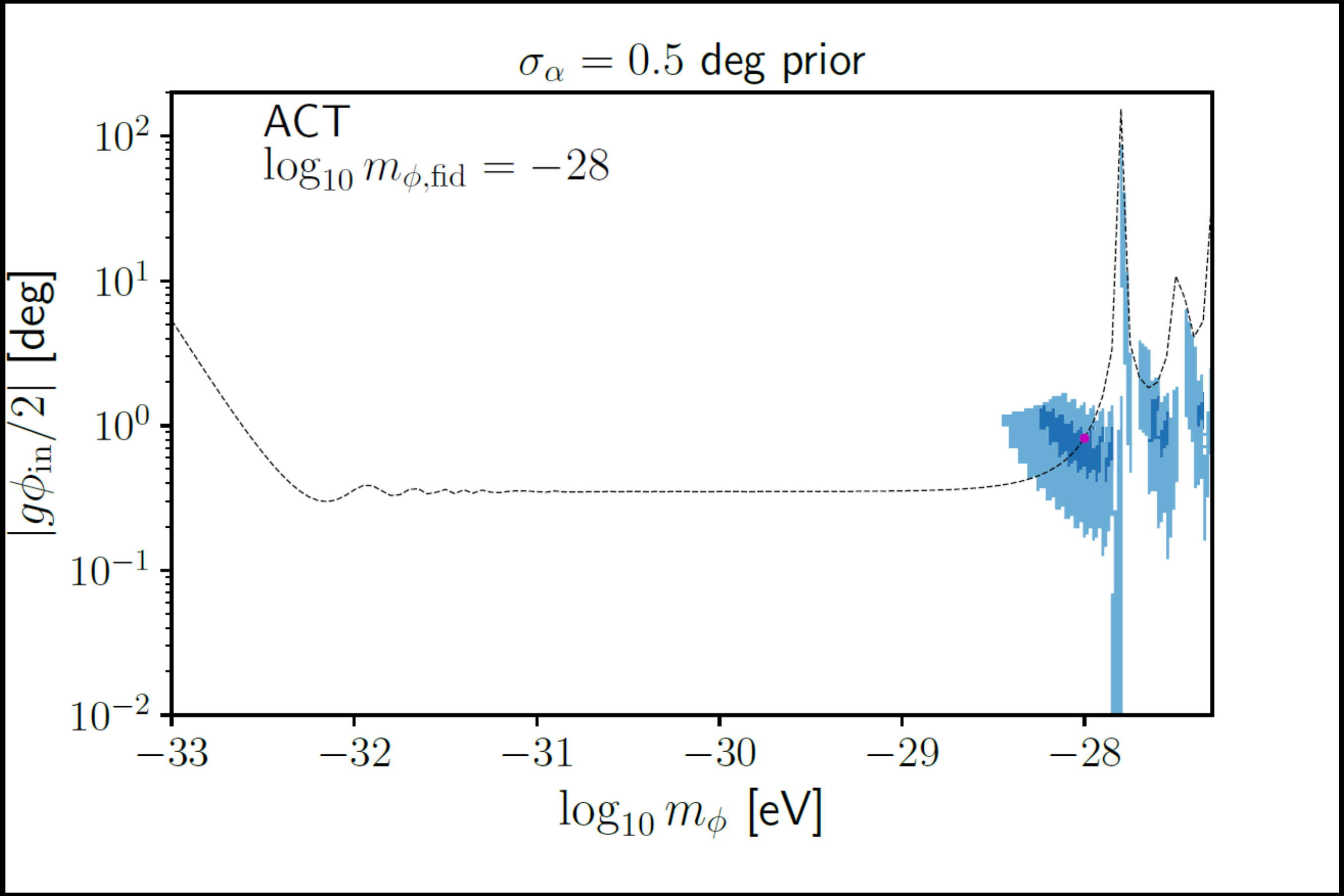
Use C_l^{EB} to simultaneously constrain m_ϕ ,amplitude and miscalibration angle (α)

Black dashed: approximate values of $|g\phi_{in}/2|$ for a given m_ϕ (to realize the Planck measurement: $\beta = 0.35$ deg)

Fiducial parameters are not ruled out by observations (Fujita, Murai, Nakatsuka & Tsujikawa 2021)

Ground-based experiments ($m_\phi = 10^{-28}$eV)

Nakatsuka, ***TN***, Komatsu (2022)



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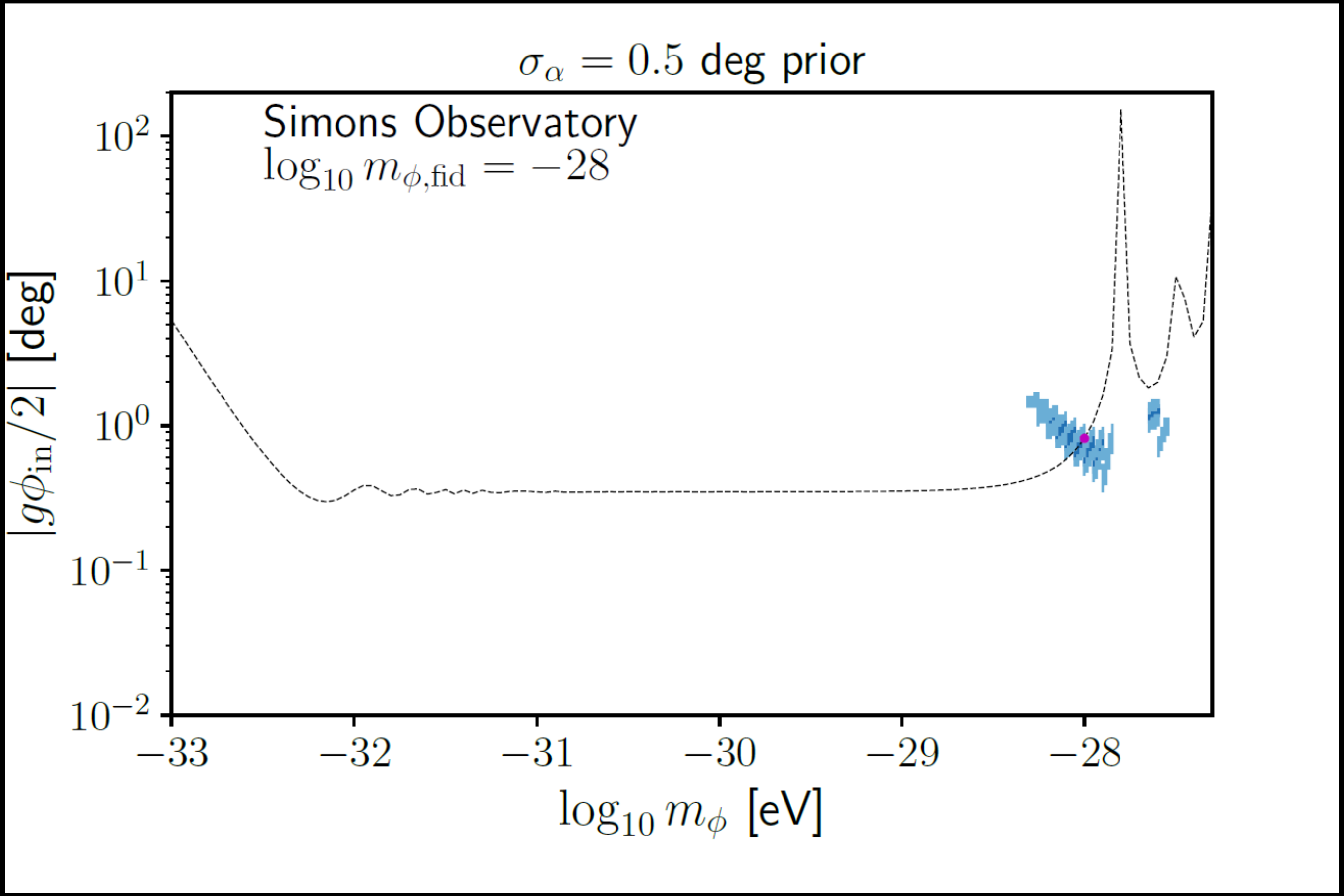

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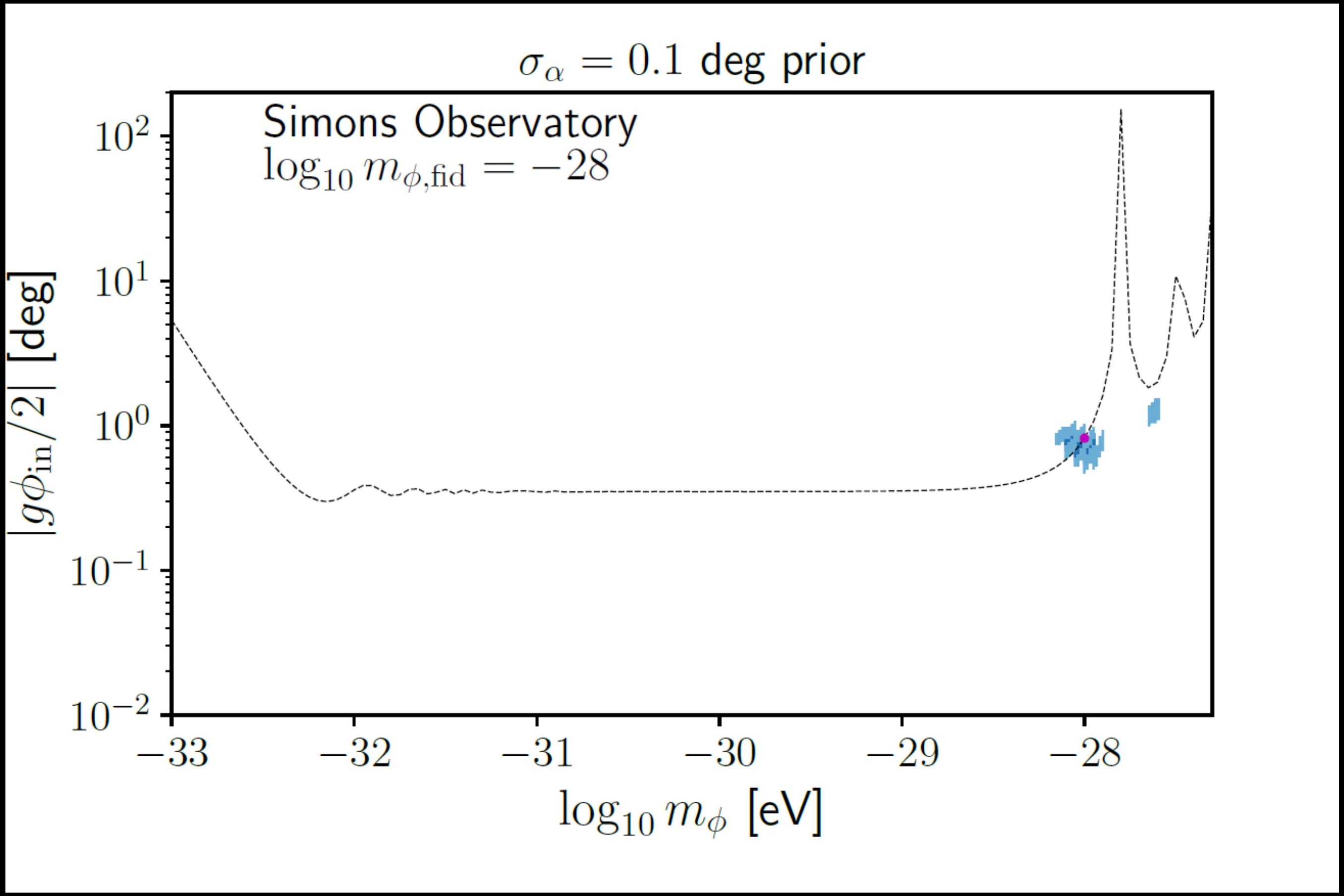

$$\chi^2 = \sum_l \left| C_l^{EB,\mathrm{obs}} - \frac{g\phi_{\rm in}}{2} C_l^{EB}(m_\phi) - \frac{\sin(4\alpha)}{2} C_l^{EE} \right|^2 / \mathrm{Var}_l(C^{EB})$$

