KiloByte Cosmic Birefringence and ALP domain walls

Feb. 2. 2020 @ APCTP ``Dark Matter as a Portal to New Physics”

Fumi Takahashi (Tohoku)

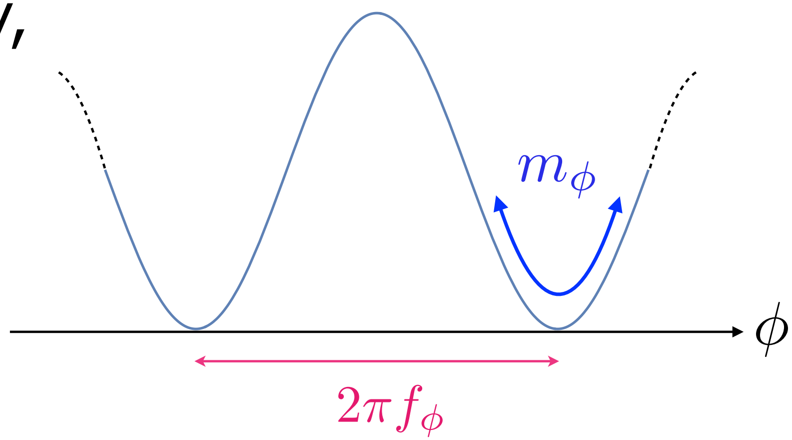
Based on 2012.11576 with Wen Yin

1. Introduction

1. Introduction

An axion enjoys a (discrete) shift symmetry,

$$\phi \to \phi + 2\pi f_\phi$$



which implies the existence of degenerate vacua.

The properties of the axion is characterized by mass m_ϕ and decay constant f_ϕ.

If the axion is very light and it has only feeble interactions, it may play an important role in cosmology (DM, DE,$\cdots$).

Axion couplings to the SM particles:

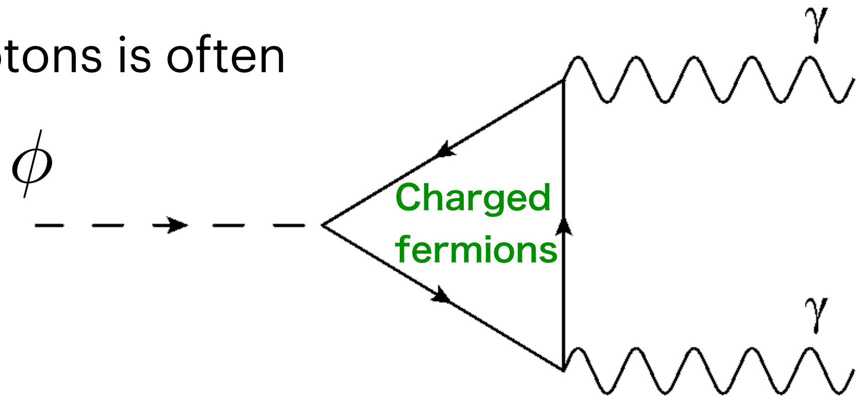
- Photons

$$\mathcal{L}_{\phi\gamma} = -c_\gamma \frac{\alpha}{4\pi} \frac{\phi}{f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu} = -\frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu},$$

$c_\gamma = O(1)$ in most models, but model-dependent.

cf. clockwork axion,
Higaki et al 1603.02090
Farina et al 1611.09855

Axion coupled to photons is often referred to as **ALP**.



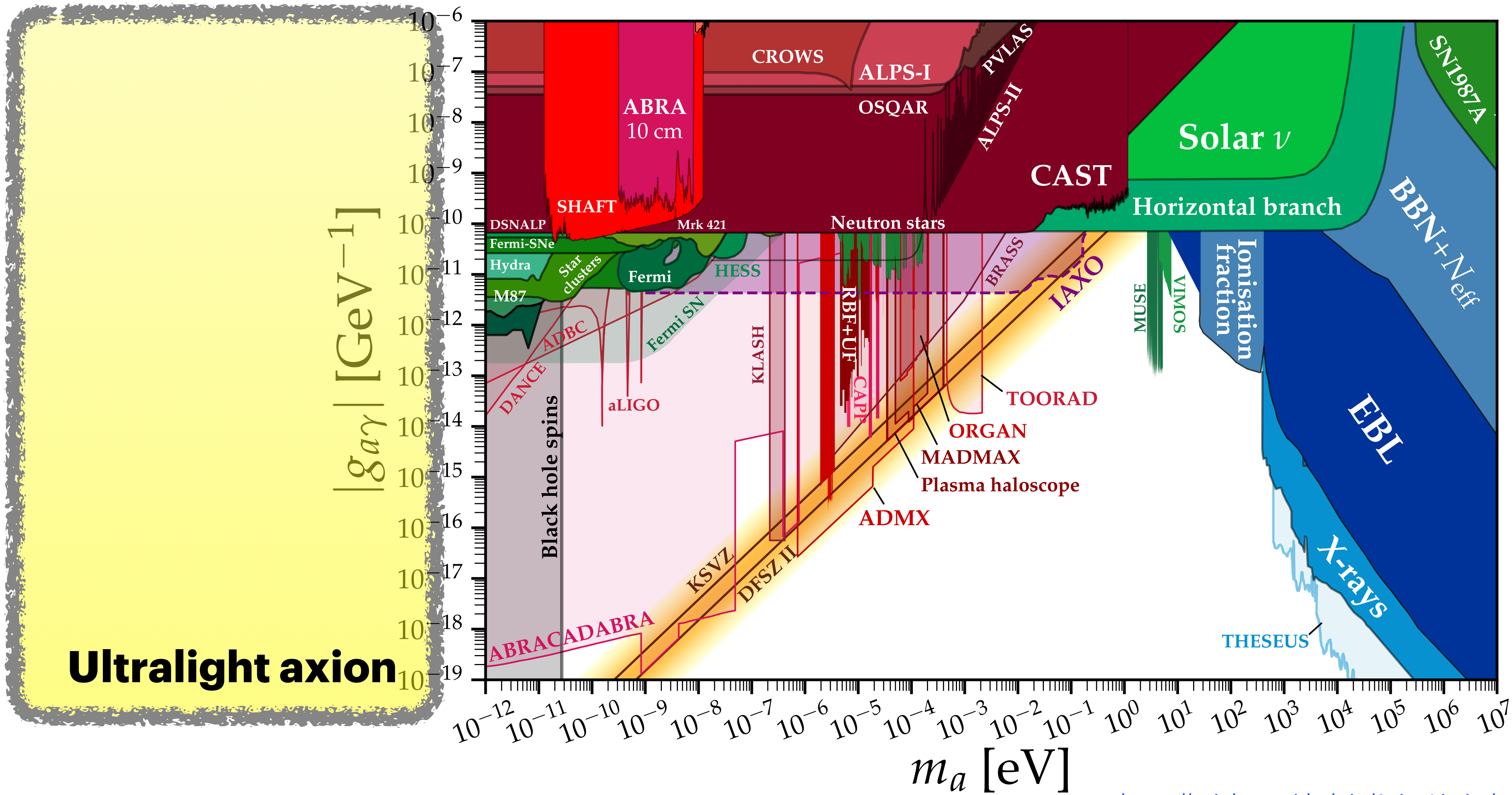
- Electrons

$$\mathcal{L}_{\phi e} = \frac{C_e}{2f_\phi} \partial_\mu \phi \left(\bar{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \right) = -i g_{\phi ee} \phi (\bar{\Psi}_e \gamma_5 \Psi_e) + \cdots$$

- Nucleons

$$\mathcal{L}_{\phi N} = \sum_{N=p,n} \frac{C_N}{2f_\phi} \partial_\mu \phi \left(\bar{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \right)$$

Searching for axion/ALP



https://cajohare.github.io/AxionLimits/

Cosmic birefringence (CB) due to ALP

Carrol, astro-ph/9806099
Lue, et al, astro-ph/9812088

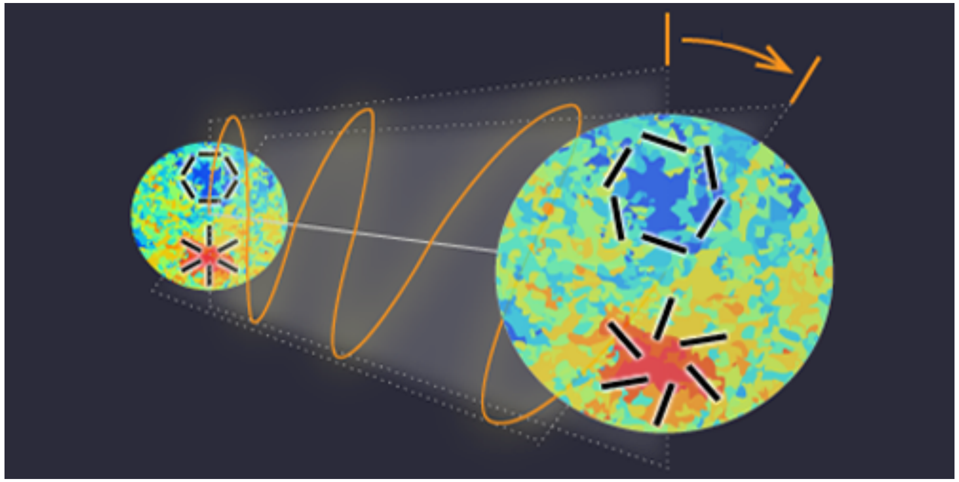
The polarization plane of CMB gets rotated

if the ALP moves after the recombination (isotropic CB),

or if it has fluctuations (anisotropic CB).

$$\mathcal{L}_{\phi\gamma} = c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{1}{4} g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

$$\Phi(\Omega) = 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi} \right) \ {\rm deg}$$



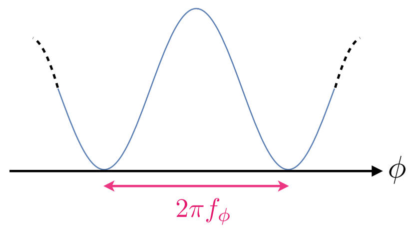
https://physics.aps.org/articles/v13/s149

Hint of isotropic CB?

$$\beta = \frac{1}{4\pi}\int d\Omega\, \Phi(\Omega) = 0.35 \pm 0.14 \ {\rm deg}$$

Minami, Komatsu, Phys. Rev. Lett. **125**, 221301

What we did

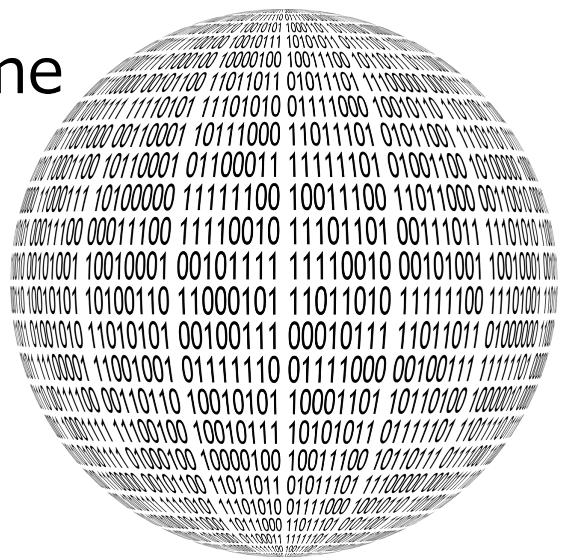


- We show that ALP domain walls can induce both isotropic and anisotropic CB.

- The CMB polarization is either not rotated at all or rotated by a fixed angle, depending on the vacuum at the last scattering.

- The number of domains is O($10^{3\text{-}4}$), thus the name

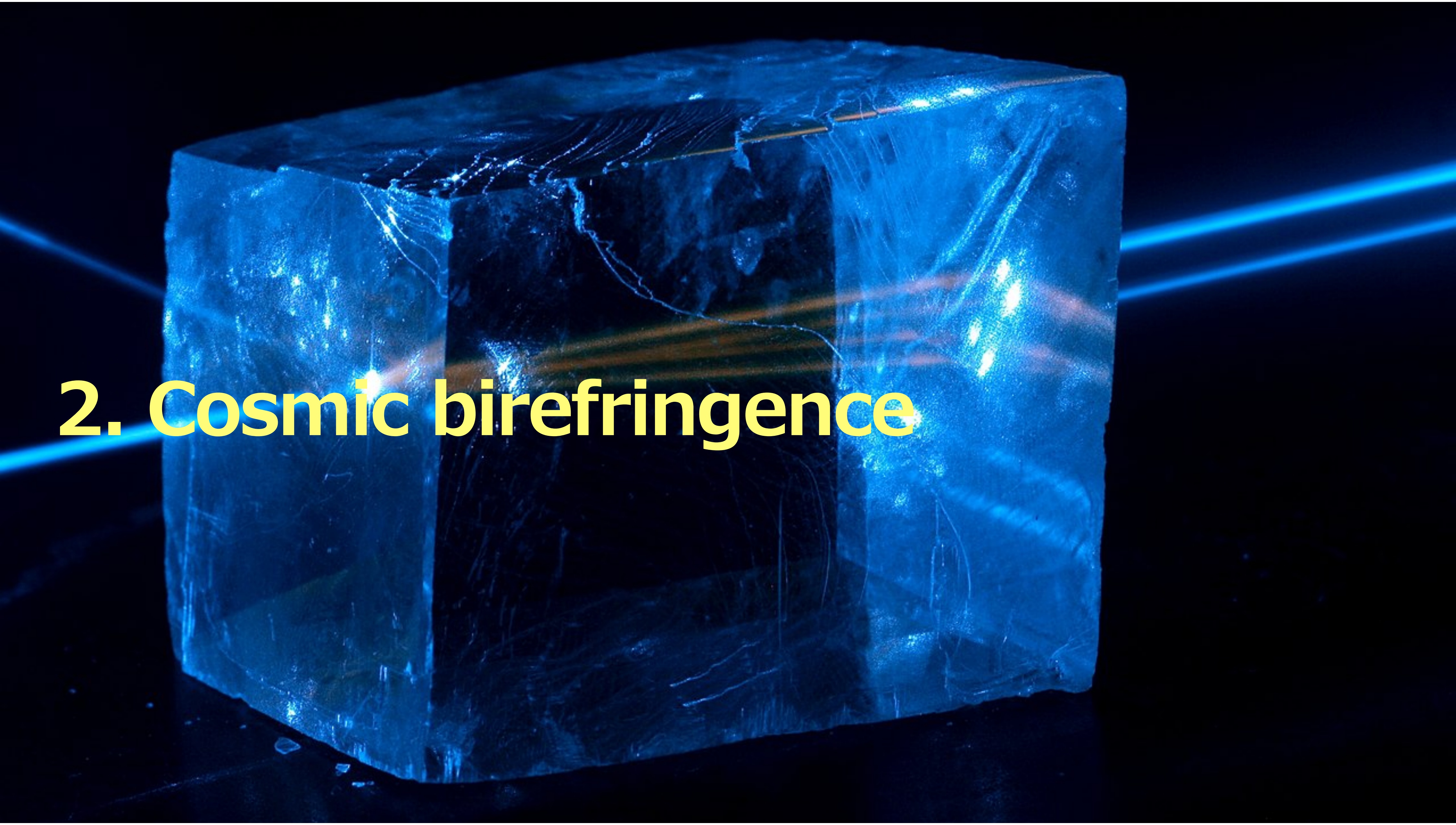
KiloByte Cosmic Birefringence (KBCB)



