Based on 2012.11576
in collaboration with Fuminobu Takahashi

Kilobyte cosmic birefringence and ALP domain walls without strings

Birefringence (複屈折)

https://ja.wikipedia.org/wiki/複屈折

Tohoku University
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Online seminar at E-lab on 19th April 2021

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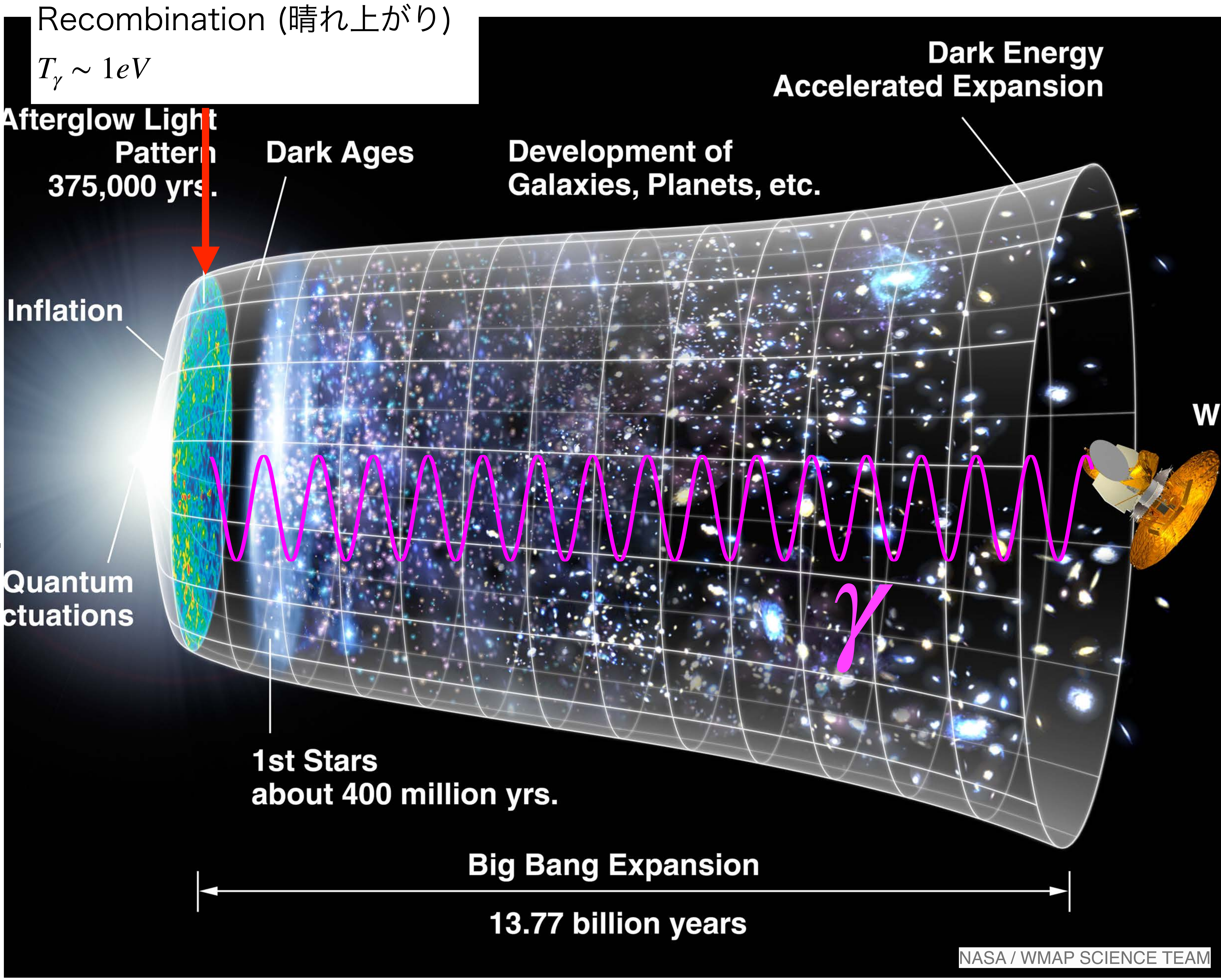
・1 Introduction

Cosmic Birefringence
(experimental side)

Cosmology and photons from recombination.

- Before recombination, photons are in thermal equilibrium.
- CMB photons ($E_\gamma \lesssim 1\mathrm{eV}$) freely propagate after recombination.
- Last scattered photons are messengers of early Universe with $T \leq 1$ eV.



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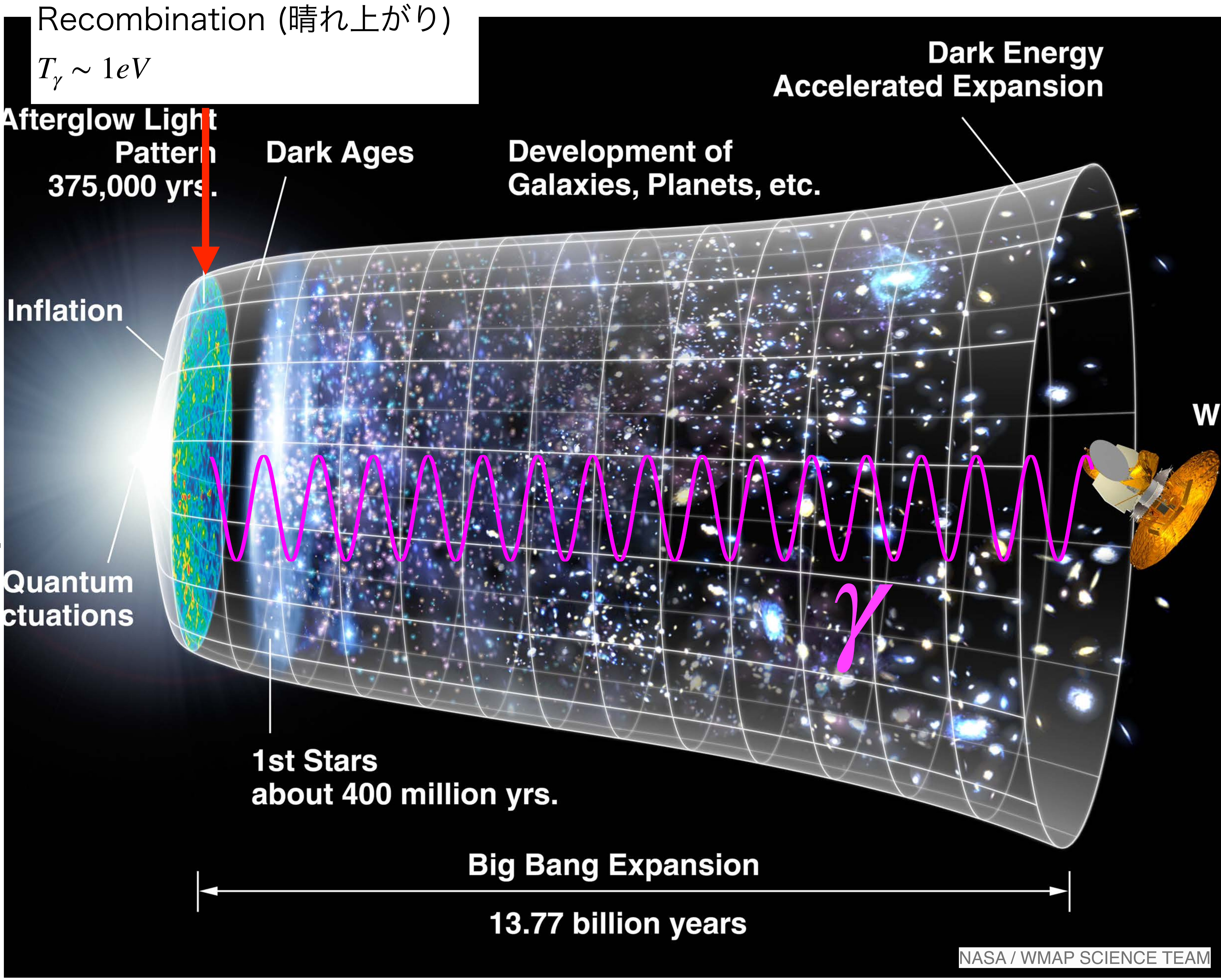
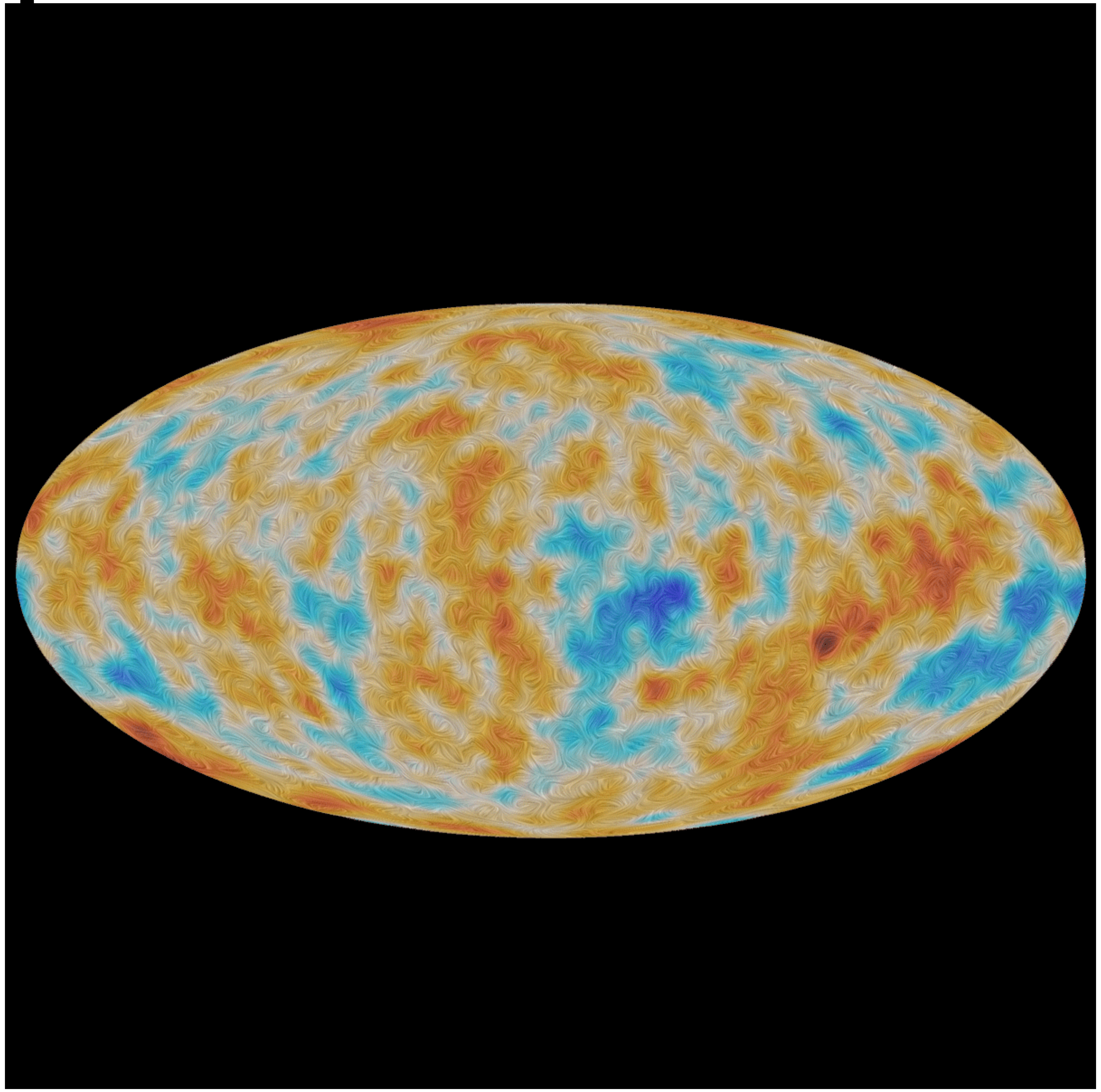
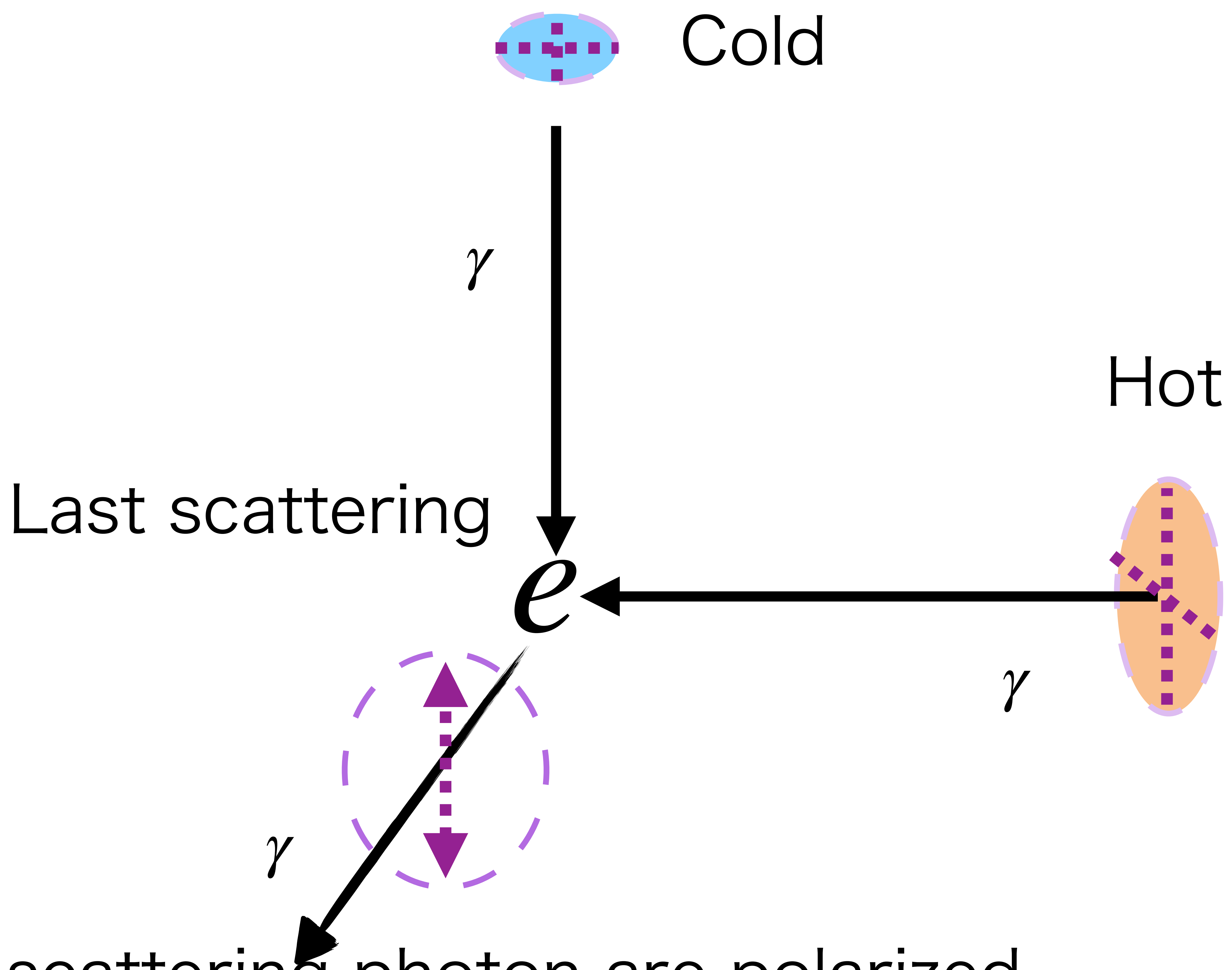


Temperature fluctuation and polarization of photon.





Last scattering photon are polarized due to the density fluctuation.

https://www.esa.int/esearch?q=Polarisation (ESA)

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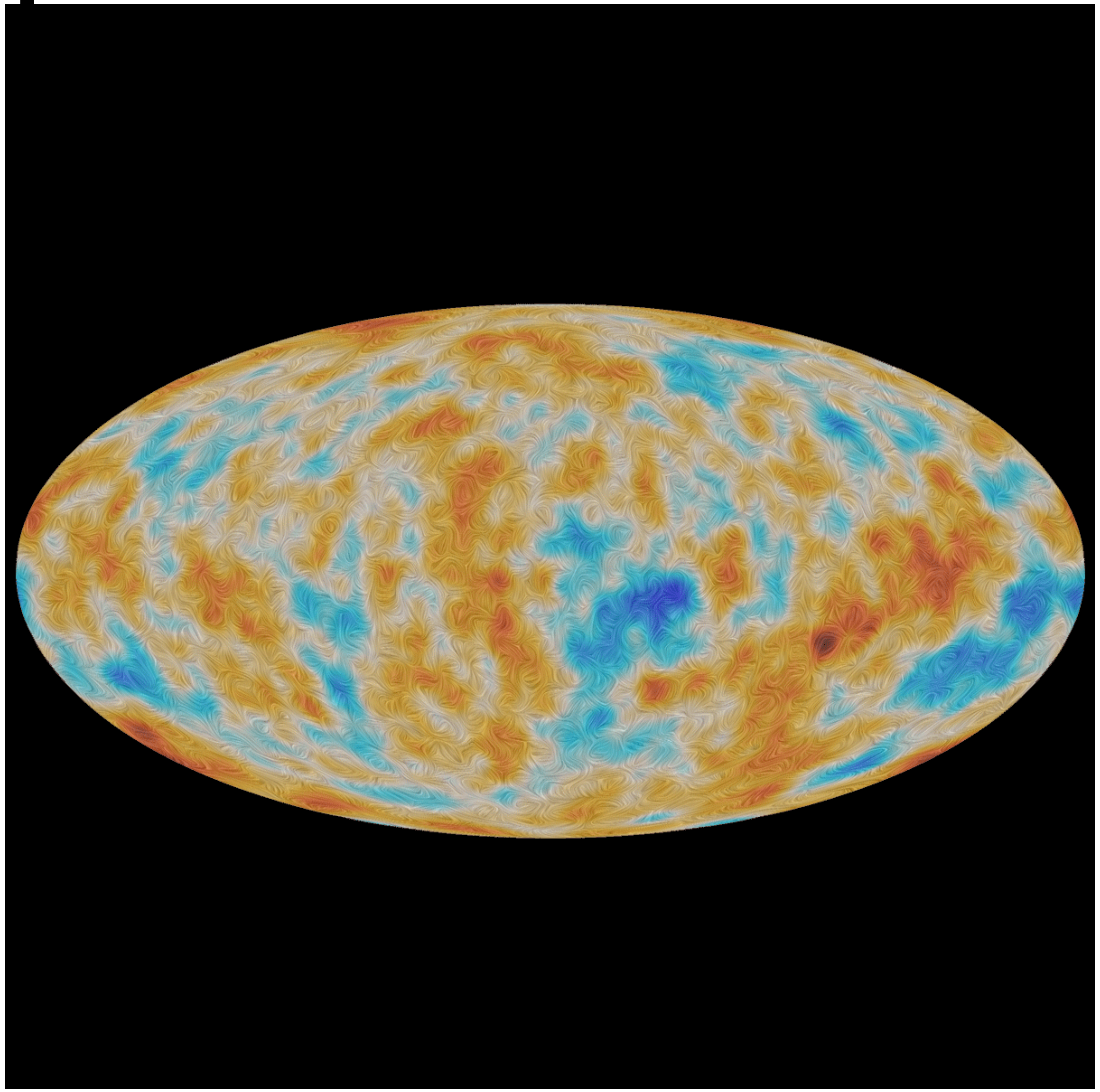

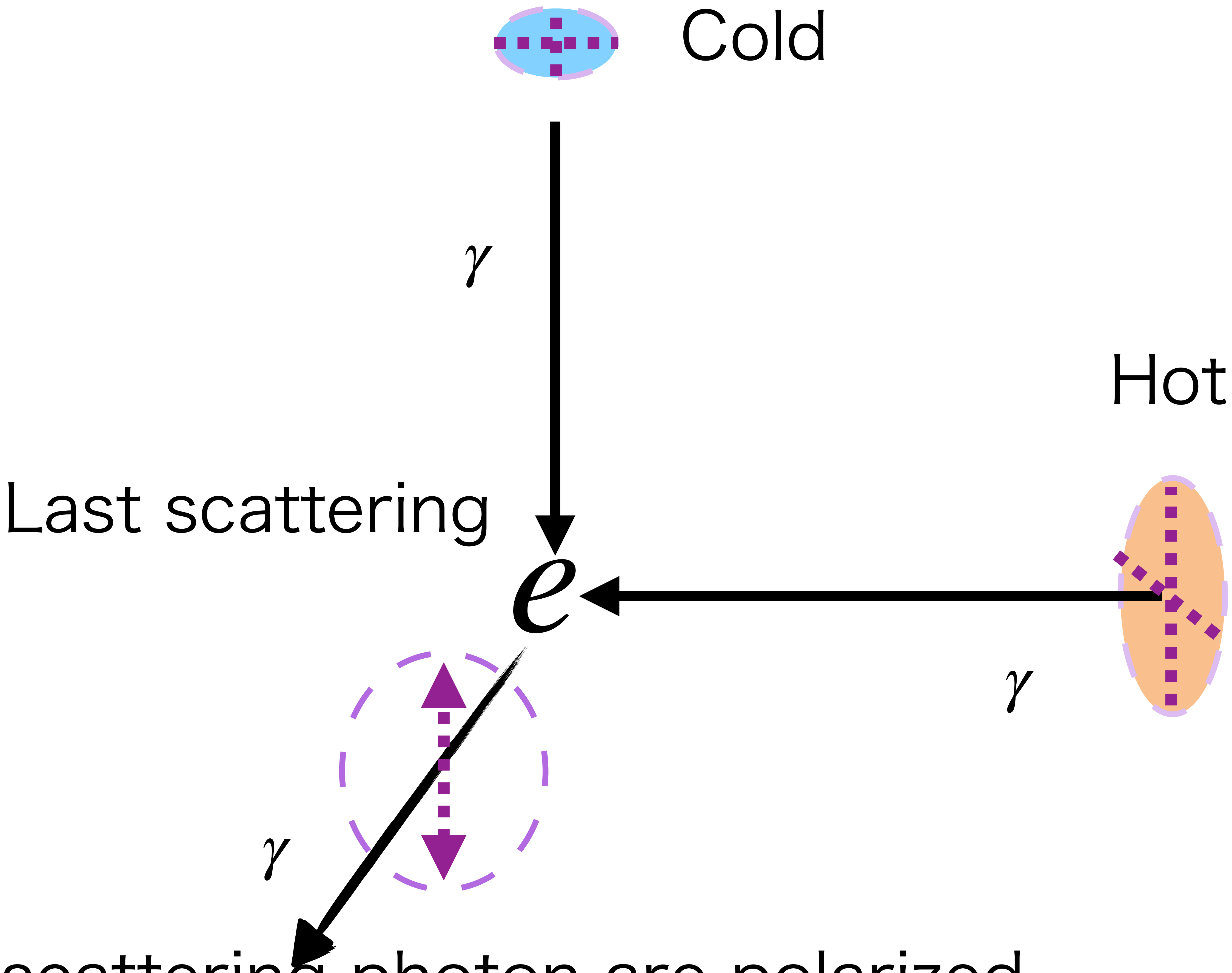

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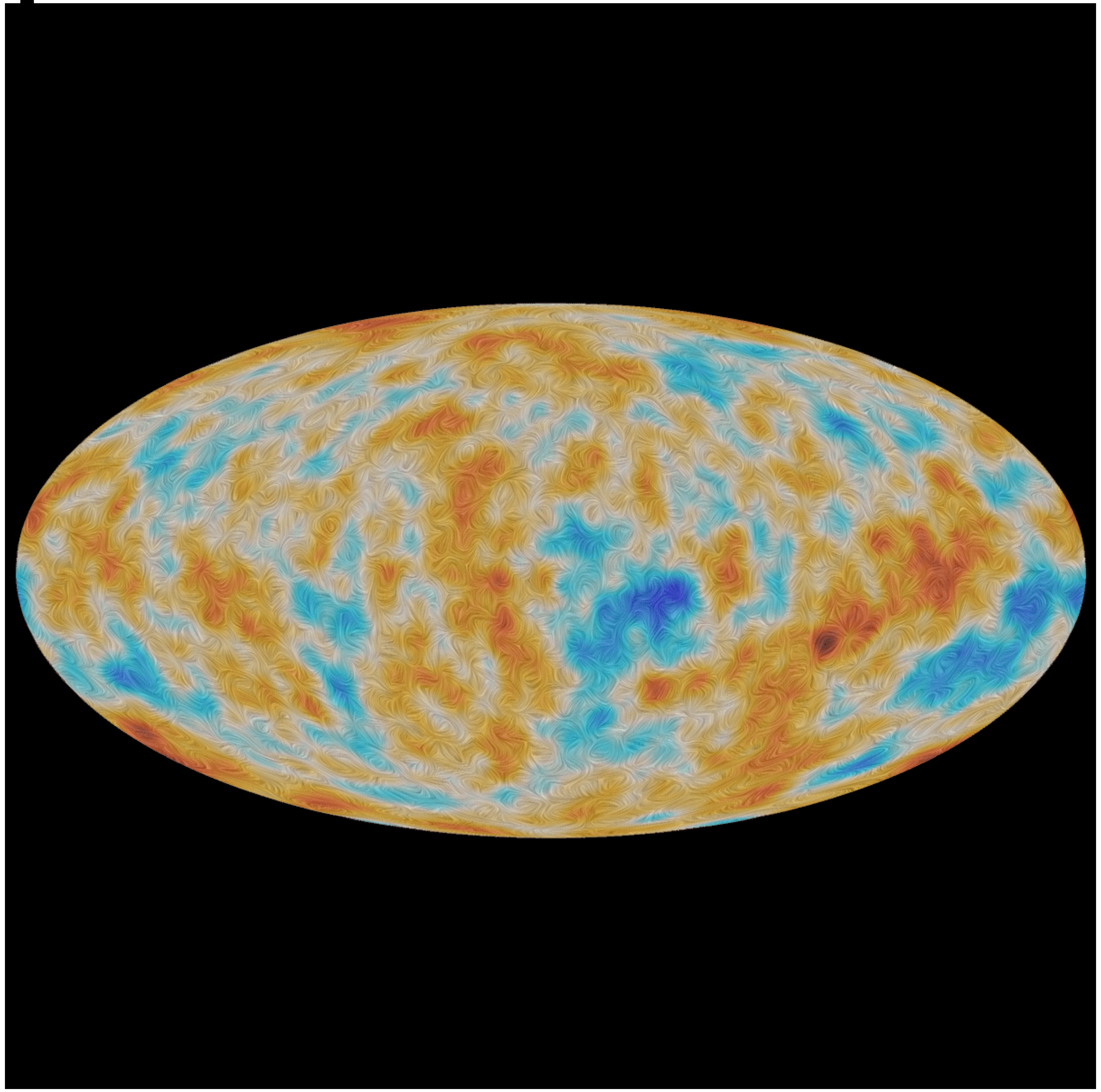

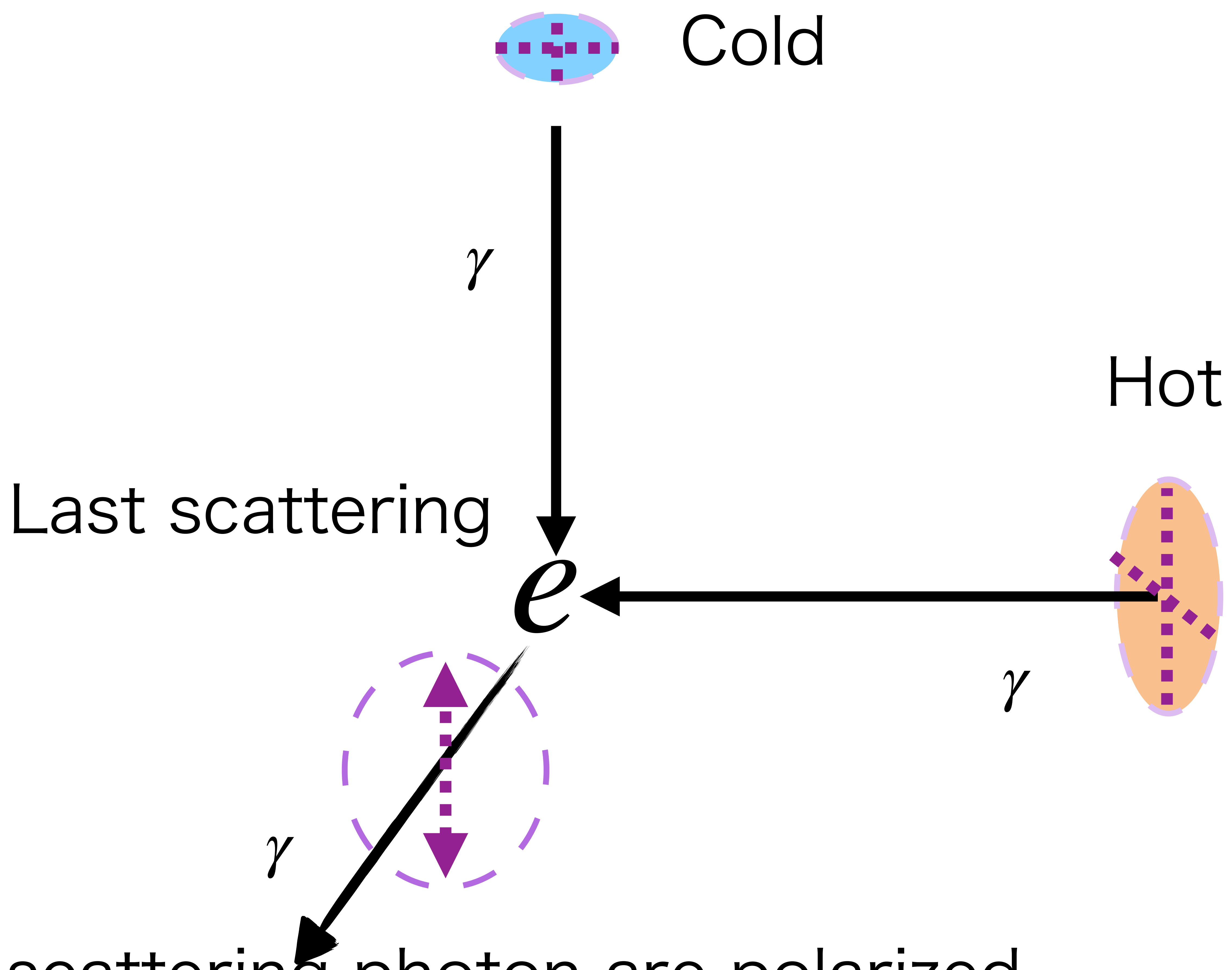

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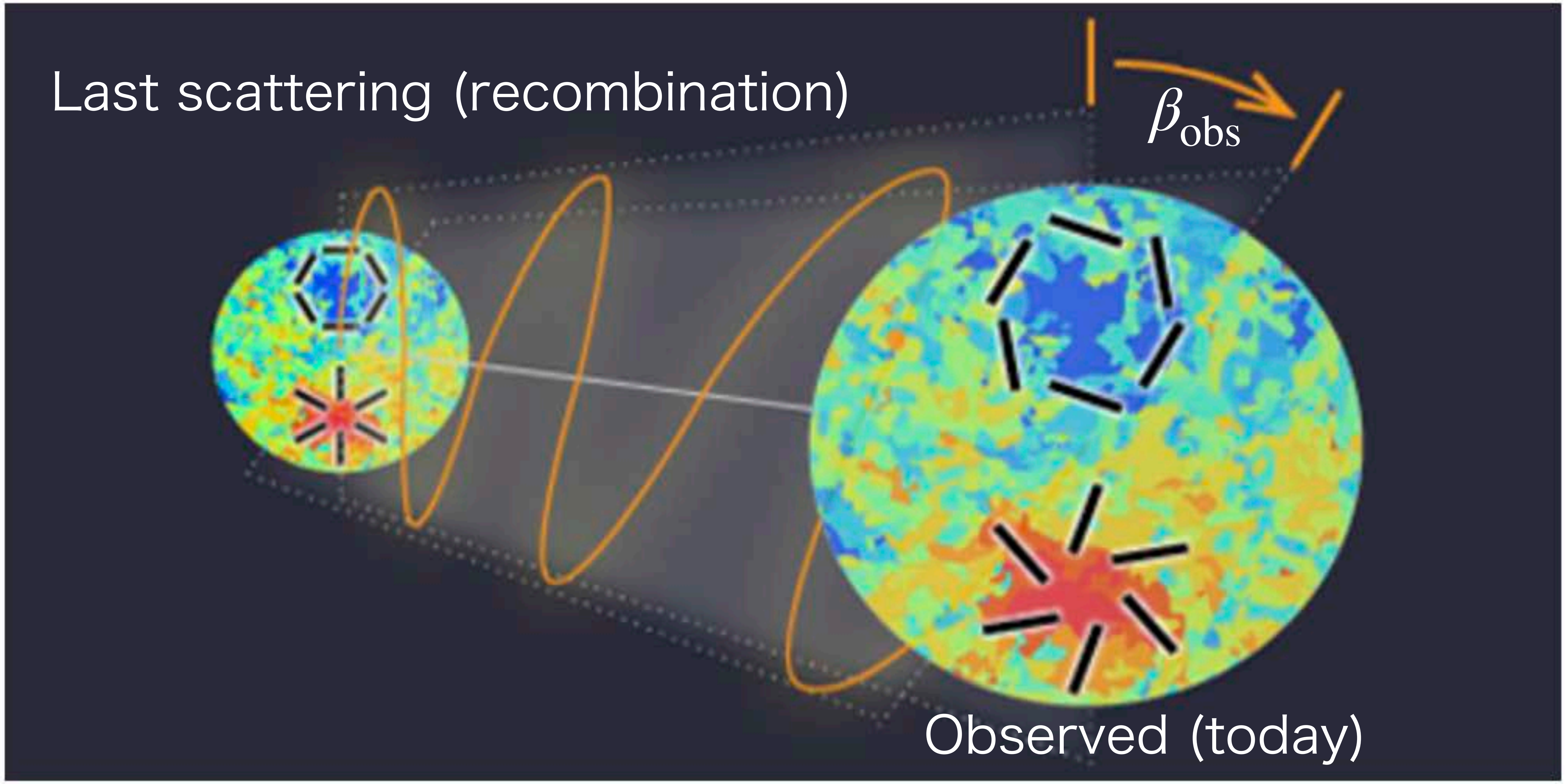
A new analysis is recently performed to get a parity-violating isotropic cosmic birefringence (CB) from Planck2018 data.