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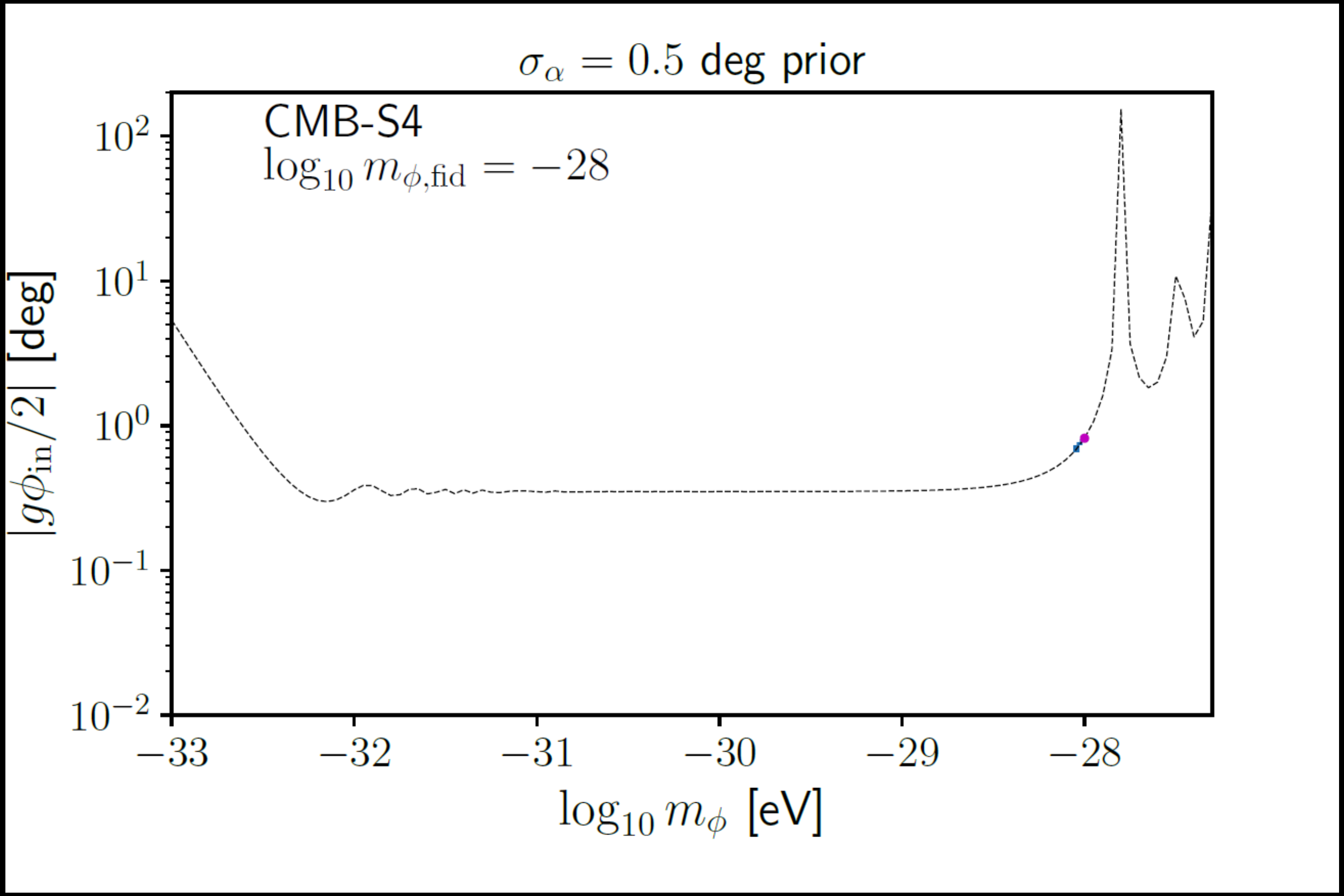

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Fiducial parameters are not ruled out by observations (Fujita, Murai, Nakatsuka & Tsujikawa 2021)

Gravitational lensing

Naokawa & TN (2023)

- So far, we have ignored lensing effect on EB

- However, small-scale CMB fluctuations are significantly affected by gravitational lensing

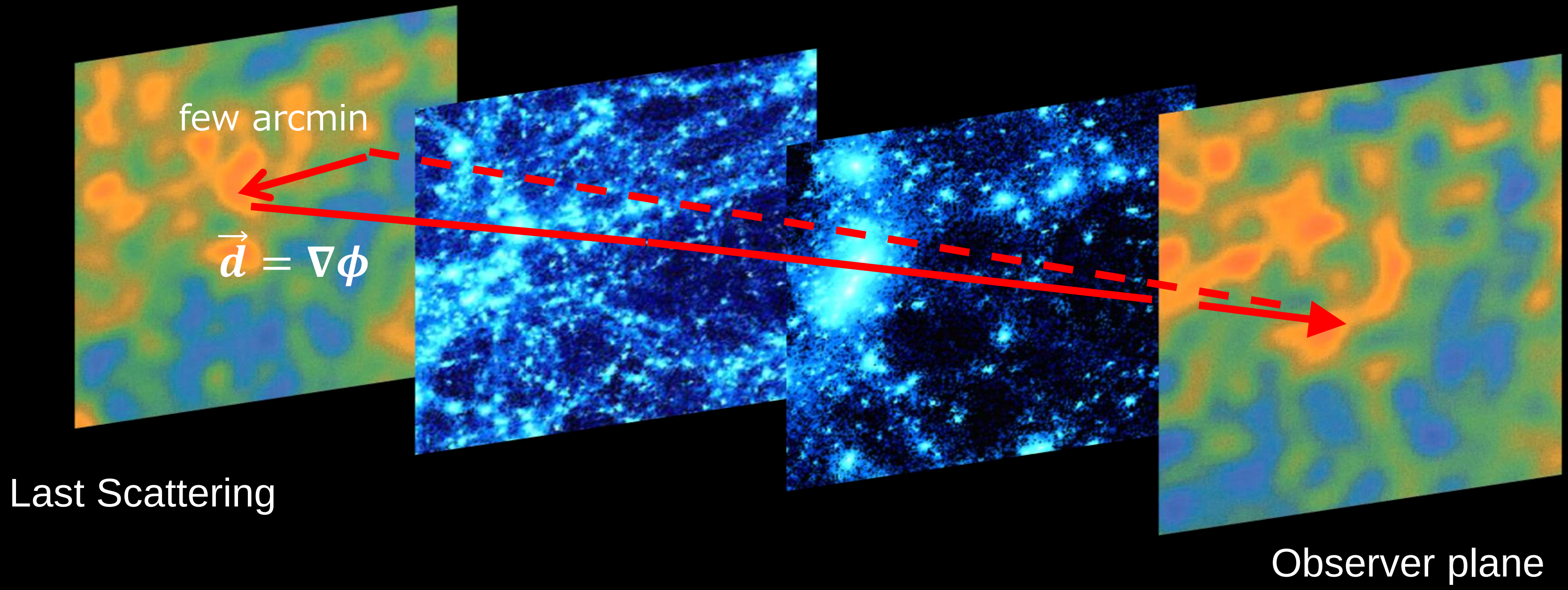
  Errors on power spectra from future CMB experiments << Lensing modification

  @ high ell

Gravitational lensing

Naokawa & TN (2023)

- Path of CMB photons are deflected by the gravitational potential of the large-scale structure



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

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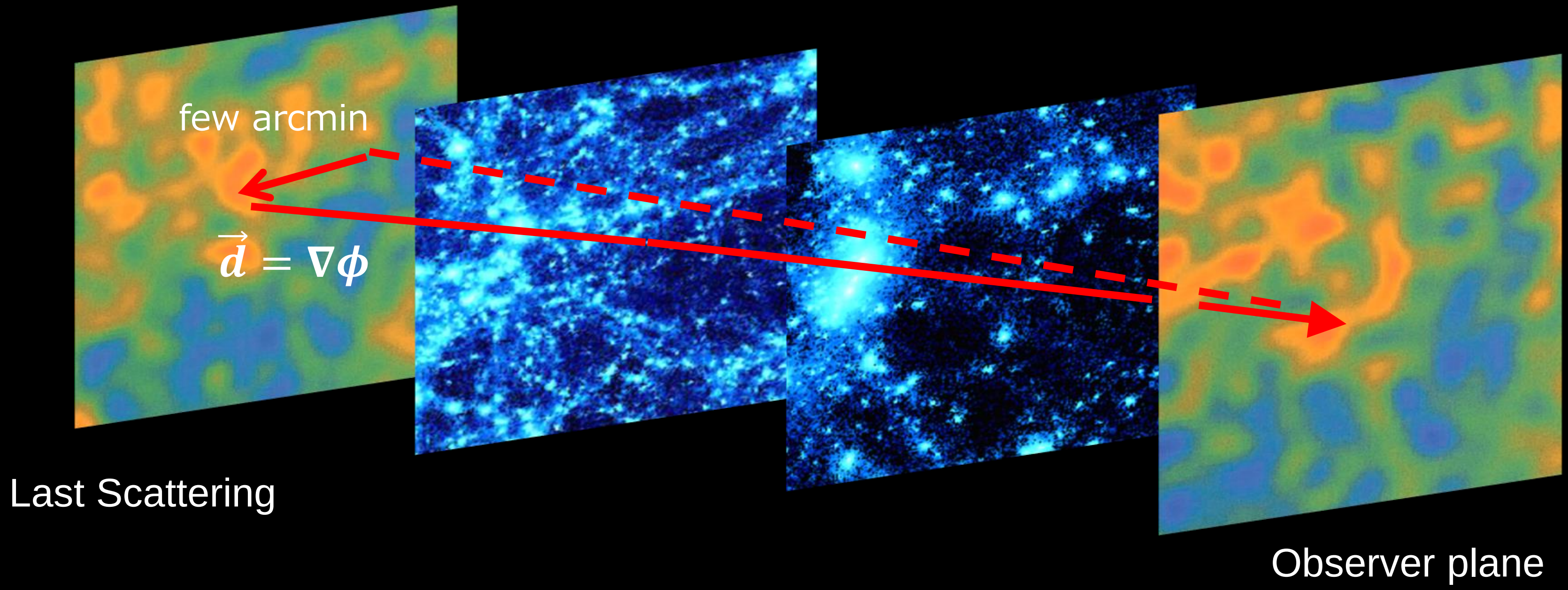


$$P'(n) = P(n + \nabla\phi) \qquad (P = Q \pm iU)$$

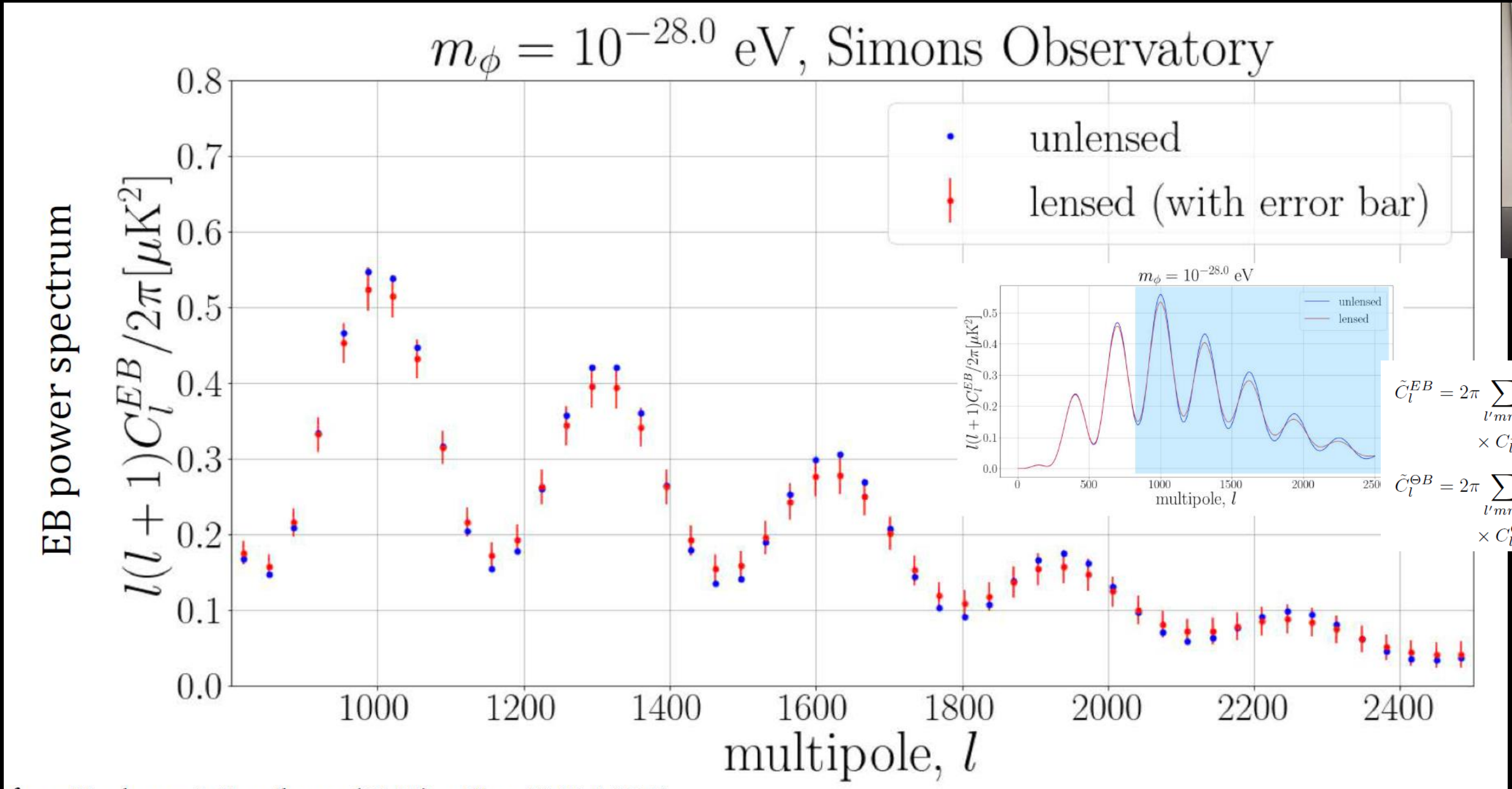
- Birefringence rotates the polarization plane along the trajectory

