Cosmic birefringence and its implication for axions

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International Workshop on Multi-probe approach to wavy dark matters
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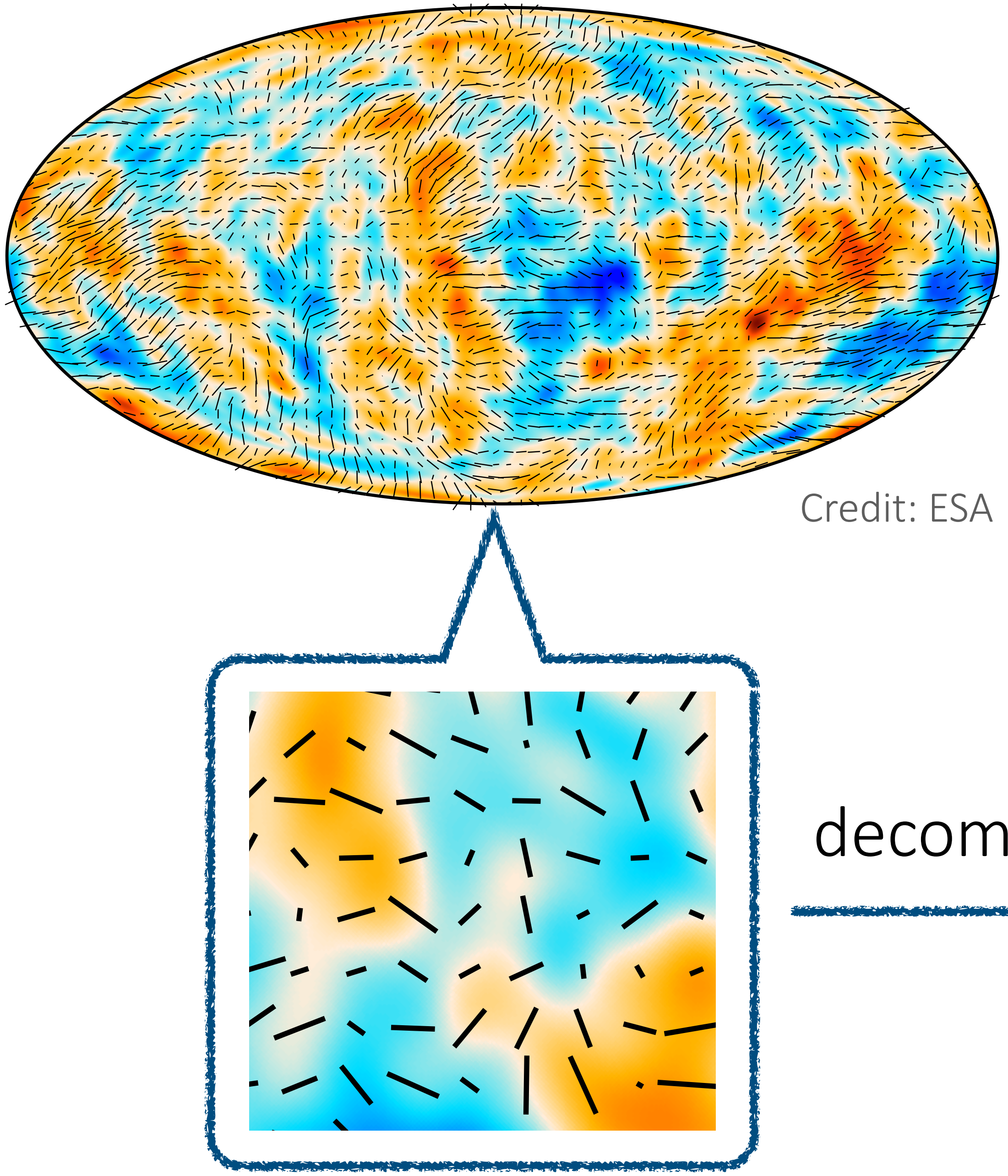
Contents

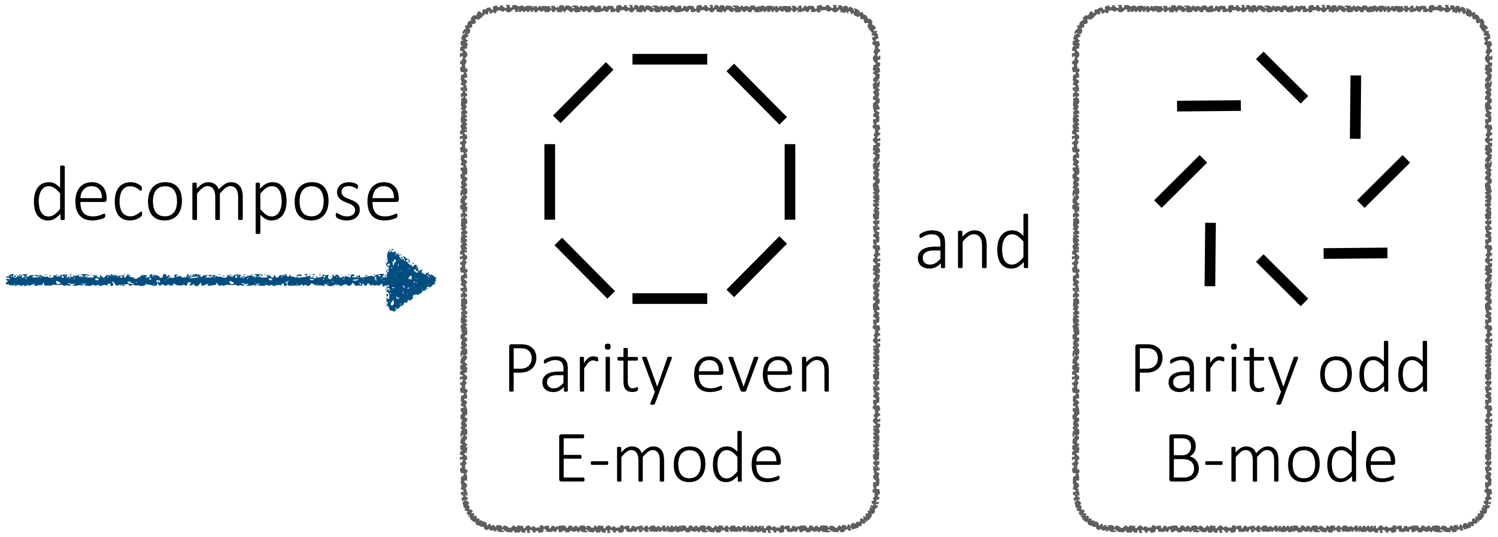
Introduction

- CMB polarization



Credit: ESA

Thomson scatterings induce linear polarization of CMB photons.



