Part 1: Cosmic Birefringence from Domain Wall without a string

Part 2: Dark Matter stability from Pauli-exclusion principle

Wen Yin (Tohoku University)

@29 March 2022
“What is dark matter? - Comprehensive study of the huge discovery space in dark matter”

Part 1

Cosmic Birefringence from Domain Wall without a string

Based on Takahashi, WY, 2012.11576
and ongoing project in collaboration with Takahashi, Kitajima and Kozai

What does the measured parity-violating cosmic birefringence (CB) suggest?

★ An ALP can alter the Maxwell equation

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

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

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

(in non-singular field space)

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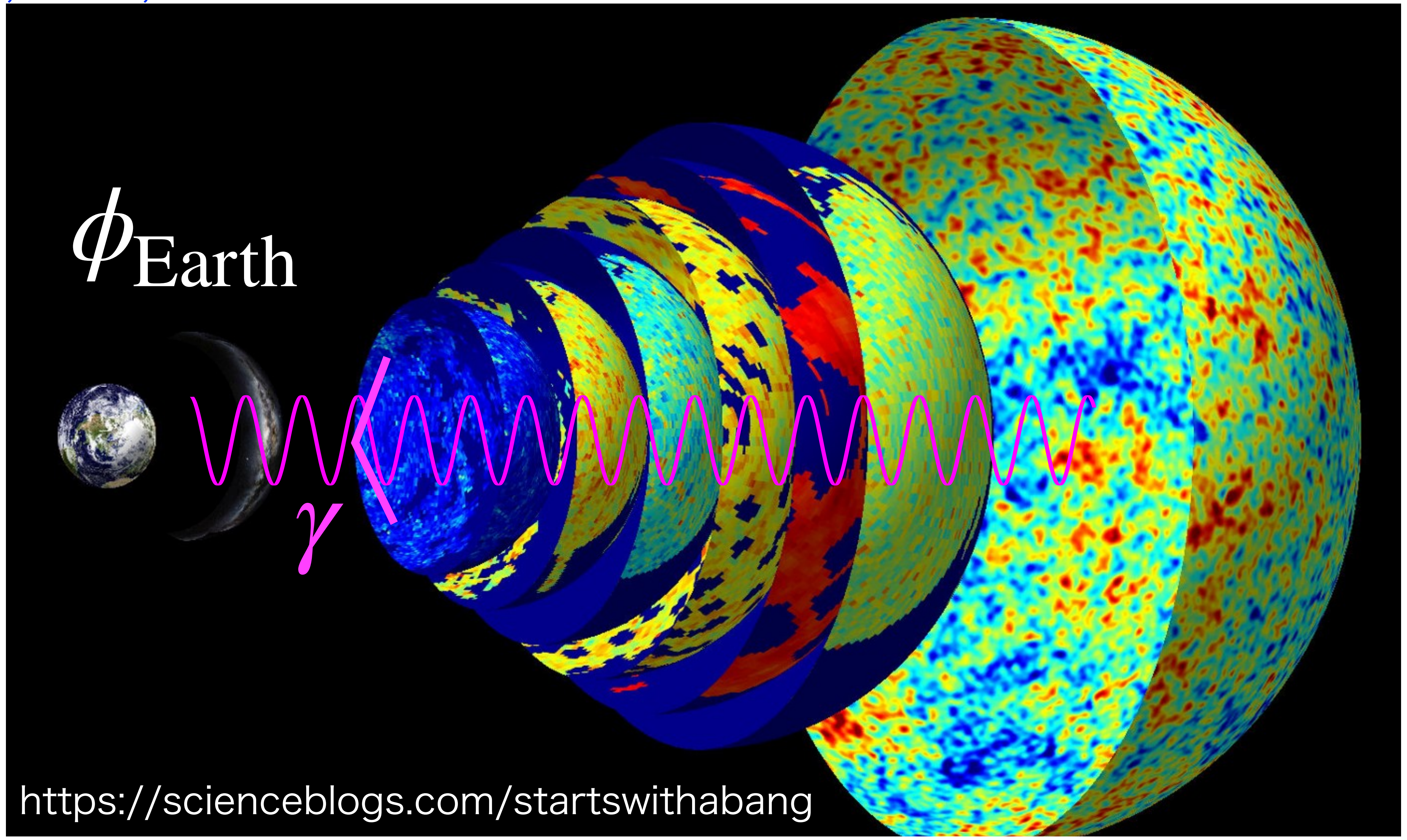
Diego-Palazuelos et al, 2201.07682

see also Minami and Komatsu, 2006.15982, and B06's session.

$$\longrightarrow \quad c_\gamma \left(\frac{\phi_{\rm Earth} - \bar{\phi}_{\rm LSS}}{f_\phi}\right) \sim (0.9\pi - 1.9\pi)$$



$$\underbrace{}_{\text{Averaged } \phi \text{ on last scattering surface}}$$

$\bar{\phi}_{\rm LSS}$

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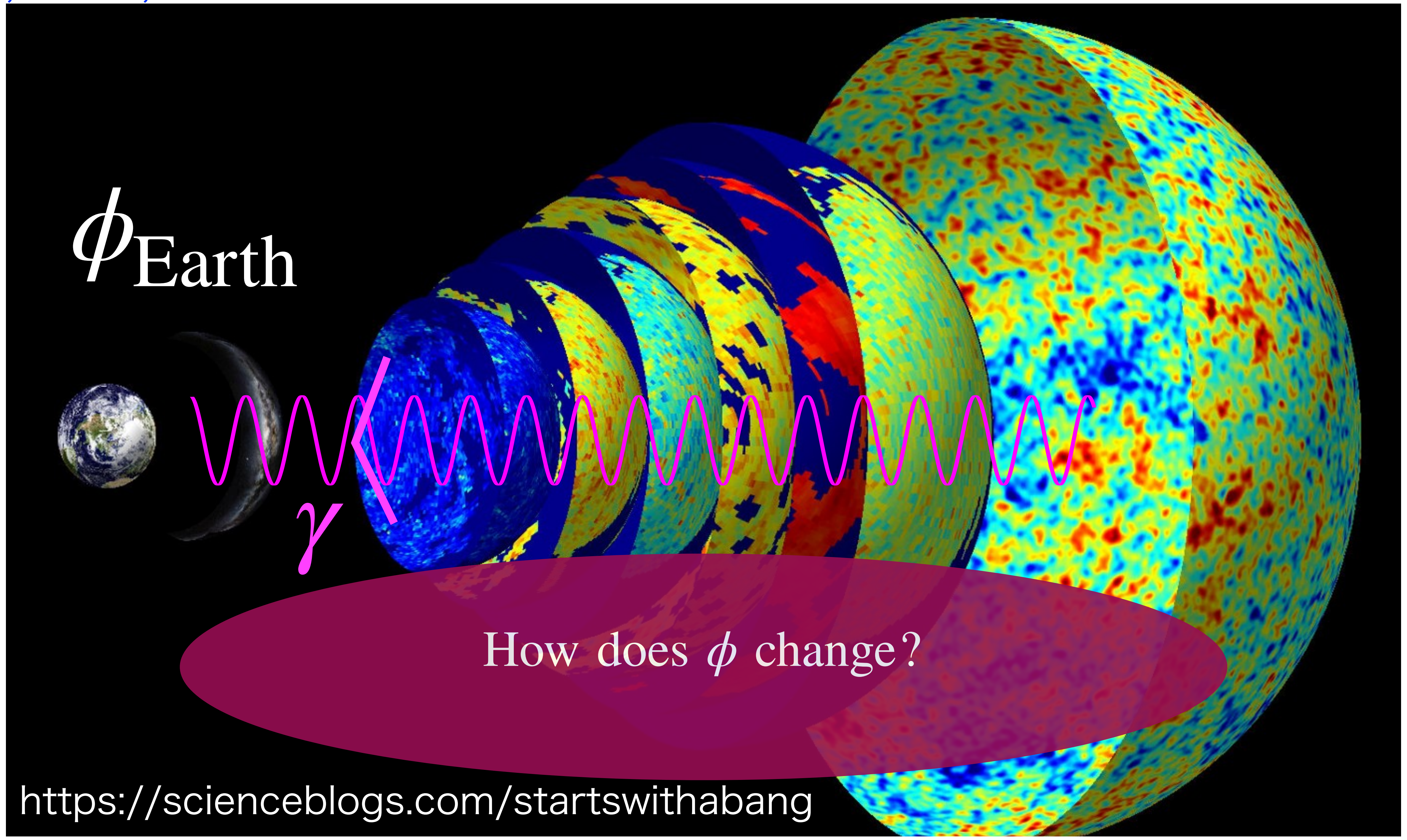

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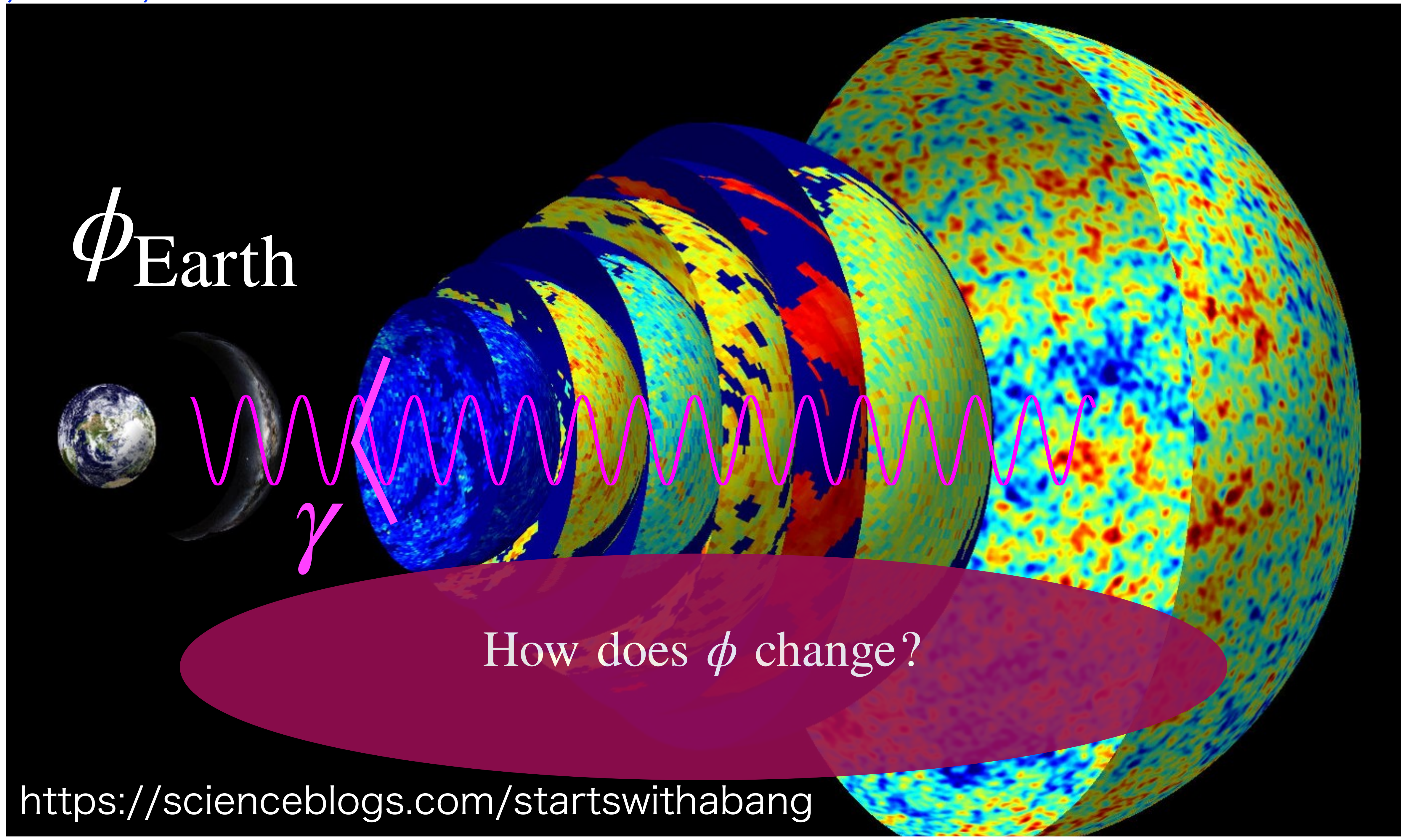