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

We derive the lensing correction to C_ℓ^{EB} by extending formula of Challinor & Lewis 2005 and implement it to CLASS

Lensing effect on EB power spectrum

Naokawa & TN (2023)



from Naokawa & Namikawa (2023) arXiv : 2305.13976

$$\tilde{C}_l^{EB} = 2\pi \sum_{l'mm'} \int_{-1}^{1} \mathrm{d}(\cos\gamma)\; d^{l'}_{mm'}(\gamma) \times C^{EB}_{l'} A^{-}_{l'}(\gamma) d^{l}_{2,-2}(\gamma)\,,$$

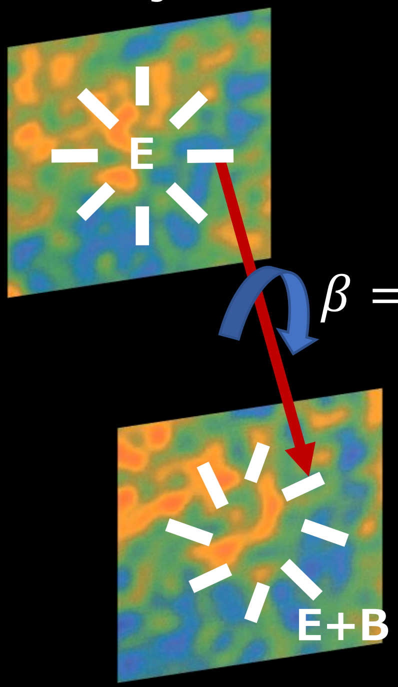
$$\tilde{C}_l^{\Theta B} = 2\pi \sum_{l'mm'} \int_{-1}^{1} \mathrm{d}(\cos\gamma)\; d^{l'}_{mm'}(\gamma) \times C^{\Theta B}_{l'} A^{X}_{l'}(\gamma) d^{l}_{20}(\gamma)\,.$$

We cannot fit observational data without lensing effect on C_ℓ^{EB}

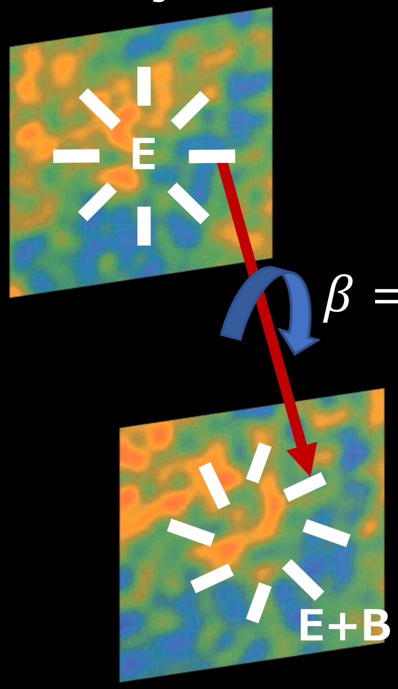
Ambiguity of phase of measured rotation angle

Naokawa et al. (in prep.)

- Observed rotation angle has ambiguity of phase of angle



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



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

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Naokawa et al. (in prep.)

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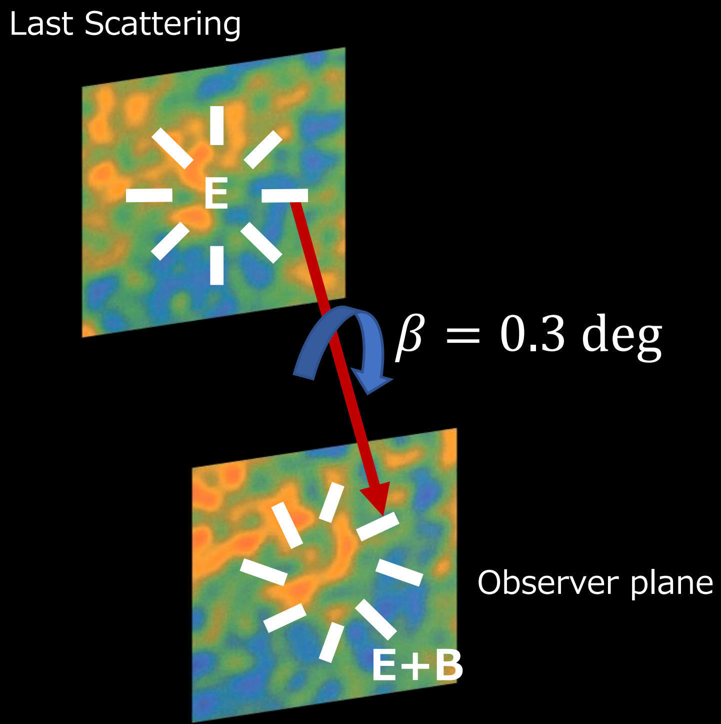

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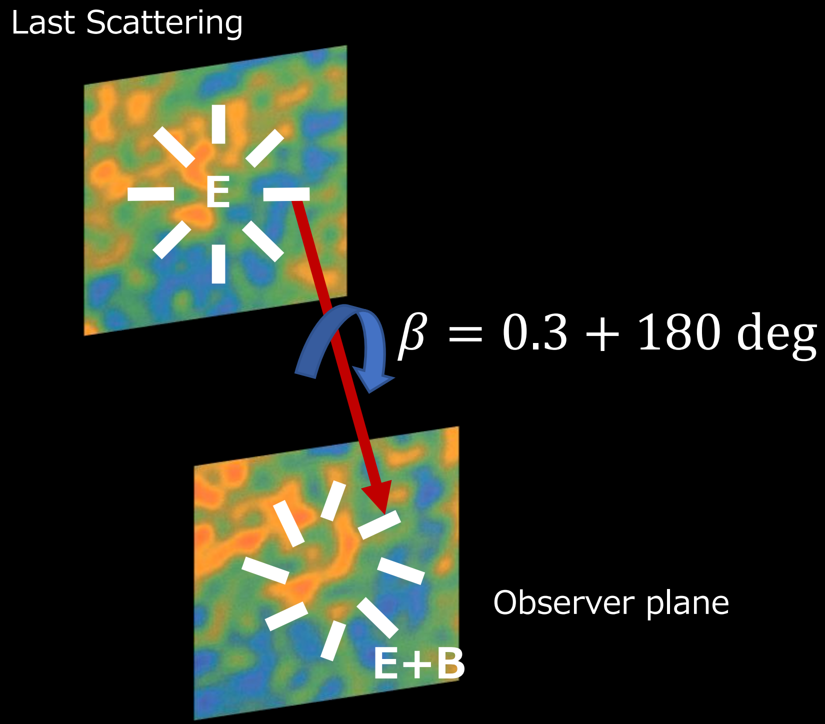

$$B^{\mathrm{obs}} = \sin(2 \times (180 + 0.3))\, E^{\mathrm{CMB}}$$

CMB birefringence analysis could not distinguish $\beta = 0.3 + m_{\circlearrowright} \times 180$ deg ($|m_{\circlearrowright}| = 0,1, \ldots$)

Ambiguity of phase of measured rotation angle

Naokawa et al. (in prep.)

- Possible constraints on $m_{\circlearrowright}$

We assume ALPs with mass m_ϕ

$\beta \propto g\Delta\phi \sim g\phi_{\rm ini}$ Large $m_{\circlearrowright}$ = Large β = Large $g\phi_{\rm ini}$

- Constraint on $g\phi_{\rm ini}$ from Fujita, Murai, Nakatsuka, Tsujikawa (2021)

$\beta < 10^6$ deg $(m_{\circlearrowright} < 10^4)$ at $10^{-32}\ {\rm eV} < m_\phi < 10^{-28}\ {\rm eV}$

- Constraint from anisotropic cosmic birefringence

$C_L^{\alpha\alpha} \propto (g\phi_{\rm ini})^2$ discuss this constraint later

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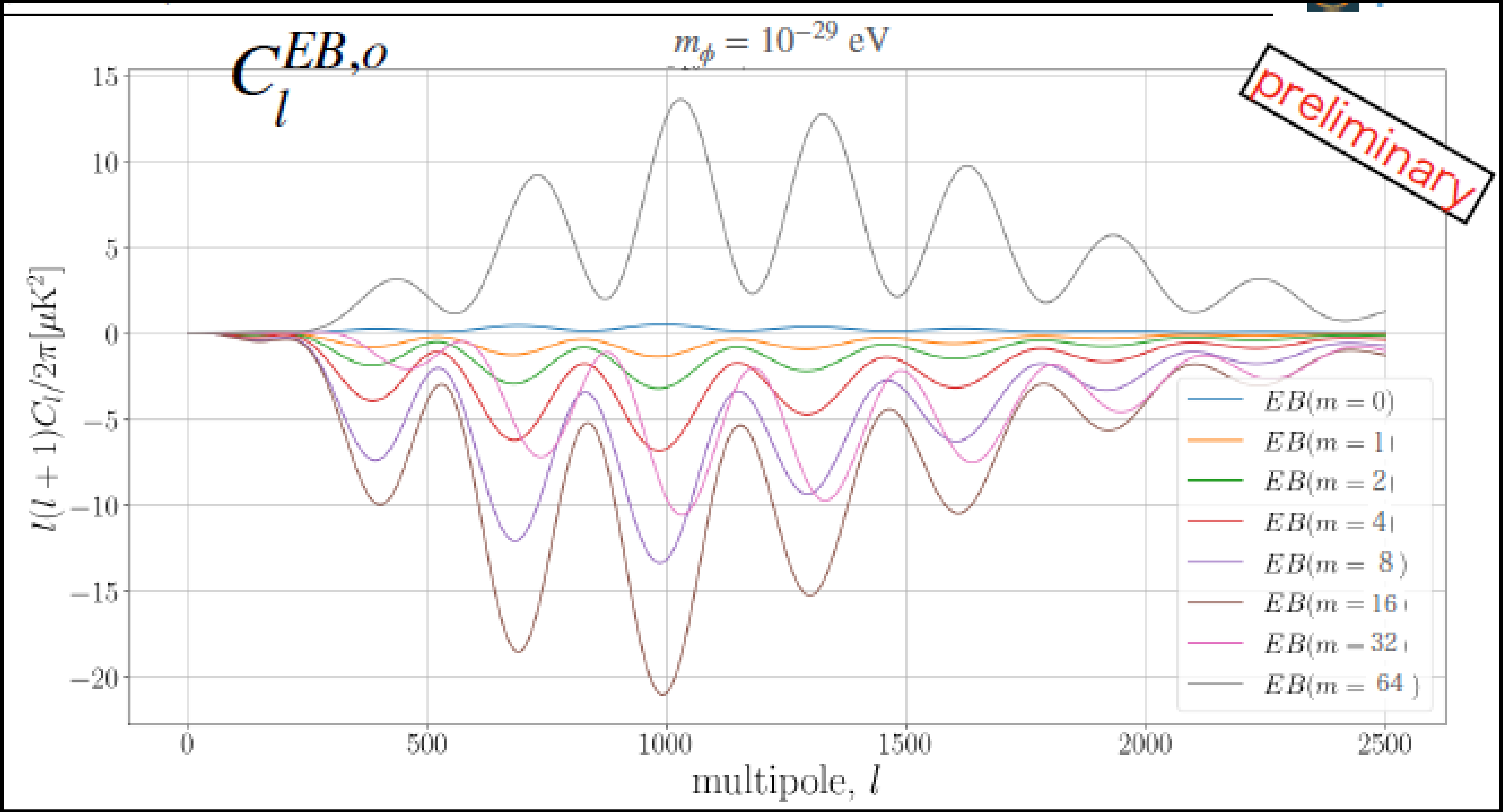
  $C_L^{\alpha\alpha} \propto (g\phi_{\mathrm{ini}})^2$ discuss this constraint later

Nonzero values of $m_{\circlearrowright}$ significantly change C_ℓ^{EB} (next slides)

Ambiguity of phase of measured rotation angle

Naokawa et al. (in prep.)