decompose

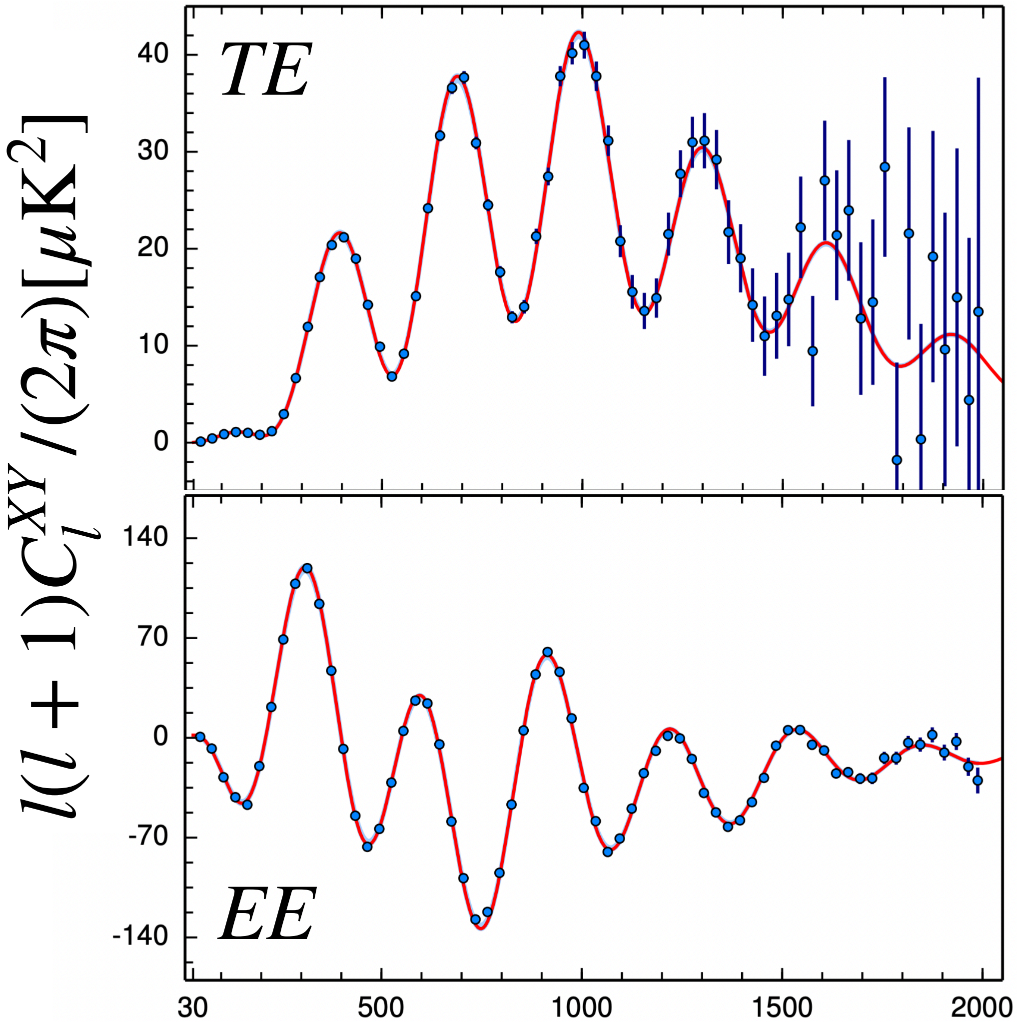
Parity even
E-mode

and

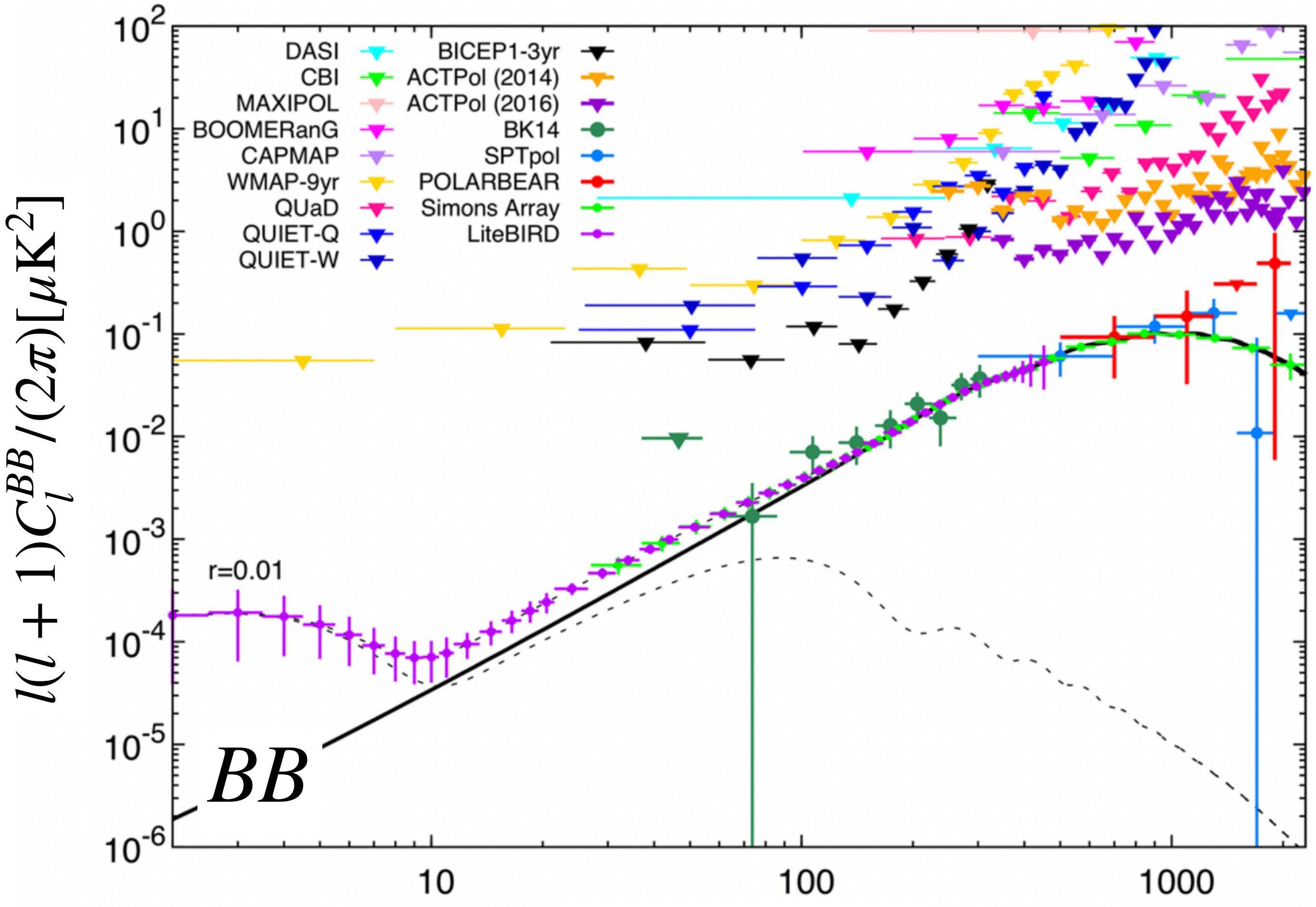
Parity odd
B-mode

Introduction

- CMB polarization and parity



[Planck Collaboration (2015)]



[Hazumi *et al.* (2019)]