Averaged ϕ on last scattering surface

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→ Isotropic CB by ALP varying in time: 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) see Masaki's talk

Isotropic CB by ALP varying in space: **ALP domain wall (DW).**

Takahashi, WY, 2012.11576 **my focus**

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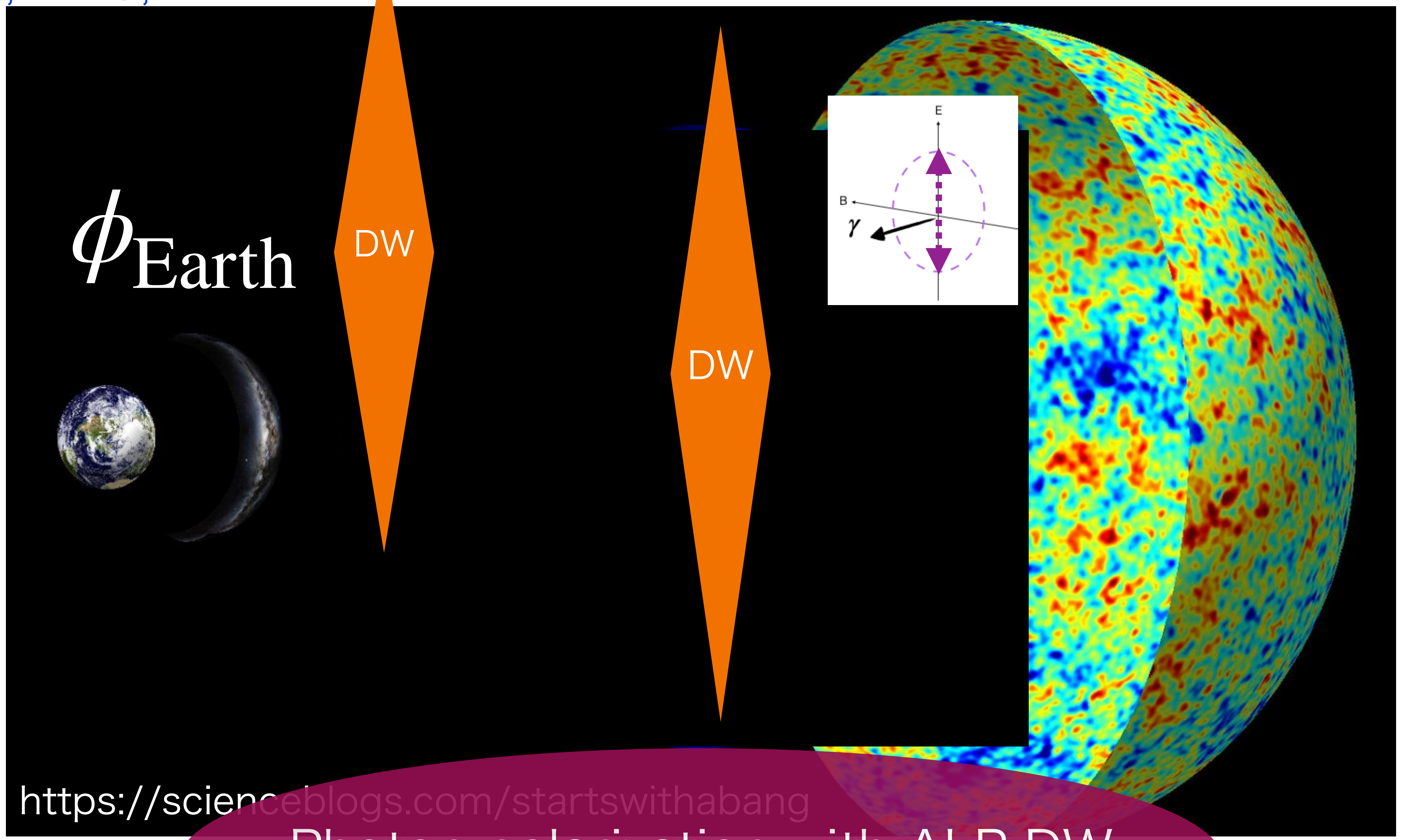

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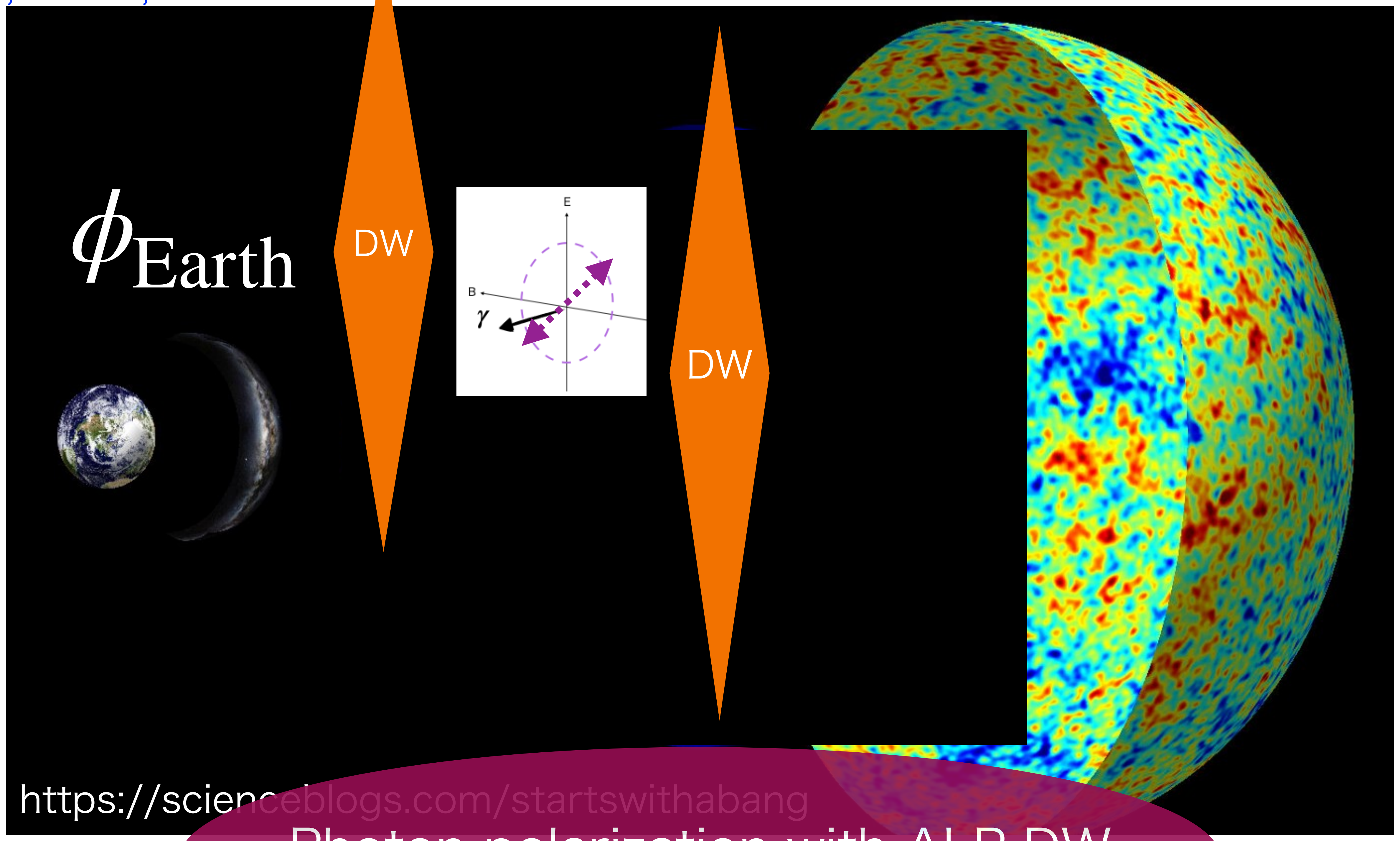

