Cosmic Birefringence and Axion

June 24. 2021, seminar@KIAS

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Based on 2012.11576 with Wen Yin, 2103.08153 with Shota Nakagawa and Masaki Yamada

1. Introduction

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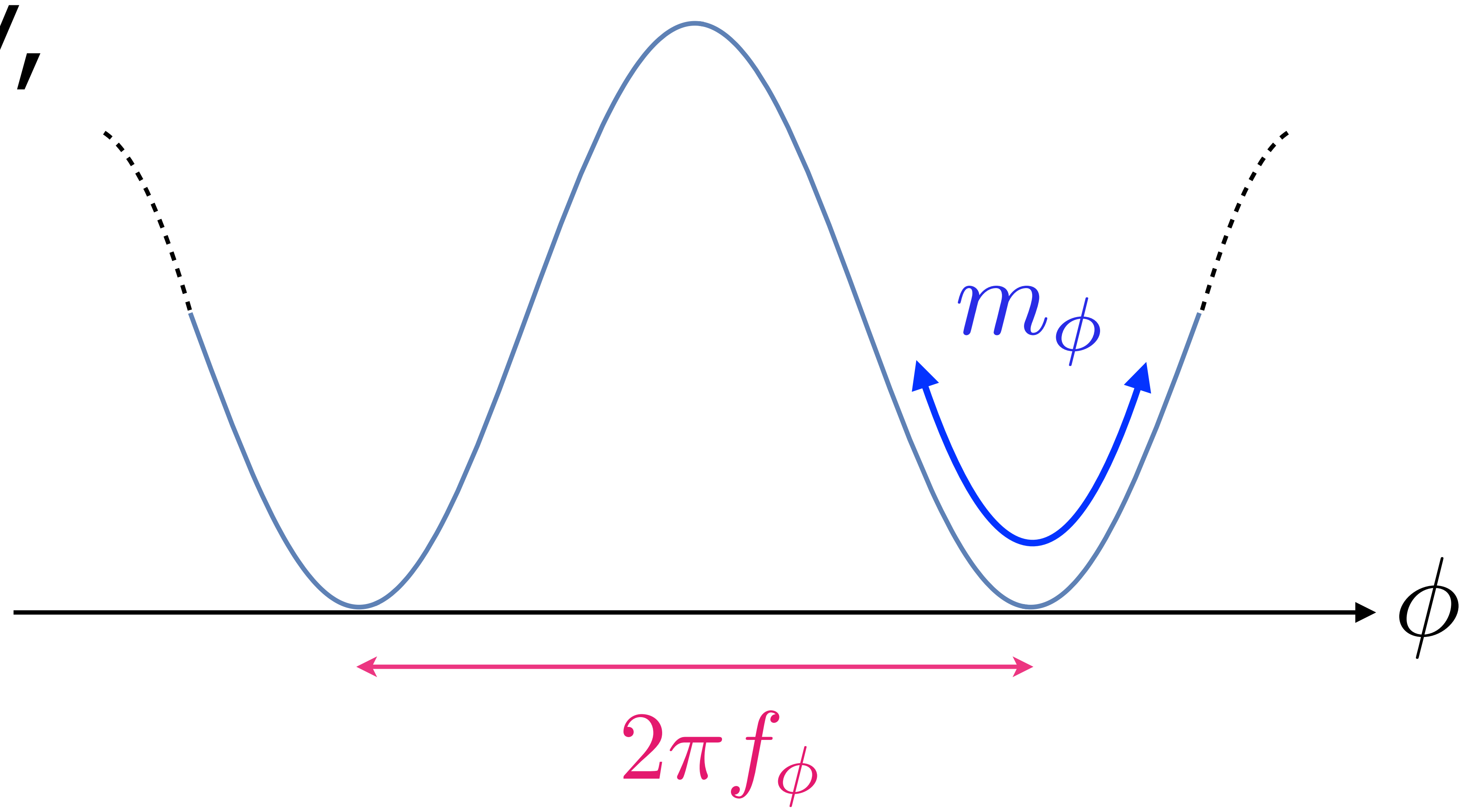
An axion enjoys a (discrete) shift symmetry,

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



which implies the existence of degenerate vacua.

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

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

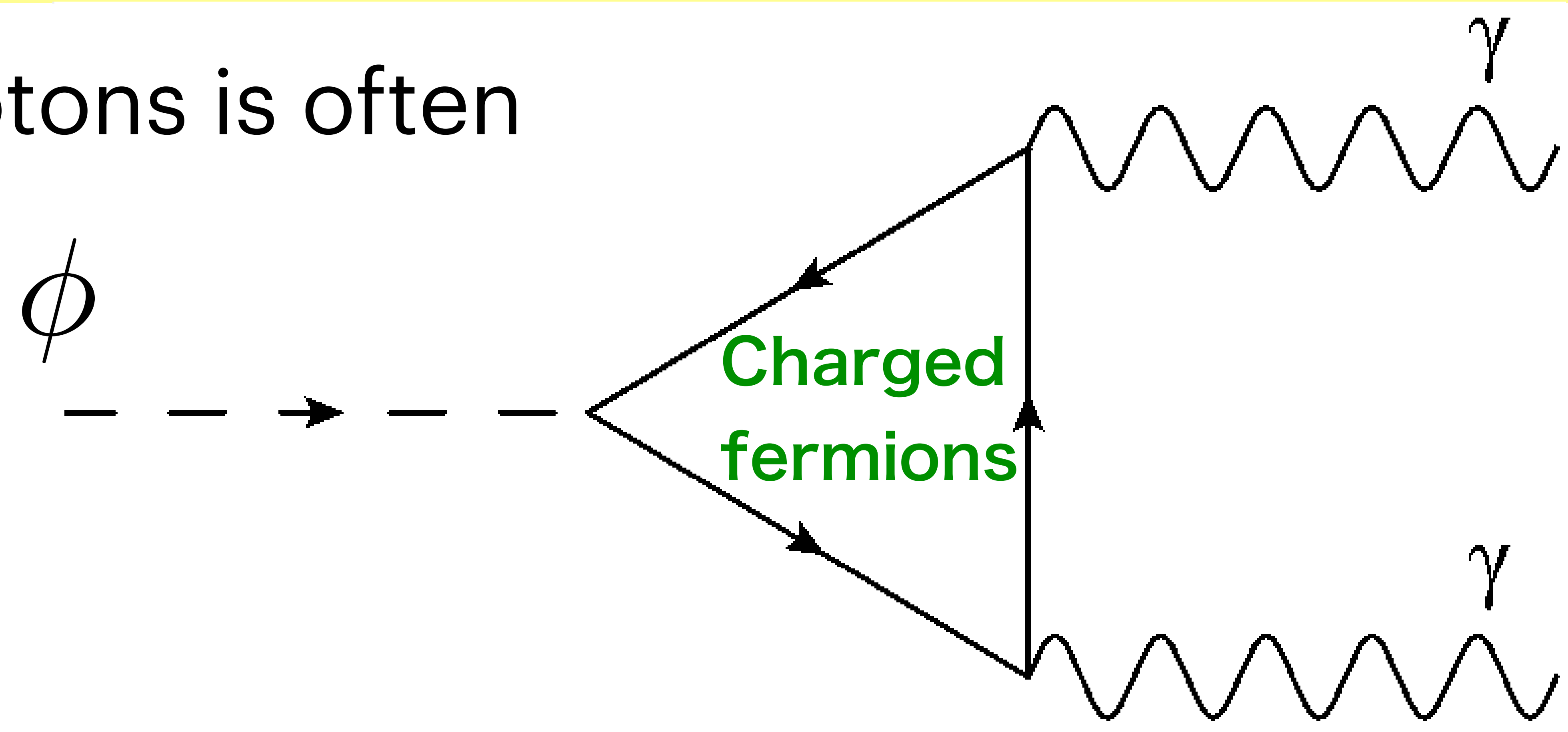
Axion couplings to the SM particles:

- 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.

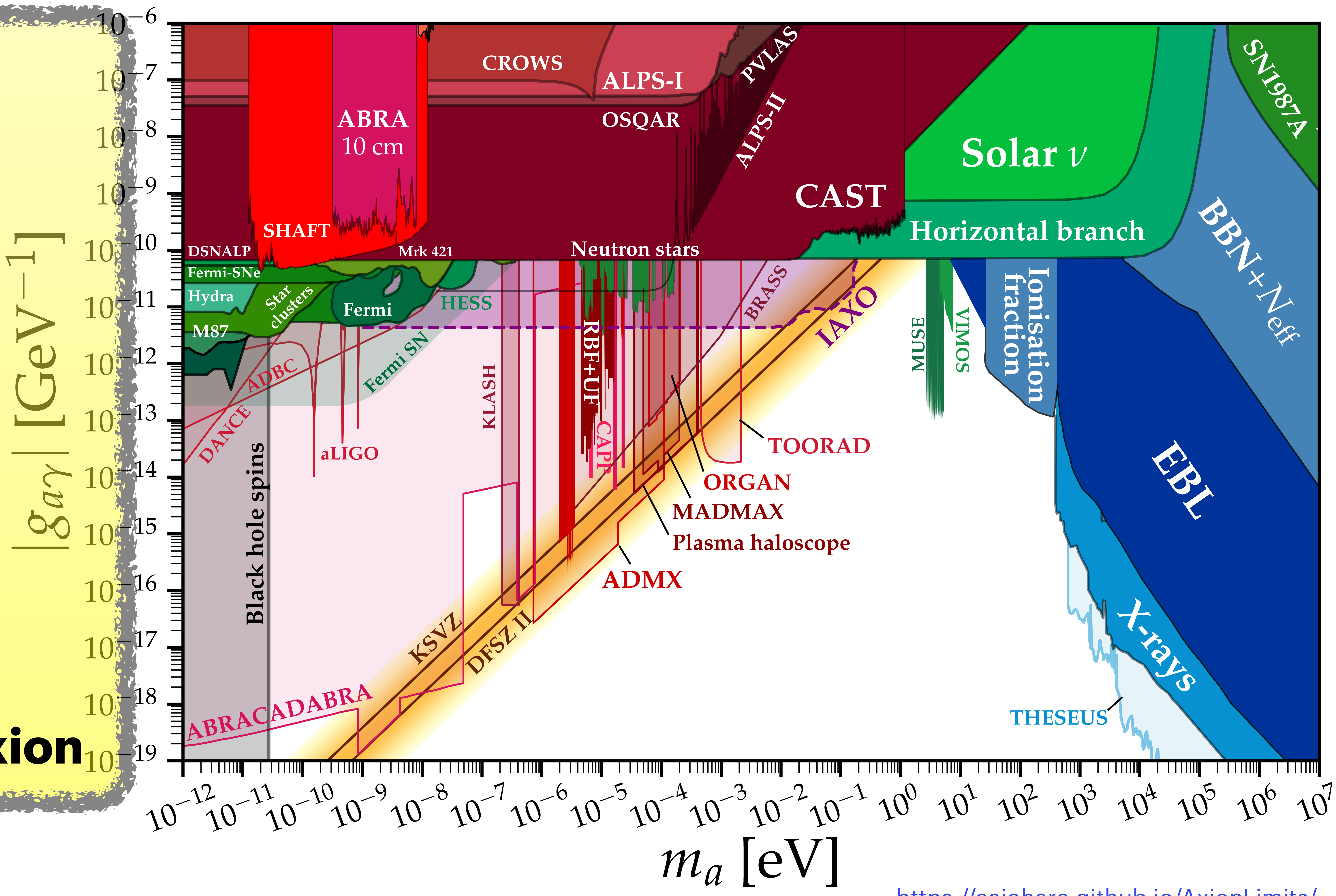
Axion coupled to photons is often referred to as **ALP**.



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

- 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



Ultralight axion

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

Cosmic birefringence (CB) due to ALP

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

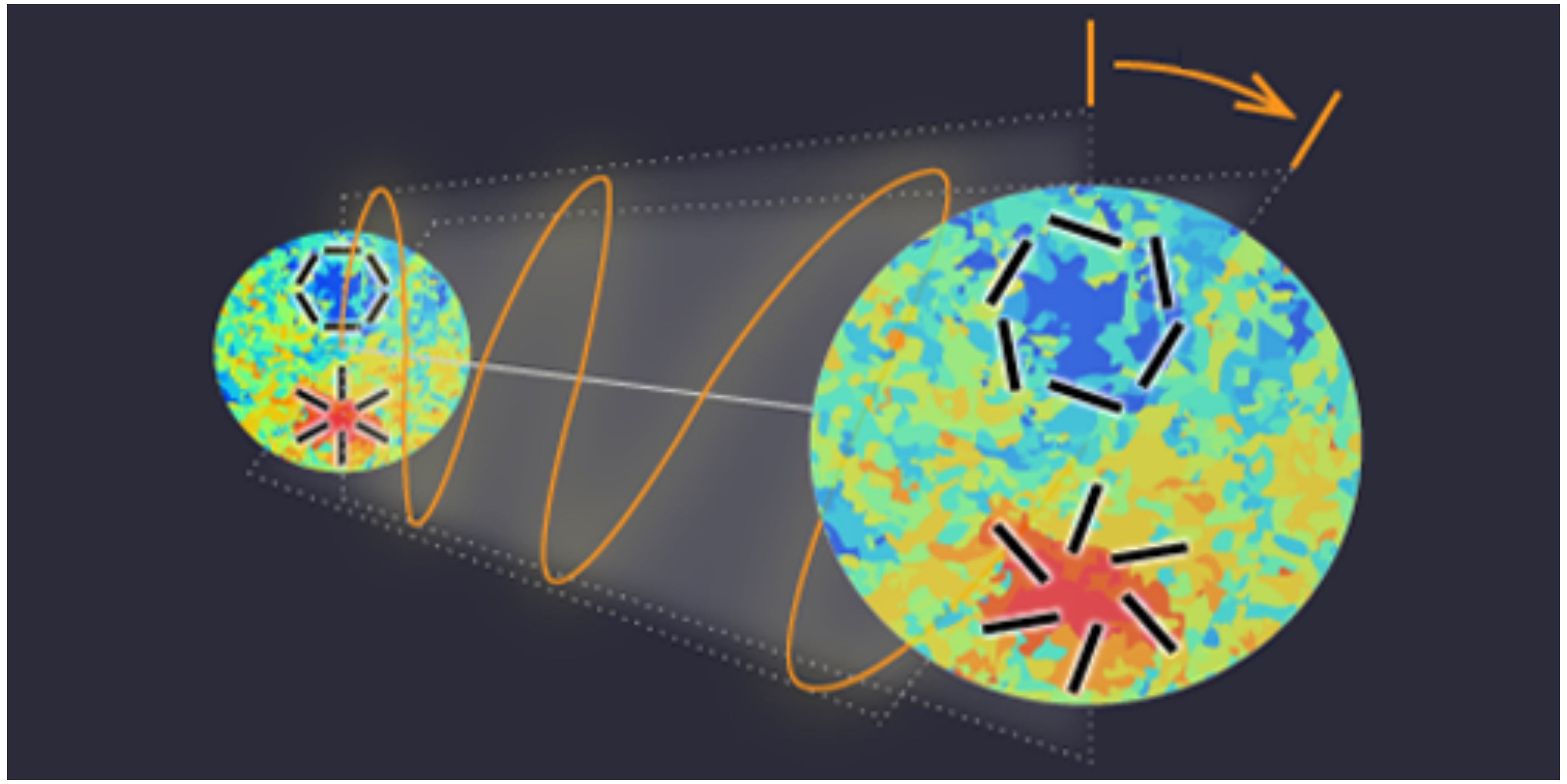
The polarization plane of CMB gets rotated

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

or if the ALP has fluctuations (anisotropic CB + isotropic CB).

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

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



Hint of isotropic CB?

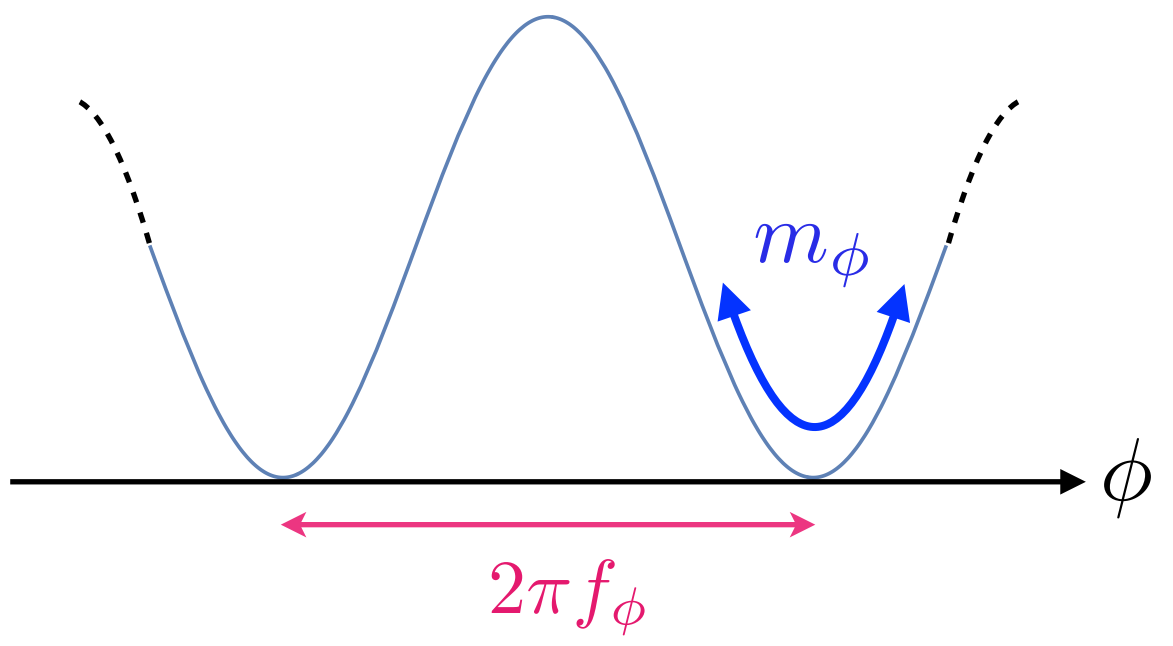
$$\beta = \frac{1}{4\pi}\int d\Omega\, \Phi(\Omega) = 0.35 \pm 0.14 \ \text{deg}$$

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

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

Implications of the hint for axion/ALP

Homogeneous ultralight axion with
mass $10^{-33}\text{eV} < m_\phi < 10^{-28}\text{eV}$?



cf. Carrol, astro-ph/9806099, Lue, et al astro-ph/9812088 for early works
Fujita et al 2011.11894

- Can it naturally explain the hinted isotropic CB?
- Why this particular masses?
- Is heavier or lighter axion possible?
- Any prediction for anisotropic CB?

(1) Axion domain walls
2012.11576 with Wen Yin

(2) Axion coupled to DM
2103.08153 with S.Nakagawa and M.Yamada

2. Cosmic birefringence

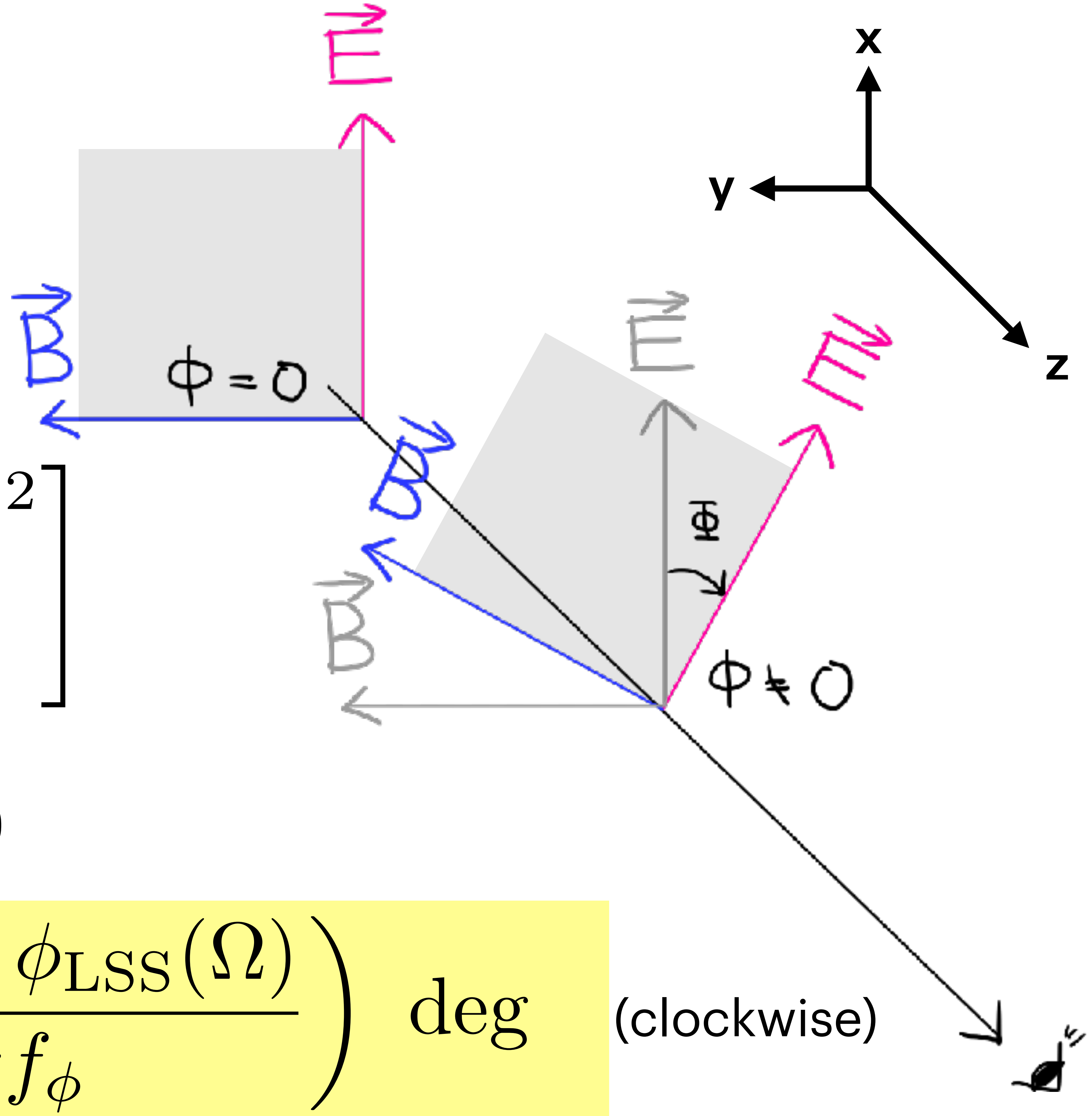
2. Cosmic birefringence

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

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

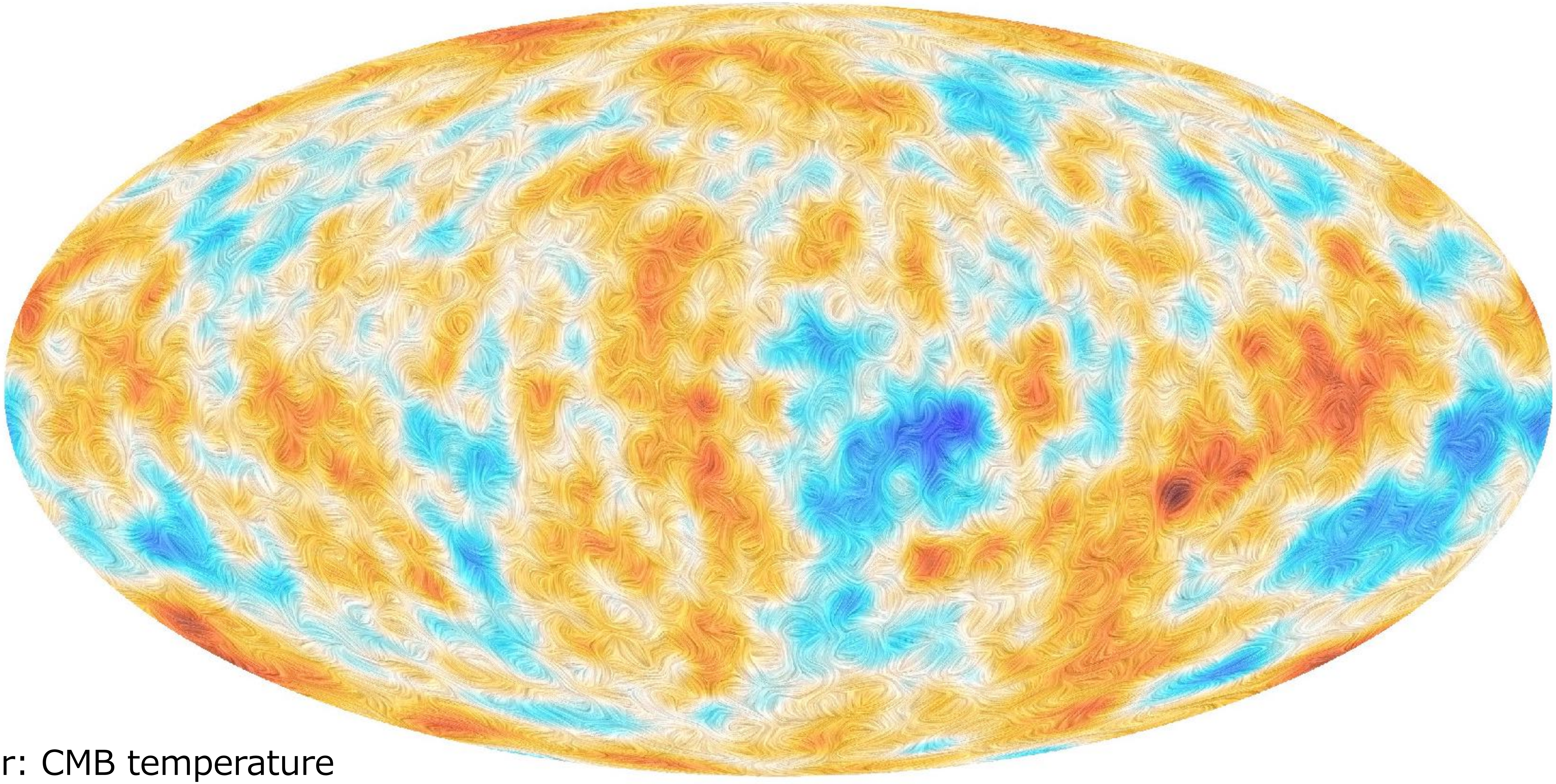
$$= \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right) + g_{\phi\gamma\gamma}\phi\vec{E}\cdot\vec{B}$$

