# Isotropic cosmic birefringence from an oscillating axion-like field

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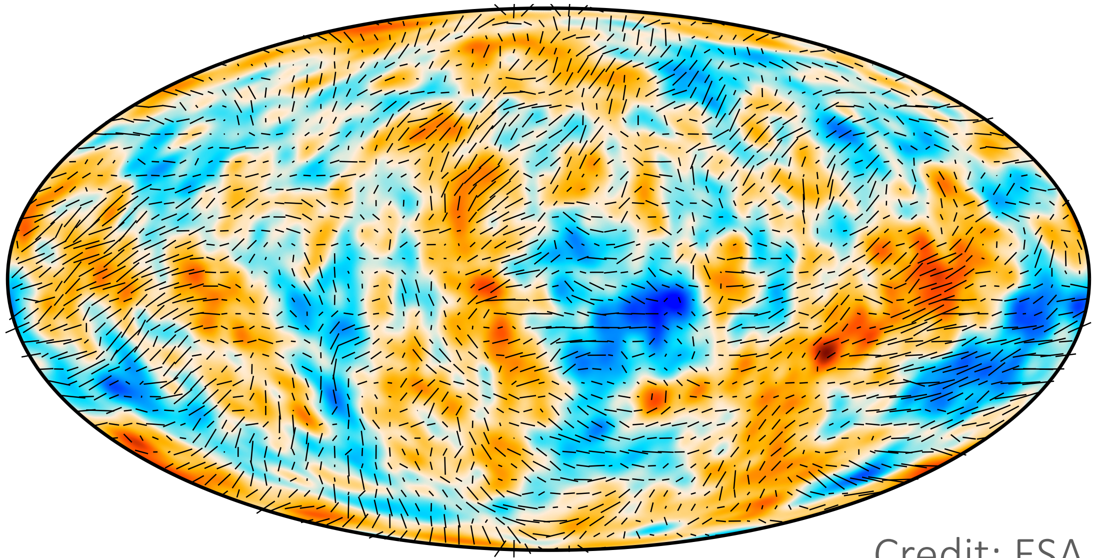
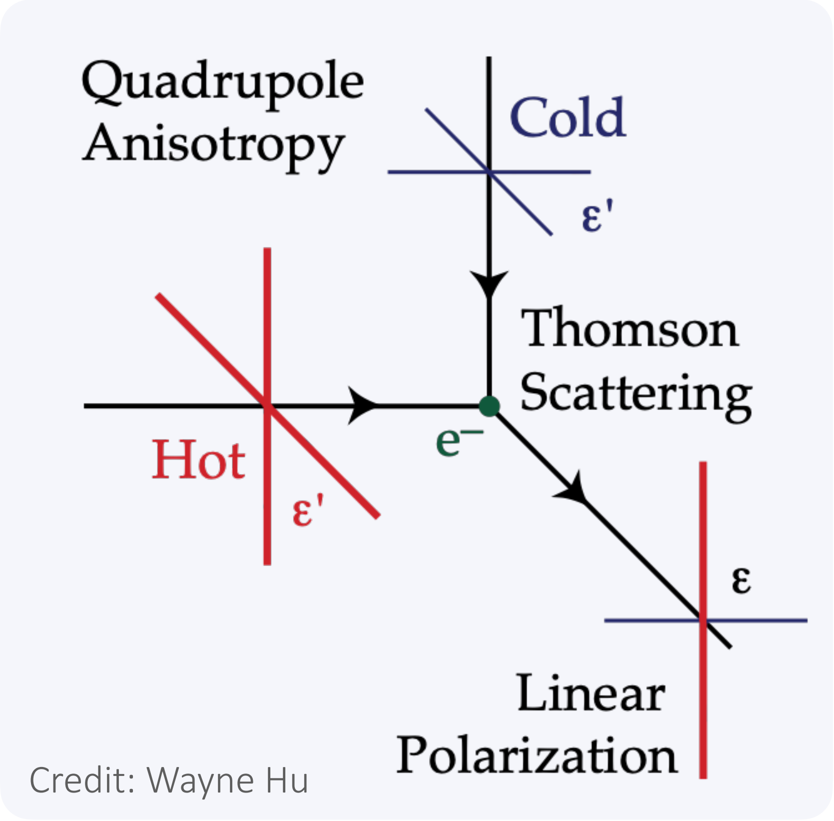
# Birefringence in CMB polarization

- CMB polarization

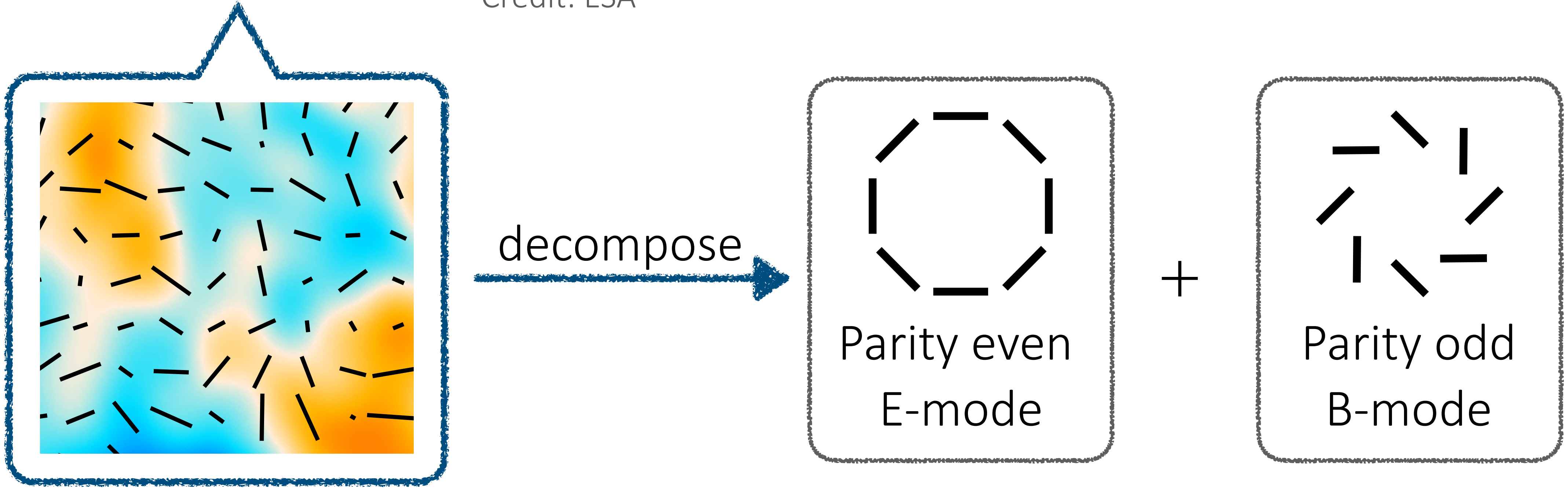
CMB photons are linearly polarized due to Thomson scatterings.