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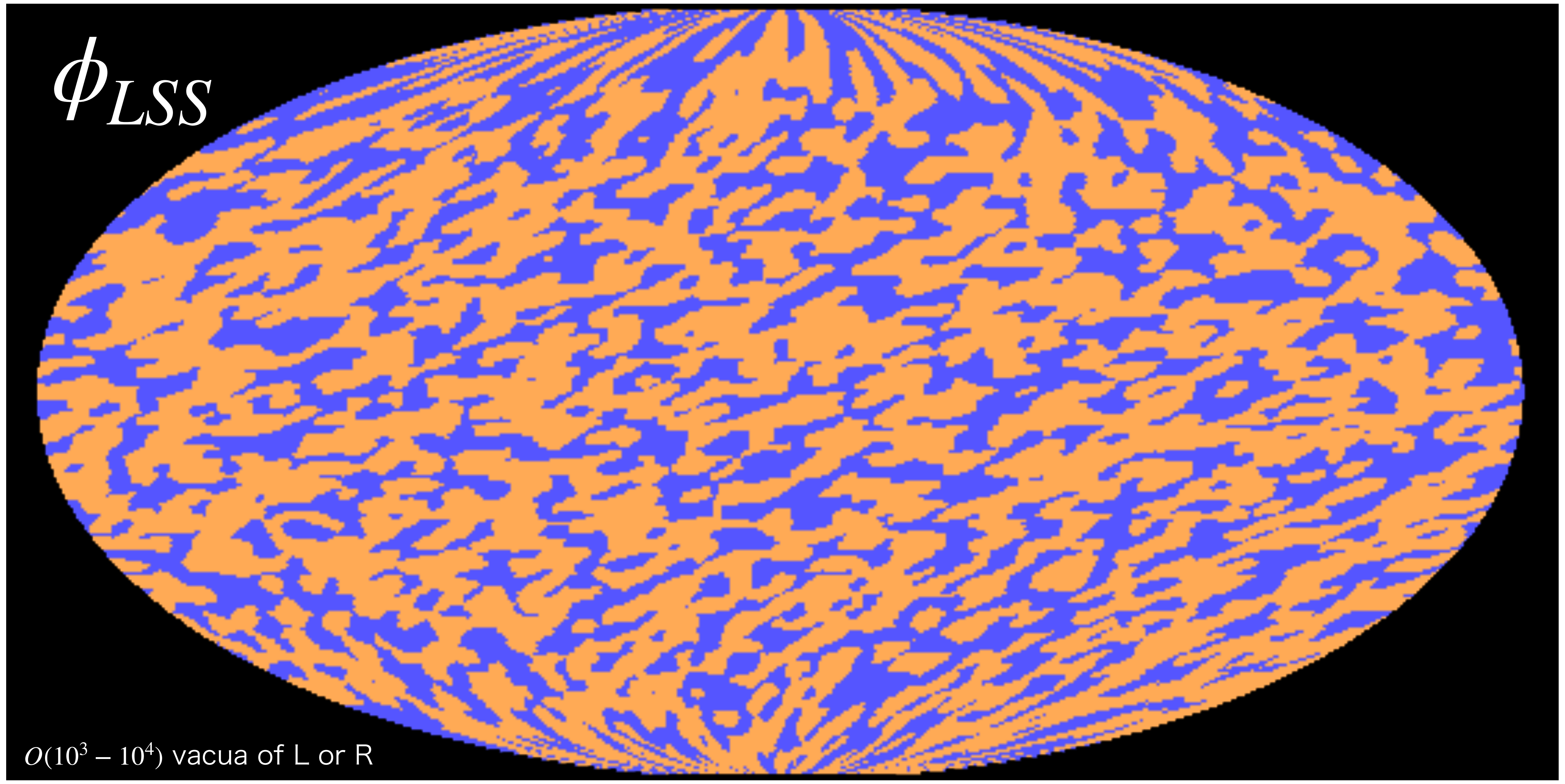
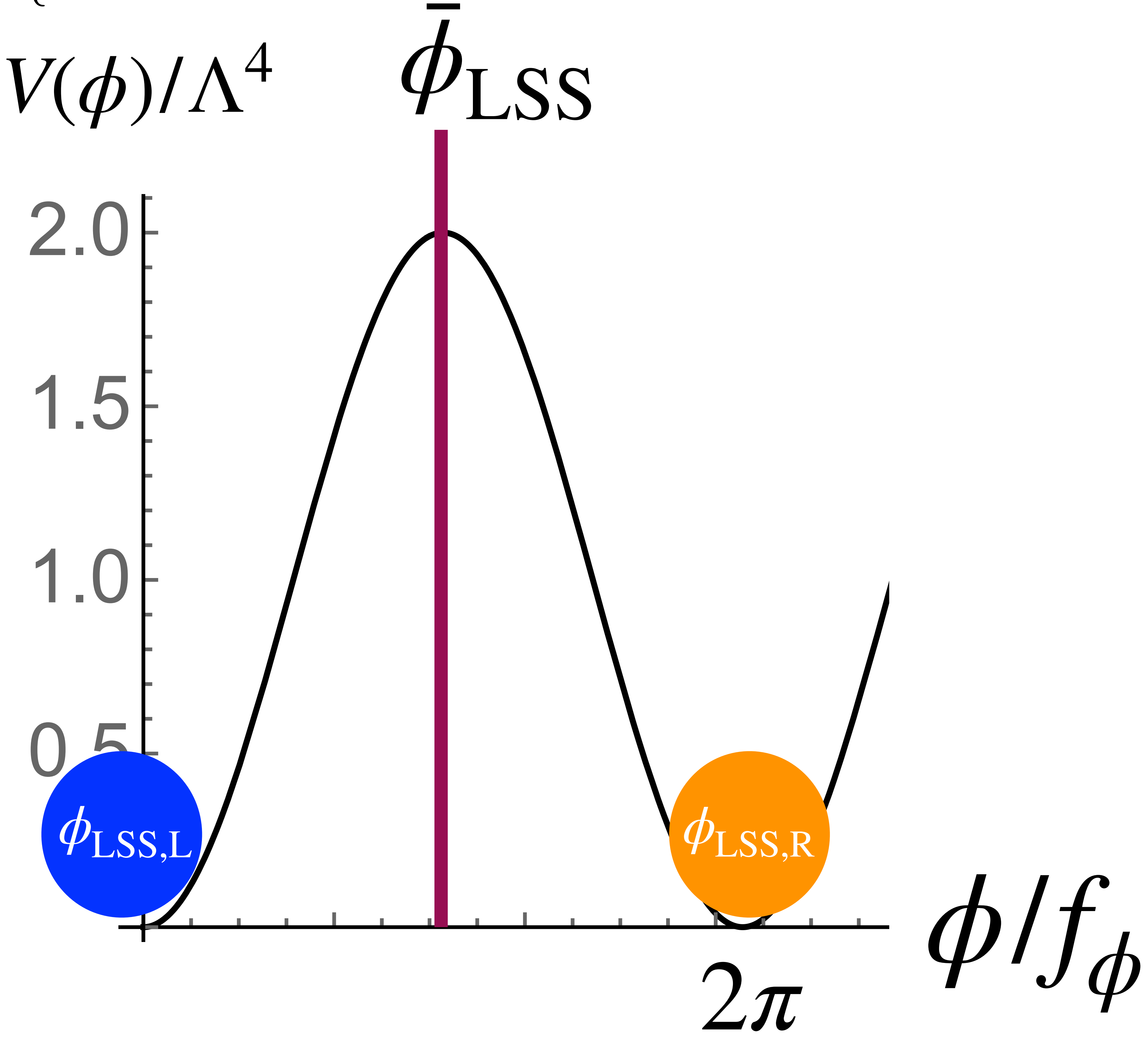
ALP DW without a string following scaling solution (≡ attractor solution with O(1) domains within a Hubble horizon) explains the isotropic CB.

Takahashi, WY, 2012.11576

$$|\beta| = 0.21\mathrm{deg}\,|c_\gamma|$$

c.f. $\begin{cases} \beta = 0.42\mathrm{deg}\dfrac{(\phi_{\rm Earth} - \bar{\phi}_{\rm LSS})}{2\pi f_\phi} c_\gamma \\ \beta_{\rm obs} = 0.30 \pm 0.11 \text{ deg,} \end{cases}$





Strings with DWs cannot induce isotropic CB Agrawal et al, 1912.02823;

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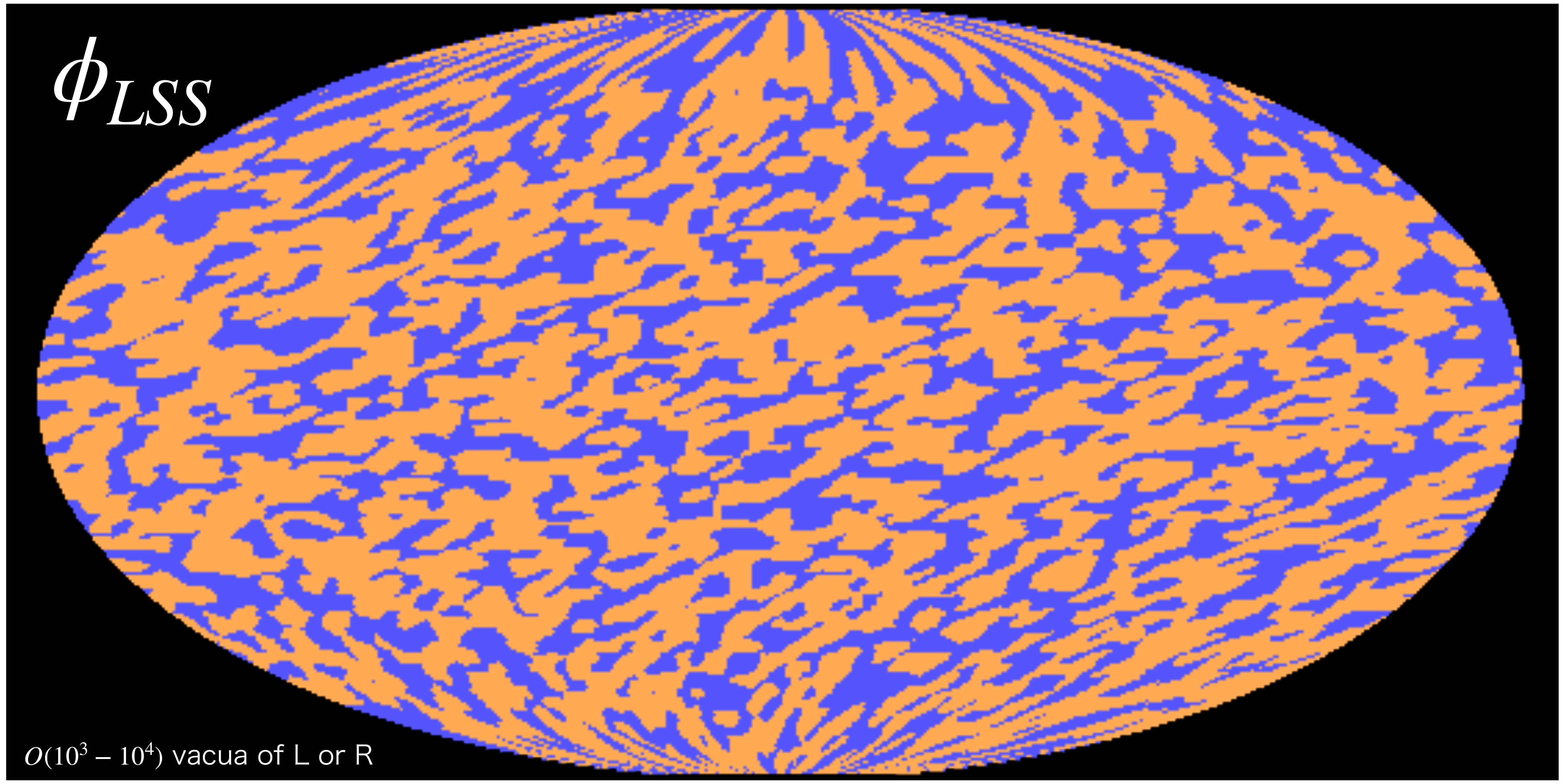