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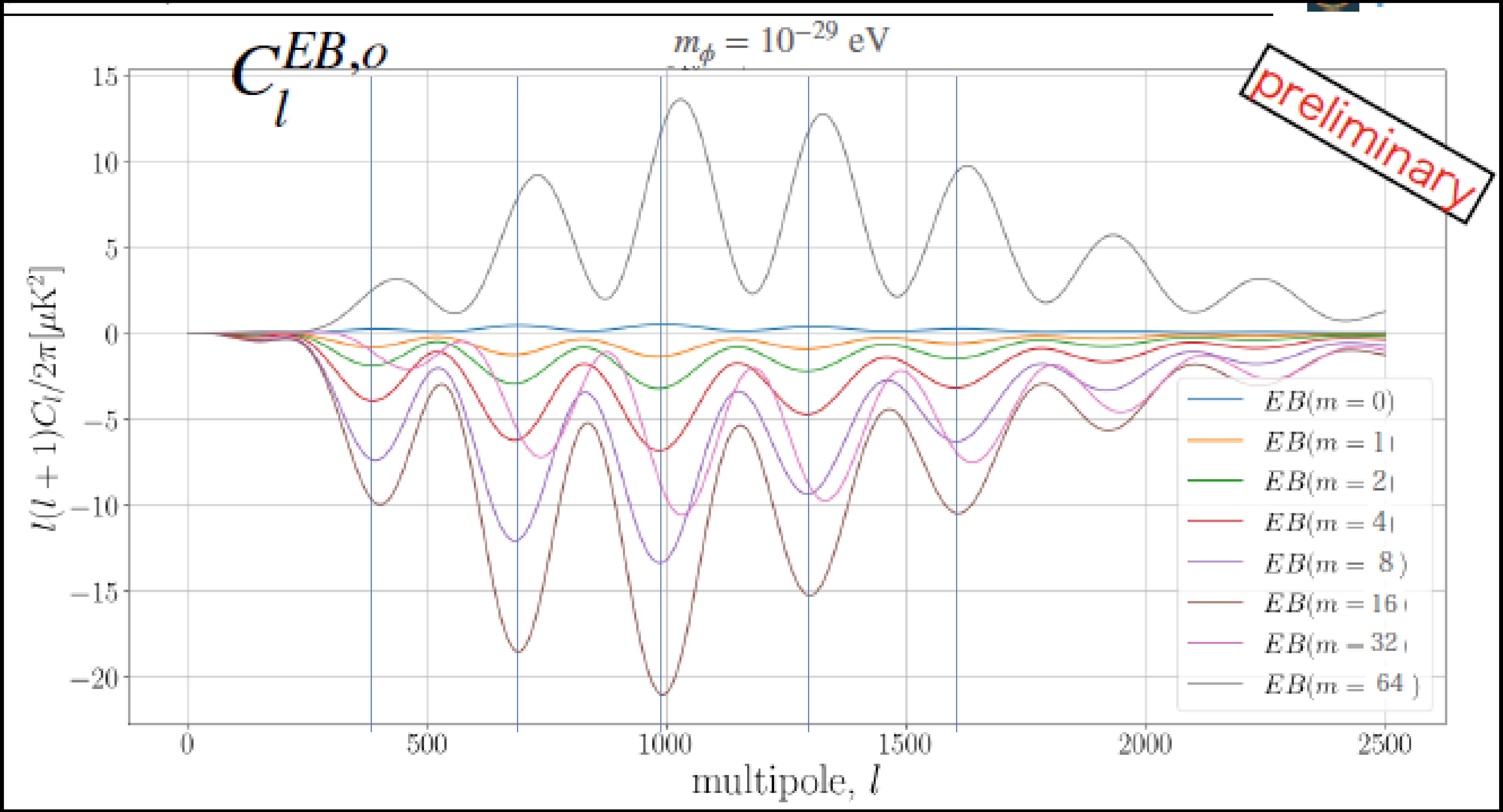
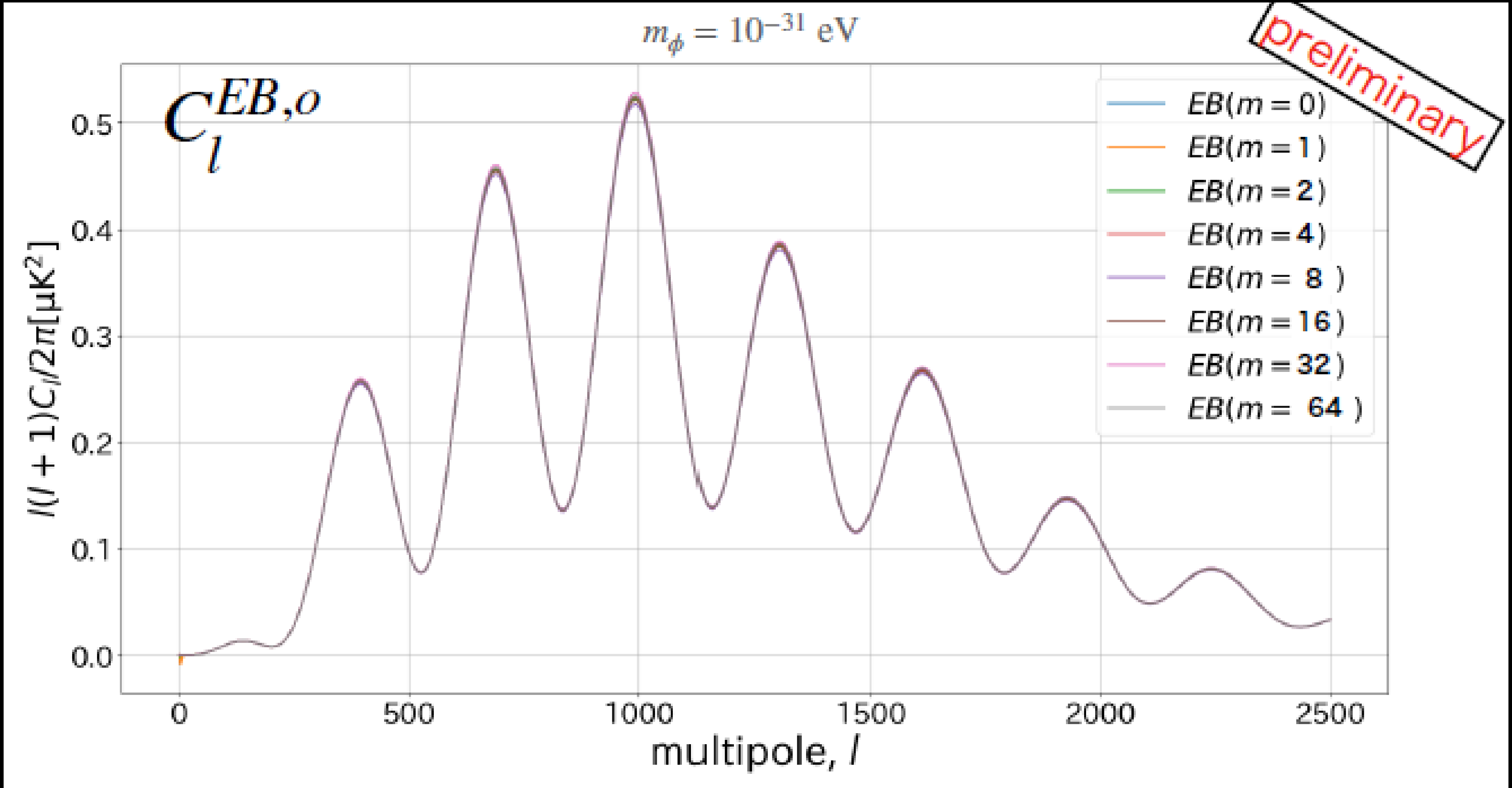


If β becomes large, the peaks are shifted significantly which can be detectable from future experiments

Ambiguity of phase of measured rotation angle

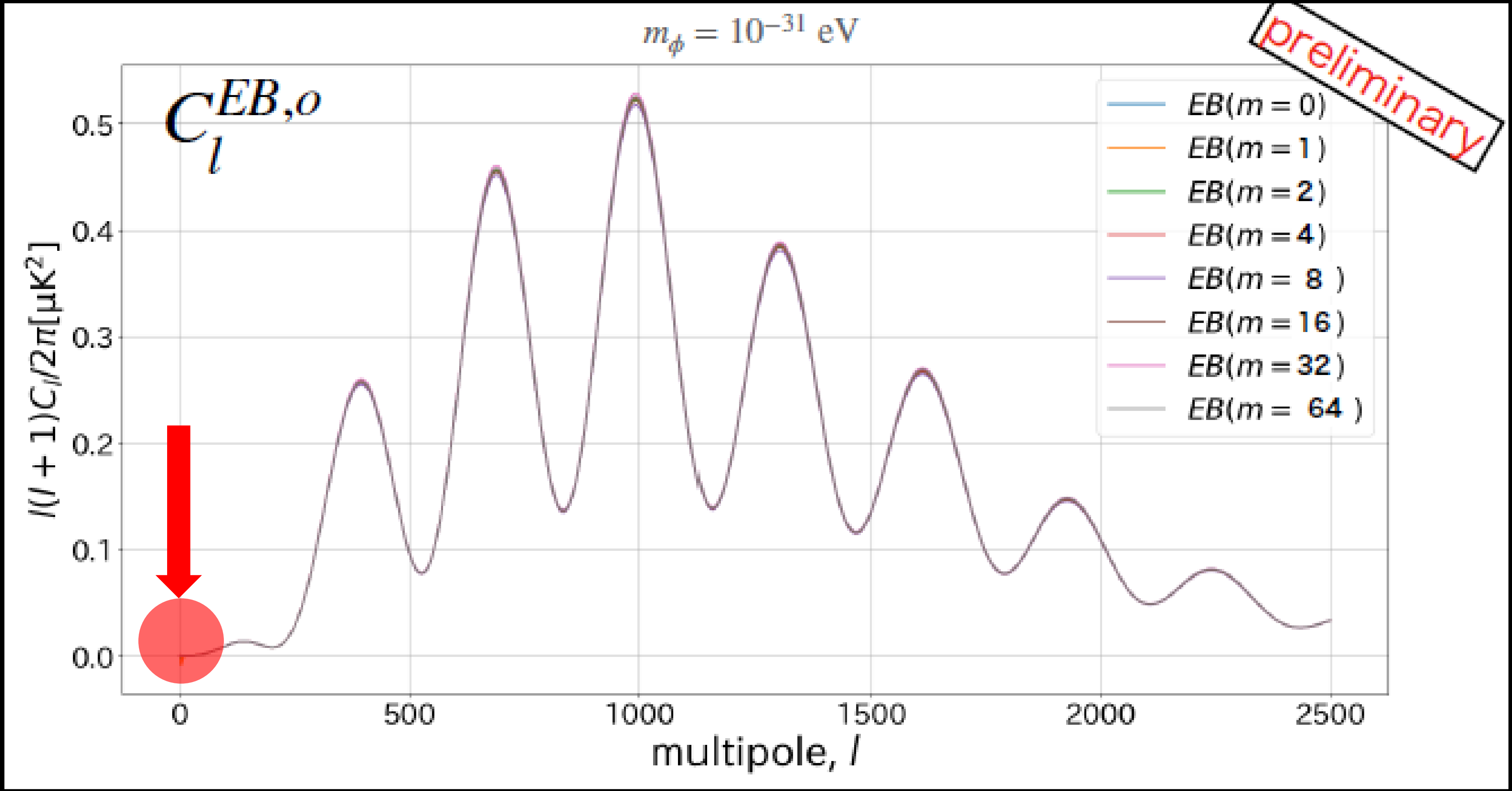
Naokawa et al. (in prep.)



