A phase uncertainty of cosmic birefringence

mini exam

Gakujyutu-Henkaku High School

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Q. Solve the following equation for β

$$\tan\ \beta = \frac{1}{\sqrt{3}}$$

A. $\beta = \frac{\pi}{6}$ $+m\pi$ (m is integers)

score : 1pt/5

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Cosmic Birefringence (宇宙複屈折)

- A new signal from CMB Minami & Komatsu (2020)

$$\tan(4\beta) \sim C_l^{EB}/C_l^{EE}$$ (β : rotation angle)

$$\beta = 0.34 \pm 0.09 \text{ deg}$$ Eskilt & Komatsu (2022)

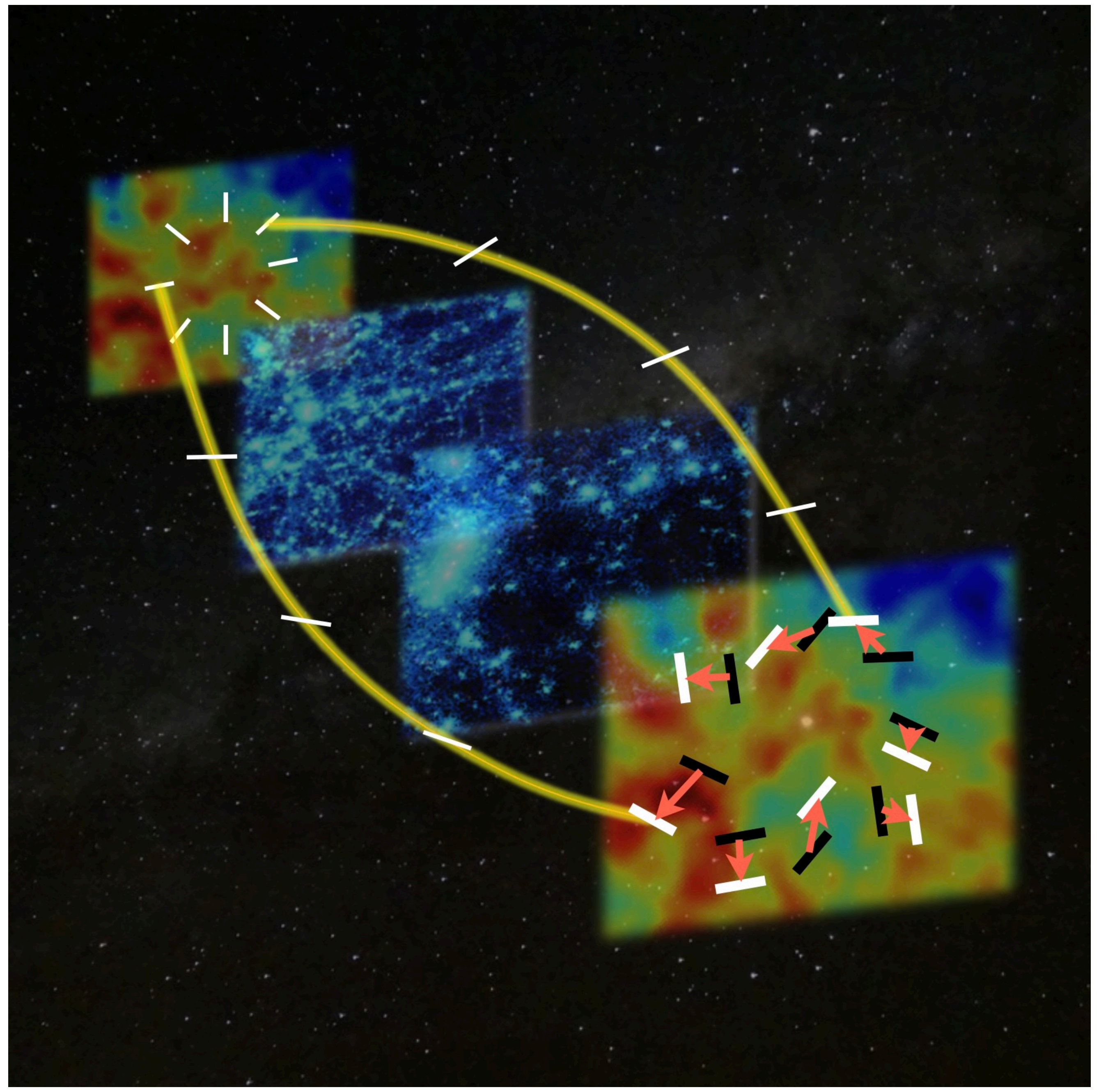
- Violating Parity Symmetry : beyond standard model ?