Y. Minami/KEK

$$\beta_{\rm obs} = 0.35 \pm 0.14 \text{ deg}, \qquad (2.4\ \sigma)$$

Minami and Komatsu, 2011.11254

See also for the development of the analysis Minami et al,1904.12440, 2002.03572 , 2006.15982,

(If the isotropic CB is true,)

What is the “crystal” in the Universe causing the birefringence?

- It couples to photon.
- It violates the parity.

・1 Introduction

Cosmic Birefringence

(Theory side)

How to violate parity in electromagnetic theory?

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - c_\gamma \frac{\alpha}{4\pi}\theta[x,t]F_{\mu\nu}\tilde{F}^{\mu\nu}$$

How to violate parity in electromagnetic theory?

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

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A simple model has an axion-Like Particle (ALP)

Cosmic Birefringence by Axion-Like Particle (ALP)

Carroll, Field, Jackiw,1990; Harari, Sikivie,1992; Carroll,1998;

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

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$$\boxed{\approx \frac{1}{2}\left[(\vec{E} + \frac{1}{2}g_{\phi\gamma\gamma}\phi\vec{B})^2 - (\vec{B} - \frac{1}{2}g_{\phi\gamma\gamma}\phi\vec{E})^2\right]}$$

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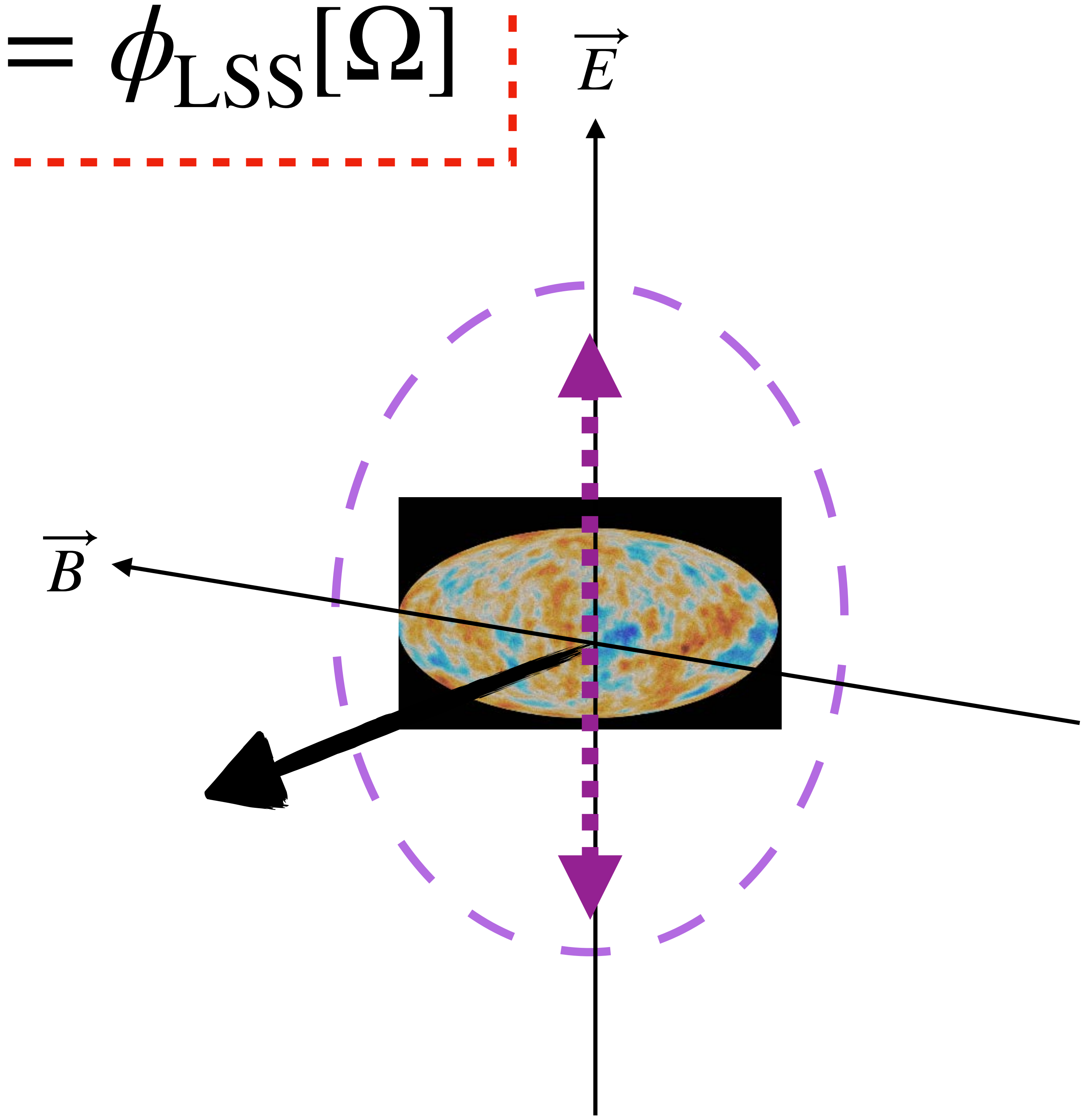

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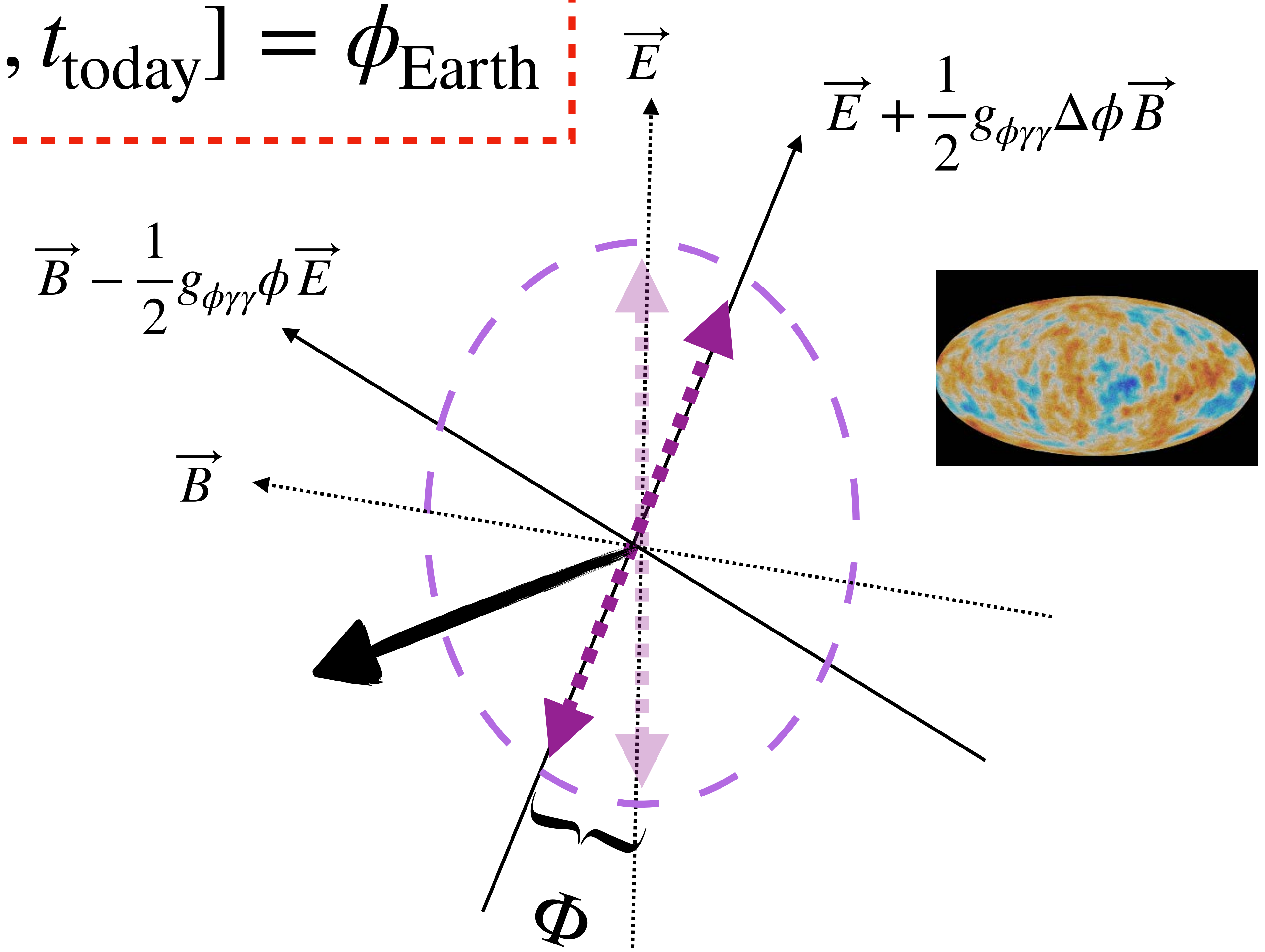

(if ALP background changes adiabatically.)

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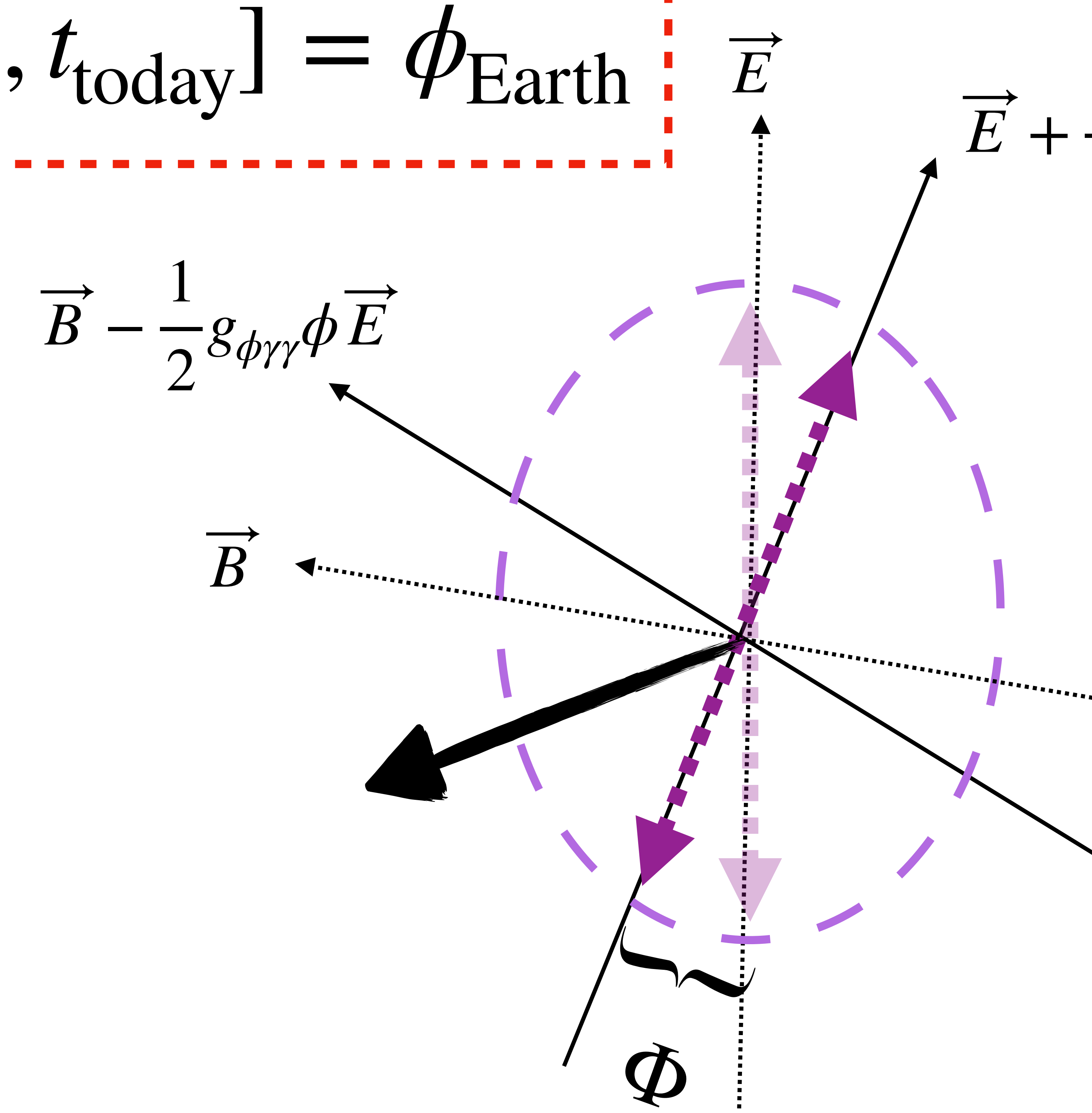

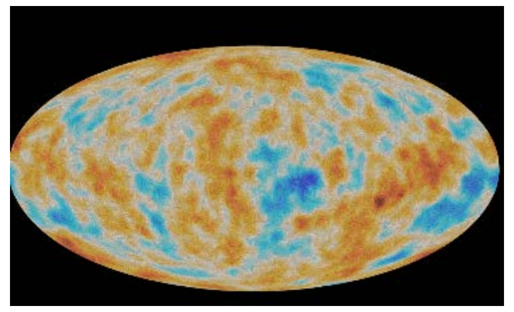

(if ALP background changes adiabatically.)

$$\Phi(\Omega) = \frac{1}{2}g_{\phi\gamma\gamma}\int_{\rm LSS}^{\rm today} d\phi = 0.42 \text{ deg} \times c_\gamma\left(\frac{\phi_{\rm Earth} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi}\right),$$

c.f. $\beta = \frac{1}{4\pi}\int d\Omega\Phi[\Omega]$

Isotropic Cosmic Birefringence by ALP models

- Isotropic CB by $\dot{\phi} \neq 0$: Slow-rolling ALP

Minami and Komatsu, 2006.15982,
Fujita et al, 2011.11894, (CB and H_0 tension)

Mehta et al, 2103.06812, (Many ALPs)
Nakagawa et al, 2103.08153, (Very light ALP)

- Isotropic CB by $|\partial_{\vec{x}}\phi| \neq 0$: Domain walls

Takahashi, WY, 2012.11576, (CB by Domain wall)

This talk

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This talk

Why Cosmic Birefringence (CB) from Domain Wall?

$$\Phi(\Omega) = \int_{\mathrm{LSS}[\Omega]}^{\mathrm{Today}} g_{\phi\gamma\gamma} d\phi/2$$

$$= 0.42 \text{ deg} \times c_\gamma \left(\frac{\phi_{\mathrm{Earth}} - \phi_{\mathrm{LSS}}(\Omega)}{2\pi f_\phi} \right),$$

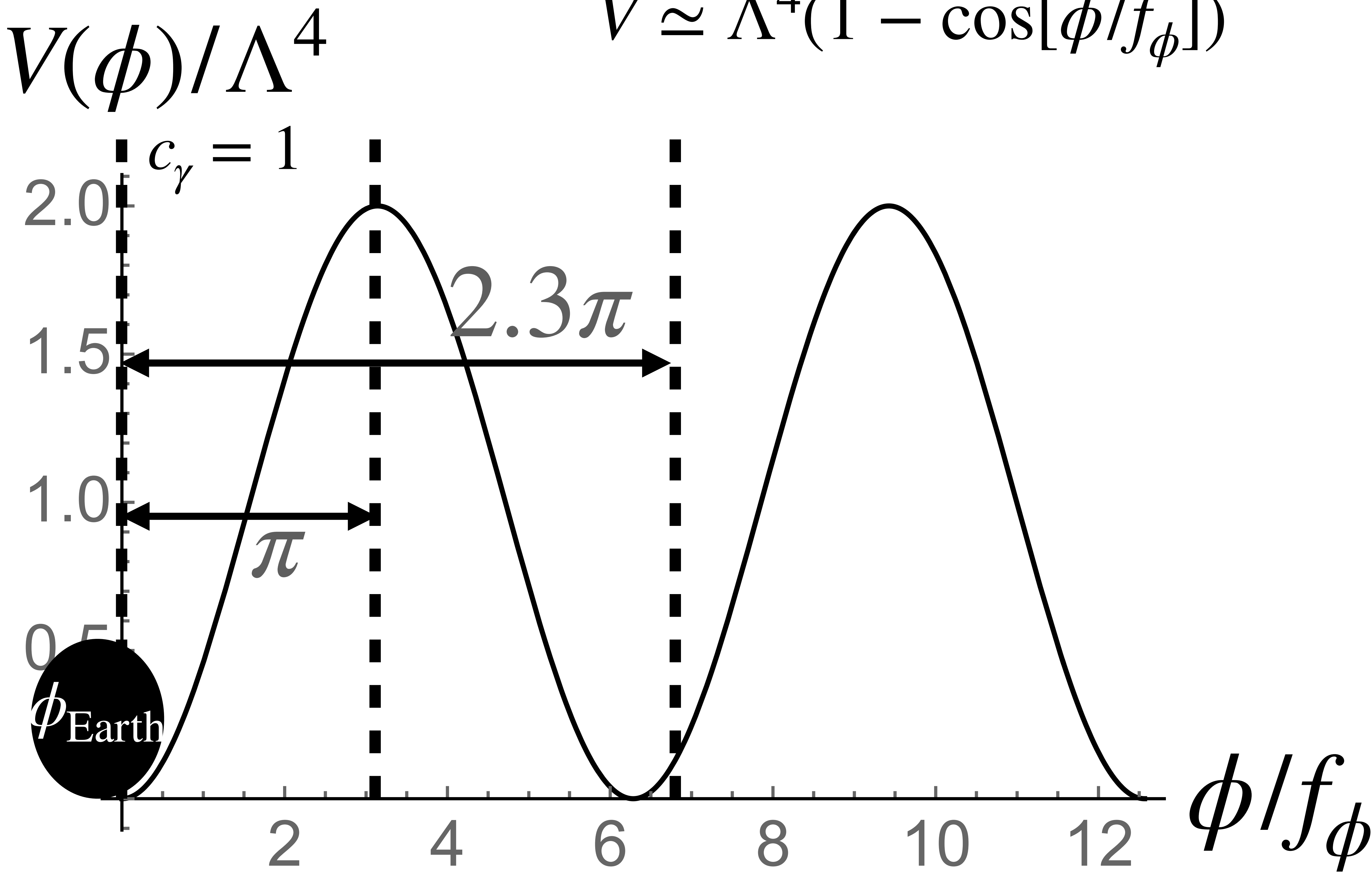
$$\beta = \frac{1}{4\pi} \int d\Omega \Phi[\Omega]$$

$$\beta_{\mathrm{obs}} = 0.35 \pm 0.14 \text{ deg},$$

Minami and Komatsu, 2006.15982,

$$\longrightarrow \quad c_\gamma \left(\frac{\phi_{\mathrm{Earth}} - \bar{\phi}_{\mathrm{LSS}}}{f_\phi} \right) \sim (\pi - 2.3\pi)$$

$V \simeq \Lambda^4(1 - \cos[\phi/f_\phi])$

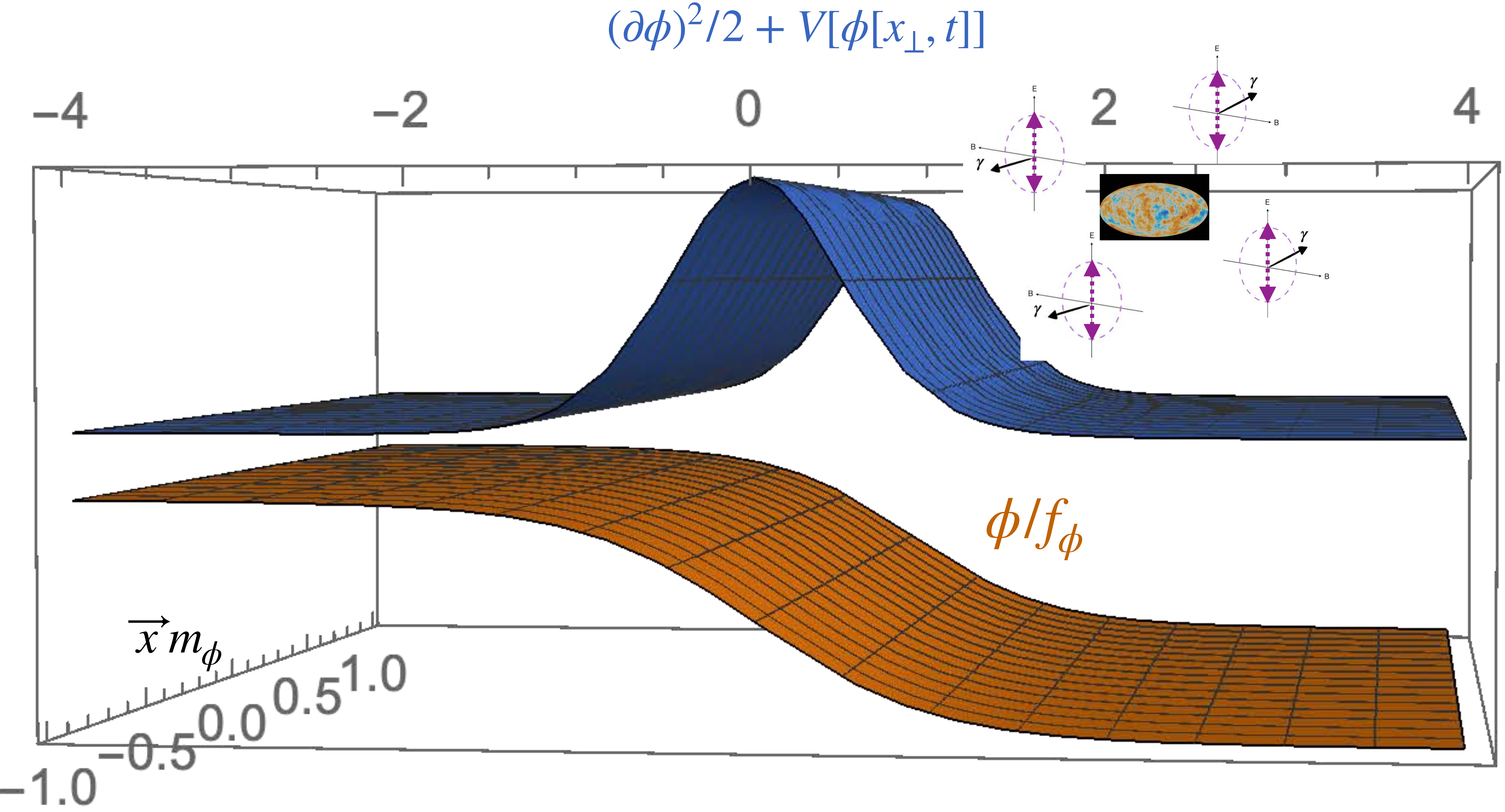


Photon emitted at recombination is likely to go through an ALP potential barrier.

→ **The measured CB (and $c_\gamma \lesssim O(1)$) suggests a domain wall.**

- CB by ALP domain walls

$$V \simeq \Lambda^4(1+\cos[\phi/f_\phi])$$



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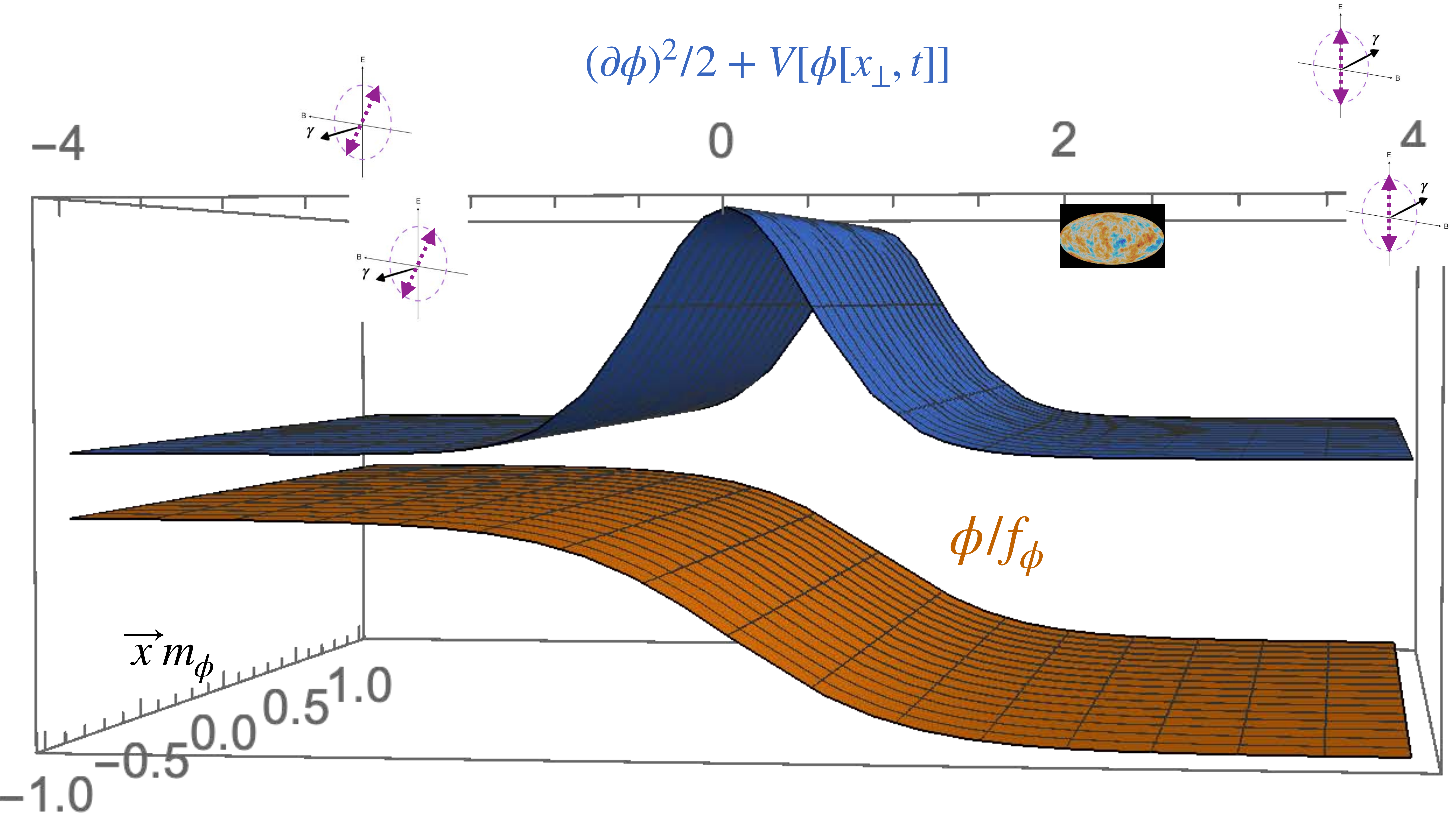

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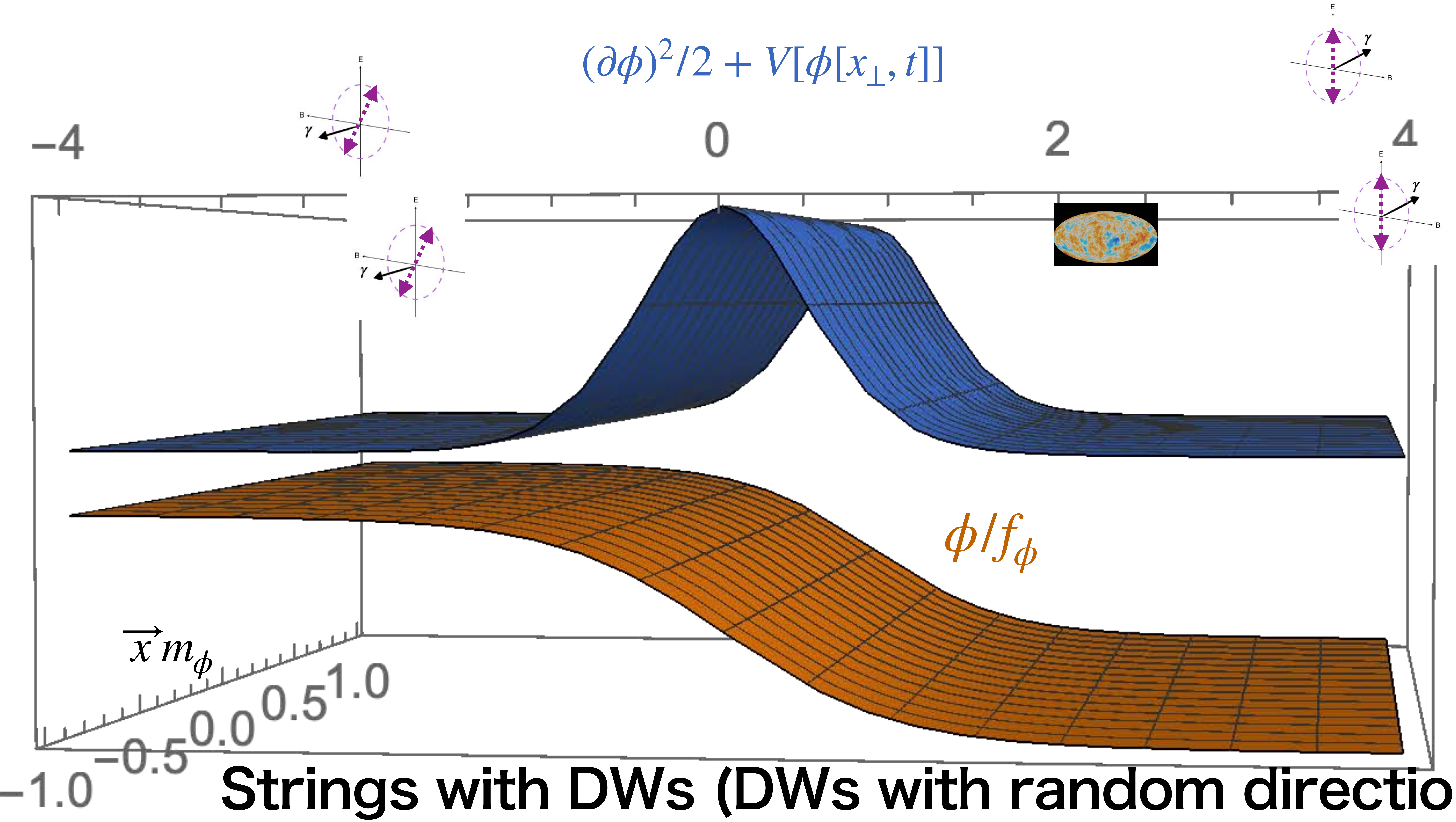


Strings with DWs (DWs with random directions) cannot induce isotropic CB Agrawal et al, 1912.02823;

2. ALP domain walls *without a string*

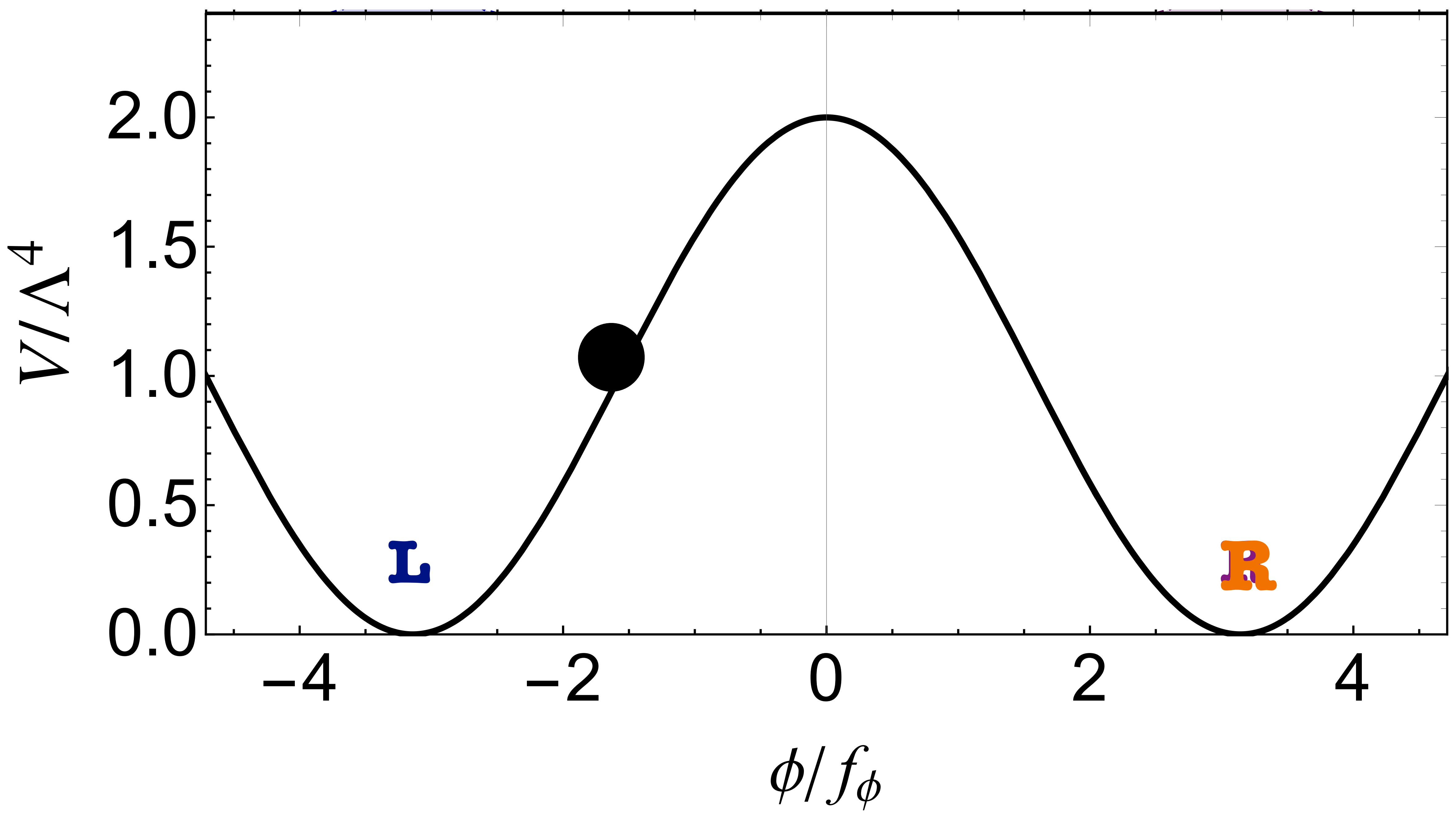
ALP domain wall does not need a string.