$$\simeq \frac{1}{2}\left[\Bigg(\underbrace{\vec{E} + \frac{g_{\phi\gamma\gamma}\phi}{2}\vec{B}}_{\vec{E}\text{ when }\phi=0}\Bigg)^2 - \Bigg(\underbrace{\vec{B} - \frac{g_{\phi\gamma\gamma}\phi}{2}\vec{E}}_{\vec{B}\text{ when }\phi=0}\Bigg)^2\right]$$



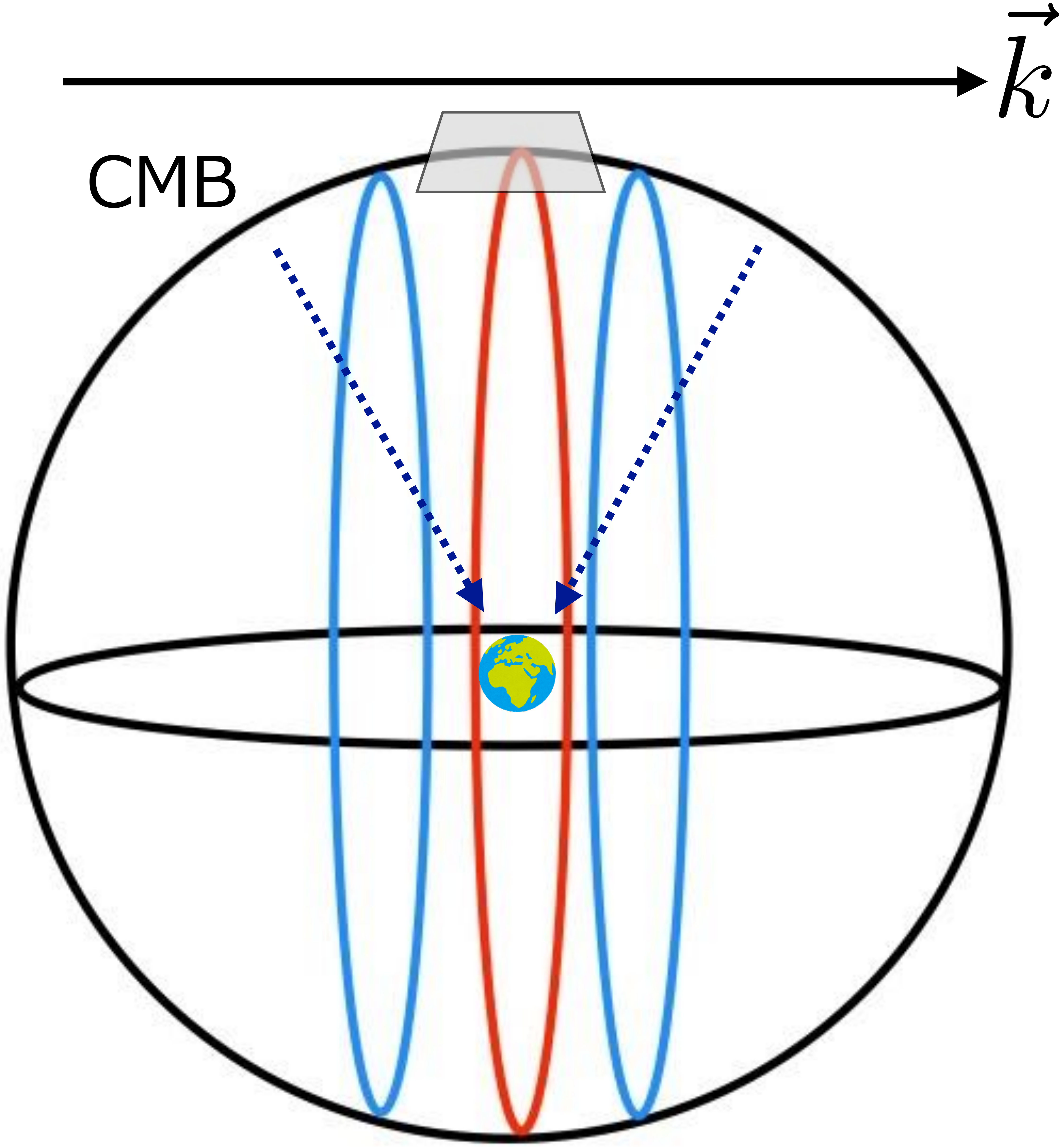
Thus, $$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42c_\gamma\left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi}\right)\ \text{deg}$$ (clockwise)

CMB photons are polarized (dominated by E-mode)

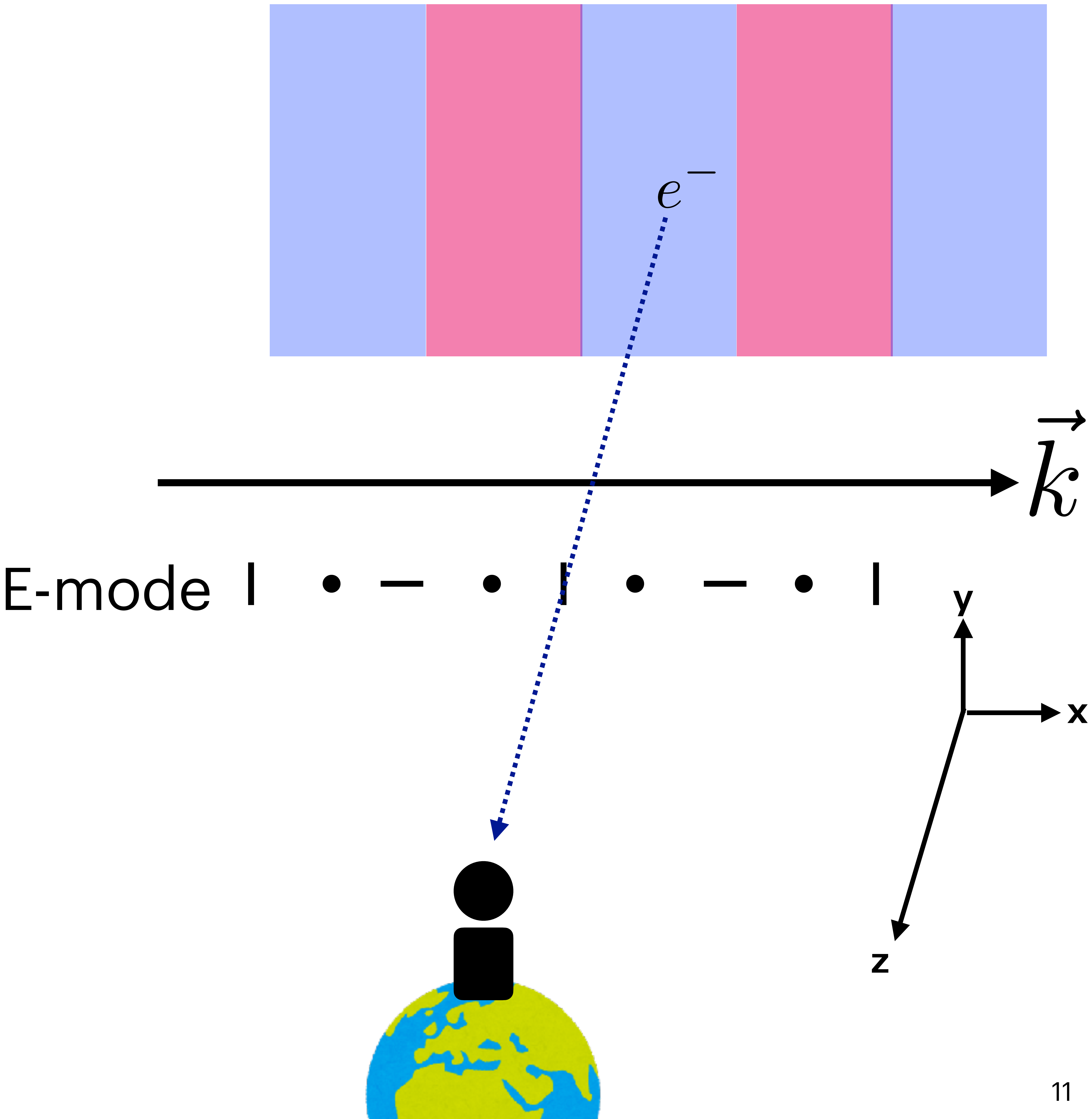


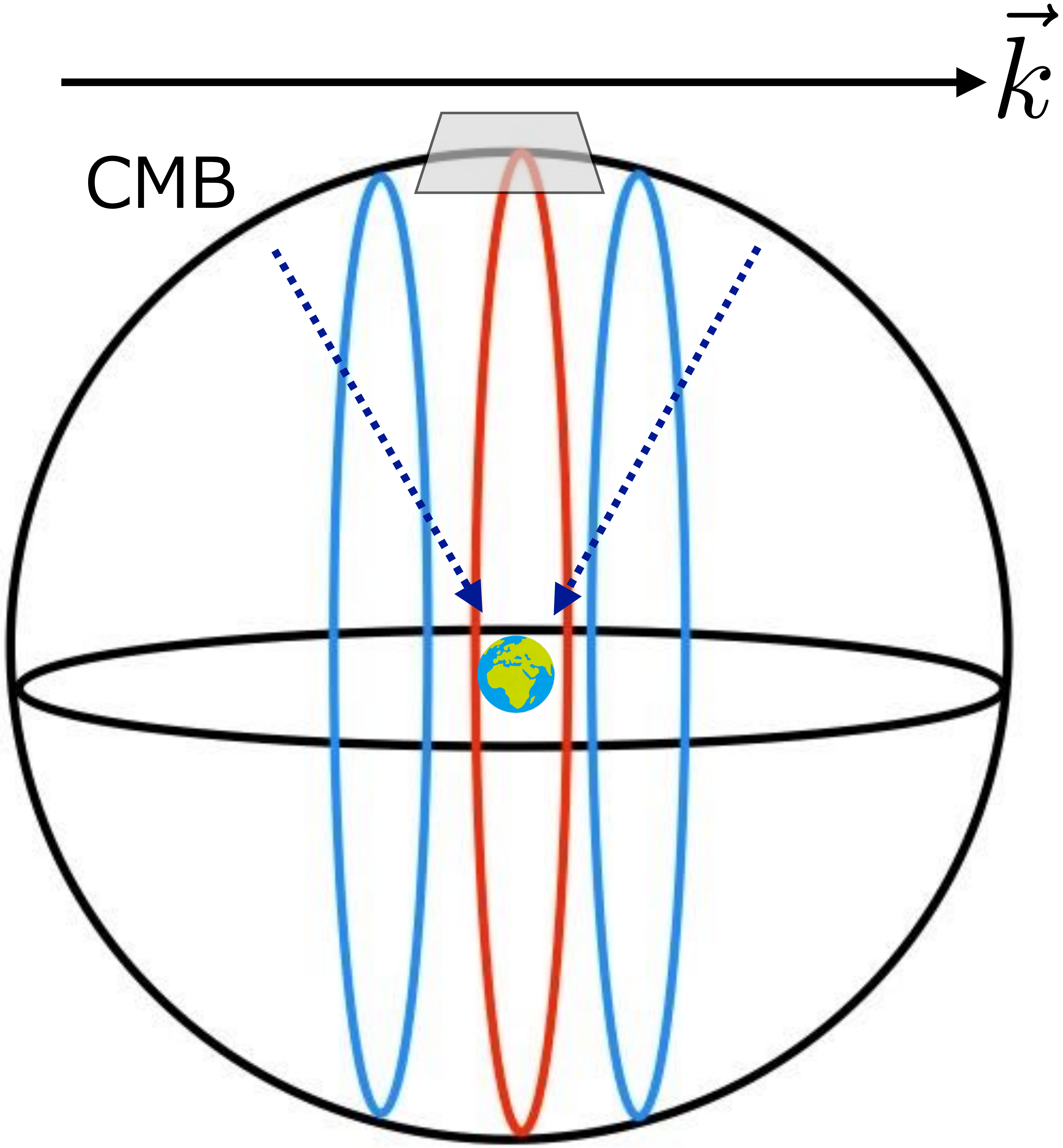
Color: CMB temperature

Texture: direction of polarization



Last scattering surface (LSS)





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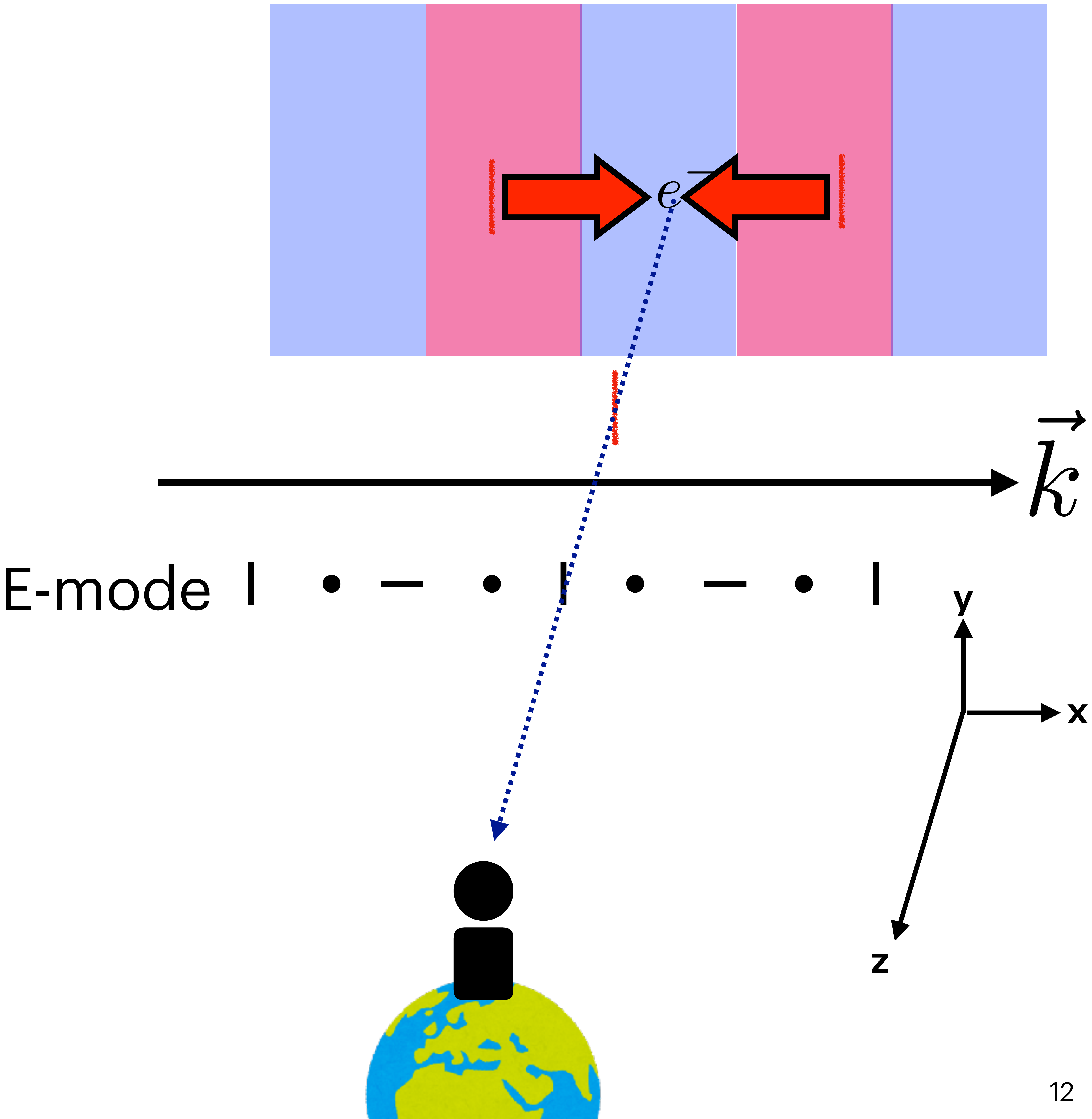