  Nakai et al. (2023) → Obata-san (小幡さん)'s talk

from IPMU HP

- Origin : Axion-like Particle ?

  Carroll et al. (1990), Harari & Sikivie (1992), Carroll (1998)



Naokawa & Namikawa,Gravitationl lensing effect on cosmic birefringence, PRD, **108**, 063525 , 2023 ,Copyright (2023) American Phsyical Soceity

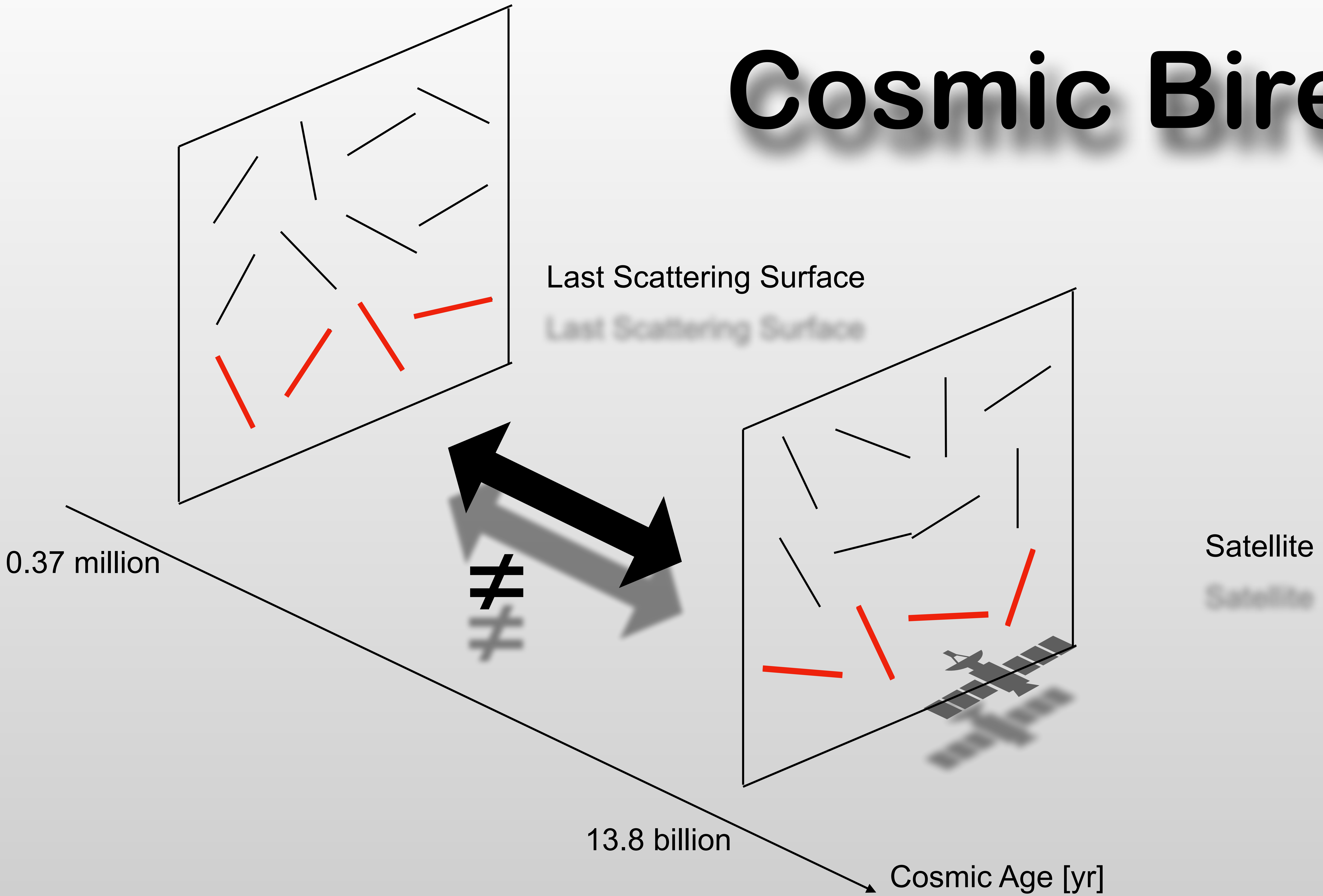
This work

- tan(4β) is a periodic function
- Don't we have to consider the phase uncertainty ?
- Does β really have a small value ?
- We reconsider possible solutions of β which can explain observations.

What is cosmic birefringence

Cosmic Birefringence

Lue et al. (1999)



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- CMB Observables

parity-even / parity-odd

Temperature Θ Polari E B

parity-even

Last Scattering Surface

- CMB power spectrum

$C_l^{\Theta\Theta}$ $C_l^{\Theta E}$ C_l^{EE} C_l^{BB} C_l^{EB} $C_l^{\Theta B}$

even even even even odd odd

Odd components become 0 in the parity symmetric universe.

0.37 million

13.8 billion

Cosmic Age [yr]

Cosmic Birefringence