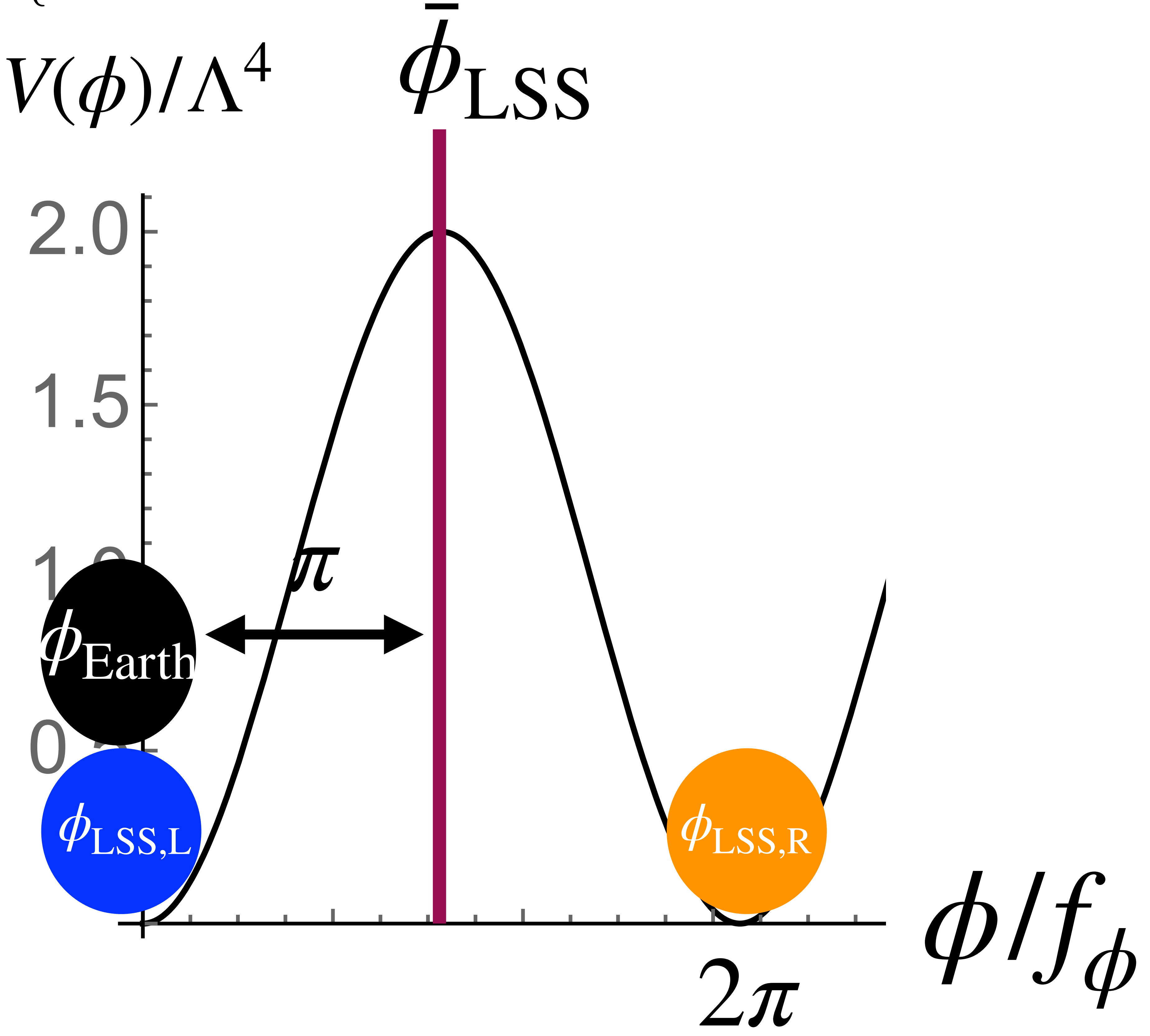

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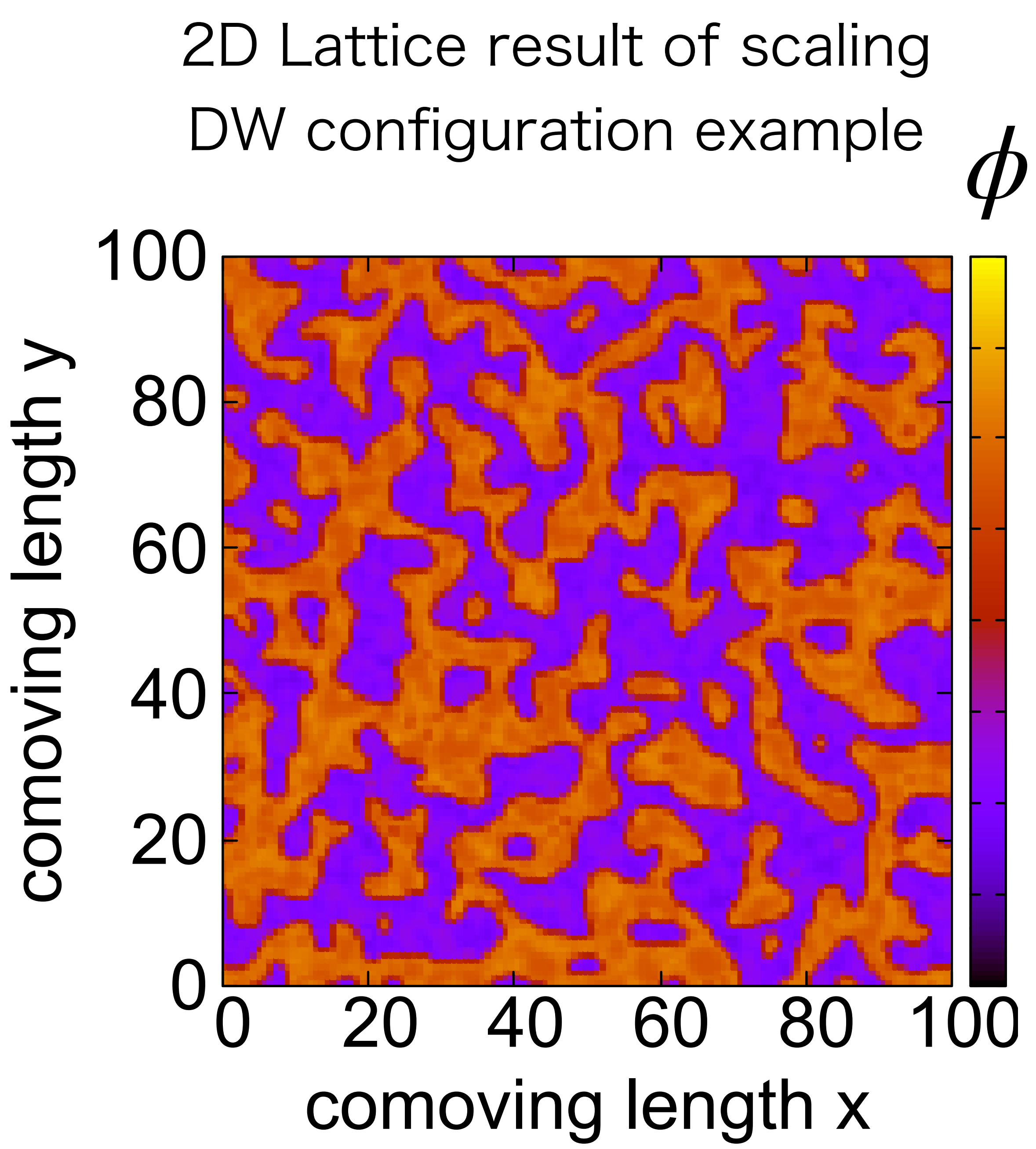
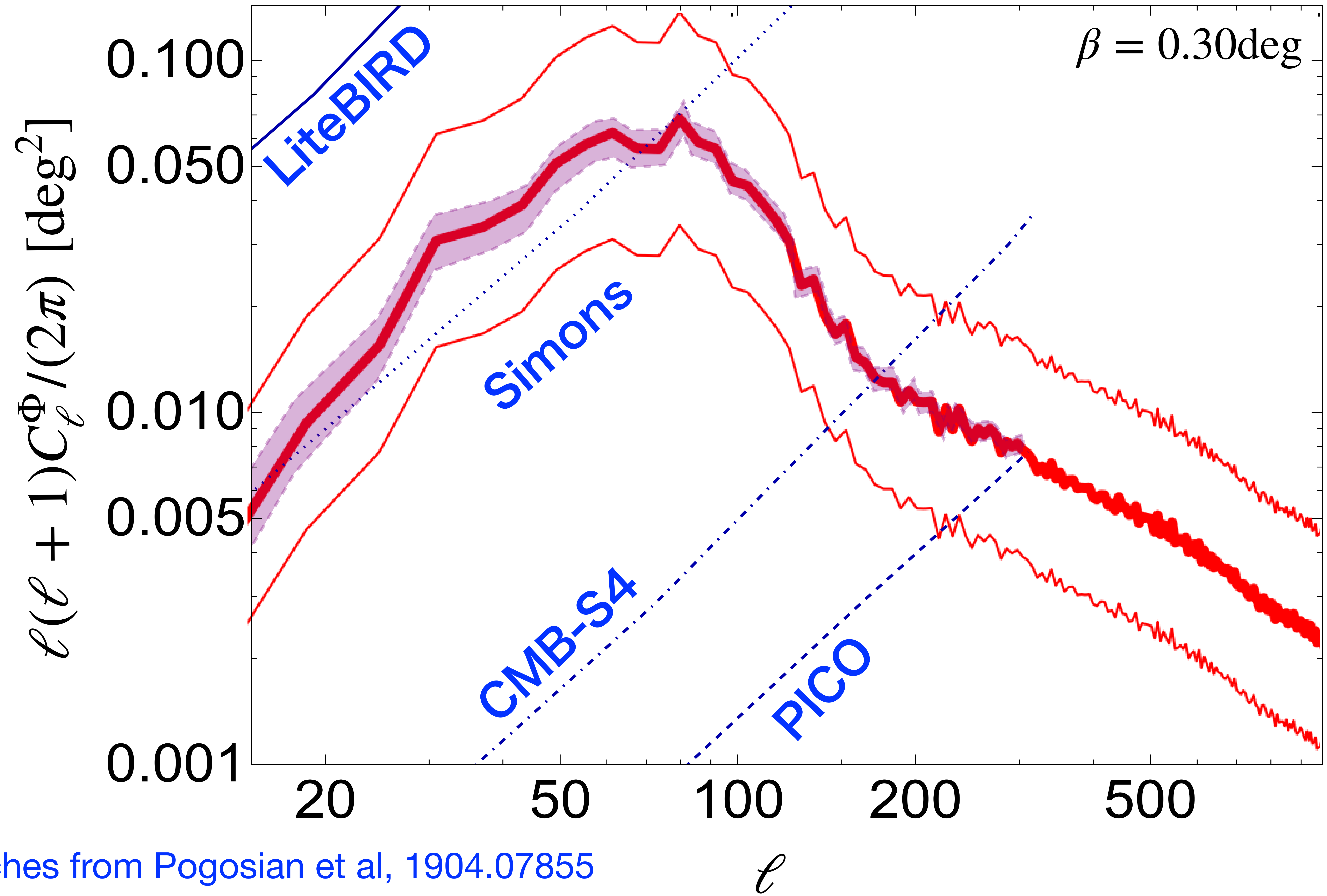
Predicted anisotropic birefringence can be tested.

We use 4096*4096 Lattice simulation to estimate the power spectrum of anisotropic cosmic-birefringence.