Credit: ESA



Credit: Wayne Hu



decompose

Parity even
E-mode

+

Parity odd
B-mode

# Birefringence in CMB polarization

- EB correlation from birefringence

Without parity-violating physics,

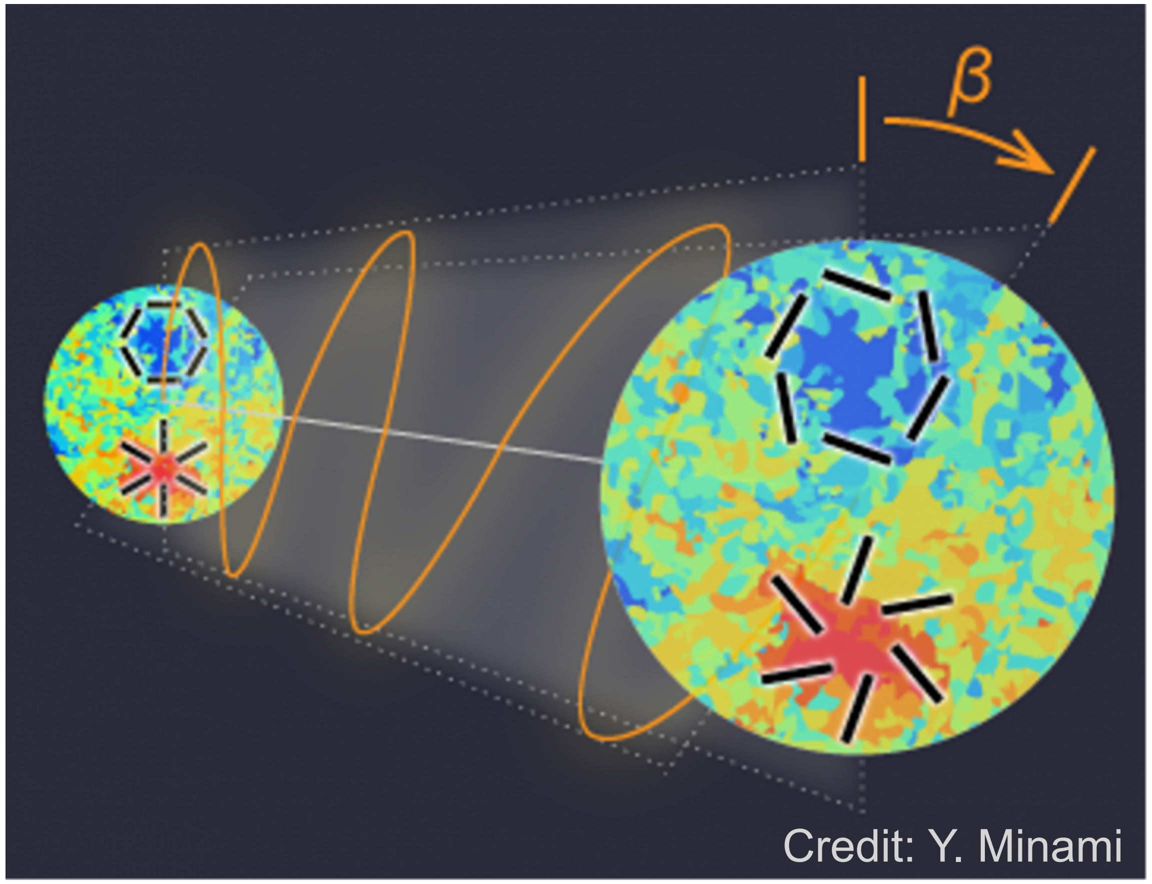
$$\langle E_l B_l \rangle = 0$$

If the linear polarization rotates in propagation,

$$\langle E_l B_l \rangle \neq 0$$

[Lue, Wang, Kamionkowski (1999)]

If all photons have the same rotation angle $\beta$,



Credit: Y. Minami

$$\tilde{E}_l = E_l \cos(2\beta) - B_l \sin(2\beta)$$

$$\tilde{B}_l = E_l \sin(2\beta) + B_l \cos(2\beta)$$

after birefringence

$$\tilde{C}_l^{EB} \simeq \tan(2\beta) \tilde{C}_l^{EE}$$

(assuming $C_l^{EB} = 0$, $C_l^{EE} \gg C_l^{BB}$)

# Birefringence in CMB polarization

- **Measurement of cosmic birefringence**

Planck (and WMAP) data suggest the rotation angle $\beta$ at 68% C.L.:

$$0.35^\circ \pm 0.14^\circ$$

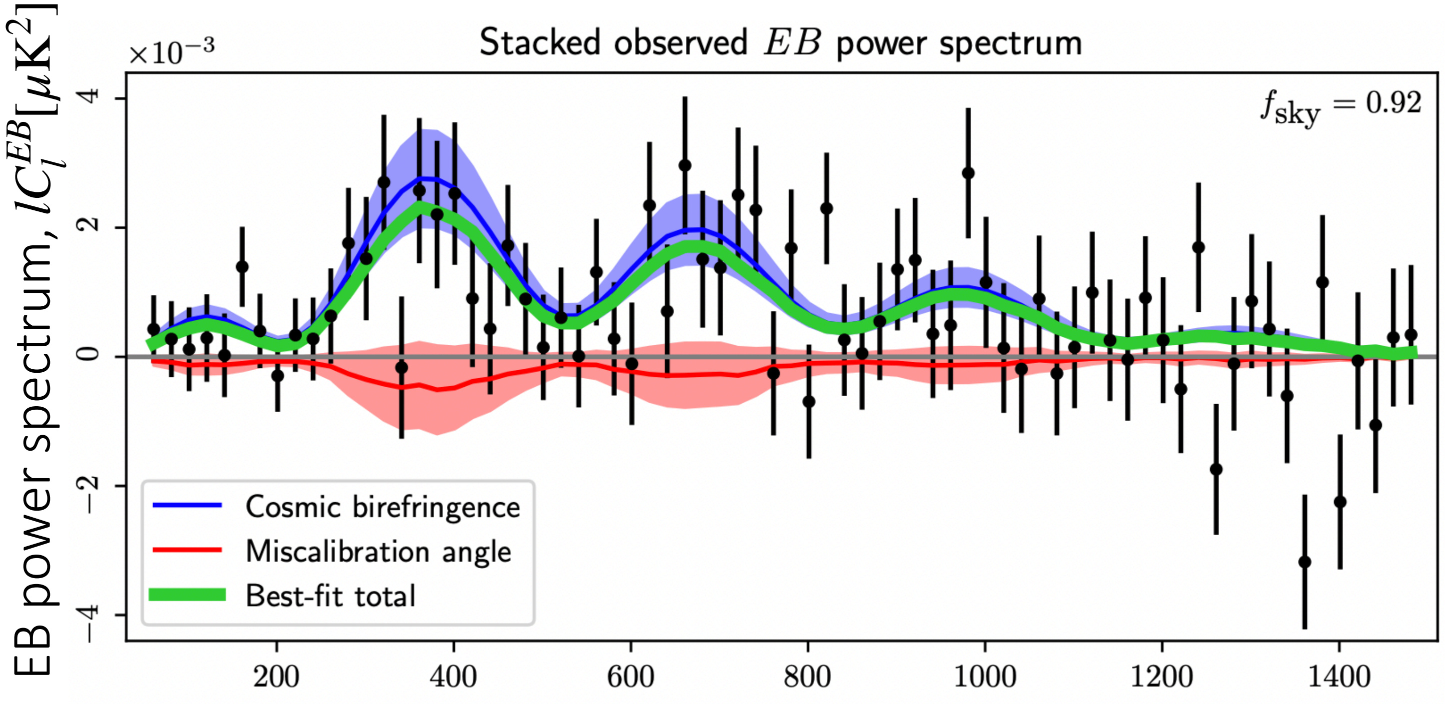
[Minami & Komatsu (2020)]

$$0.30^\circ \pm 0.11^\circ$$

[Diego-Palazuelos *et al.* (2022)]

$$0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ}$$

[Eskilt & Komatsu (2022)]



Multipole, $l$ [Eskilt & Komatsu (2022)]

$\beta$ is $\left\{\begin{array}{l}\text{isotropic.}\\ \text{consistent with no frequency dependence.}\end{array}\right.$ [Eskilt (2022)]

Note: In this talk, we do not consider the $n\pi$ ambiguity of $\beta$. [Naokawa et al. (2024)]

New physics violating parity?