Suppose that PQ symmetry never restore. During the inflation

ALP undergoes random walk due to quantum diffusion given $m_\phi \ll H_{\rm inf}$.

$$\dot{\phi}_{\rm clasical} \simeq -\frac{m_\phi^2}{H_{\rm inf}}\phi \to 0$$

(at 1 Hubble time)



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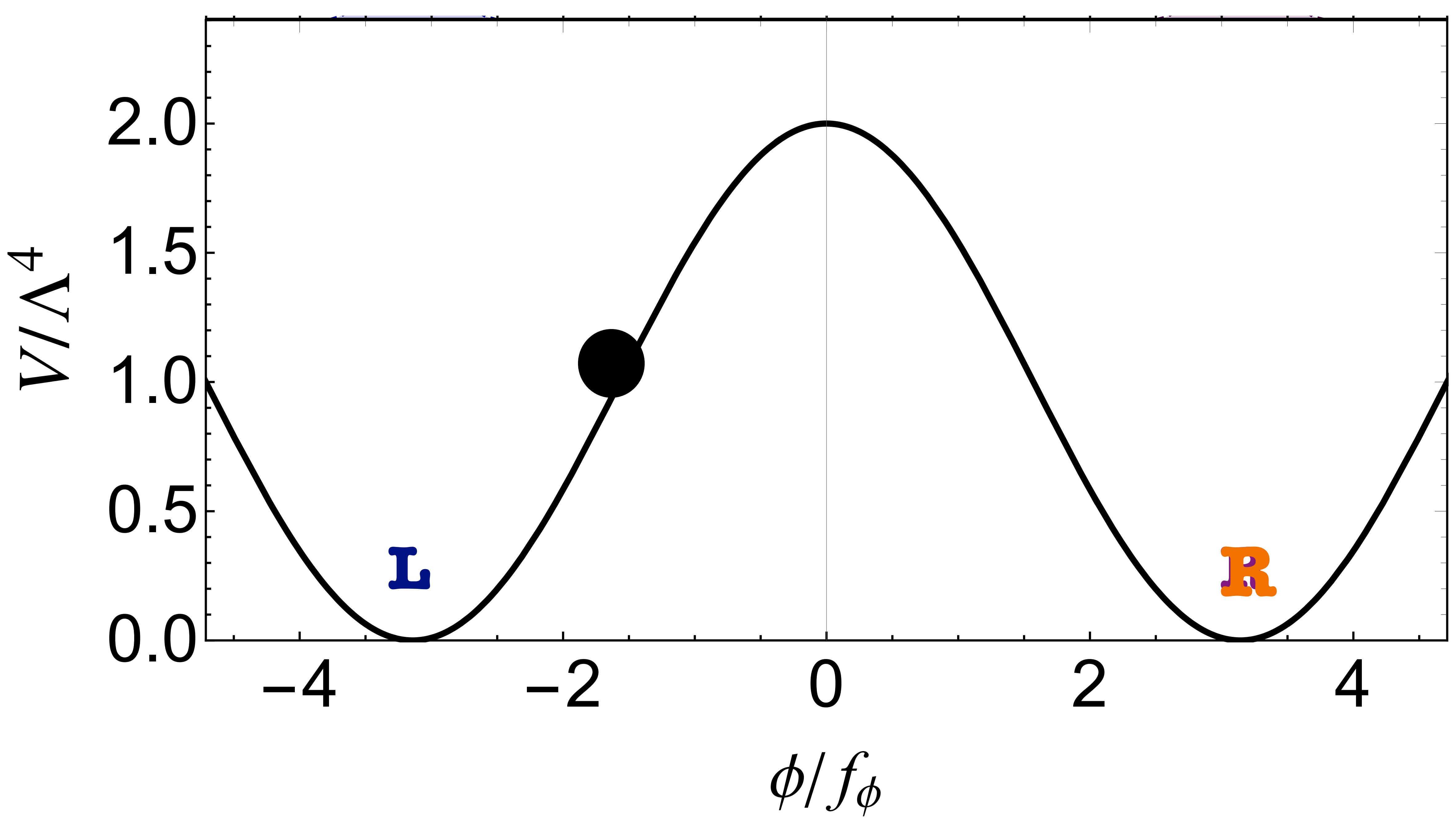

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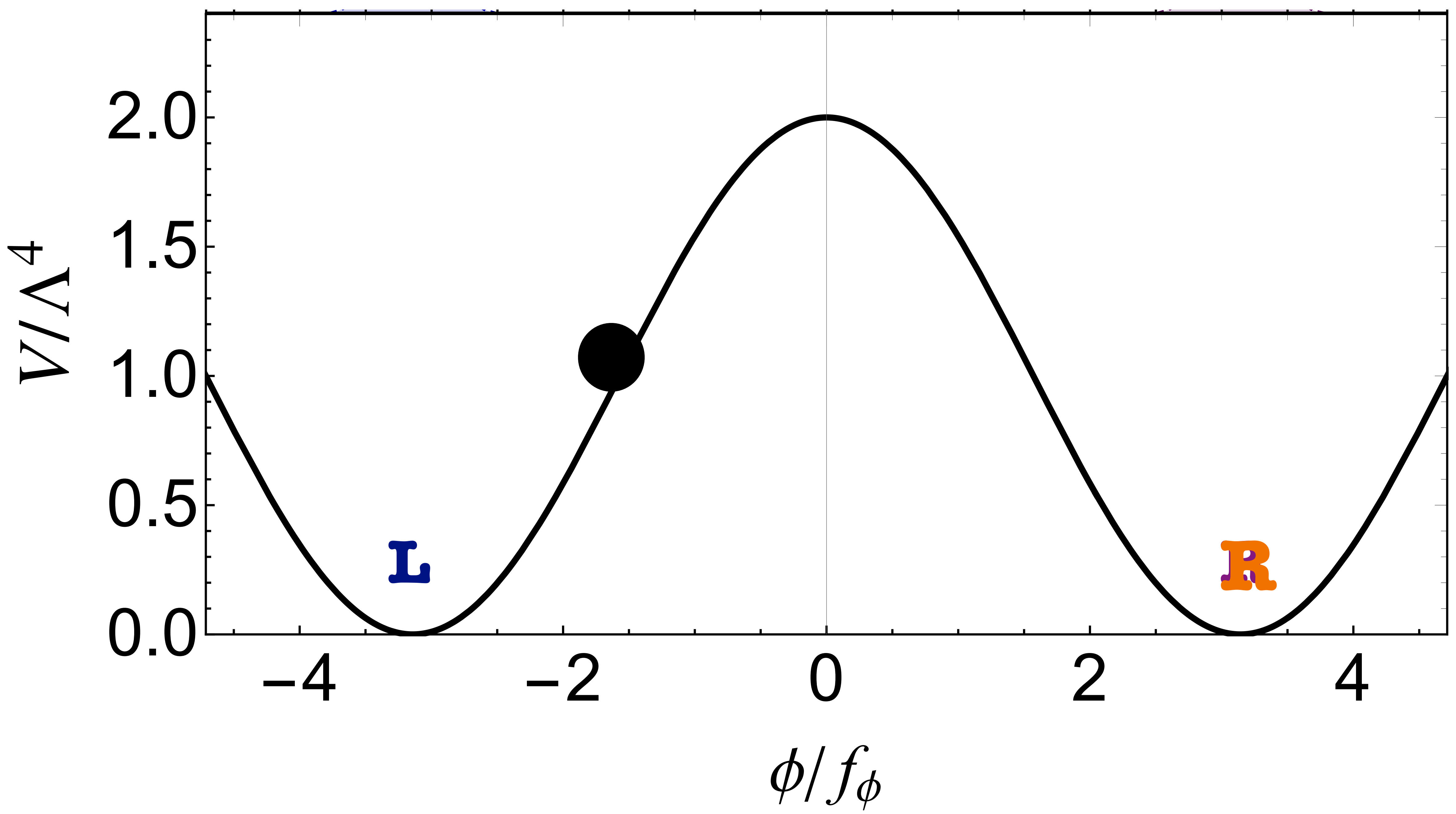
Quantum jump (Random walk) $\dfrac{\delta\phi}{f_\phi} \sim \dfrac{H_{\rm inf}}{2\pi f_\phi}$ (at 1 Hubble time)



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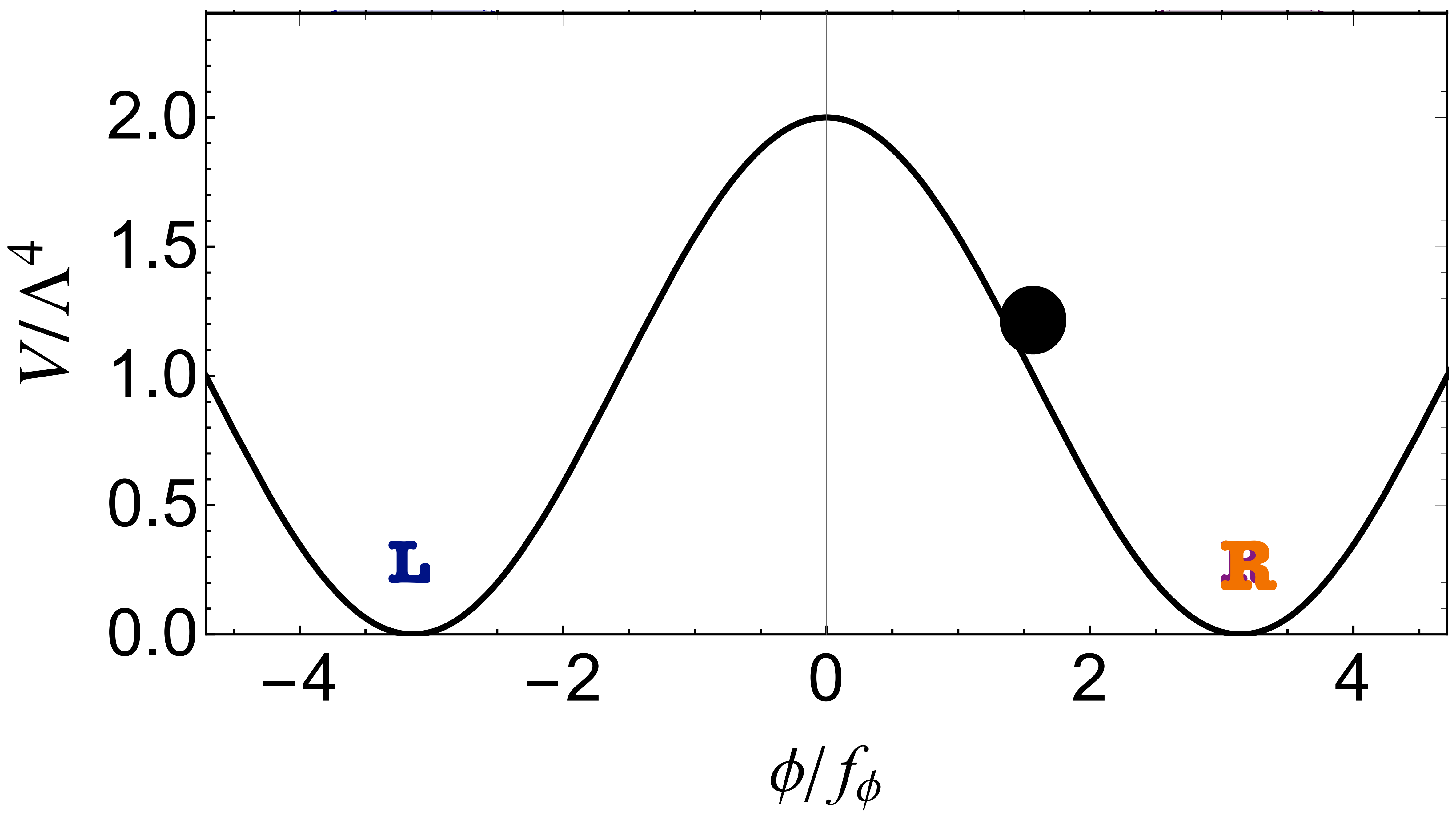
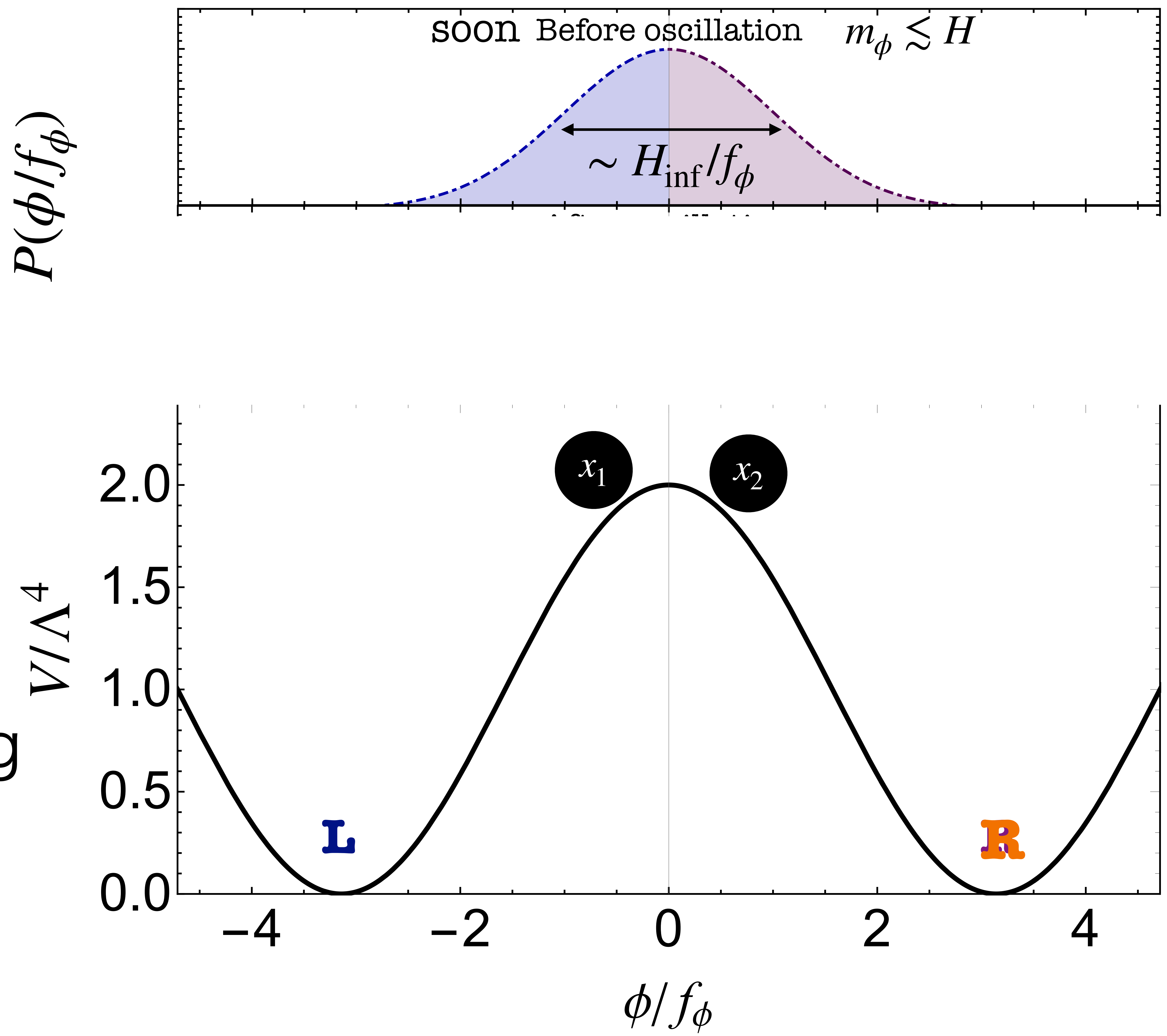


ALP domain wall does not need a string.

c.f. Resembles the domain wall from a Z_2 breaking

Let us consider that PQ symmetry never restore.

- It is natural that ϕ has a non-trivial initial distribution, e.g. during inflation $\Delta\phi \sim H_{\rm inf}/(2\pi)$.
- When $m_\phi \sim H$, ALP starts to oscillate about two vacua, L and R depending on the position.
- Domain walls!



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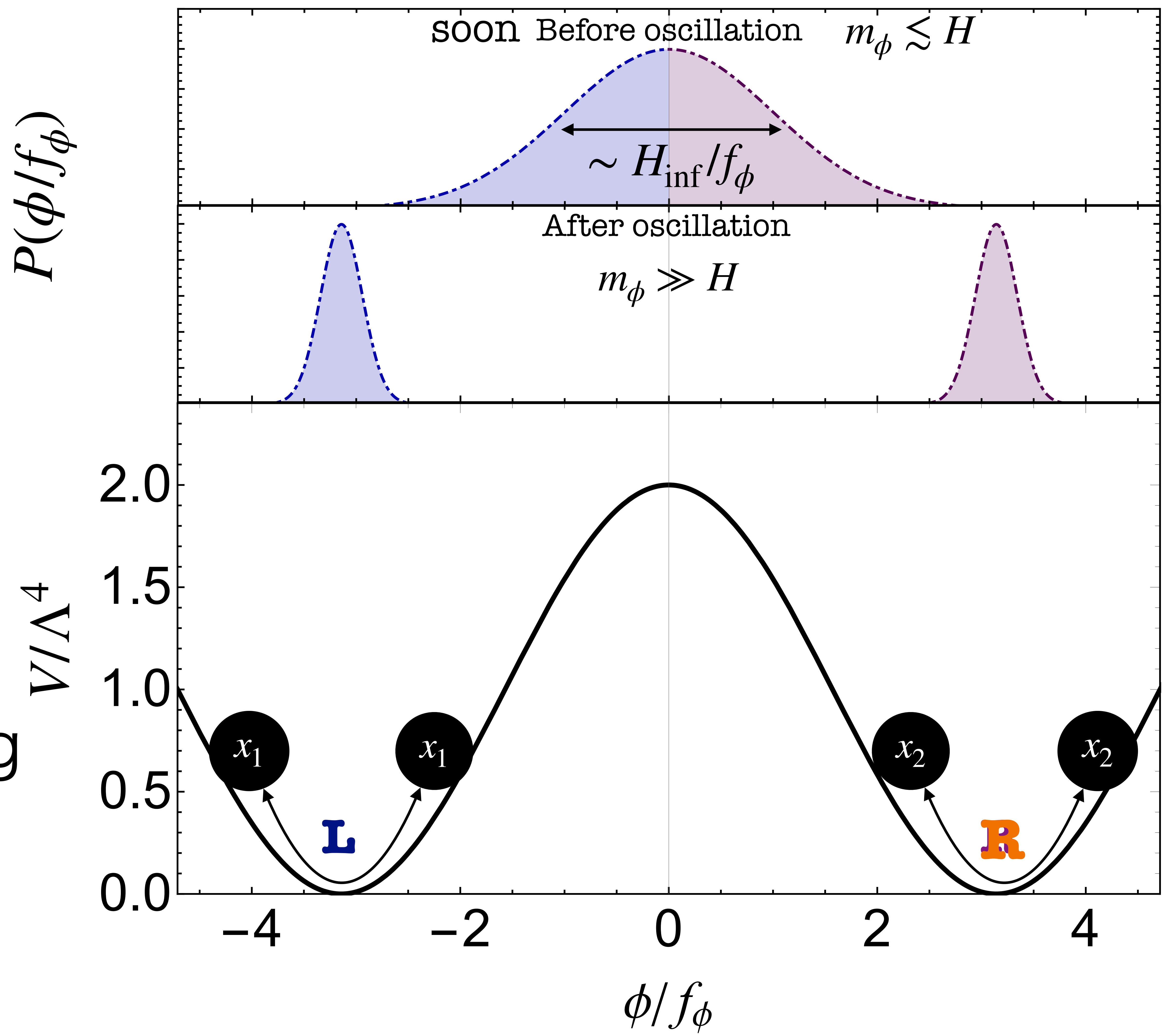


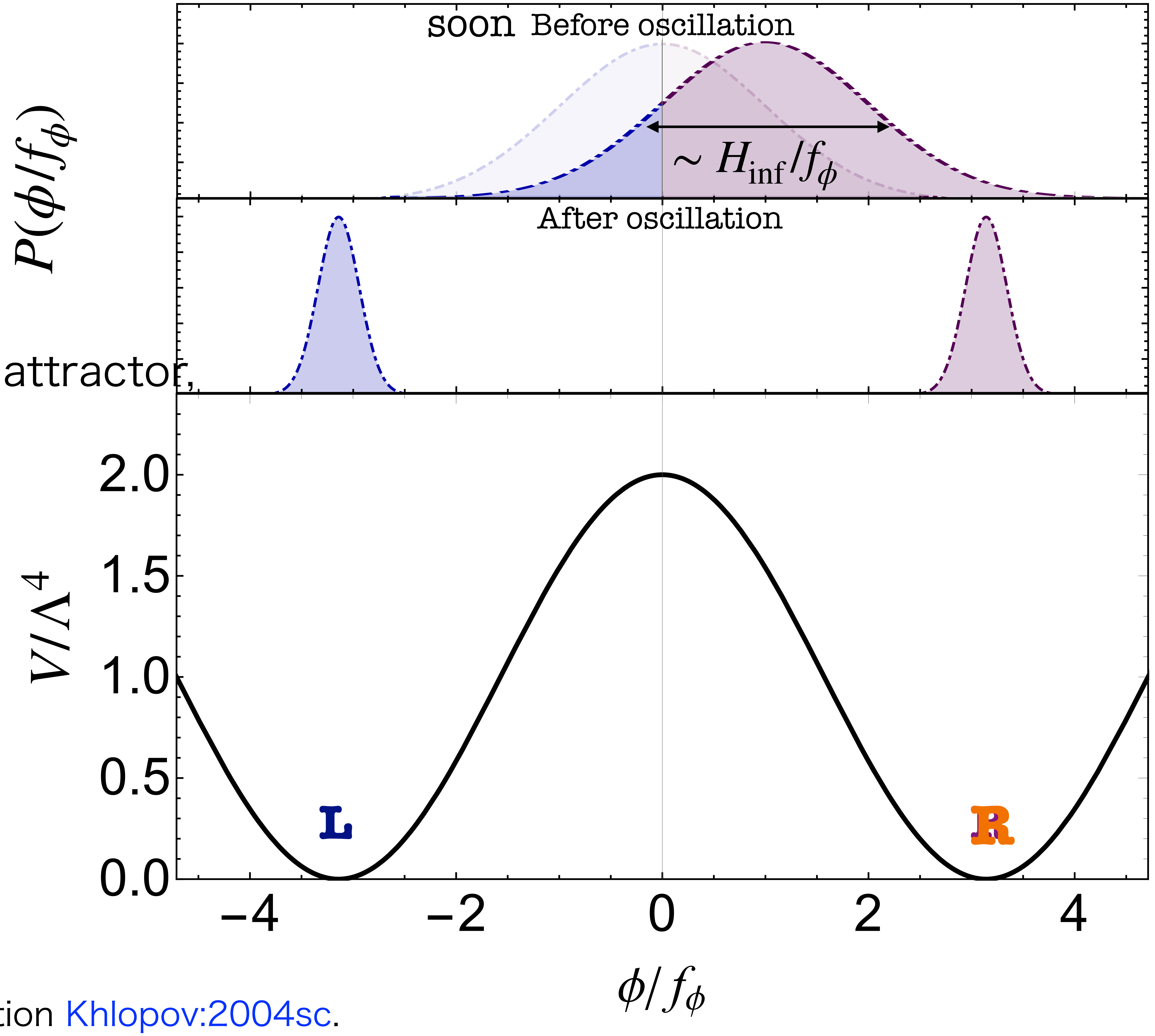
Percolation theory and domain wall network

Soon after the onset of oscillation many domain walls are formed

as long as $0.31 < \int_{-2\pi}^{0} d\theta P(\theta) < 0.69$.

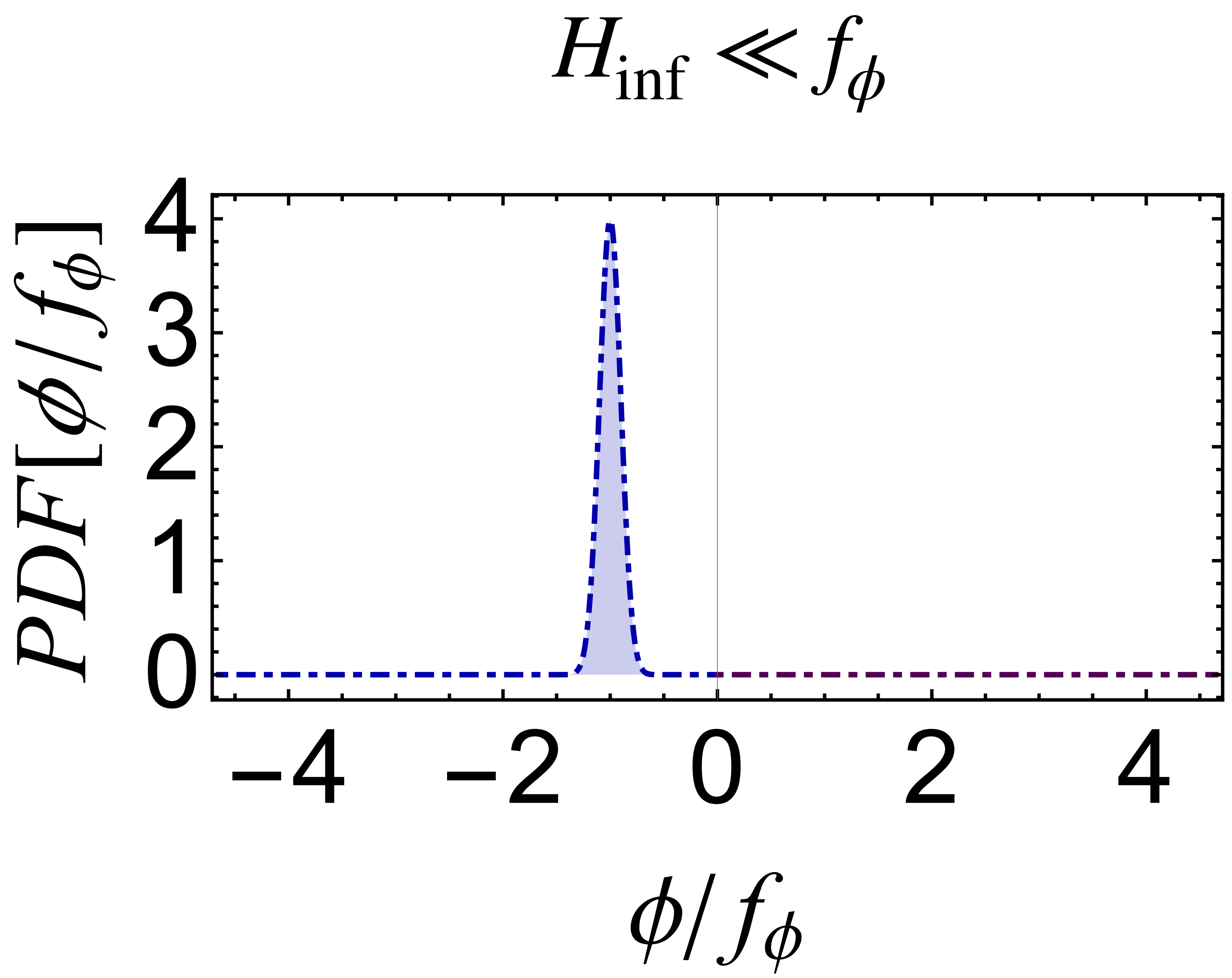
Vachaspati:1984dz,Vilenkin:1984ib

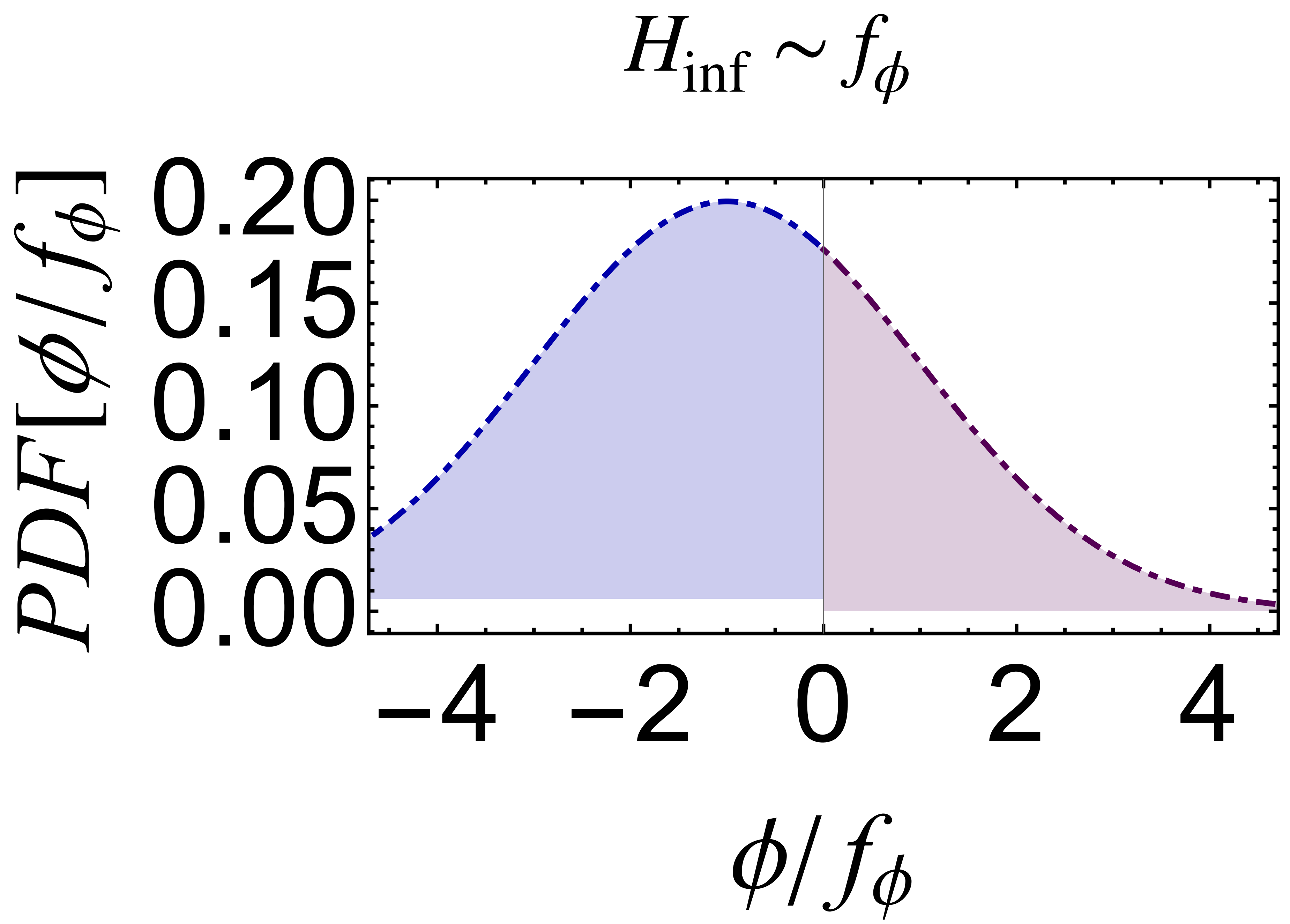
The distribution much after the onset of oscillation is an attractor, known as the scaling solution.



<u>$O(1)$ domain walls always survive in a Hubble horizon at any time.</u>

See also the PBH production scenario without satisfying the scaling solution Khlopov:2004sc.





ALP domain wall without a string can be naturally formed if $f_\phi \sim H_{\rm inf}$!

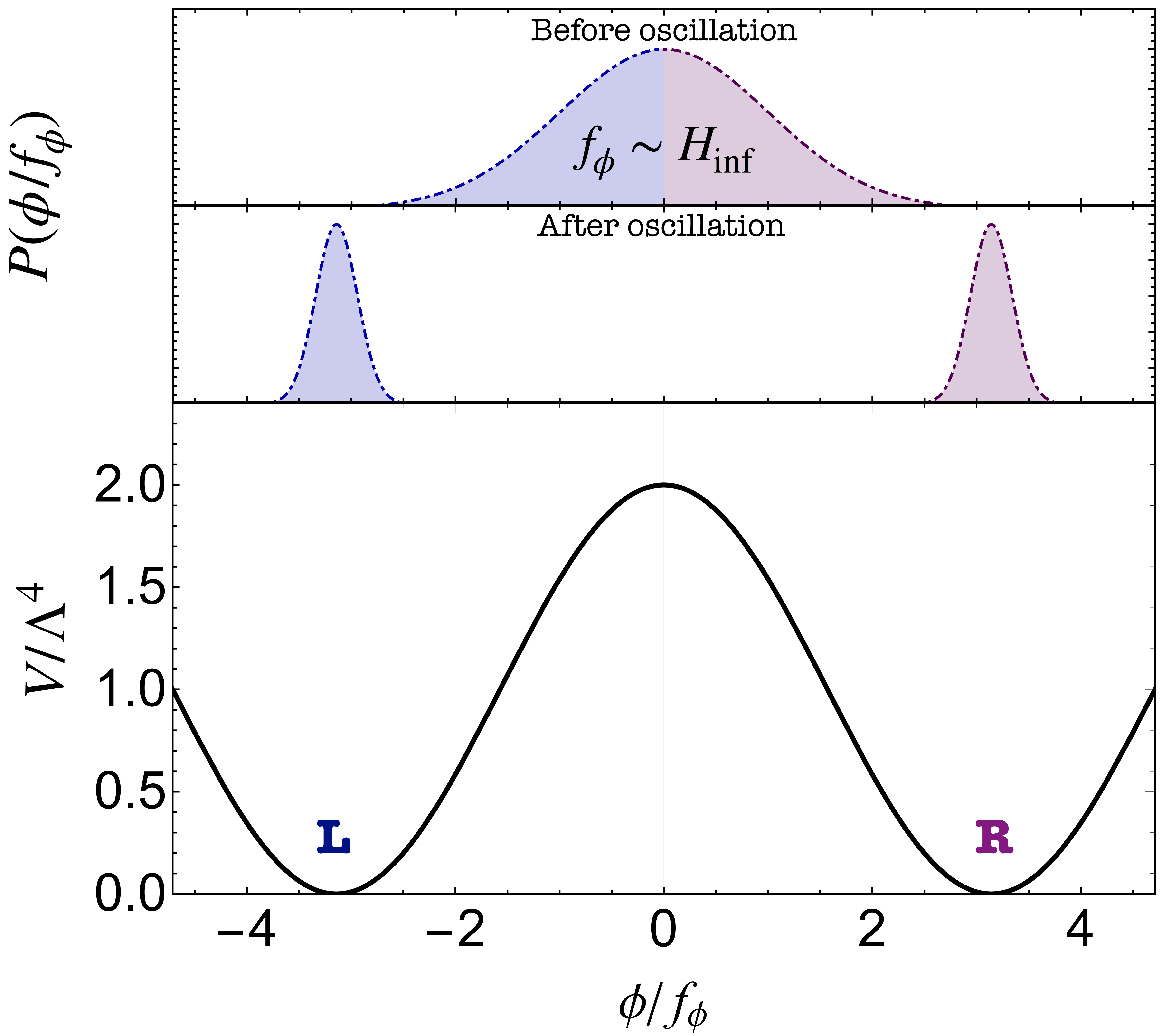
Is $f_\phi \sim H_{\rm inf}$ for DW without a string natural?