- The reported isotropic CB can be naturally explained if $c_\gamma = O(1)$.

$$\beta_{\rm KBCB} \simeq 0.21\, c_\gamma \ \ {\rm deg} \qquad \beta_{\rm obs} = 0.35 \pm 0.14 \ {\rm deg}$$

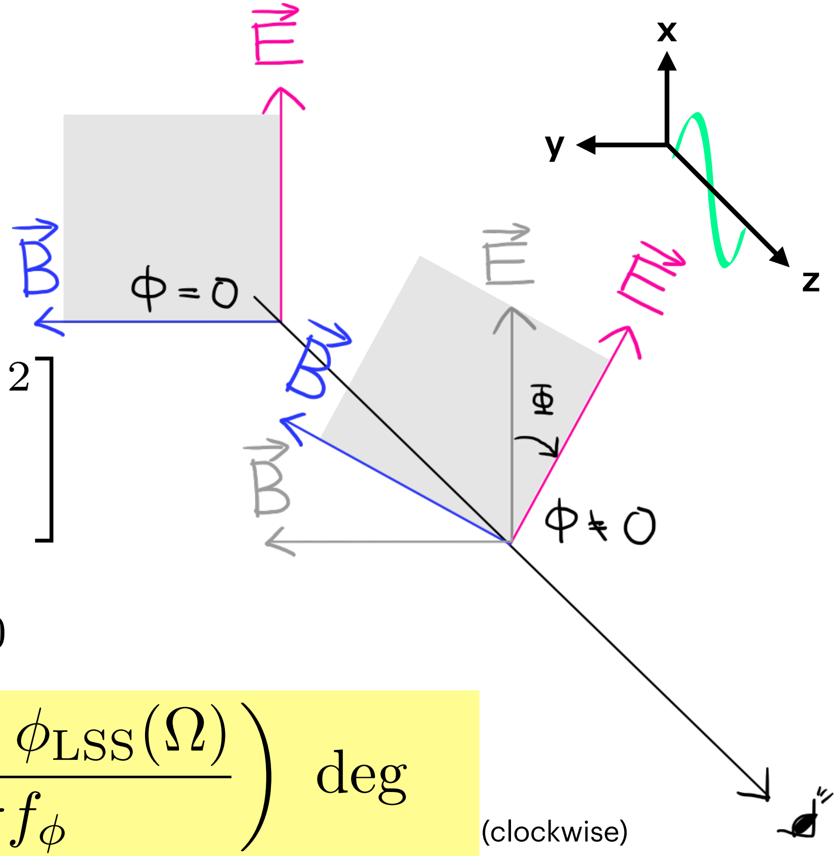
2. Cosmic birefringence



2. Cosmic birefringence

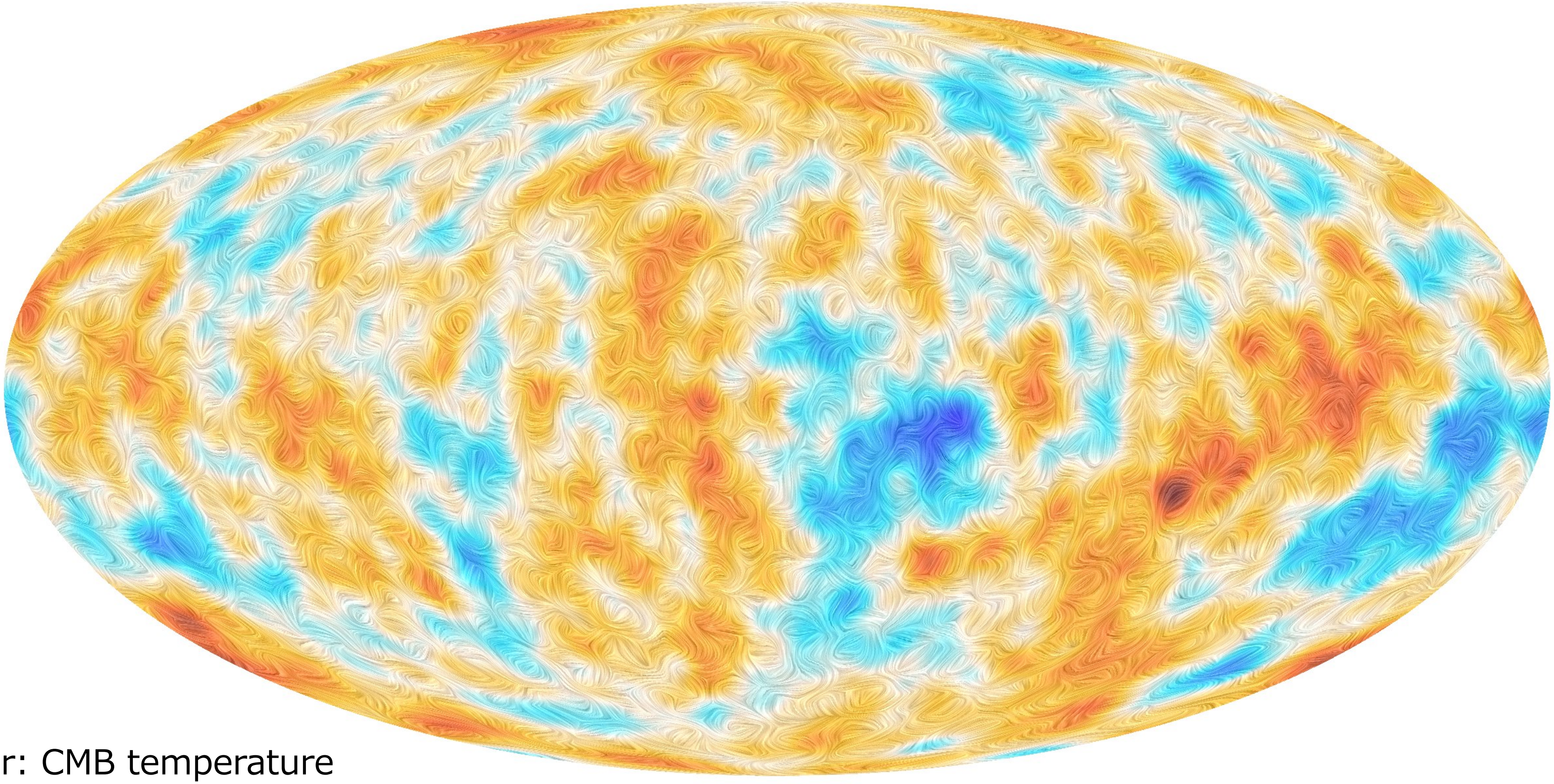
The axion dynamics rotates the polarization plane of linearly polarized light through the axion-photon coupling.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$
$$= \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right) + g_{\phi\gamma\gamma}\phi\vec{E}\cdot\vec{B}$$
$$\simeq \frac{1}{2}\left[\Bigg(\underbrace{\vec{E} + \frac{g_{\phi\gamma\gamma}\phi}{2}\vec{B}}_{\vec{E}\text{ when }\phi=0}\Bigg)^2 - \Bigg(\underbrace{\vec{B} - \frac{g_{\phi\gamma\gamma}\phi}{2}\vec{E}}_{\vec{B}\text{ when }\phi=0}\Bigg)^2\right]$$



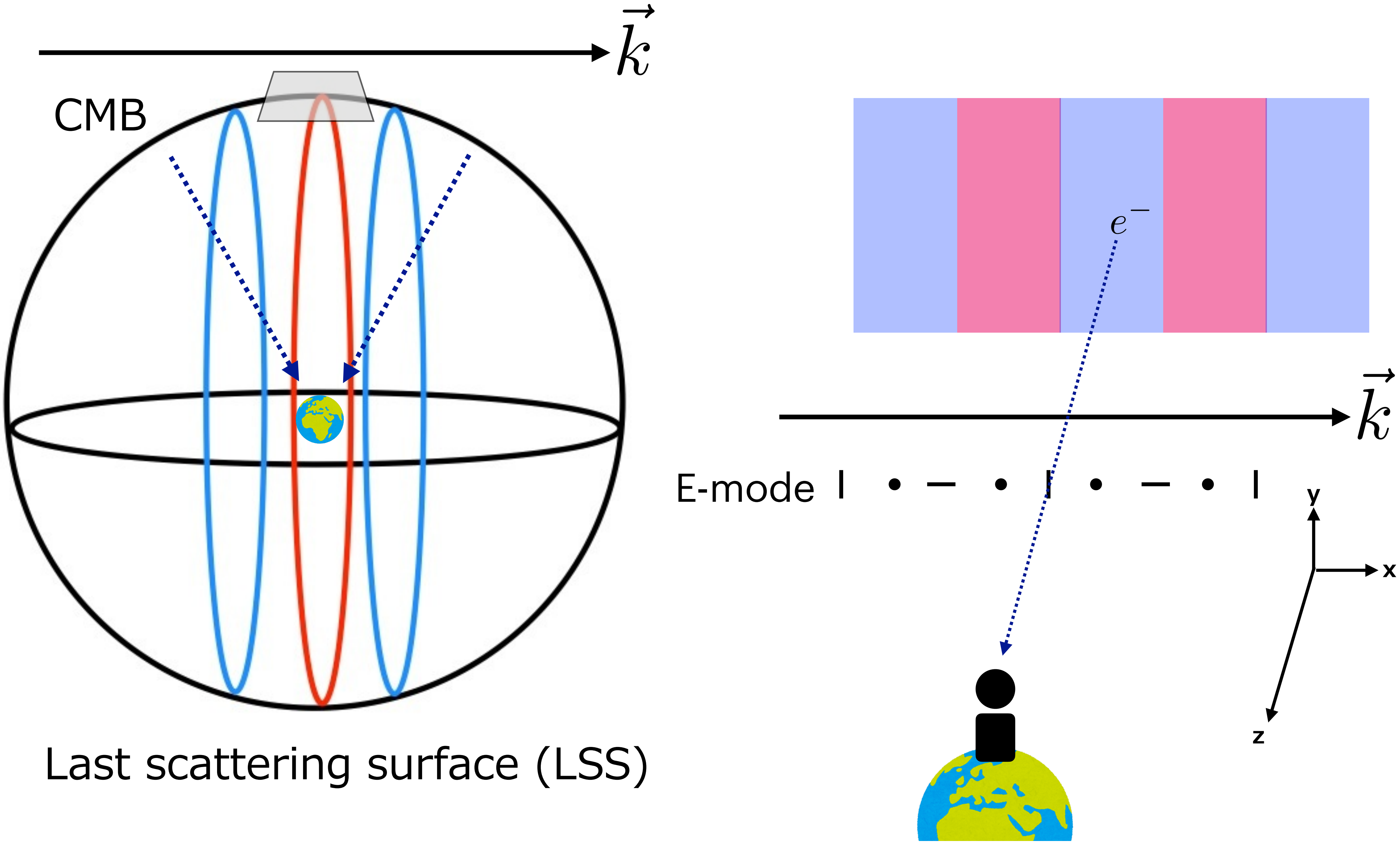
Thus, $$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42c_\gamma\left(\frac{\phi_{\text{today}} - \phi_{\text{LSS}}(\Omega)}{2\pi f_\phi}\right)\ \text{deg}$$