# Birefringence by ALP

- Axion-like particle (ALP)

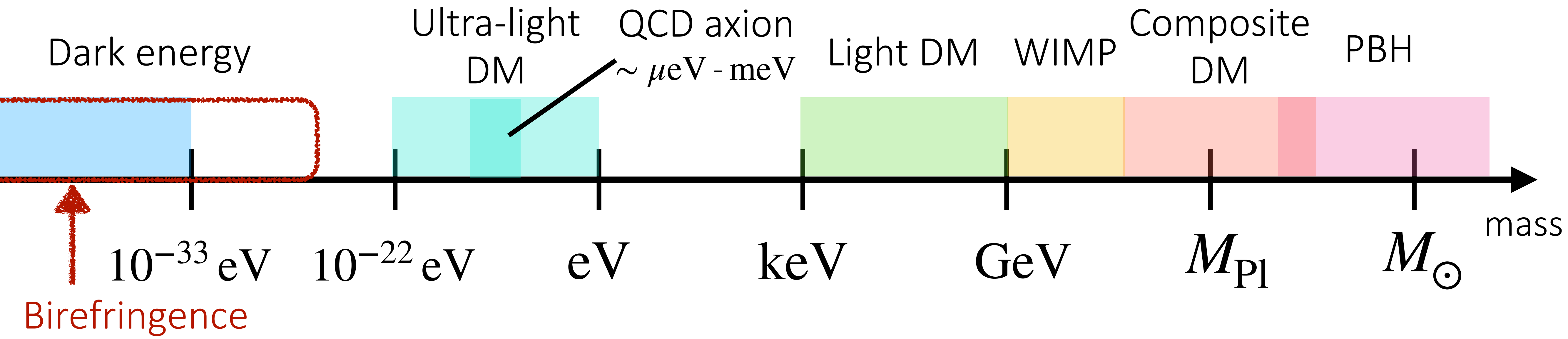
A pseudoscalar field $\phi$ arising from a SSB of a global U(1) symmetry

Chern-Simons coupling with the SM gauge fields: $\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$, …

Wide range of mass and coupling (cf. string axiverse) [Arvanitaki *et al*. (2010)]

cf.) QCD axion: A possible solution to the strong CP problem.
"Decay constant" controls its mass and couplings.

These can be ultra-light dark matter.



Dark energy

Ultra-light DM

QCD axion $\sim \mu\mathrm{eV}$ - $\mathrm{meV}$

Light DM

WIMP

Composite DM

PBH

$10^{-33}\,\mathrm{eV}$ $10^{-22}\,\mathrm{eV}$ $\mathrm{eV}$ $\mathrm{keV}$ $\mathrm{GeV}$ $M_{\mathrm{Pl}}$ $M_{\odot}$ mass

Birefringence

# Birefringence by ALP

## Origin of cosmic birefringence

$$\beta = 0.342^\circ\,{}^{+0.094^\circ}_{-0.091^\circ}$$ at 68% C.L. : Isotropic
Independent of photon freq.

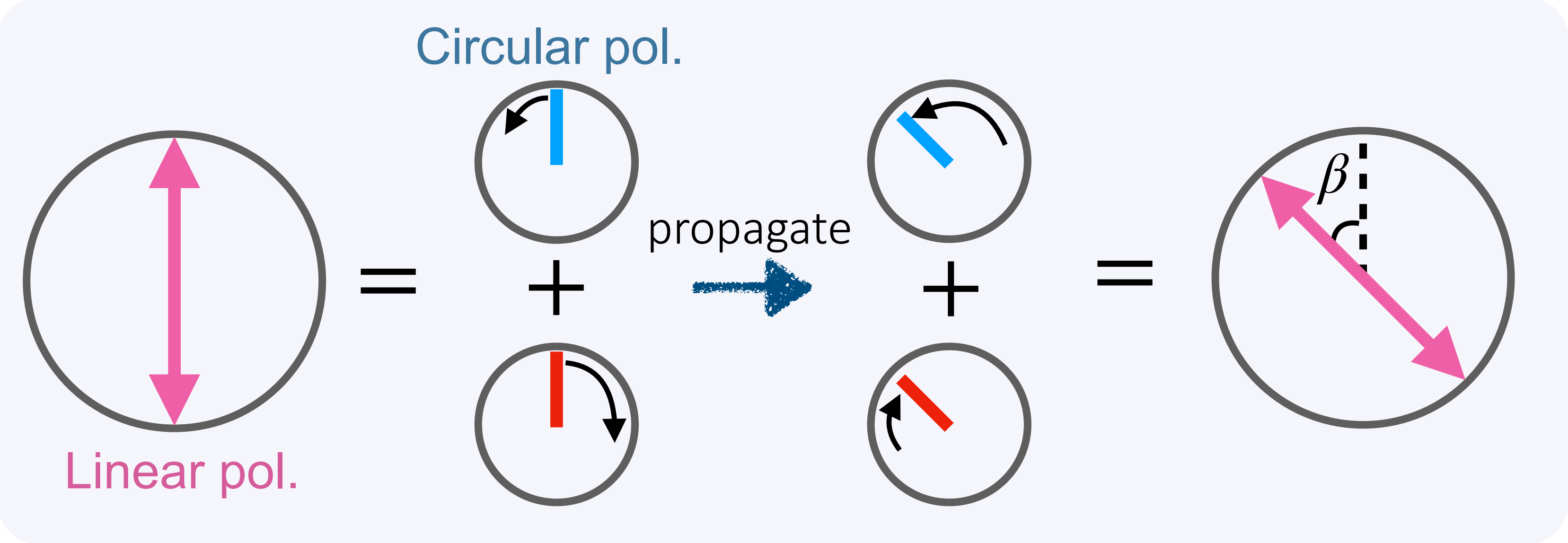
Axion/ALP can explain $\beta$ via its coupling to photons:

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

[Carroll (1998)]

Different dispersion relation for circular polarizations

$$k_\pm = \omega \pm \frac{g}{2}\frac{\mathrm{d}}{\mathrm{d}\eta}\phi(\eta, \vec{x}(\eta))$$



$$\beta = \frac{g}{2}\int \mathrm{d}\eta\,\frac{\mathrm{d}\phi}{\mathrm{d}\eta} = \frac{g}{2}(\phi_{\rm obs} - \phi_{\rm emit})$$

[Carroll, Field, Jackiw (1990)]

# Birefringence by ALP

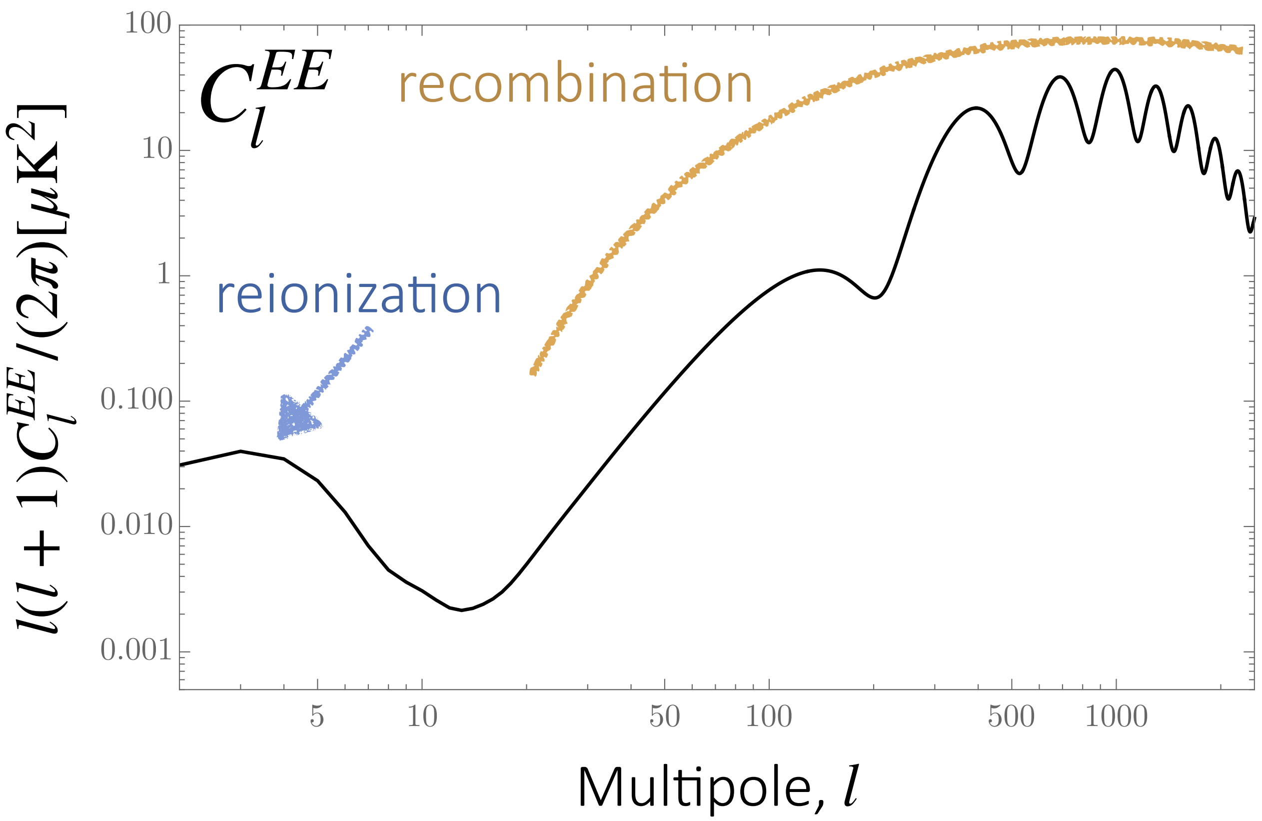
$$\beta = \frac{g}{2}(\phi_{\mathrm{obs}} - \phi_{\mathrm{emit}})$$