Given the light ALP, our predictions only rely on the condition $f_\phi \sim H_{\rm inf}$

$$\mathscr{L} \supset \sqrt{-g}R\left(\frac{\xi}{2}|S|^2 + \frac{M_{\rm pl}^2}{2}\right)$$

$$V_{\rm eff} \approx (-6\xi H_{\rm inf}^2 - m_S^2)|S|^2 + \lambda|S|^4$$

$$\xrightarrow{\text{if } \xi H_{\rm inf} \gtrsim m_S} \quad f_{\phi,{\rm inf}} \simeq 2\sqrt{\frac{3\xi}{\lambda}}H_{\rm inf}\,.$$



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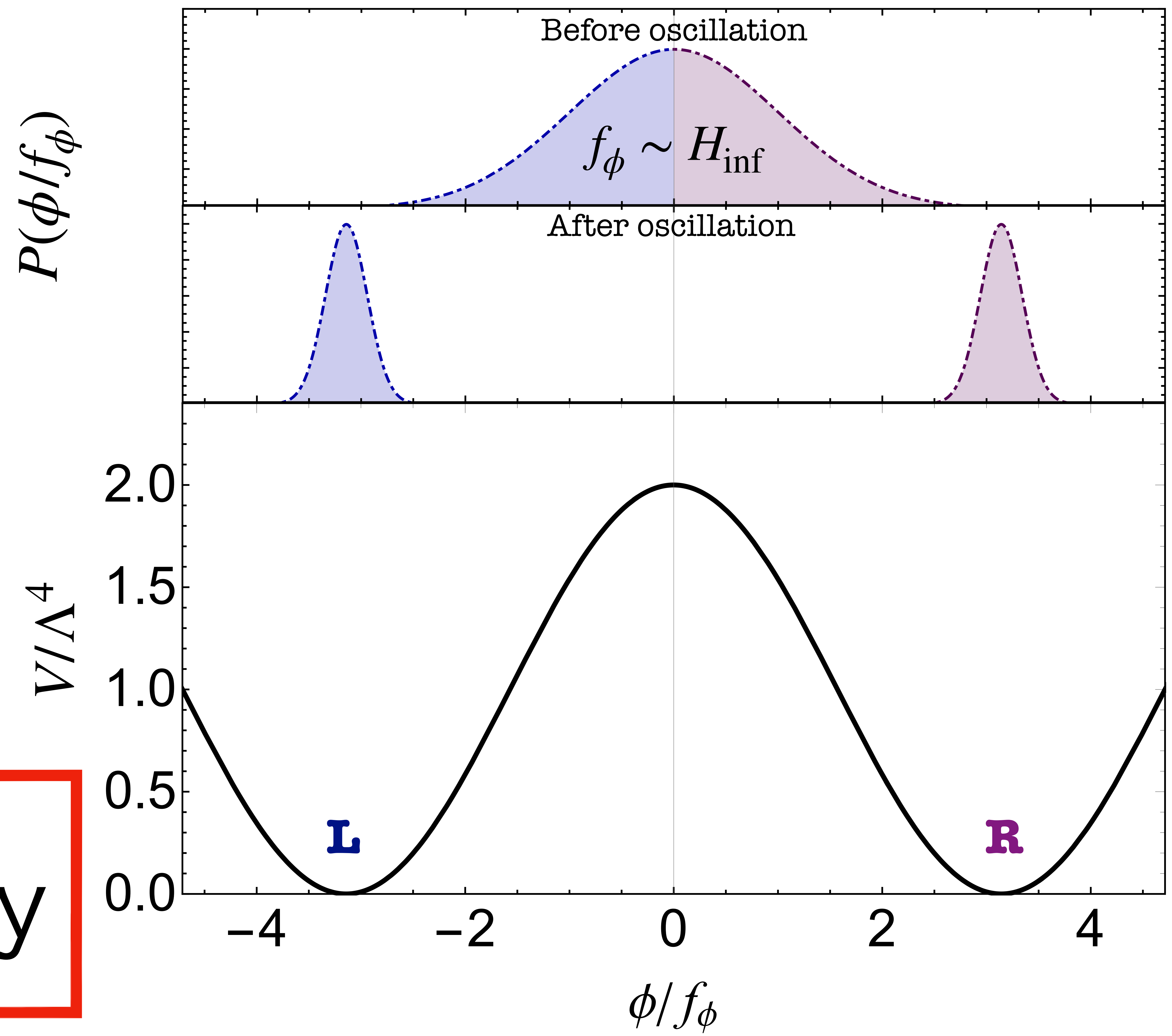
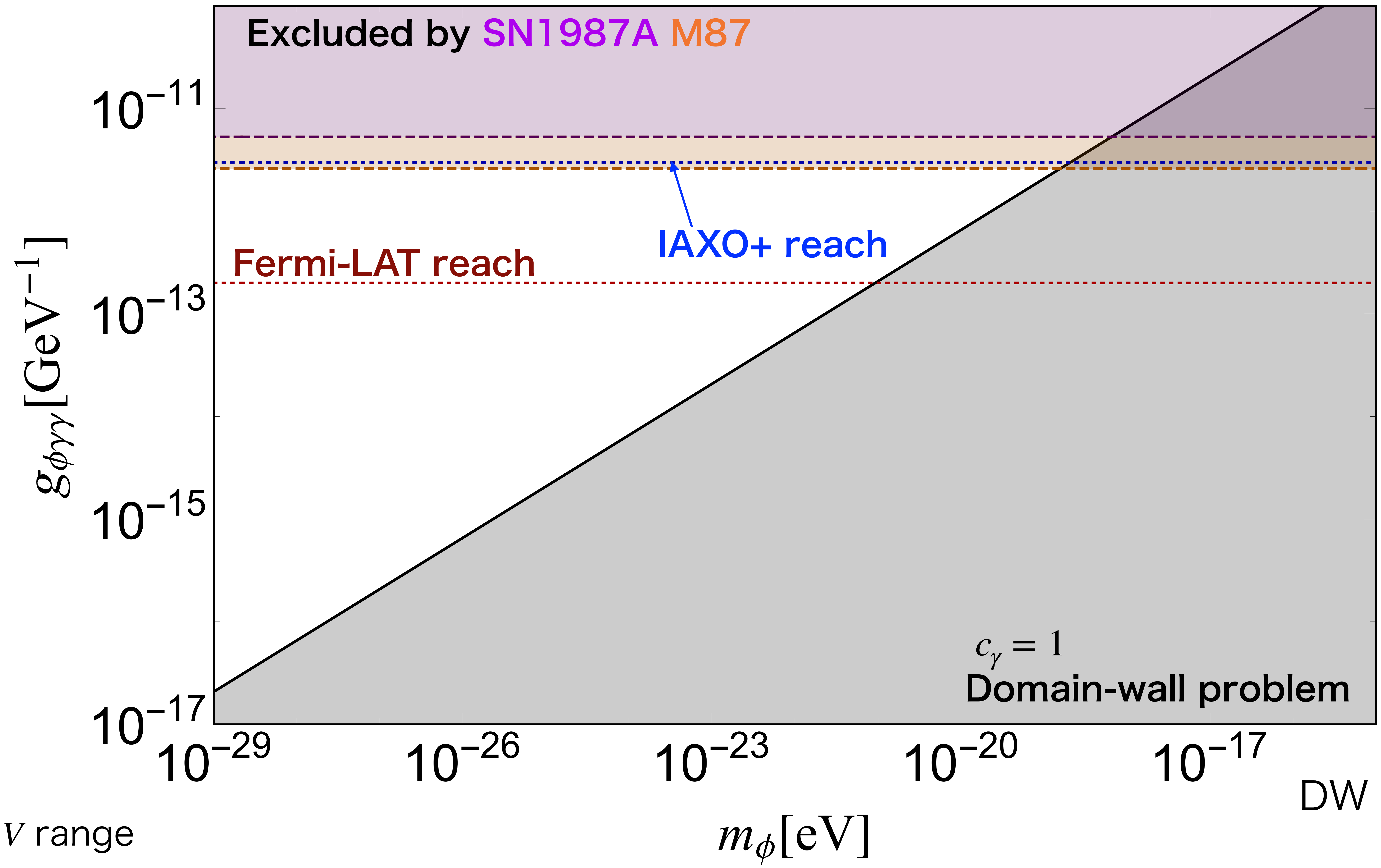


$\boxed{\text{DWs are formed naturally}}$

Parameter region of ALP domain wall in the scaling solution



$\rho_{\mathrm{DW}} \sim \sigma_{\mathrm{DW}} H$

DW tension: $\sigma_{\mathrm{DW}} \sim m_\phi f_\phi^2$

$m_\phi \lesssim 10^{-18} eV$ range

cf. $m_\phi \lesssim 10^{-28}\, eV$ Minami and Komatsu, 2006.15982, Fujita et al, 2011.11894, Mehta et al, 2103.06812,Nakagawa et al, 2103.08153

, Adiabatic condition of DW $p_\gamma \gtrsim 10^{-4}\mathrm{eV} \gg 1/\text{wall width} \sim m_\phi$

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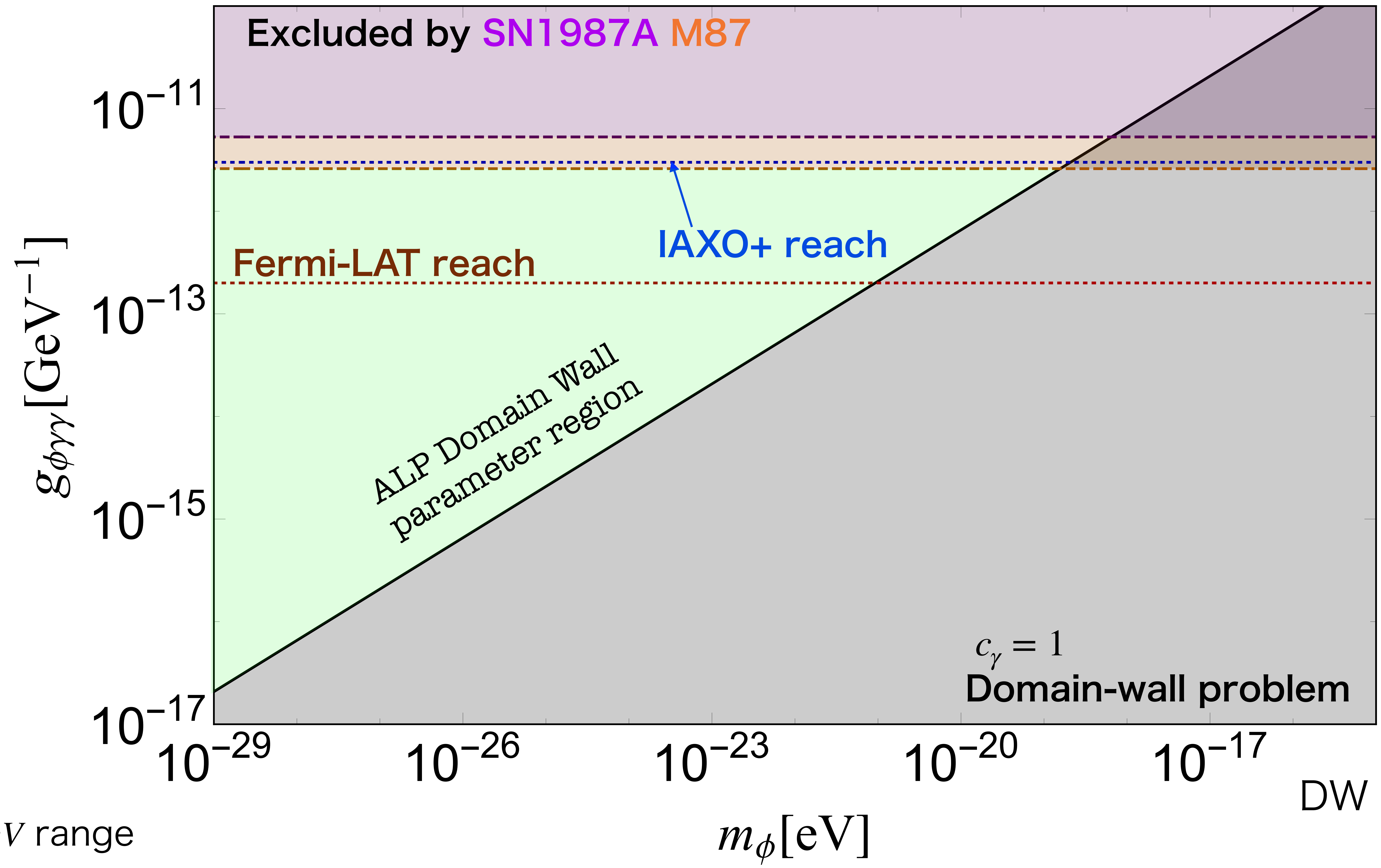

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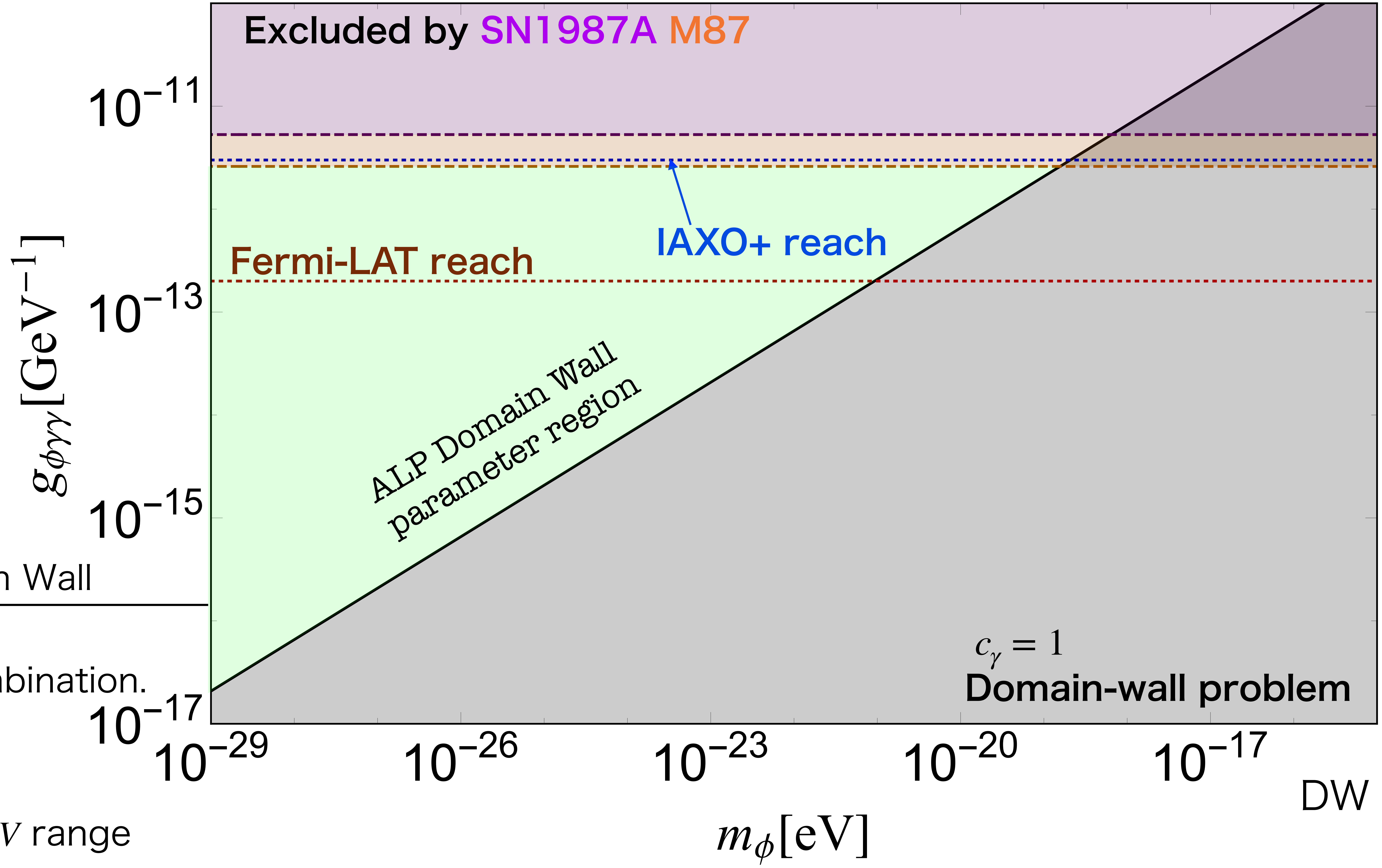

ALP Domain Wall formation after recombination.

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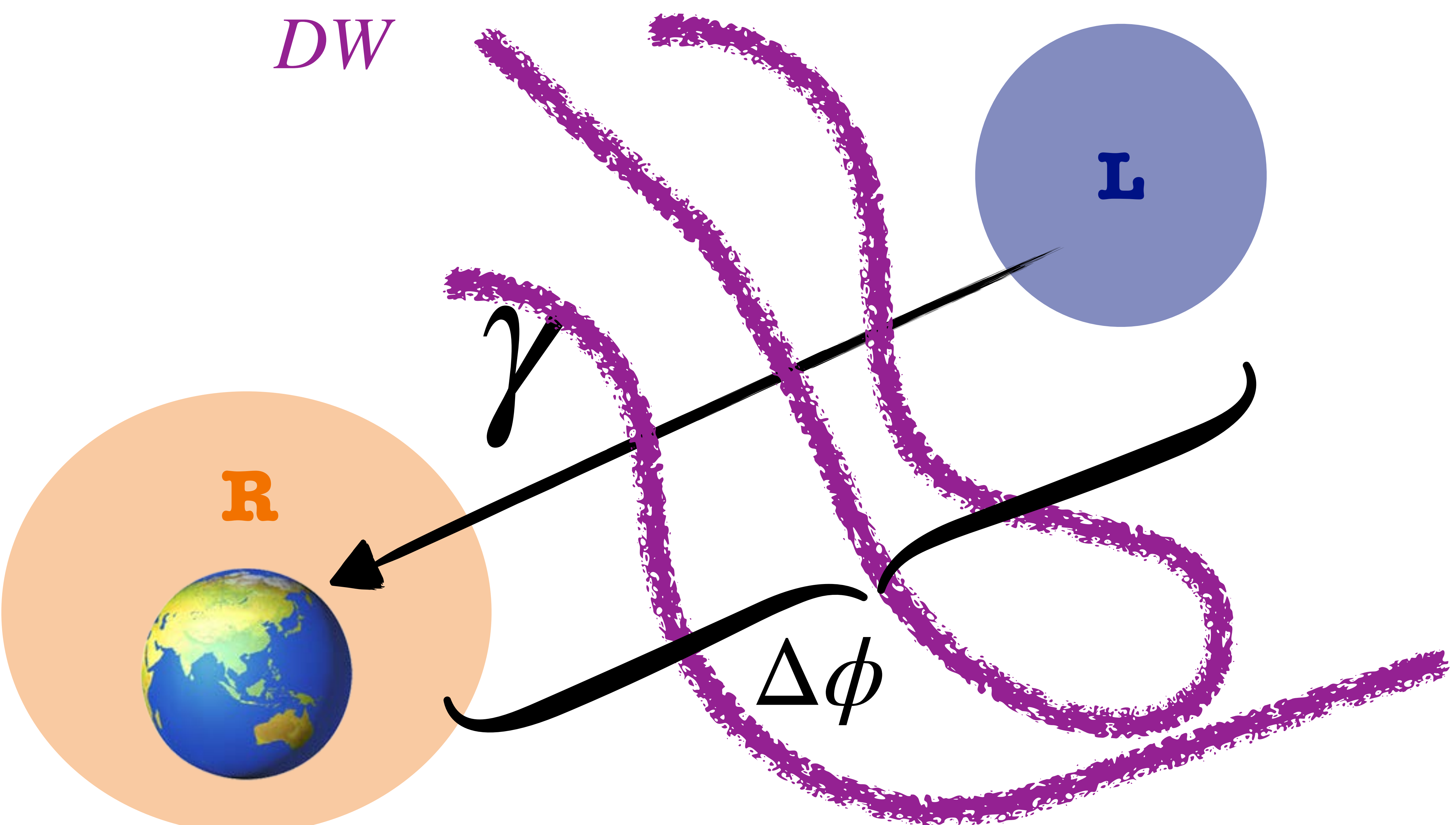
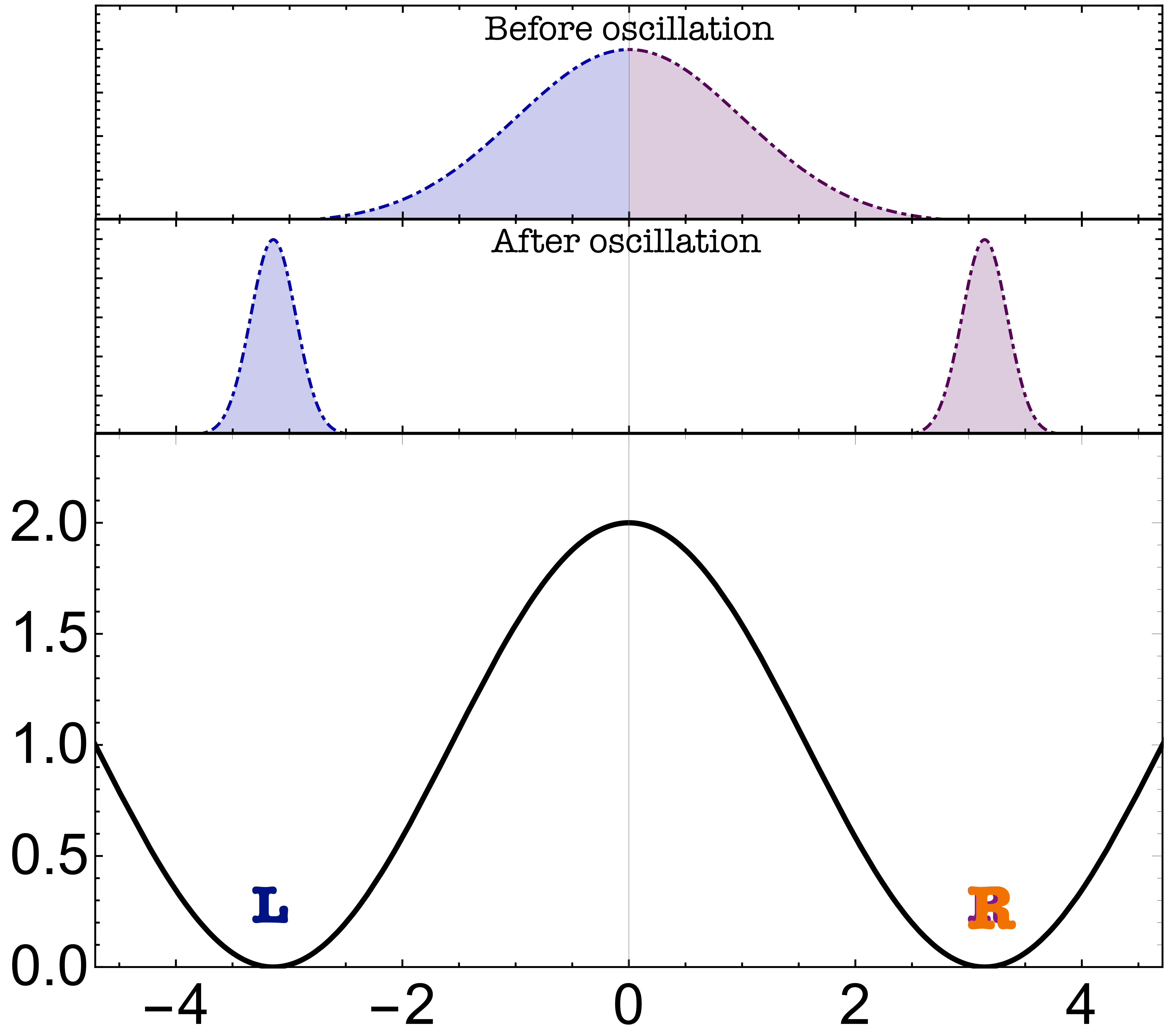
3. *Kilobyte* cosmic birefringence (KBCB)

Path-independent field excursion.

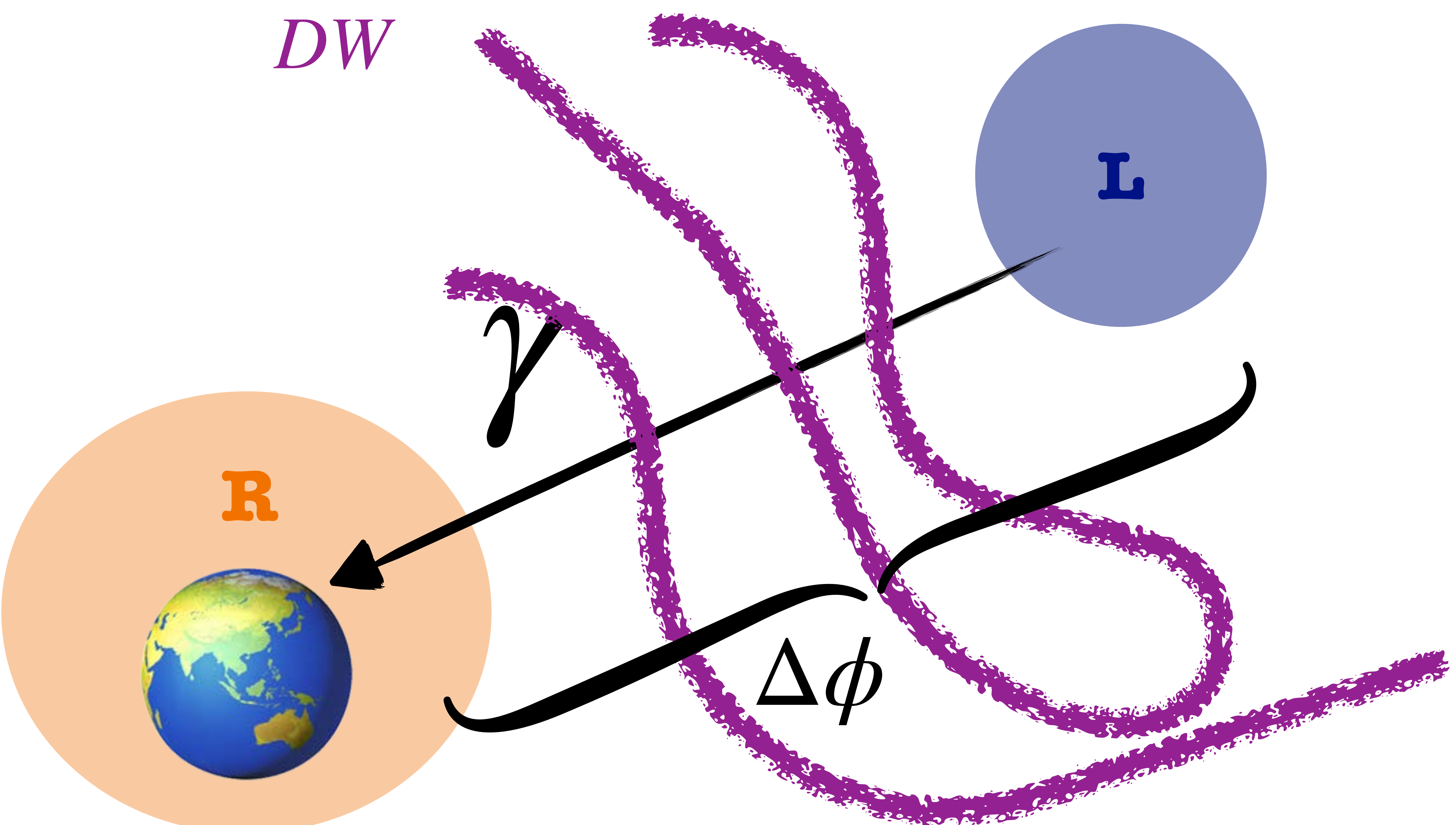
$$\Delta\phi = ?$$

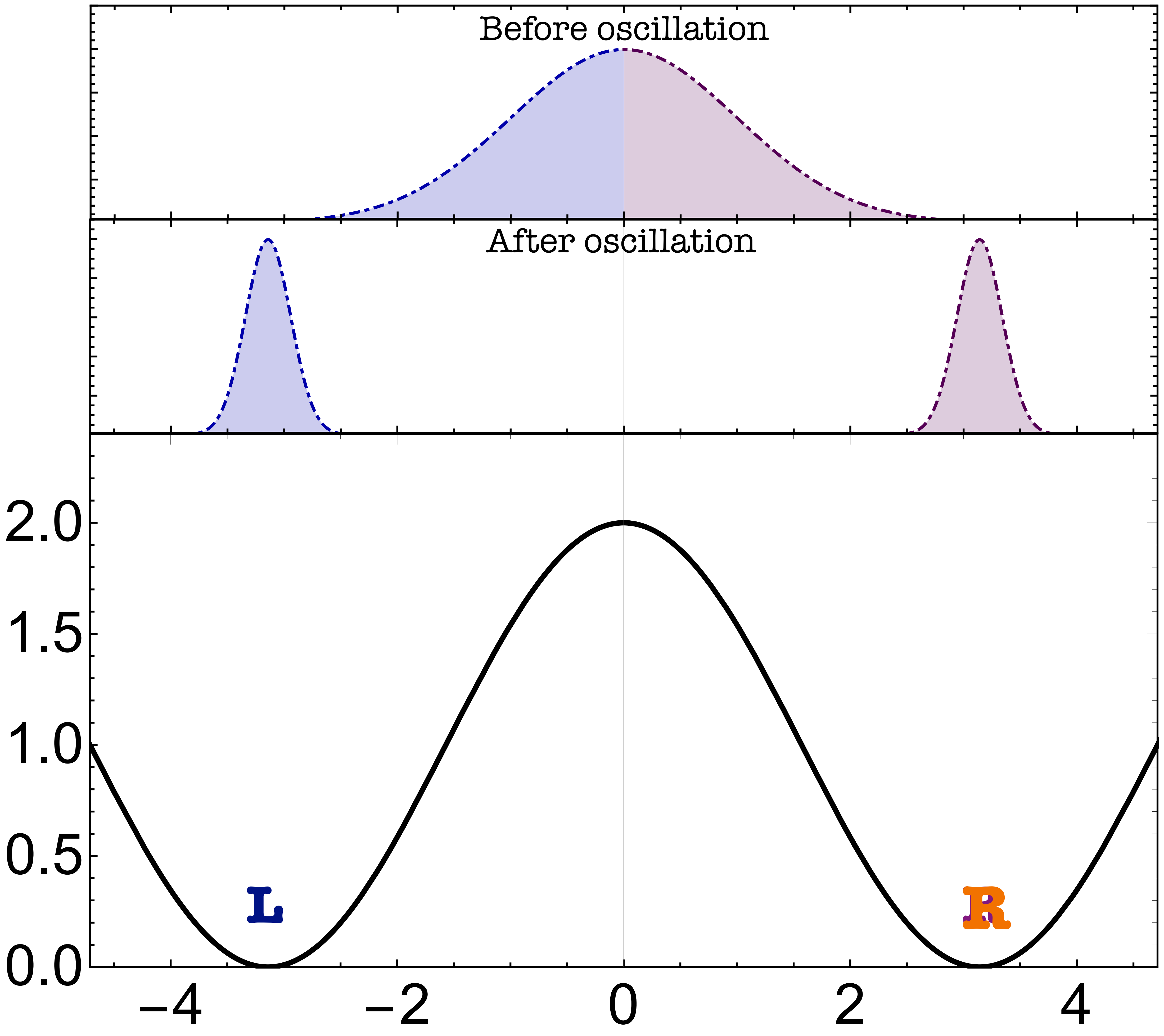




Path-independent field excursion.

$$\Delta\phi = 2\pi f_\phi$$





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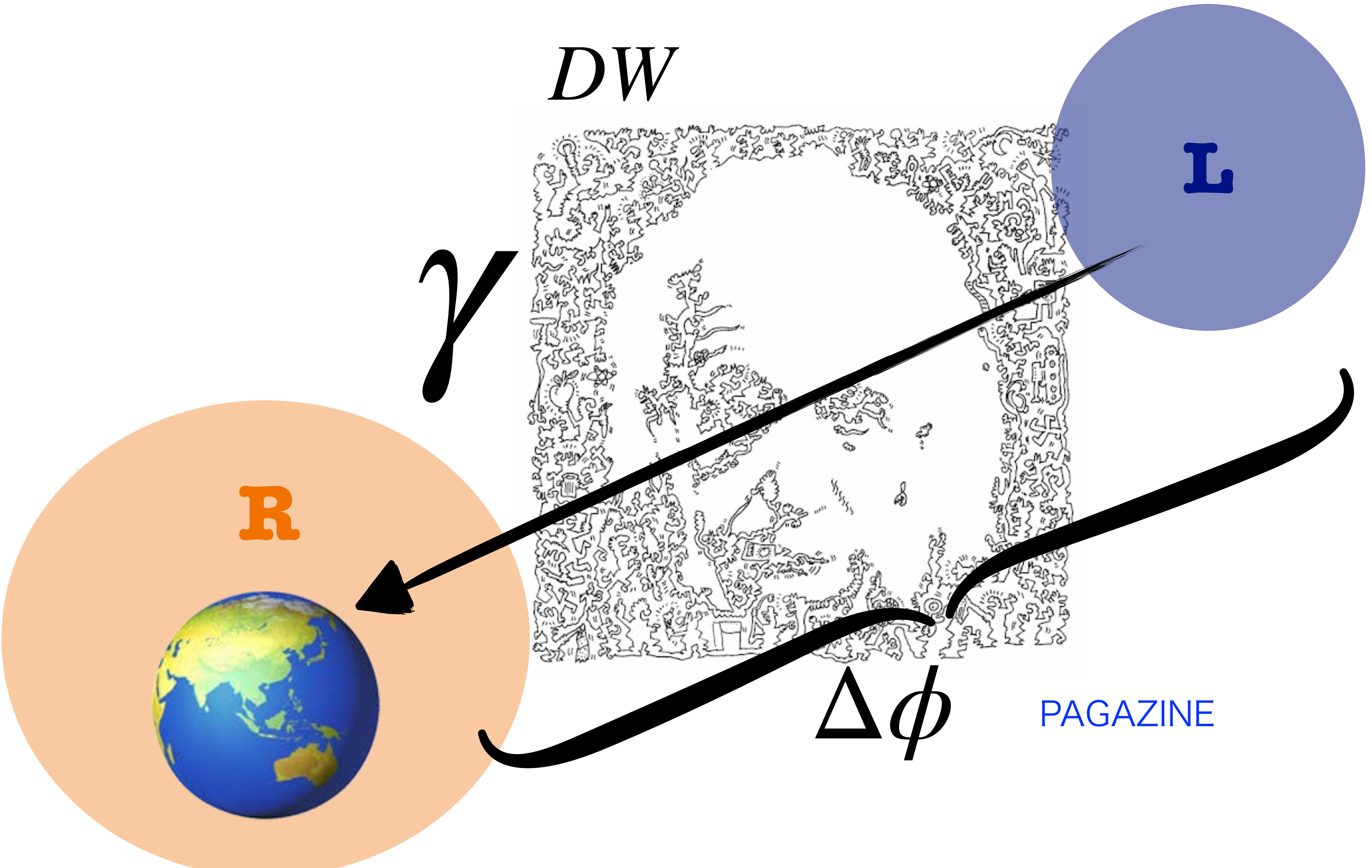