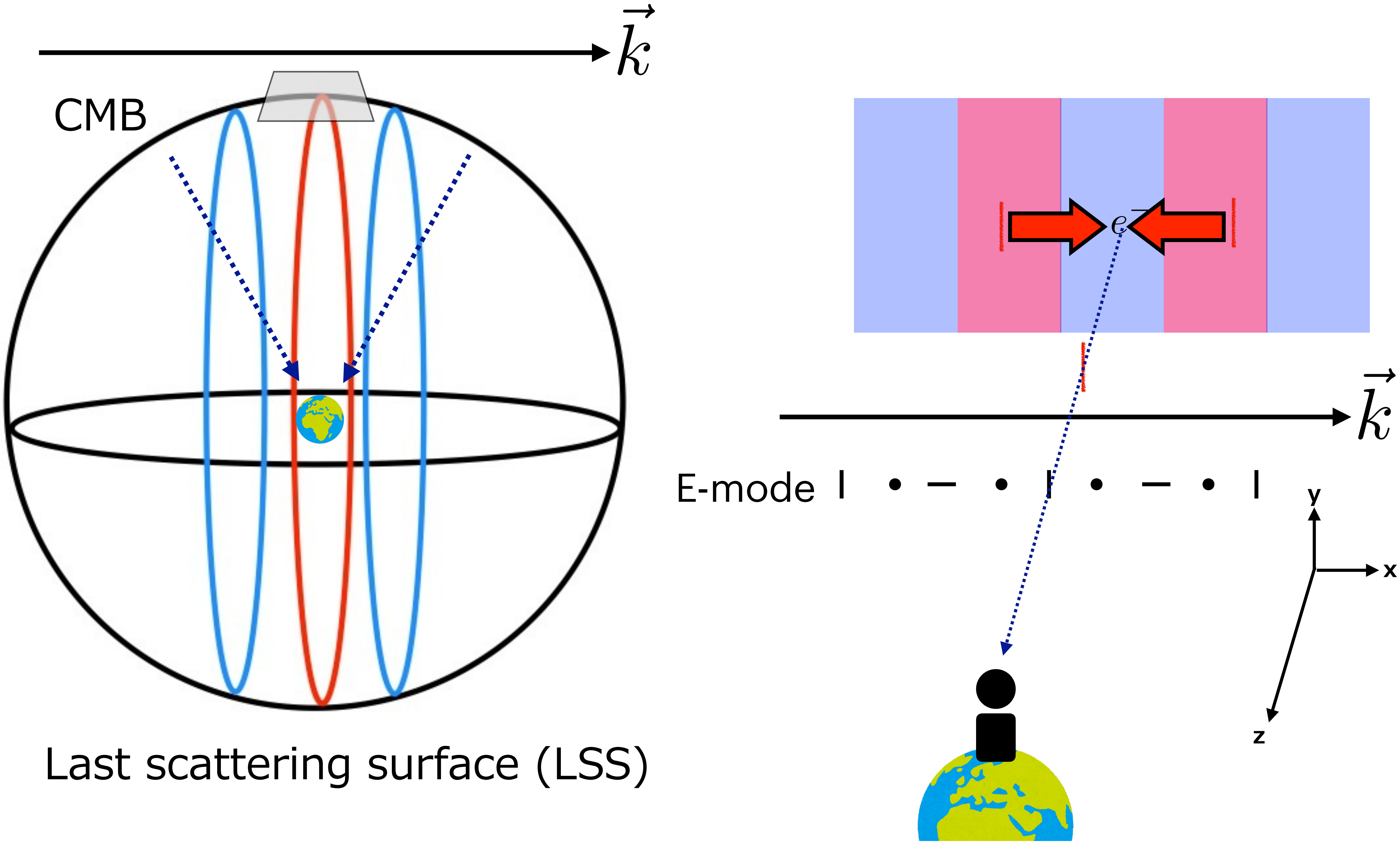
CMB photons are polarized (dominated by E-mode)



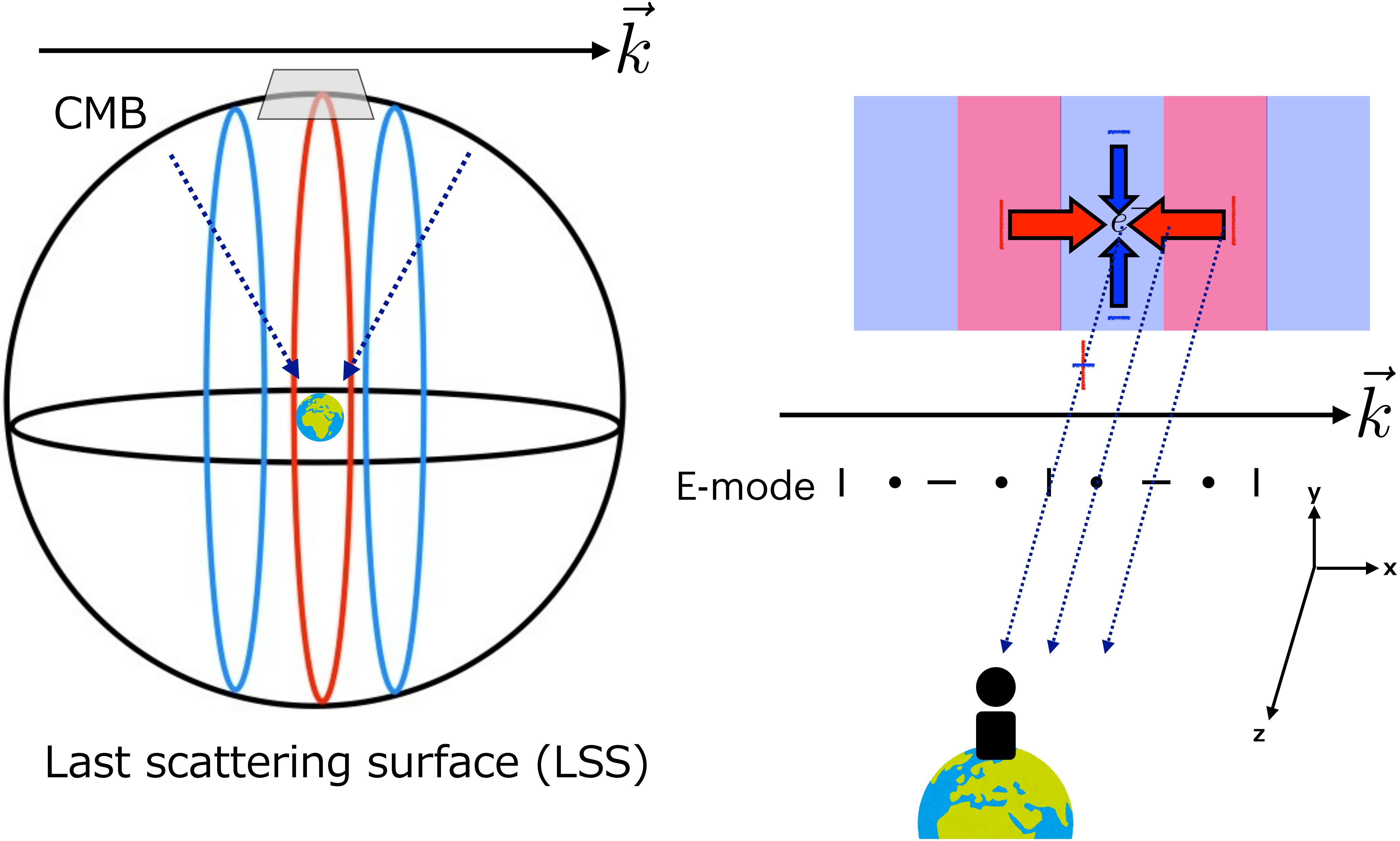
Color: CMB temperature

Texture: direction of polarization


$\vec{k}$
CMB
Last scattering surface (LSS)
e^-
$\vec{k}$
E-mode
y
x
z



k
CMB
Last scattering surface (LSS)
e−
k
E-mode
y
x
z


$\vec{k}$
CMB
Last scattering surface (LSS)
e^-
$\vec{k}$
E-mode
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x
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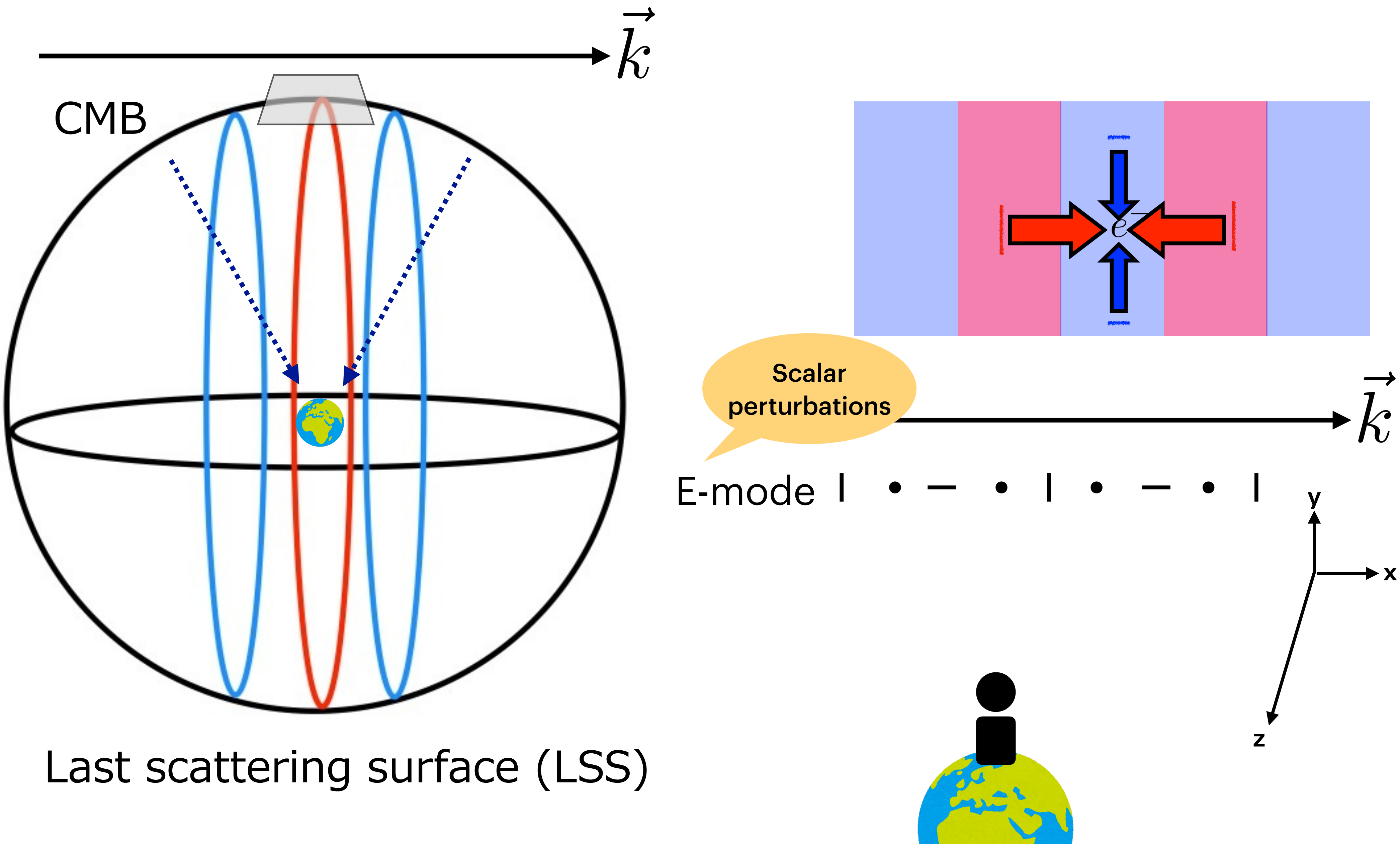
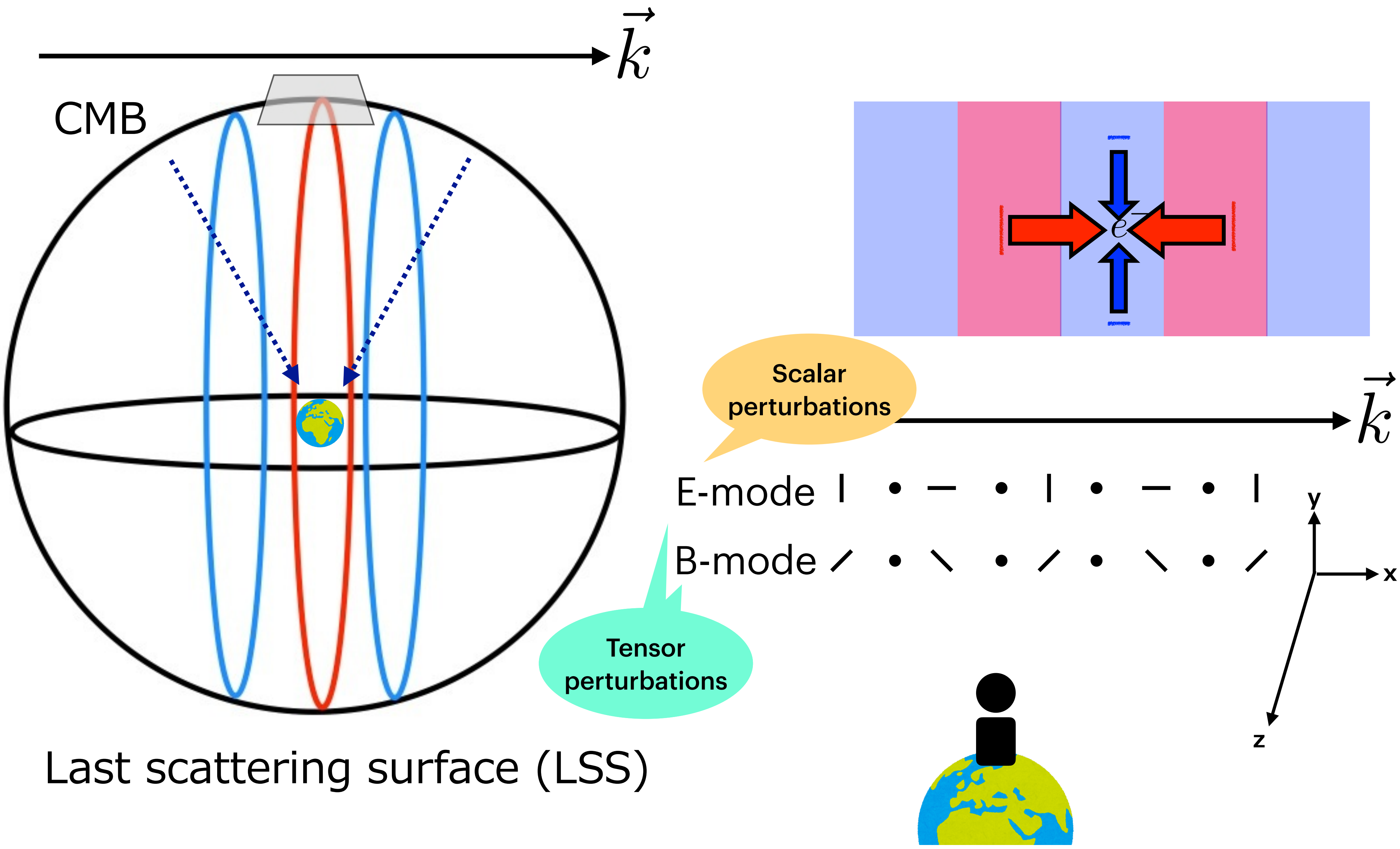
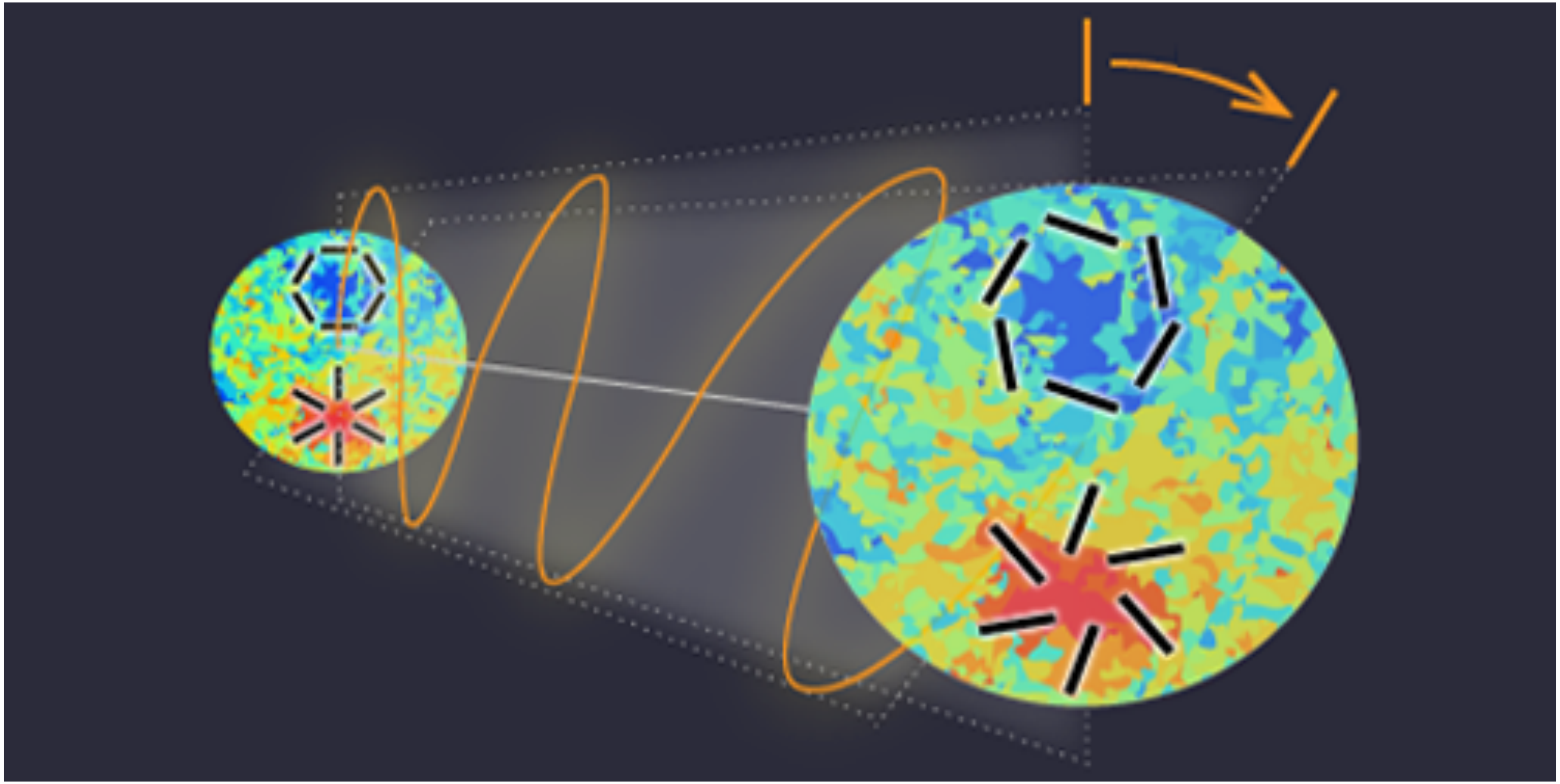