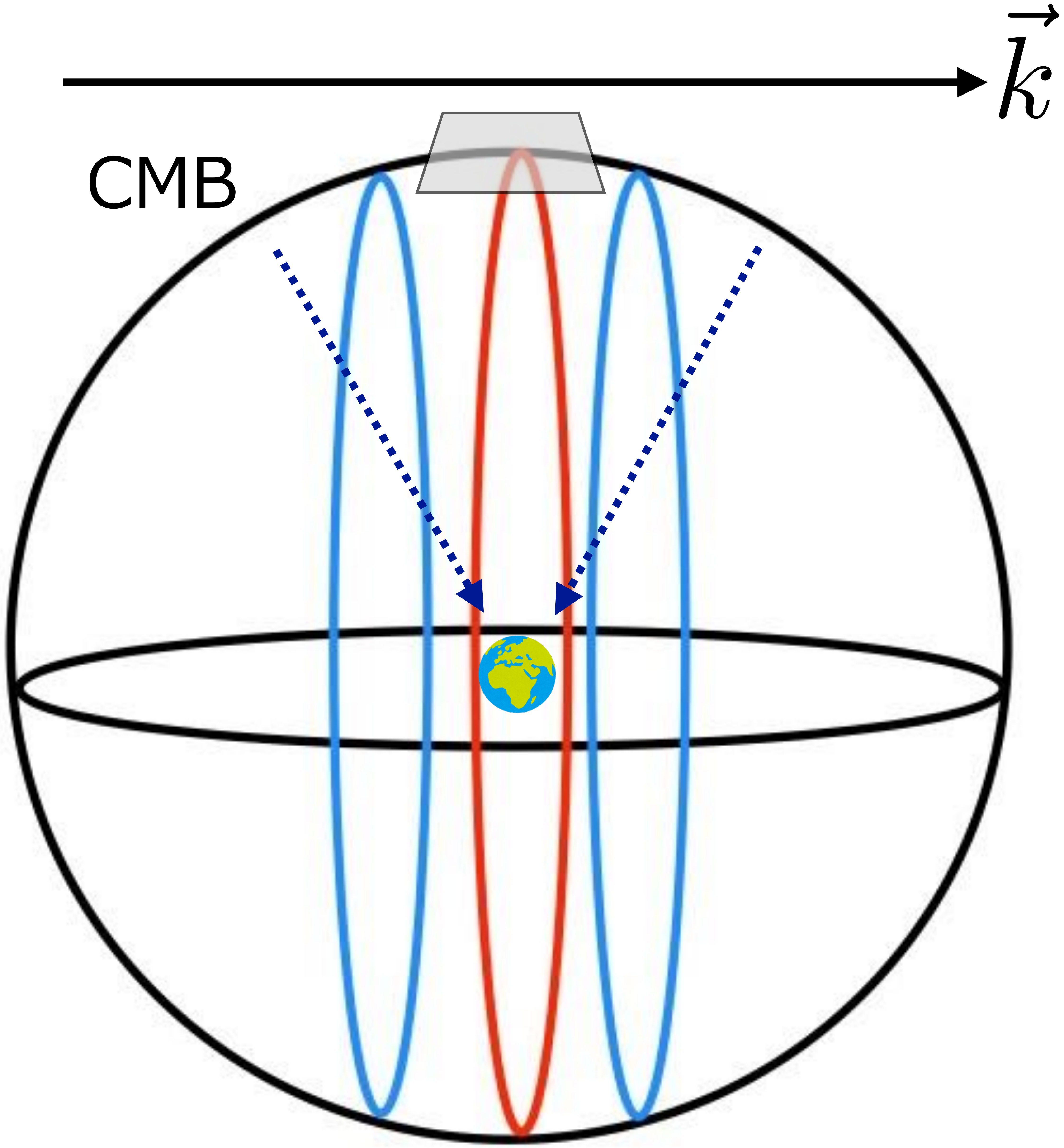

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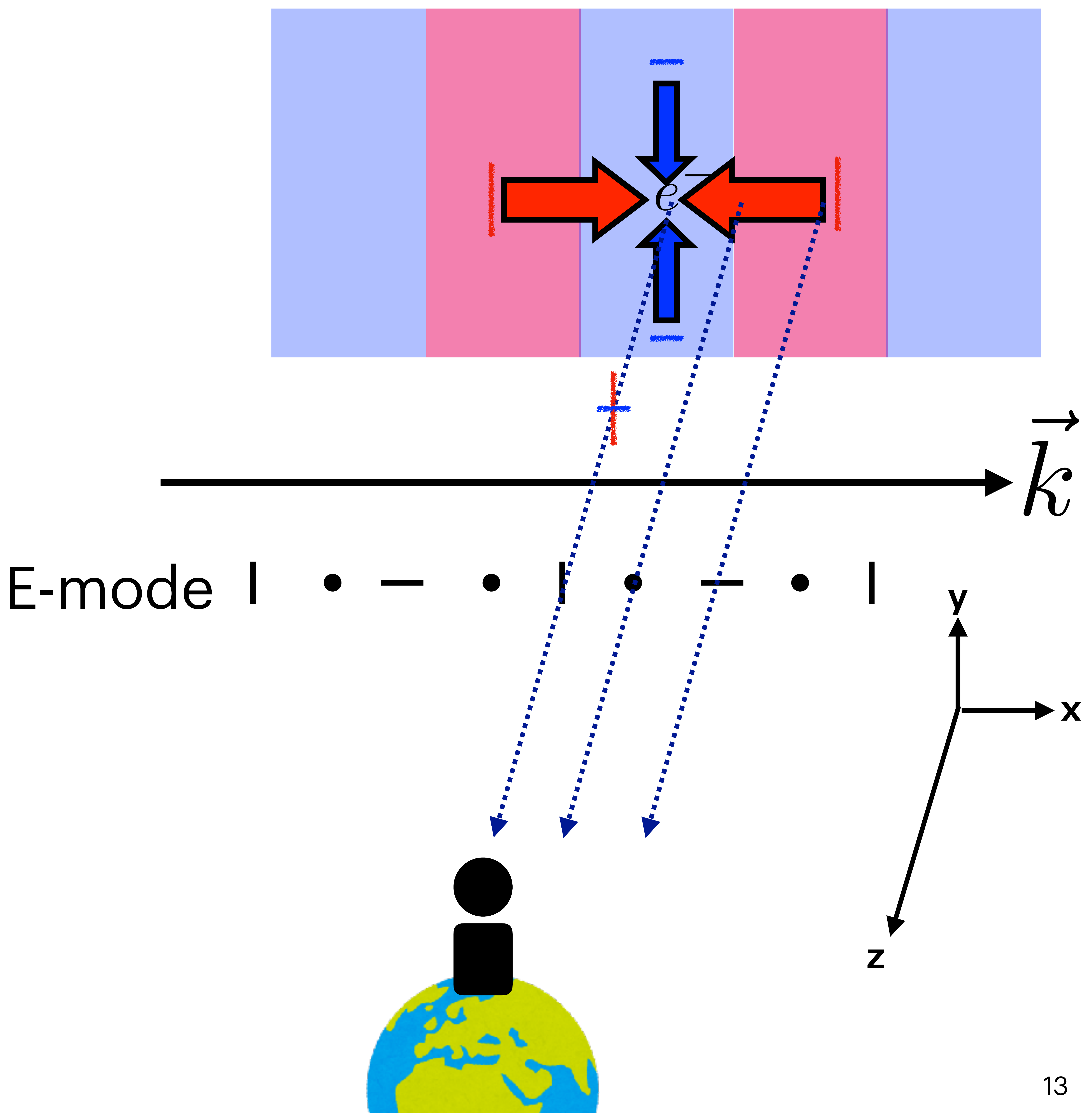

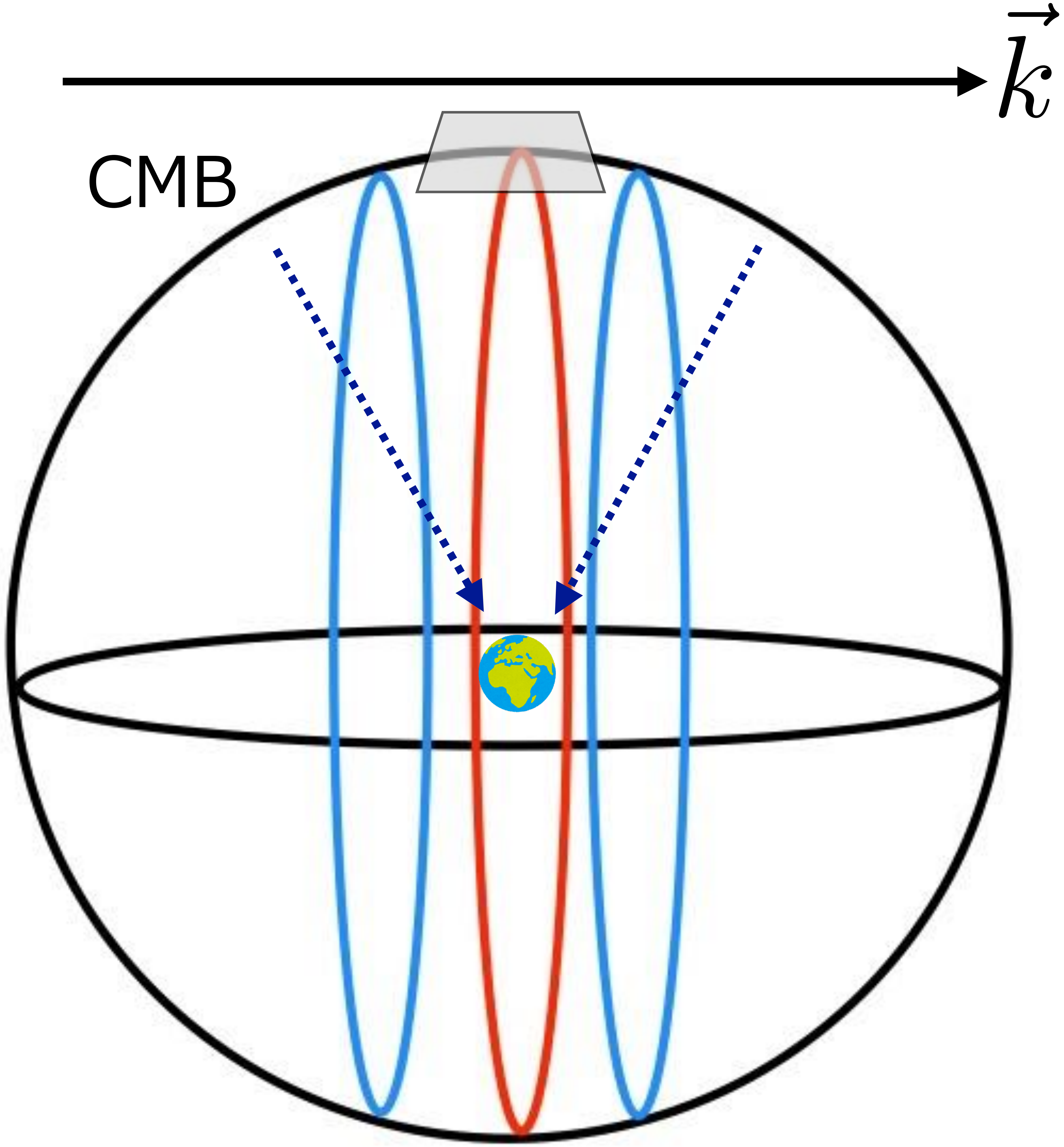

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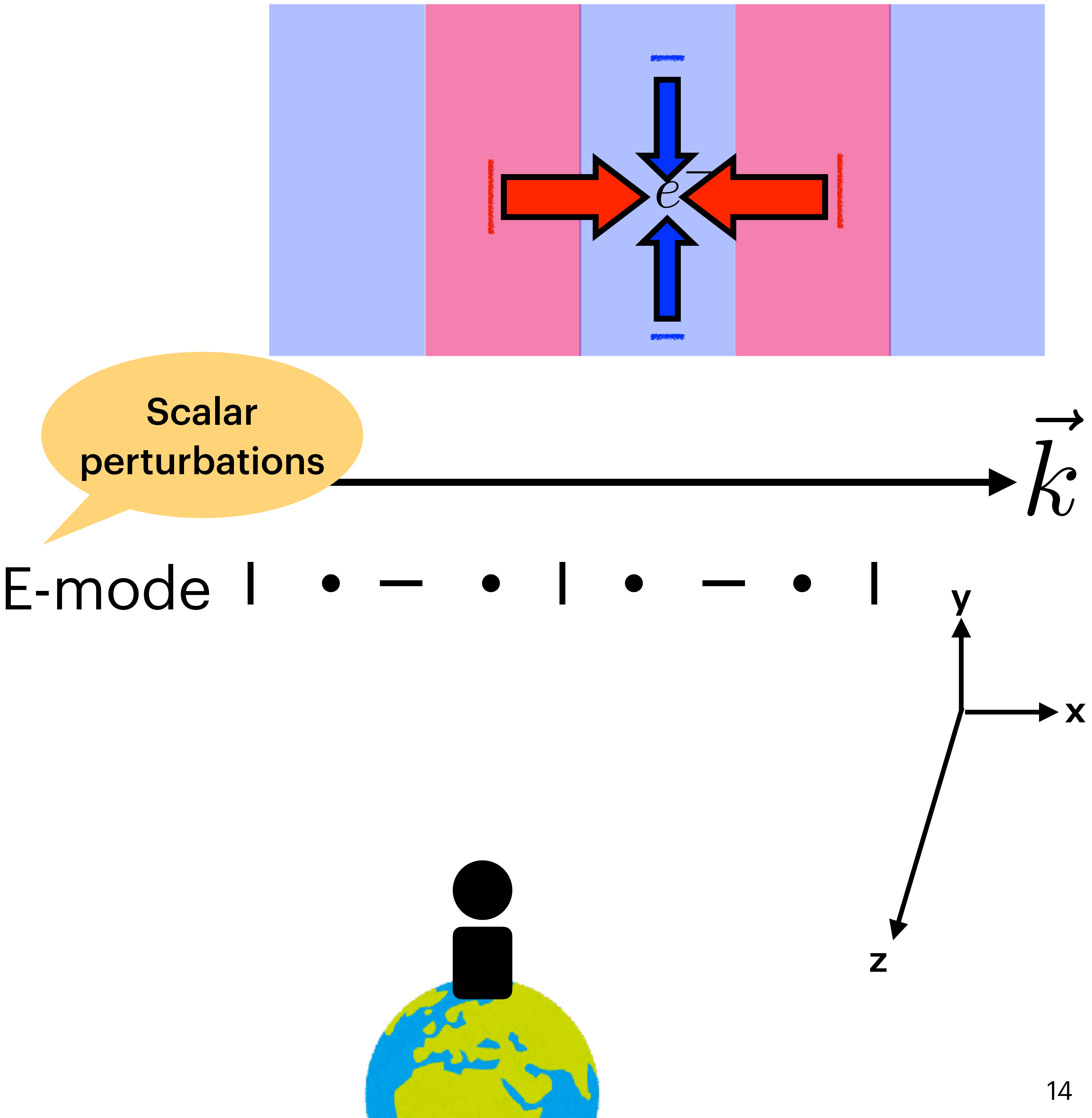

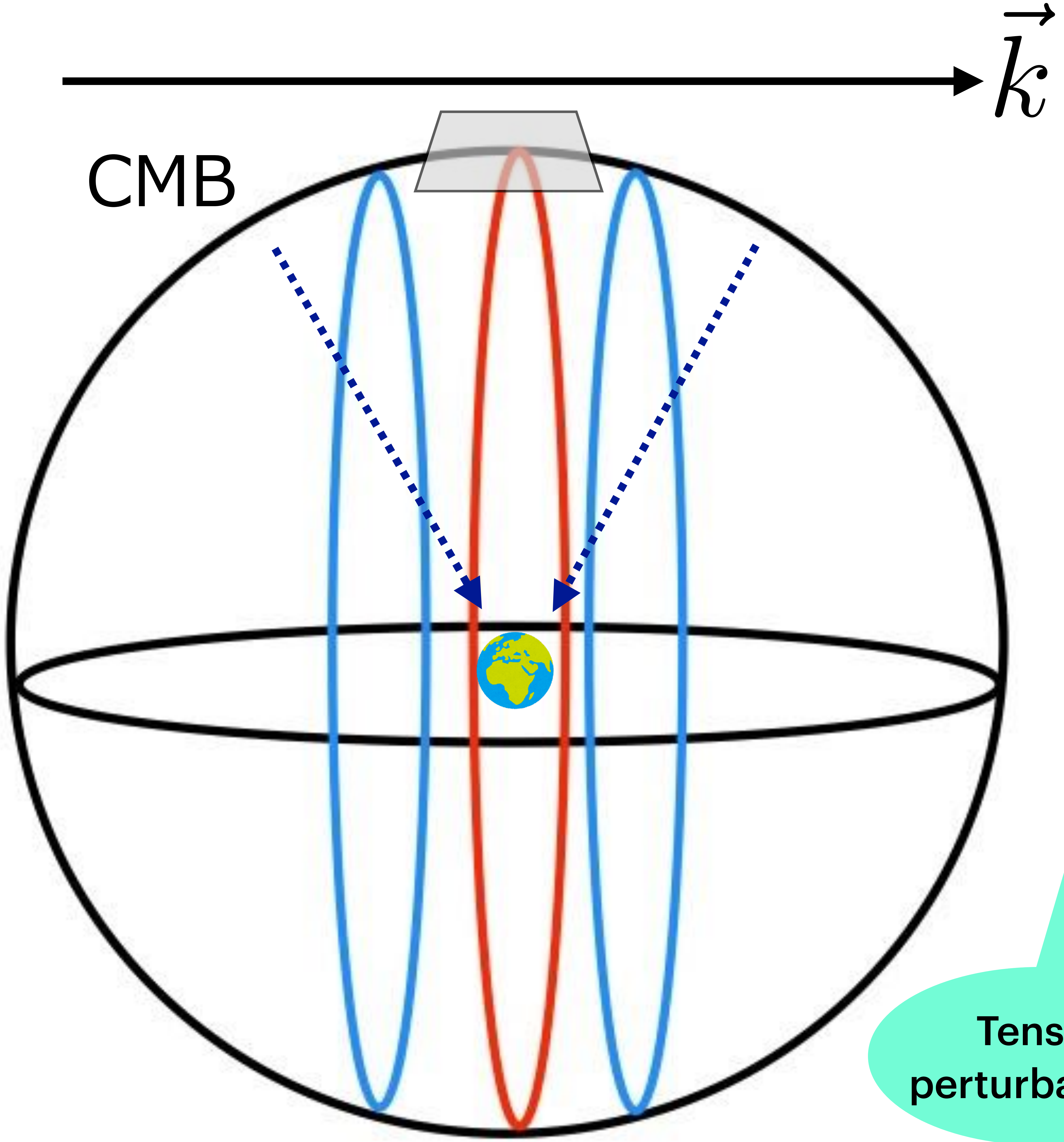

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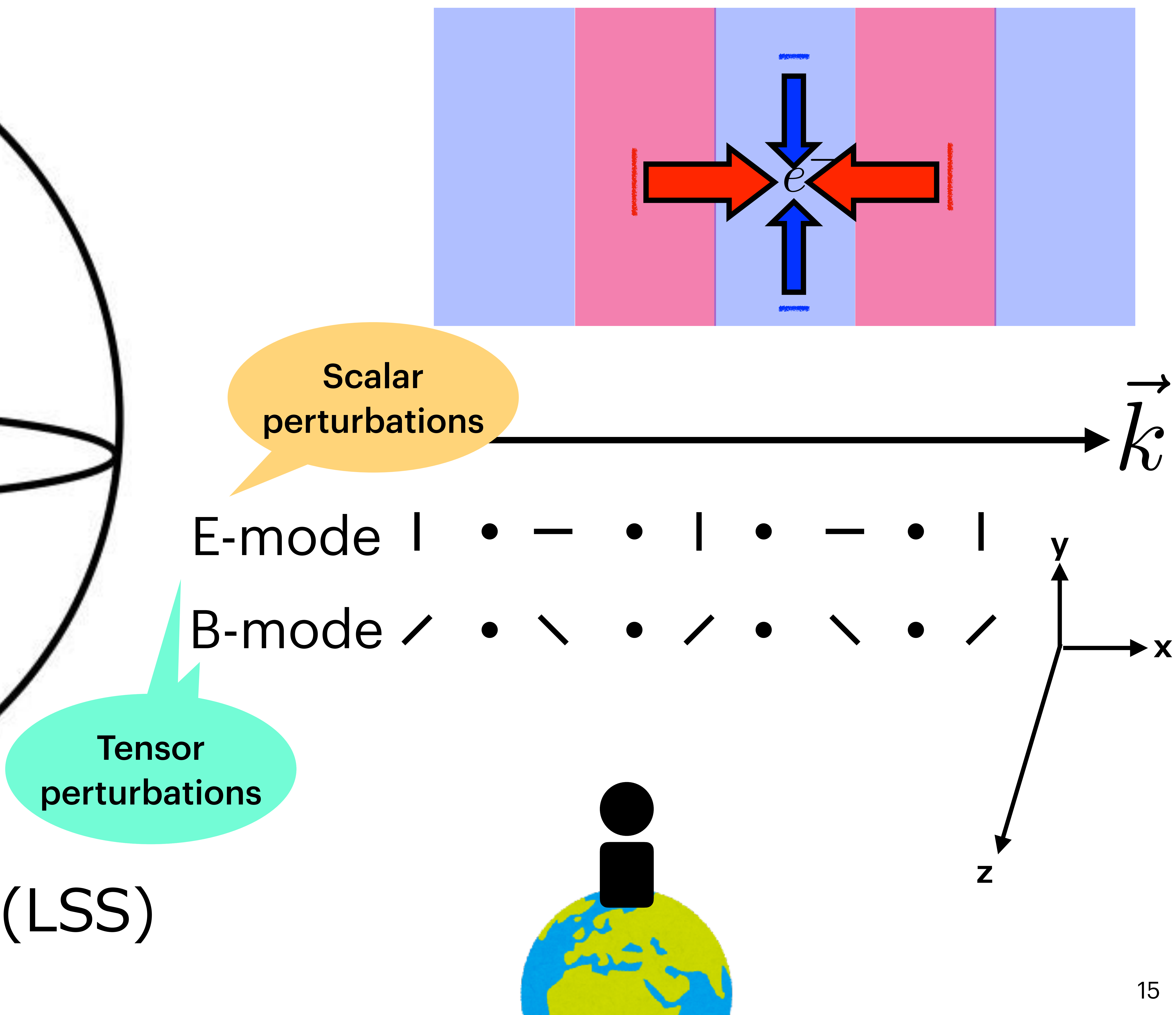
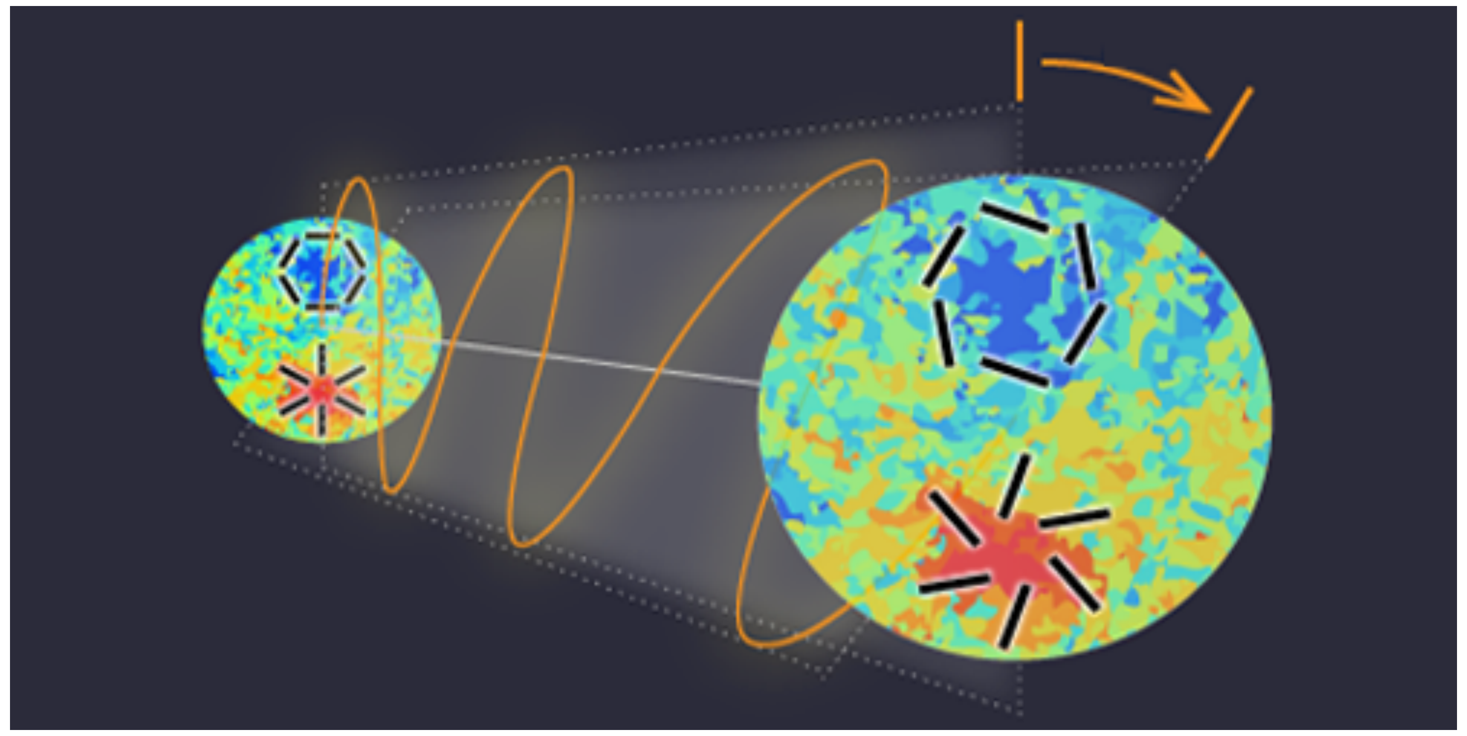


CMB constraints on the CB



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

Isotropic CB

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

from Planck 18 pol. data

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

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

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

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

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

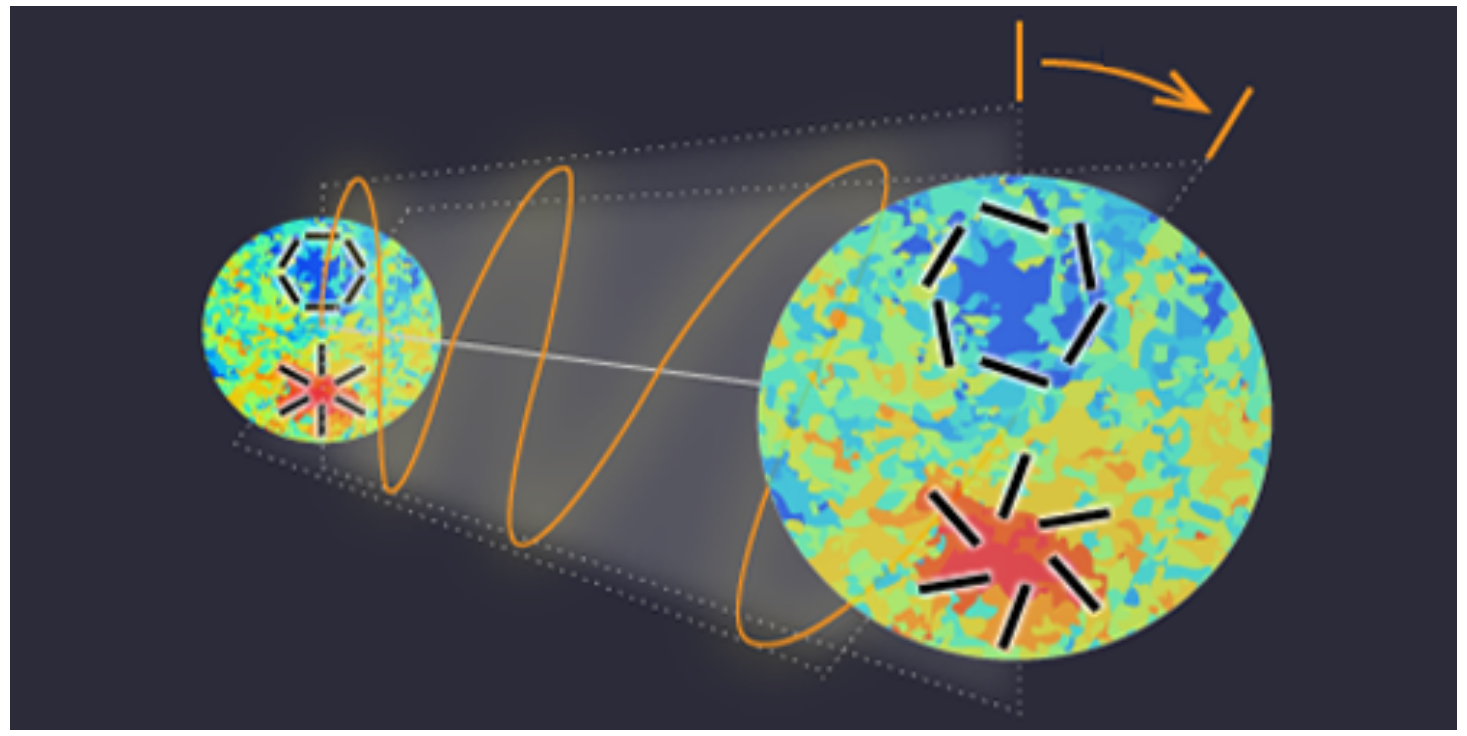
generated during inflation.