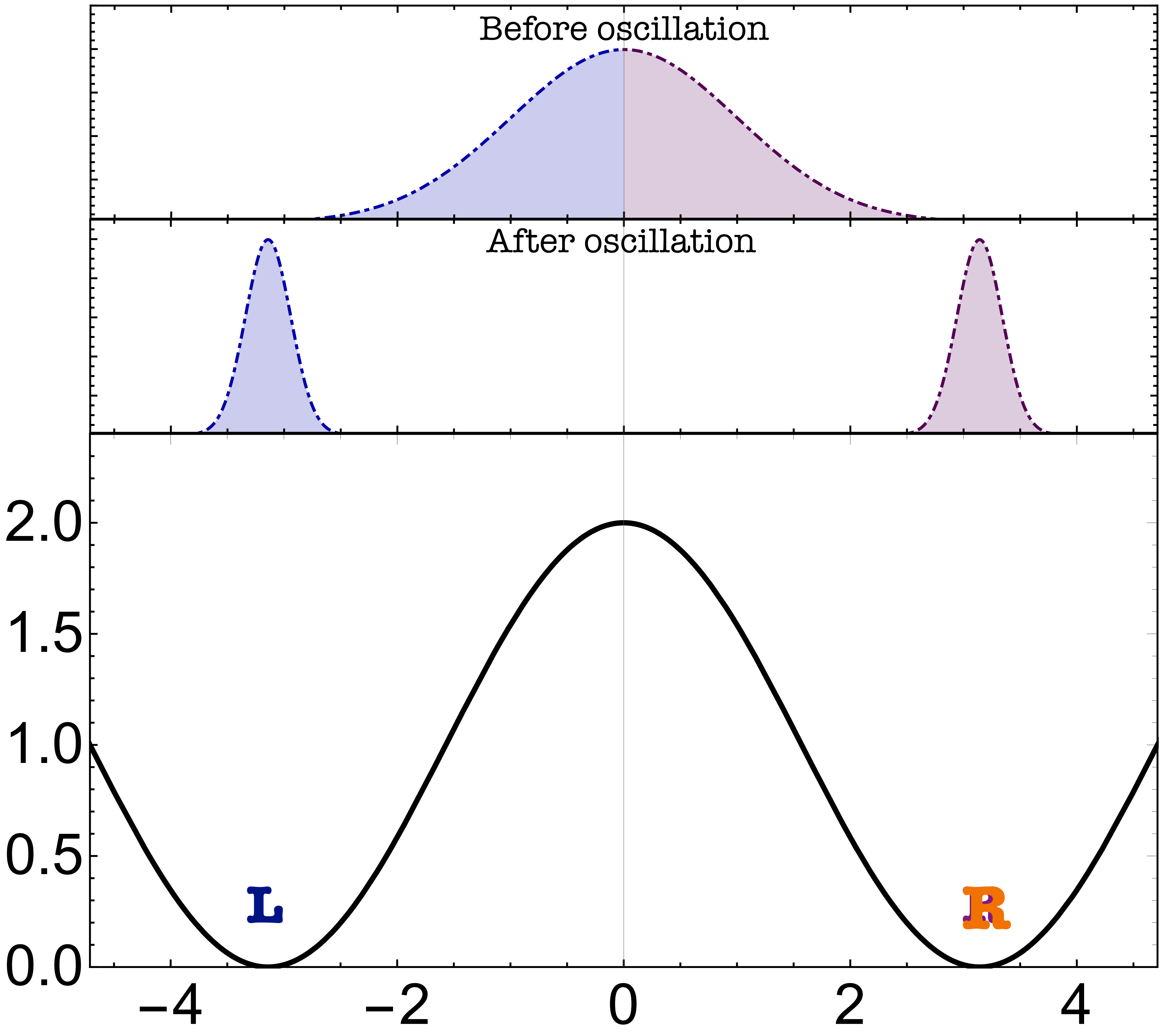

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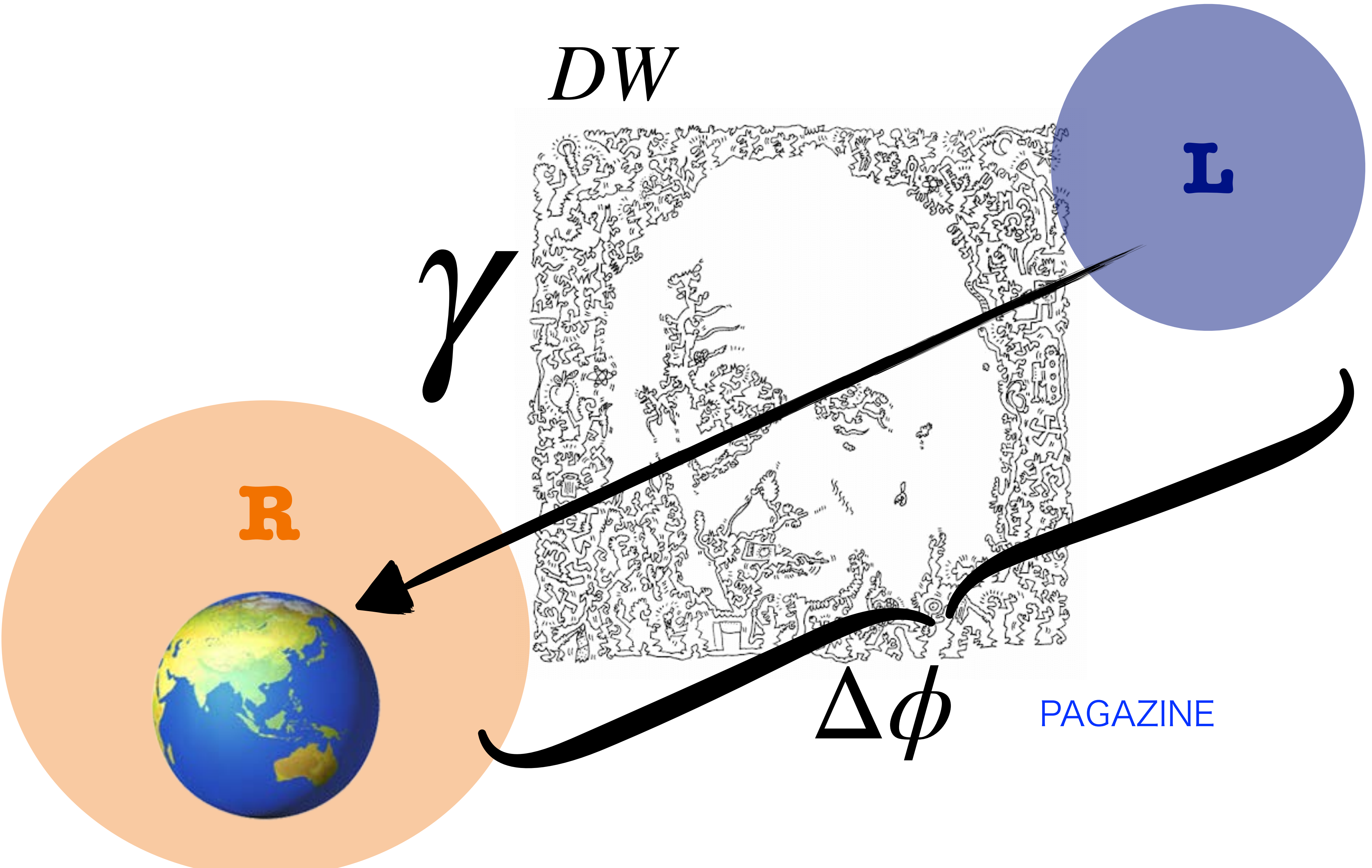

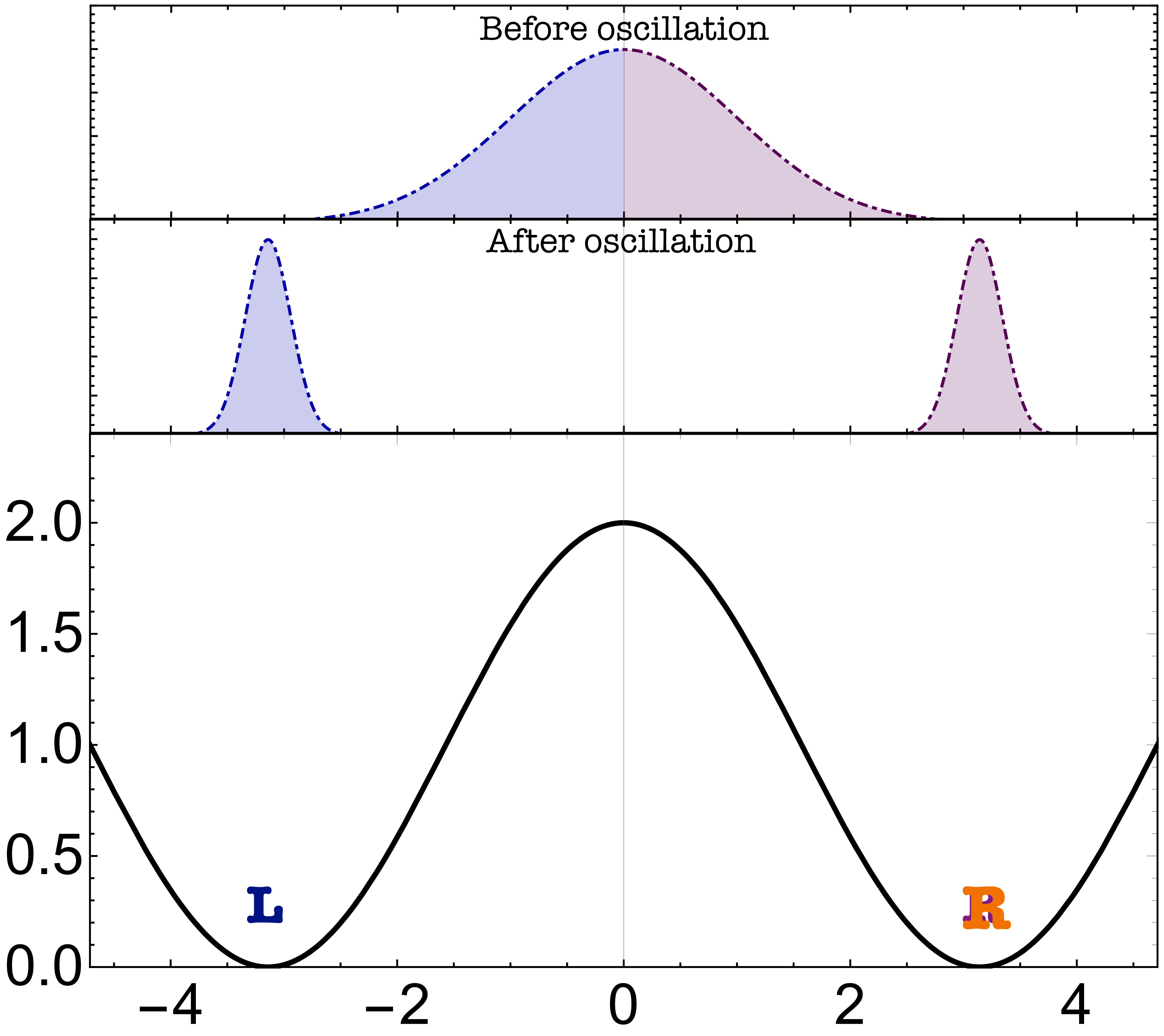

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Field excursion only depends on the the vacua at the boundaries of the path.

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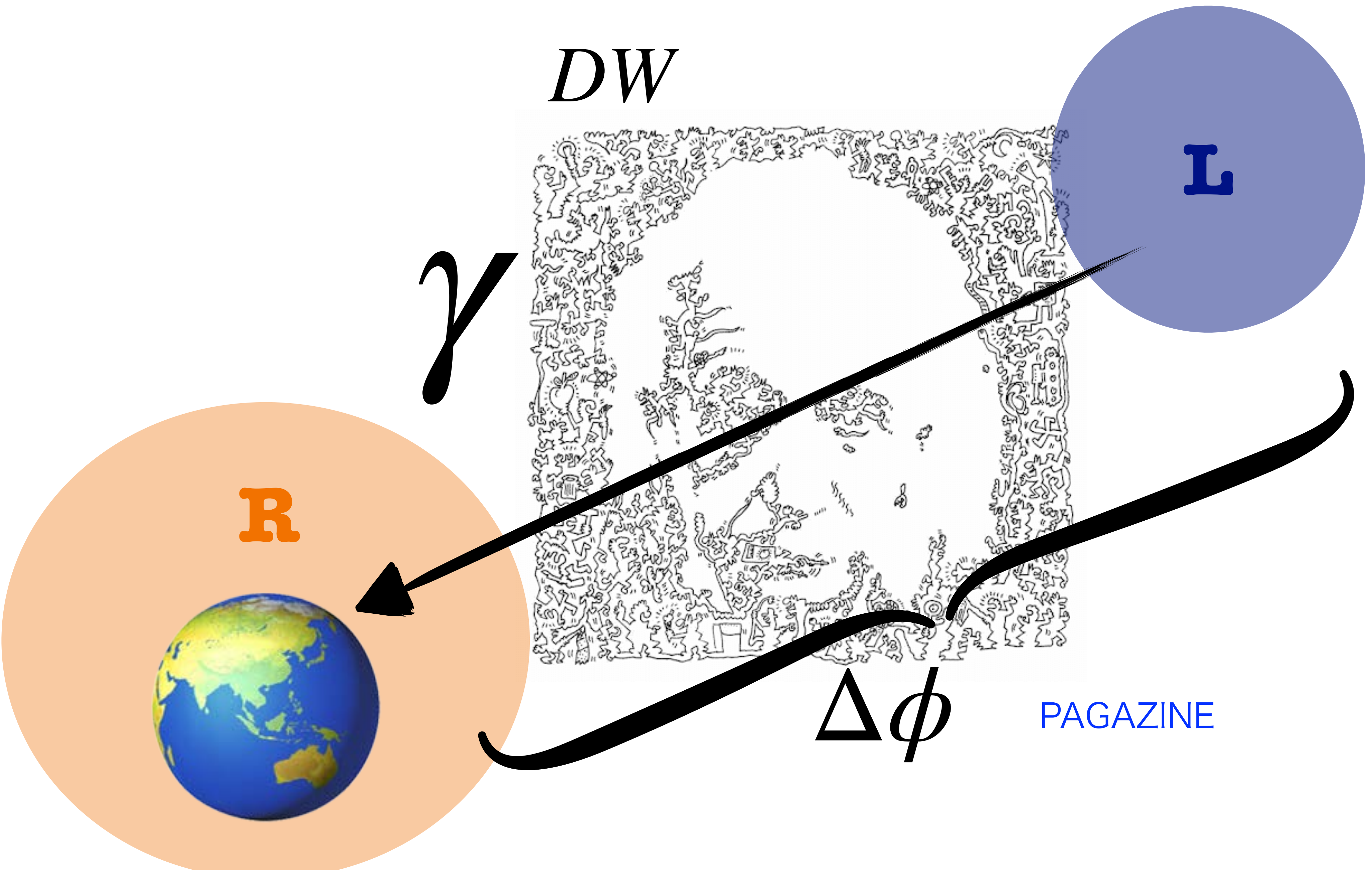
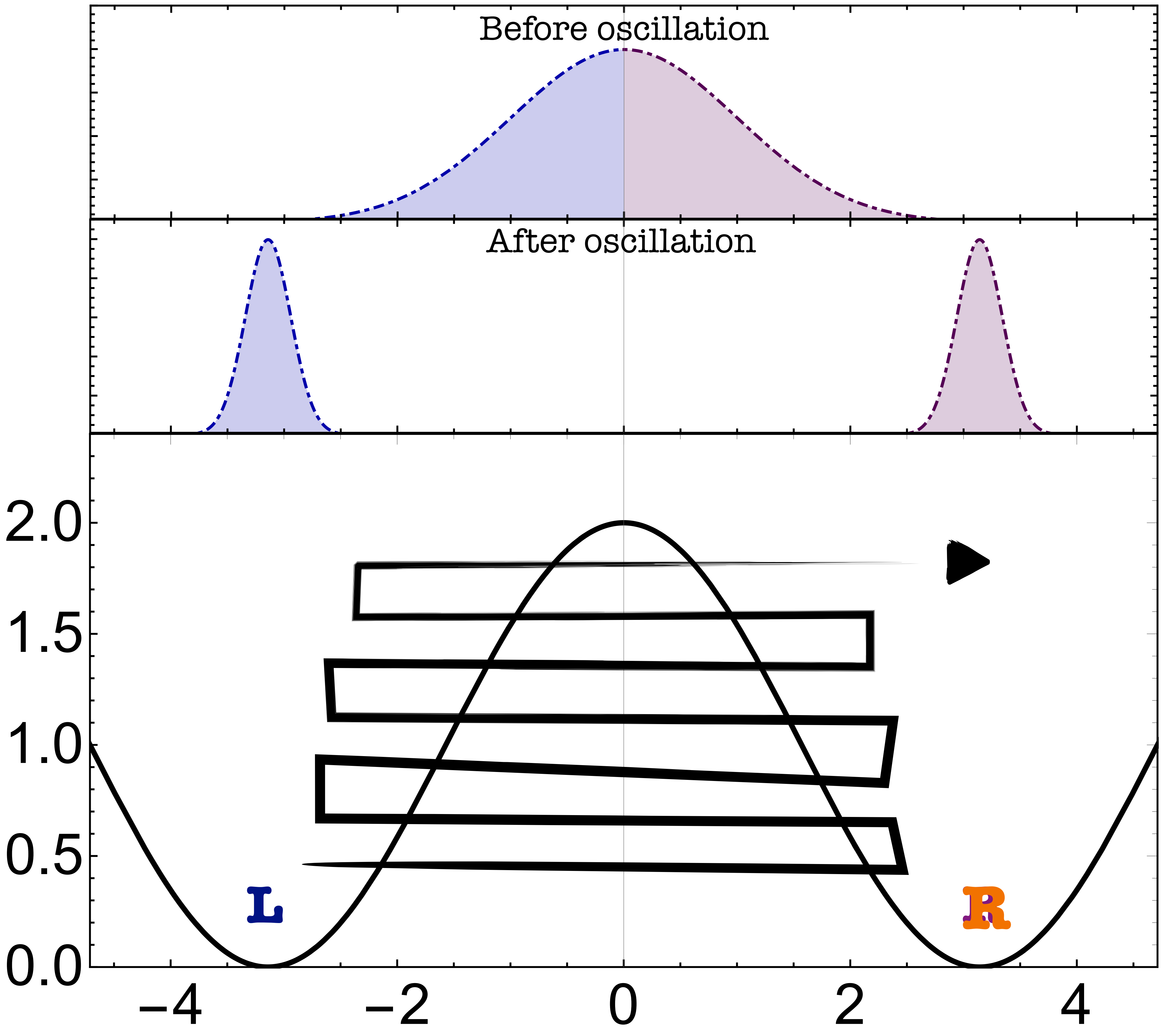


DWs have direction!

[A property special for DW **without string**]



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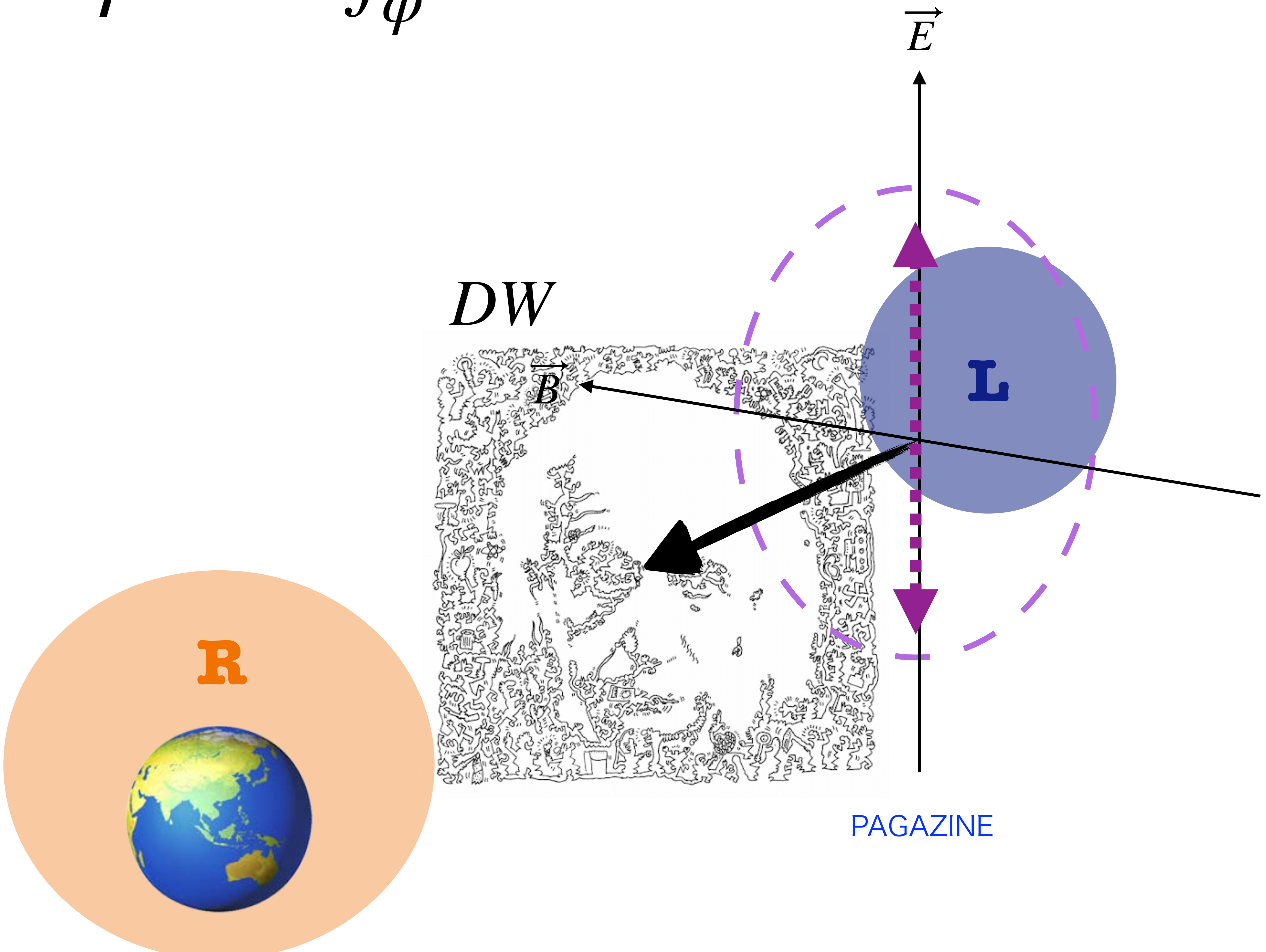
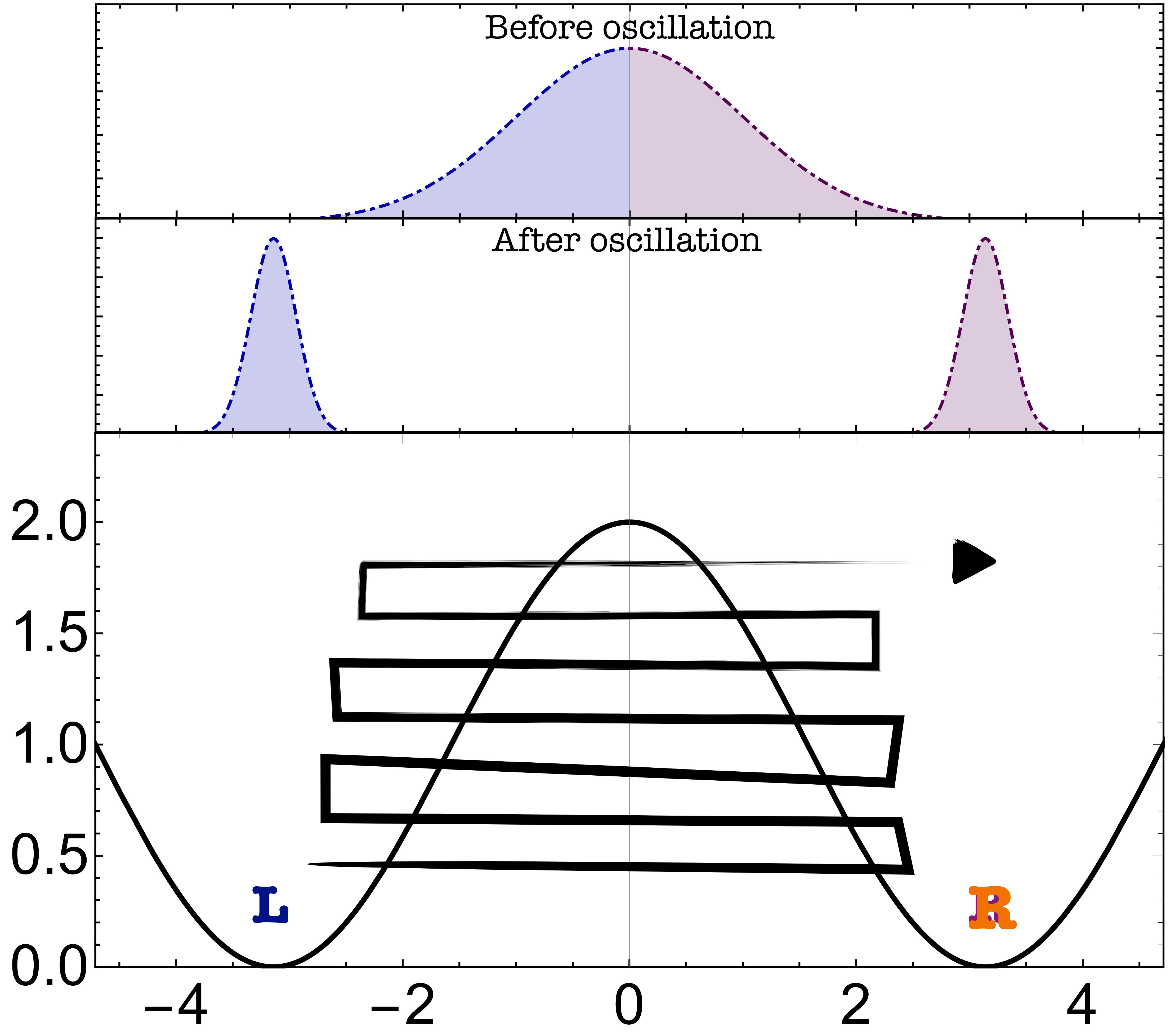


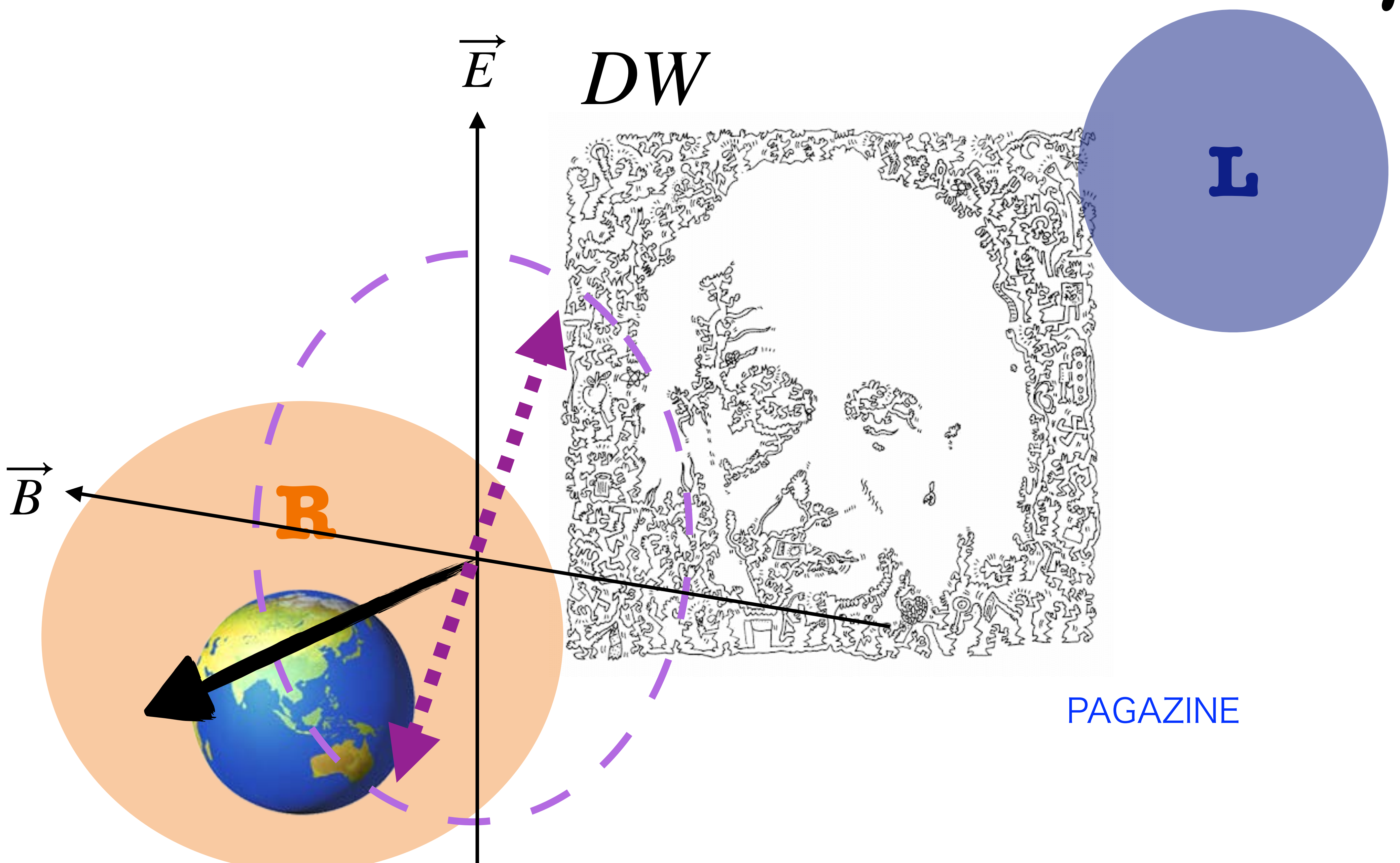


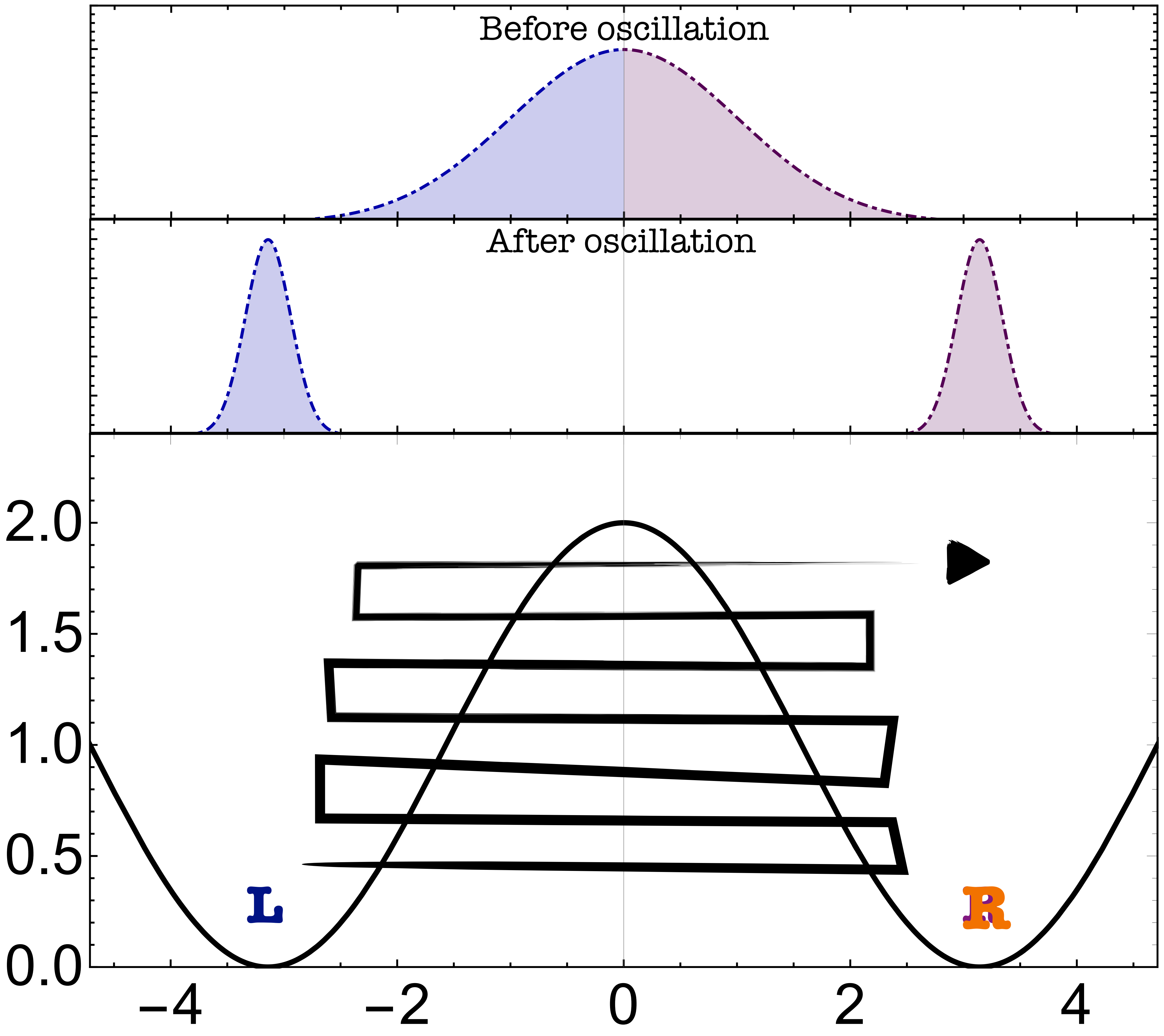
Path-independent birefringence

The net change of polarization angle only depends on the vacua from which photon are emit and detect.