$\vec{k}$
CMB
Last scattering surface (LSS)
e^-
Scalar perturbations
$\vec{k}$
E-mode
y
x
z



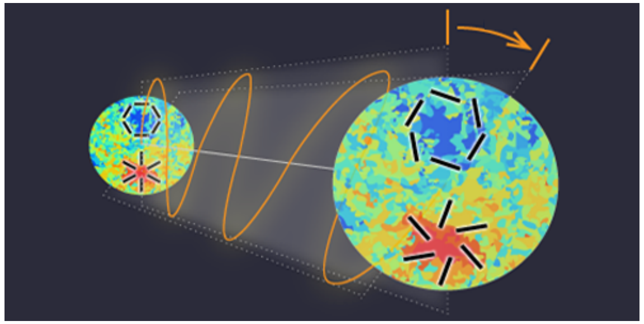
$\vec{k}$
CMB
Last scattering surface (LSS)
e^-
Scalar perturbations
$\vec{k}$
E-mode
B-mode
Tensor perturbations
y
x
z

CMB constraints on the CB



https://physics.aps.org/articles/v13/s149

CMB constraints on the CB



https://physics.aps.org/articles/v13/s149

Minami, Komatsu, Phys. Rev. Lett. **125**, 221301

Isotropic CB

$$\beta = \frac{1}{4\pi}\int d\Omega\,\Phi(\Omega) = 0.35 \pm 0.14\ \text{deg}$$

from Planck 18 pol. data

based on a new method that uses both the CMB and Galactic foreground to distinguish between CB (β) and detector orientation miscalibration (α).

Minami et al, PTEP 2019 083E02 , Minami PTEP 2020 063E01, Minami and Komatsu PTEP 2020 103E02

cf. The reported isotropic CB in the past:

$$\alpha + \beta = \begin{cases} -0.36 \pm 1.24\,\text{deg} & \text{WMAP} \\ 0.31 \pm 0.05\,\text{deg} & \text{Planck} \\ -0.61 \pm 0.22\,\text{deg} & \text{POLARBEAR} \\ 0.63 \pm 0.04\,\text{deg} & \text{SPTpol} \\ 0.12 \pm 0.06\,\text{deg} & \text{ACT} \\ 0.09 \pm 0.09\,\text{deg} & \text{ACT} \end{cases}$$

$$\sigma_{\text{syst}}(\alpha) = \begin{cases} 1.5\,\text{deg} & \text{WMAP} \\ 0.28\,\text{deg} & \text{Planck} \end{cases}$$

CMB constraints on the CB

Anisotropic CB

$$\sqrt{\frac{L(L+1)C_L}{2\pi}} = \frac{g_{\phi\gamma\gamma}}{2}\frac{H_{\rm inf}}{2\pi} < 0.18\,{\rm deg}$$
(95% CL)

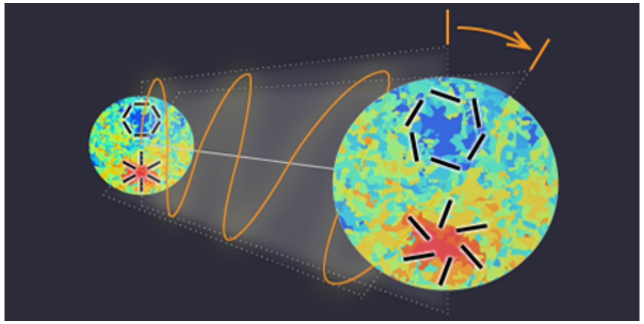
for a scale-invariant CB; e.g. the axion fluctuation

$$\delta\phi = \frac{H_{\rm inf}}{2\pi}$$

generated during inflation.

(Recall $\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2}$)

N.B. The limit mainly comes from low multipole L <100.



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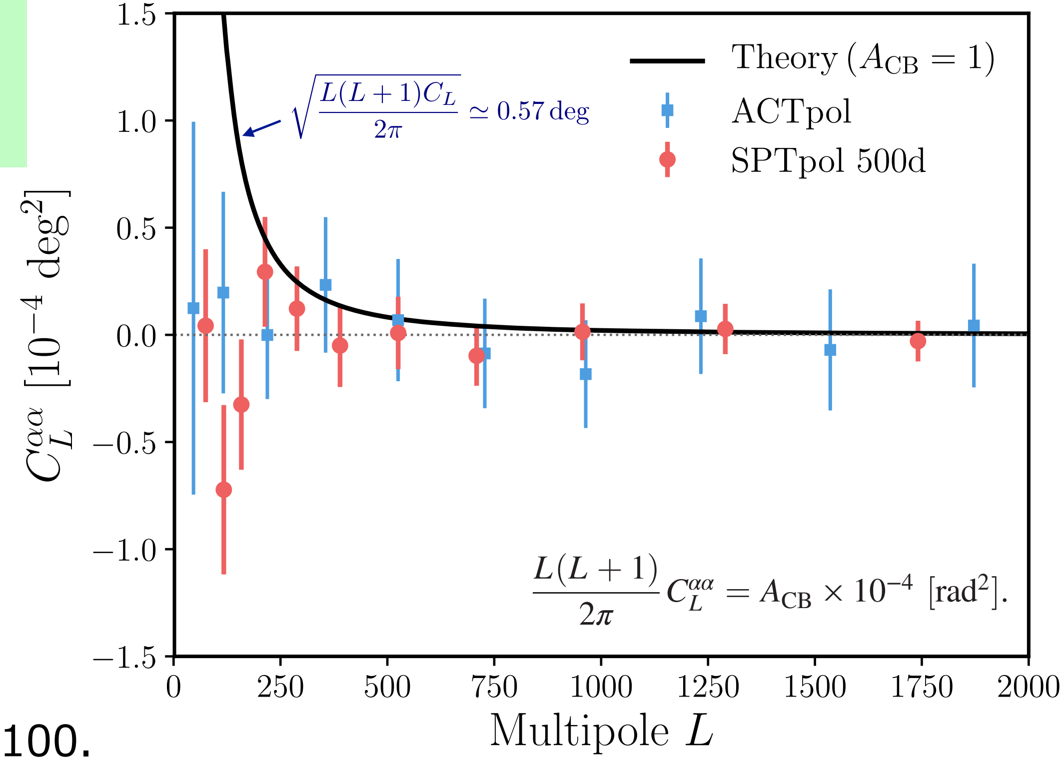
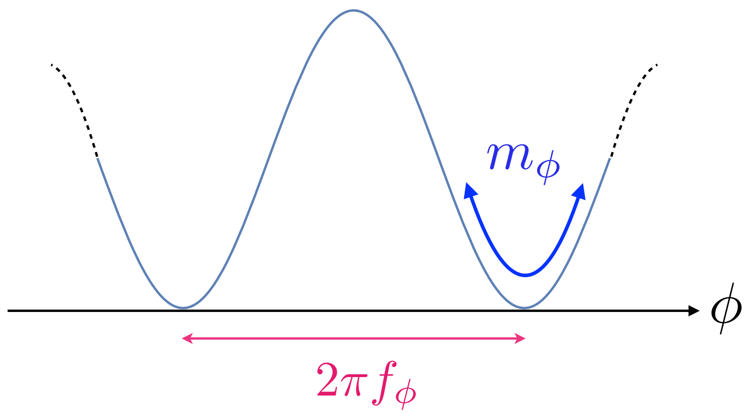


Implications for ALP

$$\mathcal{L}_{\phi\gamma} = -c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{4} g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

- The hint of the isotropic CB: $\beta = \frac{1}{4\pi}\int d\Omega\, \Phi(\Omega) = 0.35 \pm 0.14\ \mathrm{deg}$
- The ALP prediction: $\Phi(\Omega) \simeq 0.42 c_\gamma \left(\frac{\phi_{\mathrm{today}} - \phi_{\mathrm{LSS}}(\Omega)}{2\pi f_\phi}\right)\ \mathrm{deg}$

The ALP must have moved by $\Delta\phi = \mathcal{O}(\pi f_\phi)$ for $c_\gamma = O(1)$ after recombination



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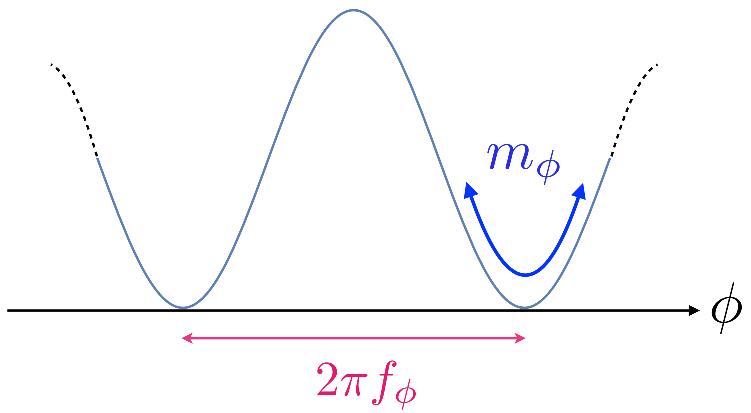
The interpretation in terms of a homogeneous ALP was studied in e.g. Fujita et al 2011.11894

☆ We study the ALP domain wall connecting the two adjacent vacua separated by $\Delta\phi = 2\pi f_\phi$.