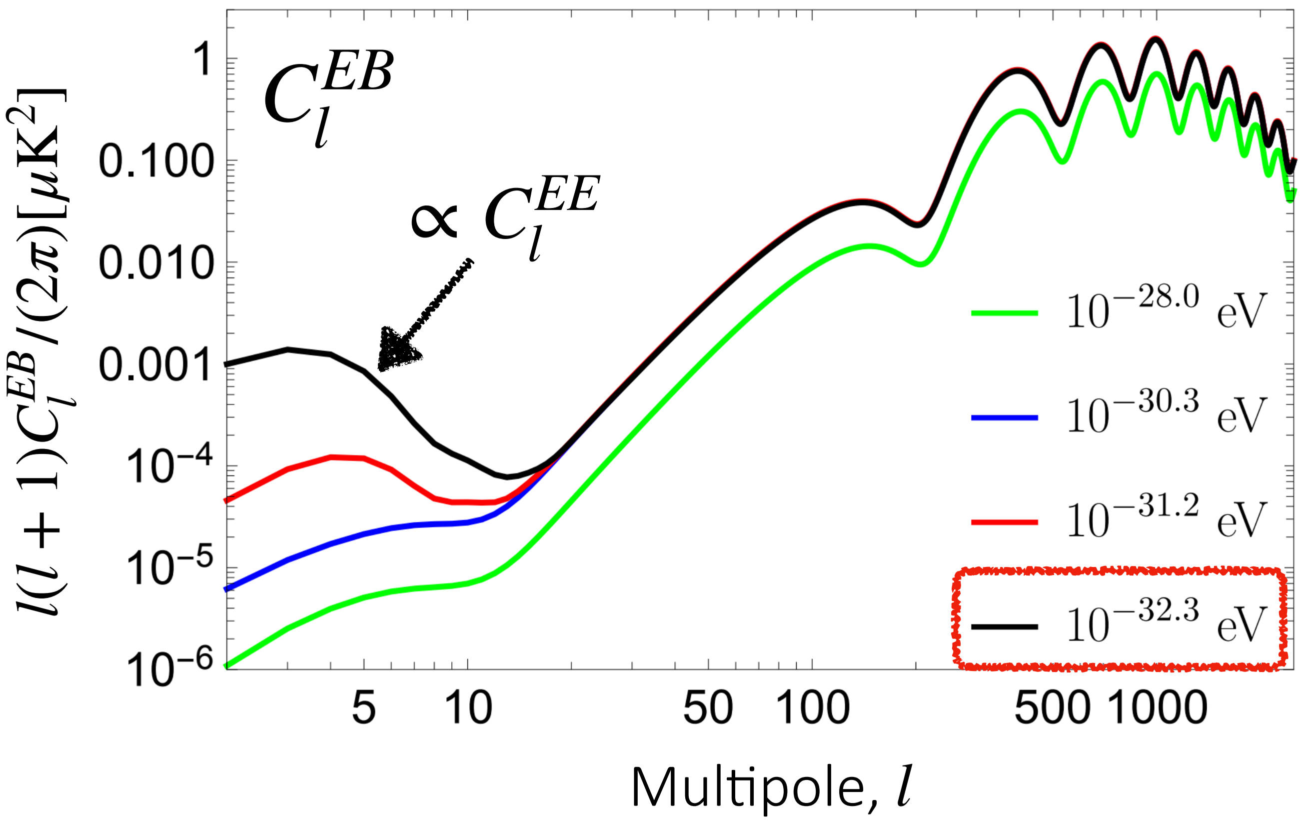
## Time evolution of the axion field

To explain $\beta \sim 0.3°$, the axion field needs to evolve after the recombination.

- $m \lesssim 10^{-31}\,\mathrm{eV}$: Oscillation after reionization

  Uniform $\beta$. We obtain $C_l^{EB} \propto C_l^{EE}$ for all $l$.





[Nakatsuka, Namikawa, Komatsu (2022)]

# Birefringence by ALP

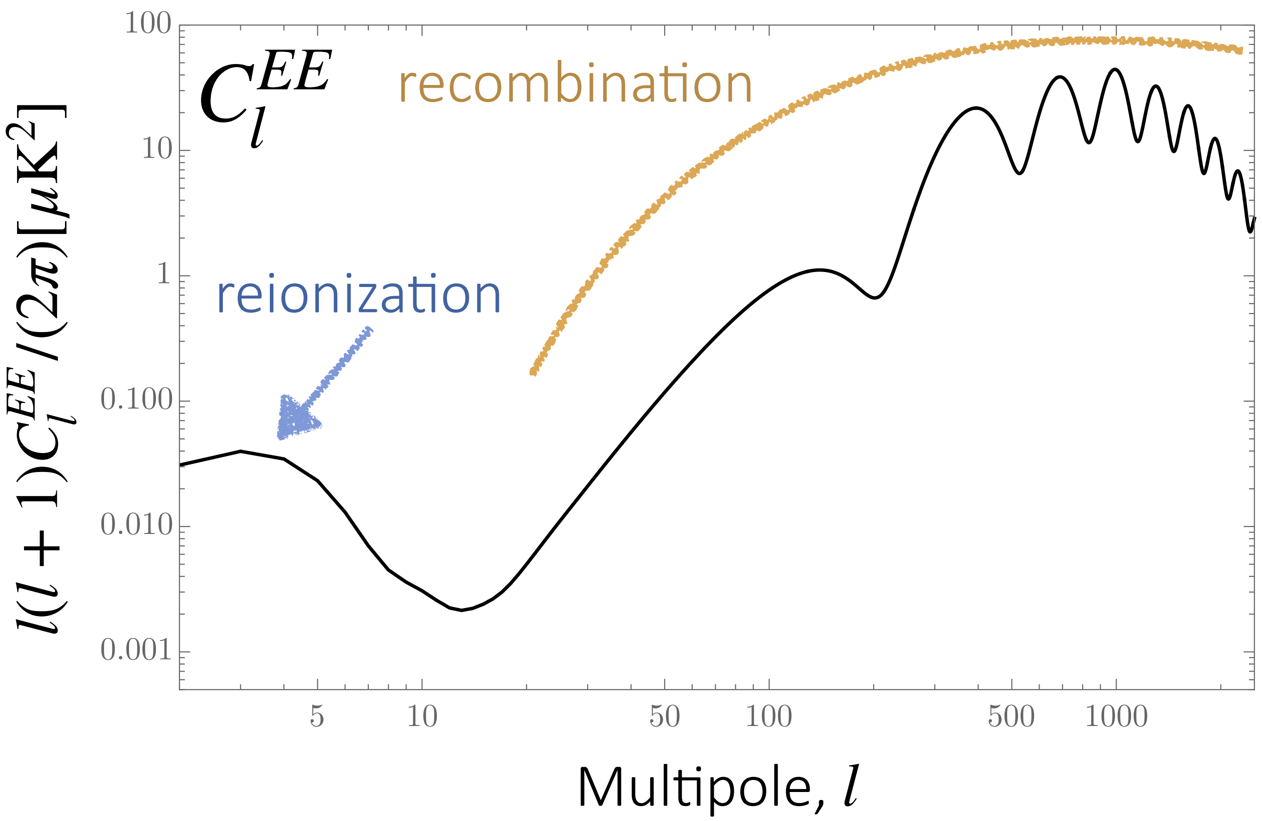
$$\beta = \frac{g}{2}(\phi_{\mathrm{obs}} - \phi_{\mathrm{emit}})$$