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

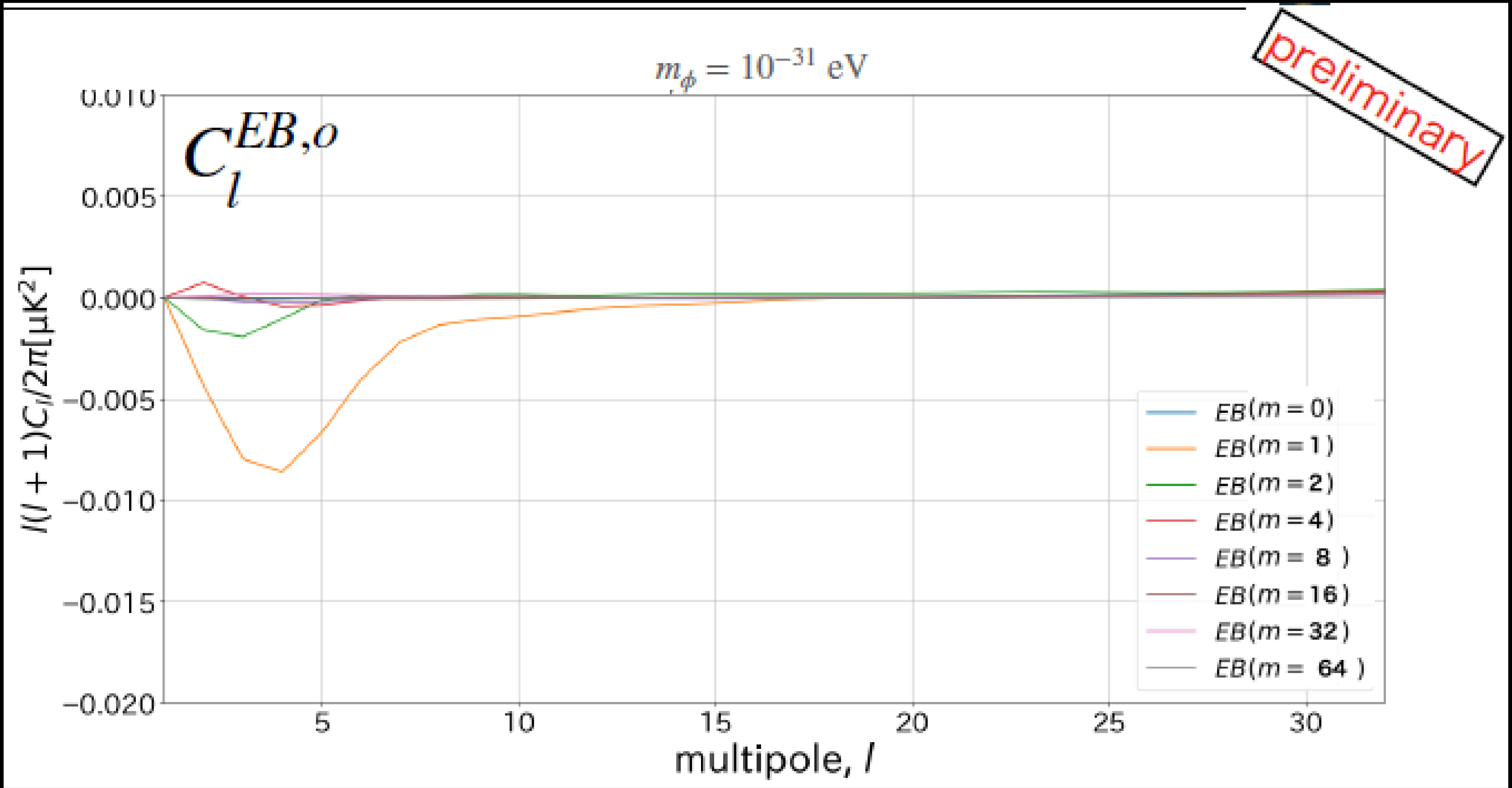
Ambiguity of phase of measured rotation angle

Naokawa et al. (in prep.)



Ambiguity of phase of measured rotation angle

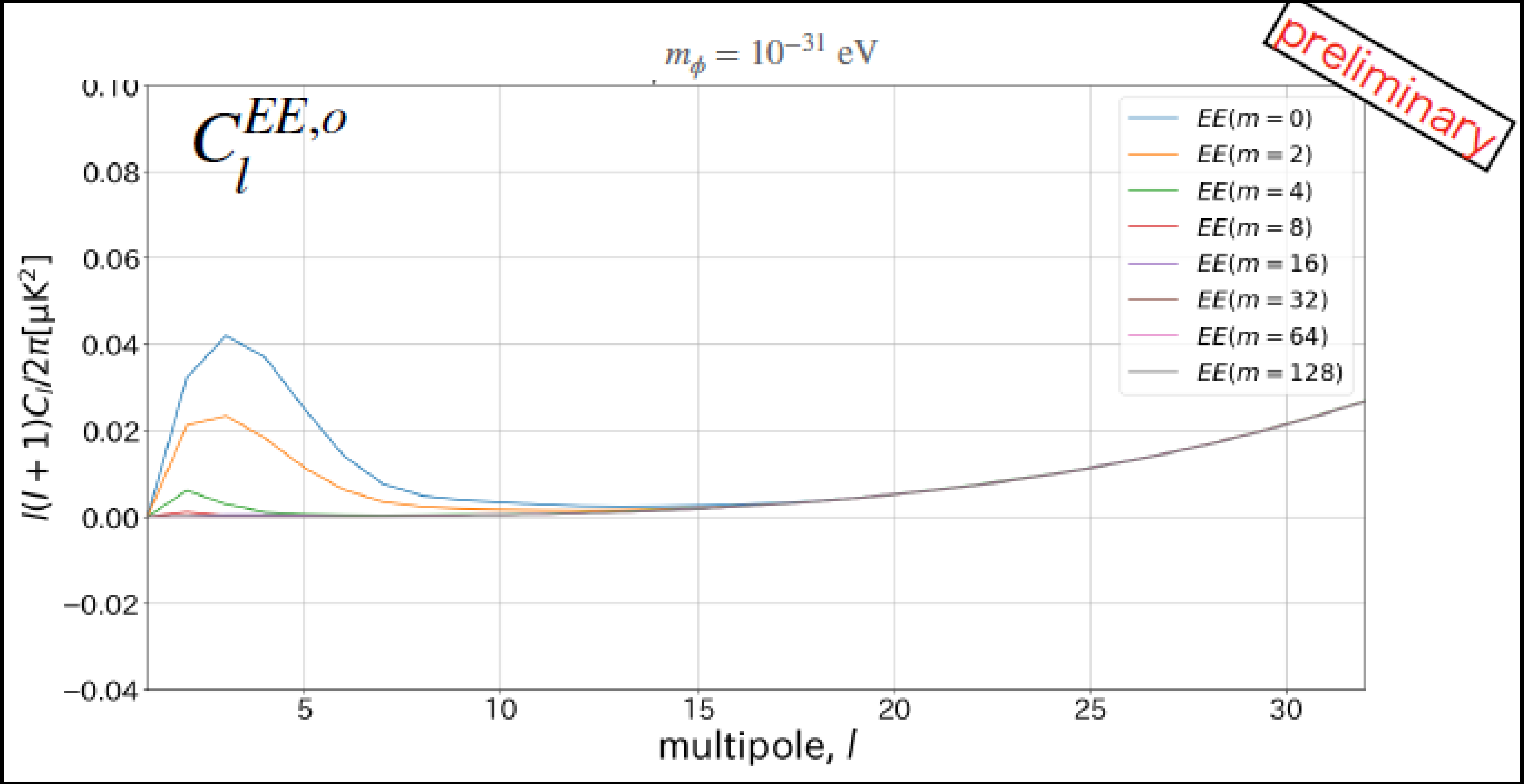
Naokawa et al. (in prep.)



The reionization bump is changed significantly

Ambiguity of phase of measured rotation angle

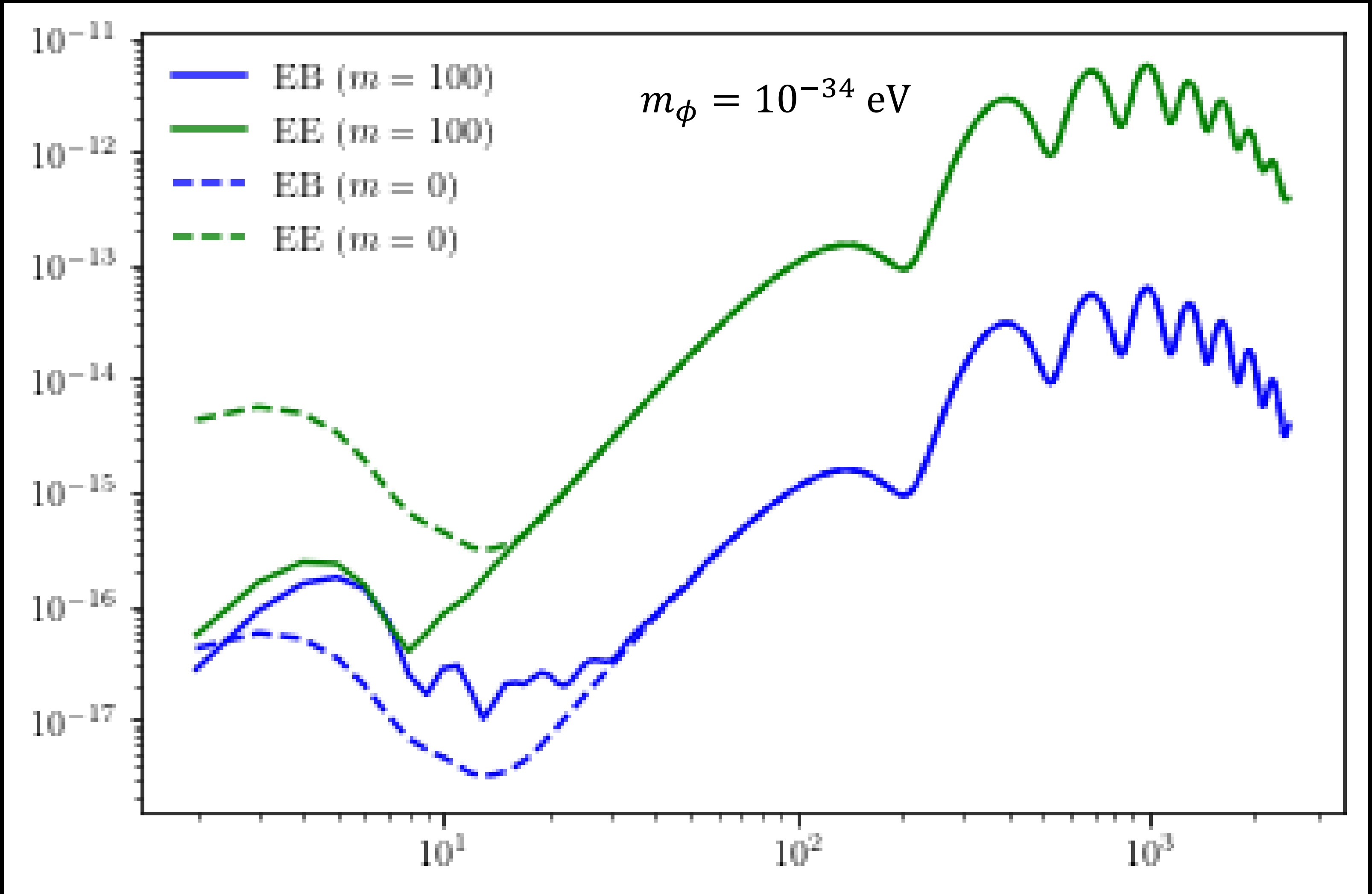
Naokawa et al. (in prep.)