Case of a homogeneous ALP

Fujita et al 2011.11894

$$V_{\cos}(\phi) = m^2 f^2 [1 - \cos(\phi/f)] \text{ with } f = M_{\rm pl}.$$

In their setup, there are four free parameters:

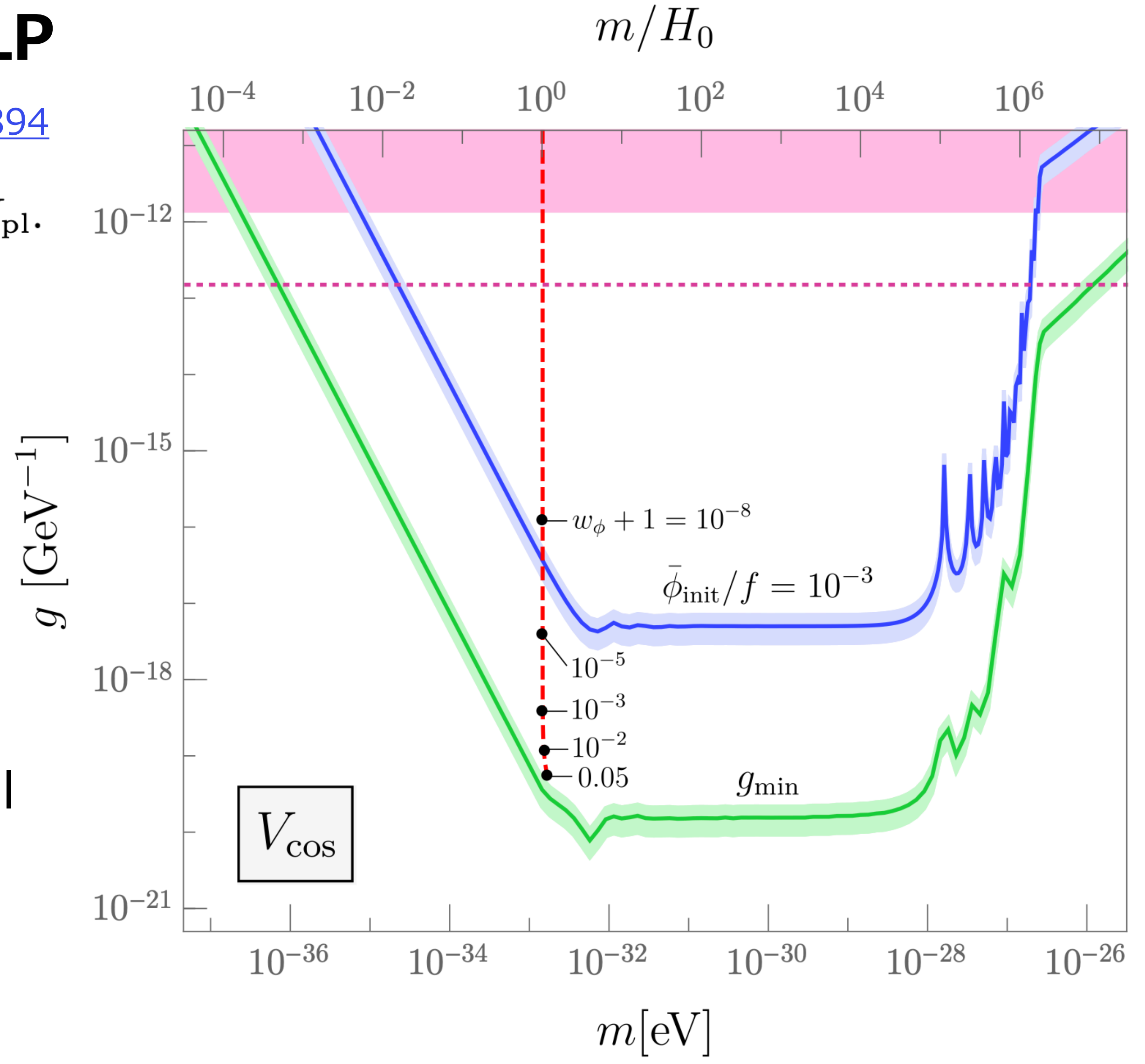
(1)mass m

(2)decay constant f → fixed to be the Planck mass in the right figure.

(3) axion-photon coupling g (or c_γ)

(4) The ALP abundance Ω_ϕ (or initial misalignment angle)

Note that the mass is lighter than $\sim 10^{-29}\mathrm{eV} \simeq H_{\rm LSS}$ in most region.



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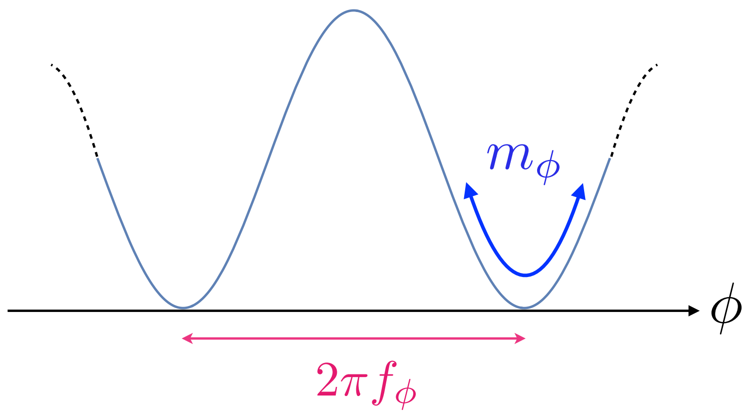


3. ALP domain walls w/o strings

3. ALP domain walls without strings

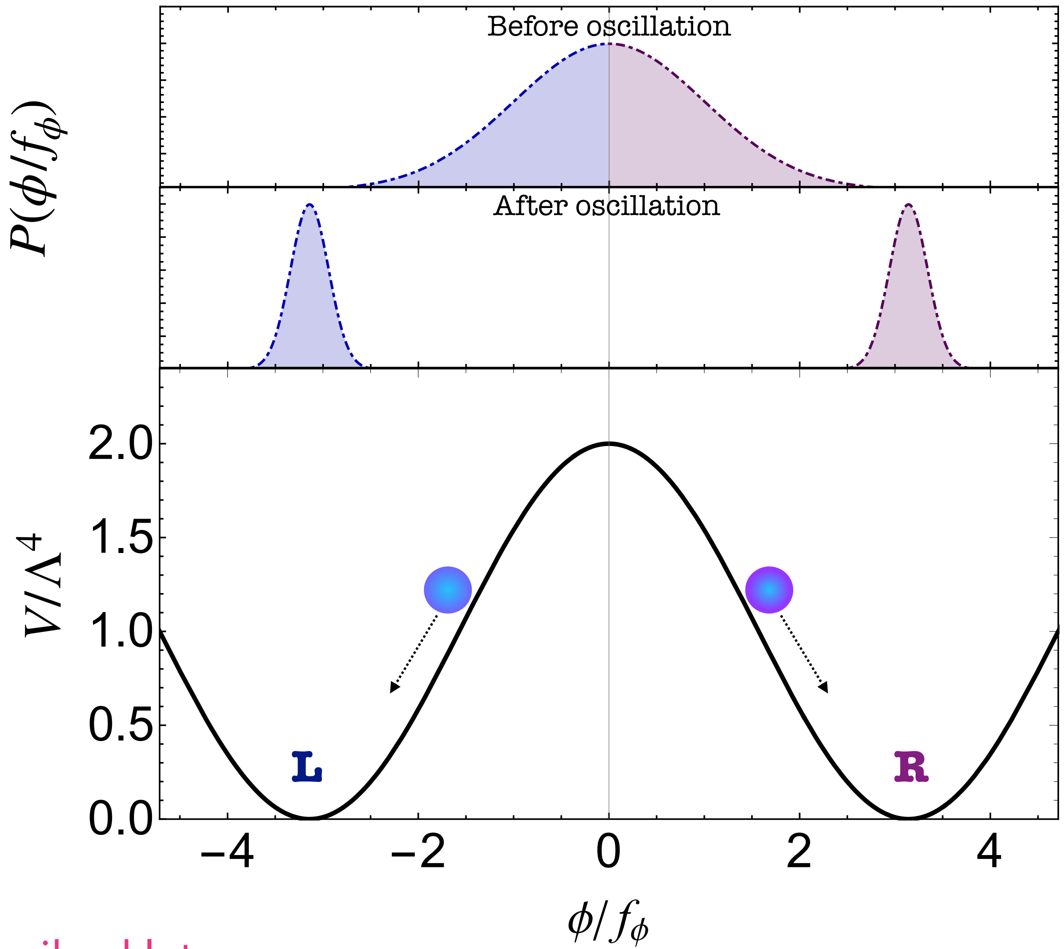
Let us consider the axion potential

$$V(\phi) = m_\phi^2 f_\phi^2 \left(1 + \cos\frac{\phi}{f_\phi}\right)$$

and focus on the adjacent minima,

$$\phi_L = -\pi f_\phi \text{ and } \phi_R = +\pi f_\phi .$$

If both vacua are populated in the early Universe with $0.3 \lesssim p_L \lesssim 0.7$, infinite domain wall (w/o strings) will appear when $H \sim m_\phi \gtrsim H_{\rm LSS}$.



Specific scenarios to obtain $\delta\theta = O(1)$ will be described later.

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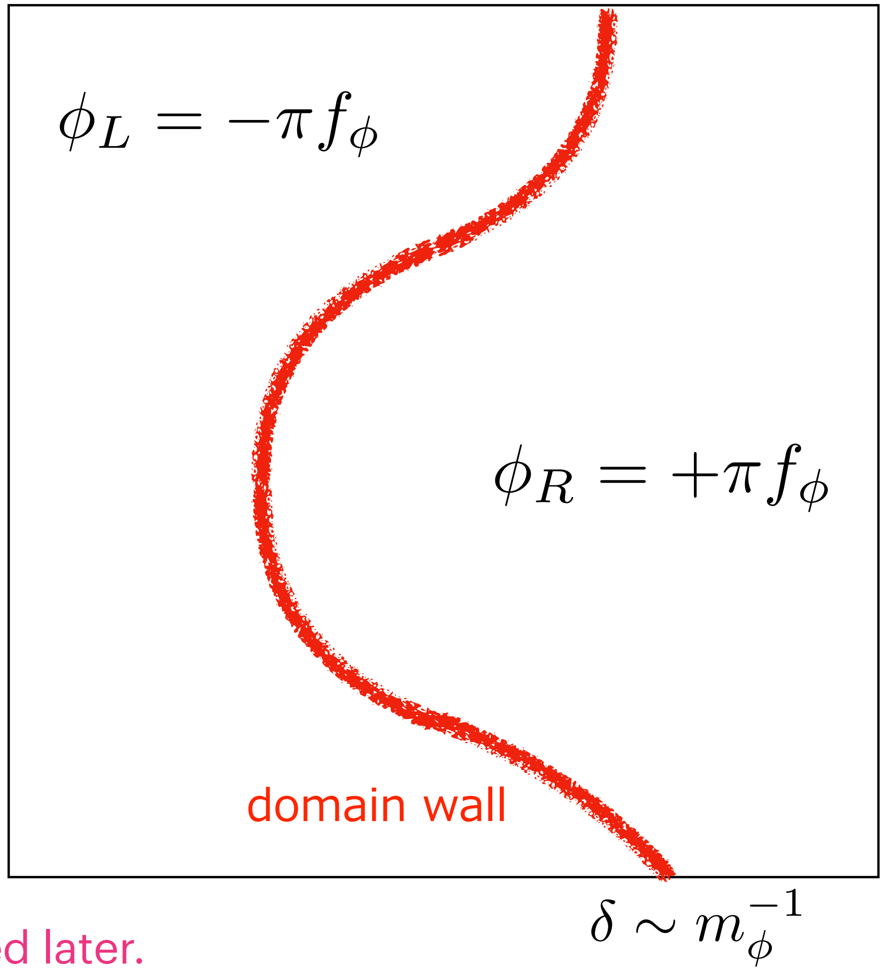


Specific scenarios to obtain $\delta\theta = O(1)$ will be described later.

Scaling solution of domain walls

Press, Ryden, Spergel `89

The scaling solution is such that the Hubble horizon contains on average about one wall:

$$\rho_{\rm DW} \sim \frac{\sigma_{\rm DW} H^{-2}}{H^{-3}} \sim m_\phi f_\phi^2 H$$

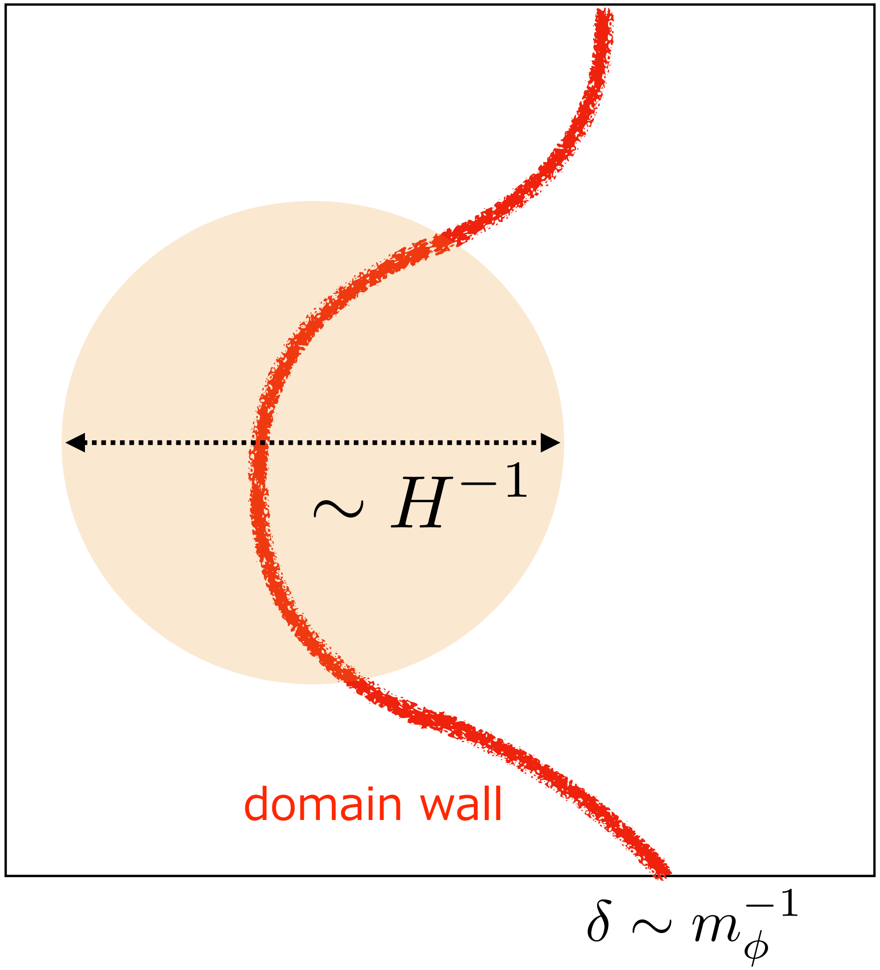
$$\sigma_{\rm DW} \simeq 8 m_\phi f_\phi^2$$