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

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

The sensitivity will be improved by a factor of ~30 in the future CMB-S4

Pogosian et al, PRD 100, 023507 (2019)



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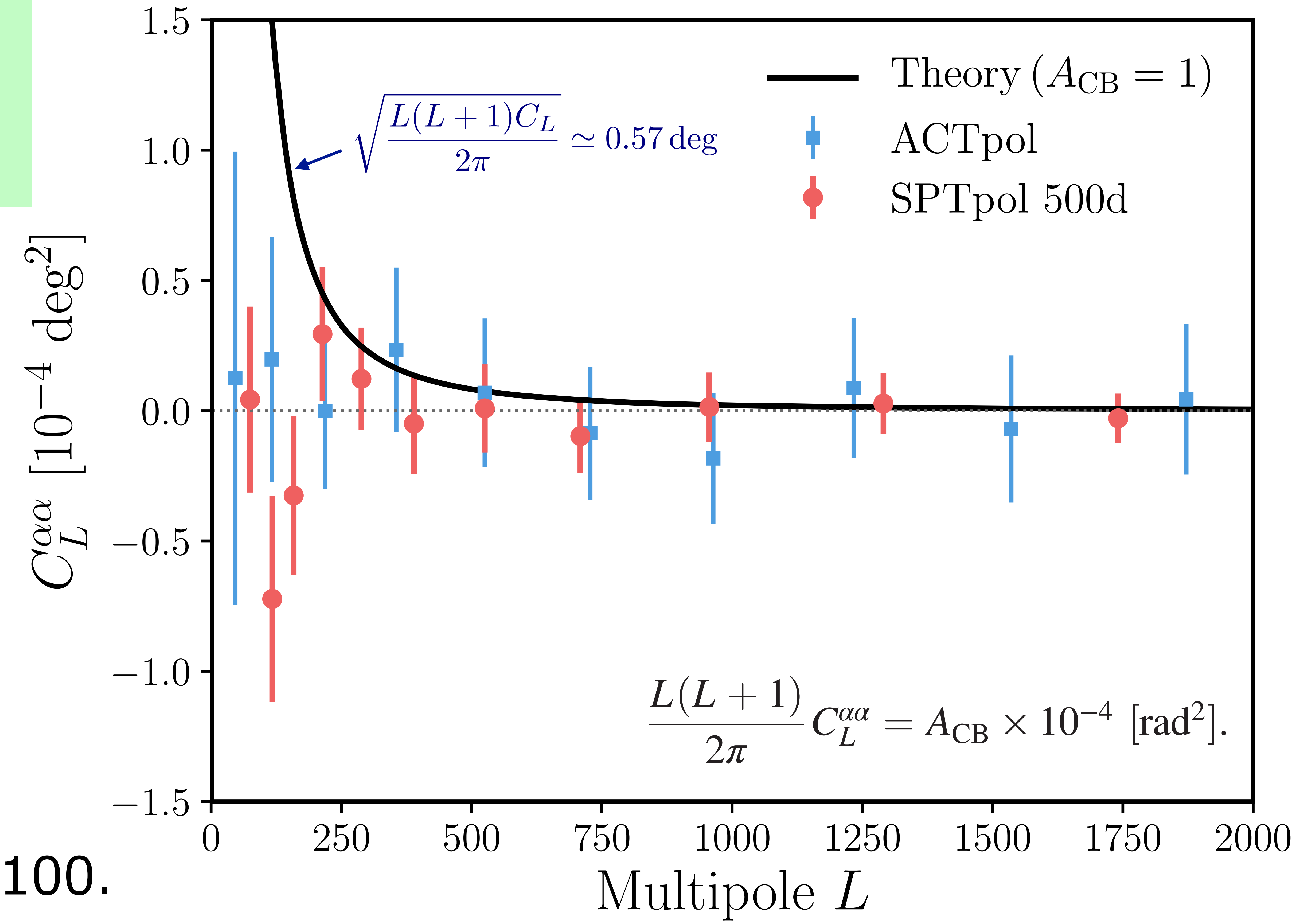


SPTpol, *Phys.Rev.D* 102 (2020) 8, 083504 (arXiv:2006.08061)

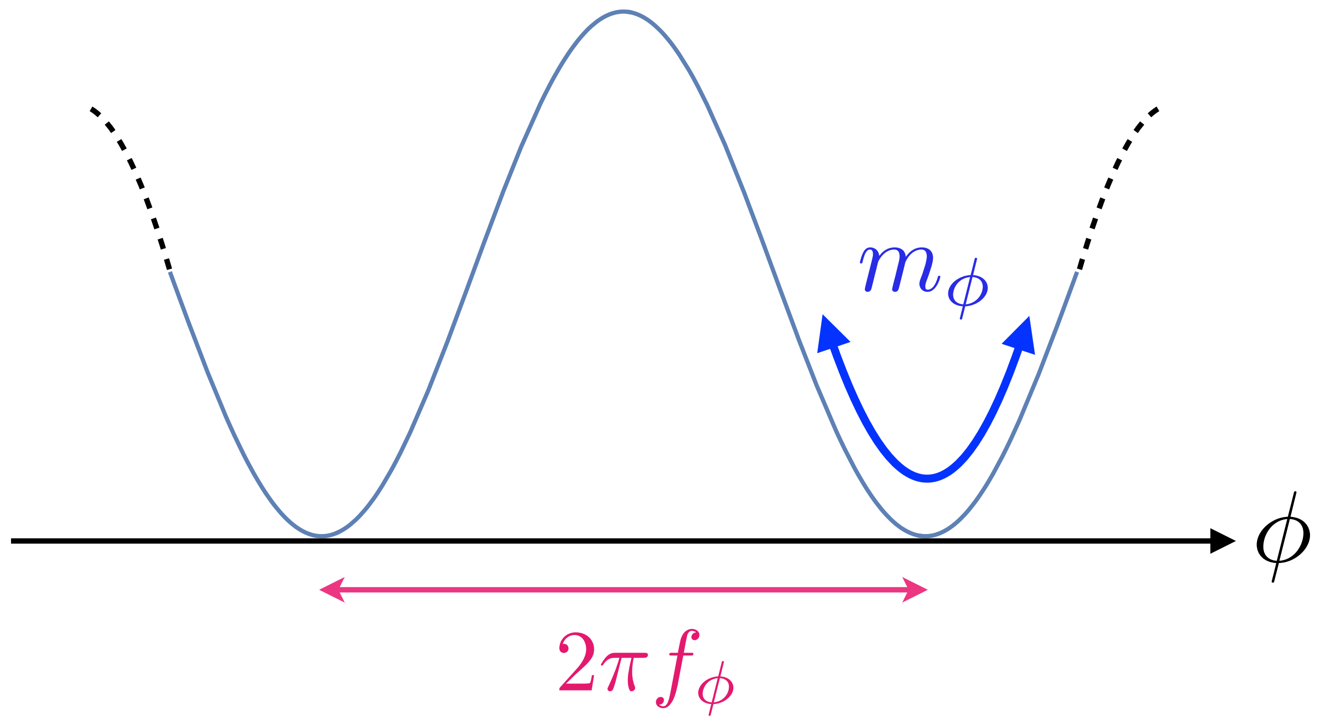
Implications for ALP

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

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

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

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



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:

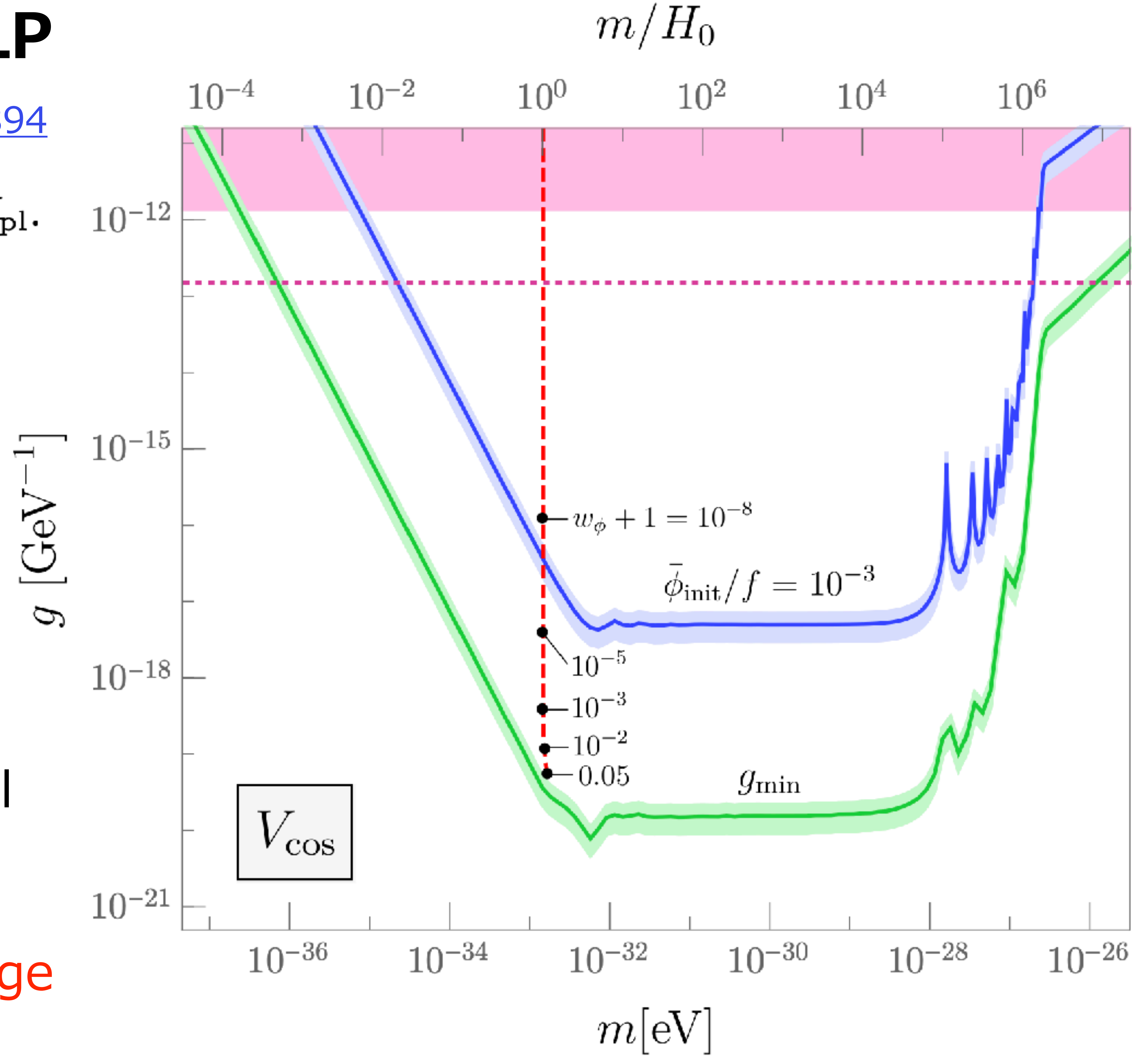
(1)mass m

(2)decay constant f $\rightarrow$ 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 interesting mass range is $10^{-33} \sim 10^{-28}$eV.



3. Scenario 1: Axion Domain Walls

ALP domain walls without strings

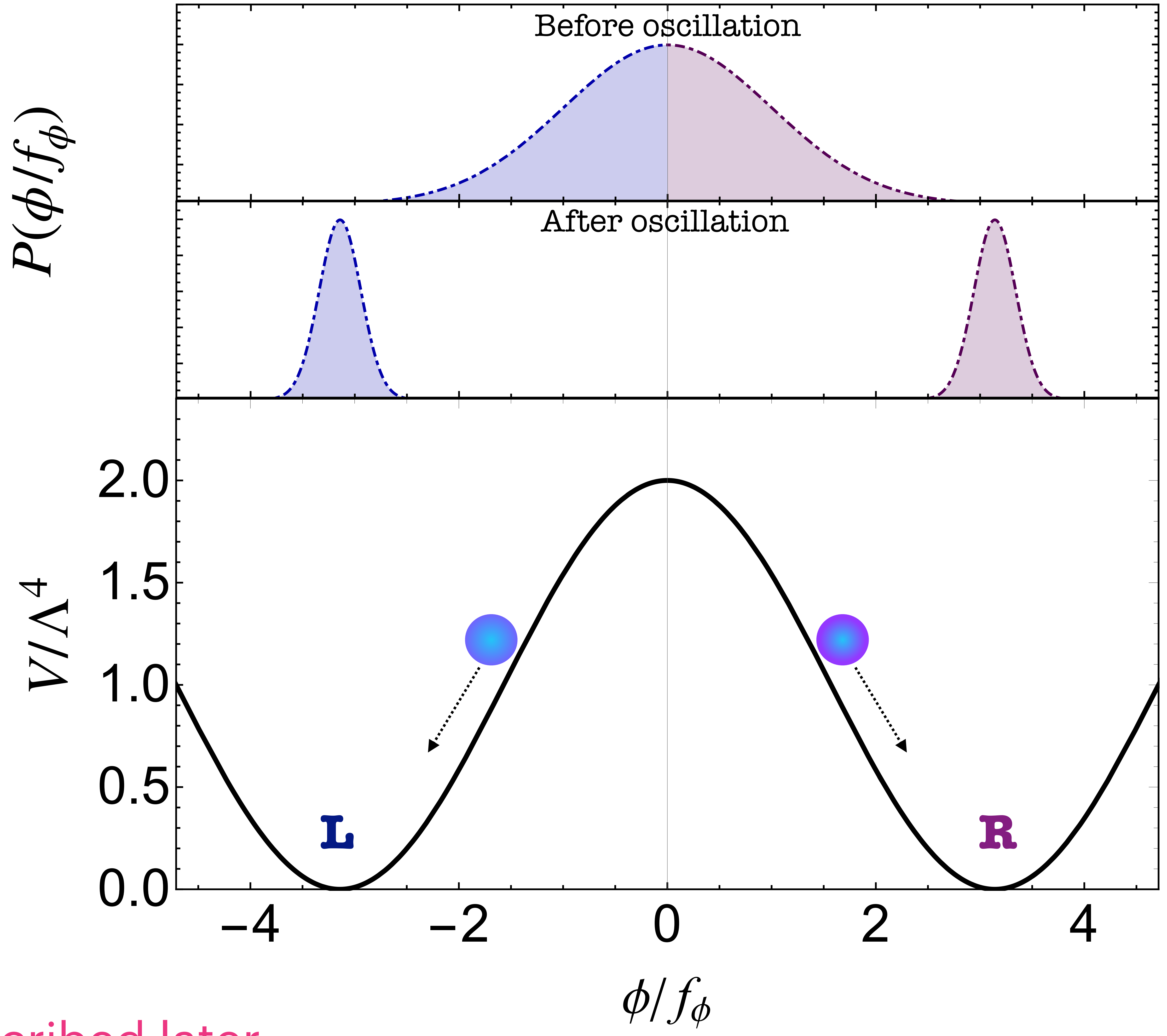
Let us consider the axion potential

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

and focus on the adjacent minima,

$\phi_L = -\pi f_\phi$ 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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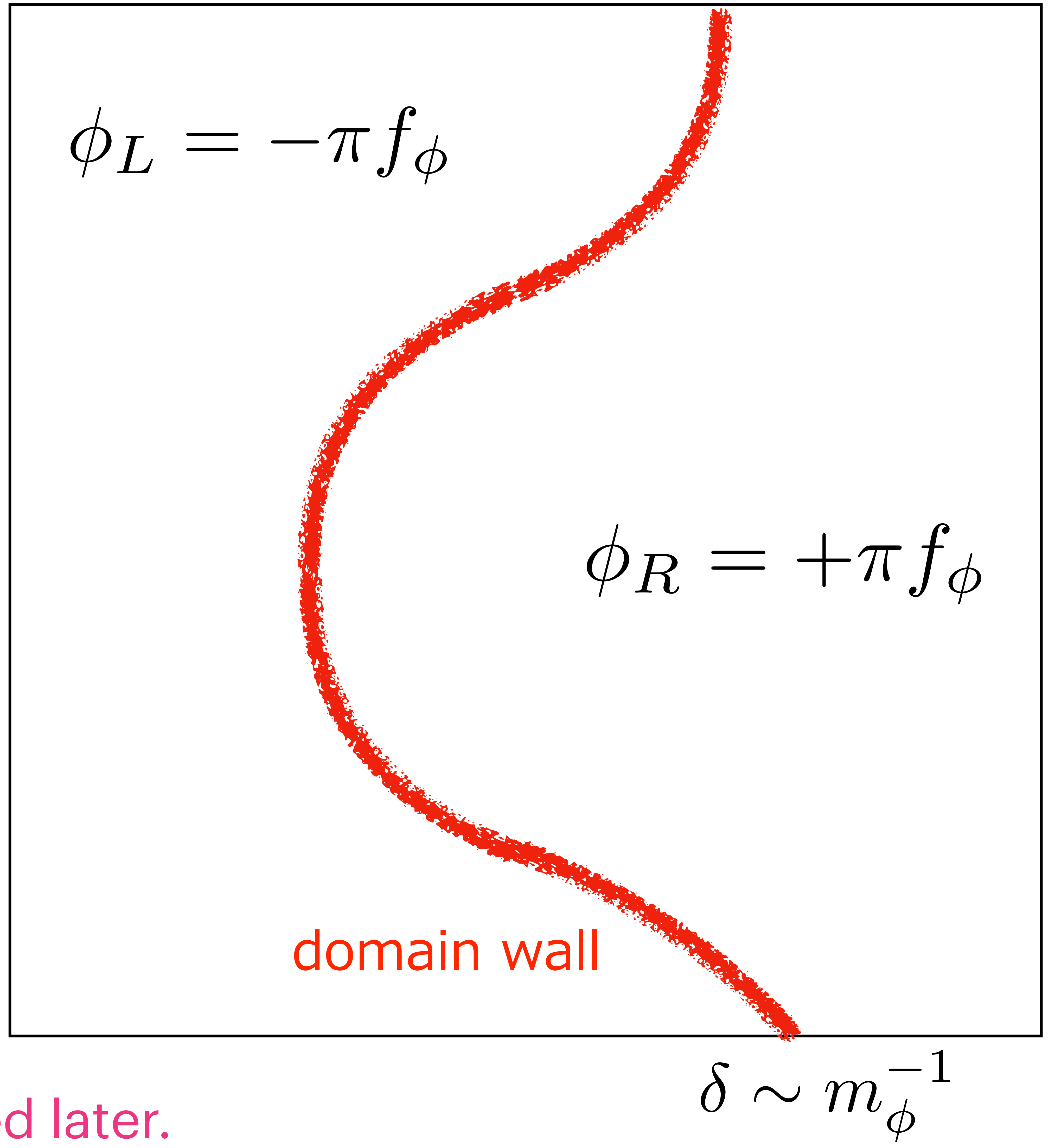


Specific scenarios to obtain $\delta\theta = O(1)$ will be described later.