If the CMB conserves parity, $\langle E_l B_l \rangle = 0$

Introduction

EB correlation from birefringence

If the linear polarization rotates in the propagation, in general,

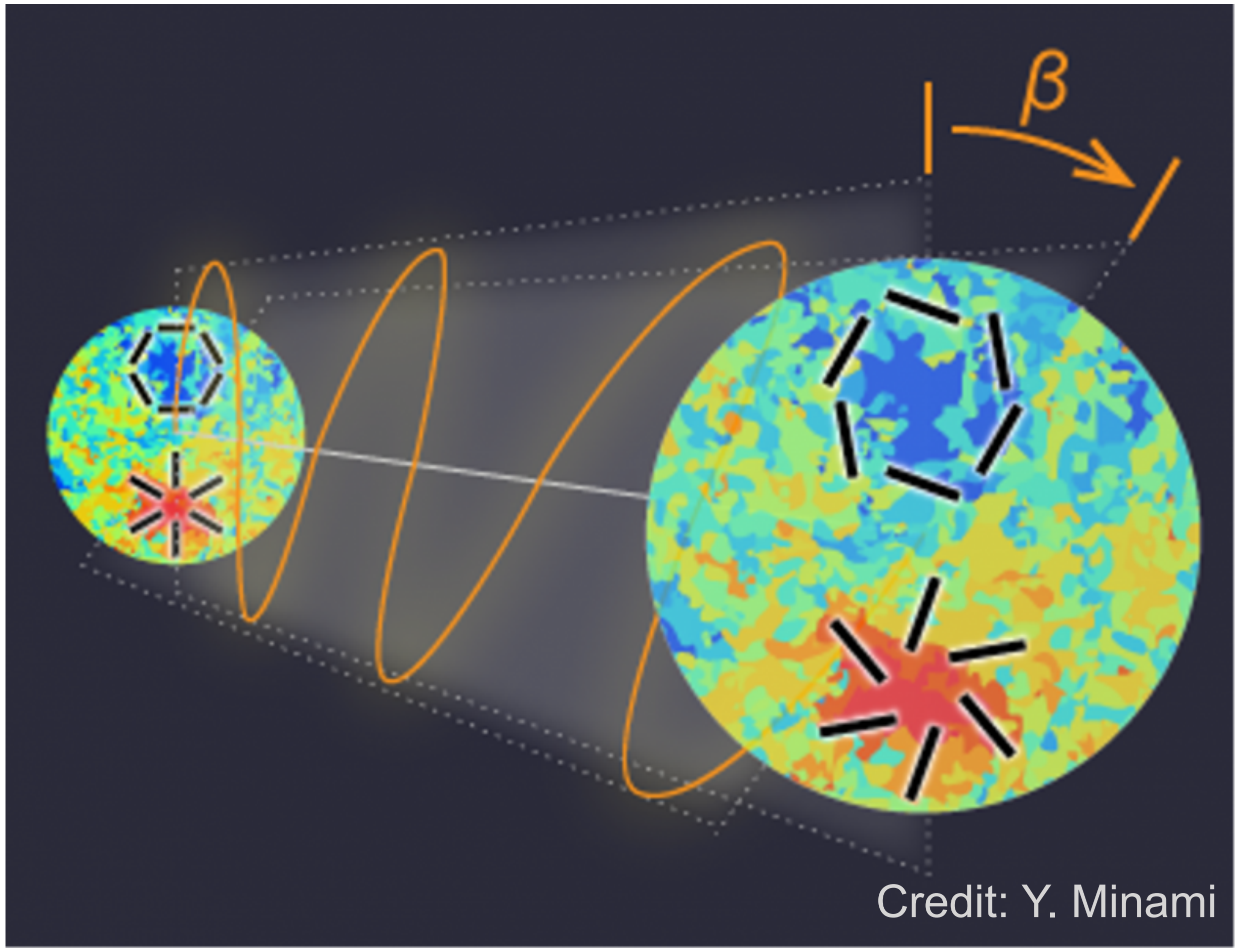
$$\langle E_l B_l \rangle \neq 0 \ .$$

In particular, if all photons experience the same rotation angle β,

After birefringence

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

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



Credit: Y. Minami

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

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

Introduction

- Measurement of cosmic birefringence

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

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

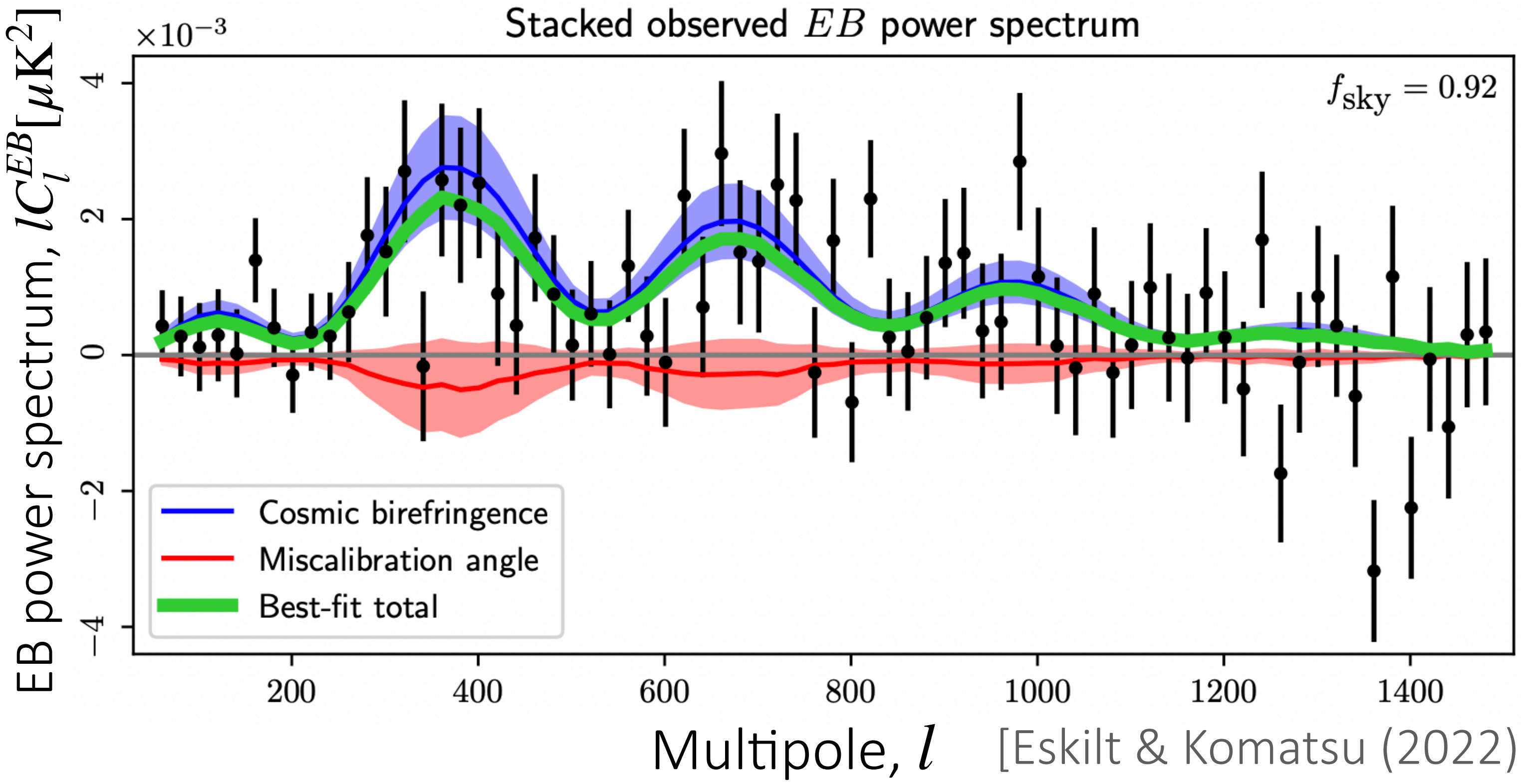
[Minami & Komatsu (2020)]

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

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

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

[Eskilt & Komatsu (2022)]



[Eskilt & Komatsu (2022)]

$$\beta \text{ is } \begin{cases} \text{isotropic.} \\ \text{consistent with no frequency dependence.} \end{cases}$$

[Eskilt (2022)]

Note: These estimate take advantage of galactic foreground to evade the uncertainty due to miscalibration of polarization. → Following talks

Introduction

- Origin of cosmic birefringence

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

- Chern-Simons coupling with axion: $\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ [Carroll (1998)]

  Isotropic birefringence is possible.
  Rotation angle independent of photon frequency

- “Faraday rotation” by magnetic field [Pogosian *et al*. (2011)]

  Magnetic field parallel with photon propagation
  Rotation angle depends on photon frequencies.

- Birefringent dark photon

  → Next talk

Contents

Cosmic birefringence by ALP

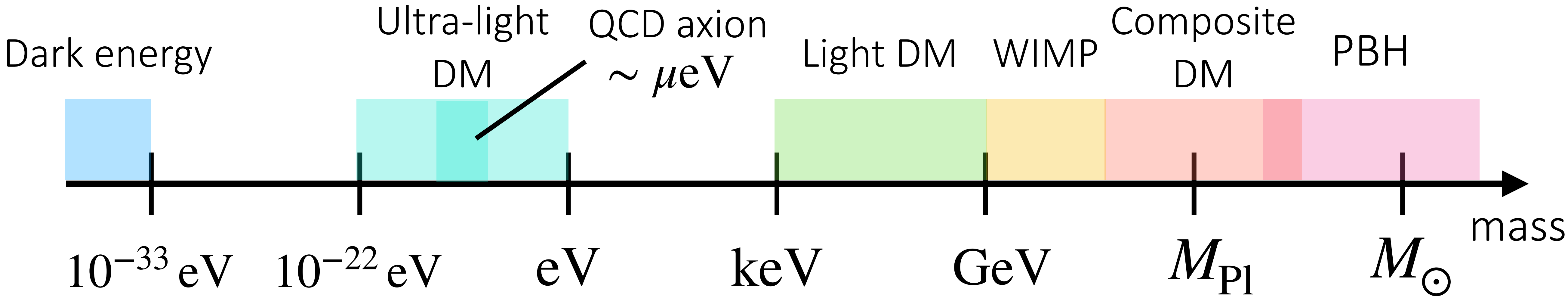
- Axion-like particle (ALP) (Talks in Dec. 1, 2)