tension of DW for the cosine potential

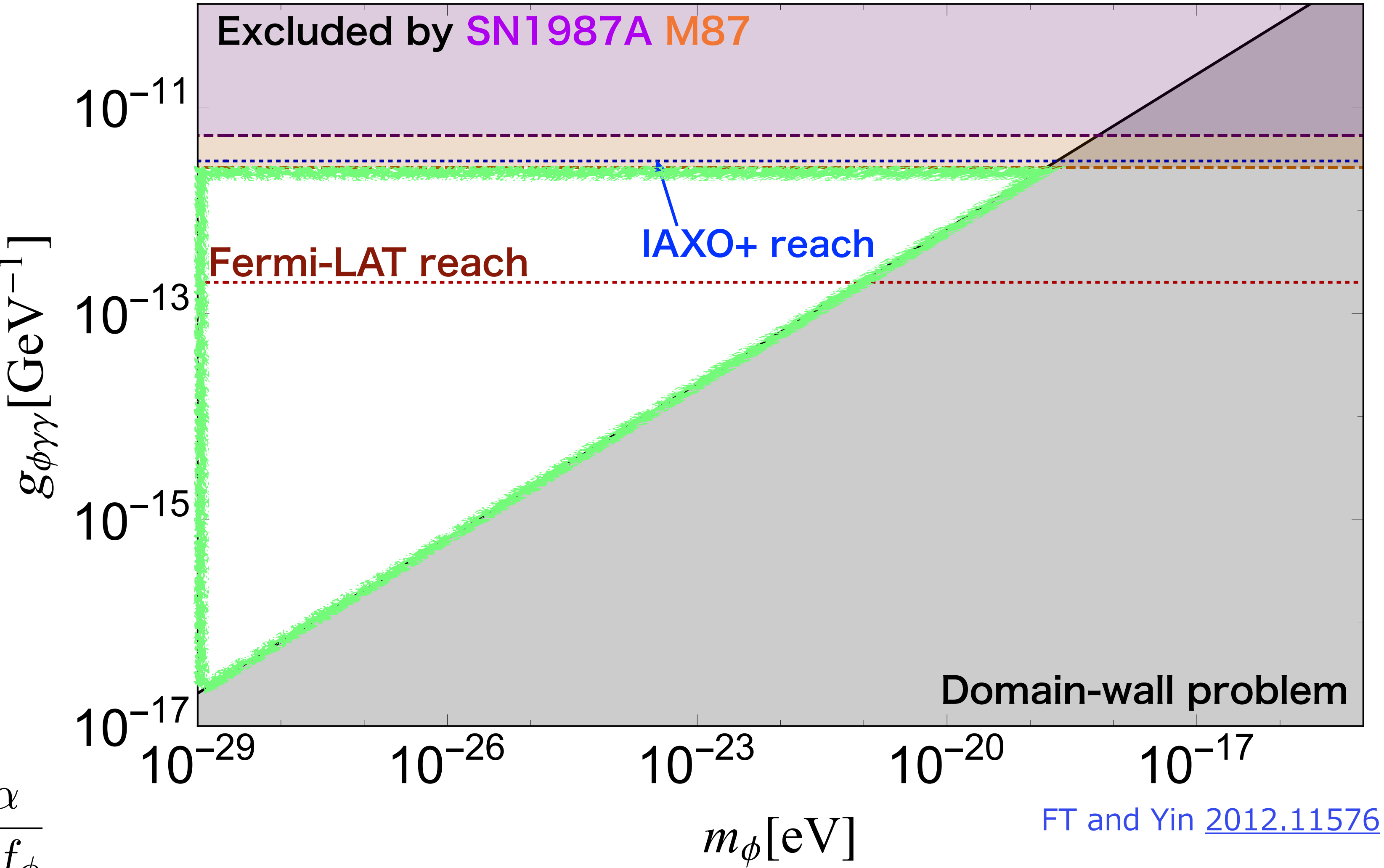
which decreases more slowly than matter, and there is a CMB bound on stable domain walls,

$$\sigma_{\rm DW} \lesssim (1\,{\rm MeV})^3$$

Zeldovich, Kobzarev, Okun `74, Sousa and Avelino, 1507.01064.



Various bounds and future sensitivity reach



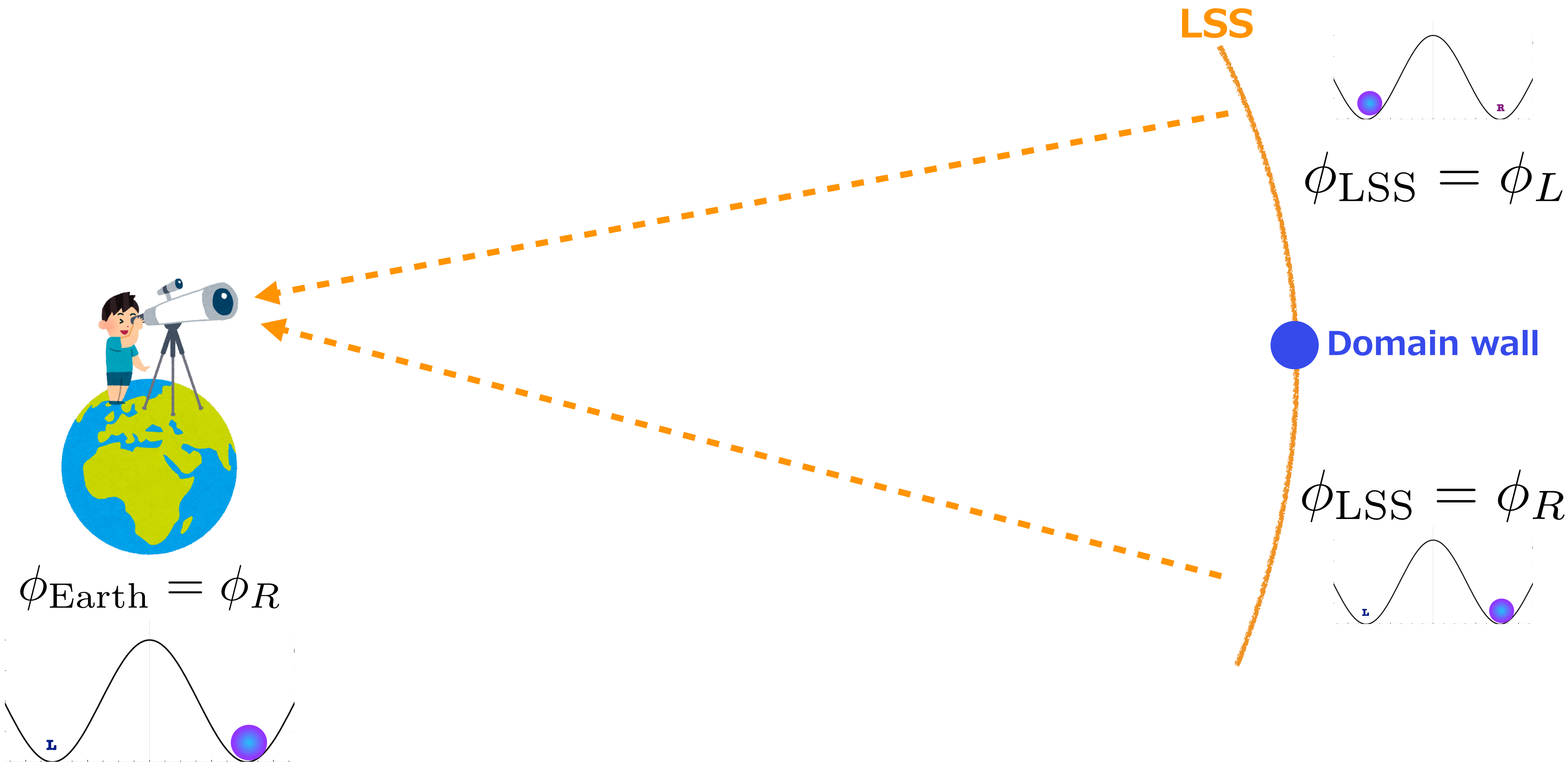
$c_\gamma = 1$

$$g_{\phi\gamma\gamma} = \frac{\alpha}{\pi f_\phi}$$

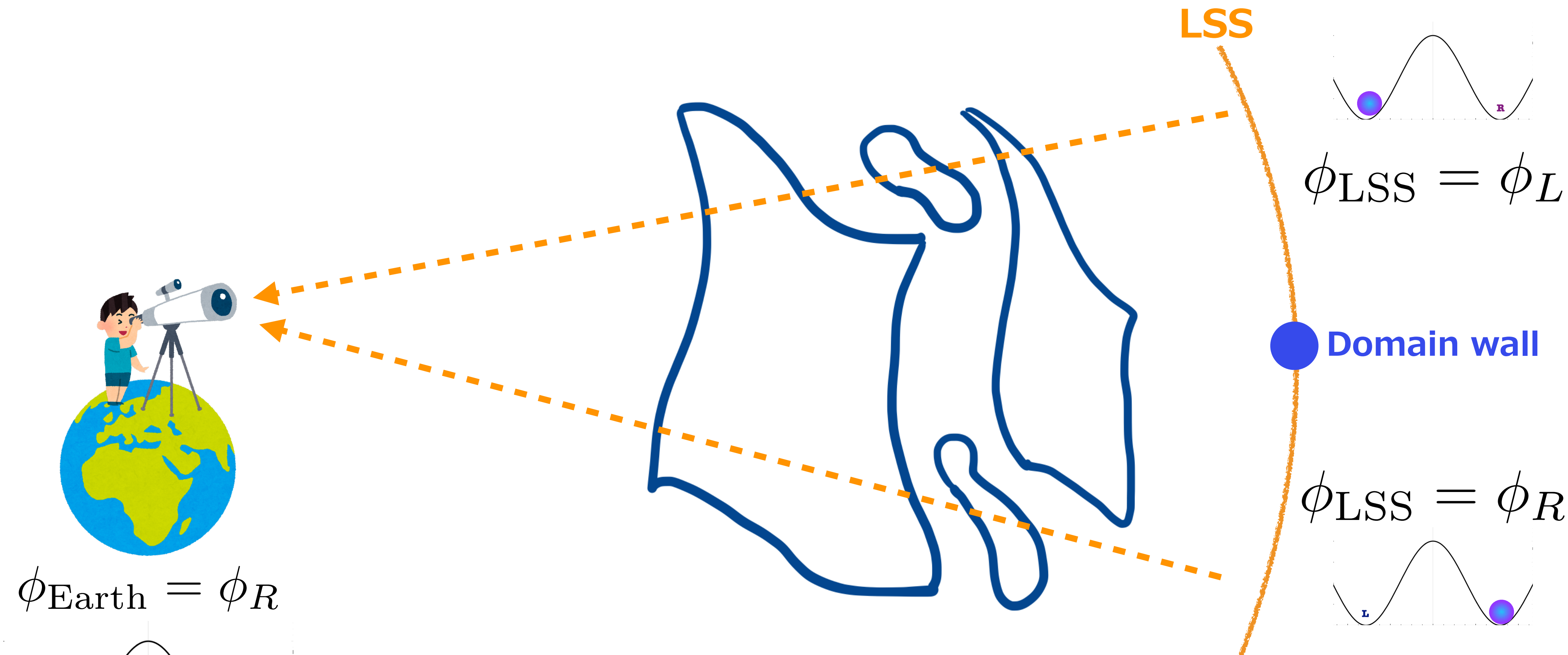
FT and Yin 2012.11576

Note that the mass is heavier than $\sim 10^{-29}\mathrm{eV} \simeq H_{\mathrm{LSS}}$