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

Ambiguity of phase of measured rotation angle

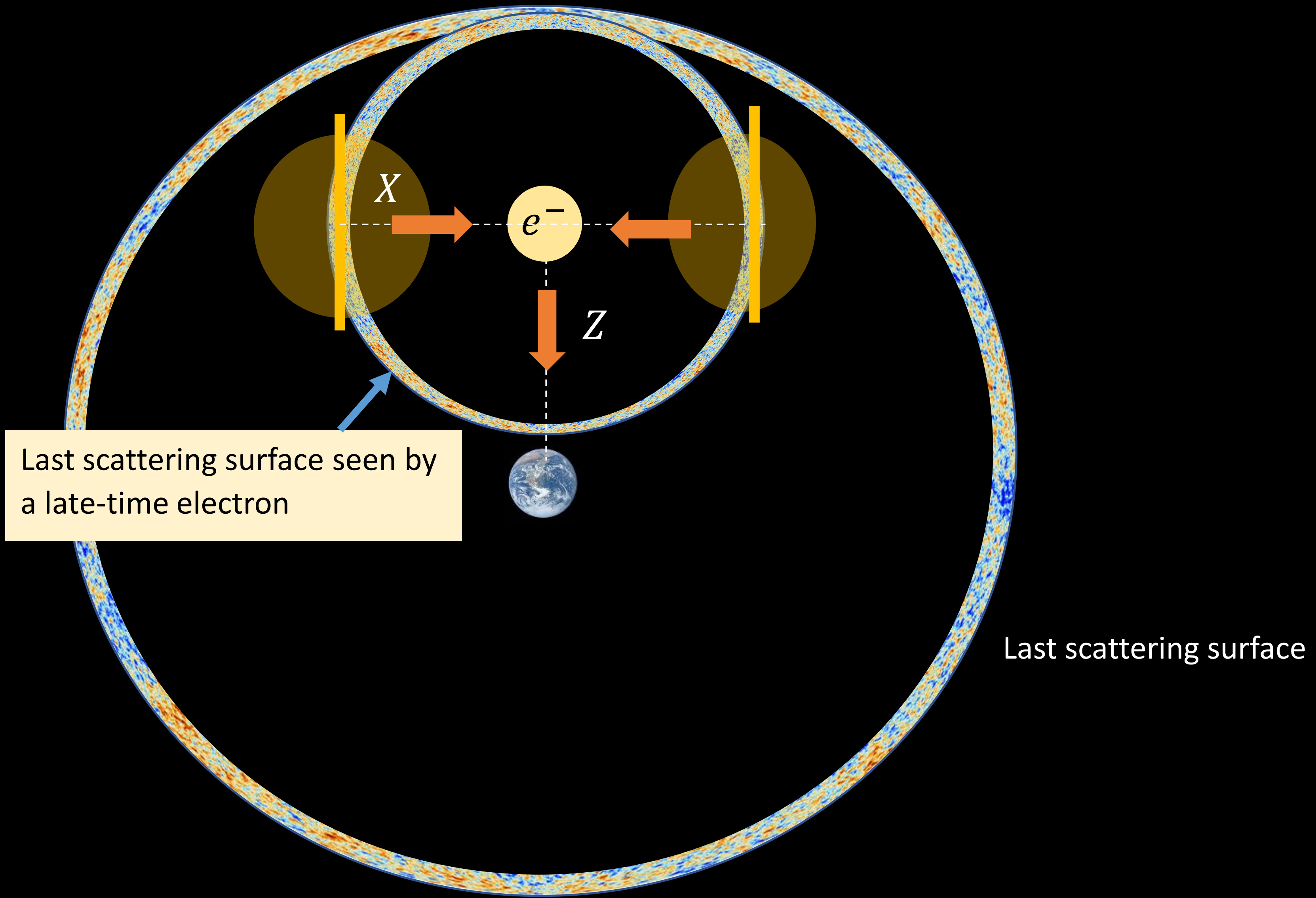
Naokawa et al. (in prep.)



The reionization bump in C_ℓ^{EE} and C_ℓ^{EB} are modified

Polarized Sunyaev Zel'dovich (pSZ) effect

TN & Obata (2023)

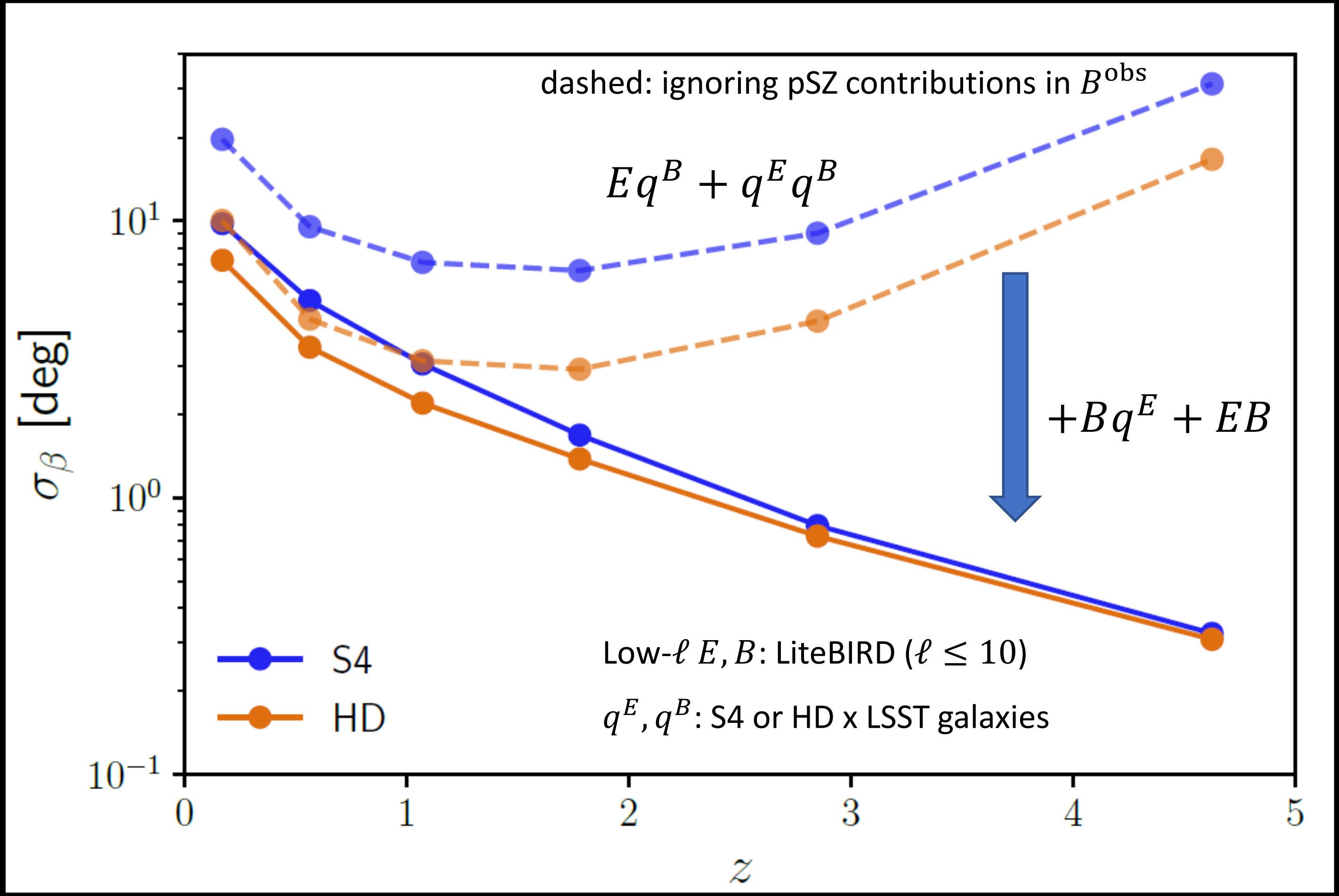


CMB polarization is generated even at low redshift (but not so efficient)

Cosmic birefringence constraints with polarization after reionization

TN & Obata (2023)

- 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

Summary

- 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)

  ⇨ Tomography of cosmic birefringence

- We developed a new tool to compute lensing correction to birefringence, thus, paving the way to more accurate interpretation of future CMB data that will seek signatures of axions via birefringence

- Measurements of CMB polarization spectra are also useful to constrain ambiguity of phase in β

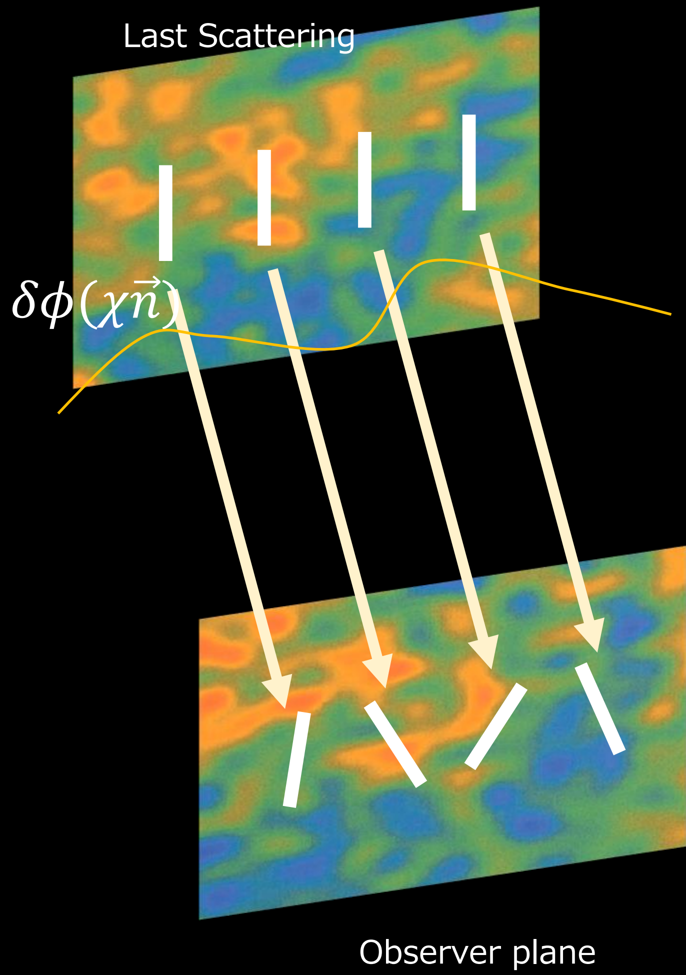
Time-evolution of anisotropic cosmic birefringence

This part is based on the following works:

- TN et al. (2020)
- TN (2024)
- Naokawa, TN, et al. (2024) in prep.

Anisotropic cosmic birefringence

- Fluctuations in ϕ can produce anisotropies in cosmic birefringence angle



$$\beta(\vec{n}) = \frac{g}{2}\Delta(\bar{\phi} + \delta\phi) = \beta + \alpha(\vec{n})$$

where $\alpha(n) = \frac{g}{2}\delta\phi(\chi_*\vec{n})$ for a polarization emitted at χ_*

e.g. Massless pseudoscalar fields $\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + k^2\delta\phi = 0$

$$\delta\phi_{\rm ini} = \frac{H_I}{2\pi}$$

Angular power spectrum becomes $C_L^{\alpha\alpha} \propto \frac{2\pi}{L(L+1)}$ at $L \ll 100$

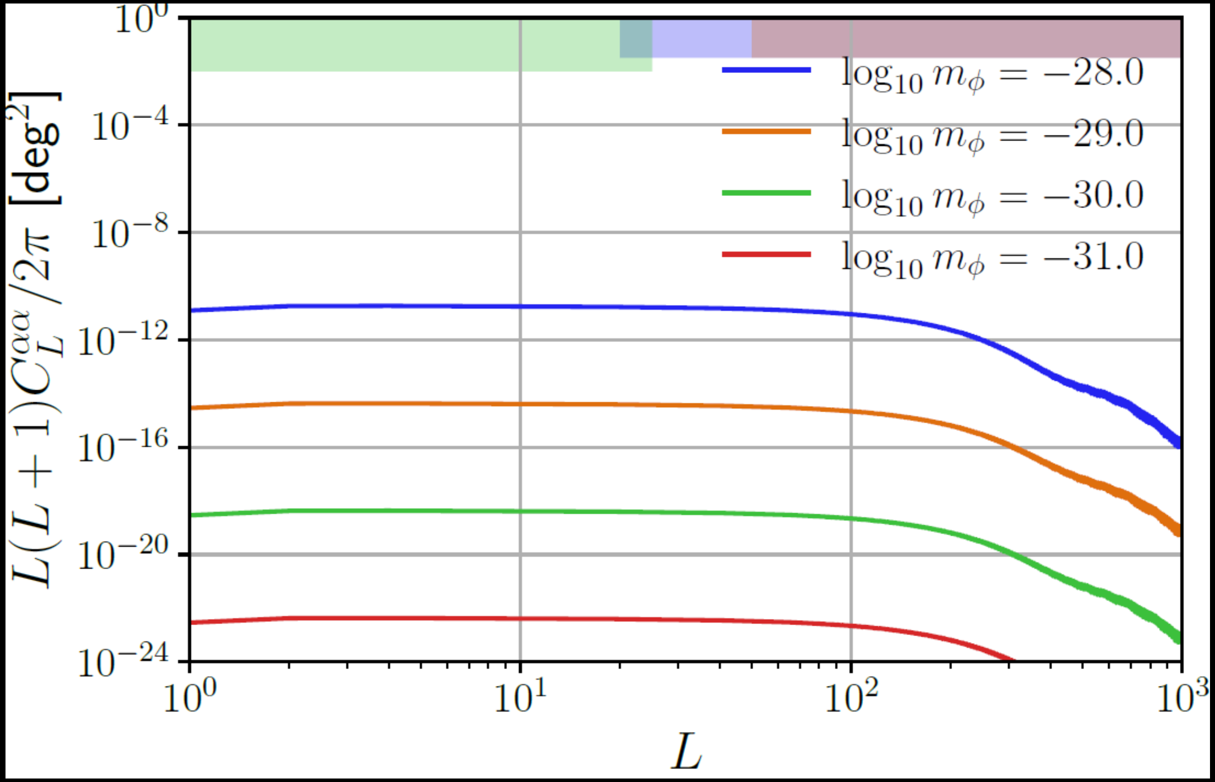
(see Takahashi-san's talk)

Anisotropic cosmic birefringence

- Massive ALPs (e.g. Caldwell et al 2011, Greco et al. 2022)