Scaling solution of domain walls

Press, Ryden, Spergel `89

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

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

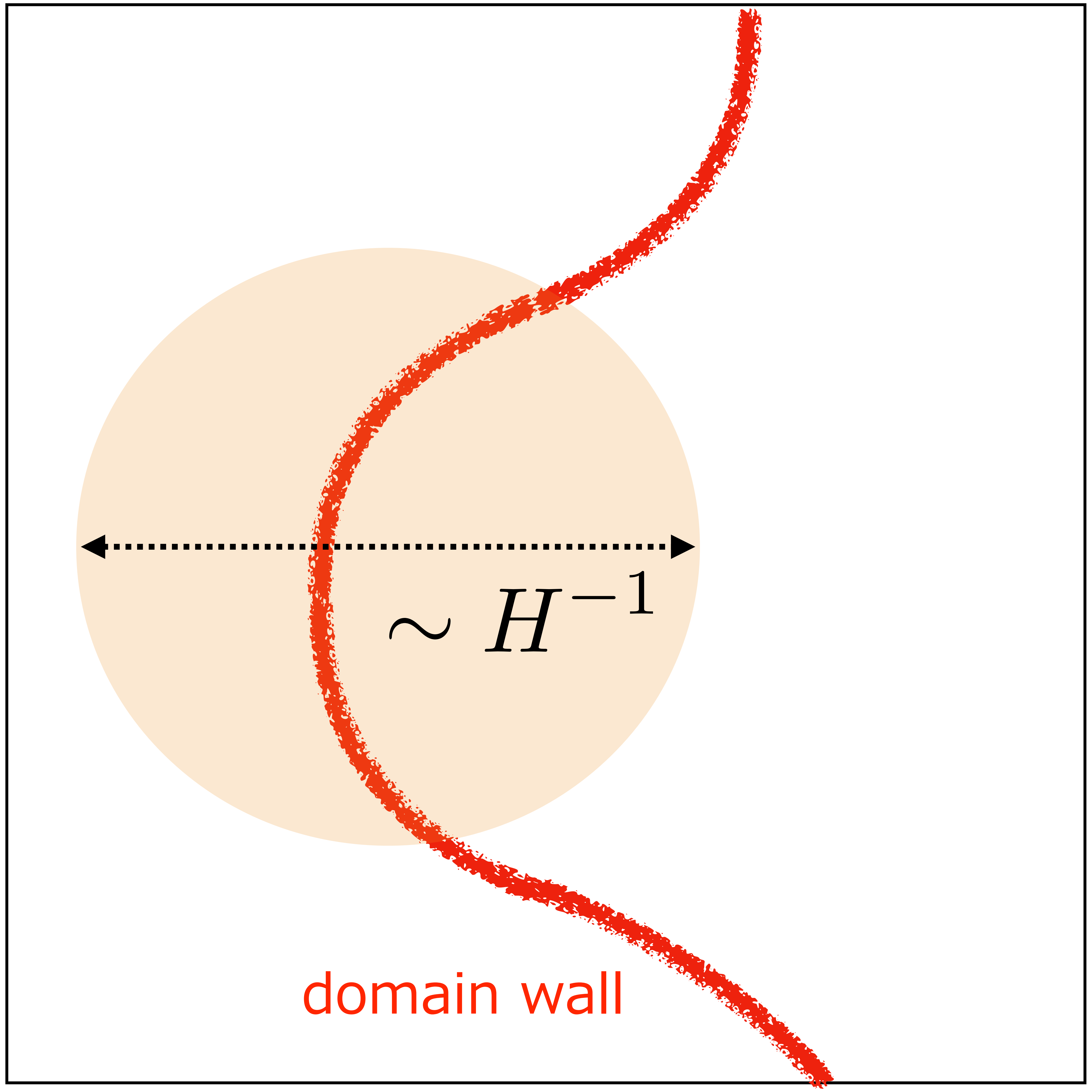
$$\sigma_{\rm DW} \simeq 8 m_\phi f_\phi^2$$

tension of DW for the cosine potential

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

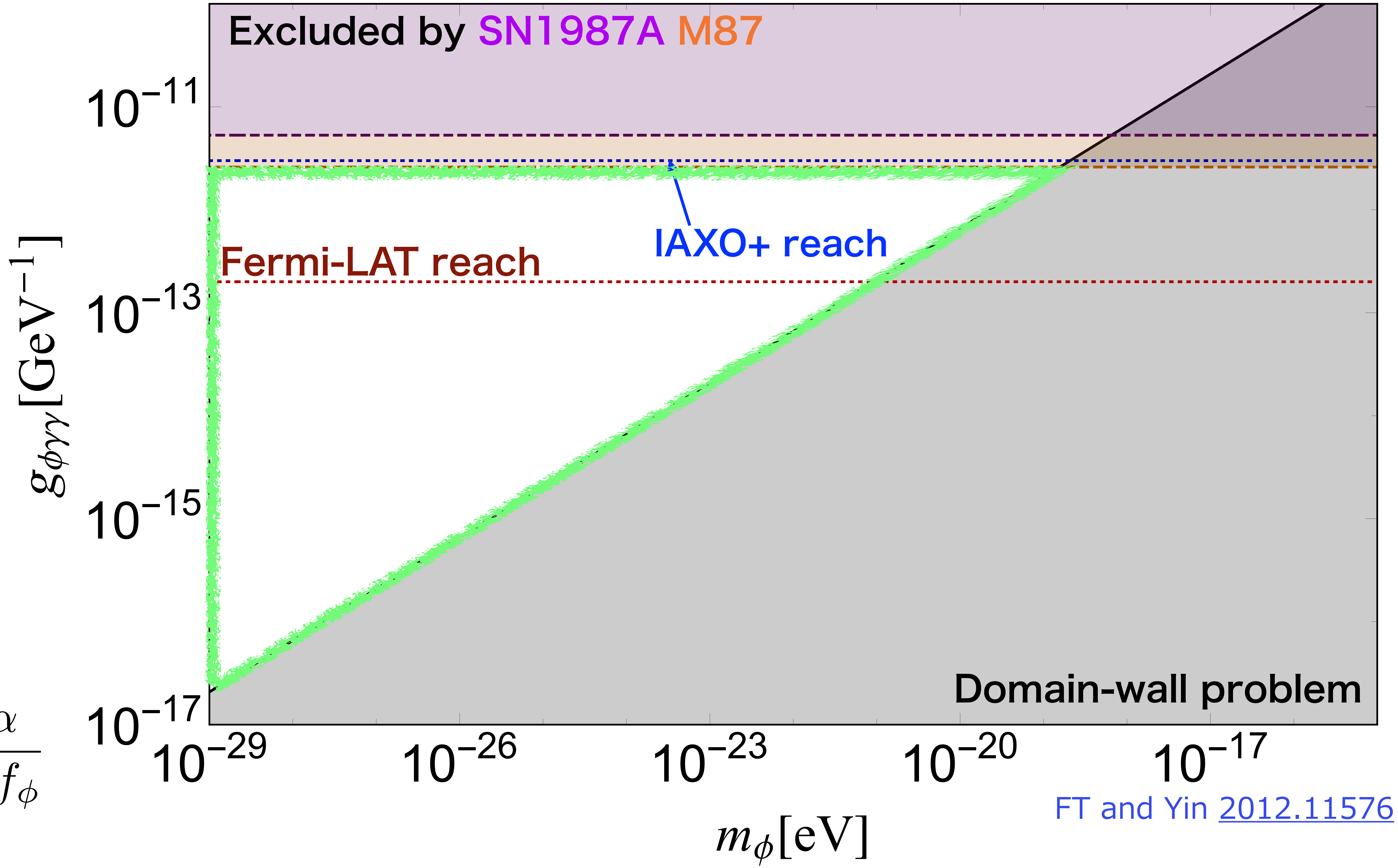
$$\sigma_{\rm DW} \lesssim (1\,{\rm MeV})^3$$

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



$\delta \sim m_\phi^{-1}$

Various bounds and future sensitivity reach



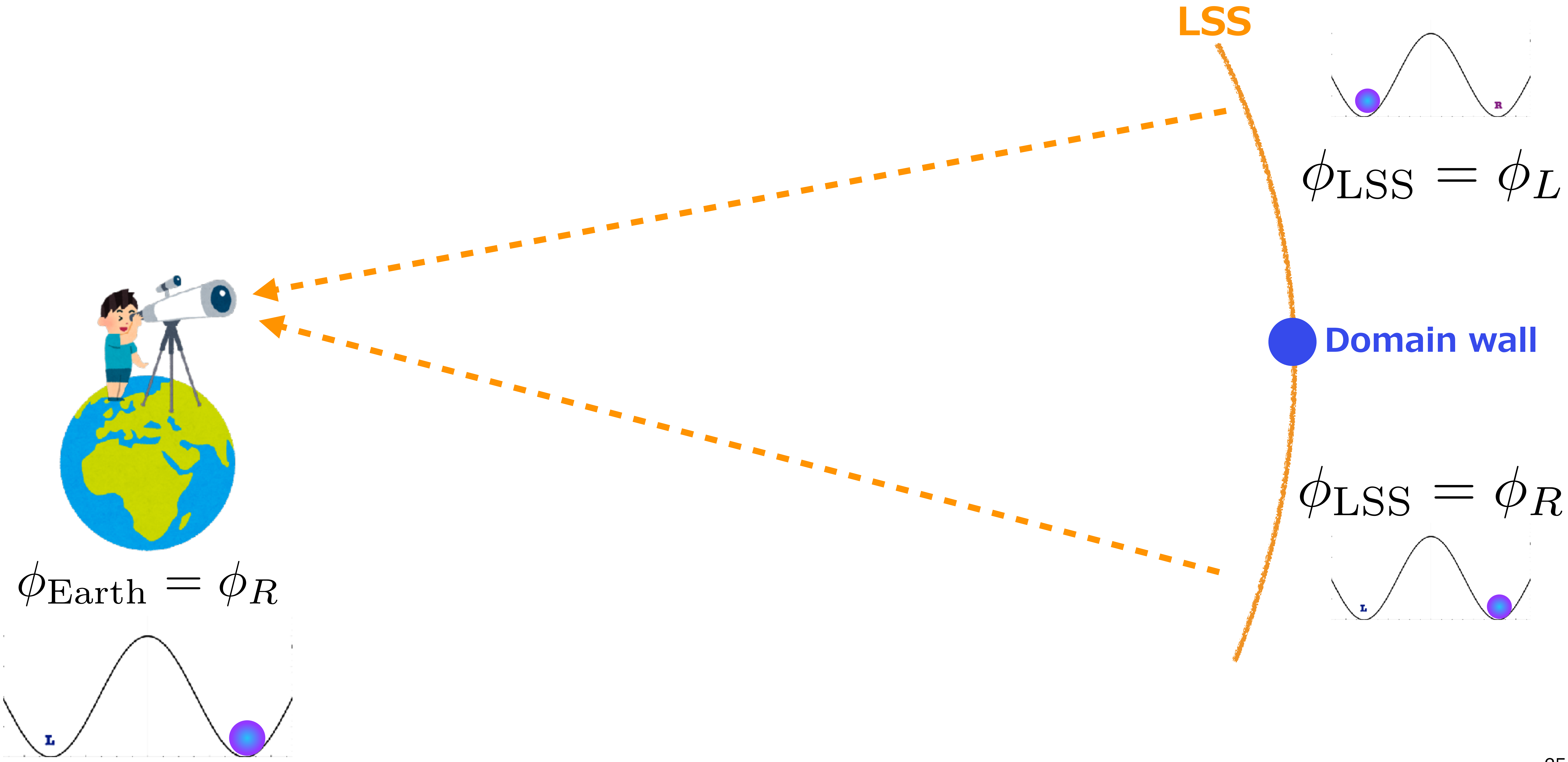
$c_\gamma = 1$

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

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



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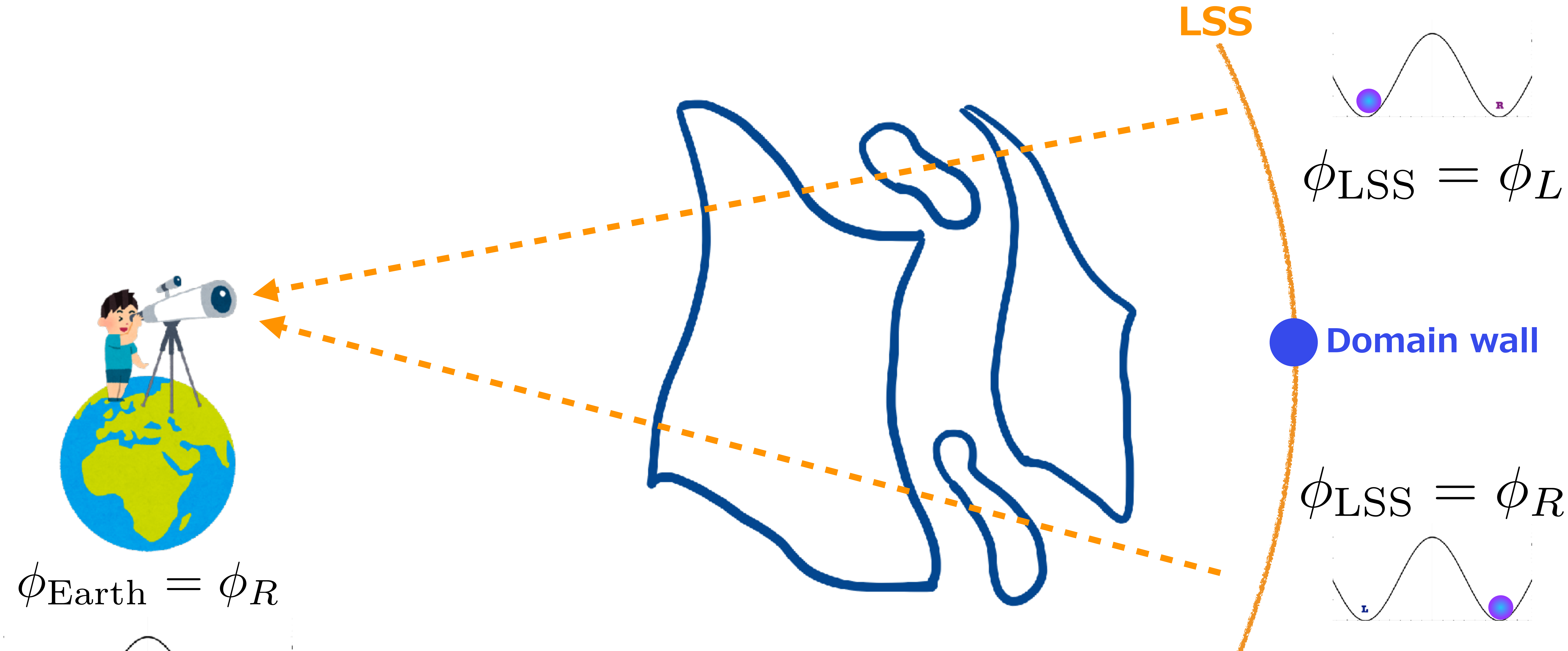
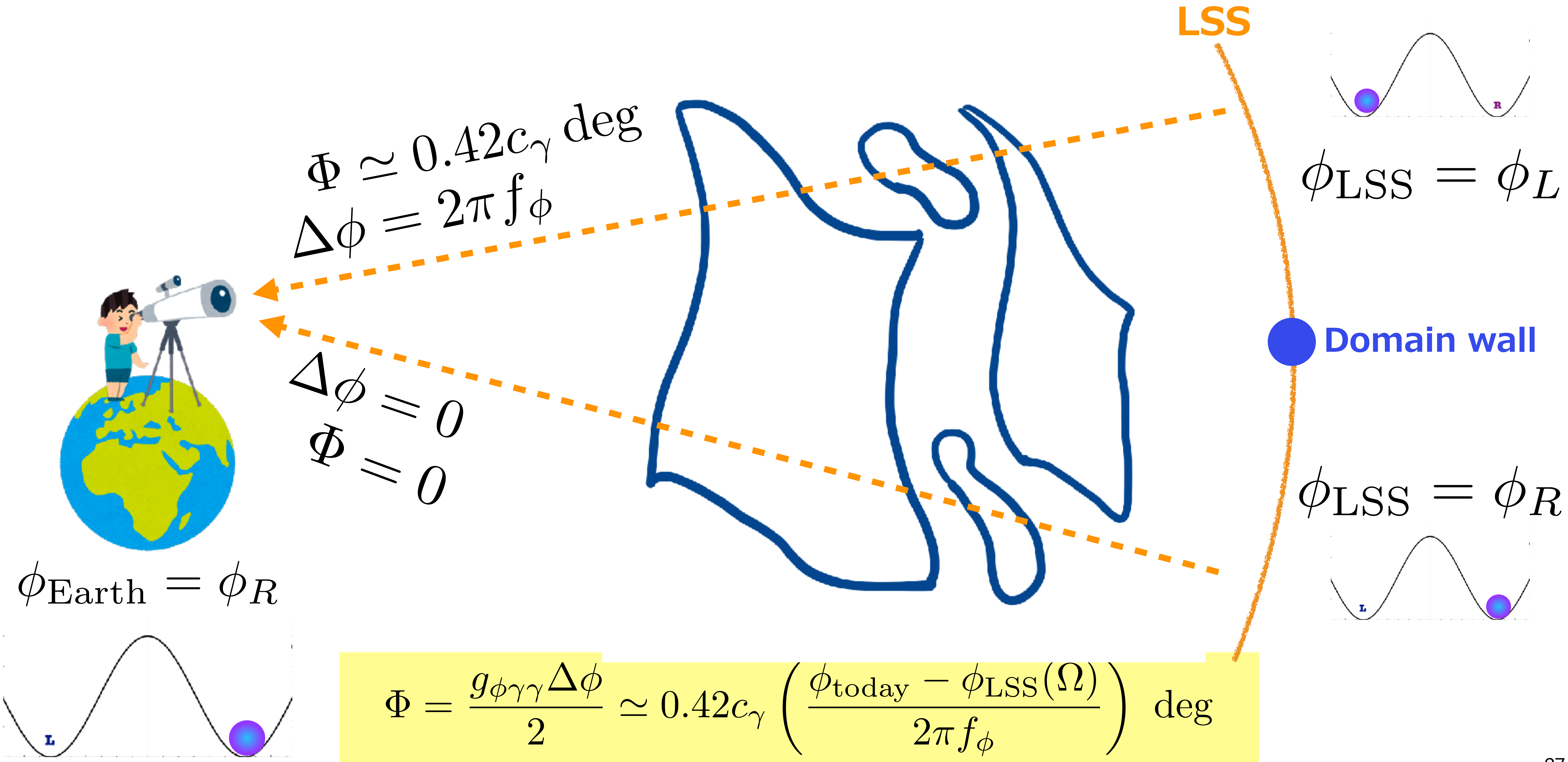


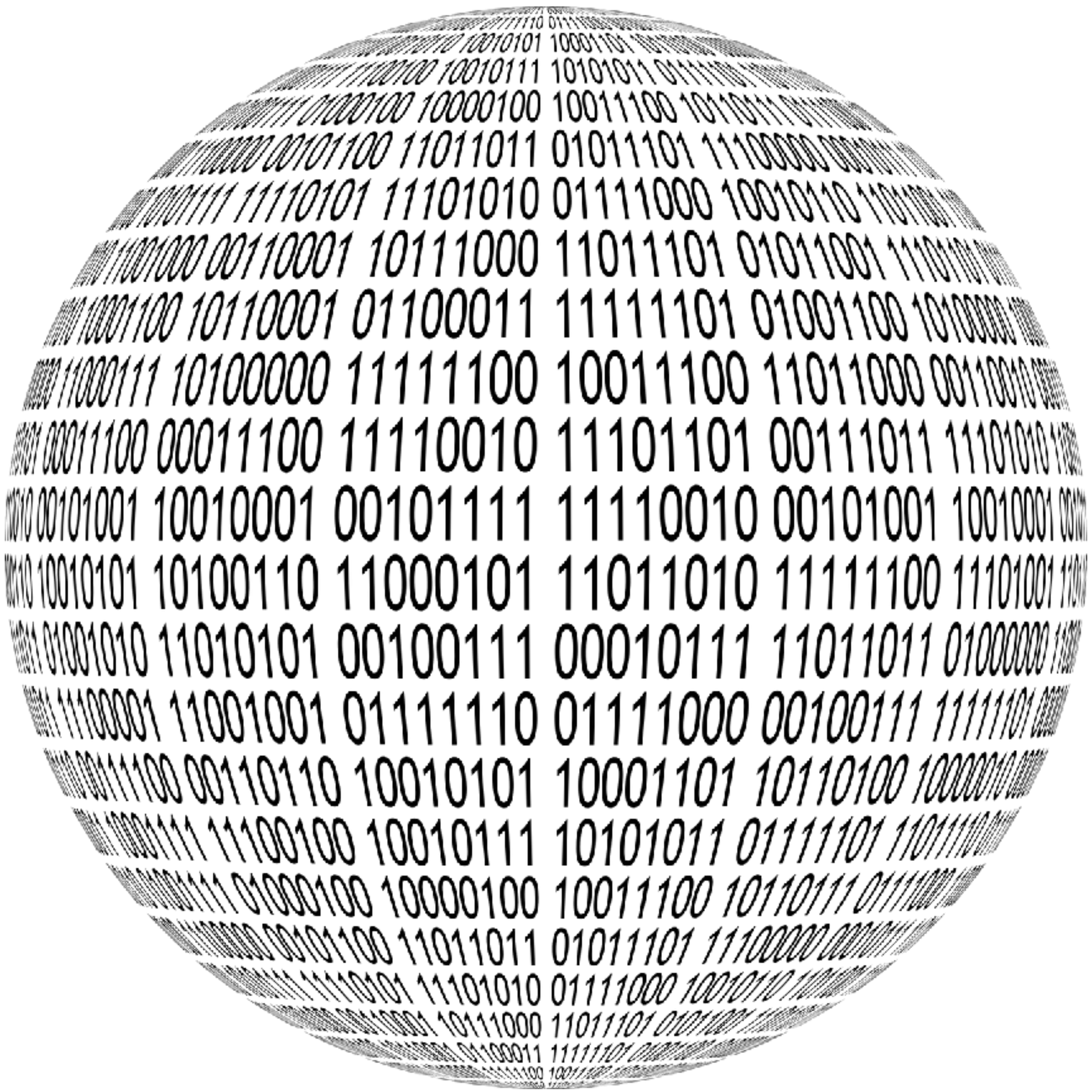
$$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi}\right) \ {\rm deg}$$

KiloByte CB from ALP domain walls



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

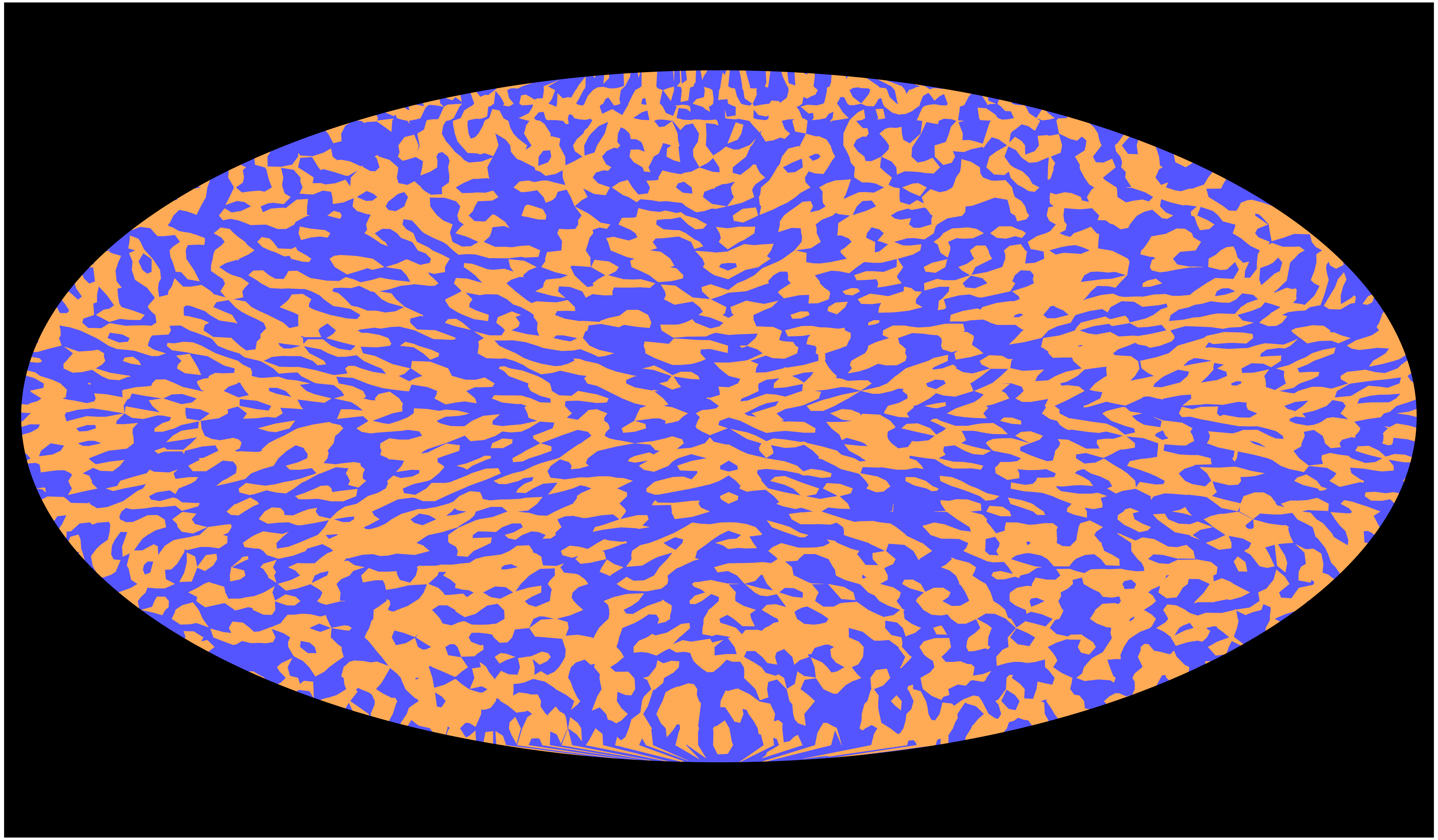
There will be $O(10^{3\text{-}4})$ domains on the LSS, and the CMB polarization from each domain is either not rotated at all or rotated by a fixed angle, $\Phi \simeq 0.42 c_\gamma \,\mathrm{deg}$.