$$\Delta\phi = 2\pi f_\phi \qquad \Phi = 0.42\ \mathrm{deg} \times c_\gamma \left(\frac{\Delta\phi}{2\pi f_\phi}\right),$$

$$\Delta\Phi[\Omega] = 0.42\mathrm{deg}\, c_\gamma$$



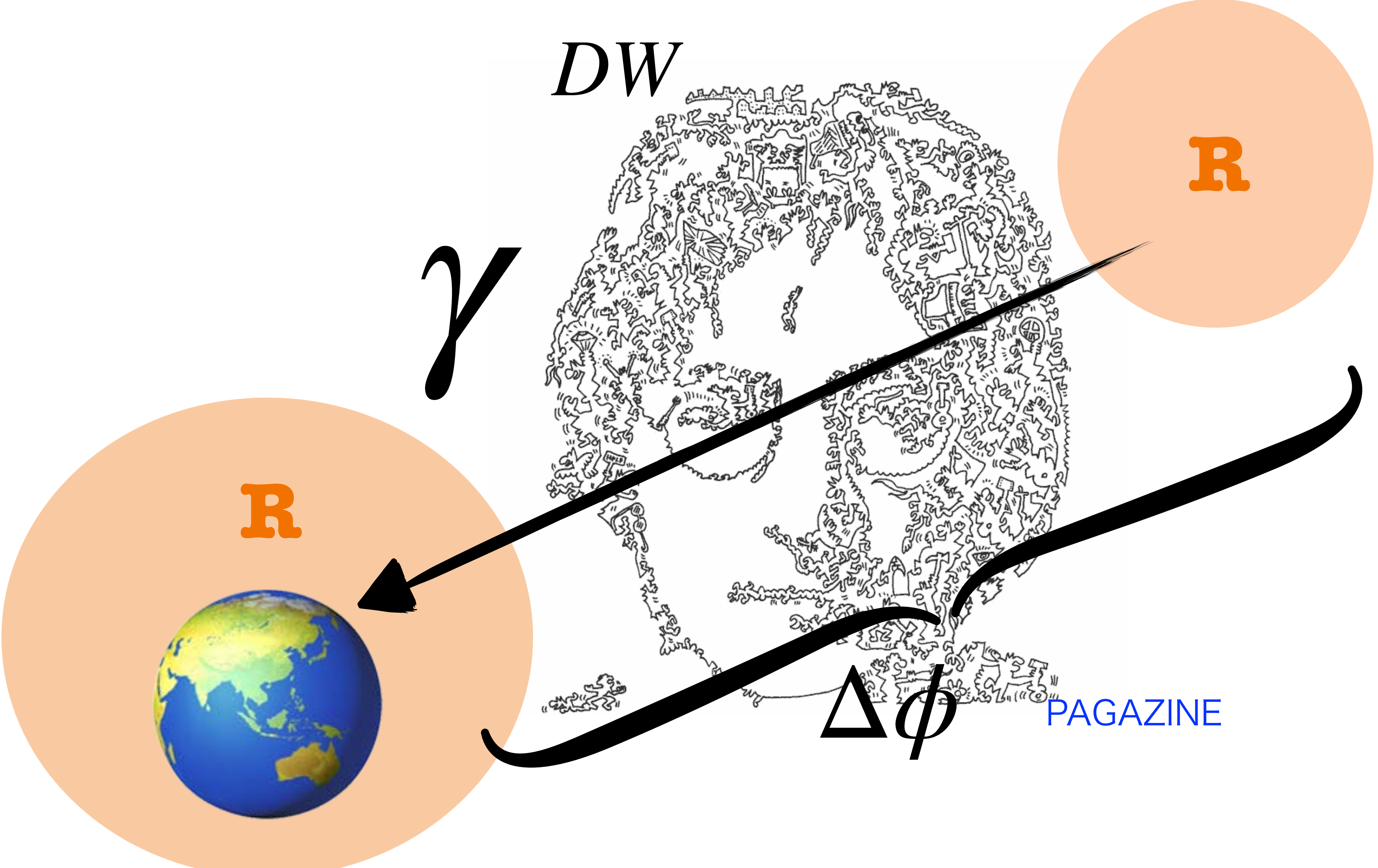


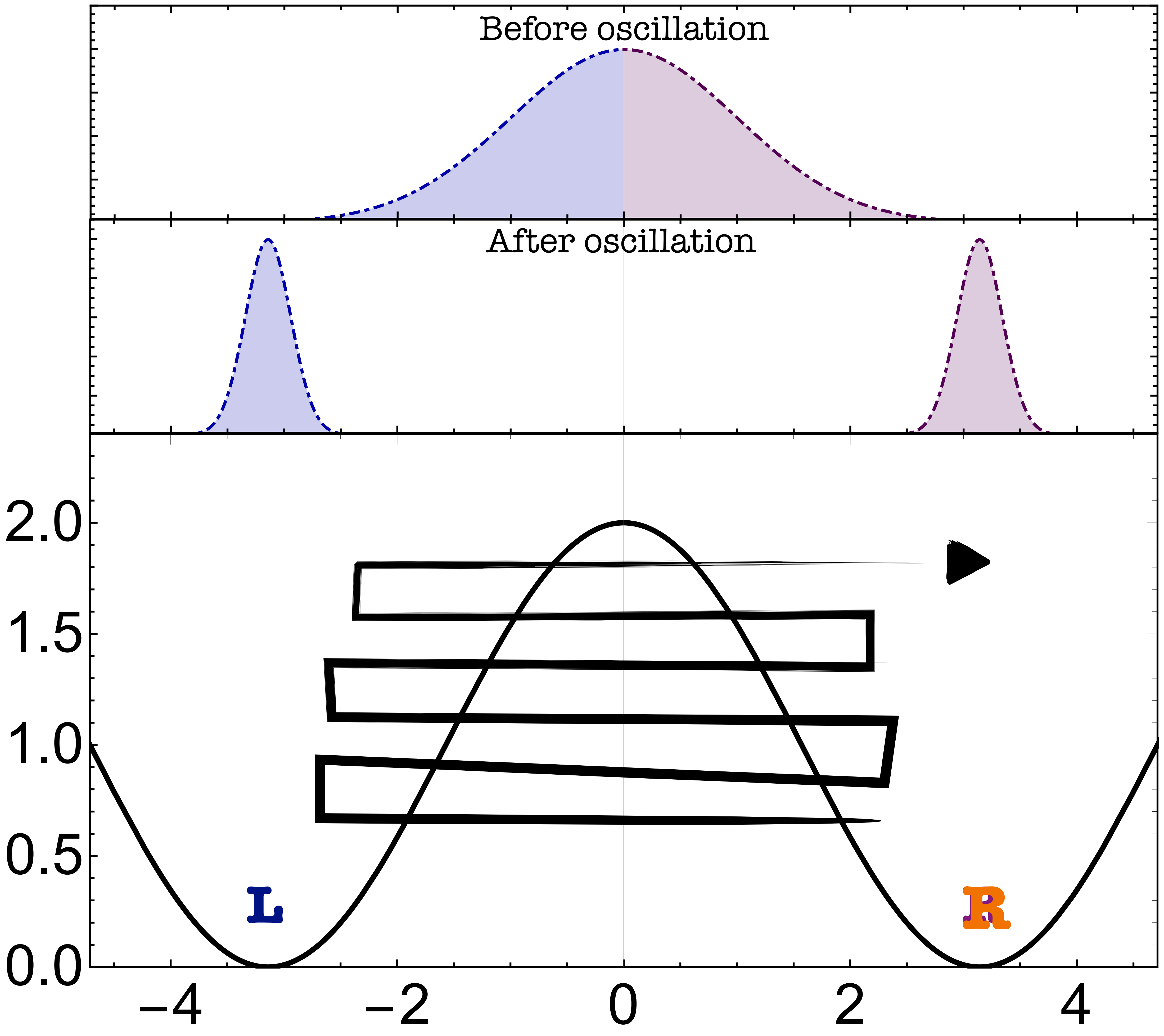
Path-independent birefringence

The net change of polarization angle only depends on the vacua from which photon are emit and detect.

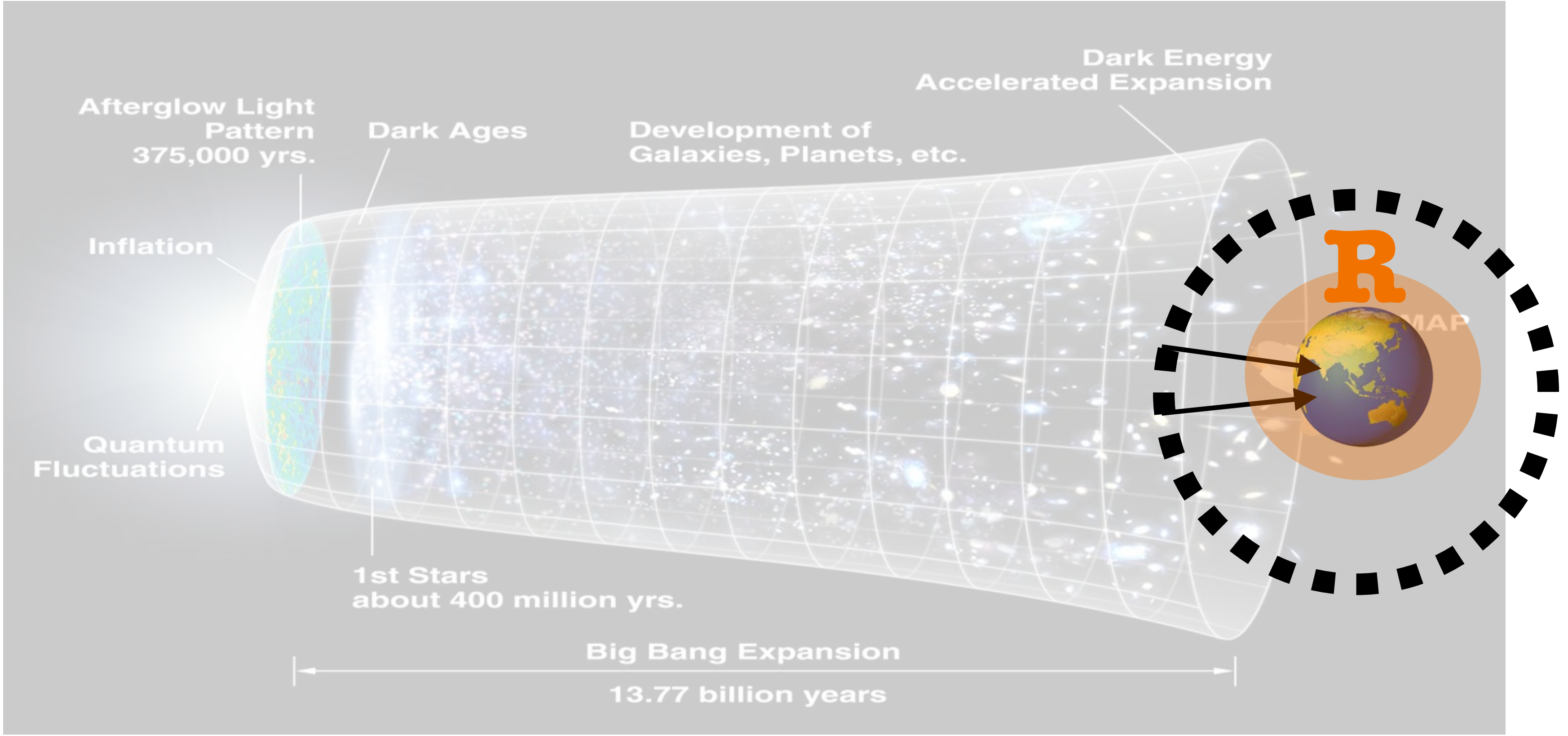
$$\Delta\phi = 0 \qquad \Phi = 0.42\ \mathrm{deg} \times c_\gamma \left(\frac{\Delta\phi}{2\pi f_\phi}\right),$$

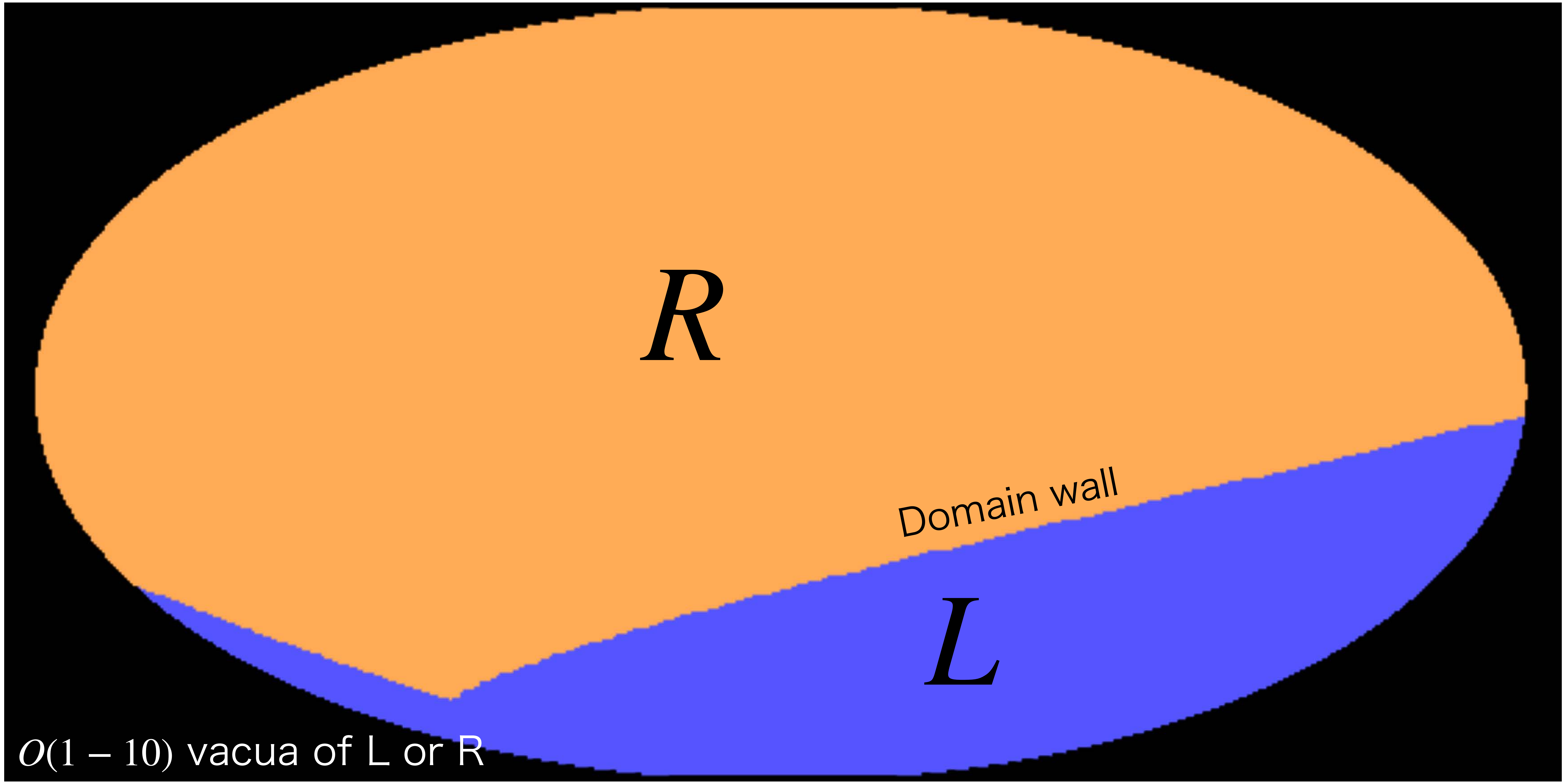
$$\Delta\Phi[\Omega] = 0$$





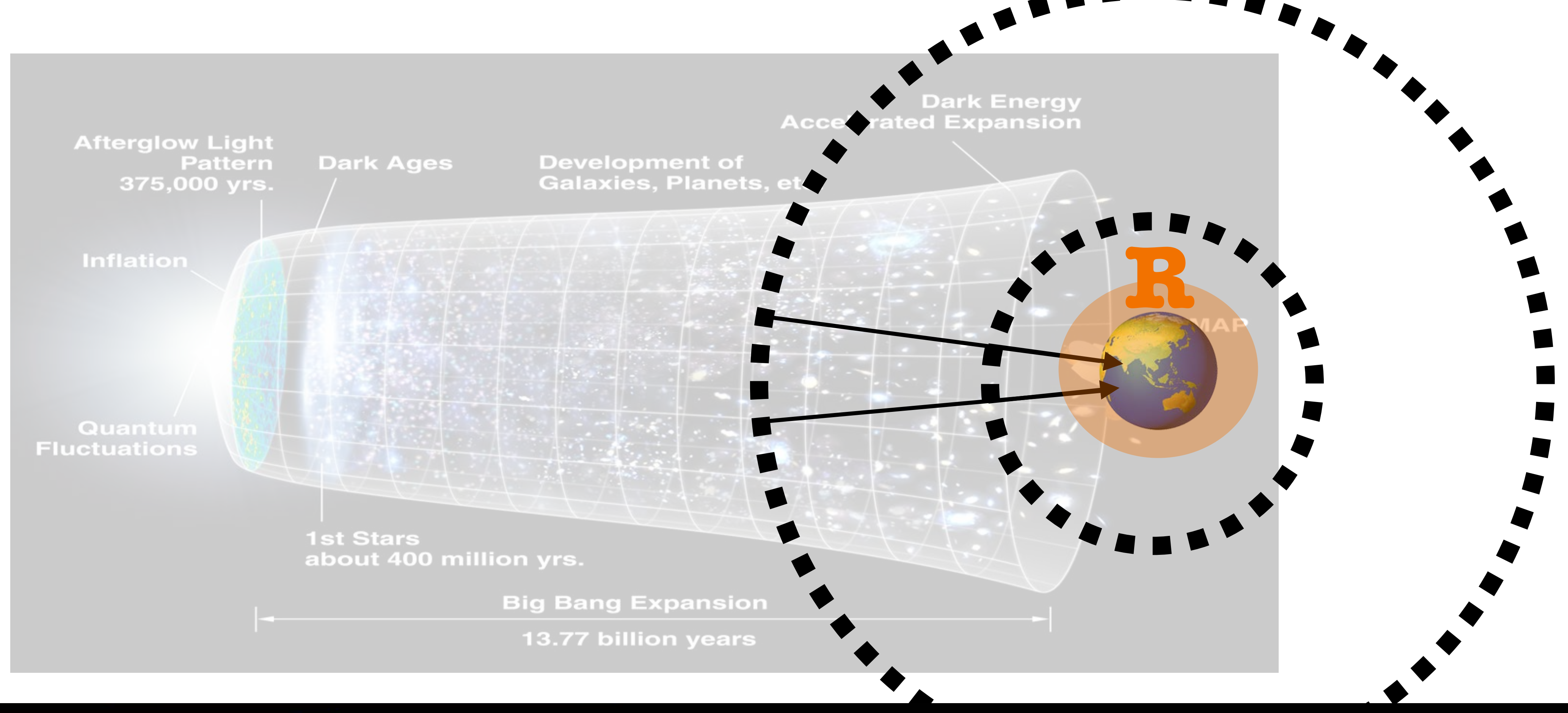
Vacua with scaling solution





Based on a simplified estimation assuming O(1) vacua per a Hubble patch at random.

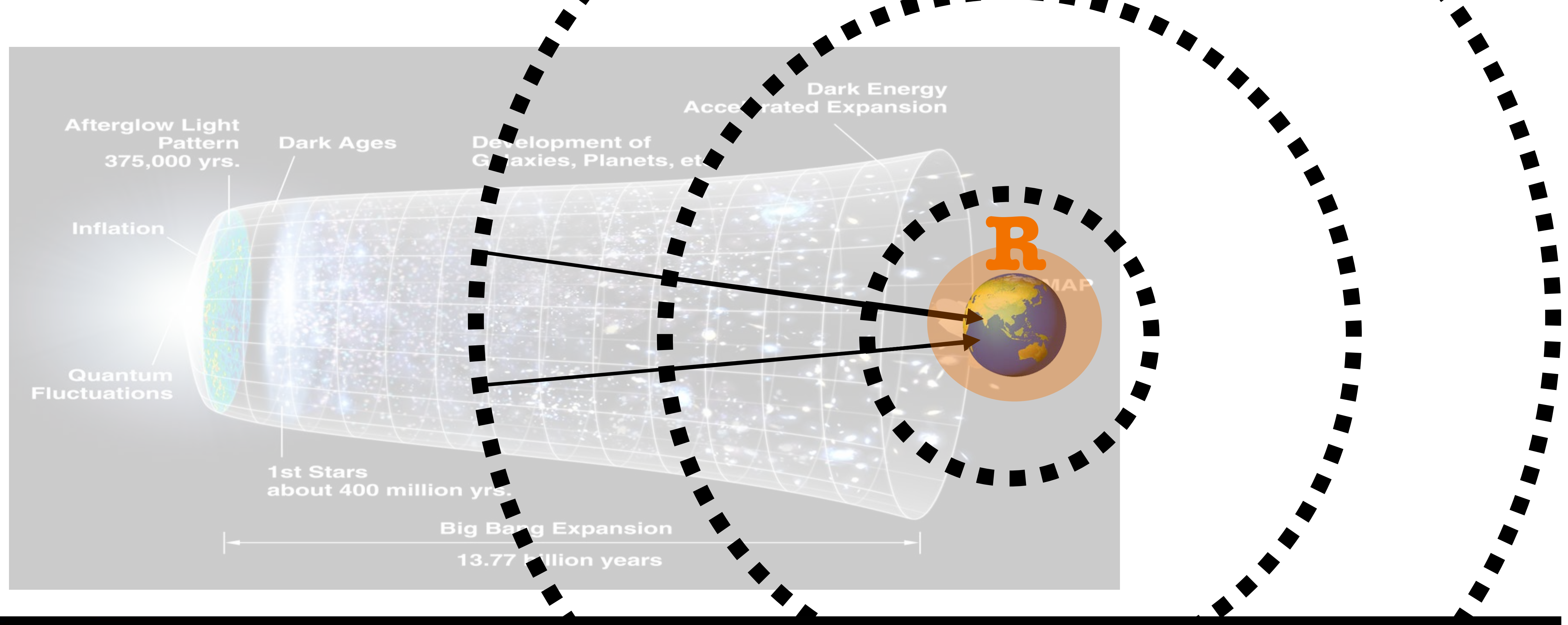
Vacua with scaling solution

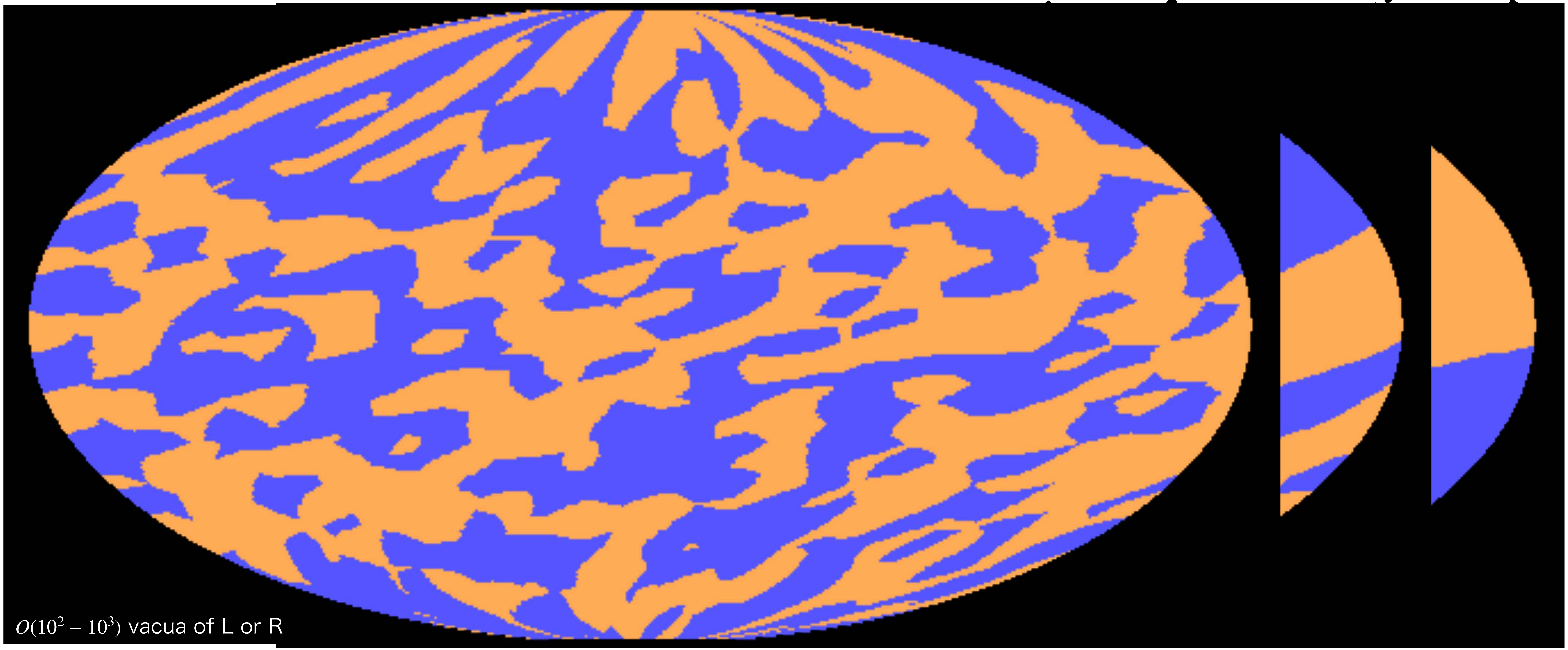



$O(10-10^2)$ vacua of L or R

Based on a simplified estimation assuming O(1) vacua per a Hubble patch at random.

Vacua with scaling solution





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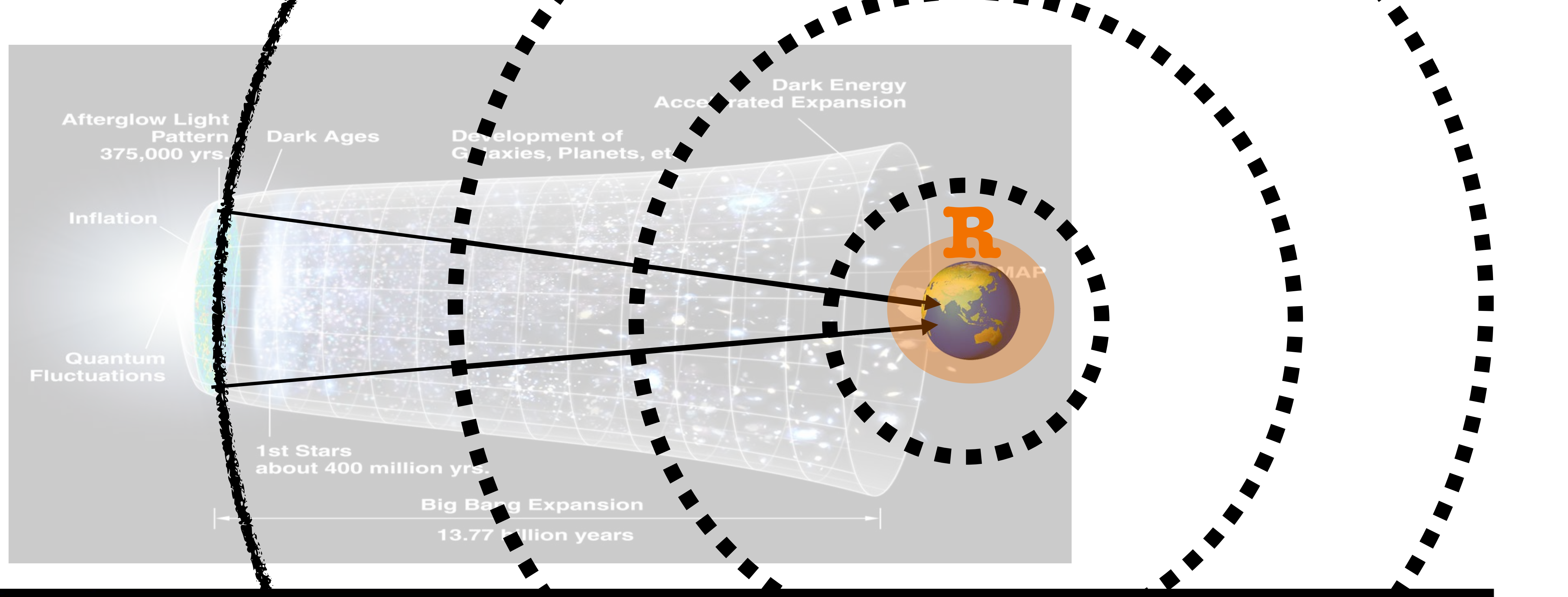
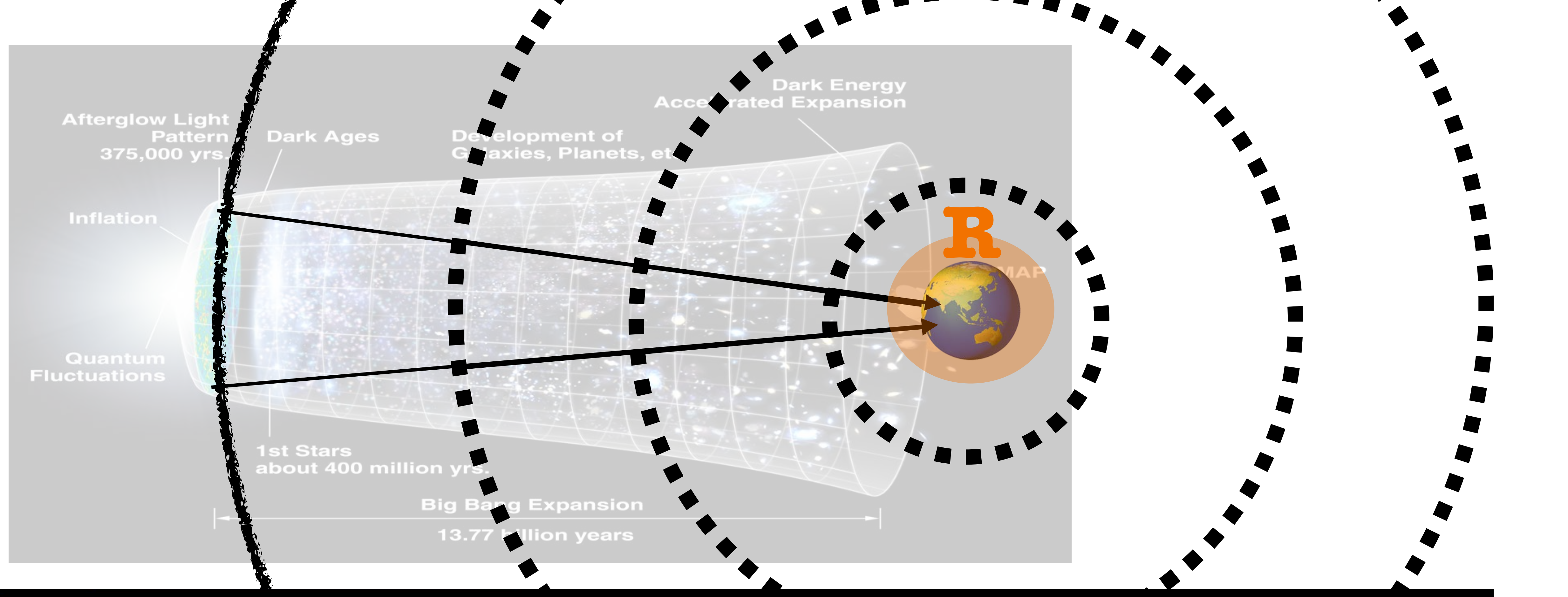
Vacua with scaling solution



Based on a simplified estimation assuming O(1) vacua per a Hubble patch at random.

Vacua with scaling solution

CMB photons are from vacua with kilobyte patterns of L or R:
kilobyte cosmic birefringence (KBCB).



Based on a simplified estimation assuming O(1) vacua per a Hubble patch at random.