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + \left(k^2 + a^2 m_\phi^2\right)\delta\phi$$
$$= \dot{\bar{\phi}}(3\dot{\Phi} + \dot{\Psi}) - 2a^2 m_\phi \bar{\phi}\Psi$$

$$C_L^{\alpha\alpha} \propto \frac{2\pi}{L(L+1)}$$ at $L \ll 100$



- Primordial magnetic fields, axion-domain wall, etc

(see Takahashi-san's talk)

Measuring anisotropic cosmic birefringence

- Anisotropies in α mixes E and B modes at different angular scales

$$Q^{\mathrm{obs}}(n) \pm iU^{\mathrm{obs}}(n) = [Q(n) \pm iU(n)]e^{\pm 2i\alpha(n)} \quad \Rightarrow \quad \begin{aligned} E_\ell^{\mathrm{obs}} &= E_\ell + \int w\, B_L\, \alpha_{\ell-L} + \cdots \\ B_\ell^{\mathrm{obs}} &= B_\ell + \int w\, E_L\, \alpha_{\ell-L} + \cdots \end{aligned}$$

Correlation between E and B modes at different angular scales

$$E_{L_1} B_{L_2} \propto \alpha_{L_1 - L_2} + \ldots$$

$$(L_1 \neq L_2)$$

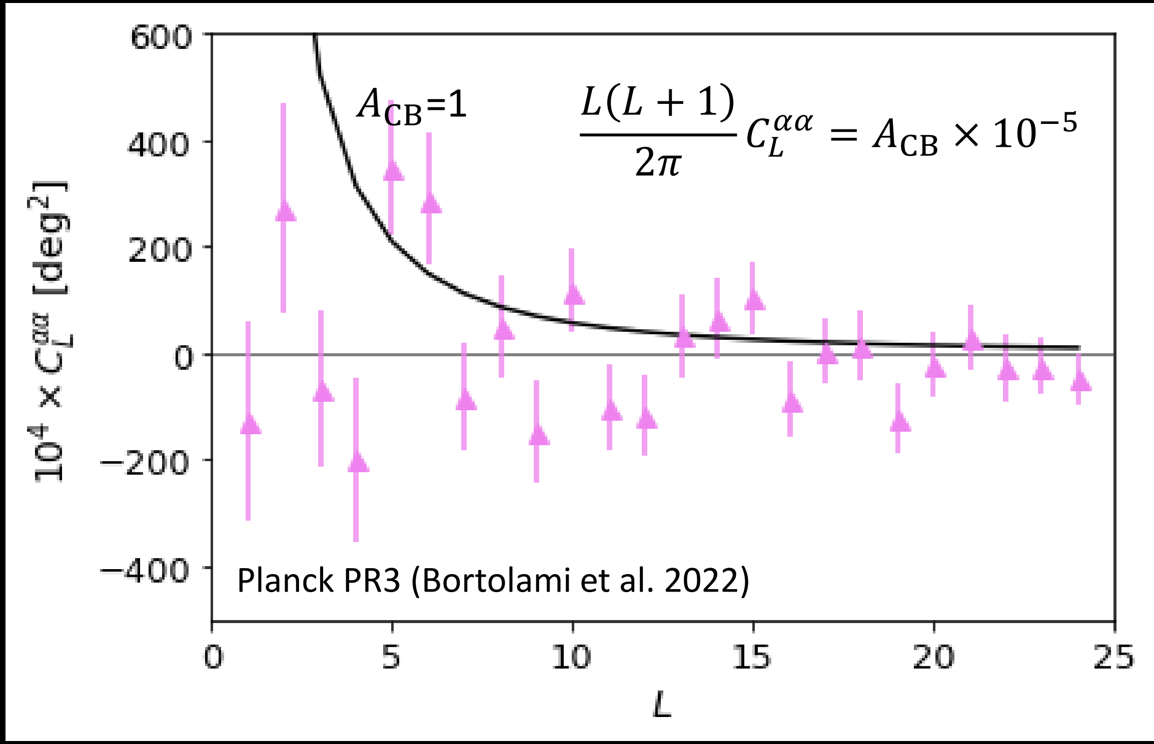
- We can reconstruct $\alpha(n)$ by correlating E and B at different angular scales with an optimal weighting

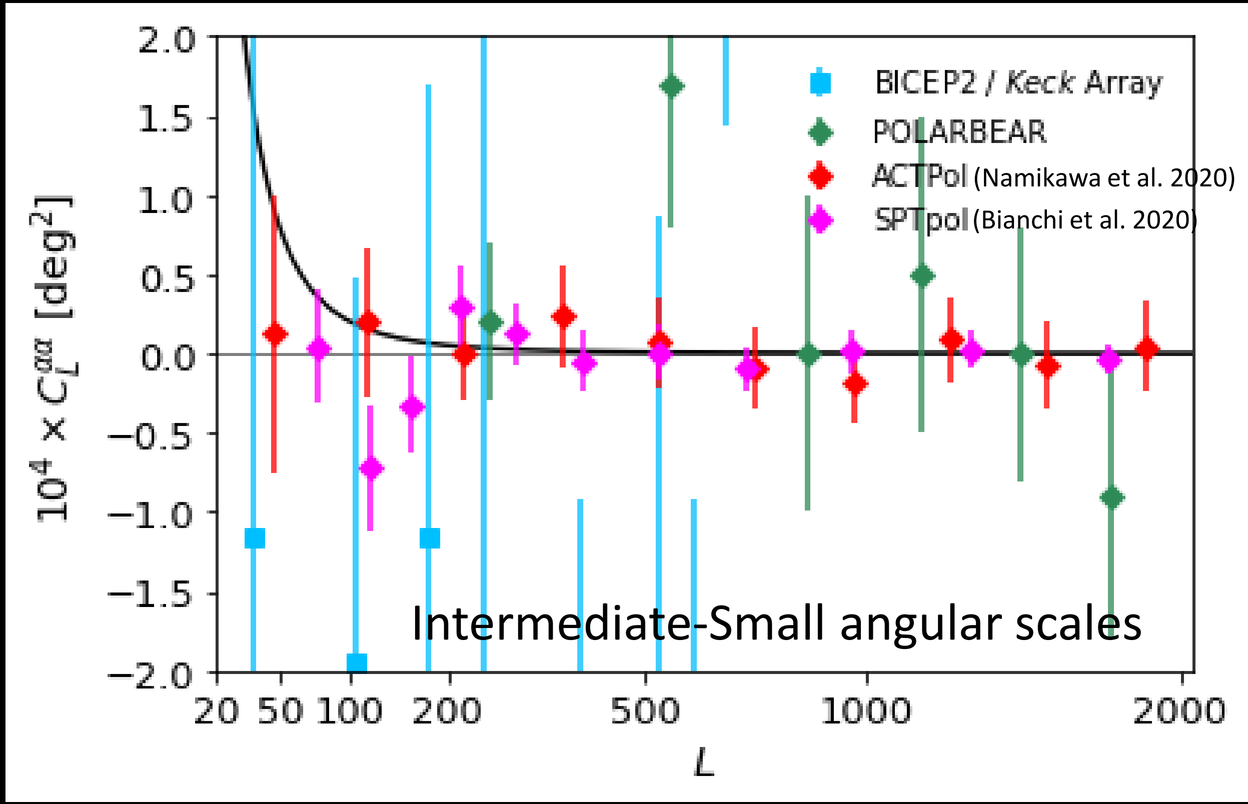
Details are given in Namikawa'17 (1612.07855)

$$\hat{\alpha}_{\vec{L}} = \int \mathrm{d}^2\vec{\ell}\; w^{\alpha}_{\vec{\ell},\vec{L}}\, E^{\mathrm{obs}}_{\vec{\ell}} B^{\mathrm{obs}}_{\vec{L}-\vec{\ell}}$$

c.f. Estimating EB power spectrum uses E and B at the same angular scales $\hat{C}_\ell^{EB} = E^{\mathrm{obs}}_{\vec{\ell}} \left(B^{\mathrm{obs}}_{\vec{\ell}}\right)^*$

Constraint on anisotropic cosmic birefringence: Current status

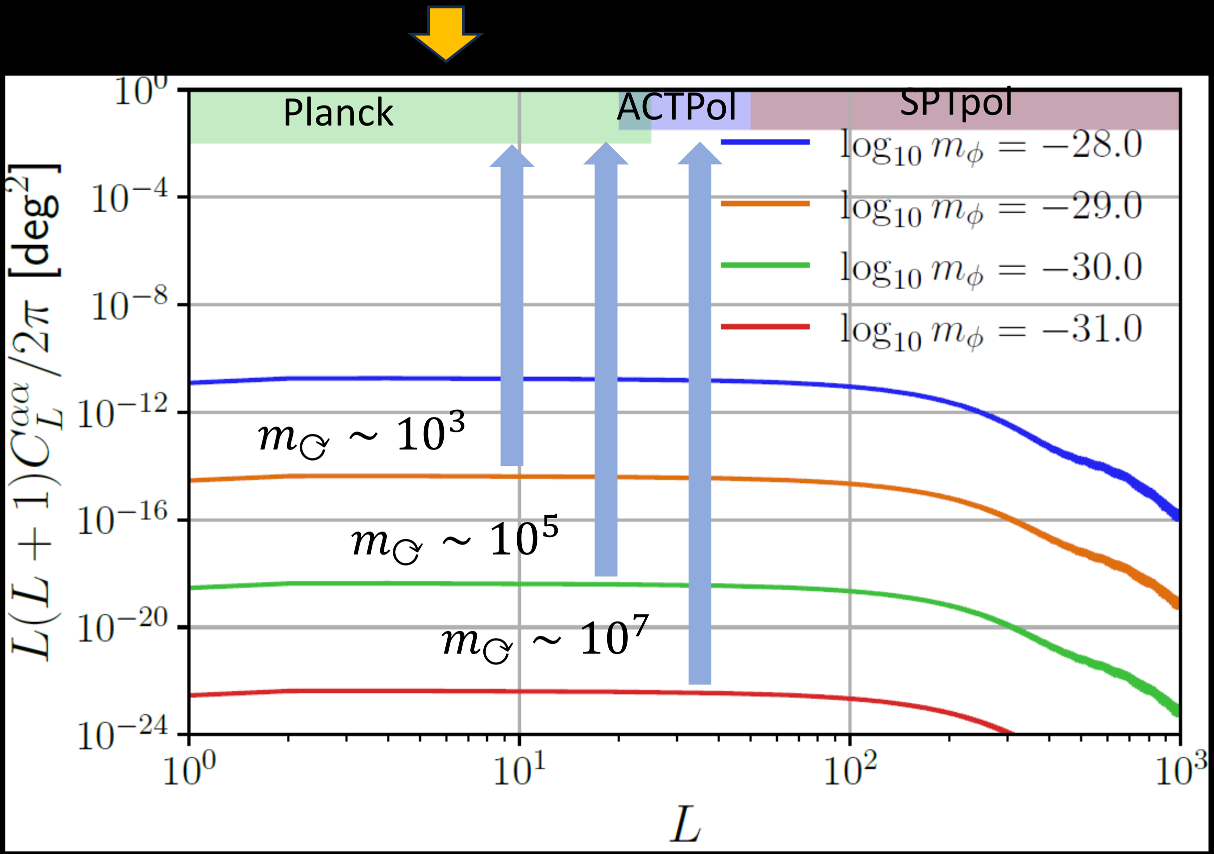




No detection of signals place a new bound on the birefringence; $A_{CB} \lesssim 0.1$ (95%CL)

Constraint on ambiguity of phase of rotation angle

$$C_L^{\alpha\alpha}(m_\circlearrowleft) \sim C_L^{\alpha\alpha}(m_\circlearrowleft = 0) \times 10^5 {m_\circlearrowleft}^2$$



Measurements of anisotropic cosmic birefringence limits $m_\circlearrowleft$ (depending on mass)