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

"KiloByte Cosmic Birefringence" (KBCB)

KBCB from ALP domain walls



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

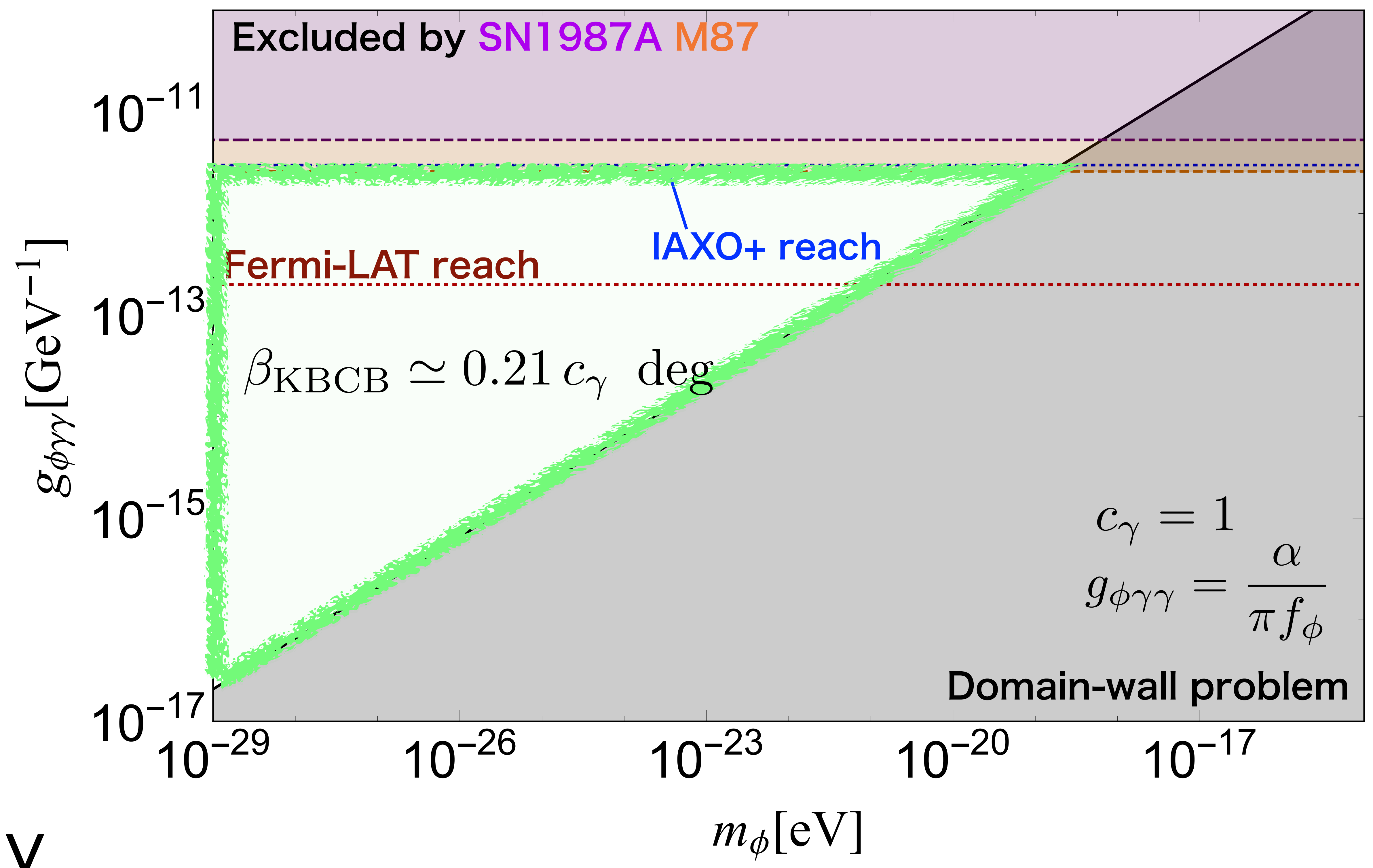
N.B. This figure is NOT a result of numerical simulations, but just a mock sample.

Predictions of KBCB

Isotropic CB

$$\beta = \frac{1}{4\pi}\int d\Omega\,\Phi(\Omega) = \frac{1}{2}c_\gamma \alpha \simeq 0.21 c_\gamma\,\mathrm{deg}\,.$$

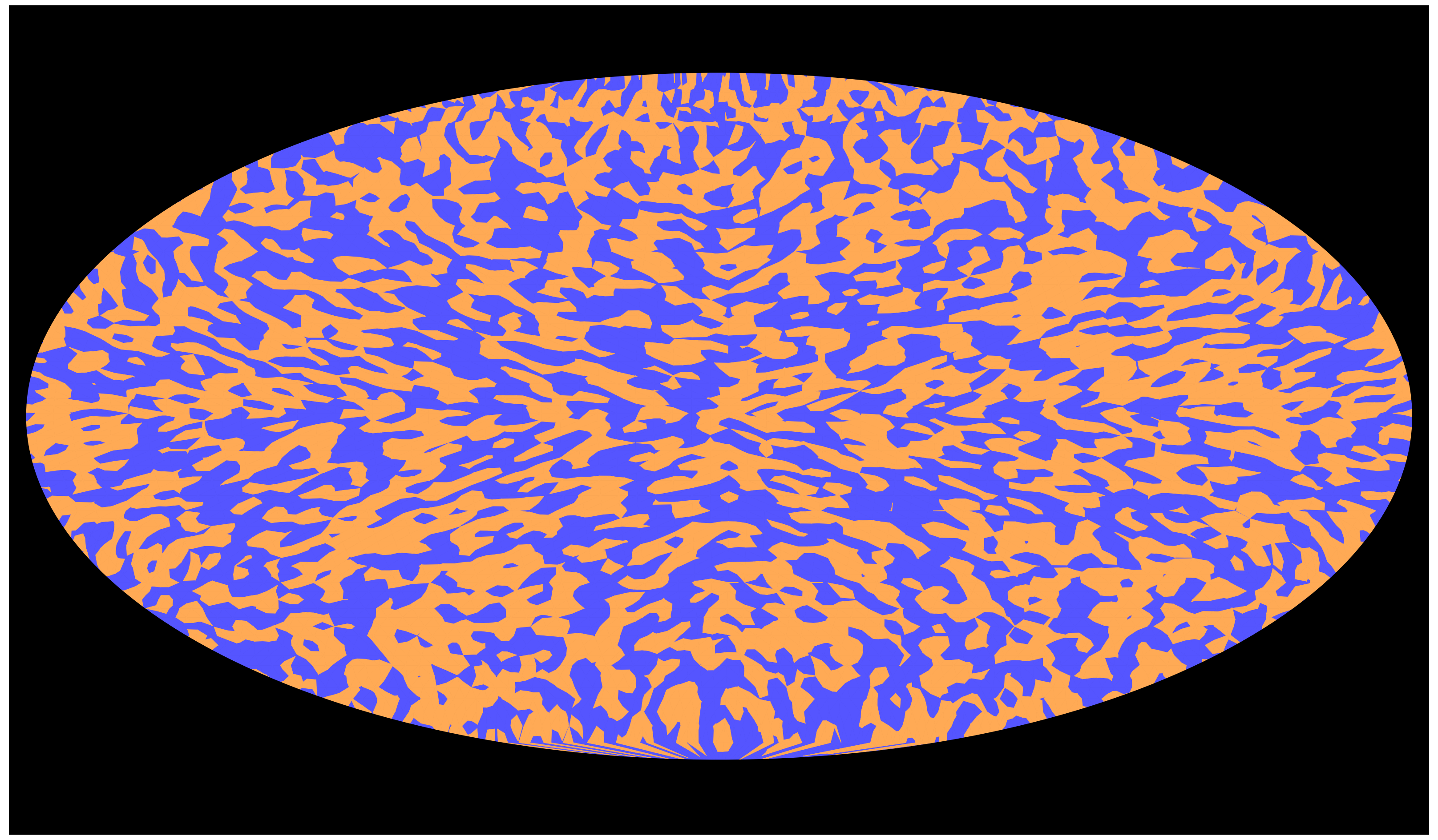
independent of m_ϕ and f_ϕ .



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

$$\Delta\Phi(\Omega) \equiv \Phi(\Omega) - \beta$$

$\Delta\Phi(\Omega) = \pm\beta$

$$= \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\Omega) \quad \text{i.e.} \quad a_{\ell m} = \int d\Omega\, \Delta\Phi(\Omega) Y^*_{\ell m}(\Omega)\,.$$

The angular power spectrum:

$$C^\Phi_\ell \equiv \frac{1}{2\ell+1} \sum_m a^*_{\ell m} a_{\ell m} = 2\pi \int d\cos\theta\, \Delta\Phi(0,0)\Delta\Phi(\theta,0)\, P_\ell(\cos\theta)$$

Then, $\displaystyle \int d\Omega \left(\Delta\Phi(\Omega)\right)^2 = \sum_\ell (2\ell+1) C^\Phi_\ell = 4\pi\beta^2$

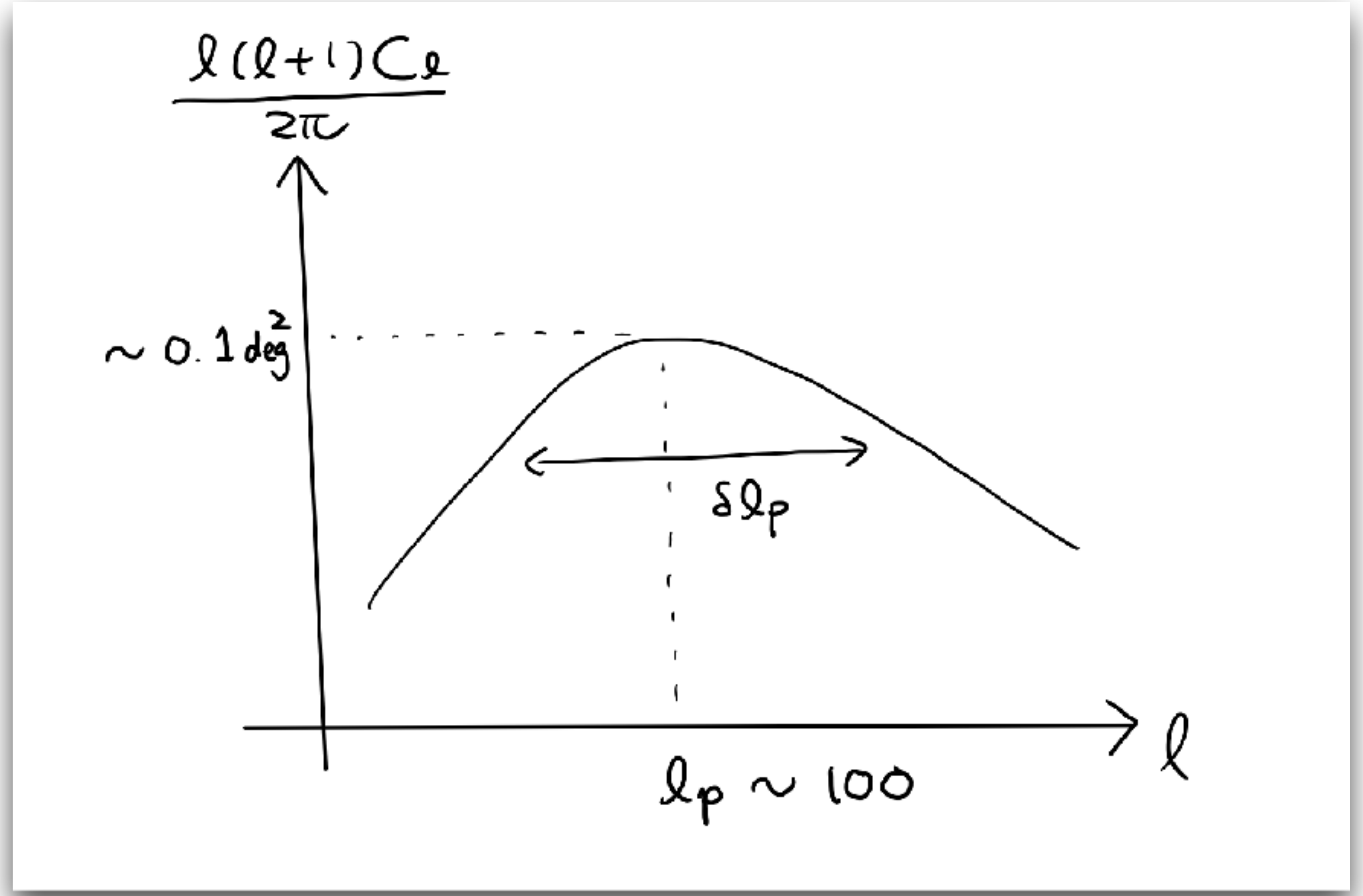
Predictions of KBCB

Anisotropic CB

$$\int d\Omega \left(\Delta\Phi(\Omega)\right)^2 = \sum_{\ell} (2\ell + 1) C_\ell^\Phi = 4\pi\beta^2$$

If the peak is broad, $\ell_p \sim \delta\ell_p$

$$\frac{\ell_p(\ell_p + 1)C_{\ell_p}^\Phi}{2\pi} \lesssim 0.1 \left(\frac{\beta}{0.35\,\mathrm{deg}}\right)^2 \mathrm{deg}^2$$



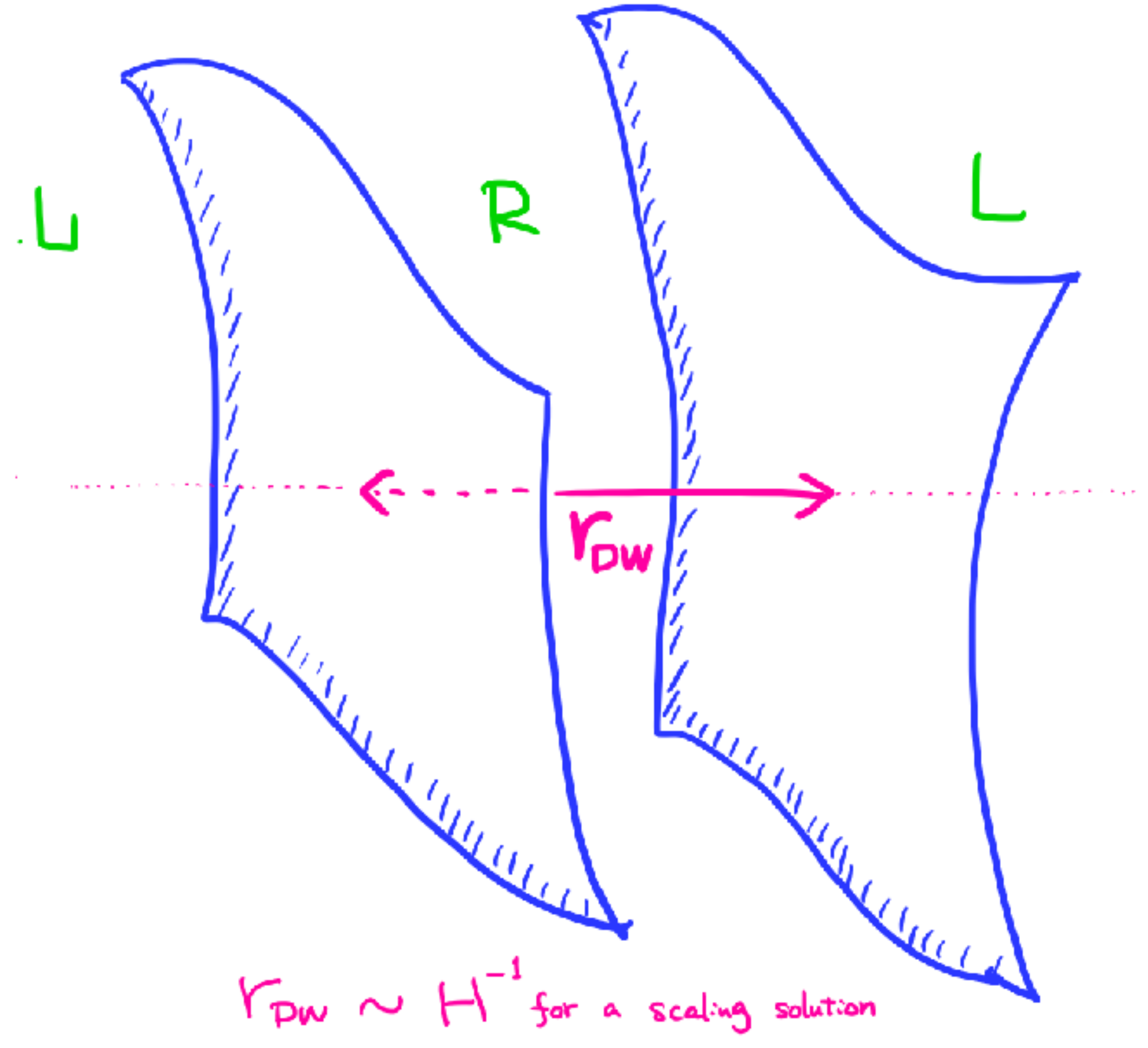
The peak location corresponds to the Hubble horizon at the LSS.

A simple model of the domain-wall network

Let $\mathscr{D}_{\rm DW} = r_{\rm DW}^{-1}$ be the DW density along a straight line, where $r_{\rm DW}$ is the average distance b/w walls.

For a scaling solution, we have

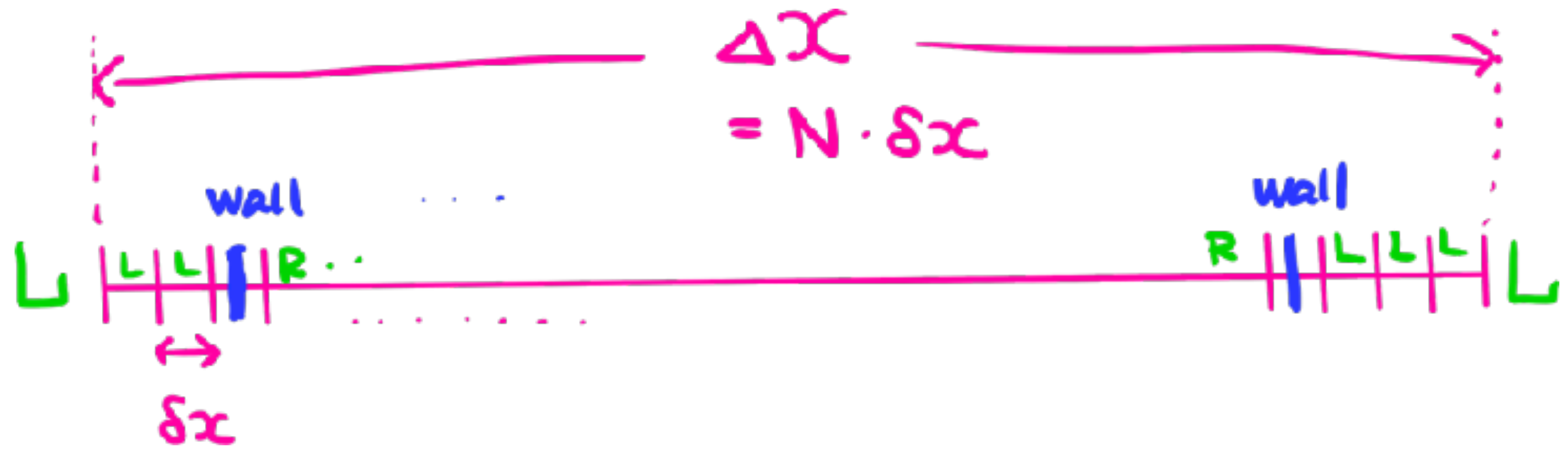
$$\mathscr{D}_{\rm DW} = \kappa_{\rm DW} H \quad \text{with} \quad \kappa_{\rm DW} = \mathcal{O}(1)$$