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

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

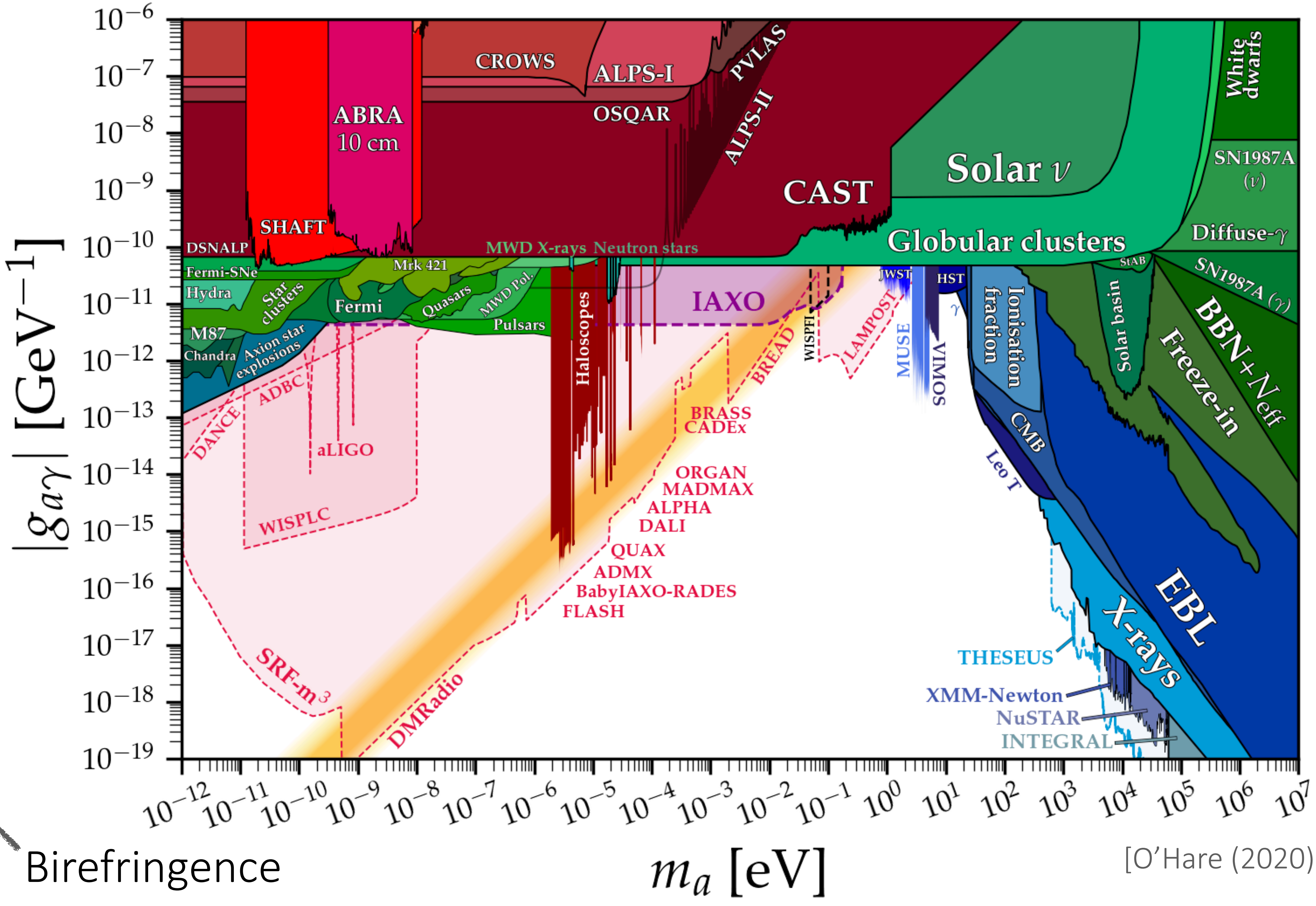
Wide range of mass and coupling

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



Cosmic birefringence by ALP

- ALP-photon coupling



Birefringence

[O'Hare (2020)]

Cosmic birefringence by ALP

- Photon coupled with axion-like particle

Let us consider $$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \underline{\frac{g}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

$\Big\downarrow$ EoM for A_μ

[Ni (1977); Turner & Widrow (1988)]

$$\vec{A}'' - \vec{\nabla}^2\vec{A} + \vec{\nabla}\left(\vec{\nabla}\cdot\vec{A}\right) = g\left(\phi'\vec{\nabla}\times\vec{A} - \vec{\nabla}\phi\times\vec{A}'\right)$$

Consider a plain wave: $\vec{A} \propto e^{-i\omega\eta + i\vec{k}\cdot\vec{x}}$ with $\vec{k} = k\hat{z}$.

$$\underline{k_\pm} = \omega \pm \frac{g}{2}\left(\phi' + \hat{\mathbf{k}}\cdot\vec{\nabla}\phi\right) = \underline{\omega \pm \frac{g}{2}\frac{\mathrm{d}}{\mathrm{d}\eta}\phi(\eta, \vec{x}(\eta))},$$

$\rightarrow$ $$\begin{pmatrix}A_1\\A_2\end{pmatrix} = \underline{\begin{pmatrix}1\\i\end{pmatrix}, \begin{pmatrix}1\\-i\end{pmatrix}}$$ have different dispersion relations.

circular pol.

Cosmic birefringence by ALP

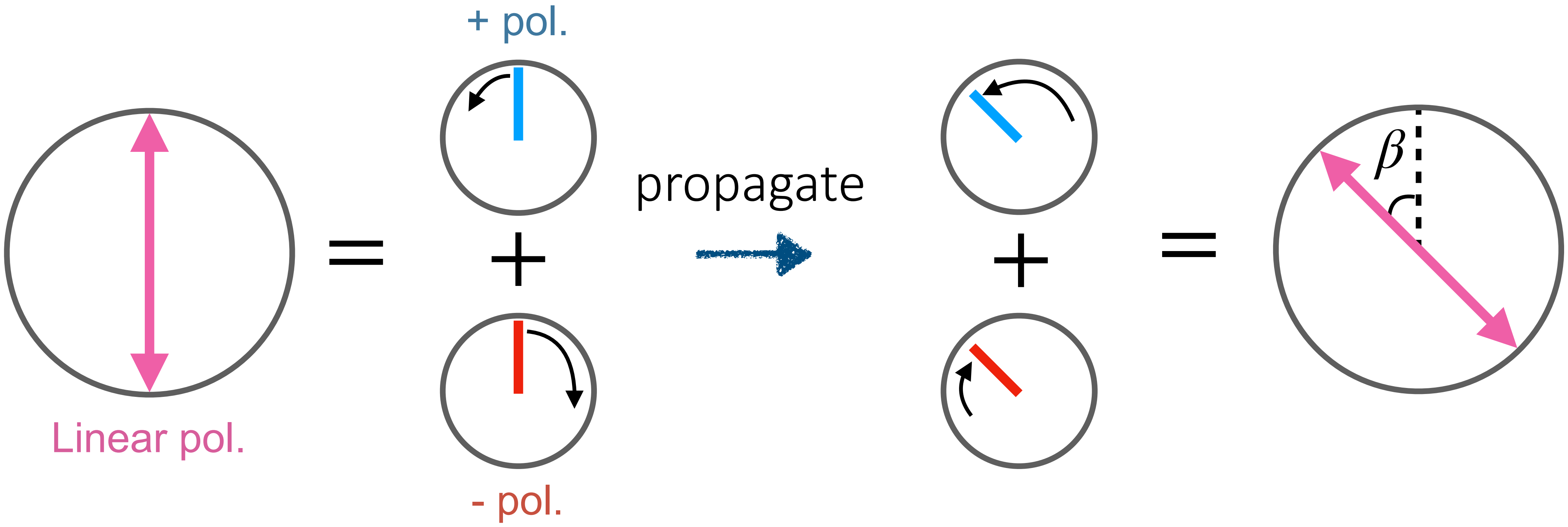
- Rotation of linear polarization

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

→ The plane of linear polarization rotates by

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

[Carroll, Field, Jackiw (1990)]



Cosmic birefringence by ALP

- Birefringence by axion

$$\mathscr{L} \supset \frac{g}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \longrightarrow \beta = \frac{g}{2}(\phi_{\mathrm{obs}} - \phi_{\mathrm{emit}})$$

- β is determined only by g, ϕ_{obs}, and ϕ_{emit}.
- Homogeneous mode of ϕ corresponds to isotropic β.
- β is independent of the photon frequency.

To explain the isotropic β,
homogeneous $\phi(t)$ should vary between the last scattering and now.

Contents

Implication for ALPs

- Dark energy ALP

Let us consider a toy model:

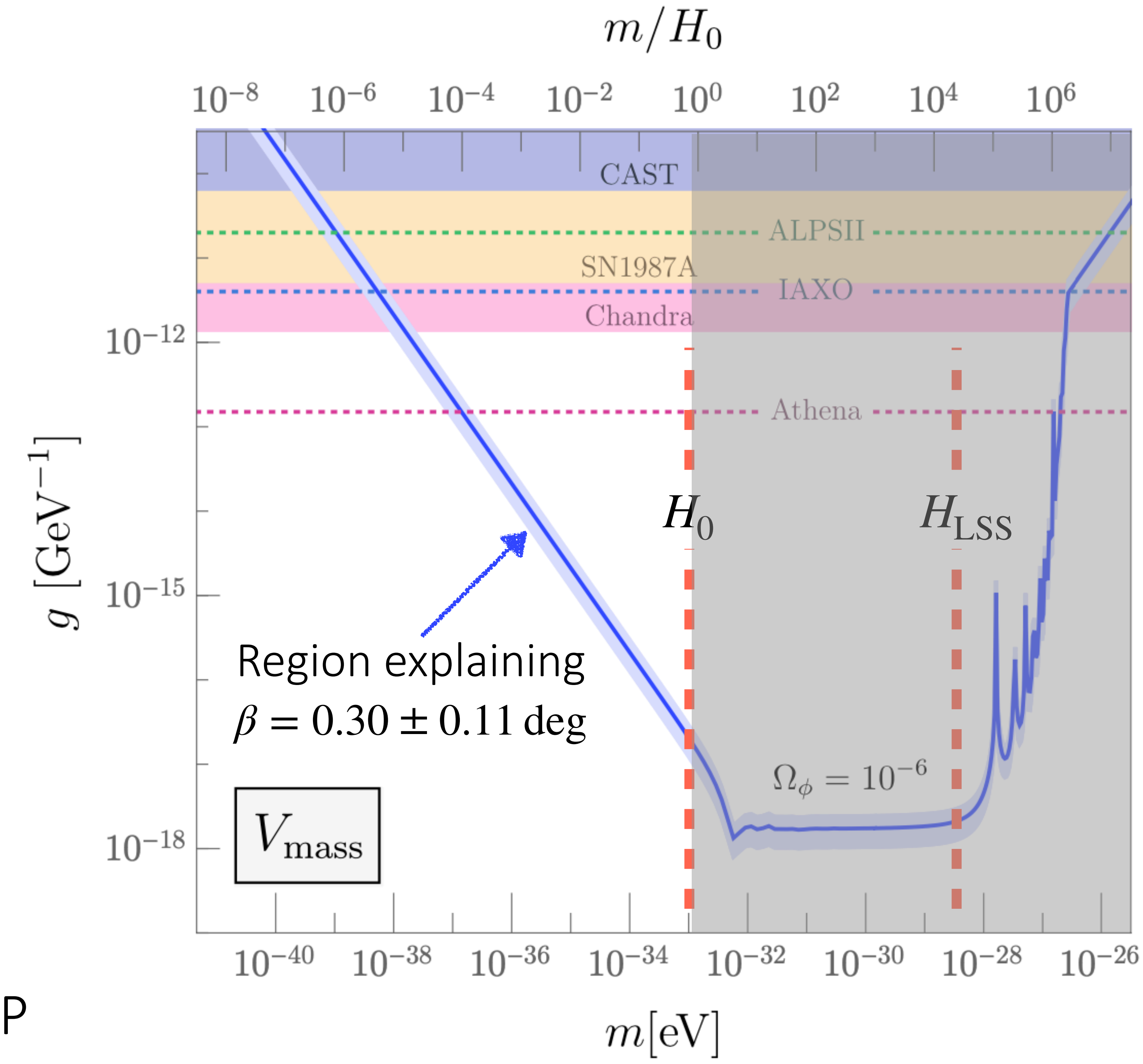
$$V(\phi) = \frac{1}{2}m^2\phi^2$$

and also assume $m < H_0$:

$$\dot{\phi} \simeq -\frac{m^2}{3H}\phi$$

$$\beta \simeq \frac{gm^2\phi_{\rm init}}{6}\int \frac{{\rm d}t}{H(t)}$$

Simple relation for DE-like ALP



Region explaining $\beta = 0.30 \pm 0.11$ deg

[Fujita, KM, Nakatsuka, Tsujikawa (2020)]

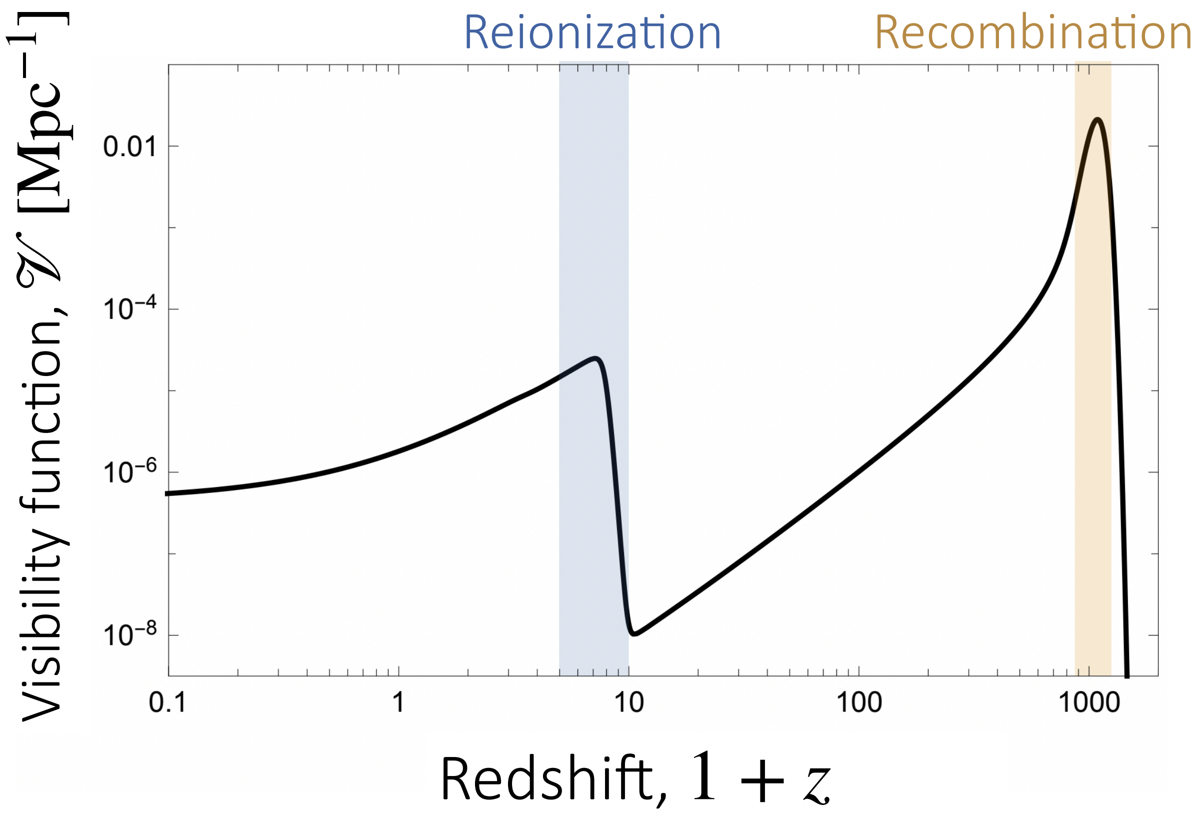
Implication for ALPs

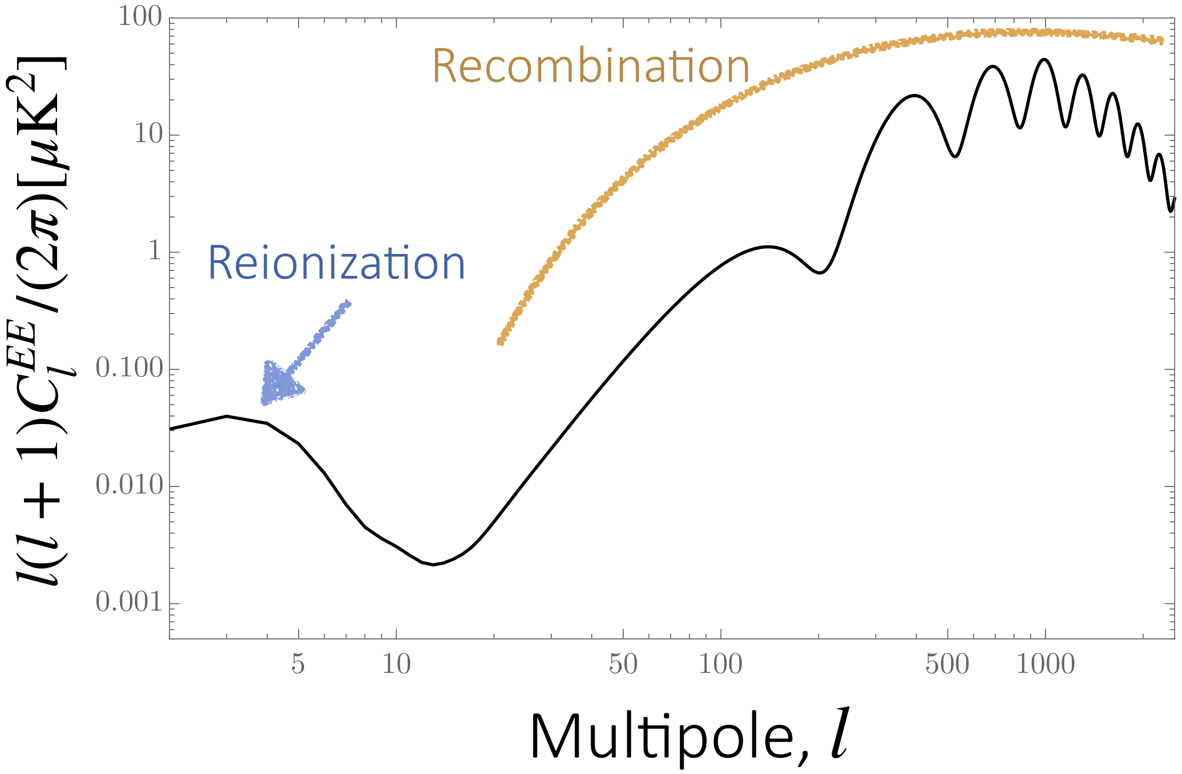
- Heavier ALPs

If $m \gtrsim 10^{-31}\,\mathrm{eV}$, ϕ starts to oscillate before reionization.