C_ℓ^{BB} from anisotropic cosmic birefringence

- C_ℓ^{BB} from anisotropic cosmic birefringence

  We usually adopt the thin approximation for the CMB last-scattering surface

C_ℓ^{BB} from anisotropic cosmic birefringence

- C_ℓ^{BB} from anisotropic cosmic birefringence

We usually adopt the thin approximation for the CMB last-scattering surface

Inclusion of the thickness makes the C_ℓ^{BB} calculation very complex

$$C_\ell^{BB} = \frac{4\pi}{2\ell+1}\sum_{m=-\ell}^{\ell}\int \mathrm{d}\ln q\, \mathcal{P}_{\mathcal{R}}(q)\sum_{\ell_1\ell_2} \mathrm{i}^{-\ell_1+\ell_2}\sqrt{(2\ell_1+1)(2\ell_2+1)}$$
$$\times \int \mathrm{d}^2\hat{n}\, \left[{}_2Y^*_{\ell_1 0}(\hat{n})\,{}_2Y_{\ell m}(\hat{n}) + {}_{-2}Y^*_{\ell_1 0}(\hat{n})\,{}_{-2}Y_{\ell m}(\hat{n})\right] \int \mathrm{d}^2\hat{n}'\, \left[{}_2Y_{\ell_2 0}(\hat{n}')\,{}_2Y^*_{\ell m}(\hat{n}') + {}_{-2}Y_{\ell_2 0}(\hat{n}')\,{}_{-2}Y^*_{\ell m}(\hat{n}')\right]$$
$$\times \int_0^{\eta_0} \mathrm{d}\eta \int_0^{\eta_0} \mathrm{d}\eta'\; s_{\ell_1}(q,\eta)\, s_{\ell_2}(q,\eta')\,\langle \alpha(\eta,\hat{n})\alpha(\eta',\hat{n}')\rangle\,,$$

Thickness of the last-scattering surface changes C_ℓ^{BB} significantly for the Faraday rotation

Pogosian et al. (2011)

C_ℓ^{BB} from anisotropic cosmic birefringence

- C_ℓ^{BB} from anisotropic cosmic birefringence

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$$\times \int_0^{\eta_0} \mathrm{d}\eta \int_0^{\eta_0} \mathrm{d}\eta'\, s_{\ell_1}(q,\eta)\, s_{\ell_2}(q,\eta') \langle \alpha(\eta,\hat{n})\, \alpha(\eta',\hat{n}') \rangle \,,$$

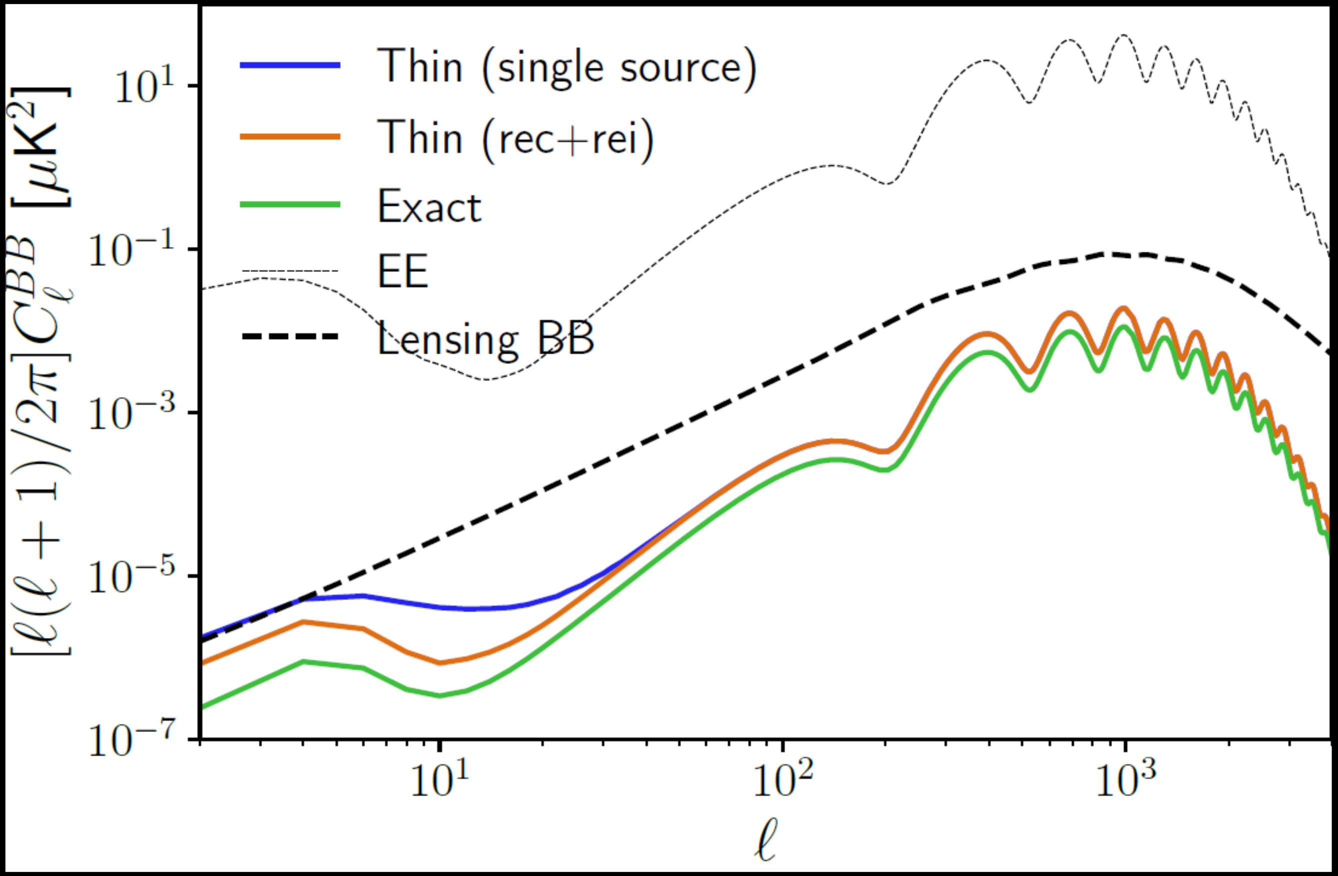
Thickness of the last-scattering surface changes C_ℓ^{BB} significantly for the Faraday rotation

Pogosian et al. (2011)

We check how the thickness changes C_ℓ^{BB} for the massless ALPs

C_ℓ^{BB} from anisotropic cosmic birefringence

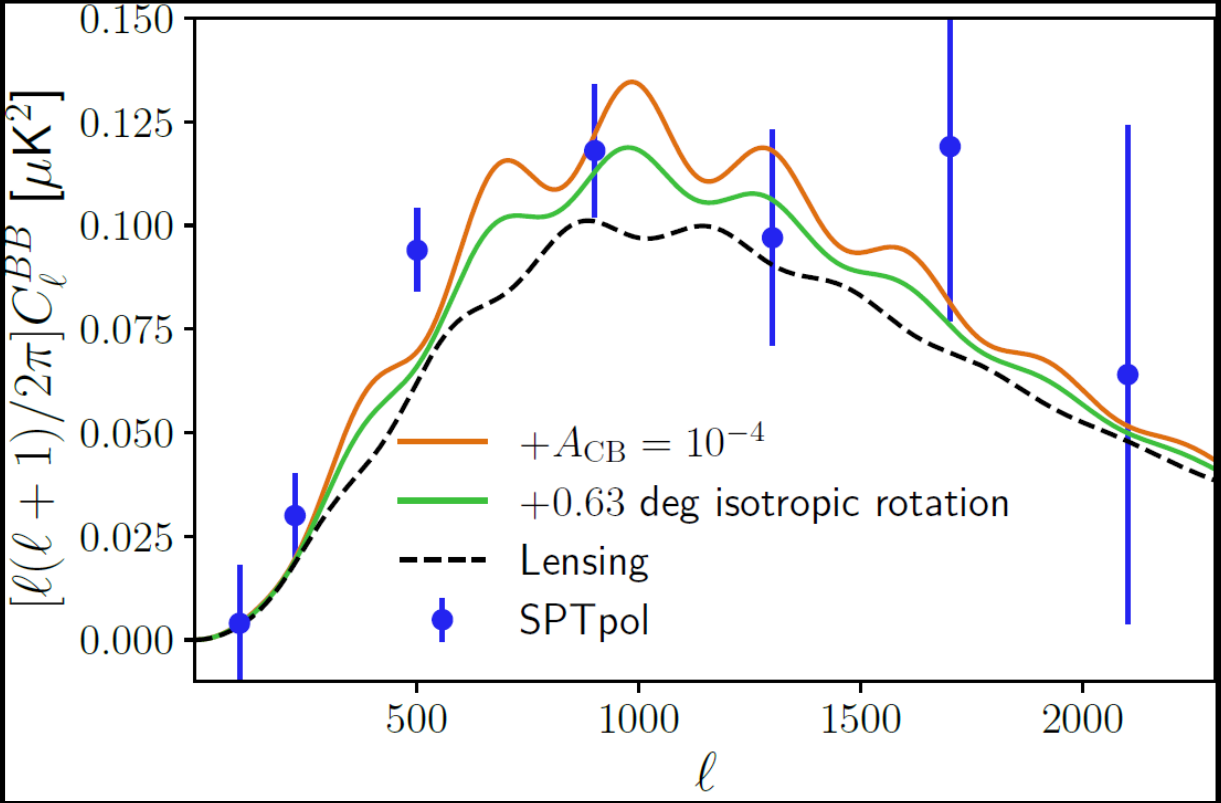
- C_ℓ^{BB} with thickness of the CMB last-scattering surface

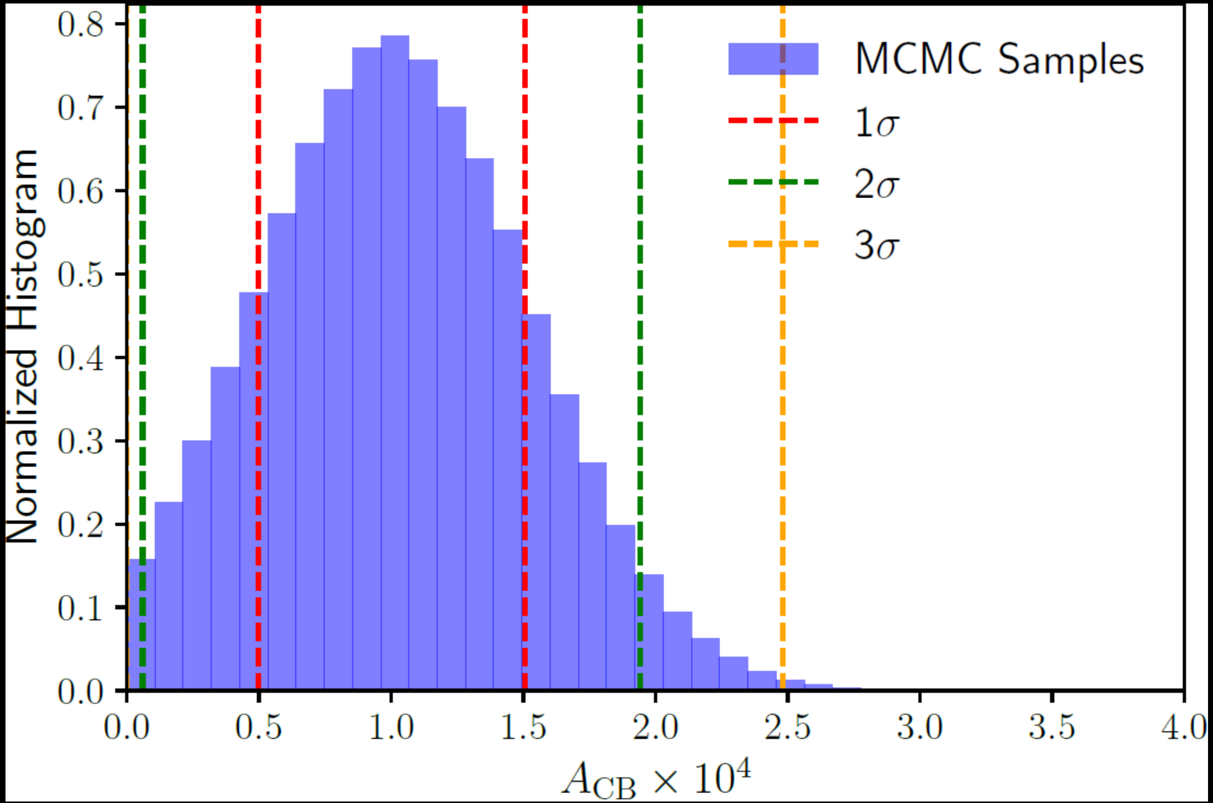


BB power spectrum is suppressed due to the time-evolution of $\delta\phi$ during the recombination

Constraint on anisotropic cosmic birefringence

- SPTpol C_ℓ^{BB} for constraining anisotropic cosmic birefringence





SPTpol data suggests $A_{CB} \times 10^4 = 1.03^{+0.91}_{-0.97}$ (2σ), a slight preference for a nonzero value

Summary

- Planck and WMAP data currently shows a hint for cosmic birefringence; $\beta = 0.34^{+0.094}_{-0.091}$ deg

- We consider ALPs for a possible origin of cosmic birefringence and how the evolution of ALPs impacts on CMB power spectrum

- We introduce the current observations of anisotropic cosmic birefringence and make implications

More observations for cosmic birefringence are necessary to confirm the signals and explore the origin