Then the probability of being in the same vacuum at a point Δx apart is

$$P_{\rm match}[\Delta x] = \sum_{N/2 \geq m = 0} {}_N C_{2m} (\mathscr{D}_{\rm DW}\delta x)^{2m} (1 - \mathscr{D}_{\rm DW}\delta x)^{N-2m}$$

$$\to \frac{1}{2}(1 + e^{-2\mathscr{D}_{\rm DW}\Delta x})$$

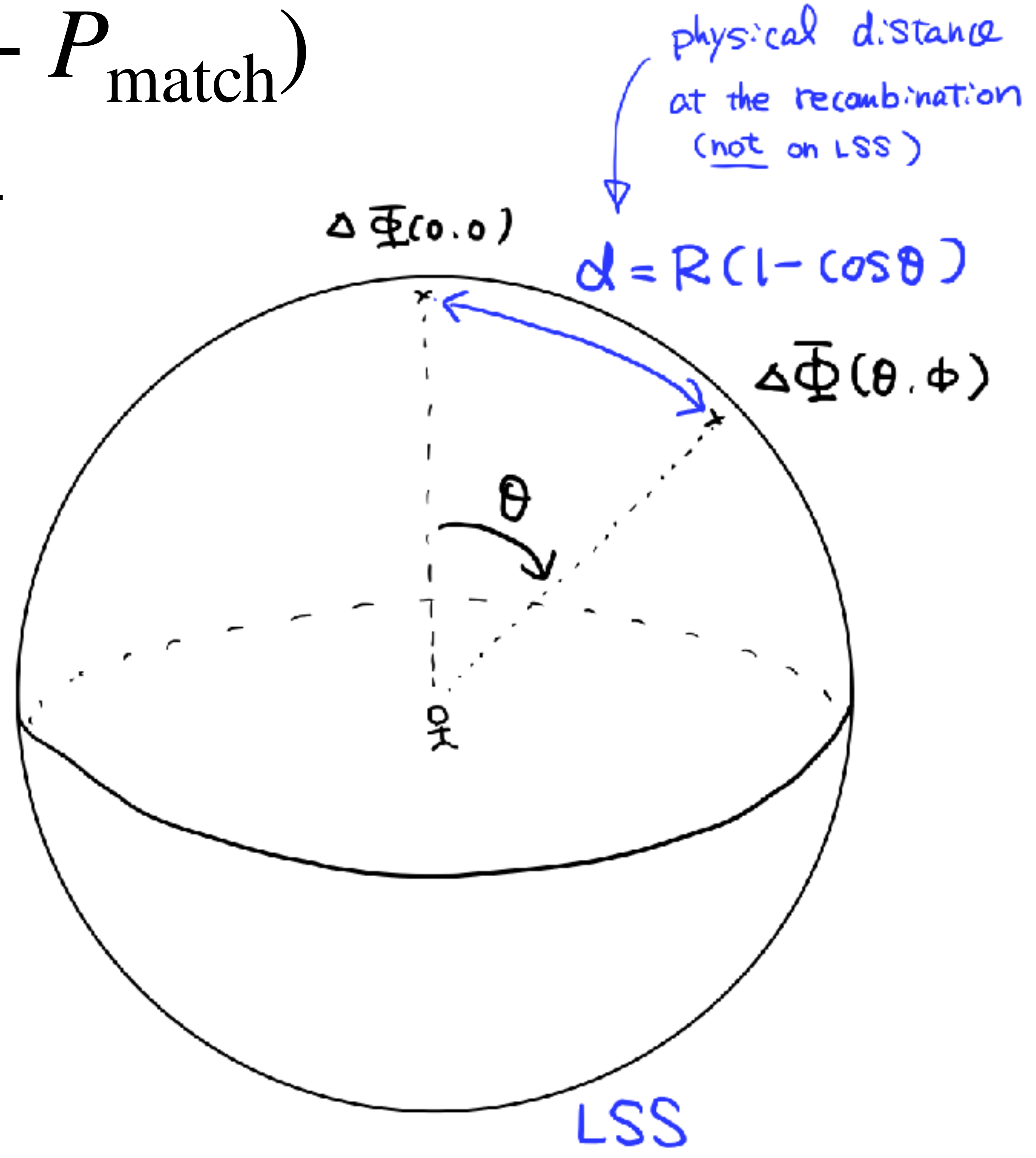


$2m$: the number of domain walls in $\Delta x = N\delta x$

A simple model of the domain-wall network

$$\langle \Delta\Phi(0,0)\Delta\Phi(\theta,\phi)\rangle \simeq \beta^2 P_{\mathrm{match}} + \beta(-\beta)(1 - P_{\mathrm{match}})$$

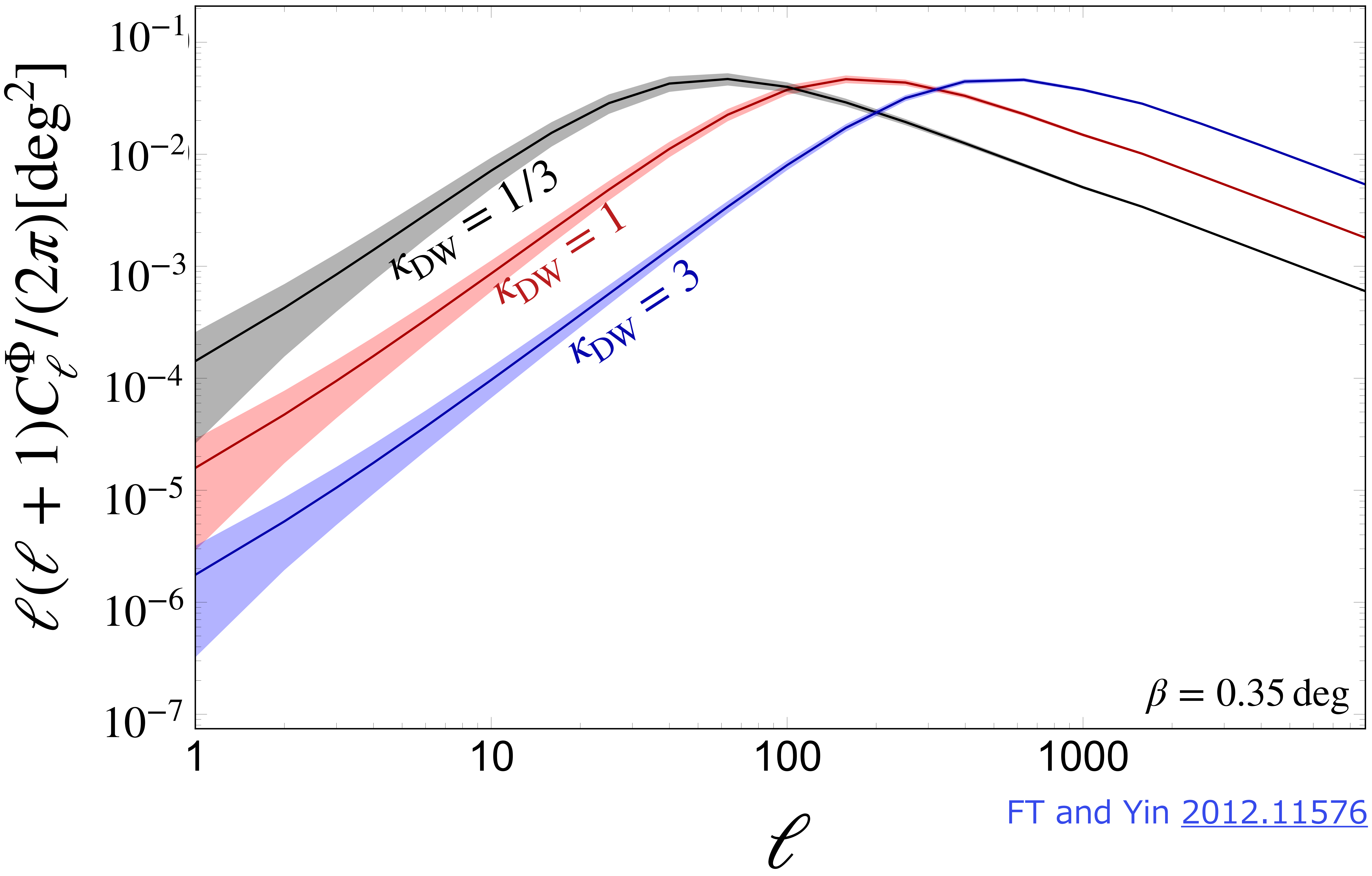
$$= \beta^2 e^{-2\mathscr{D}_{\mathrm{DW}} R\sqrt{2(1-\cos\theta)}}$$



Then, we can estimate the angular power spectrum (with the ensemble average) by substituting the above into

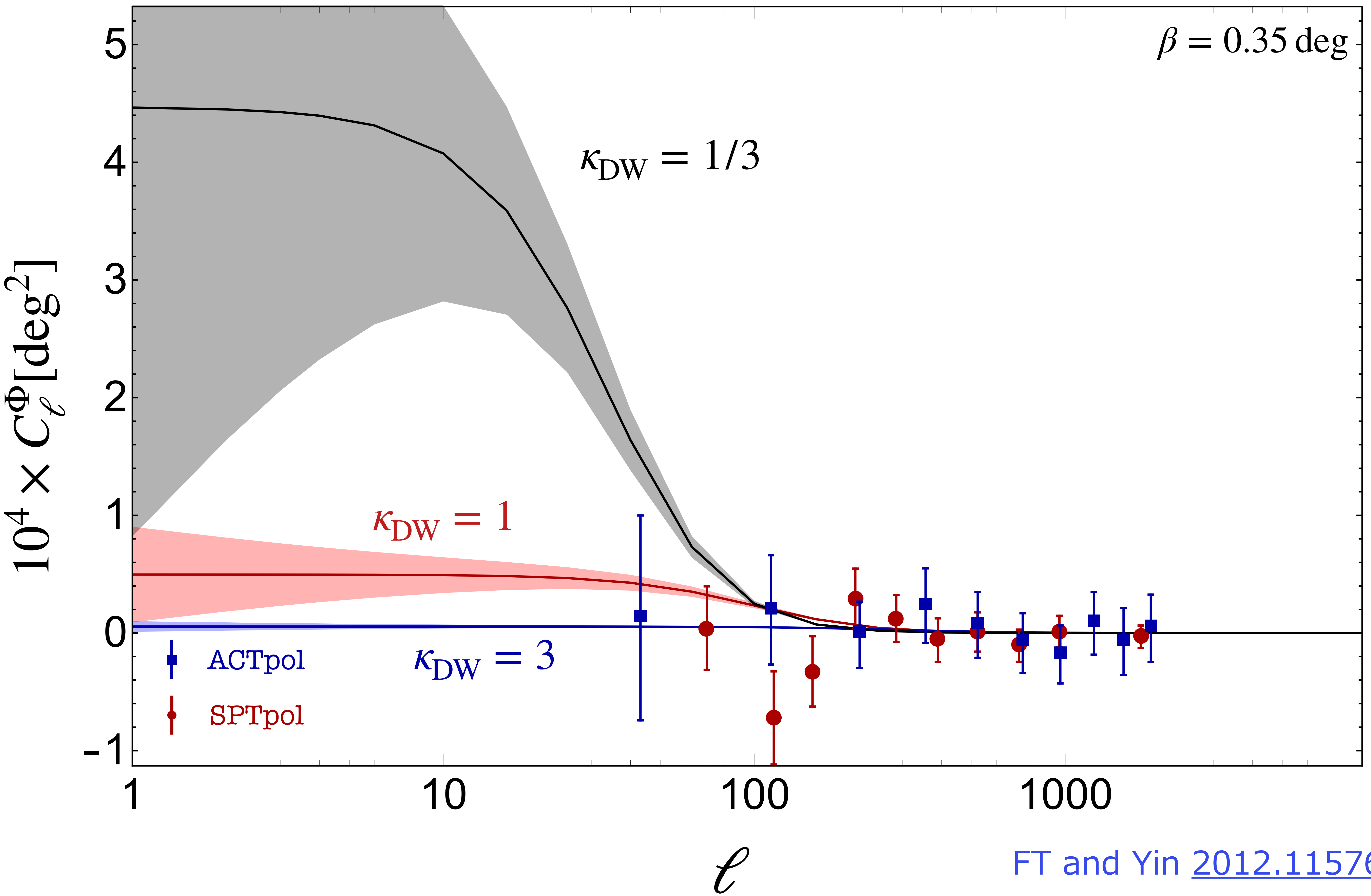
$$C_\ell^{\Phi} = 2\pi \int d\cos\theta \, \langle \Delta\Phi(0,0)\Delta\Phi(\theta,0)\rangle \, P_\ell(\cos\theta)$$

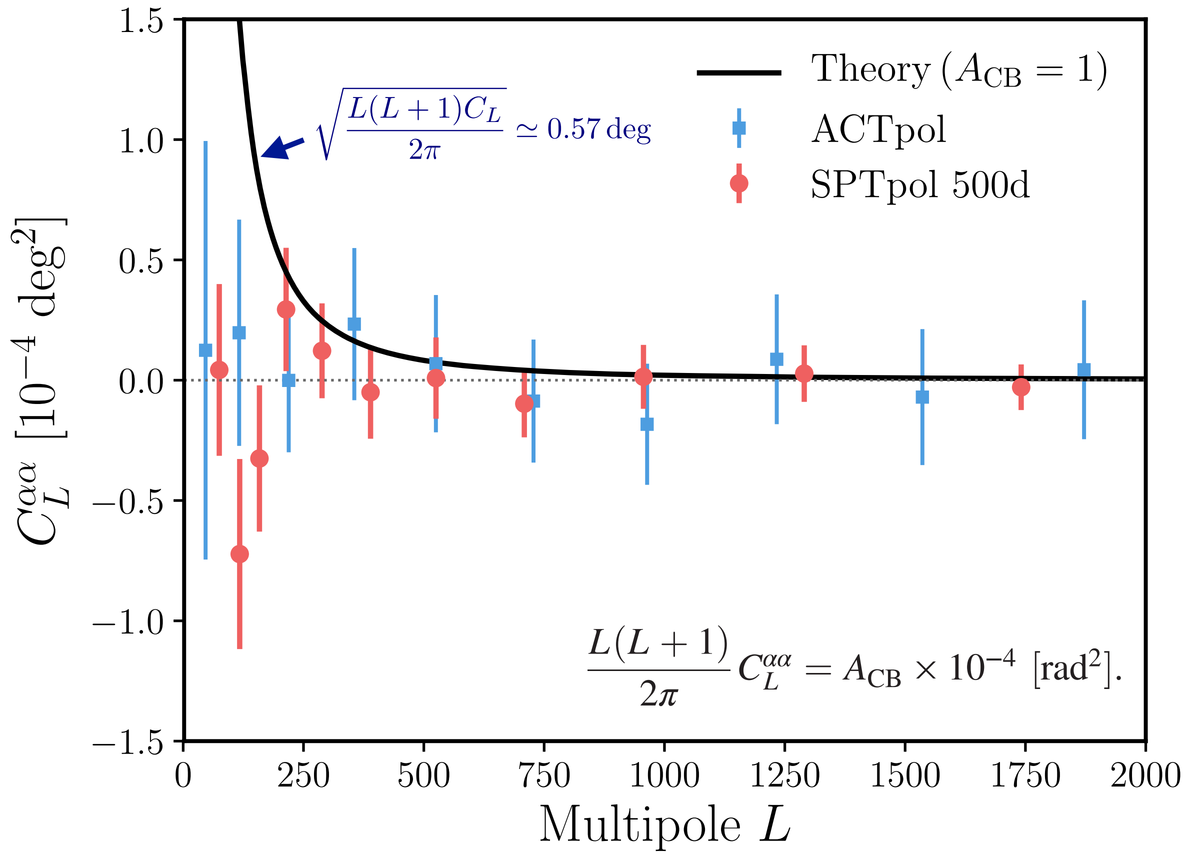
Anisotropic CB of ALP domain walls



FT and Yin 2012.11576

Anisotropic CB of ALP domain walls





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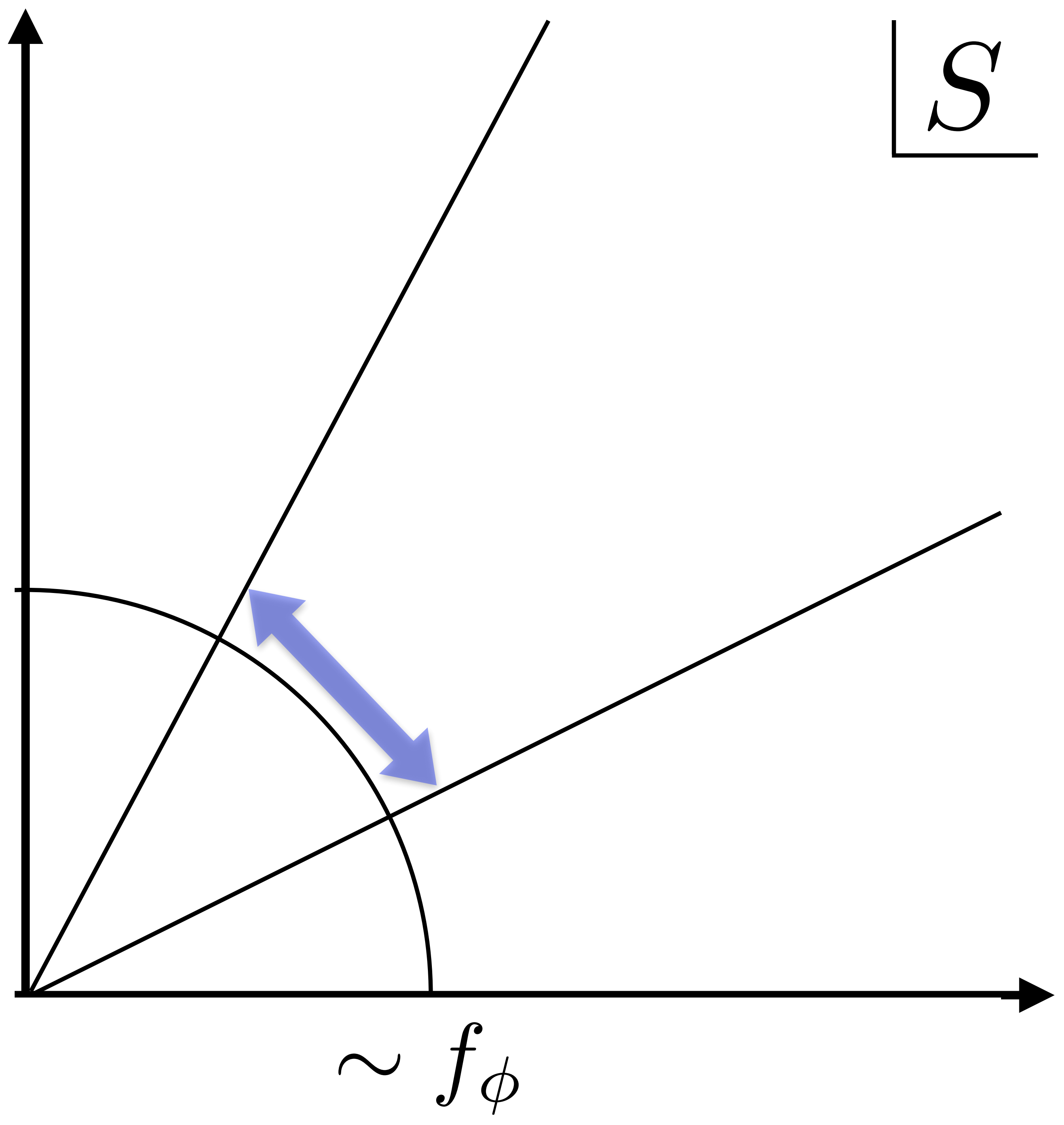
A model with a negative Hubble mass

Suppose that the PQ symmetry is linearly realized as

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

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



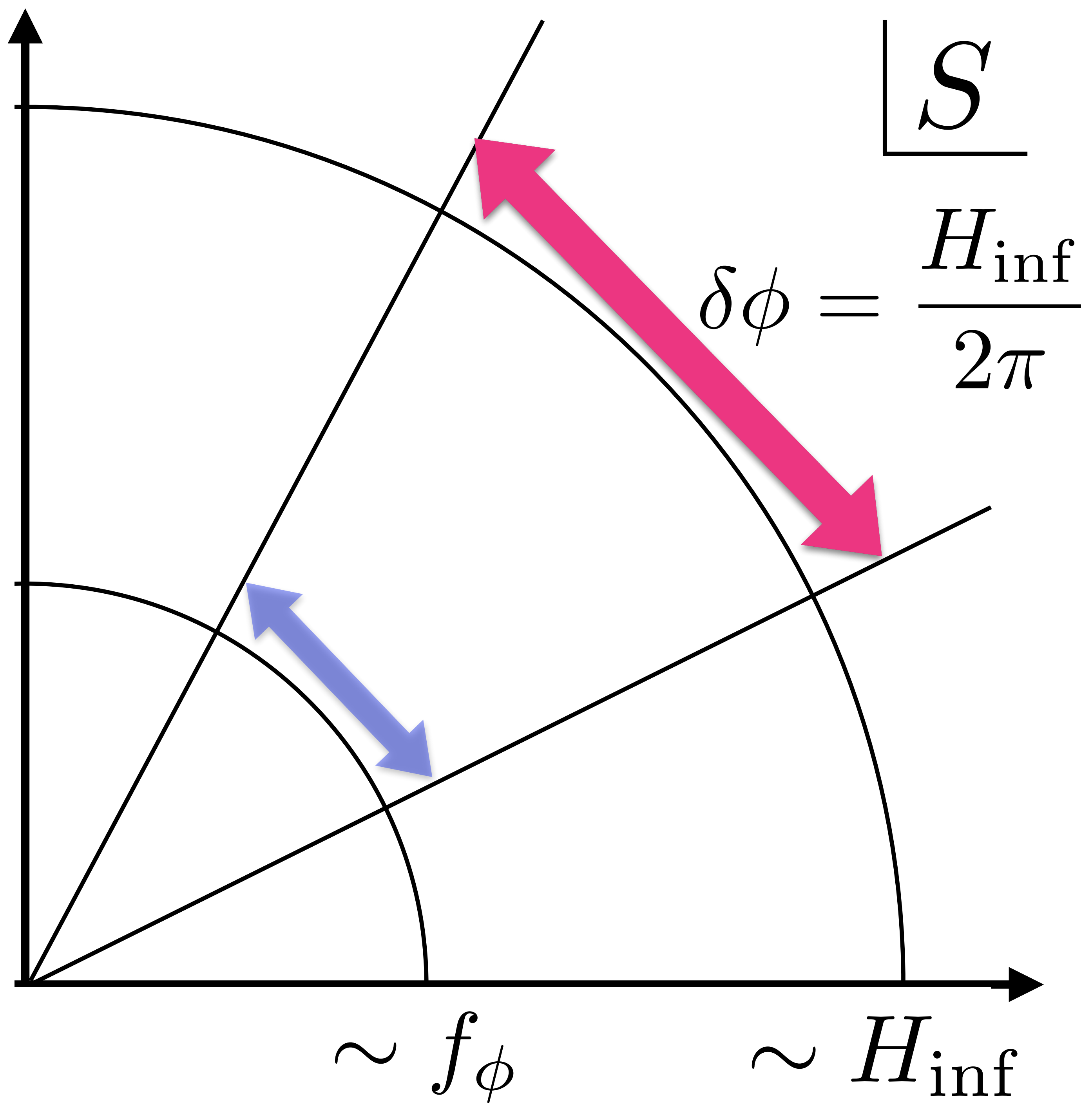
A model with a negative Hubble mass

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)

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



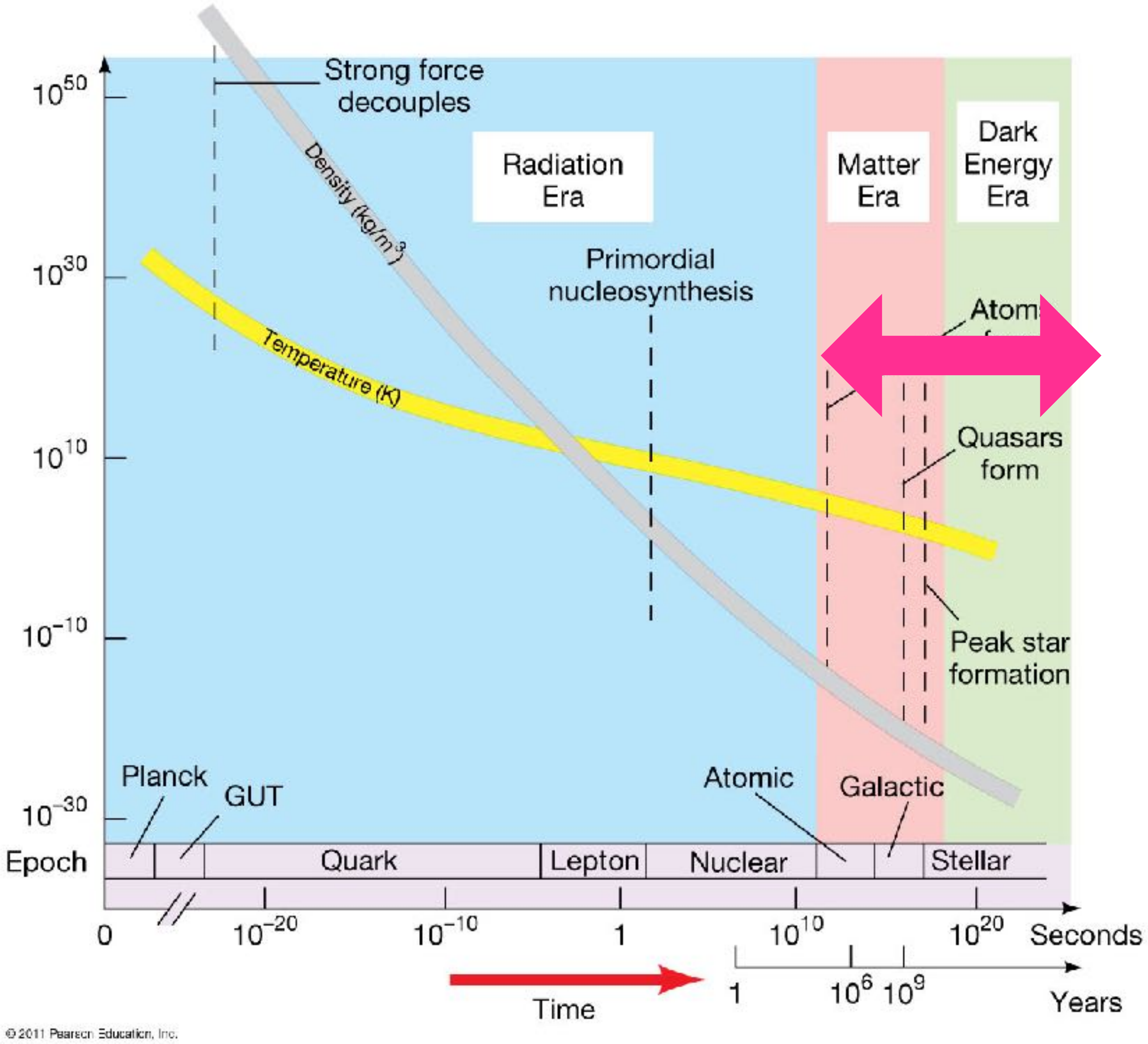
During inflation, the effective decay constant can be as large as $H_{\rm inf}$, and the axion acquires quantum fluctuations of $O(H_{\rm inf})$.