If $m \gtrsim 10^{-28}\,\mathrm{eV}$, ϕ starts to oscillate before recombination.

The time evolution of ϕ affects the shape of C_l^{EB}.





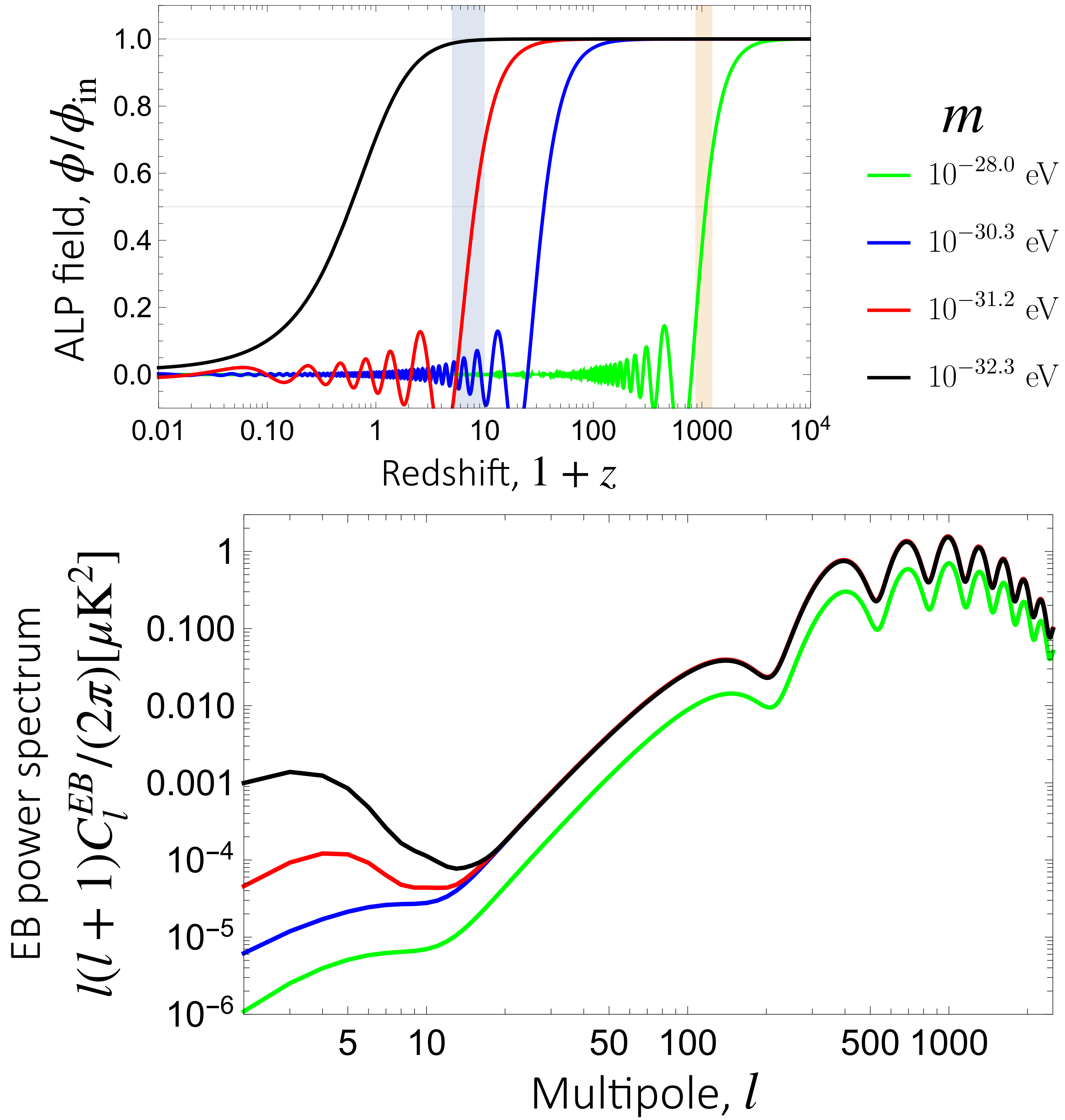
[Nakatsuka, Namikawa, Komatsu (2022)]

Implication for ALPs

- Heavier ALPs

Depending on mass, ϕ evolves during/before the recombination.

The contributions from the reionization/recombination can be suppressed.



[Nakatsuka, Namikawa, Komatsu (2022)]

Implication for ALPs

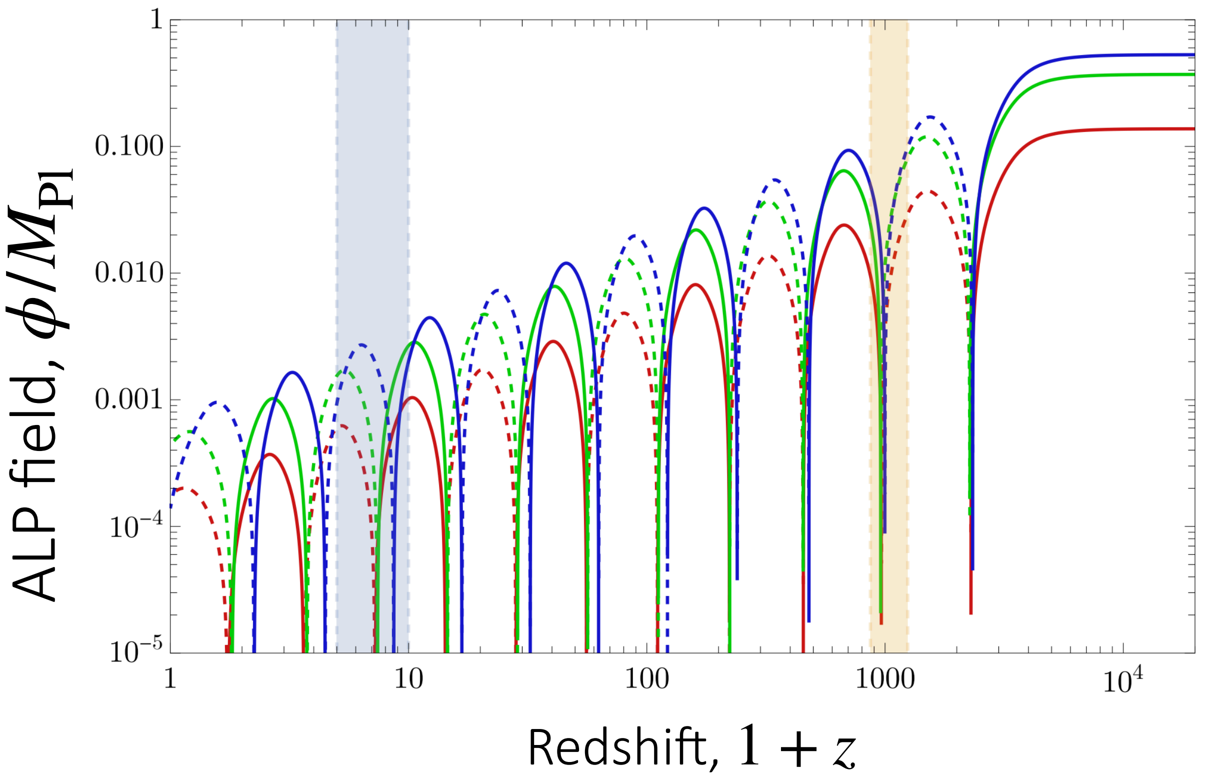
- Early dark energy (EDE)