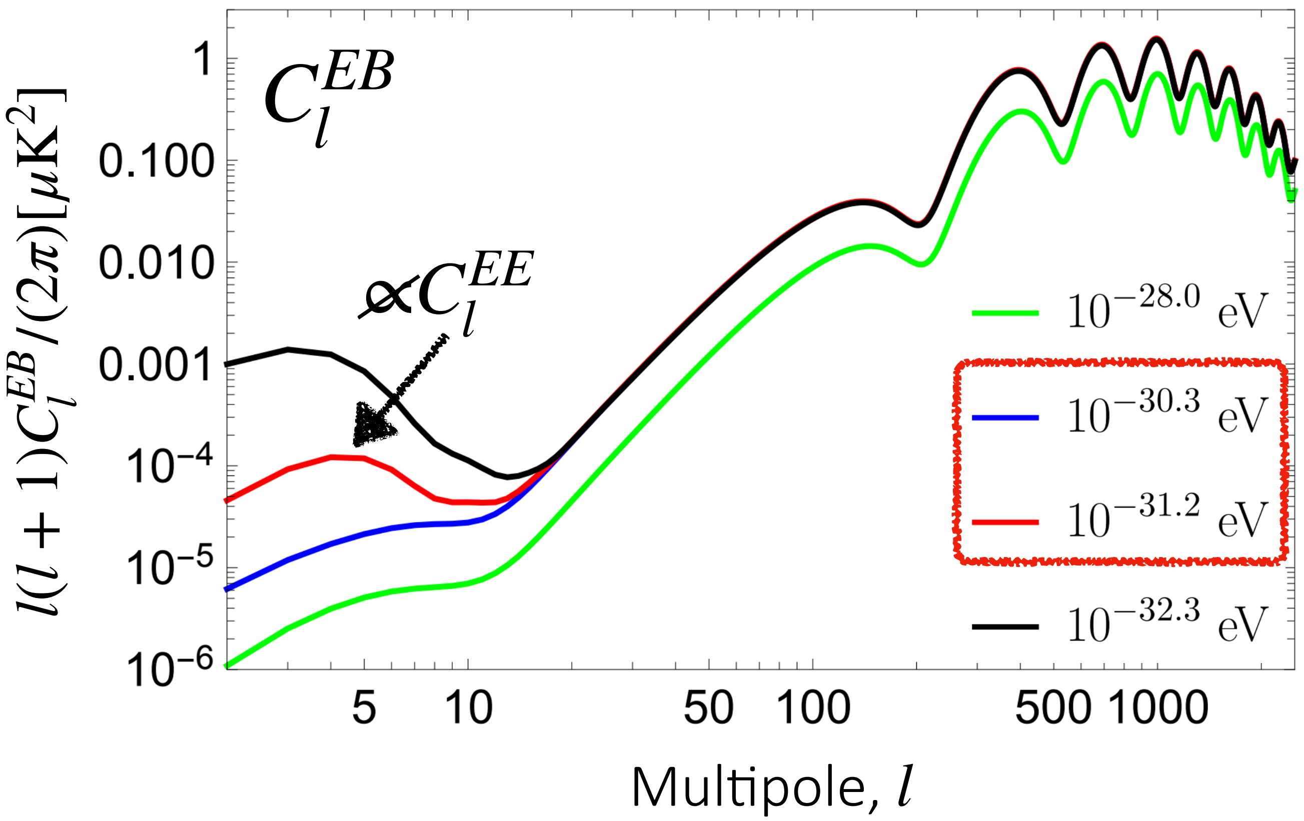
- Time evolution of the axion field

To explain $\beta \sim 0.3^\circ$, the axion field needs to evolve after the recombination.

- $m \gtrsim 10^{-31}\,\mathrm{eV}$: Oscillation before reionization

  $C_l^{EB} \propto C_l^{EE}$ except for the reionization bump





[Nakatsuka, Namikawa, Komatsu (2022)]