Takahashi, Kitajima, Kozai, WY, preliminary

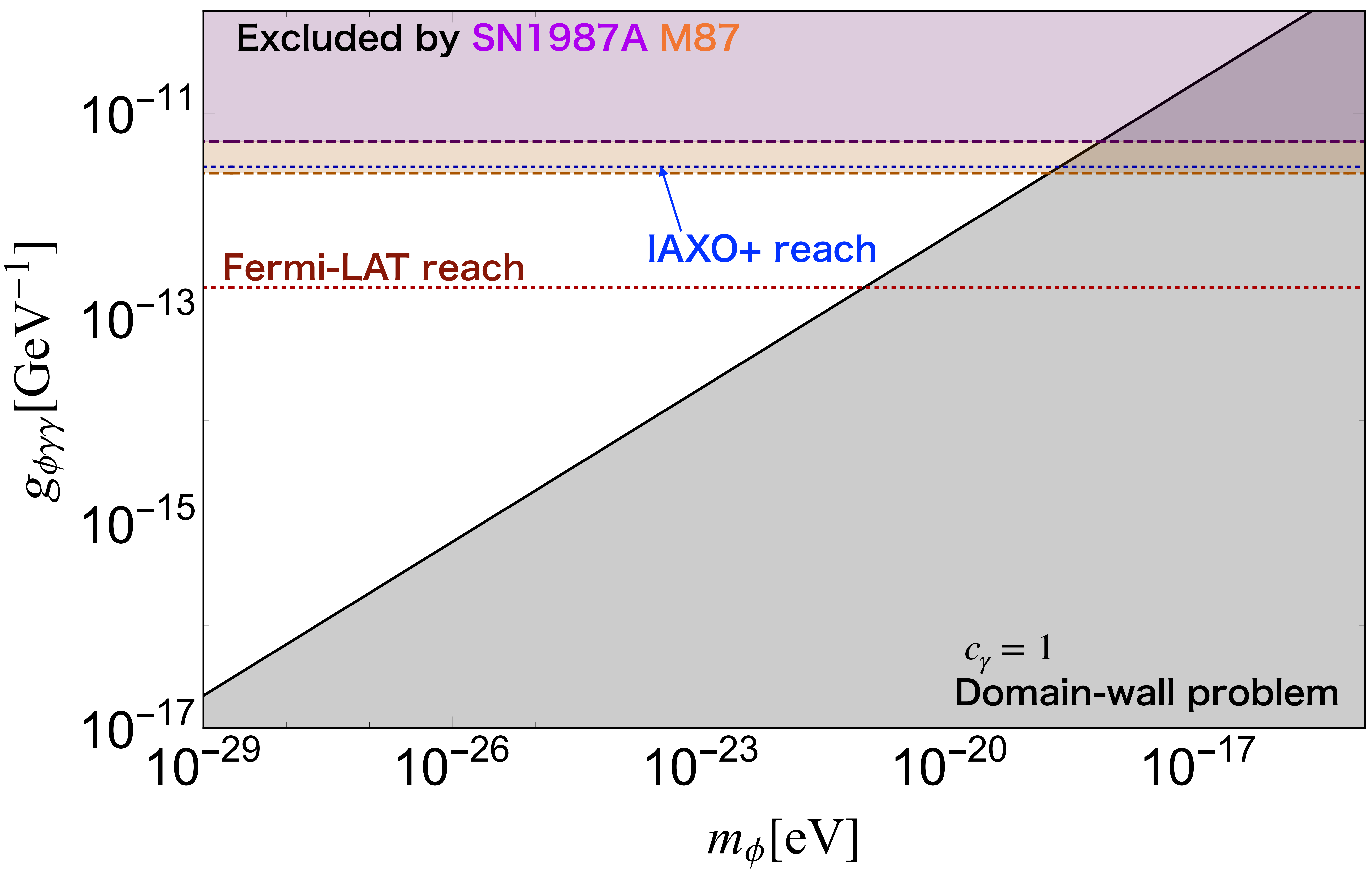




Future reaches from Pogosian et al, 1904.07855

Parameter region and other testability

Takahashi, WY, 2012.11576



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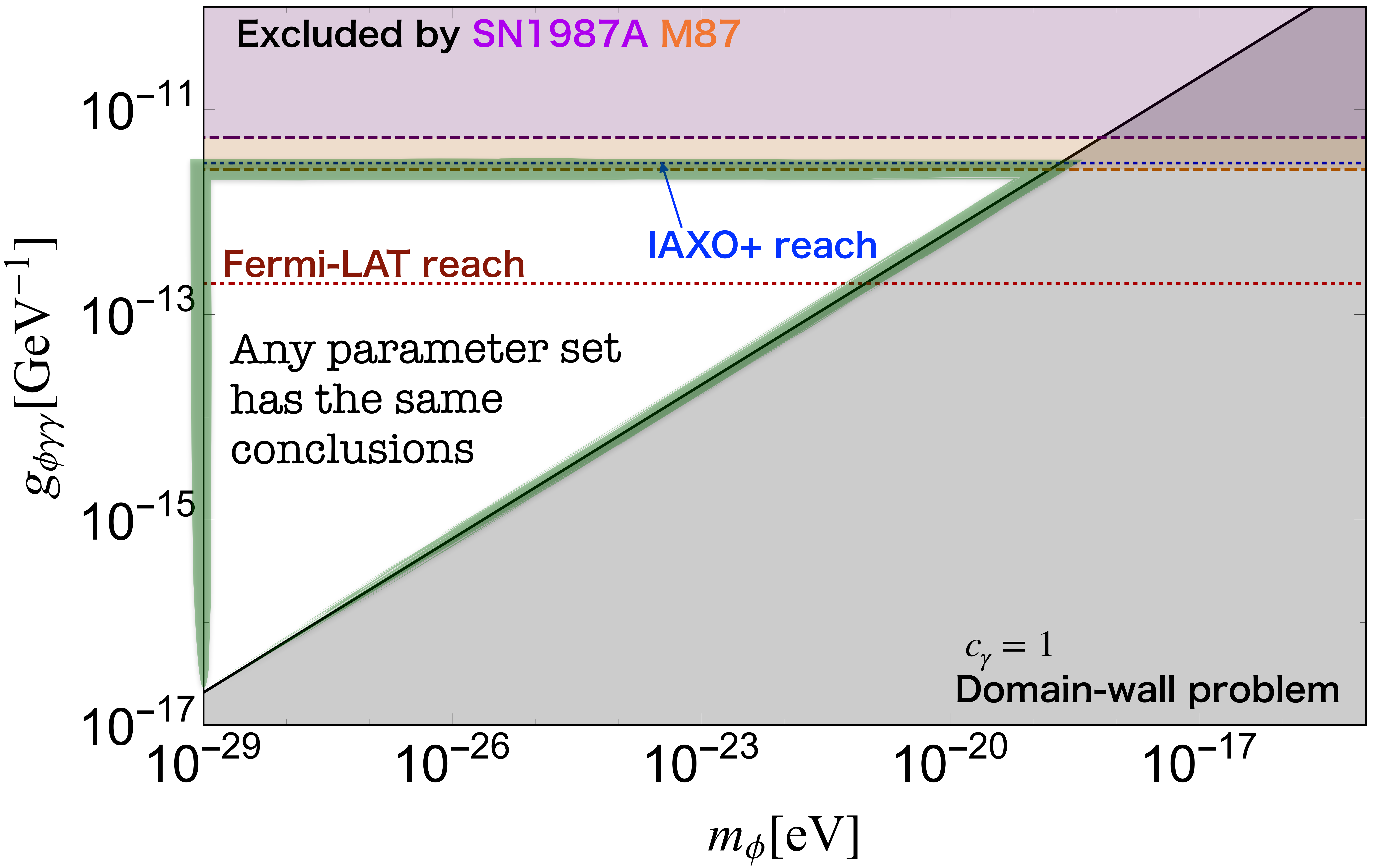
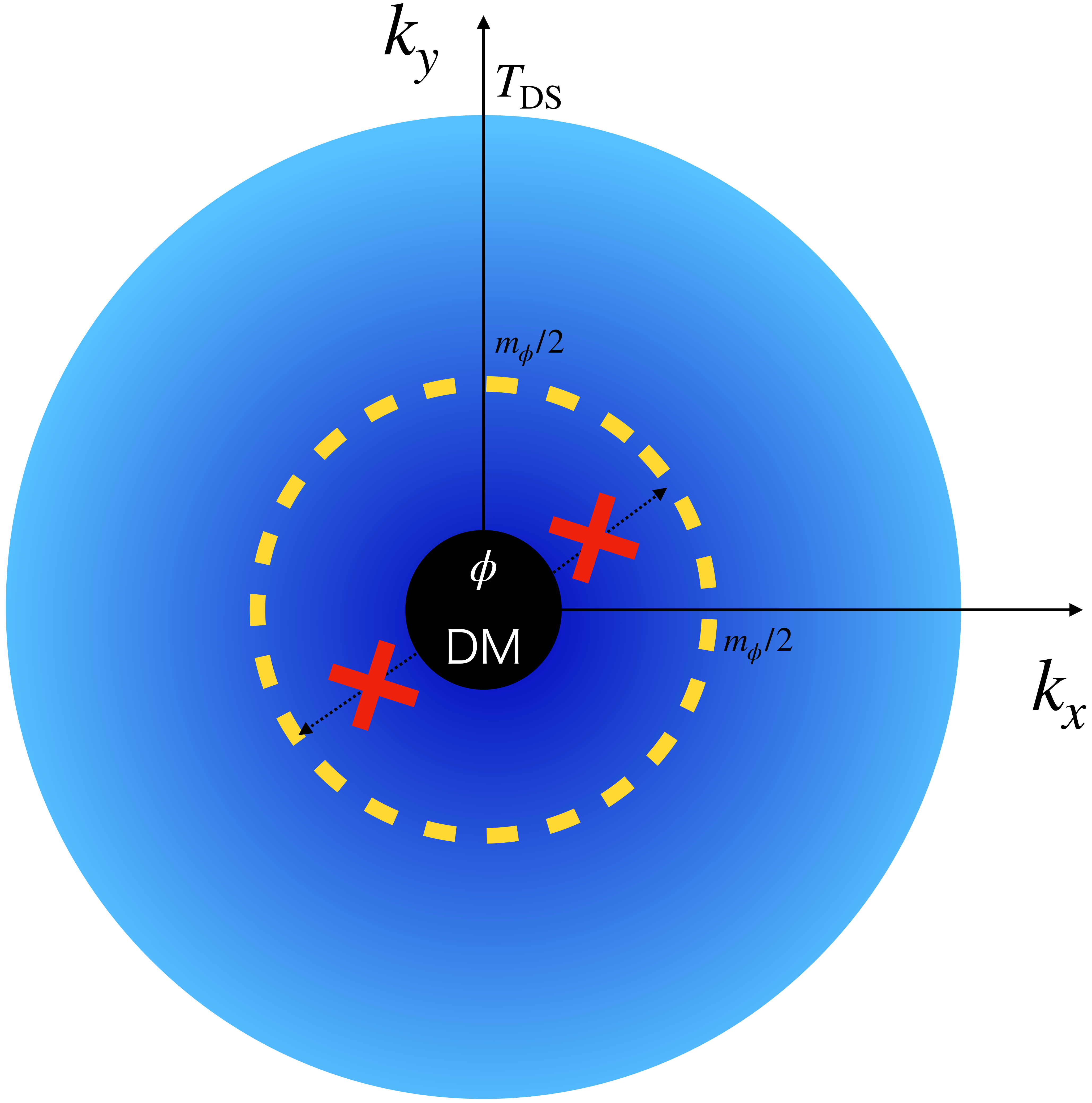


Part 2

DM stability from Pauli-exclusion principle



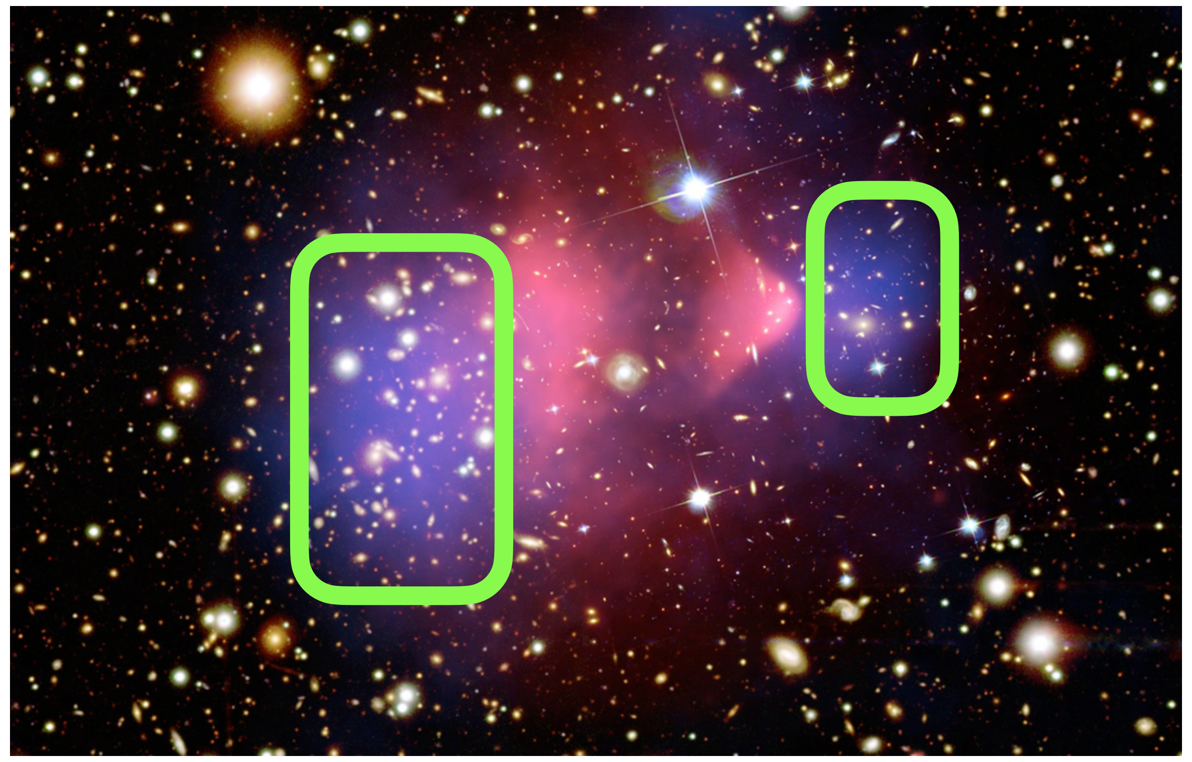
Based on ongoing project in collaboration with Brian Batell (Pittsburgh University)