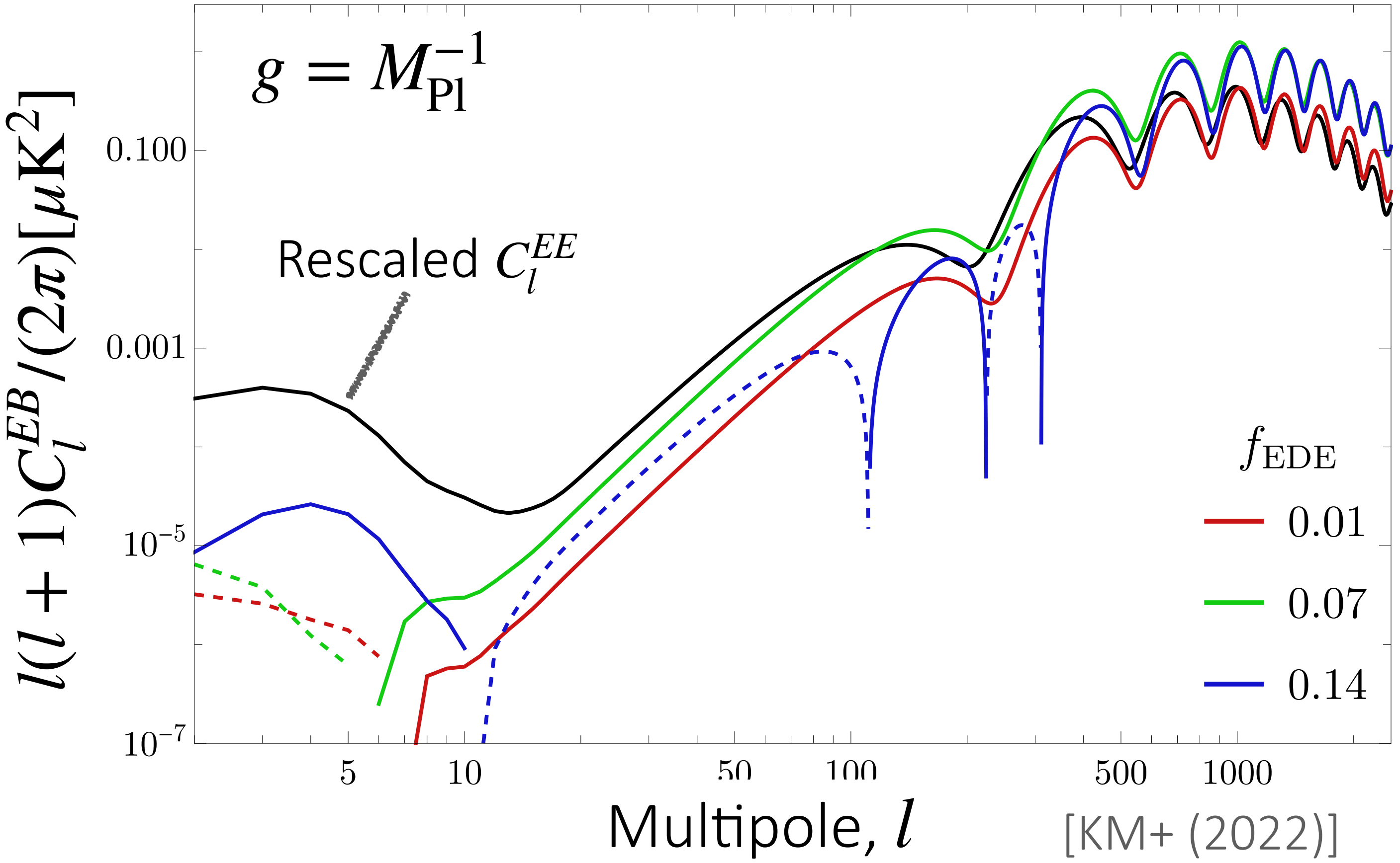
EDE is motivated by Hubble tension and slowly oscillates after $z = \mathcal{O}(10^4)$.

Due to the sign flip of ϕ at $z \sim 10^3$, the sign of C_l^{EB} can also flip.

From the violation of $C_l^{EB} \propto C_l^{EE}$, the birefringence from EDE can be constrained. [Eskilt, KM+ (2023)]

C_l^{EB} works a probe of $\phi(t)$.





[KM+ (2022)]

Implication for ALPs

- Other effects of cosmic birefringence
  - Oscillating birefringence

    Local ALP DM oscillates.

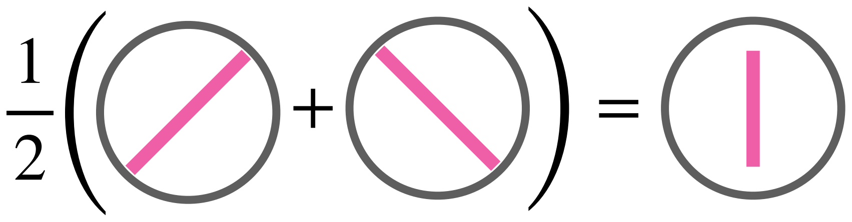
    Oscillation of polarization

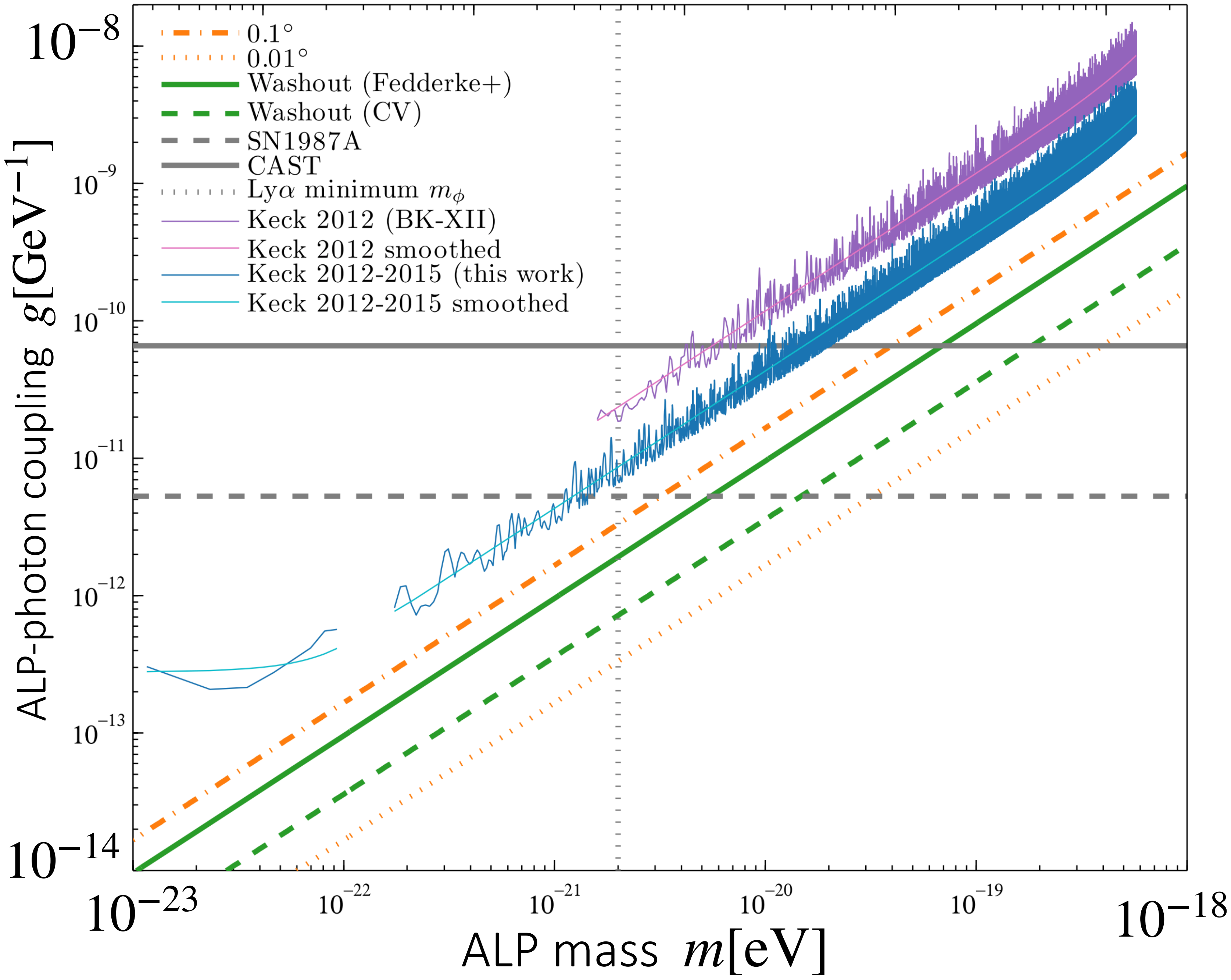
  - Washout

    ALP oscillation during LSS

    Suppress the polarization

    [Fedderke, Graham, Rajendran (2019)]





[BICEP/Keck Collaboration (2022)]