Lue et al. (1999)

✔ Parity Violation

✔ $C_l^{\Theta B}$ C_l^{EB}

How to determine β

: ALP : photon

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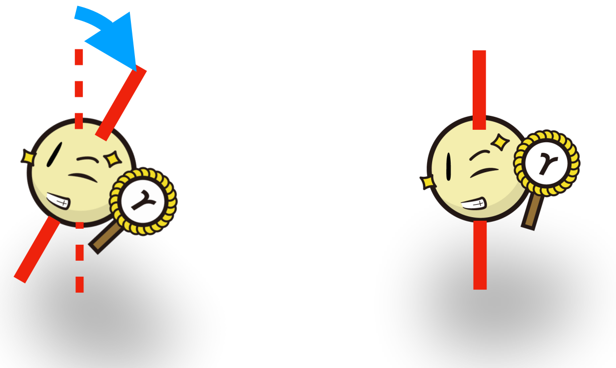
When the polarization plane rotates by β, CMB power spectrum is transformed as



$$C_l^{\Theta E,o} = C_l^{\Theta E}\cos(2\beta) \qquad C_l^{\Theta E,o} \simeq C_l^{\Theta E}$$

$$C_l^{\Theta B,o} = C_l^{\Theta E}\sin(2\beta) \qquad C_l^{\Theta B,o} \simeq 2\beta C_l^{\Theta E}$$

SN is low

$$C_l^{EE,o} = C_l^{EE}\cos^2(2\beta) + C_l^{BB}\sin^2(2\beta) \qquad C_l^{EE,o} \simeq C_l^{EE}$$

$$\xrightarrow{\beta \ll 1}$$

$$C_l^{BB,o} = C_l^{EE}\sin^2(2\beta) + C_l^{BB}\cos^2(2\beta) \qquad C_l^{BB,o} \simeq C_l^{BB}$$

$$C_l^{EB,o} = \frac{1}{2}(C_l^{EE} - C_l^{BB})\sin(4\beta) \qquad C_l^{EB,o} \simeq 2\beta(C_l^{EE} - C_l^{BB})$$

sensitive to β

From these, we can derive

$$C_l^{EB,o} = \frac{1}{2}(C_l^{EE,o} - C_l^{BB,o})\tan(4\beta) \qquad \therefore \qquad \tan(4\beta) = \frac{2C_l^{EB,o}}{C_l^{EE,o} - C_l^{BB,o}}$$