# Birefringence by ALP

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

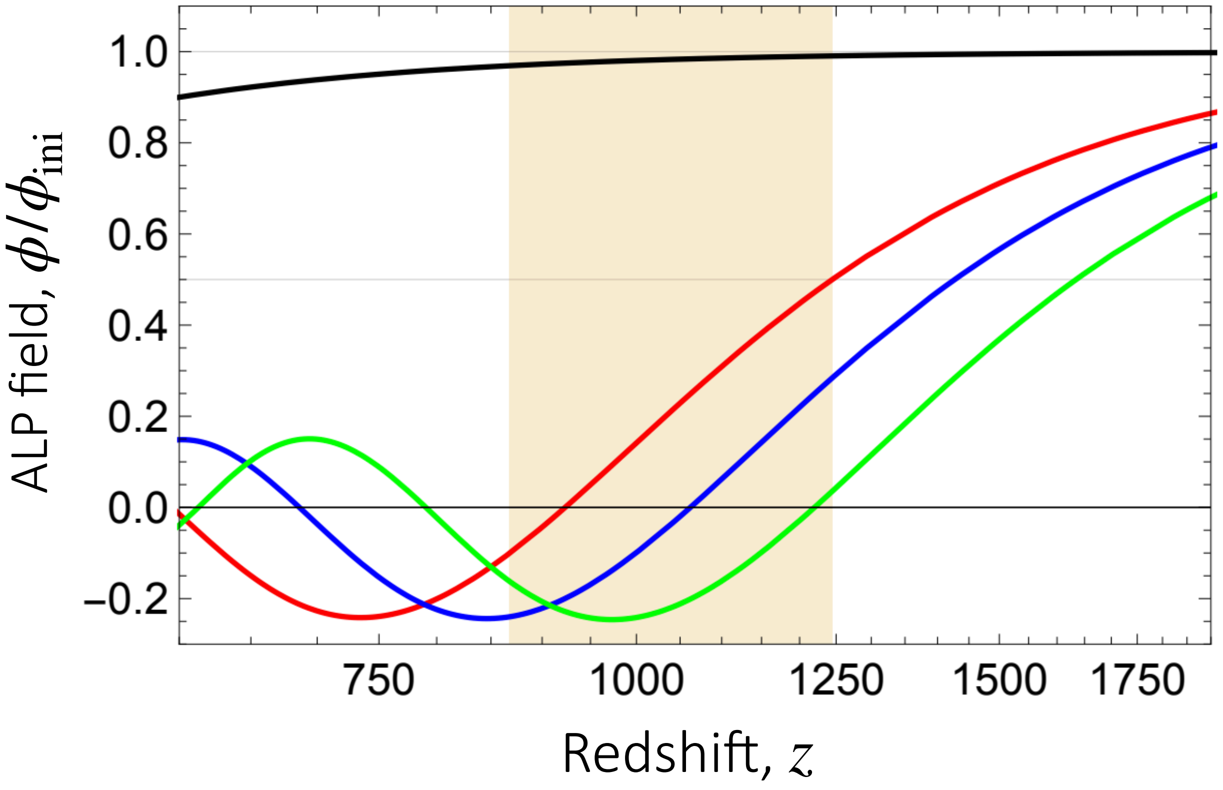
- Time evolution of the axion field

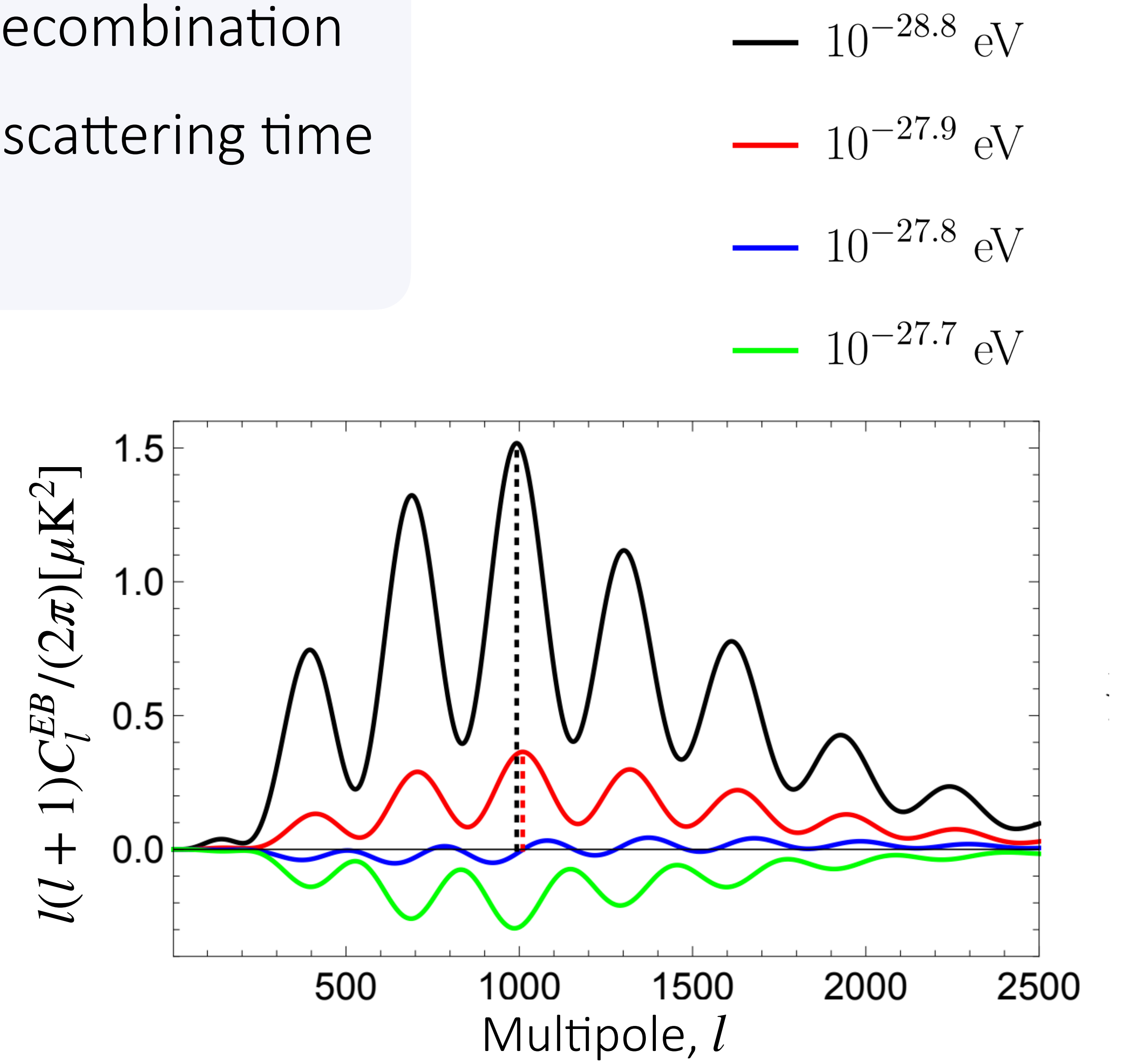
To explain $\beta \sim 0.3^\circ$, the axion field needs to evolve after the recombination.

- $m \gtrsim 10^{-28}\,\mathrm{eV}$: Oscillation before recombination

  Oscillating $\beta$ depending on the last scattering time

  Negligible $C_l^{EB}$ and reduced $C_l^{EE}$





[Nakatsuka, Namikawa, Komatsu (2022)]

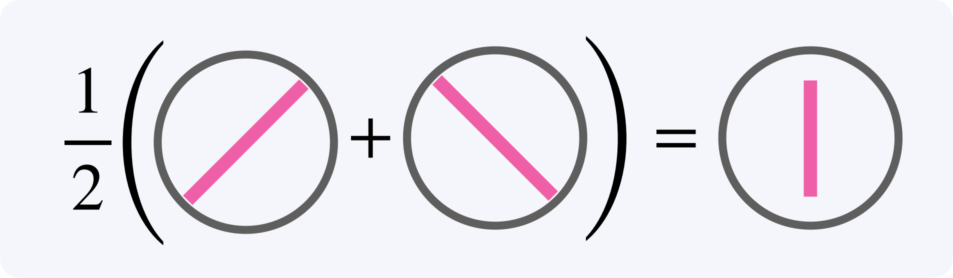
# Washout of polarization

- Axion oscillation during the recombination

Washout effect: [Fedderke, Graham, Rajendran (2019)]

Axion oscillation in the recombination → Oscillation of the polarization plane

After averaging, (parity violation) $\sim 0$ and reduction of linear polarization



Axion with $m \gtrsim 10^{-28}\,\mathrm{eV}$ CANNOT explain $\beta \sim 0.3^\circ$ .

The washout effect is limited from the observations:

$$C^{EE}_{l,\mathrm{wo}} \simeq \underbrace{j_0^2(g\langle\phi\rangle_*)}_{\gtrsim 0.99} C^{EE}_{l,0} \qquad \frac{1}{T}\int_0^T \mathrm{d}t\, \cos\left[g\langle\phi\rangle_* \sin\left(\frac{2\pi t}{T}\right)\right] = J_0(g\bar{\phi}_*)$$

→ Justify this formula via numerical simulations

Possibility of $\beta \sim 0.3^\circ$ from an axion oscillating before the recombination?