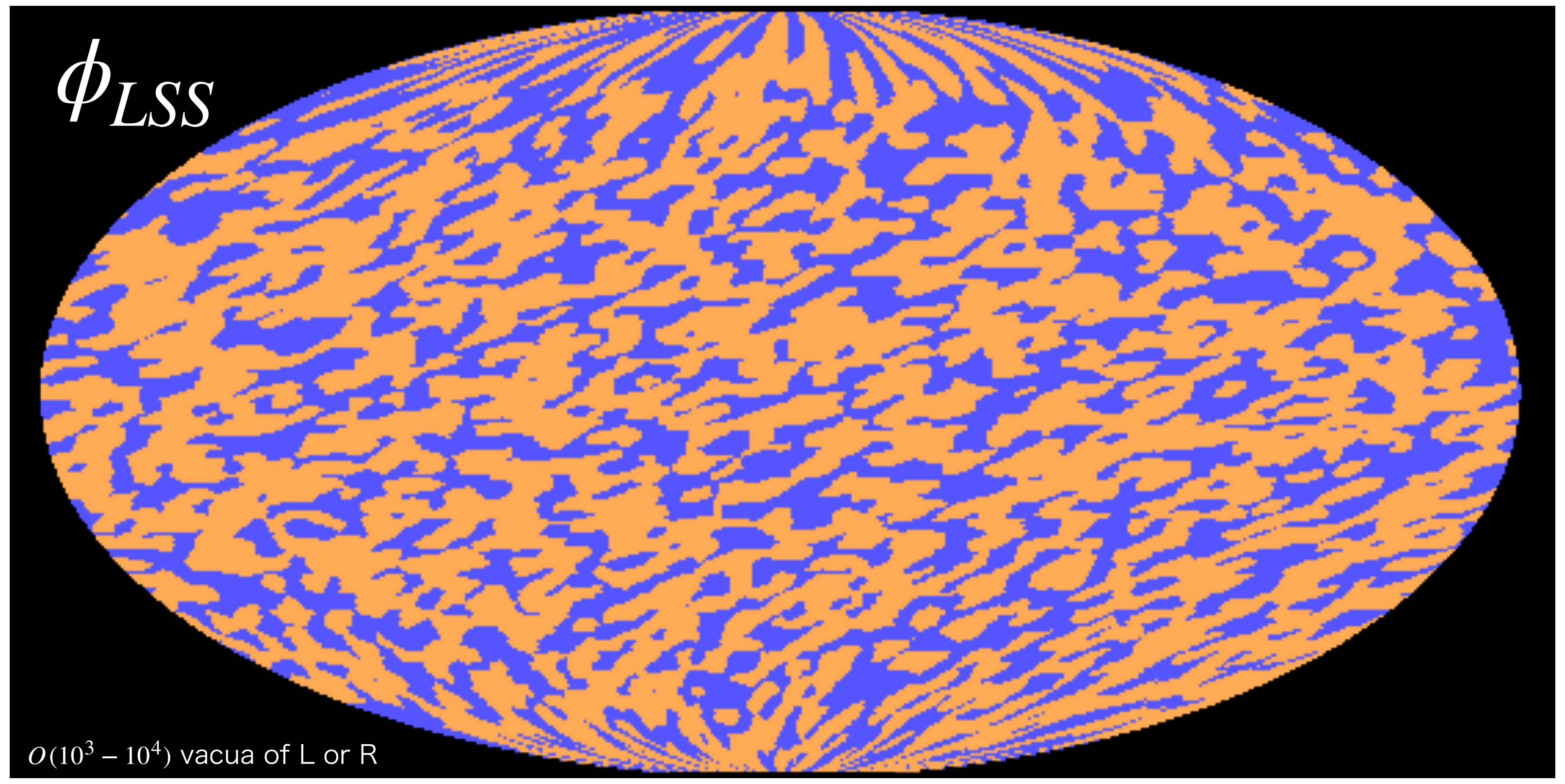
Spectrum of KBCB

Isotropic KBCB

$$\Phi(\Omega) = \int_{\mathrm{LSS}[\Omega]}^{\mathrm{Earth}} c_\gamma \frac{d\phi}{2f_\phi} = \frac{c_\gamma \alpha}{2\pi f_\phi}(\phi_{\mathrm{Earth}} - \phi_{\mathrm{LSS}}[\Omega])$$

$\phi_{\mathrm{LSS}} = -\pi f_\phi$ or $\pi f_\phi, \phi_{\mathrm{Earth}} = \pi f_\phi$

$$\boxed{\begin{aligned}\beta &= \frac{1}{4\pi}\int d\Omega \Phi[\Omega] = \alpha c_\gamma/2 \\ &= 0.21 c_\gamma \mathrm{deg}\end{aligned}}$$



$\beta_{\mathrm{obs}} = 0.35 \pm 0.14$ deg,

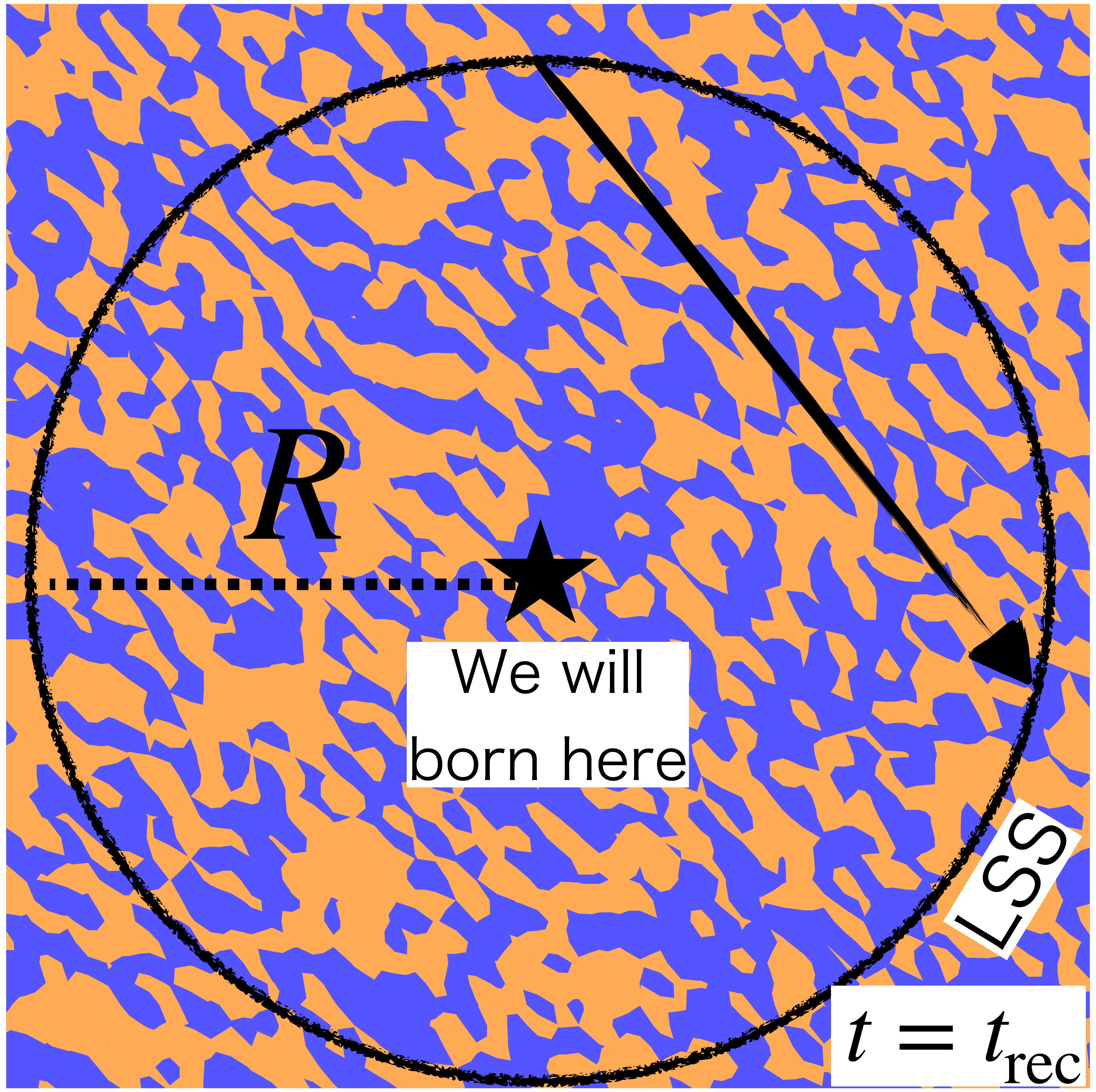
The attractor (scaling solution) prediction is consistent with measured one!

A modeling for anisotropic KBCB

Angular power spectrum: $\overline{C}_\ell^\Phi = 2\pi \int d\cos\theta \langle \Delta\Phi(0,0)\Delta\Phi(\theta,0)\rangle P_\ell(\cos\theta)$

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

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



$$L \xrightarrow{\Delta x = N\delta x} L$$

$$P_{\text{DW}} = \kappa_{\text{DW}} H_{\text{rec}}, \quad \kappa_{\text{DW}} = O(1)$$

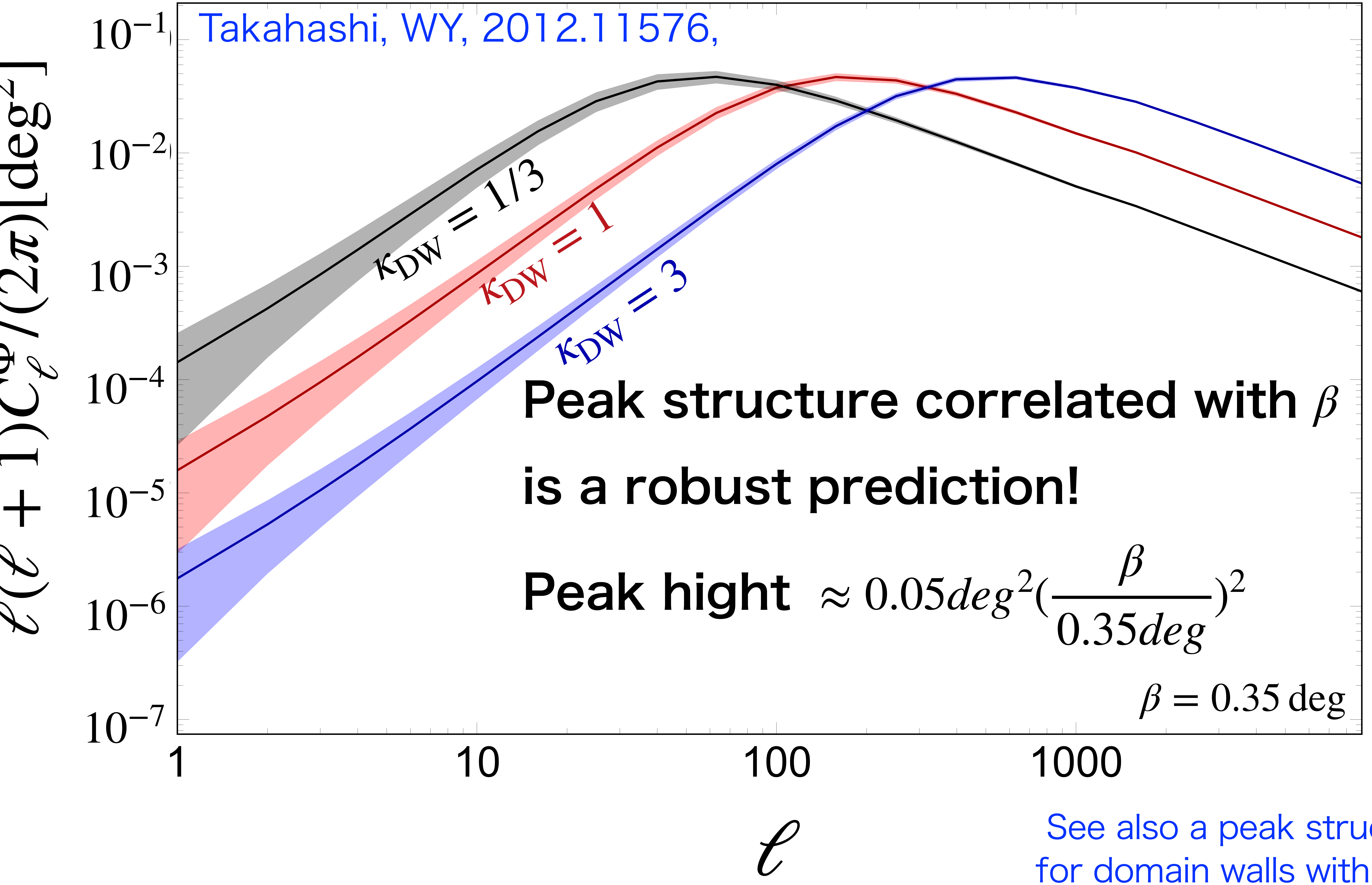
(i.e. O(1) DW within one Hubble)

$$P_{\text{match}}[\Delta x] = \sum_{N/2 \geq m=0} \frac{N!}{2m!(N-2m)!}(P_{\text{DW}}\delta x)^{2m}(1 - P_{\text{DW}}\delta x)^{N-2m} \to \frac{1}{2}(1 + e^{-2P_{\text{DW}}\Delta x}),$$

Our DW modeling:

$$\boxed{\langle \Delta\Phi(0,0)\Delta\Phi(\theta,0)\rangle \simeq \beta^2 e^{-2P_{\text{DW}}R\sqrt{2(1-\cos\theta)}} \sim \beta^2 e^{-176\kappa_{\text{DW}}\sqrt{1-\cos\theta}}}$$

Anisotropic KBCB



Peak structure correlated with β

is a robust prediction!

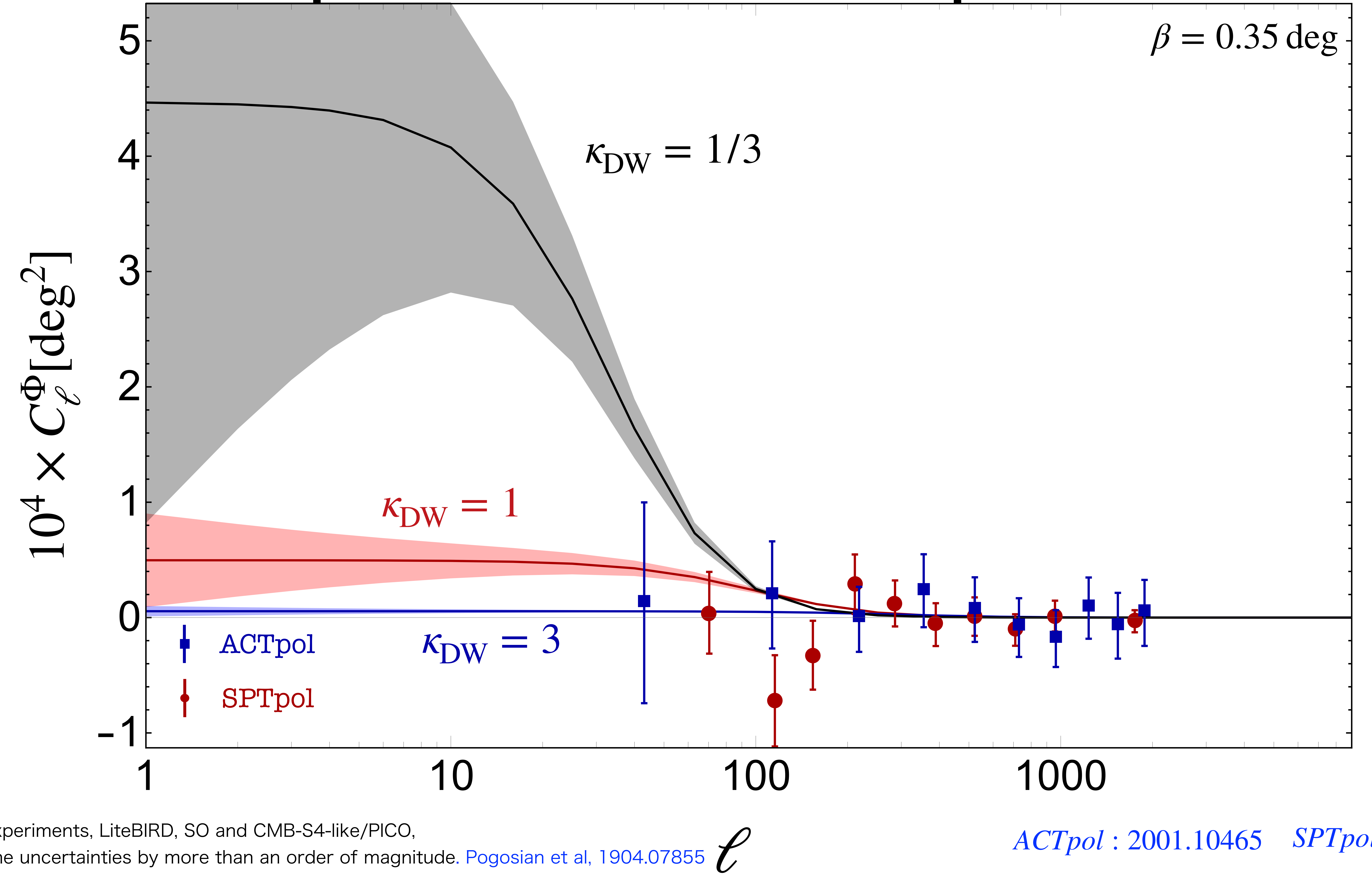
Peak hight $\approx 0.05 deg^2 (\dfrac{\beta}{0.35 deg})^2$

Cosmic variance:

$$\Delta C_\ell^\Phi \approx \sqrt{\frac{2}{2\ell+1}}\overline{C}_\ell^\Phi$$

See also a peak structure
for domain walls with strings, Jain et al, 2103.10962

Anisotropic KBCB and experimental data



Future CMB experiments, LiteBIRD, SO and CMB-S4-like/PICO,
may reduce the uncertainties by more than an order of magnitude. Pogosian et al, 1904.07855

ACTpol : 2001.10465 *SPTpol* : 2006.08061

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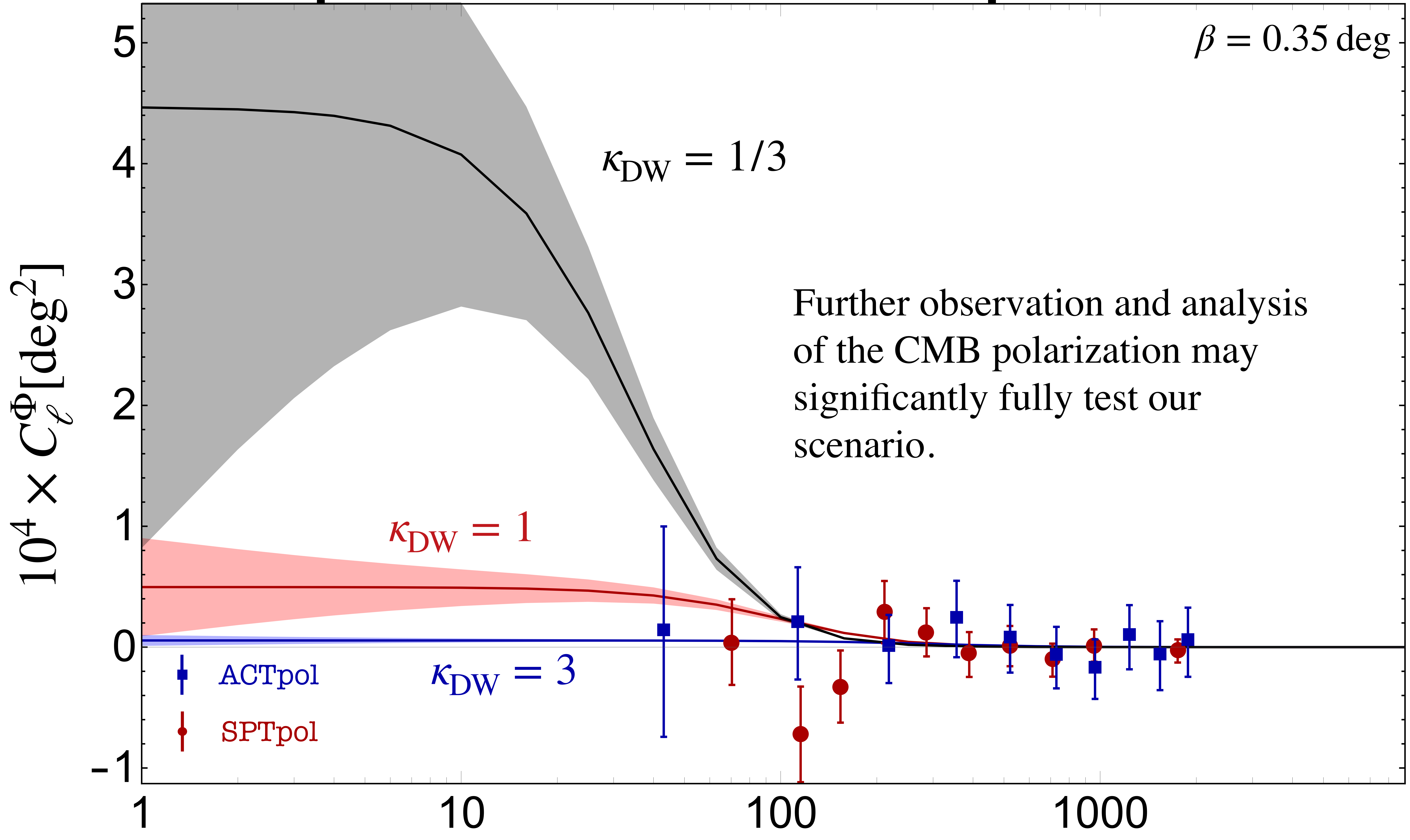

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Conclusions

■ Isotropic cosmic birefringence (CB) implies slow-roll ultra-light ALP or ALP domain wall without a string.

■ALP domain wall without a string can be naturally formed due to inflation fluctuation. (It can also be formed by the mixing with QCD axion. Takahashi WY 2012.11576)

■The attractor scaling solution of the domain wall predicts a kilobyte (KB) CB.

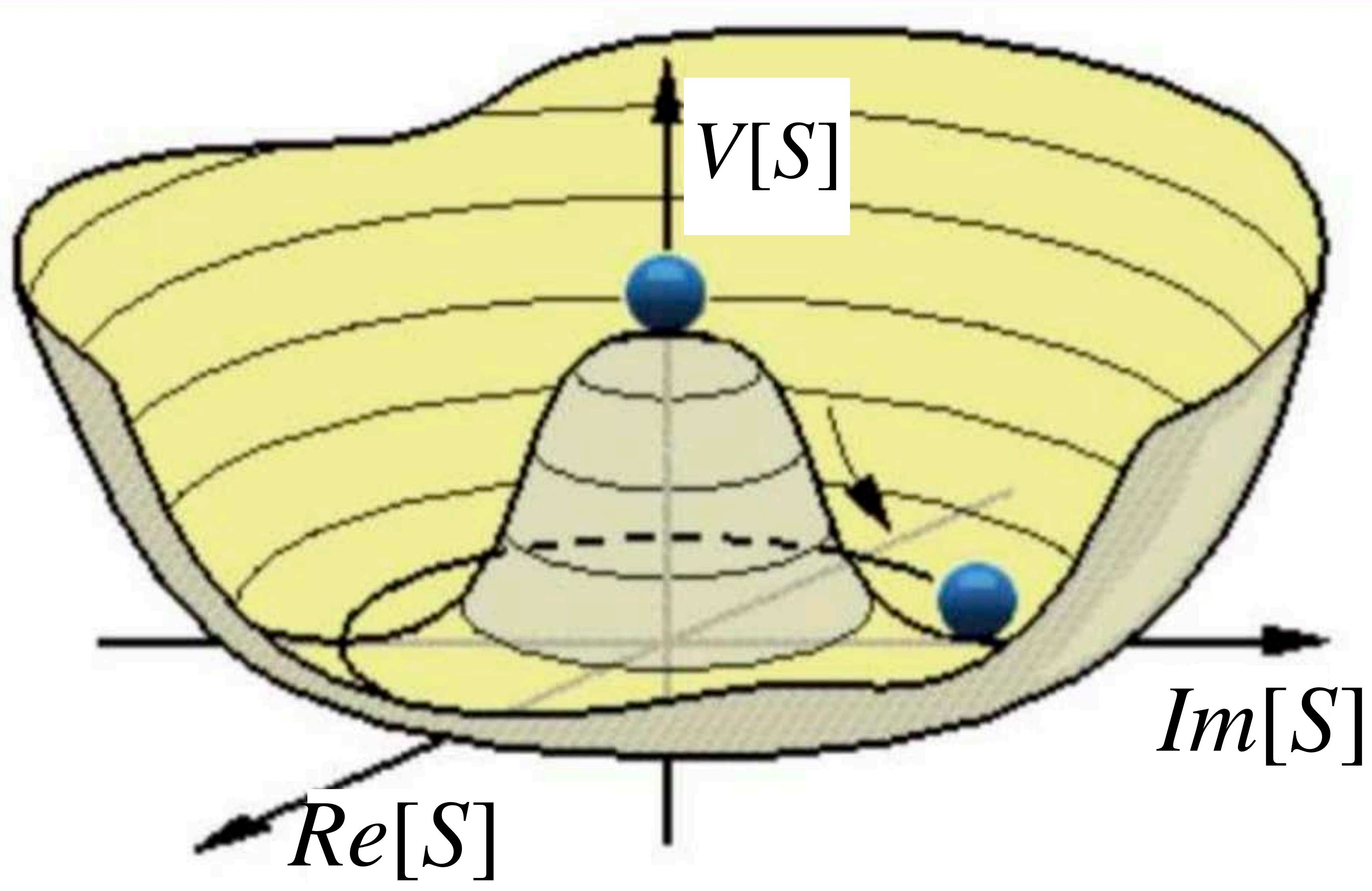
■The attractor predictions of the isotropic and anisotropic KBCB are correlated and are recently consistent with the observations!

■Further observation and analysis of the CMB polarization may reveal the information of order KB encoded on the LSS.

backup

ALP: Nambu Goldstone boson of a global Peccei-Quinn (PQ) symmetry U(1) that is anomalous to photons.

If a continuous global U(1) symmetry is *spontaneously* broken, there is a massless NGB.

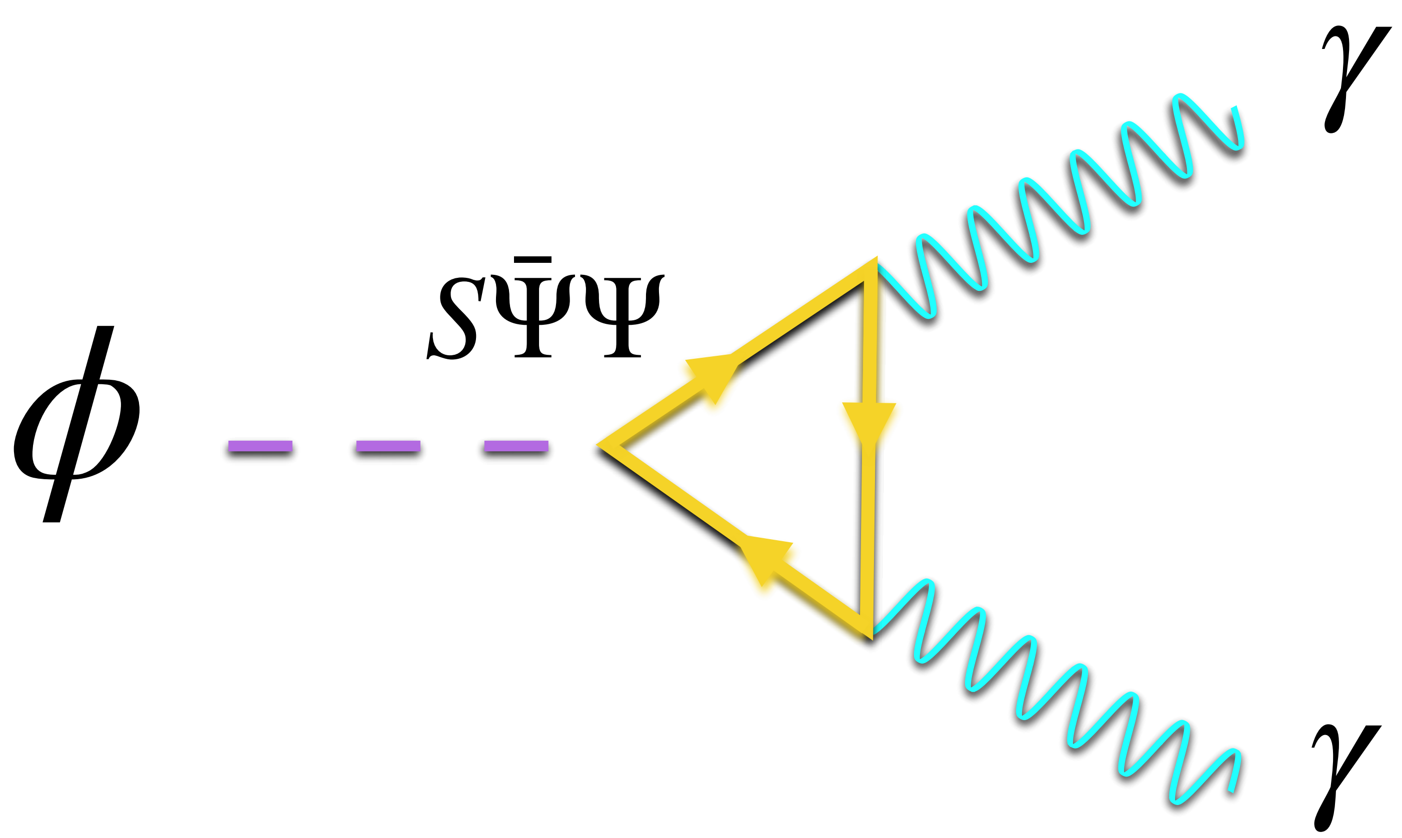


https://physicsforme.com/2012/01/31/a-historical-profile-of-the-higgs-boson/

$$S \sim (v+h)\exp(i\frac{\phi}{\sqrt{2}v})$$

$$U(1) \quad \phi \to \phi + \alpha$$

$$V[\phi] = V[\phi + \alpha]$$



$$\mathscr{L} = -c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad c_\gamma = q_\Psi^2$$

-> naturally ϕ gets masses due to (small) instantons (or quantum gravities).

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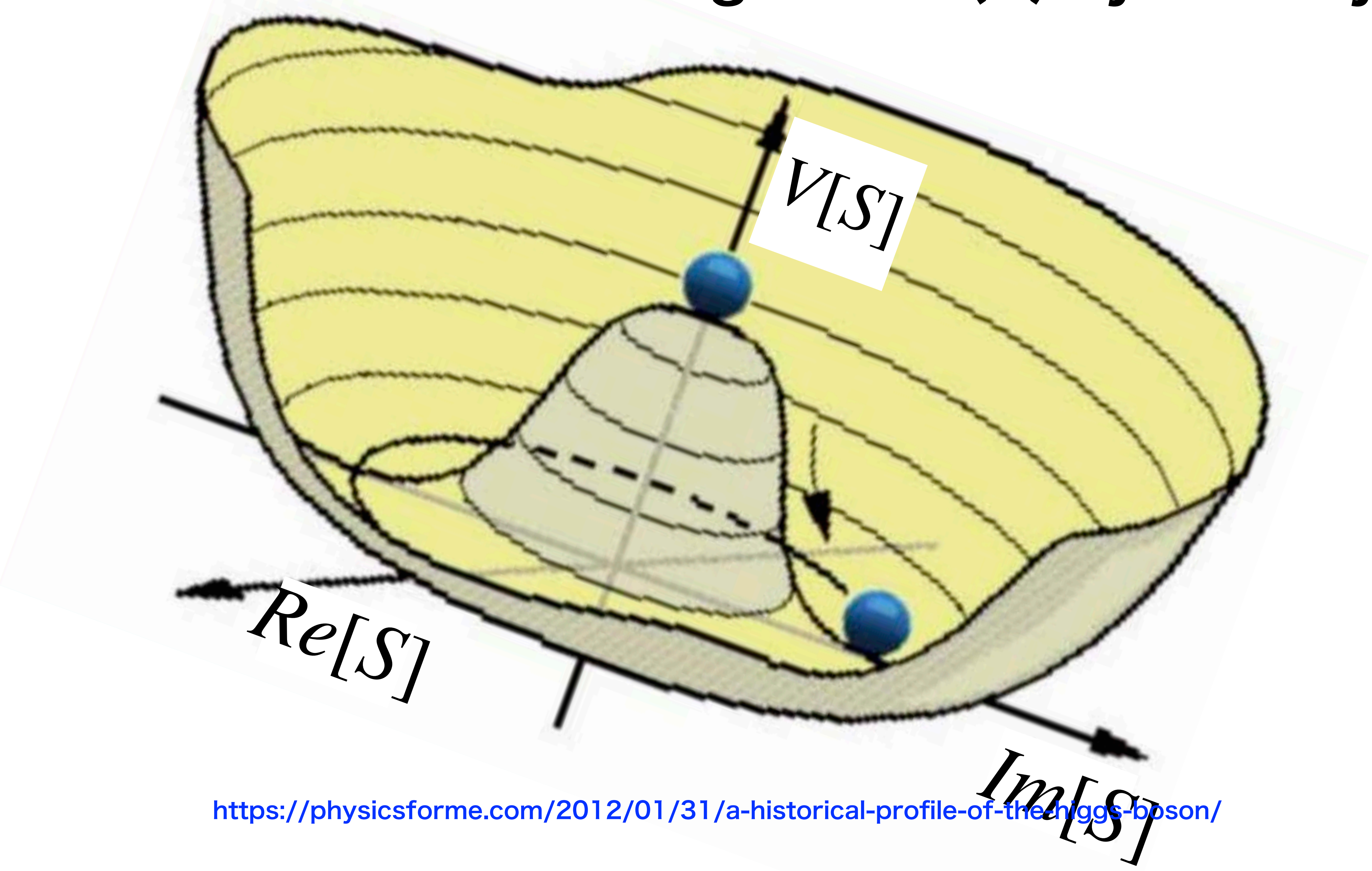

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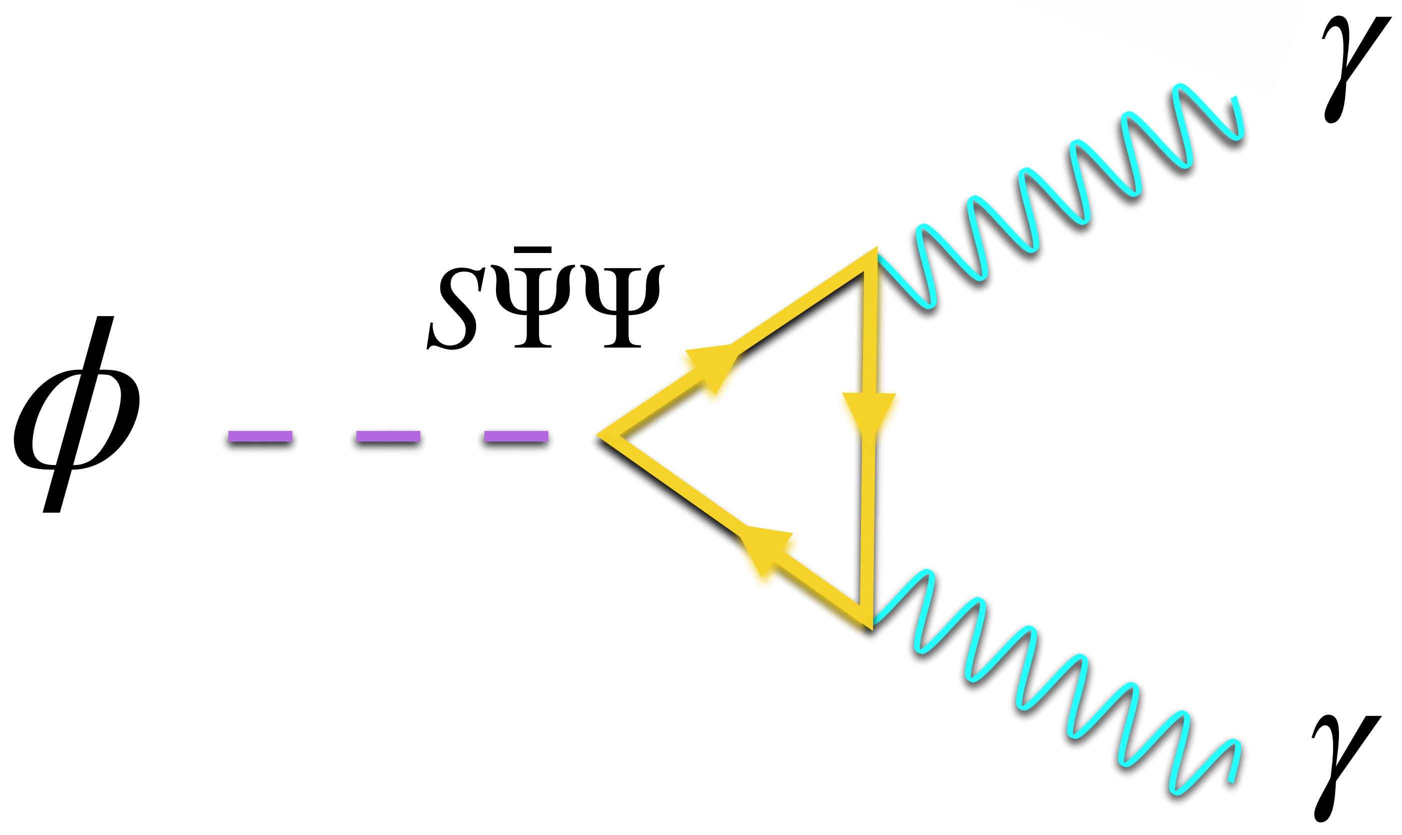