Dark matter

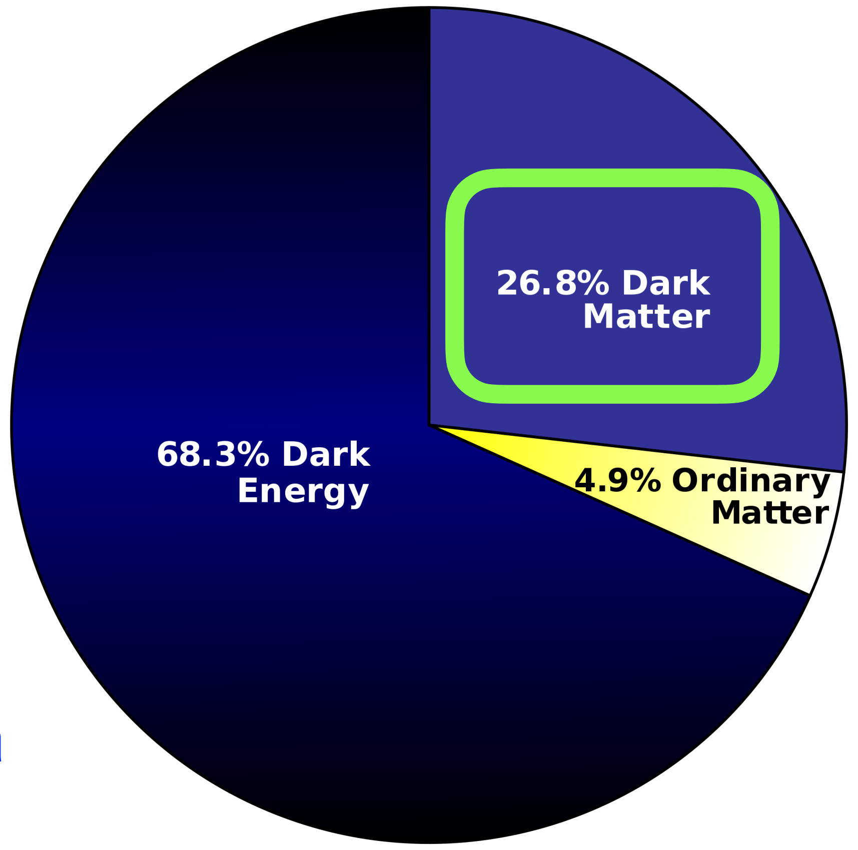
- **What is dark matter?**

<u>Very stable</u>
Neutral
Cold

$\rho_{\rm DM} \sim {\rm keVcm^{-3}}$



wikipedia



- **Why is dark matter very stable?**

"Charge" conservation, e.g. WIMP

Small mass/coupling,

$1/\Gamma_{\rm DM}^{\rm decay} \gg 13.8{\rm Gyr}$

c.f. electron, proton

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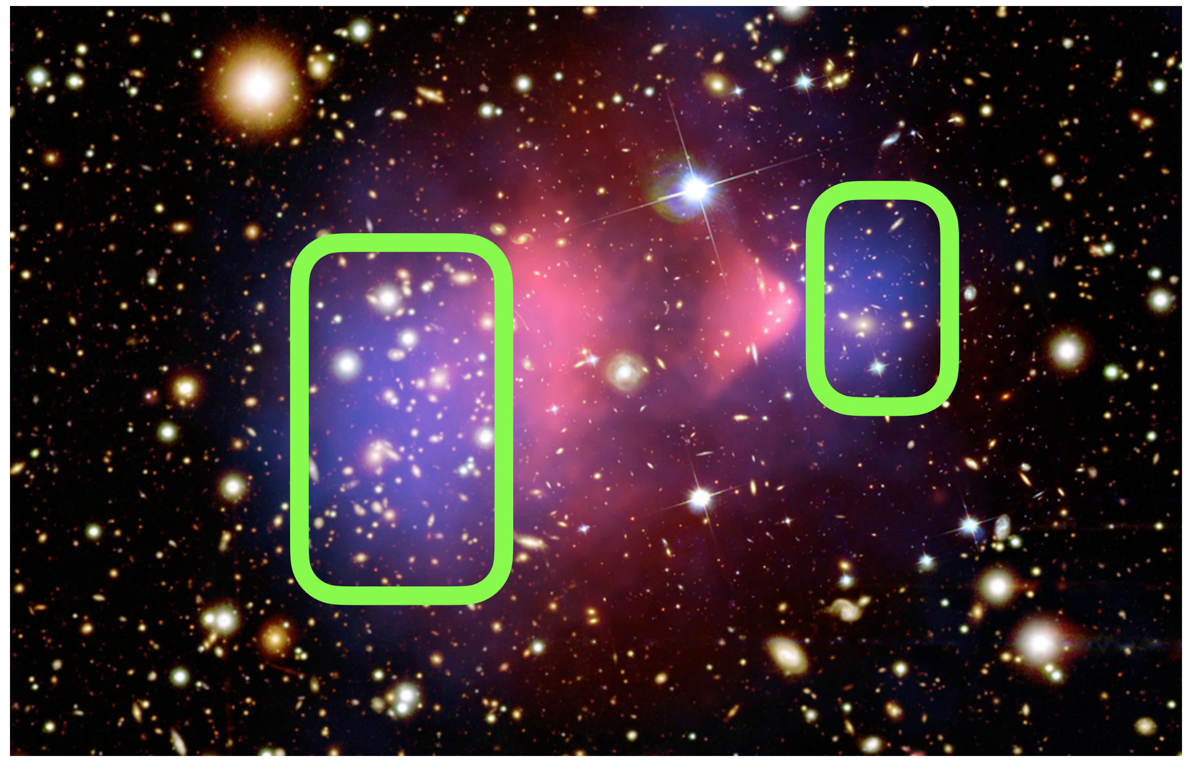

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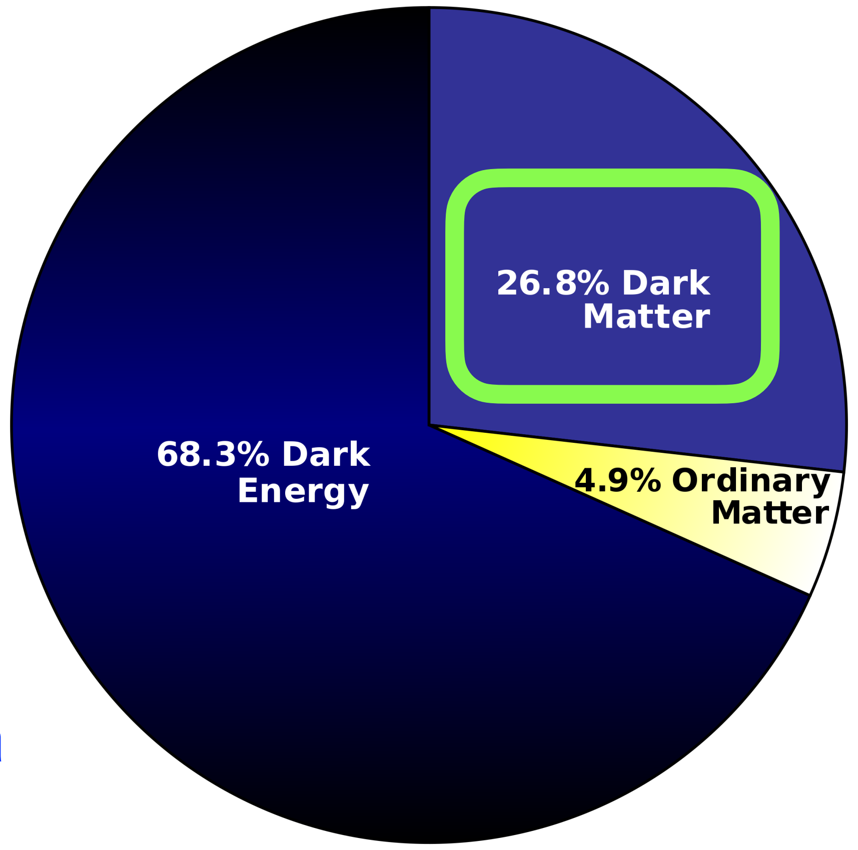

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DM on Sea of Fermions Batell, WY, in progress $1/\Gamma_{\rm DM}^{\rm decay} \ll 13.8{\rm Gyr}$

What I will be talking about

setup

$$\mathscr{L} \supset -\frac{y}{2}\phi\bar{\psi}^c\psi$$

$\phi : DM$ $\quad \psi :$ light fermion

$$V = m_\phi^2\phi^2/2$$

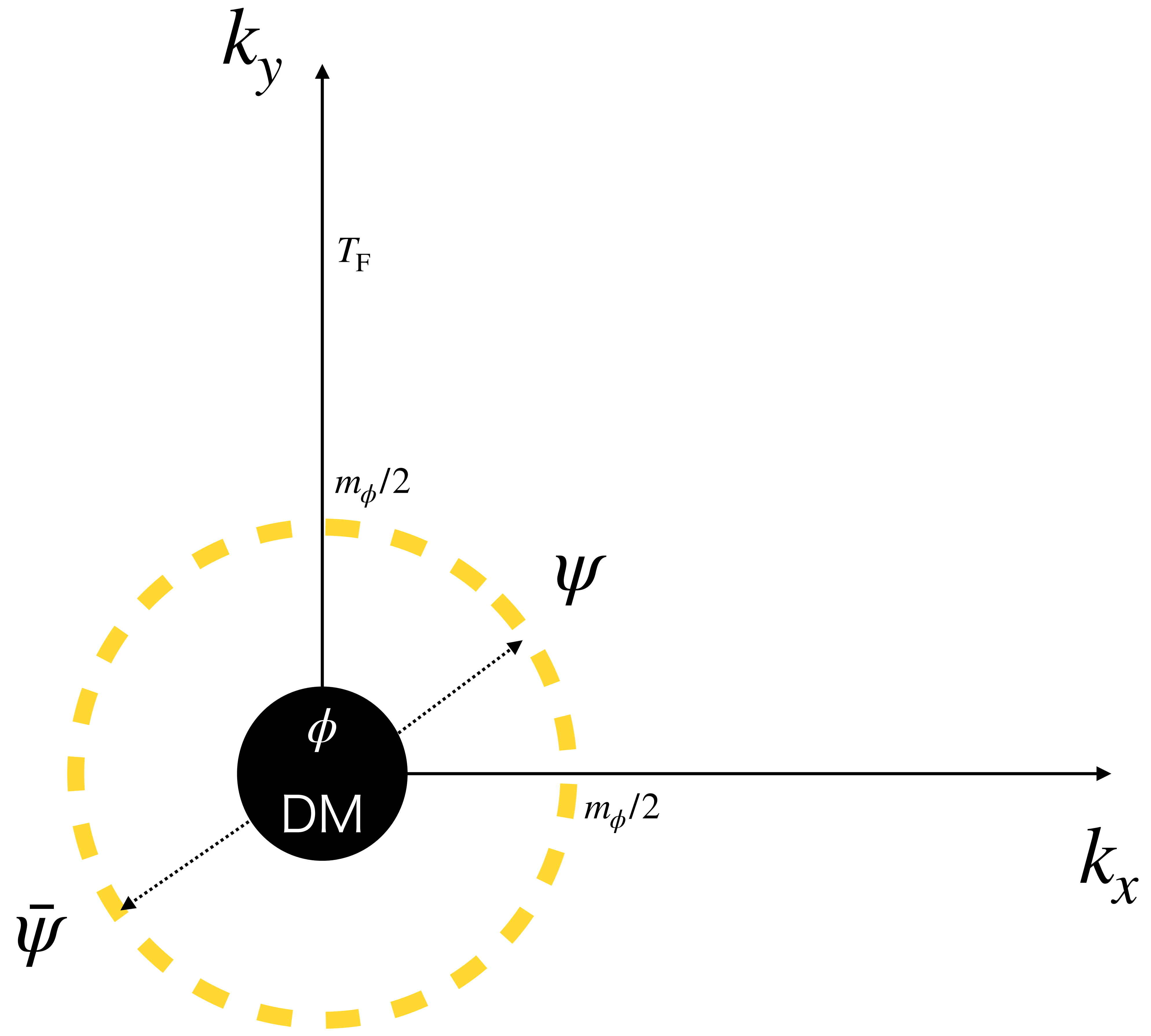
$1/\Gamma_{\phi\to\psi\psi} \ll$ 13.8Gyr