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

4. Scenario 2: Axion coupled to DM

Why does the ALP starts to move at such a special timing i.e. between the recombination and the present?

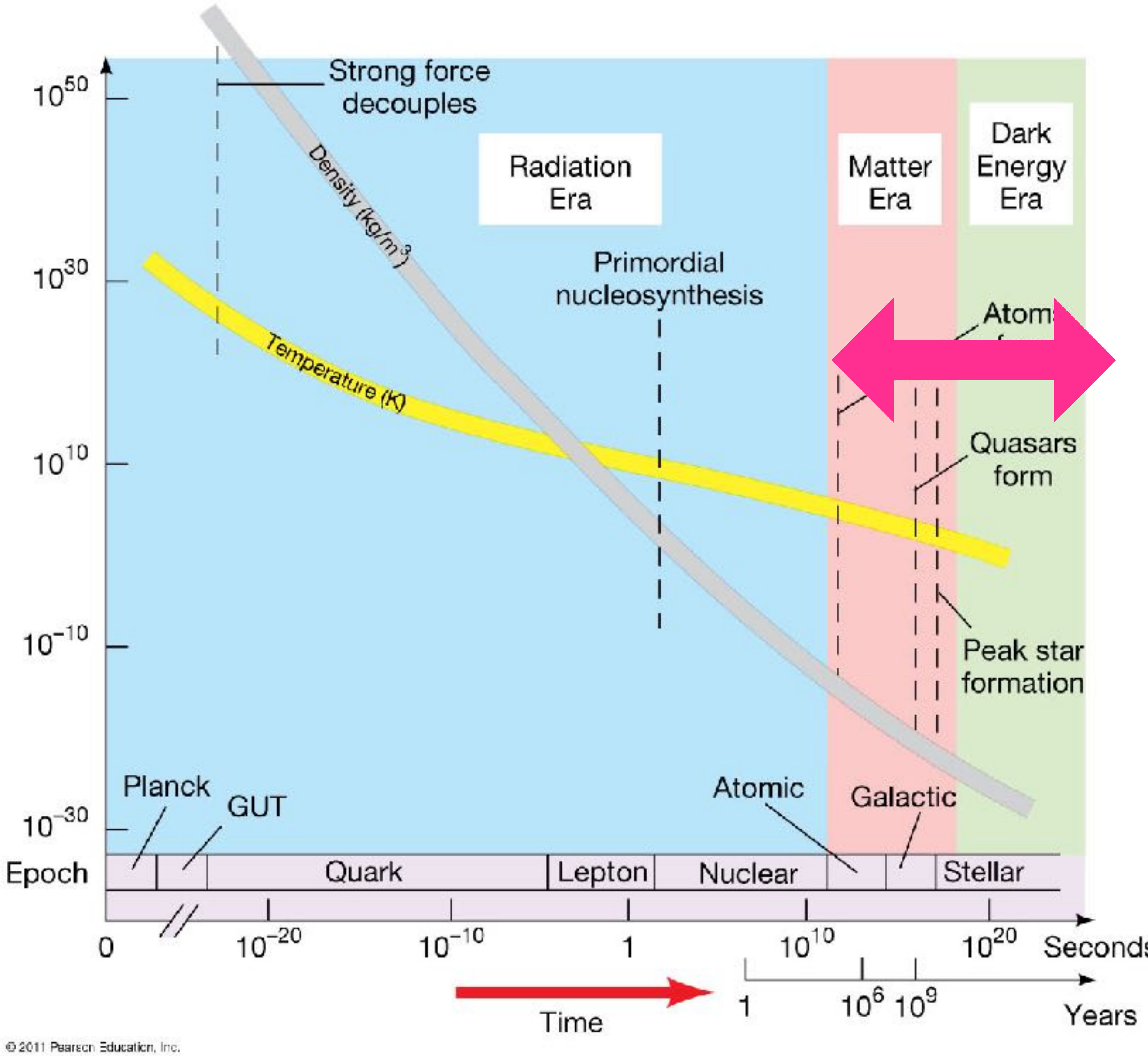
A (mild) coincidence problem ?



Why does the ALP starts to move at such a special timing i.e. between the recombination and the present?

A (mild) coincidence problem ?

-Maybe natural in string axiverse?
- Number of axions?
- Coupling to photons?



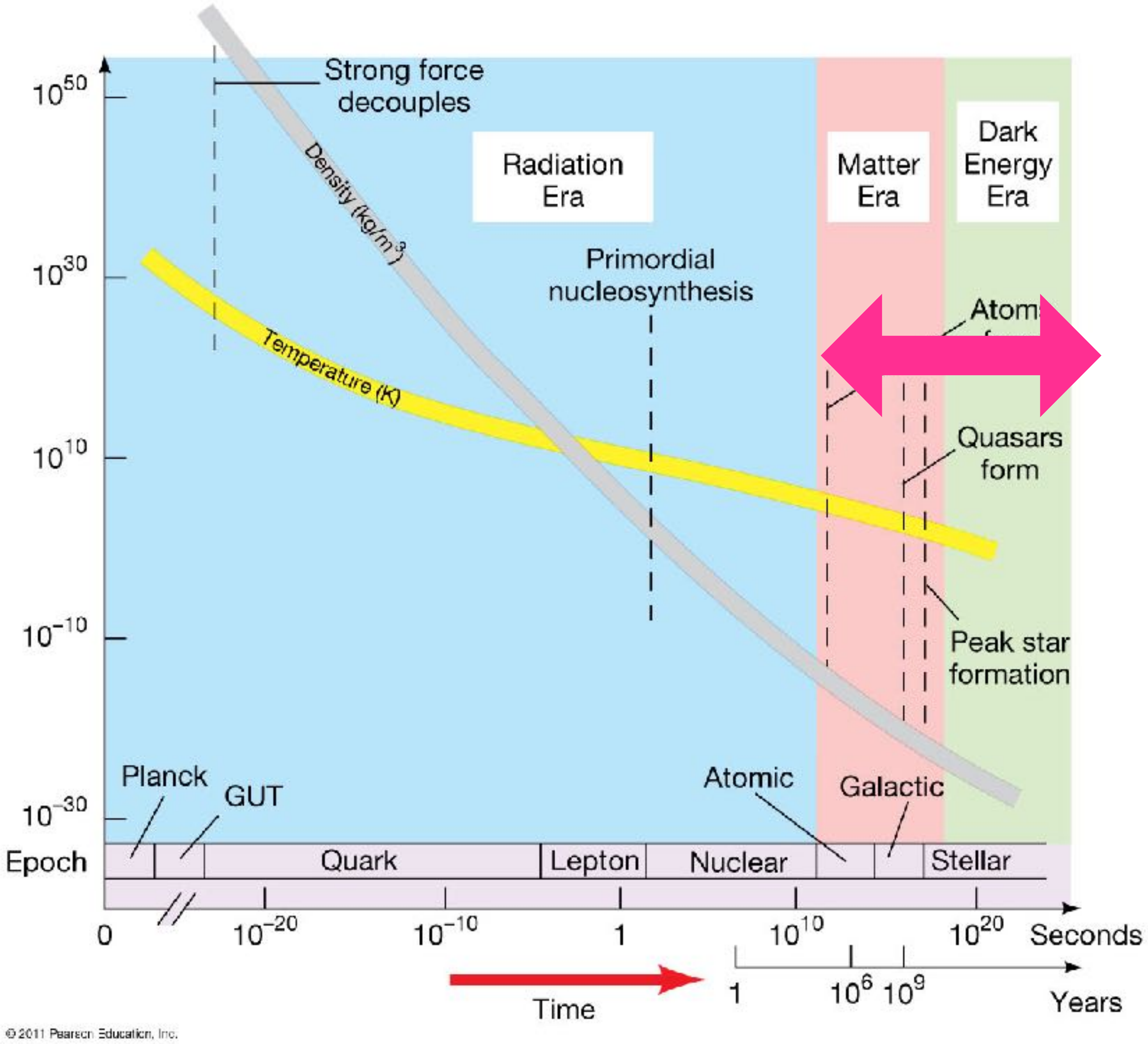
Why does the ALP starts to move at such a special timing i.e. between the recombination and the present?

A (mild) coincidence problem ?

-Maybe natural in string axiverse?
 - Number of axions?
 - Coupling to photons?

If the ALP is coupled to DM, it may acquire an effective mass which becomes relevant only after matter-radiation equality (~ recombination).

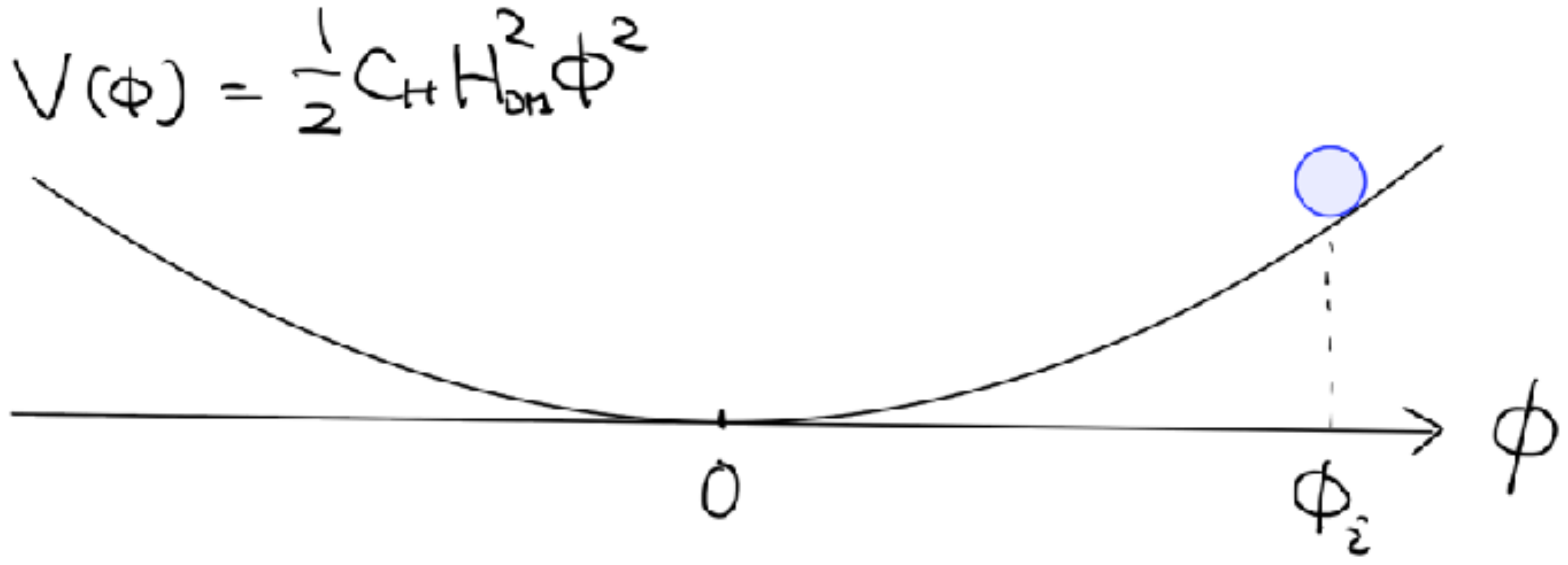
$$V(\phi) \sim \frac{\rho_{\rm DM}}{M_p^2}\phi^2$$



CB triggered by DM domination

Consider a “massless” ALP with

$$V(\phi) = \frac{1}{2} c_H H_{\rm DM}^2 \phi^2 \quad \text{with} \quad H_{\rm DM}^2 \equiv \frac{\rho_{\rm DM}}{3M_p^2}$$



<u>cf. Hidden monopole DM (Witten effect)</u>

$$\mathscr{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\alpha_H}{8\pi} \frac{\phi}{f_\phi} X_{\mu\nu} \tilde{X}^{\mu\nu} \quad \Rightarrow \quad c_H = 3 \left(\frac{\rho_{\rm monopole}}{\rho_{\rm DM}} \right) \left(\frac{\alpha_H}{4\pi} \frac{M_p}{f_\phi} \right)^2$$

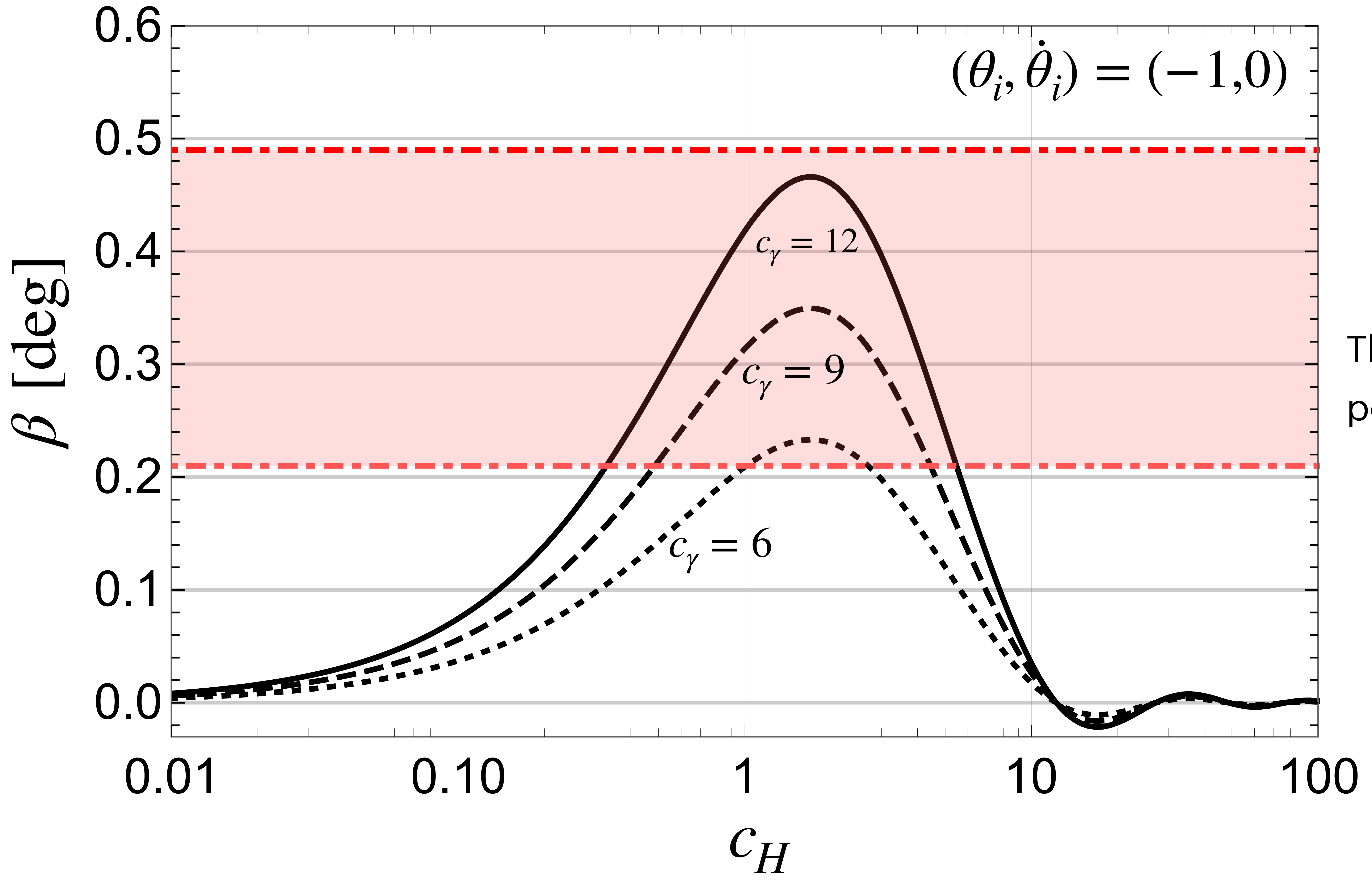
$c_H \sim 1$ for $\rho_{\rm monopole} \sim \rho_{\rm DM}, \quad \alpha_H \sim 0.01, \quad f_\phi \sim 10^{15}\,{\rm GeV}$

The ALP starts to move after the matter-radiation equality if $c_H = O(1)$.

$$\ddot{\phi} + 3H\dot{\phi} + c_H H_{\rm DM}^2 \phi = 0$$

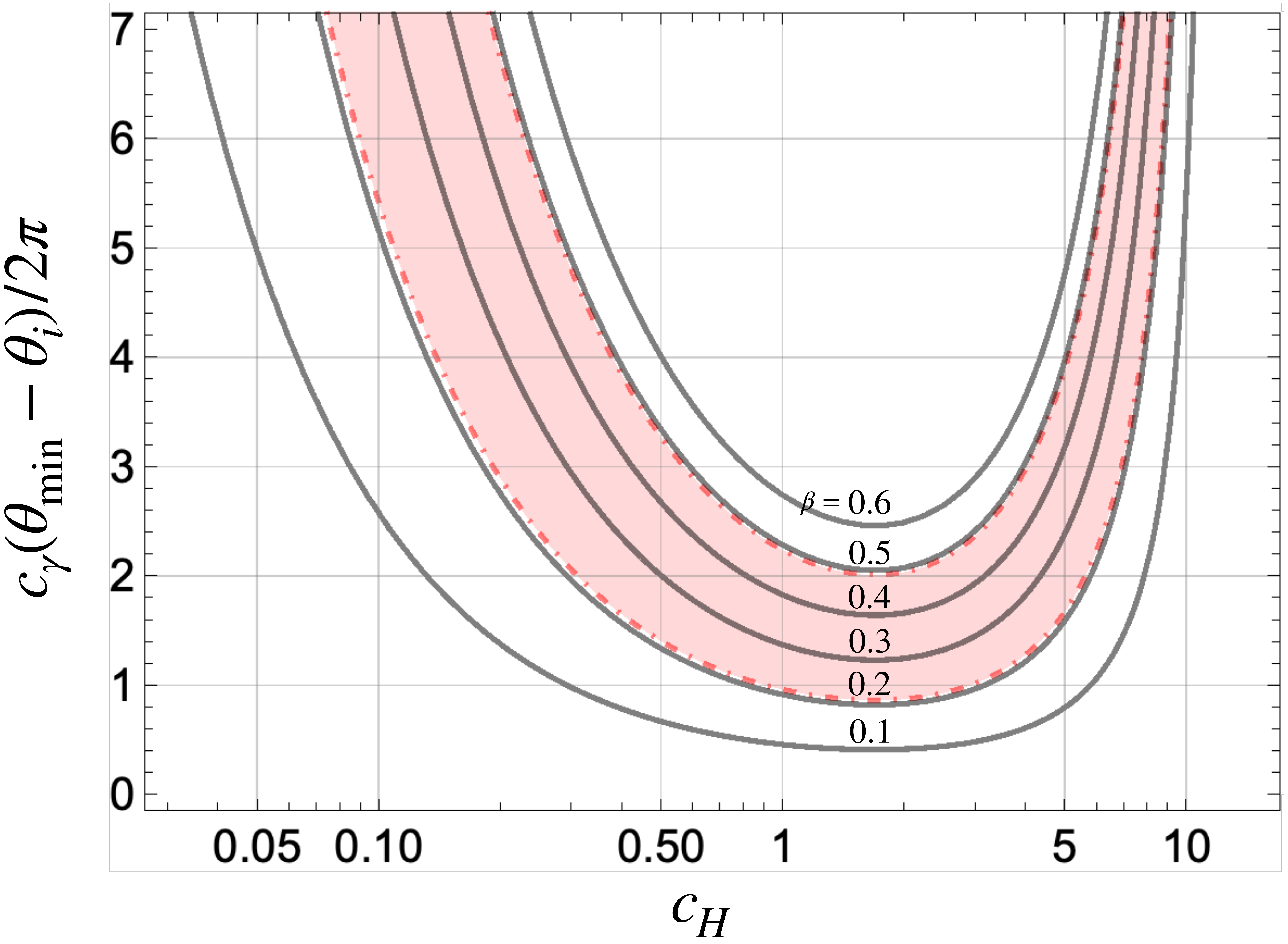
$$H^2 = H_0^2 \left(\Omega_{\rm rad} a^{-4} + \Omega_{\rm mat} a^{-3} + \Omega_\Lambda \right)$$

CB triggered by DM domination



The rotation angle is peaked at $c_H \sim 2$.

CB triggered by DM domination



No fine-tuning of the initial angle is needed for $c_H \sim c_\gamma = O(1)$.

5. Summary

- Recent hint for the isotropic CB may be due to ultralight ALP.

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

- ALP domain walls naturally explains the isotropic CB over a wide range of the axion mass and axion-photon coupling.

$\beta_{\rm KBCB} \simeq 0.21\, c_\gamma \ \ {\rm deg}$ independent of m_ϕ and f_ϕ.

Also predicts a peculiar anisotropic CB, which may be checked by future CMB observations.

- ALP coupled to DM works even for a massless ALP; e.g. the ALP coupled to hidden monopole DM with $f_\phi \sim 10^{15}\,{\rm GeV}$.