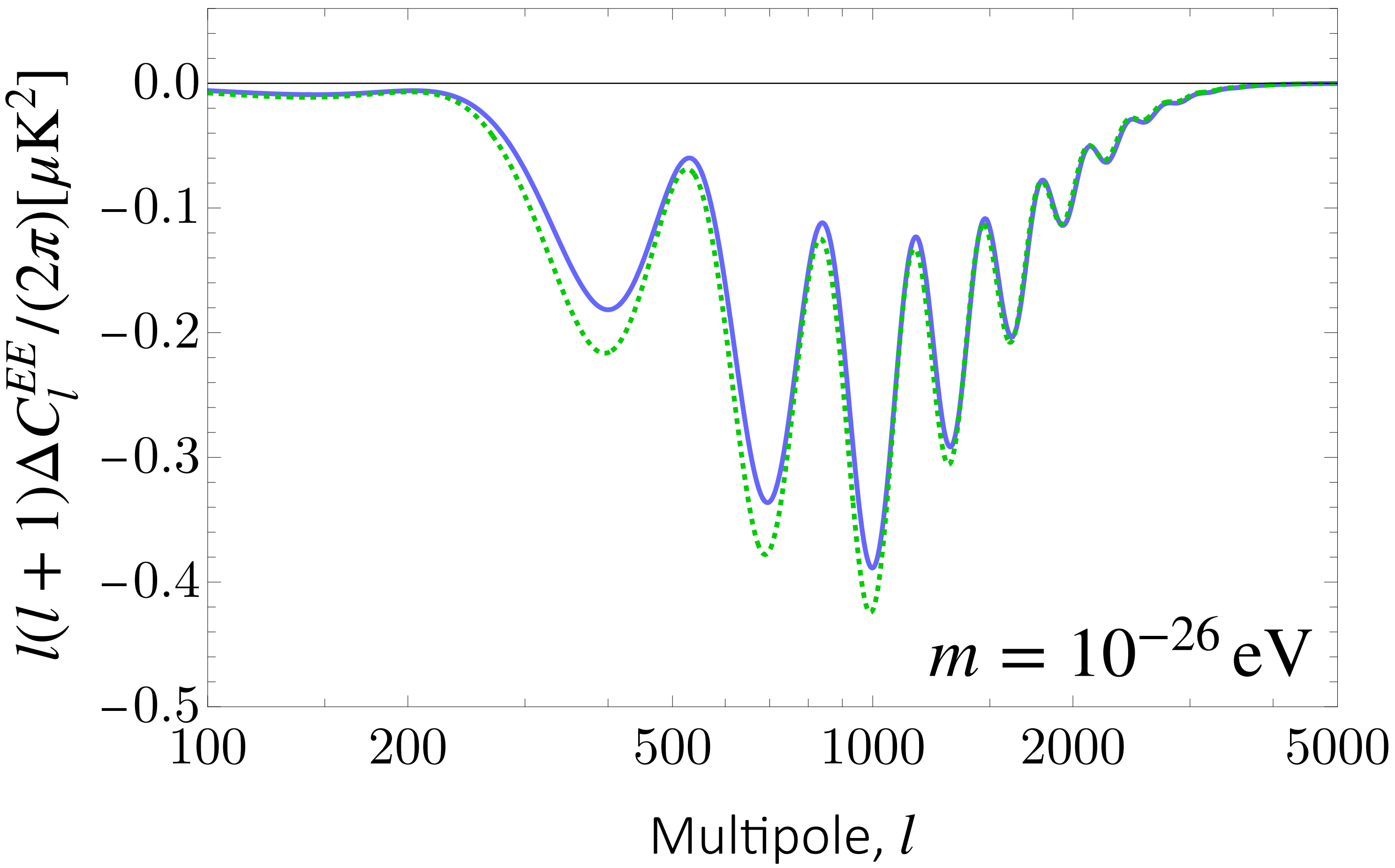
# Washout of polarization

- Numerical result for washout effect

Extend the public code CLASS to include the birefringence.
Tune to include rapid oscillation of the axion. [Nakatsuka, Namikawa, Komatsu (2022)]

$$C^{EB}_{l,\mathrm{num}} \simeq C^{EB}_{l,\mathrm{approx}} \text{ at } \sim 10\,\%$$

The time-evolving $\phi$ amplitude modifies the shape of $C_l^{EE}$, though it is negligibly small.



[KM (2024)]

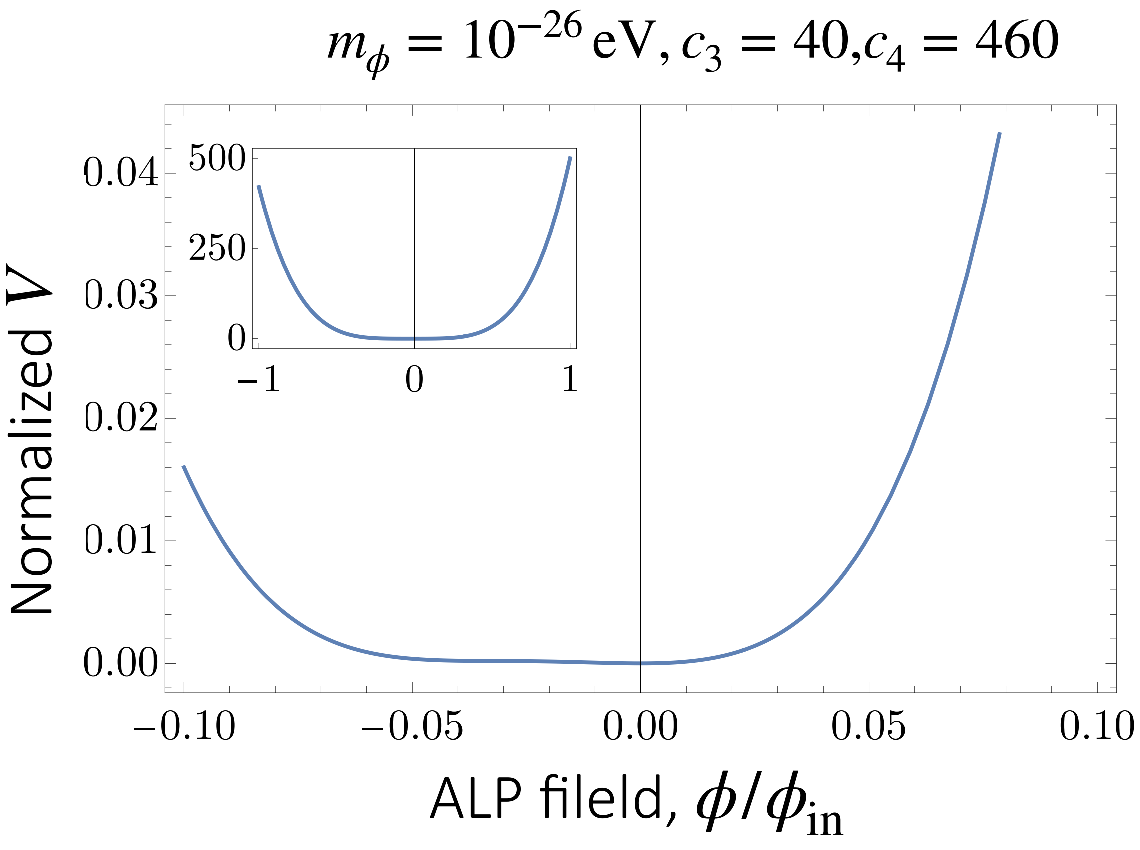
# Birefringence by asymmetric oscillations

- Asymmetric potential

A toy-model potential asymmetric for $\phi \leftrightarrow -\phi$

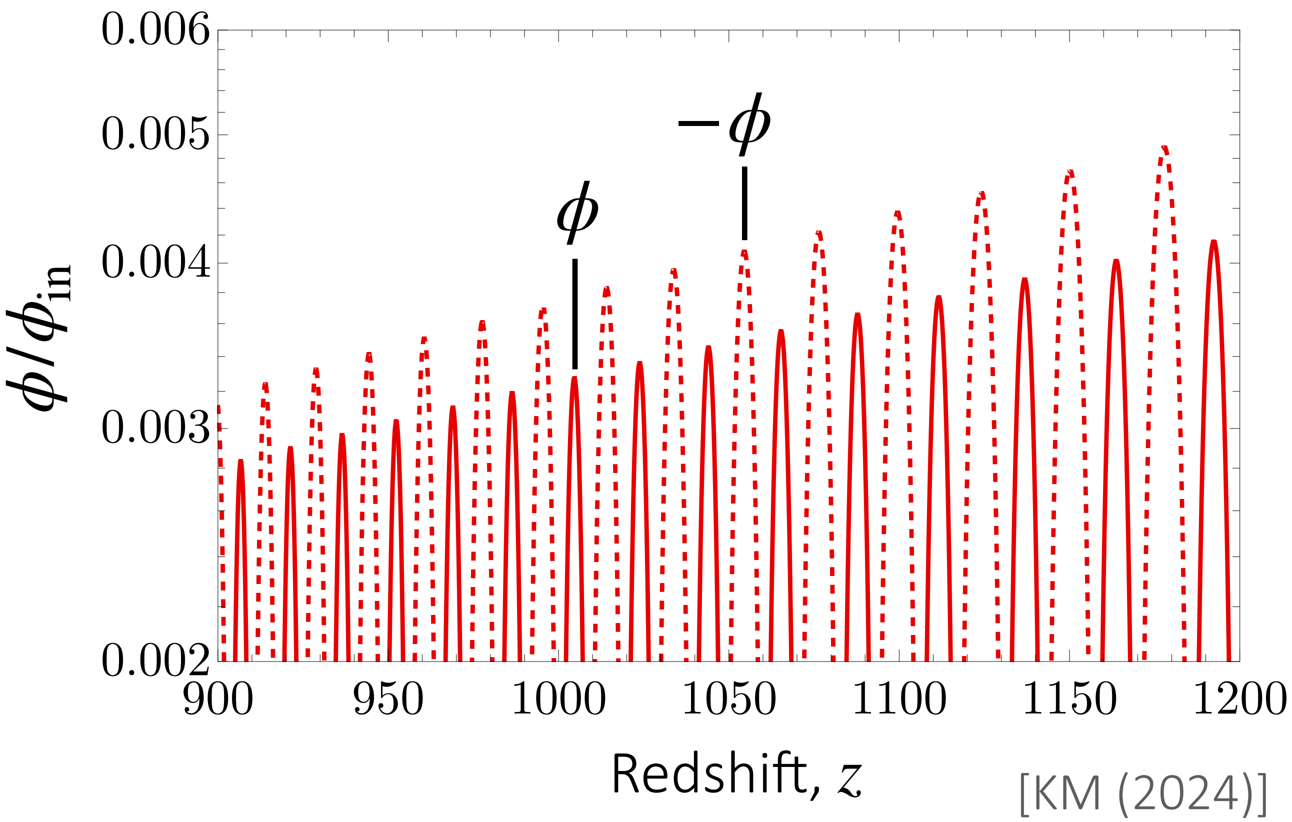
$$V(\varphi) = \frac{m_\phi^2 \phi_{\rm in}^2}{2}\left(\varphi^2 + c_3\varphi^3 + c_4\varphi^4\right) \quad \left(\varphi \equiv \frac{\phi}{\phi_{\rm in}}\right)$$