This work : Phase Uncertainty

$$\tan(4\beta) = \frac{2C_l^{EB,o}}{C_l^{EE,o} - C_l^{BB,o}}$$

$$\beta = \frac{1}{4}\arctan\left(\frac{2C_l^{EB,o}}{C_l^{EE,o} - C_l^{BB,o}}\right)$$

	β [deg]	Data
Minami & Komatsu (2020)	0.35 ± 0.14	Planck
P. Diego-Palazuelos et al. (2022)	0.30 ± 0.11	Planck
J. Eskilt (2022)	0.33 ± 0.10	Planck
J. Eskilt & Komatsu (2022)	0.34 ± 0.09	Planck + WMAP

$$\beta = \frac{1}{4}\arctan\left(\frac{2C_l^{EB,o}}{C_l^{EE,o} - C_l^{BB,o}}\right) + m\pi \quad (m \in \mathbb{Z})$$

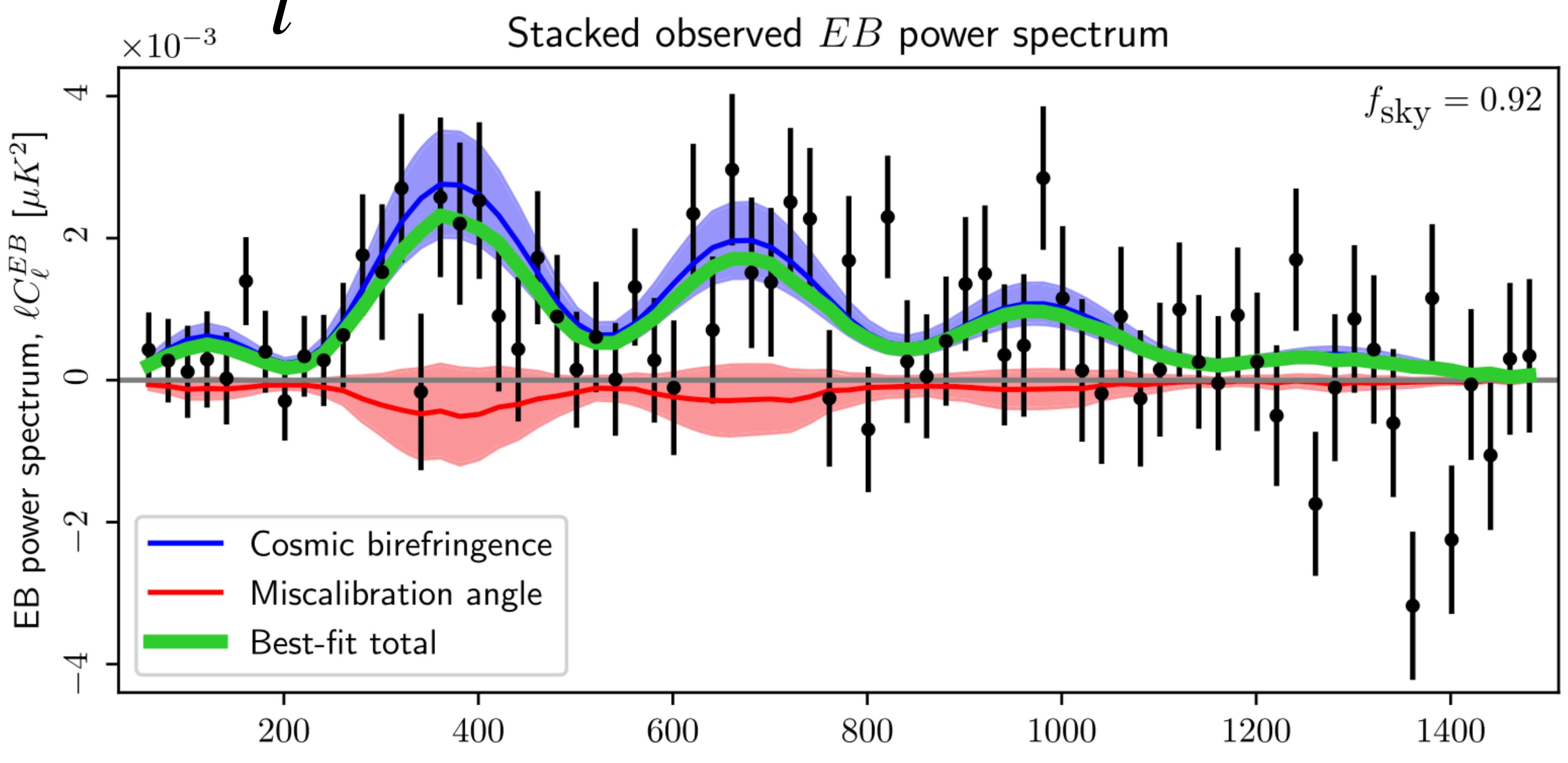
$\equiv \beta_0 \sim 0.3$ deg

$\pm 180, 360, 540, \cdots$ deg

can explain → $C_l^{EB,o}$

can also explain ↓

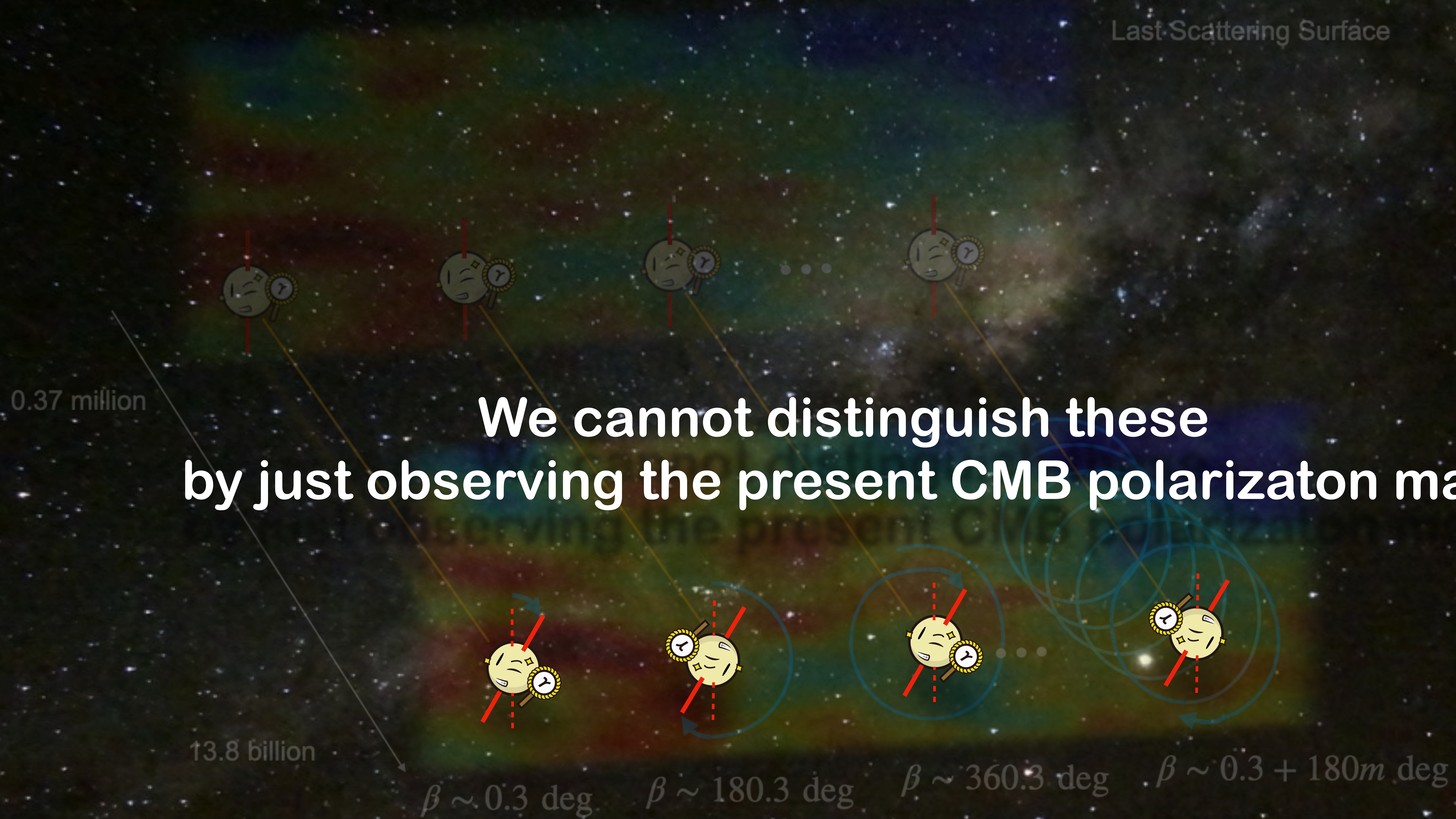
$$C_l^{\Theta E,o} \quad C_l^{\Theta B,o} \quad C_l^{EE,o} \quad C_l^{BB,o}$$