KiloByte CB from ALP domain walls

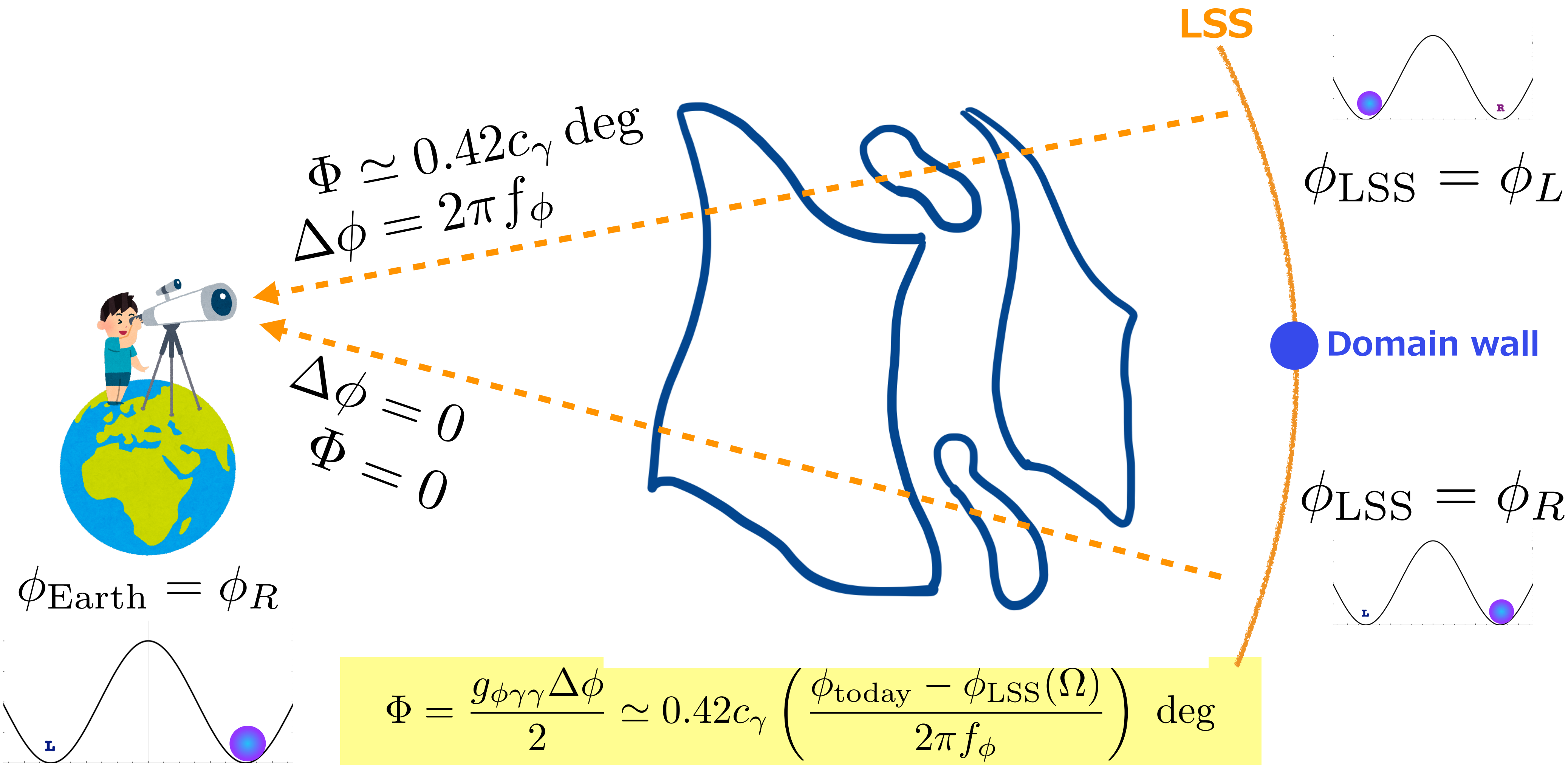


KiloByte CB from ALP domain walls



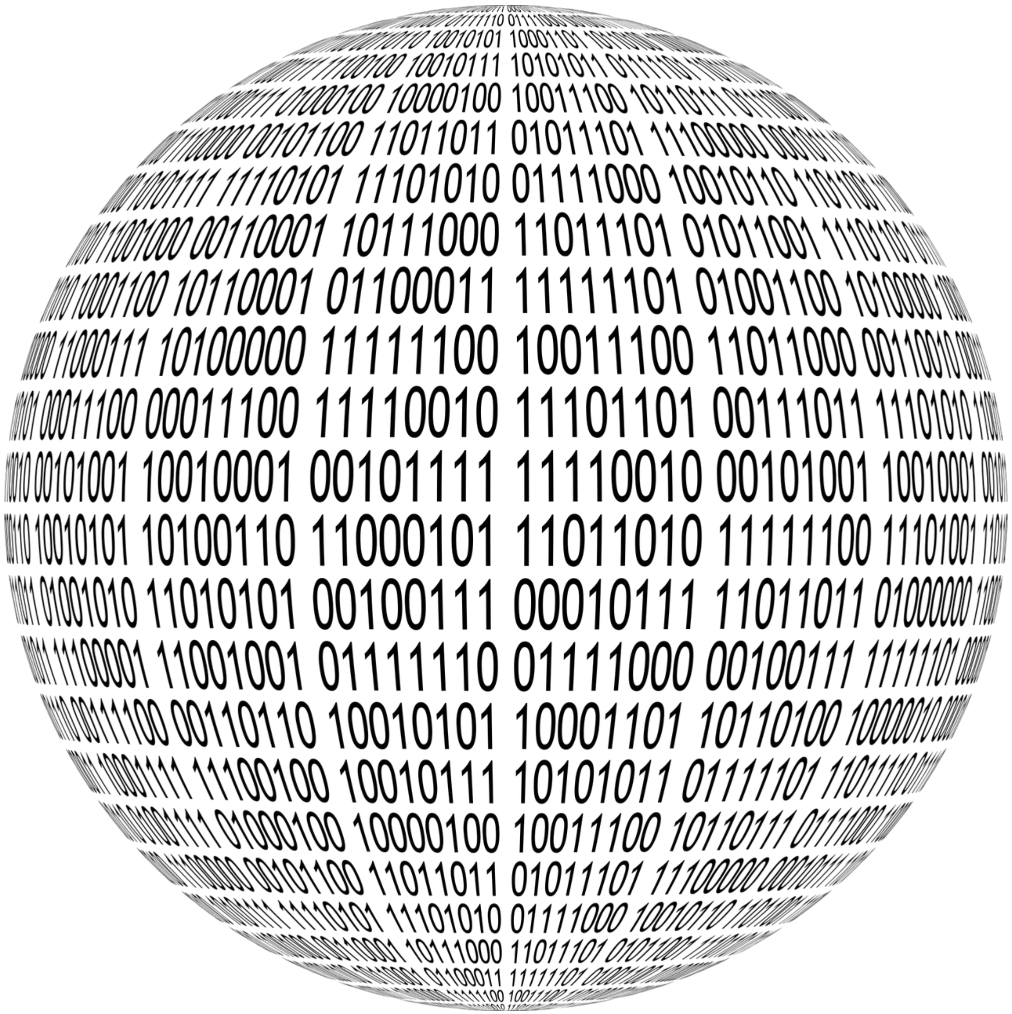
$$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\mathrm{today}} - \phi_{\mathrm{LSS}}(\Omega)}{2\pi f_\phi} \right) \ \mathrm{deg}$$

KiloByte CB from ALP domain walls



$$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi} \right) \ \mathrm{deg}$$

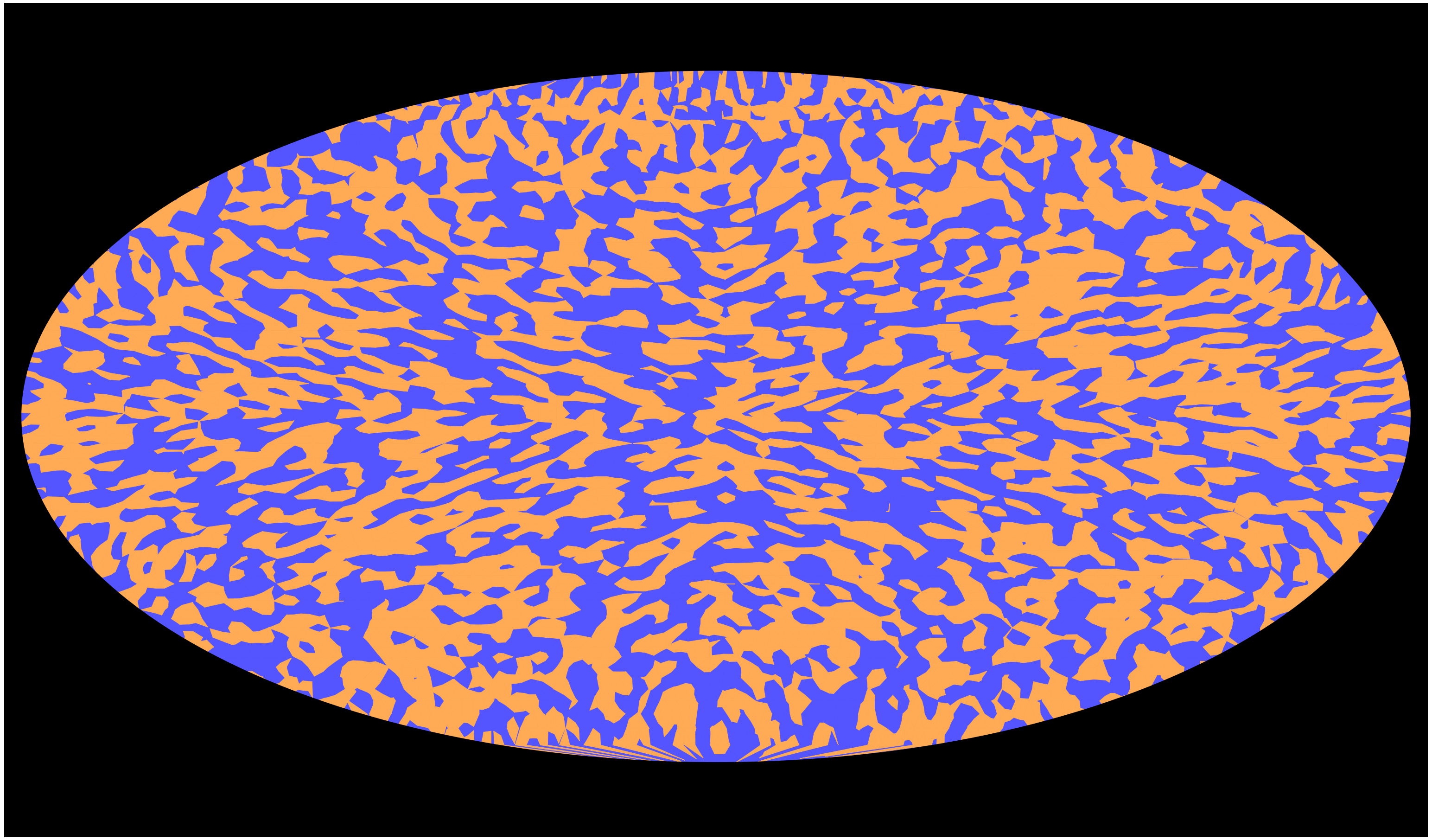
There will be $O(10^{3\text{-}4})$ domains on the LSS, and the CMB polarization from each domain is either not rotated at all or rotated by a fixed angle, $\Phi \simeq 0.42 c_\gamma \, \mathrm{deg}$.



$$= 2^N, \quad N = O(10^{3-4})$$

"KiloByte Cosmic Birefringence"
(KBCB)

KBCB from ALP domain walls



Blue: $\Phi = 0$ Orange: $\Phi \simeq 0.42 c_\gamma \,\mathrm{deg}$

N.B. This figure is NOT a result of numerical simulations, but just a mock sample.

Predictions of KBCB

Isotropic CB

$$\beta_{\rm KBCB} \simeq 0.21\, c_\gamma \ \ {\rm deg}\cdot$$

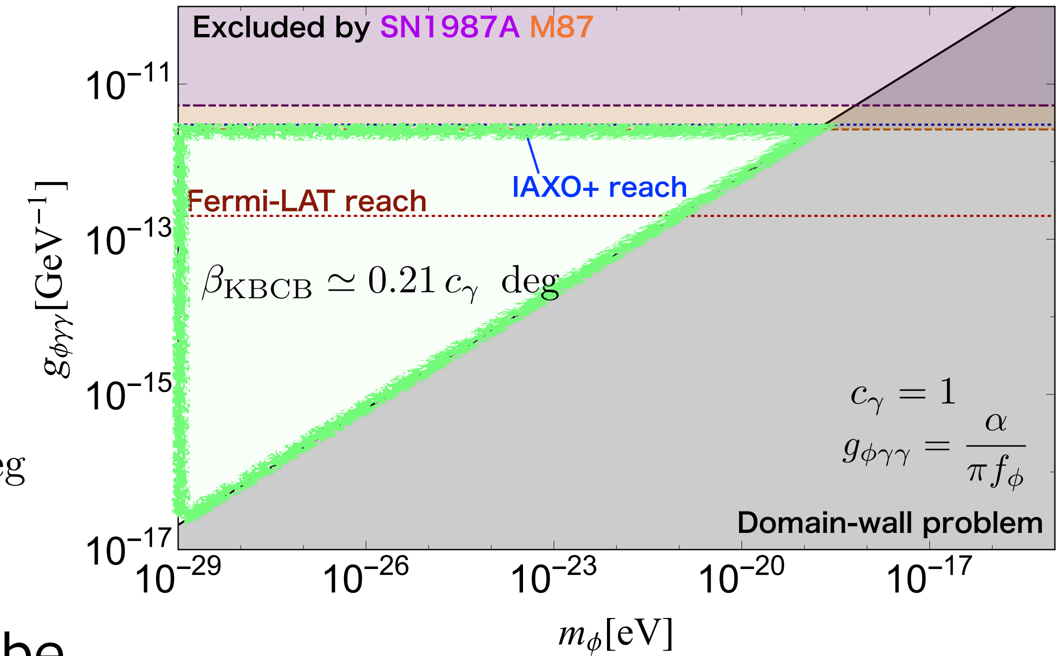
independent of m_ϕ and f_ϕ.

Recall $\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi}\right)$ deg

cf. $\beta_{\rm obs} = 0.35 \pm 0.14$ deg. can be

Minami, Komatsu, Phys. Rev. Lett. **125**, 221301

explained for $c_\gamma = O(1)$.

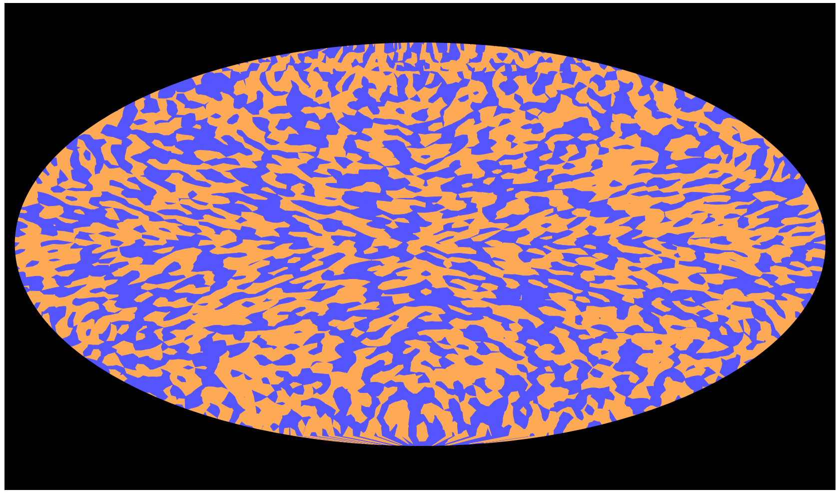


The predicted isotropic CB is the same over the viable parameter space (green triangle).