Implication for ALPs

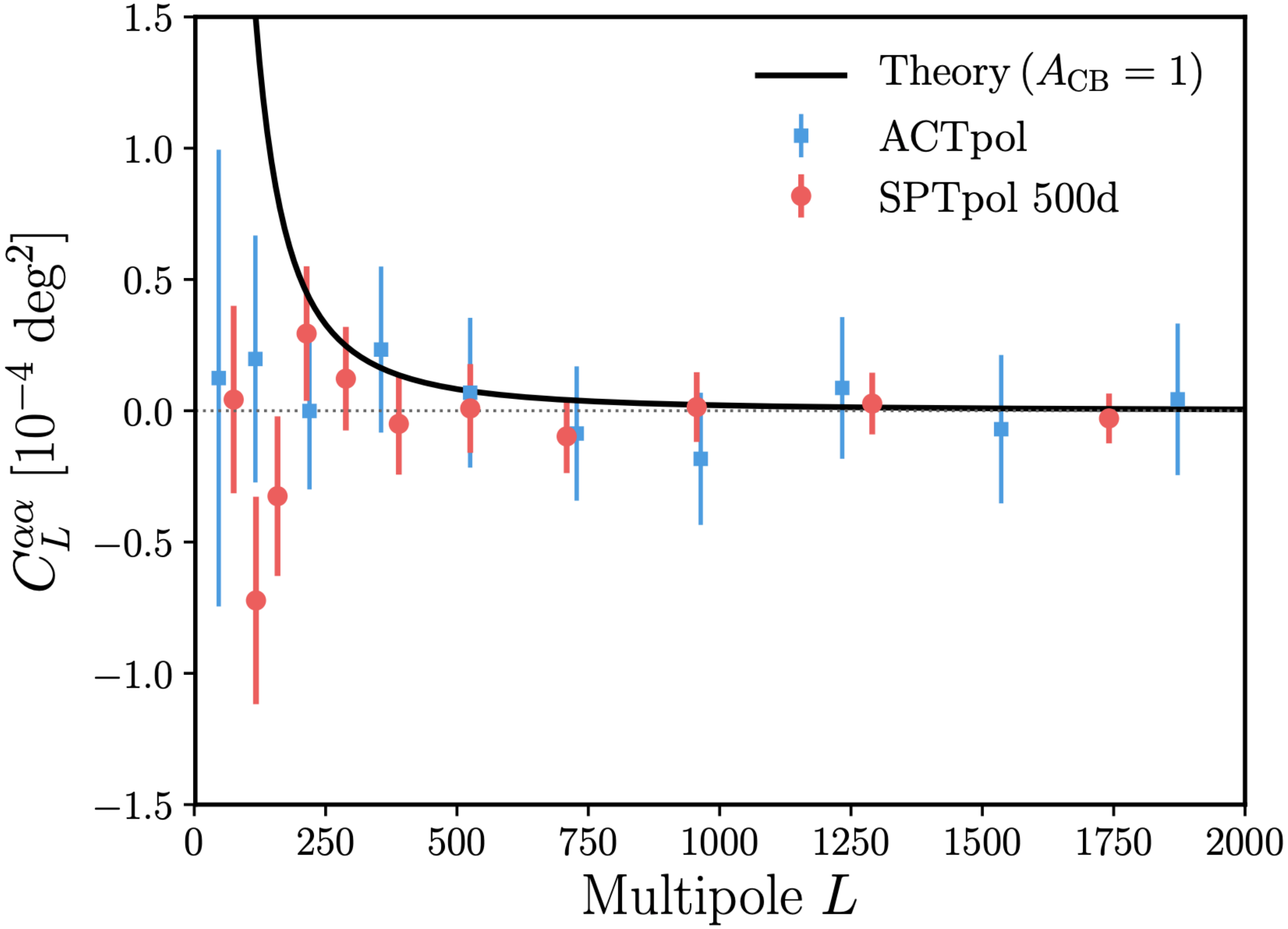
Other effects of cosmic birefringence

- Anisotropic birefringence

If ALP is the origin of $\beta \simeq 0.3^\circ$, perturbations at LSS will induce anisotropic birefringence $\alpha(\hat{n})$, which is not detected yet.

Constraints on

$\left(\begin{array}{l}\text{ALP isocurvature pert.}\\ \text{primordial magnetic fields}\end{array}\right.$



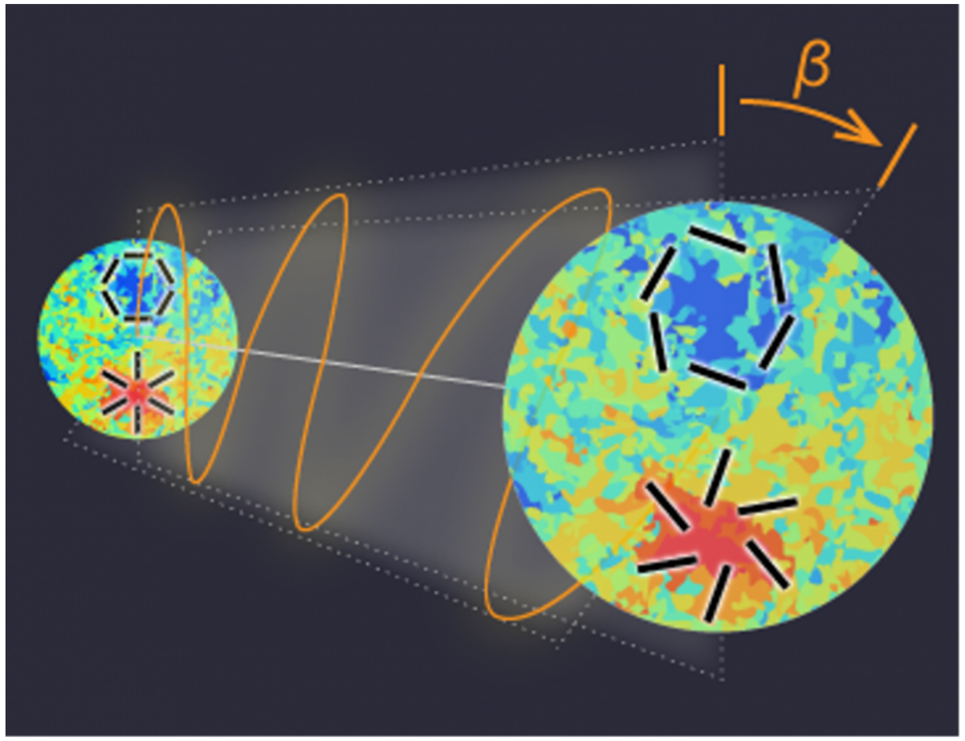
[SPT Collaboration (2020)]

Contents

Summary

- Parity-violating signals in the CMB polar. data, which imply isotropic cosmic birefringence:

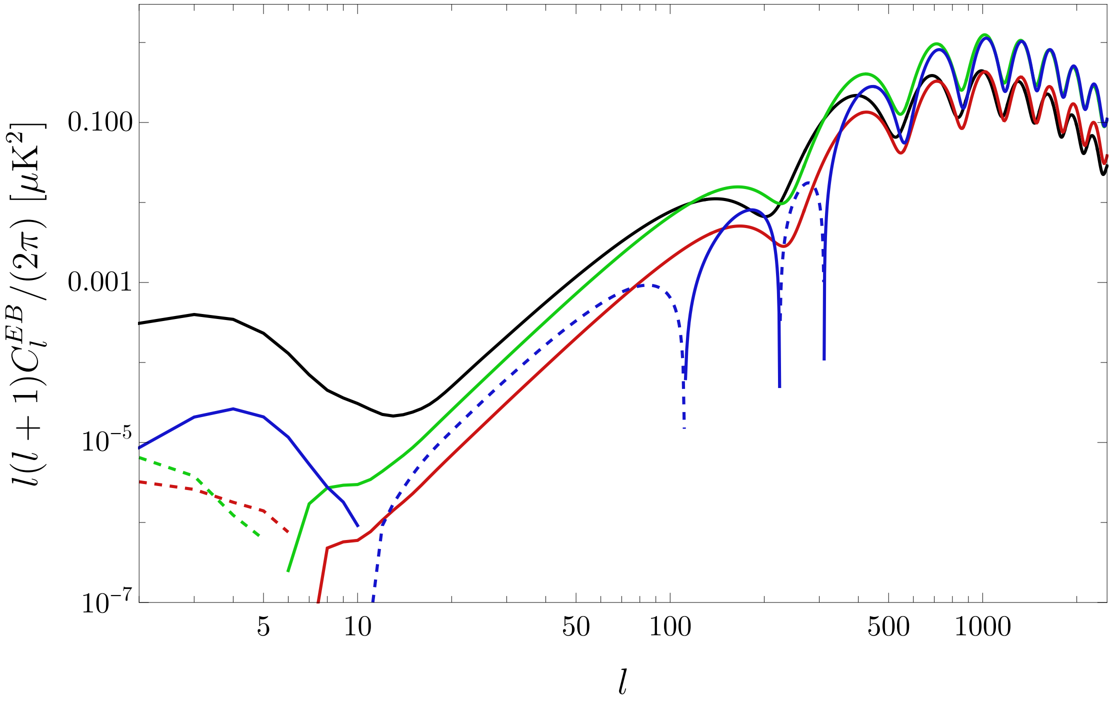
$$\beta \simeq 0.3^\circ$$



- $\phi F\tilde{F}$ of ALP can be the origin of β :

$$\beta = \frac{g}{2}\Delta\phi$$

- While $C_l^{EB} \propto C_l^{EE}$ for uniform β, time evolution of ALP leads to different shape of C_l^{EB}.



- Cosmic birefringence by ALP can also be tested by anisotropic biref. and oscillation of polarization.