J. Eskilt & Komatsu, PRD, 106, 063503 (2022)

Last Scattering Surface
0.37 million
13.8 billion
$\beta \sim 0.3$ deg
$\beta \sim 180.3$ deg
$\beta \sim 360.3$ deg
$\beta \sim 0.3 + 180m$ deg

We cannot distinguish these
by just observing the present CMB polarizaton map



This work : Phase Uncertainty

The general solution of Cosmic Birefringence angle β is

$$\beta = \underbrace{\frac{1}{4}\arctan\left(\frac{2C_l^{EB,o}}{C_l^{EE,o} - C_l^{BB,o}}\right)}_{\equiv \beta_0 \sim 0.3\ \mathrm{deg}} + \underbrace{m\pi}_{\pm 180,\ 360,\cdots\ \mathrm{deg}}$$

m : maki-maki parameter

$$m = \pm 1,2,3,\cdots \in \mathbb{Z}$$

- not only $\beta \sim 0.3^\circ$ but also $\beta \sim 180.3^\circ$, 360.3°, $\cdots$ can explain all the observed CMB power spectra.
- This formula does not depend on the origin of cosmic birfringence.

Question :

No matter how large the value of β is,

is it physically permitted as a solution of cosmic birefringence ?

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No matter how large value β is, is it physically permitted as a solution of cosmic birefringence ?