Conclusions

1. DM is stabilized due to Pauli-blocking from the produced fermi-gas.

2. Dark radiation of the fermi gas is self-interacting and may alleviate the Hubble tensions.

Generic conditions for DM on Sea of Fermions



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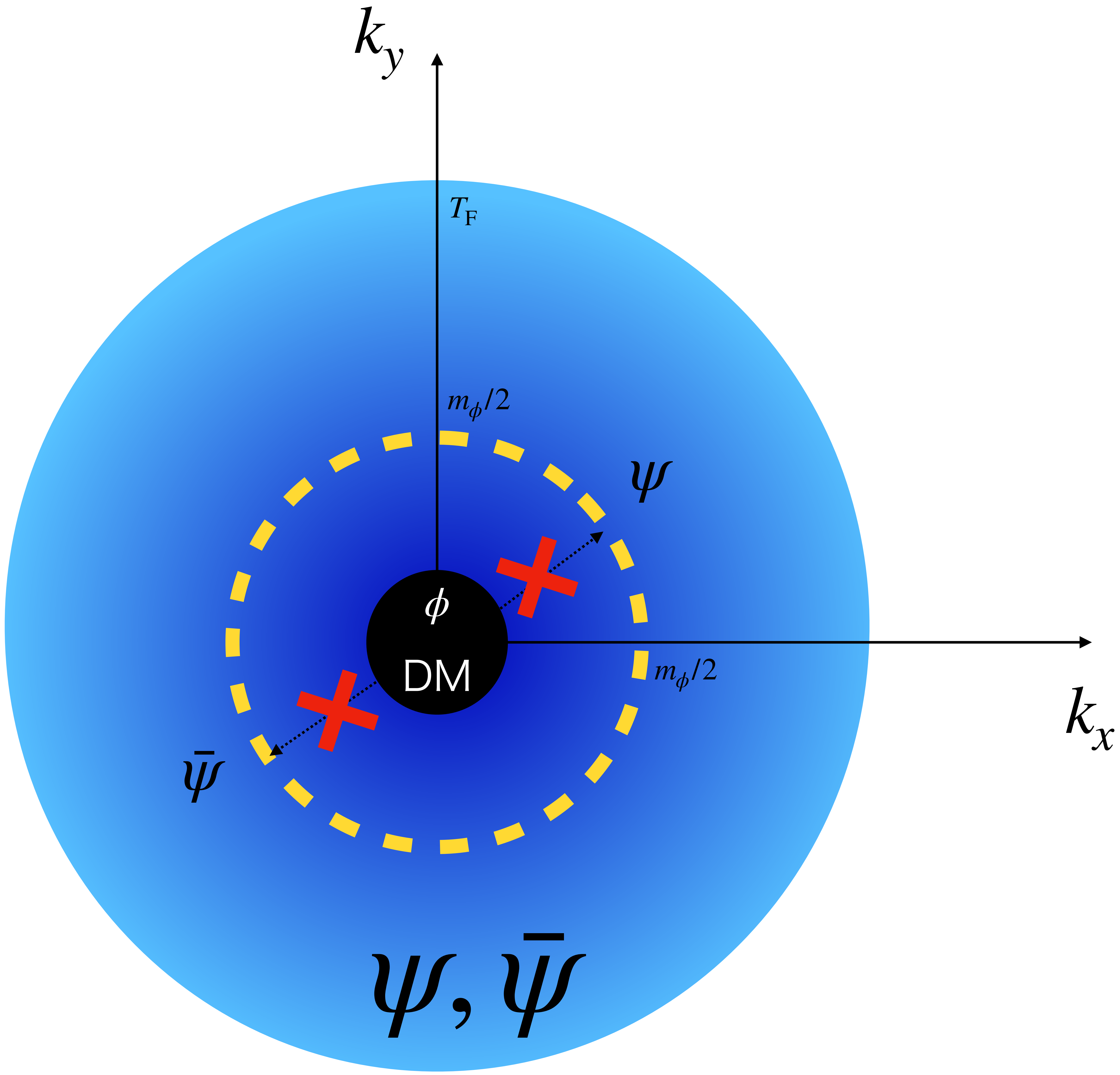

$$T_\mathrm{F} \gtrsim m_\phi/2$$

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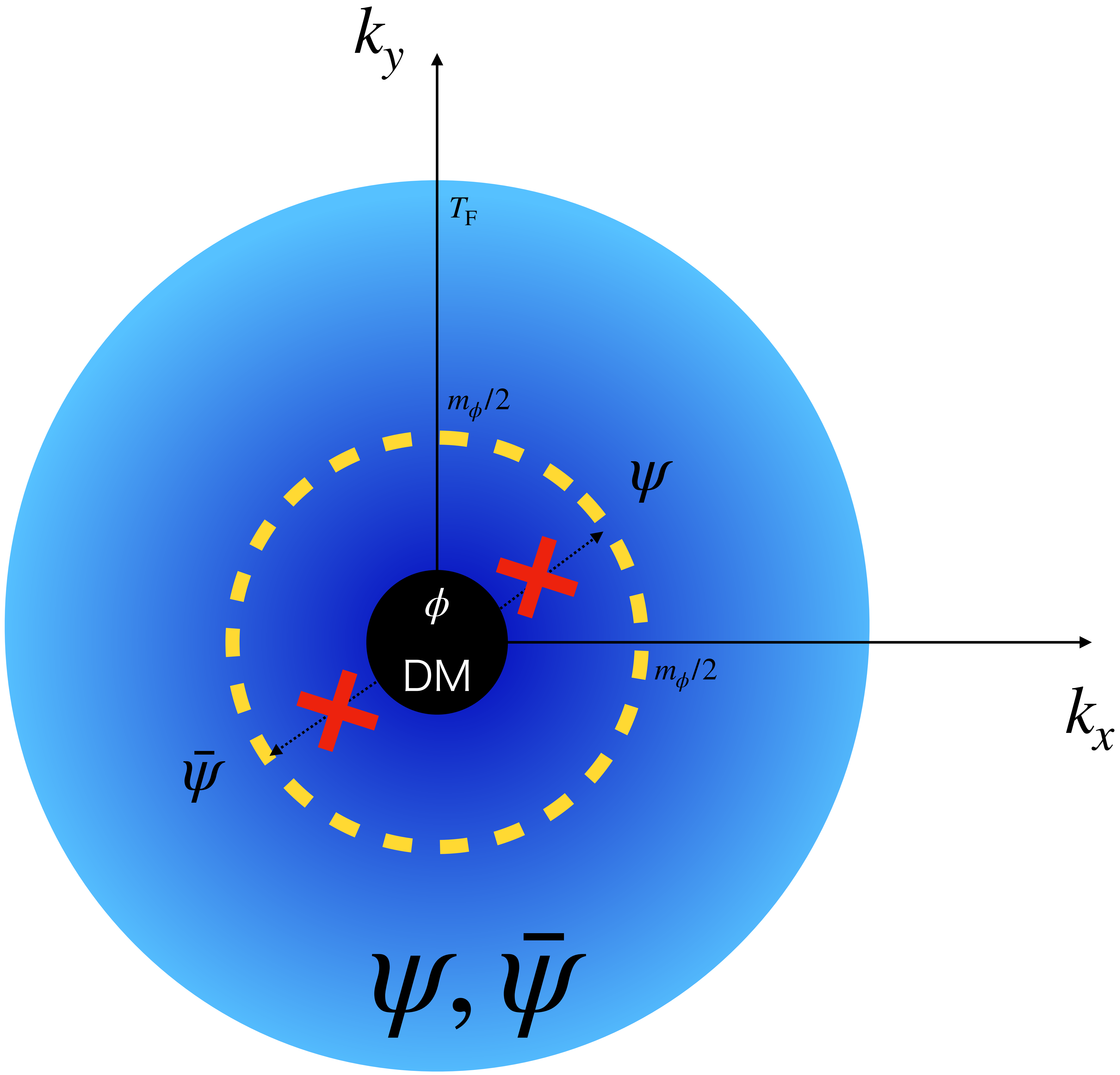

$$T_F \gtrsim m_\phi/2$$

Present Universe should have

$$\rho_\phi \sim \mathrm{keV}cm^{-3} \gg T_F^4$$

$$\boxed{m_\phi \lesssim 0.01\mathrm{eV}}$$

Thus I will talk about a system

- DM is light
- Number density is large

Cosmology of DM on Sea of Fermions

DM production and very early stage

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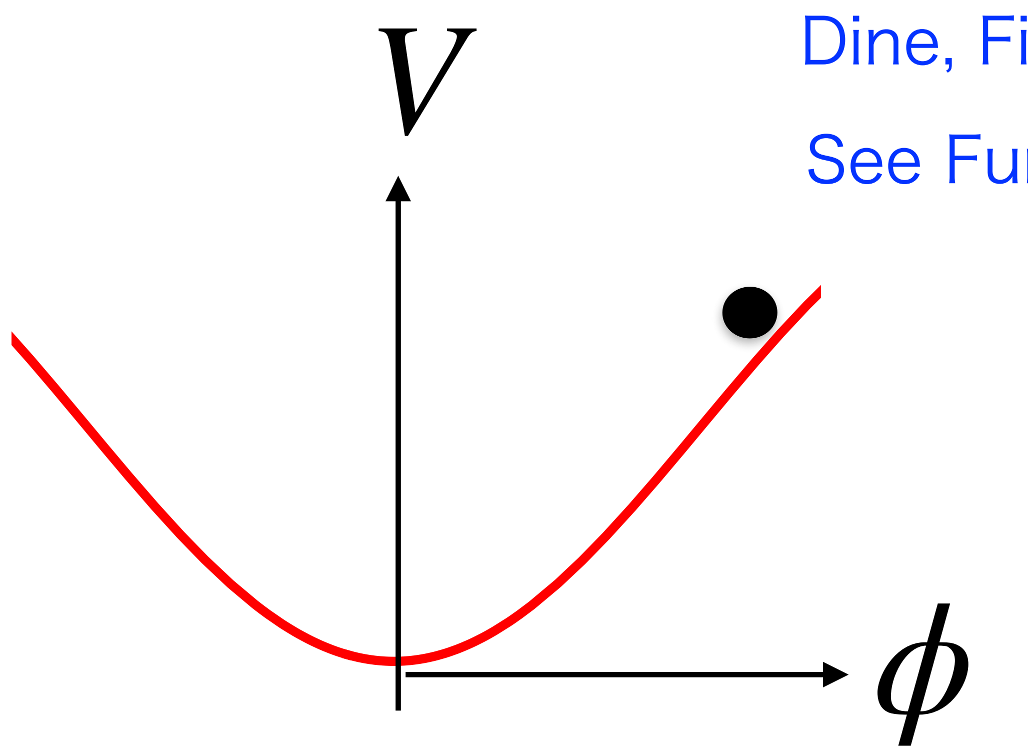
1. Misalignment mechanism to produce ϕ condensate.