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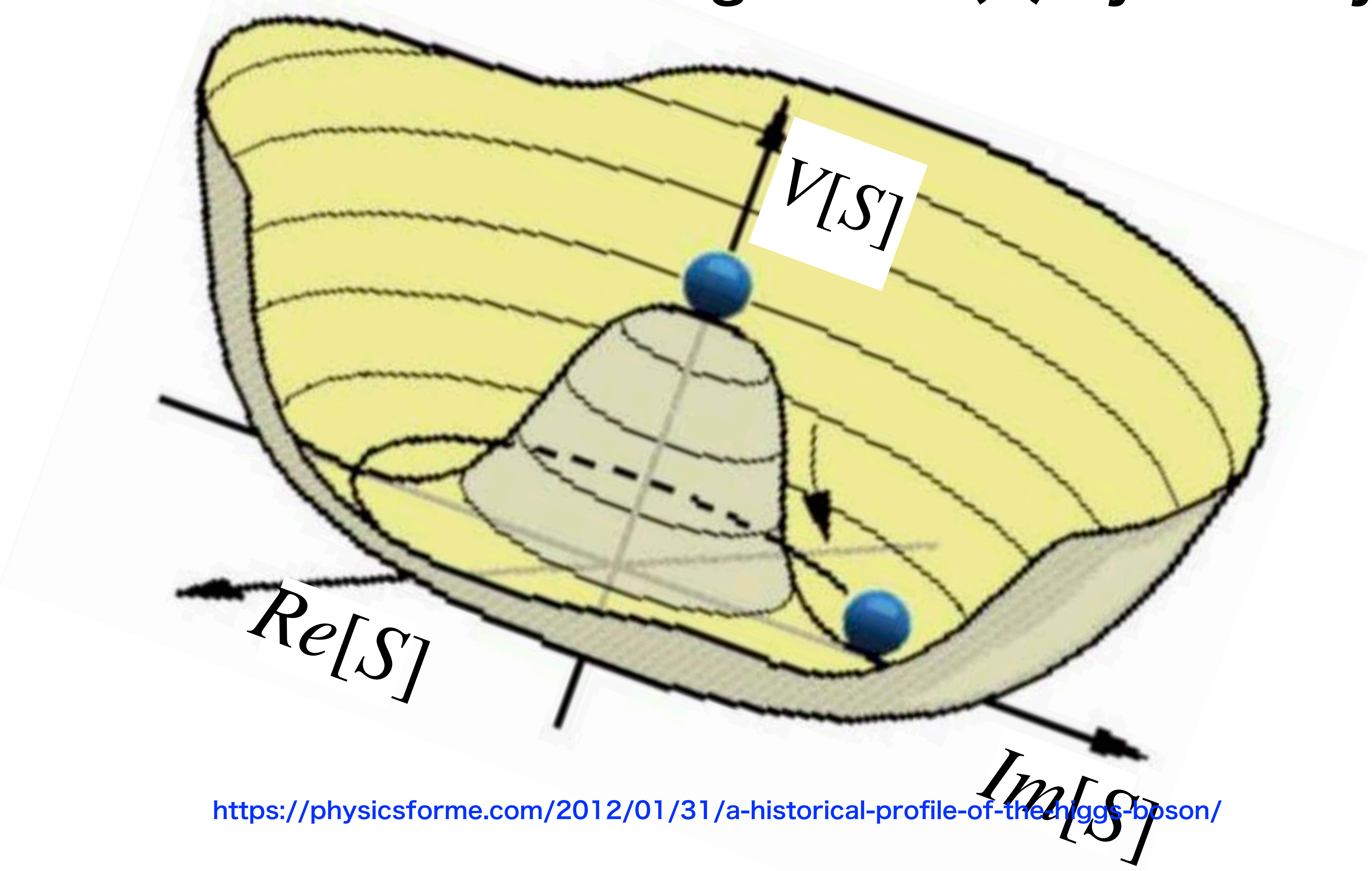

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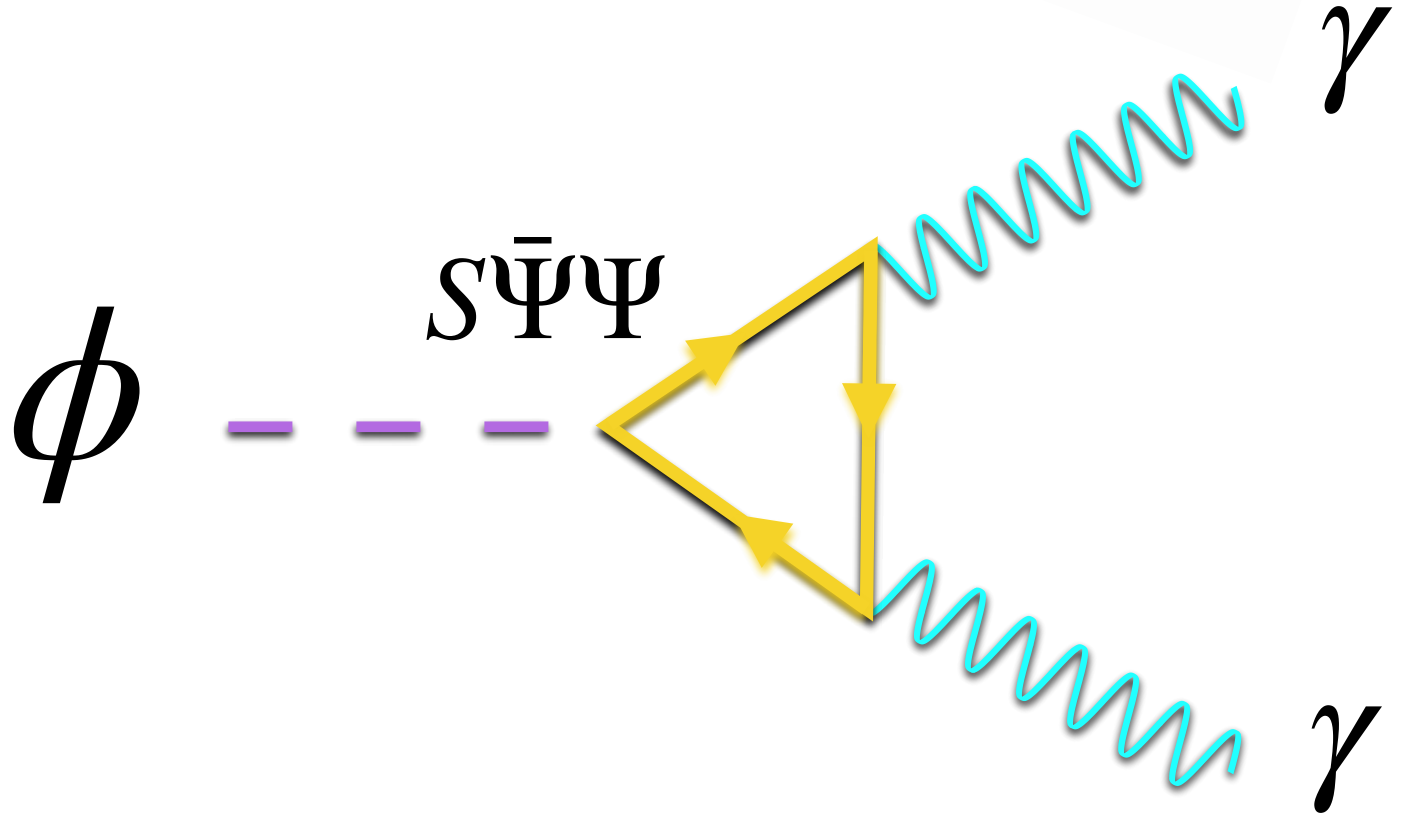

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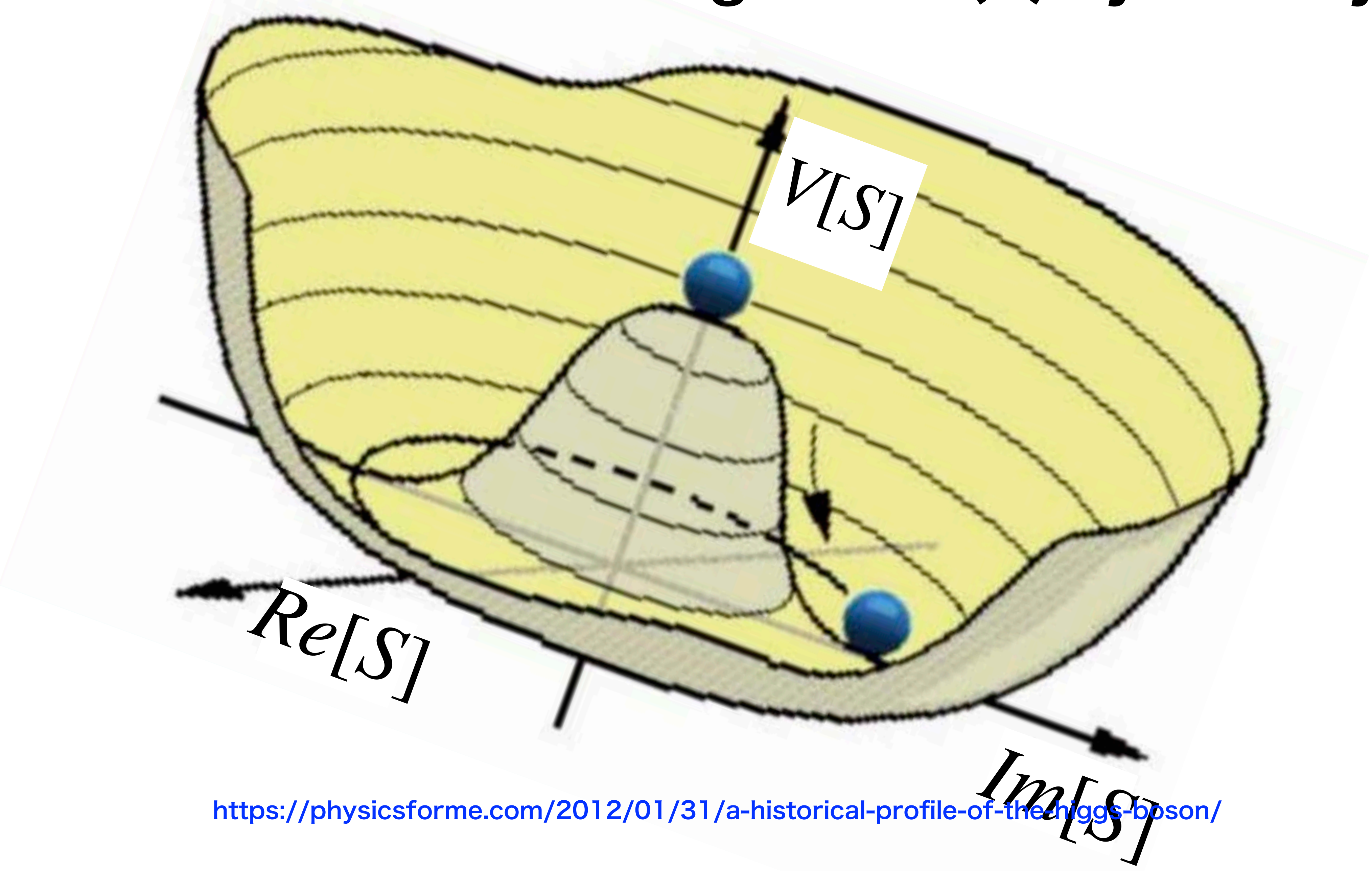

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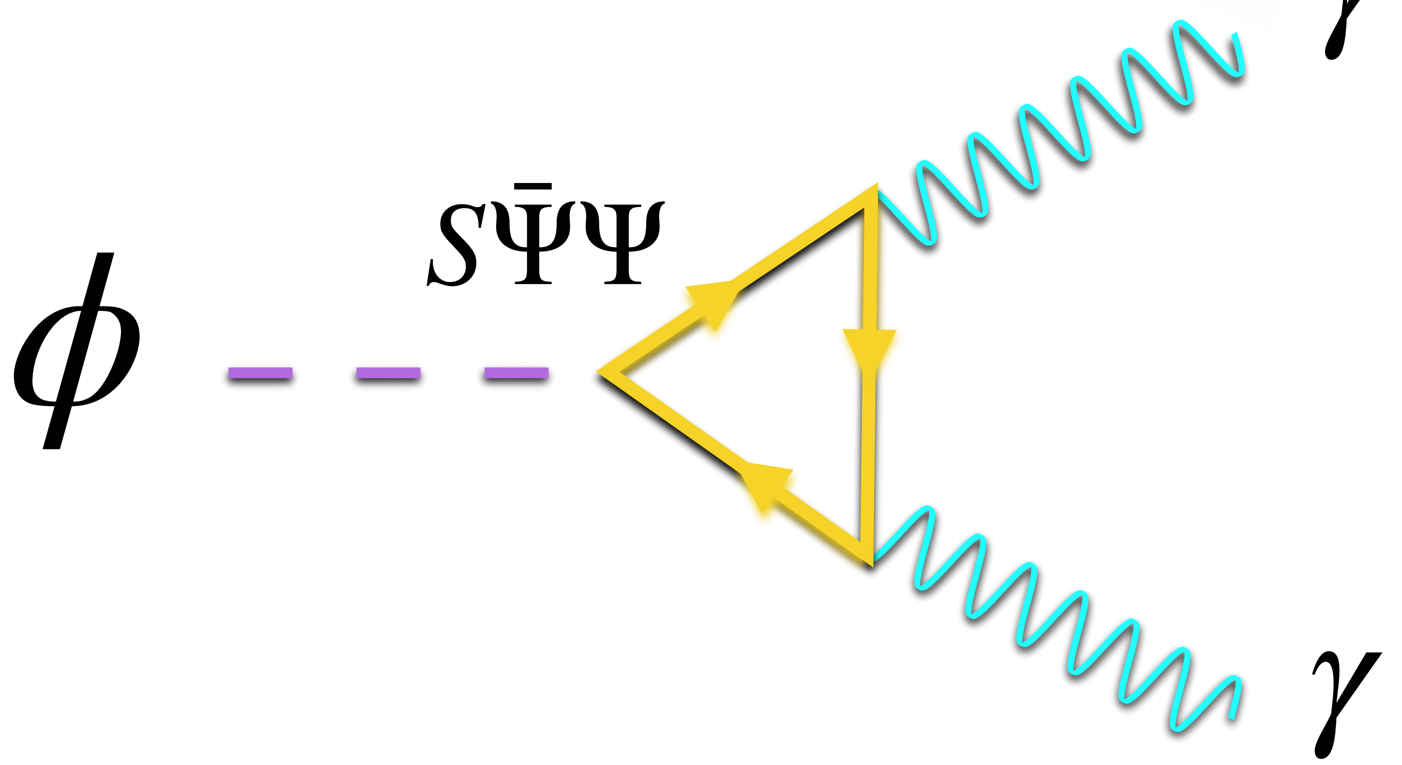

-> naturally ϕ gets masses due to (small) instantons (or quantum gravities).

ALPs are predicted in axiverse of string or M theory.

Isotropic Cosmic Birefringence by ALP models

- Isotropic CB by $\dot{\phi} \neq 0$: Slow-rolling ALP

Minami and Komatsu, 2006.15982,
Fujita et al, 2011.11894, (CB and H_0 tension)

Mehta et al, 2103.06812, (Many ALPs)
Nakagawa et al, 2103.08153, (Very light ALP)

- Isotropic CB by $|\partial_{\vec{x}}\phi| \neq 0$: Domain walls

Takahashi, WY, 2012.11576, (CB by Domain wall)

This talk

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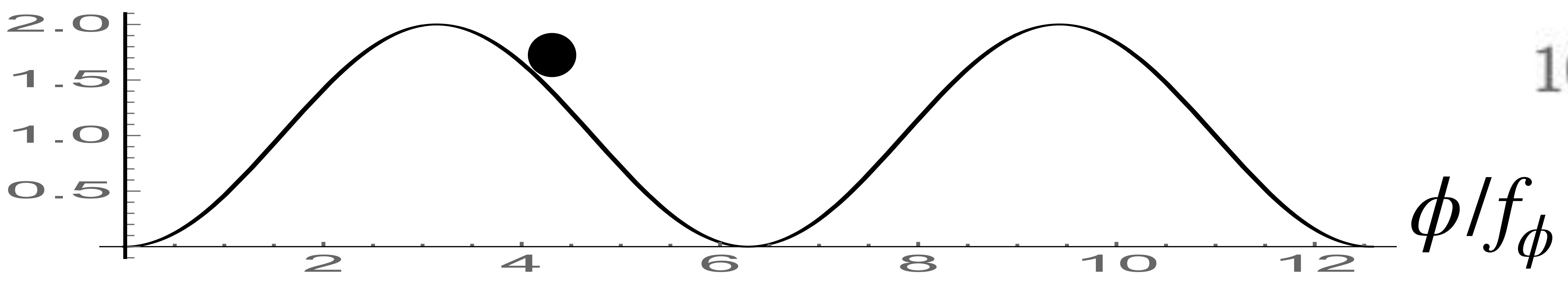
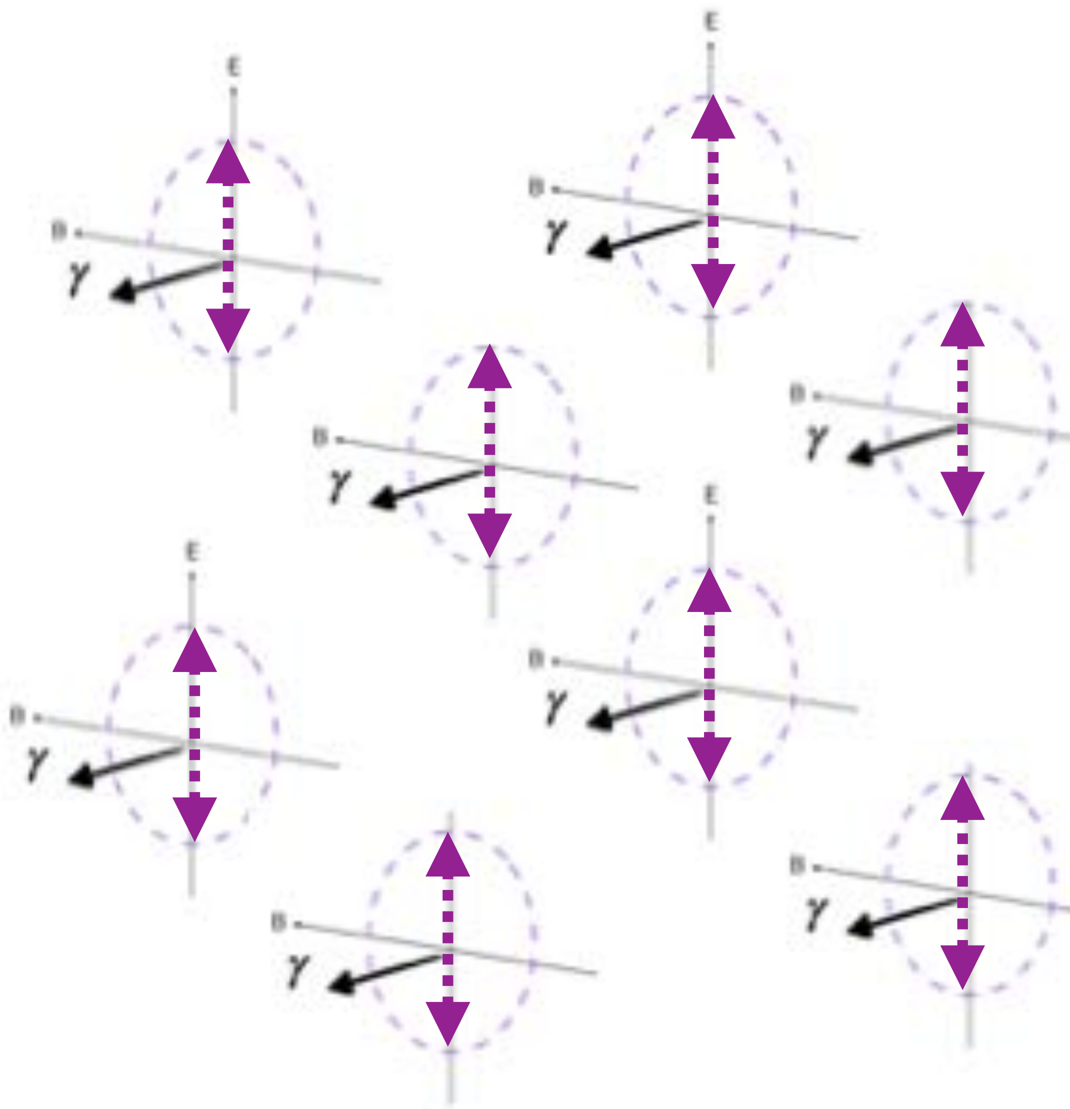
This talk

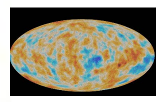
∘ Slow-rolling ALP

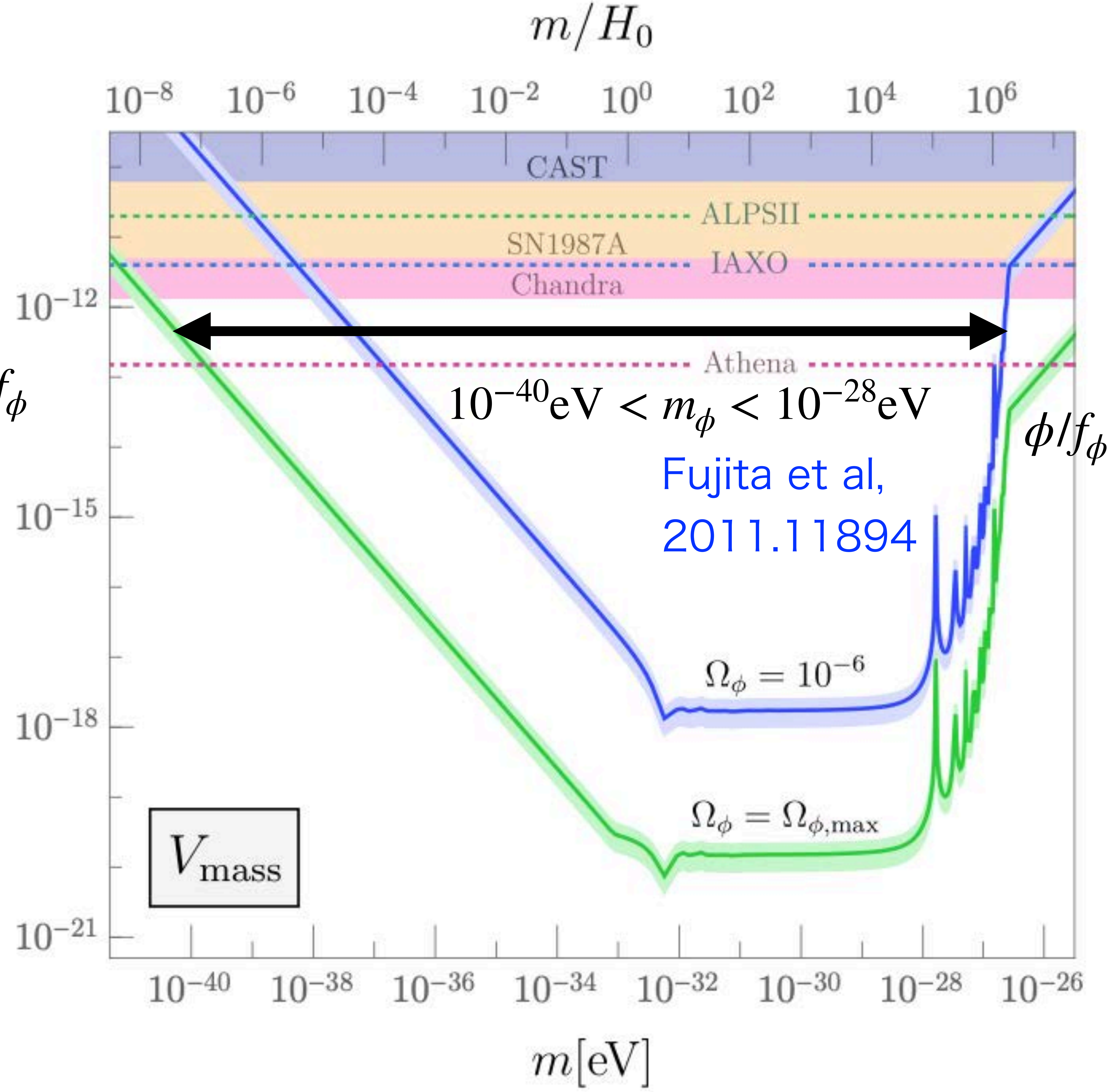
$V(\phi)/\Lambda^4$ $\dot{\phi} \sim -m_\phi^2 \phi/(3H)$



$t = t_{\rm rec}$







Hidden monopole DM coupled to ALP, ALP can be lighter Nakagawa et al, 2103.08153.

◦ Slow-rolling ALP

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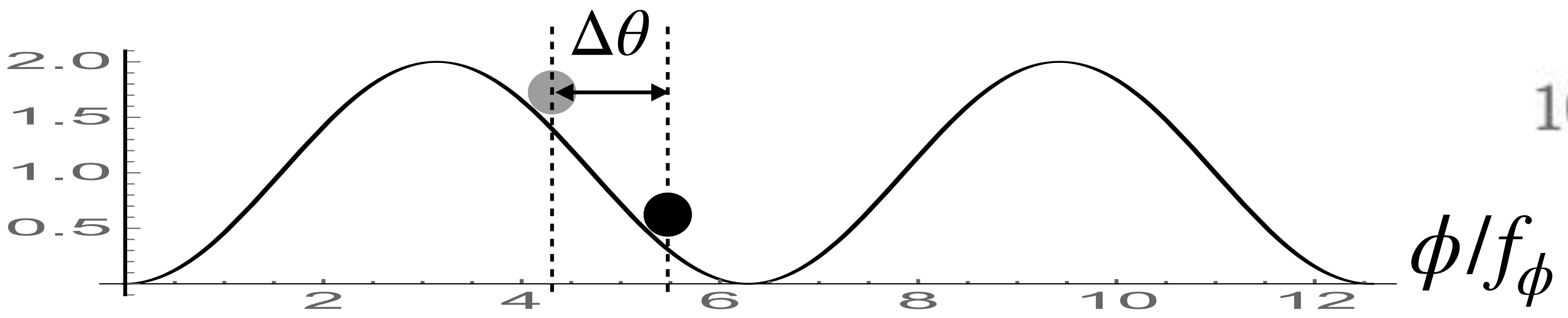
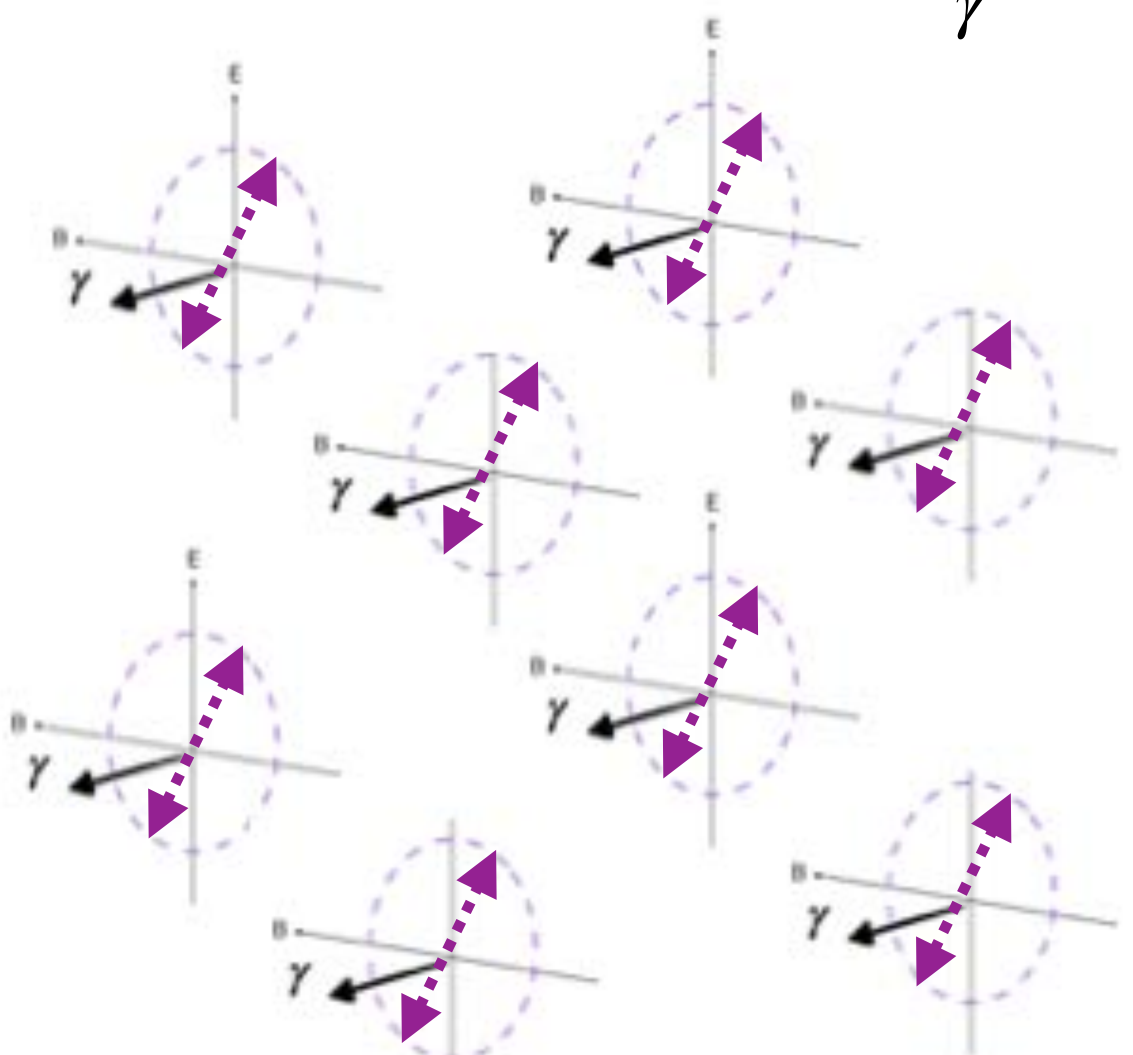
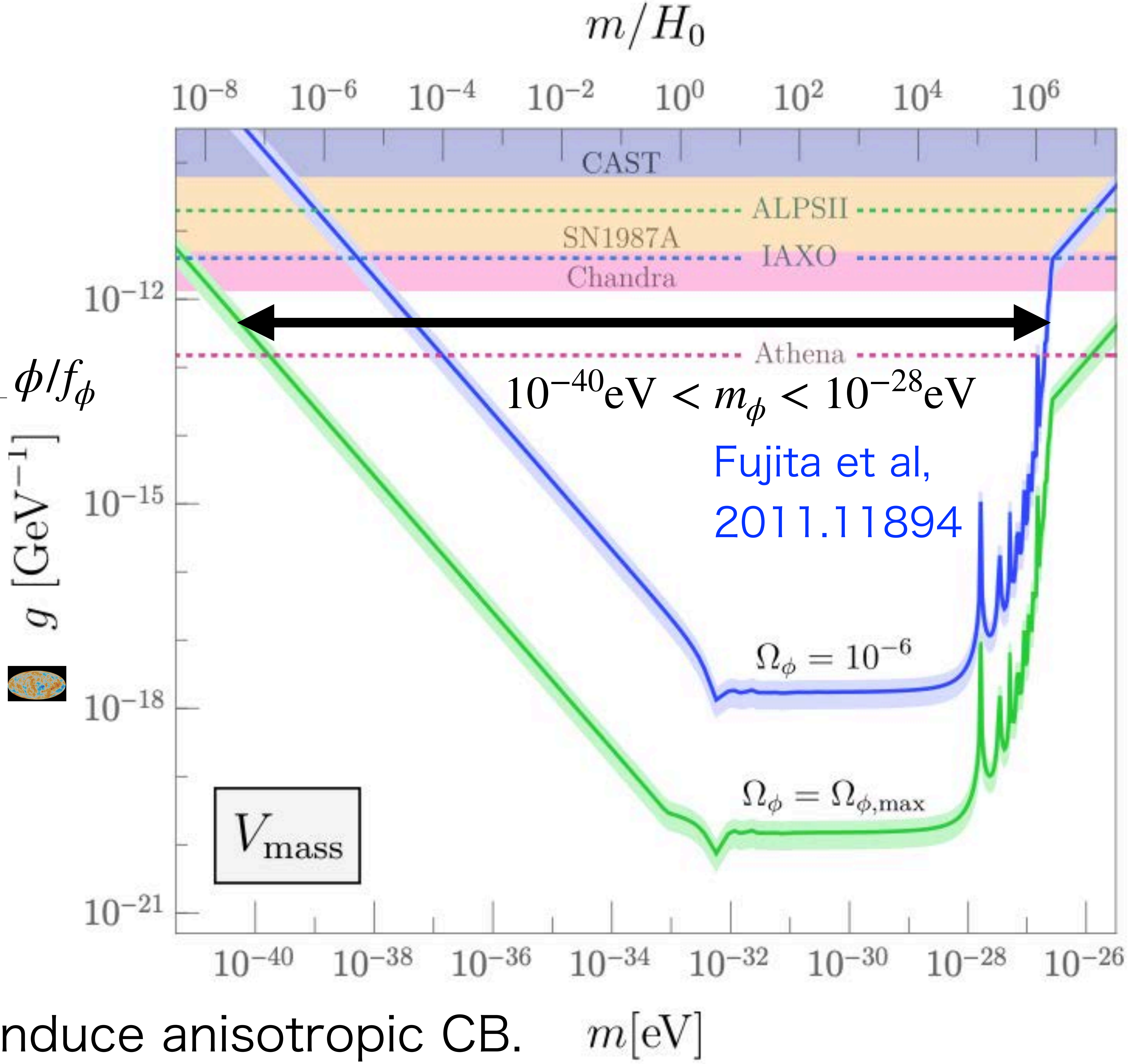


$t = \Delta t + t_{\rm rec}$

$\Phi = \alpha c_\gamma \Delta\theta$





Fujita et al, 2011.11894

Inflationary fluctuation can also induce anisotropic CB.

Hidden monopole DM coupled to ALP, ALP can be lighter Nakagawa et al, 2103.08153.

Review: Cosmic Birefringence from Strings

Agrawal et al, 1912.02823;

- PQ symmetry breaking after inflation induces strings (with domain walls).
- Anisotropic cosmic birefringence but **negligible isotropic cosmic birefringence.**

$$\beta = \frac{1}{4\pi}\int d\Omega \Phi[\Omega] \simeq 0$$