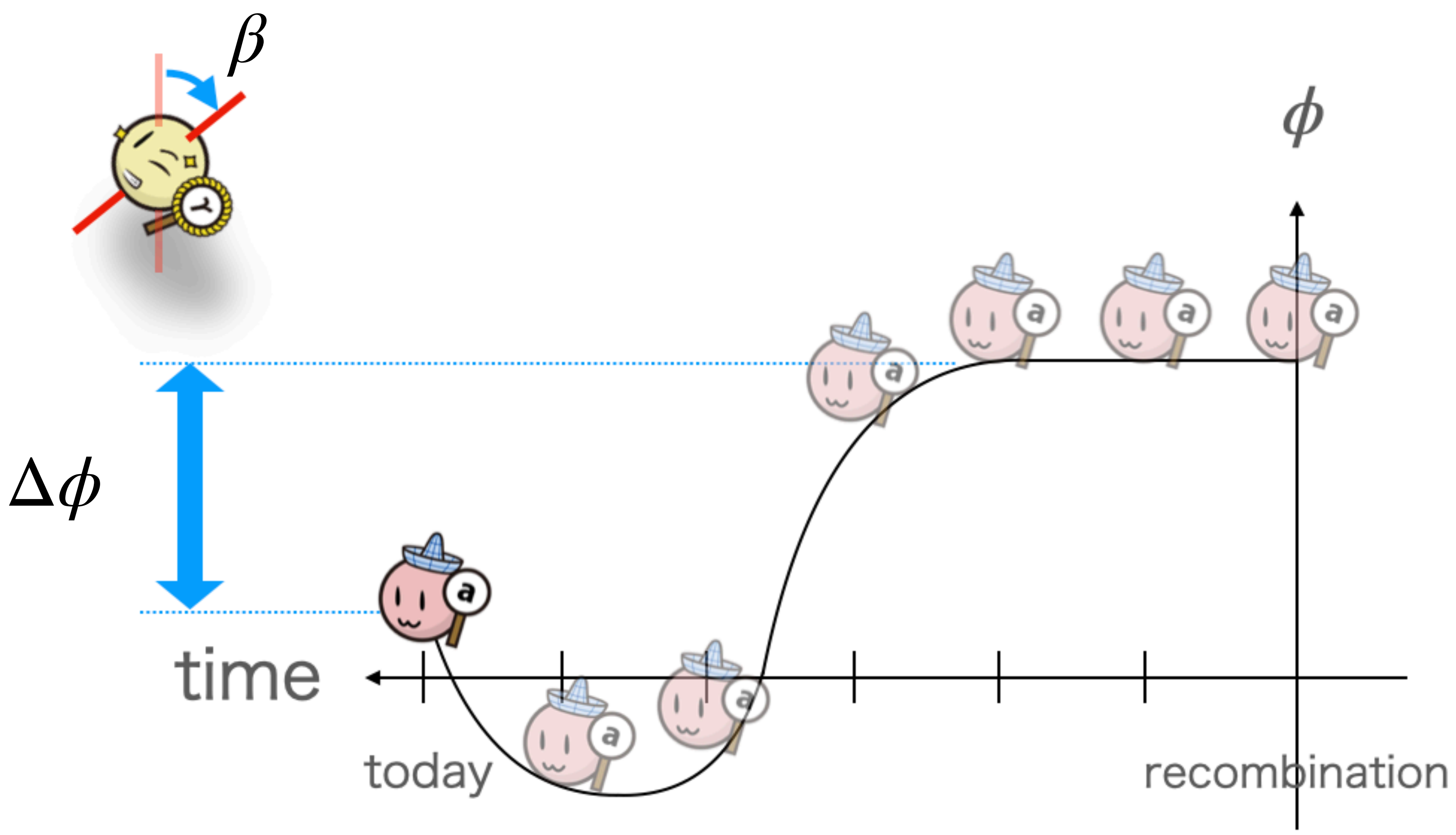
- Assuming the origin of Cosmic Birefringence is ALP,

$$\mathscr{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Rightarrow \beta \propto g\Delta\phi \sim g\phi_{\rm ini}$$

coupling constant btw photon & ALP variation of ALP

large β (large m) means large $g\phi_{\rm ini}$



- Constraint 1 : Upper limit on $g\phi_{\rm ini}$ → $\beta \lesssim 10^6$ deg $(m \lesssim 10^4)$ for 10^{-32} eV $\lesssim m_\phi \lesssim 10^{-28}$ eV

  Fujita et al. (2021)

- Constraint 2 : Anistropic cosmic birefringence Greco et al. (2023), Greco et al. (2024)

  Fluctuation of ϕ should make anistropy of β, which is amplified by large β.

- Constraint 3 : spectral shape of power spectrum Nakatsuka et al. (2021)

  The time evolution of $\phi(t)$ during recombination or reionization modifies the shape of power spectrum , which is amplifed by large β.