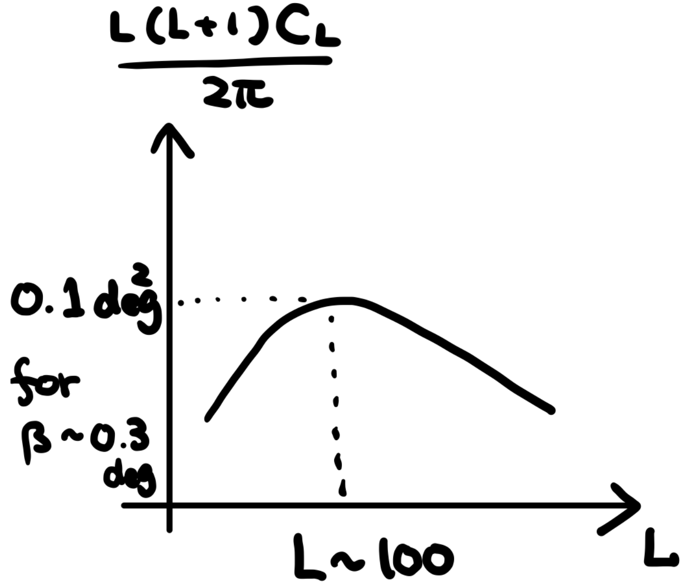
Predictions of KBCB

Anisotropic CB

Expected to have a (broad) peak at a scale corresponding to the Hubble horizon at LSS, and suppressed at larger and smaller scales.



$$\sqrt{\frac{L(L+1)C_L}{2\pi}} \sim 0.3\left(\frac{\beta}{0.3\,\mathrm{deg}}\right)\mathrm{deg}$$



cf. For a scale-invariant anisotropic CB,

$$\sqrt{\frac{L(L+1)C_L}{2\pi}} = \frac{g_{\phi\gamma\gamma}}{2}\frac{H_{\mathrm{inf}}}{2\pi} < 0.18\,\mathrm{deg}$$

which mainly comes from low multipole L <100.

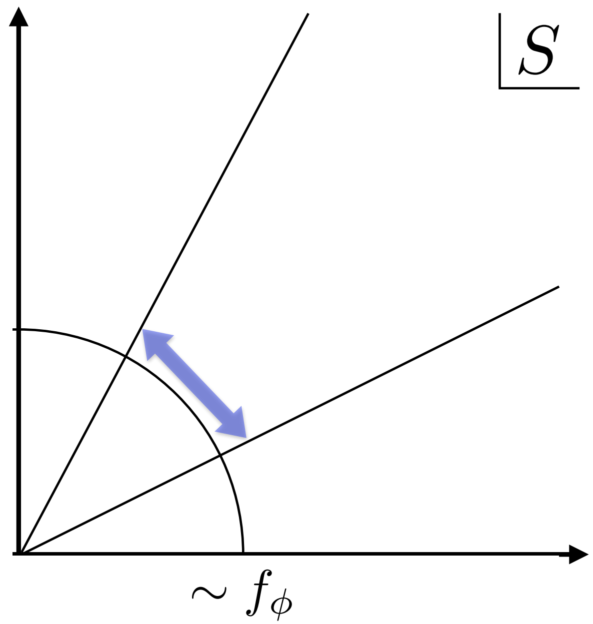
4. Specific models for ALP domain wall formation

4.1 A model with a negative Hubble mass

Suppose that the PQ symmetry is linearly realized as

$$S = \frac{f_\phi}{\sqrt{2}} e^{i\frac{\phi}{f_\phi}}$$

$$V(S) = -m_S^2 |S|^2 + \frac{\lambda}{4}|S|^4$$



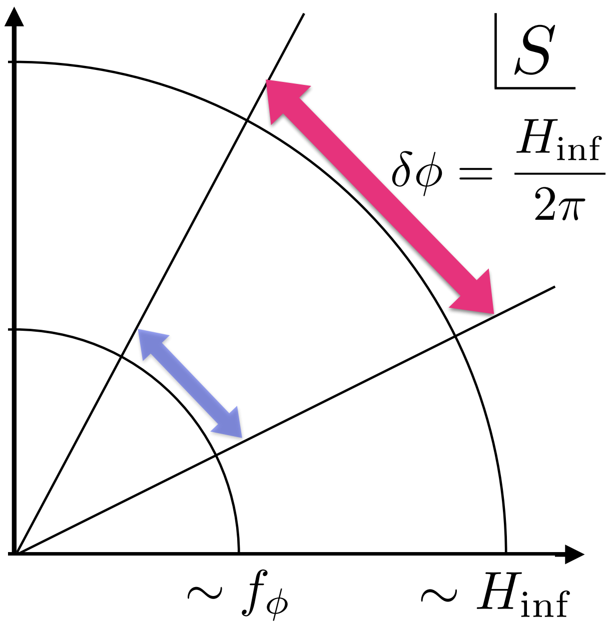
4.1 A model with a negative Hubble mass

Suppose that the PQ symmetry is linearly realized as

$$S = \frac{f_\phi}{\sqrt{2}} e^{i\frac{\phi}{f_\phi}} \quad \Rightarrow \quad S \sim H_{\rm inf} e^{i\frac{\phi}{H_{\rm inf}}}$$

(during inflation)

$$V(S) = -m_S^2 |S|^2 + \frac{\lambda}{4}|S|^4 - H_{\rm inf}^2 |S|^2$$



During inflation, the effective decay constant can be as large as $H_{\rm inf}$, and the axion acquires quantum fluctuations of $O(H_{\rm inf})$.

$$\Rightarrow \quad \delta\theta = \mathcal{O}(1)$$

4.2 A model with mixing b/w QCD axion and ALP

Consider two axions whose linear combinations become the QCD axion and the ultralight ALP in the low energy.

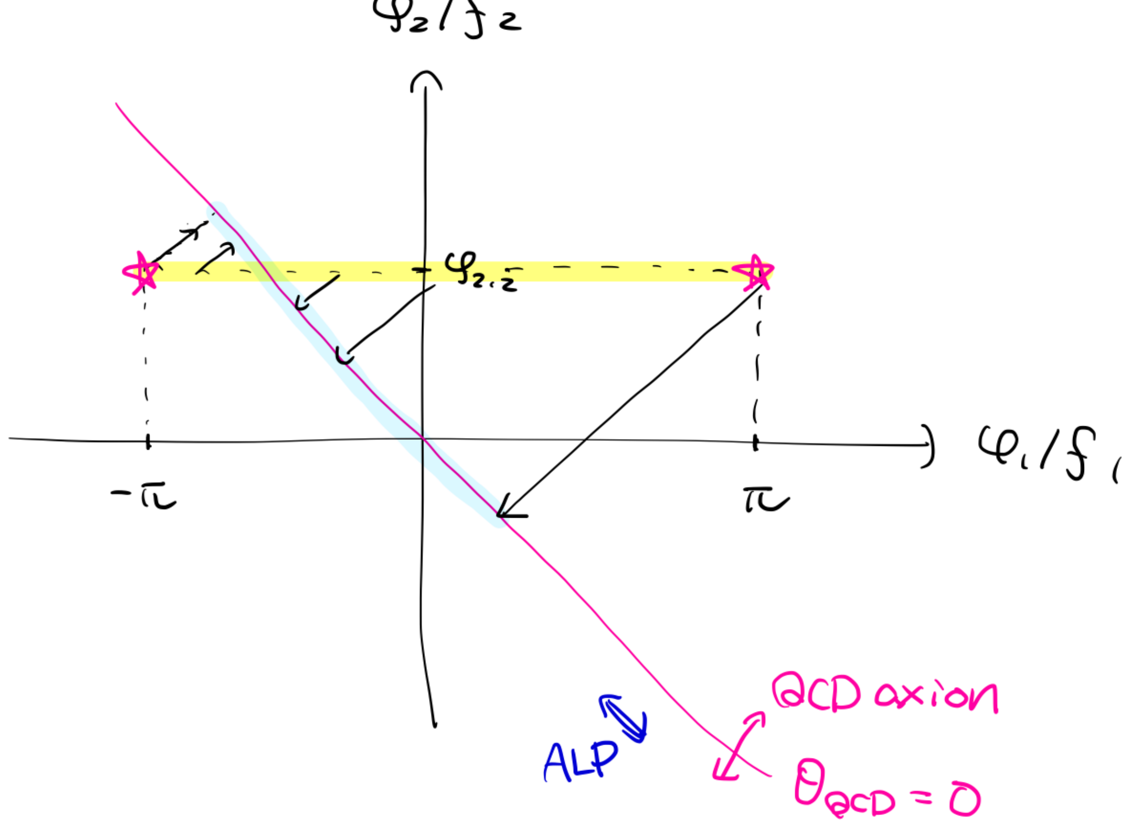
$$\frac{g_s^2}{32\pi^2}\left(\frac{\varphi_1}{f_1}+\frac{\varphi_2}{f_2}\right)G_{a\mu\nu}\tilde{G}_a^{\mu\nu}, \qquad S_i = \frac{f_i}{\sqrt{2}}e^{i\varphi_i/f_i}$$

QCD axion: $\frac{a}{f_a} = \frac{\varphi_1}{f_1}+\frac{\varphi_2}{f_2}$ with $f_a^{-2} \equiv f_1^{-2}+f_2^{-2}$

Ultralight ALP: $\frac{\phi}{f_a} = \frac{\varphi_1}{f_2}-\frac{\varphi_2}{f_1}$

If the φ_2 acquires a periodic potential with $\varphi_2 \to \varphi_2 + 2\pi p f_2$, the ultralight ALP has a decay constant, $f_\phi = \frac{f_1}{p f_2} f_a$.

Suppose that S_1 develops a nonzero VEV after inflation, while S_2 already has a VEV during inflation. Then, φ_1/f_1 randomly takes values between $-\pi$ and π (here $N_{\rm DW} = 1$ is assumed) and strings are formed.



Suppose that S_1 develops a nonzero VEV after inflation, while S_2 already has a VEV during inflation. Then, φ_1/f_1 randomly takes values between $-\pi$ and π (here $N_{\rm DW} = 1$ is assumed) and strings are formed.

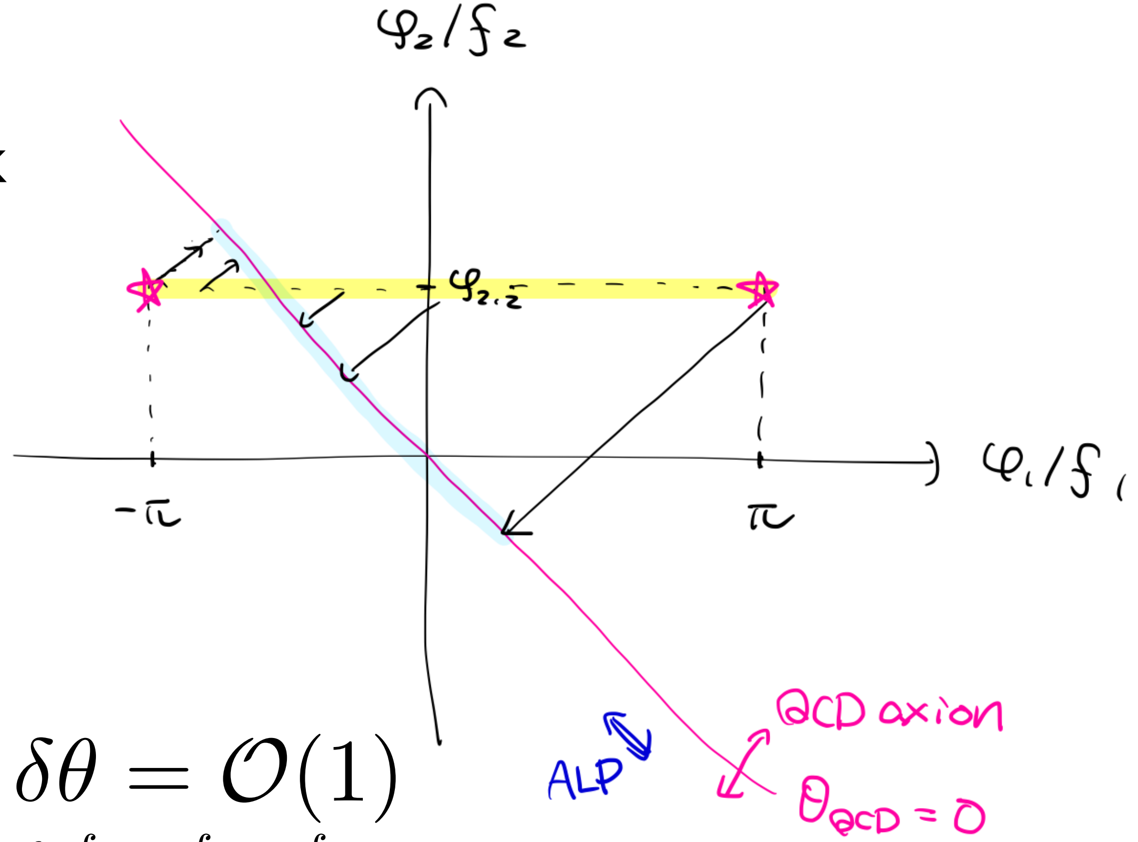
During the QCD phase transition, the QCD axion string-wall network is formed and disappears soon because of $N_{\rm DW} = 1$.

A part of fluctuations is left along the ultralight ALP,

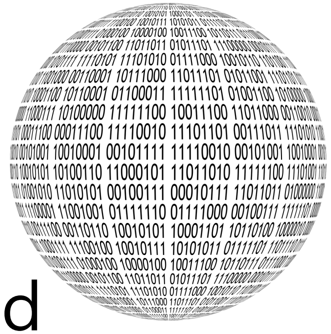
$$\phi = -\frac{f_a}{f_1}\varphi_{2i} \pm \pi \frac{f_1^2}{\sqrt{f_1^2 + f_2^2}}$$

$$\delta\theta = \mathcal{O}(1)$$

if $f_1 \sim f_2 \sim f_\phi$



5. Summary



- Axion domain walls w/o strings induce both isotropic and anisotropic CB: **KiloByte CB**

- It naturally explains the recent hint on the isotropic CB over a wide range of the axion mass and axion-photon coupling.

$$\beta_{\rm KBCB} \simeq 0.21\, c_\gamma \ \ {\rm deg} \quad \text{independent of } m_\phi \text{ and } f_\phi\,.$$

cf. $\beta_{\rm obs} = 0.35 \pm 0.14 \ {\rm deg}$

- The predicted anisotropic CB has a peculiar feature determined by the domains on the LSS: determined by domains on the LSS, which may be checked by future CMB observations.