cf.) superposition of cos-type potentials



When the cubic term is relevant,
the axion oscillation becomes asymmetric.

→ Incomplete cancelation of parity violation
Non-negligible EB spectrum



[KM (2024)]

# Birefringence by asymmetric oscillations

- EB spectrum from asymmetric oscillations

From the average of $\phi$ in the recombination epoch ( $\equiv \bar{\phi}_*$) , we can estimate the EB spectrum:

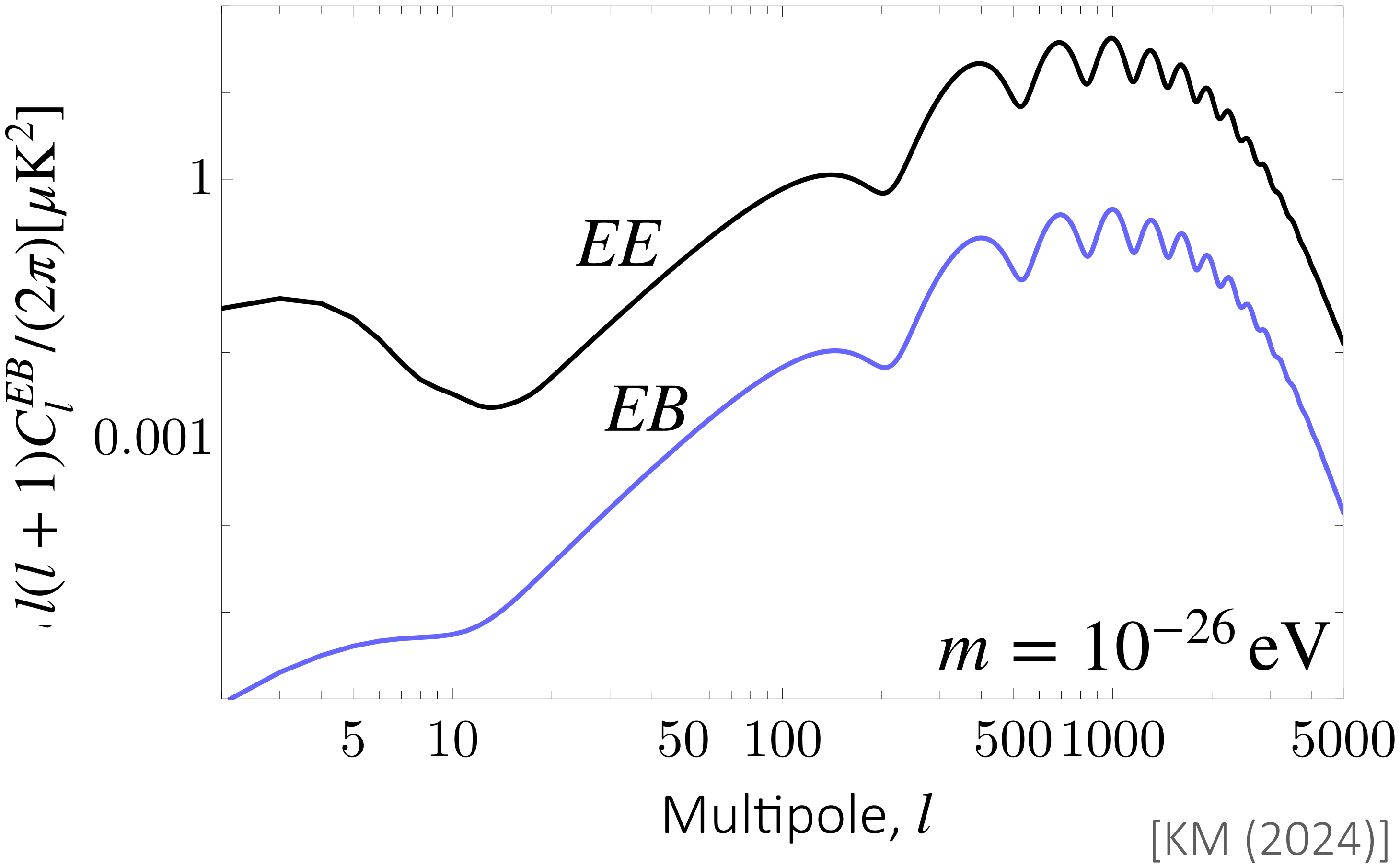
$$C_{l,\mathrm{approx}}^{EB} \simeq \frac{1}{2} C_{l,0}^{EE} \sin(2g\bar{\phi}_*)$$

Numerical result for $C_l^{EB}$:

$C_{l,\mathrm{num}}^{EB} \simeq C_{l,\mathrm{approx}}^{EB}$ at $\lesssim 25\,\%$

We can obtain $C_l^{EB}$ for $\beta \sim 0.3^\circ$ without limited by the washout.

No reionization bump in $C_l^{EB}$



[KM (2024)]

# Future direction

## Isotropic birefringence by dark matter

We found that the asymmetrically oscillating birefringence can induce $C_l^{EB}$ corresponding to $\beta \sim 0.3^\circ$ while consistent with the washout limit for $C_l^{EE}$.

This result opens up the possibility of isotropic birefringence from ALP DM.
However, there remains some problems to solve…

- Simulation for $m \gg 10^{-26}\,\mathrm{eV}$

  Due to high numerical costs, we need improve our code.
  However, we expect that $C_l^{EB}$ hardly depend on $m$ as far as $m \gg 10^{-28}\,\mathrm{eV}$.

- Consistent expansion history including the ALP

  When the cubic and quartic terms are relevant,
  the equation-of-state parameter of the axion, $w_\phi$, deviates from zero.
  We need consistently test the ALP scenario.

# Summary

- Isotropic $\beta \sim 0.3^\circ$ from the CMB polarization data
- Axion can explain this signal.
- If the axion starts to oscillate before the recombination epoch,

$$\begin{cases} \text{EB spectrum is negligibly small.} \\ \text{EE spectrum is reduced due to the washout effect.} \end{cases}$$

- Validated the formula for the washout effect via numerical simulations.
- With an asymmetric potential for the axion,
  we can reproduce $C_l^{EB}$ for $\beta \sim 0.3^\circ$ with safely small washout.

- We expect a similar result even for $m \gtrsim 10^{-22}\,\mathrm{eV}$ .
- Open the possibility of isotropic birefringence by dark matter?