Preskill et al, 1983;
Abbott, Sikivie, 1983;
Dine, Fishler, 1983;

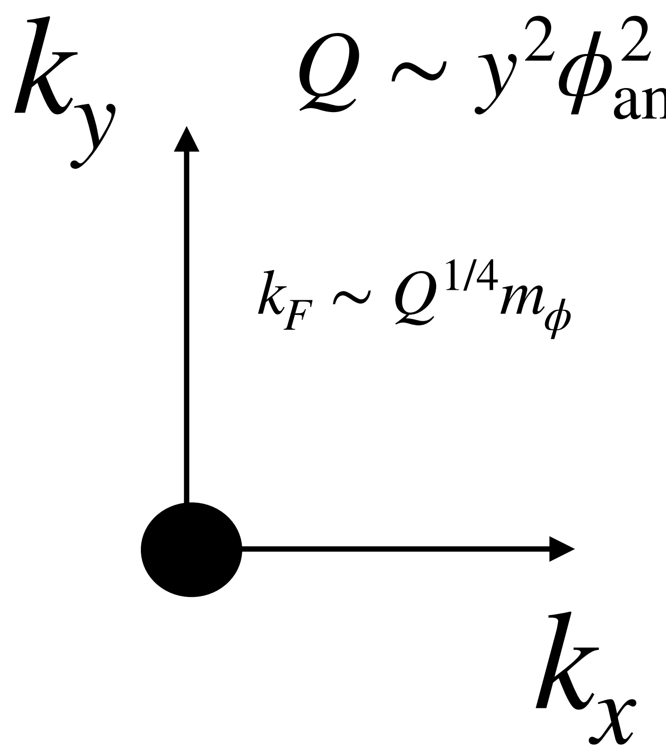
See Fumi's talk



2. Initial Fermi sea produced via parametric resonance

Greene:1998nh,Baacke:1998di,Greene:2000ew

$Q \sim y^2\phi_{\rm amp}^2/m_\phi^2$



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$$\rho_\psi \sim \frac{g_\psi}{2\pi^2}Q^{5/4}m_\phi^4 = \frac{g_\psi}{\pi^2}y^2Q^{1/4}\rho_\phi$$
$$\sim m_\phi^4 \quad (Q \sim 1)$$

We can also consider other production mechanisms as well, such as the light DM from inflaton decay, Moroi WY, 2011.09475;_2011.12285

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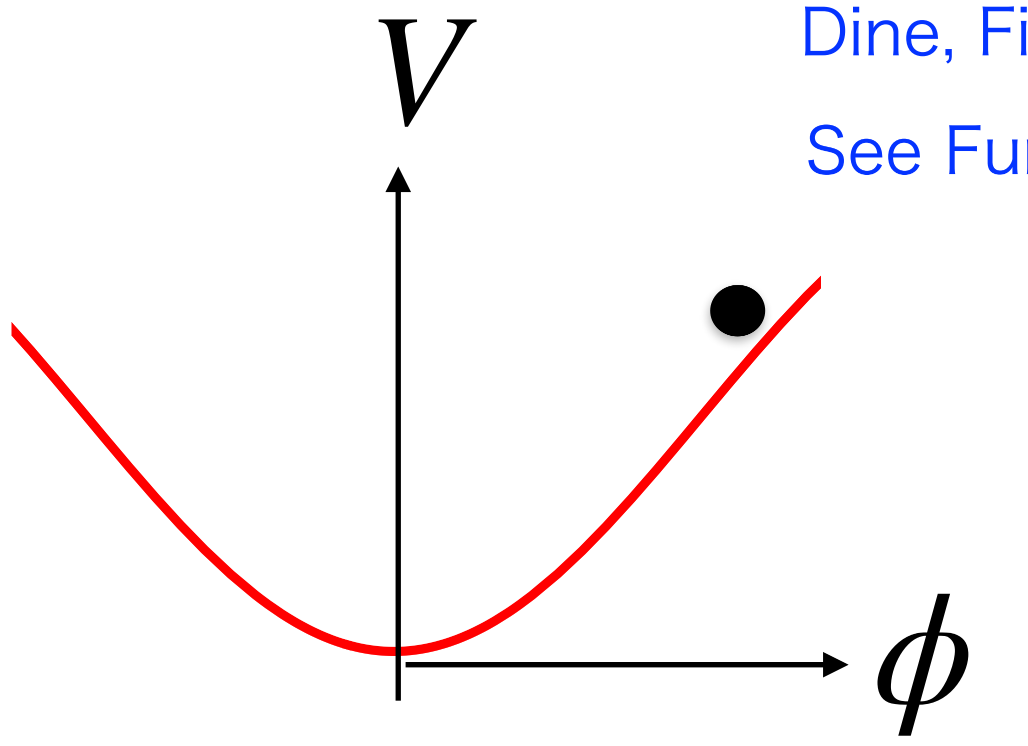

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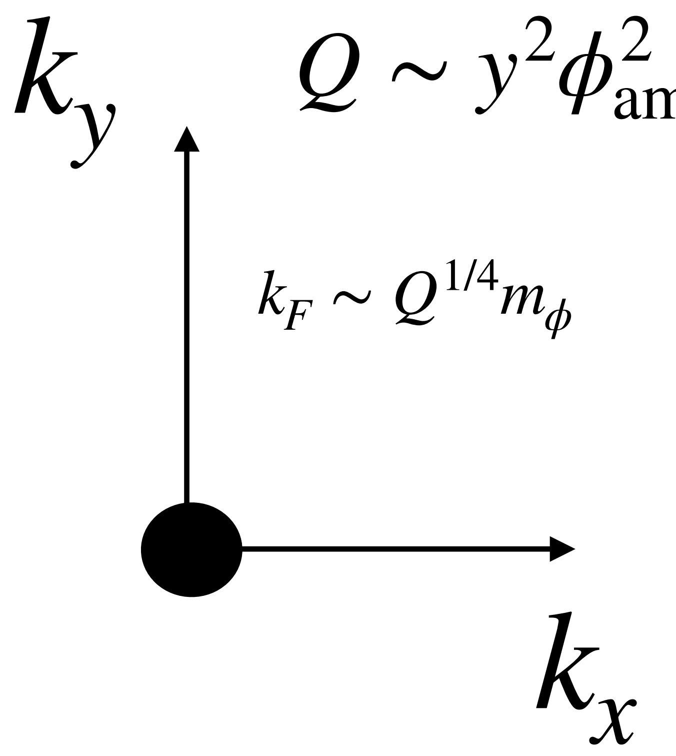

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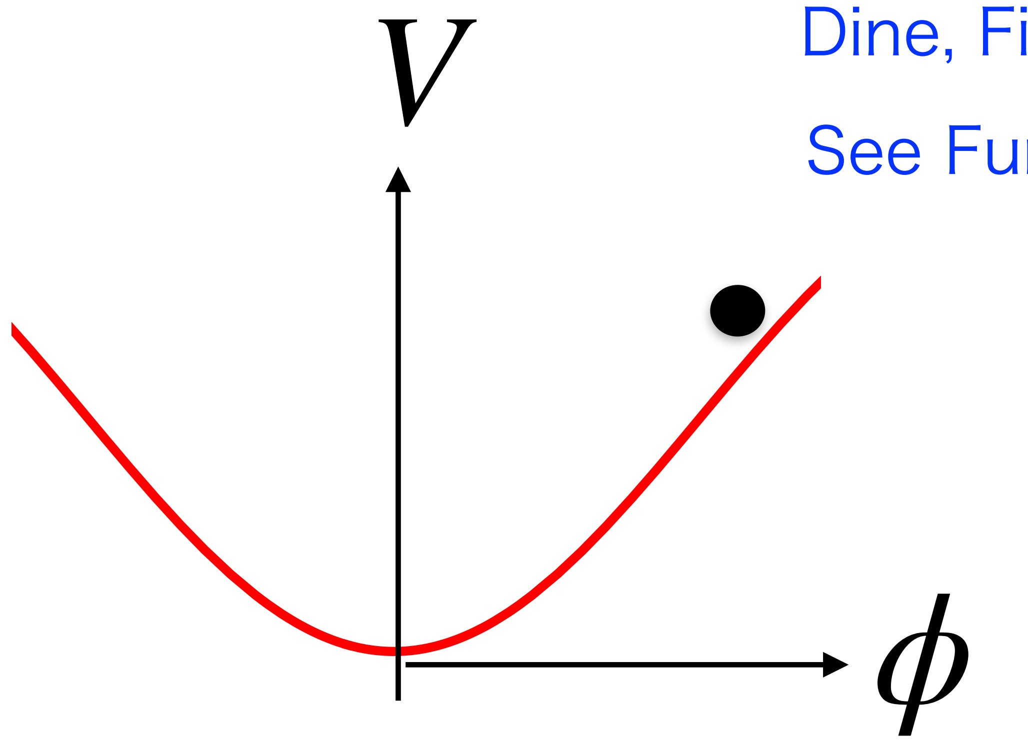

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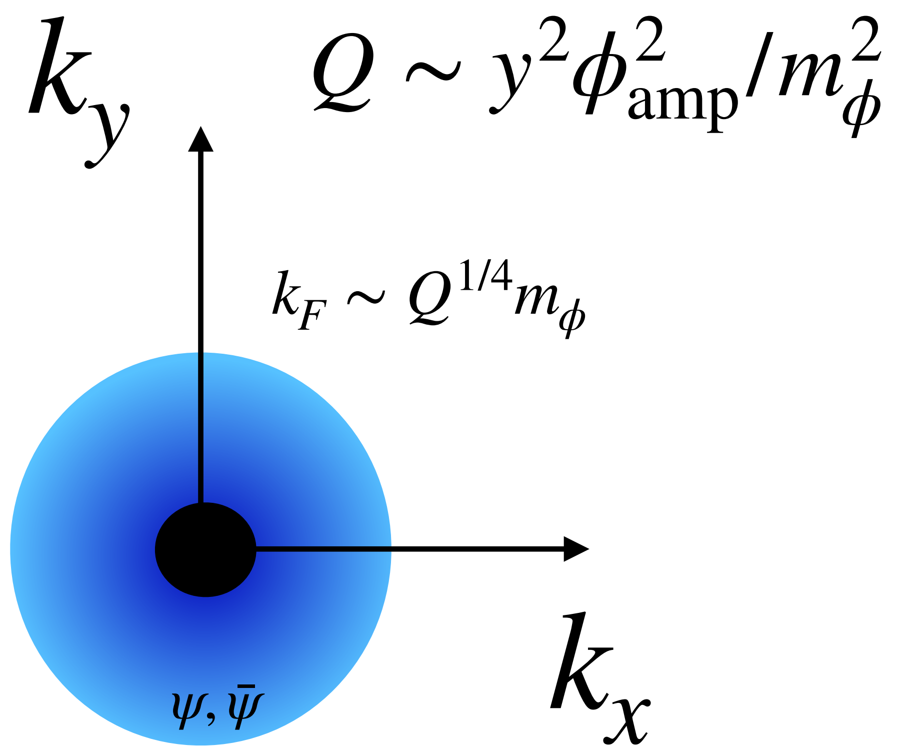

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DM stability in perturbative regime

Q redshifts to Q $\ll 1$, we can use the Boltzmann equation to study the stability.

Boltzmann equation

$$\frac{\partial f_\phi(p_\phi, t)}{\partial t} - p_\phi H \frac{\partial f_\phi(p_\phi, t)}{\partial p_\phi} = C^\phi(p_\phi, t),$$

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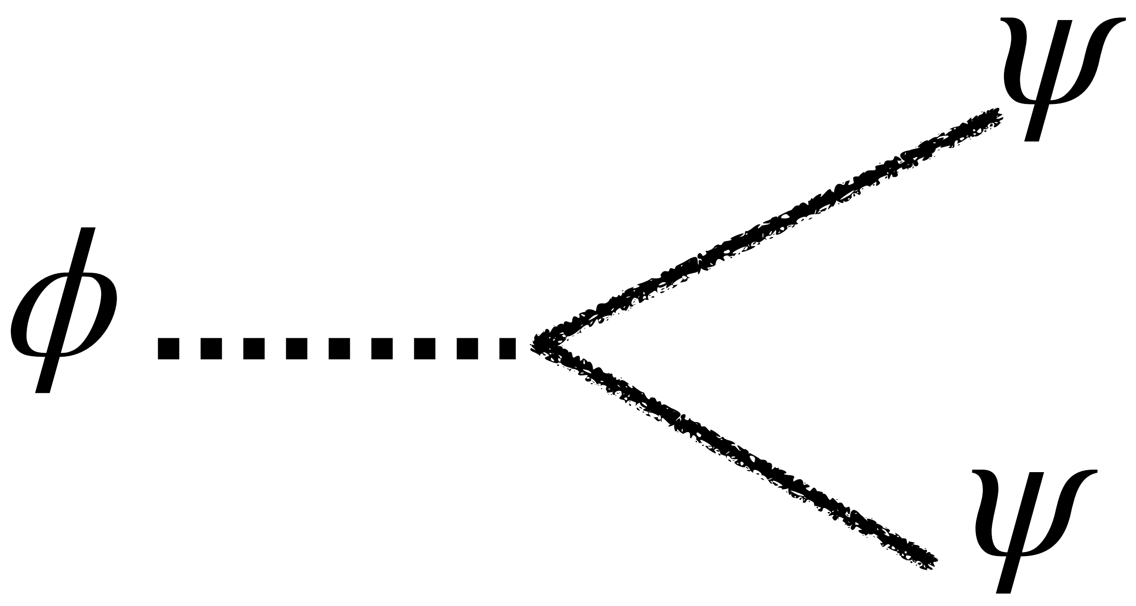

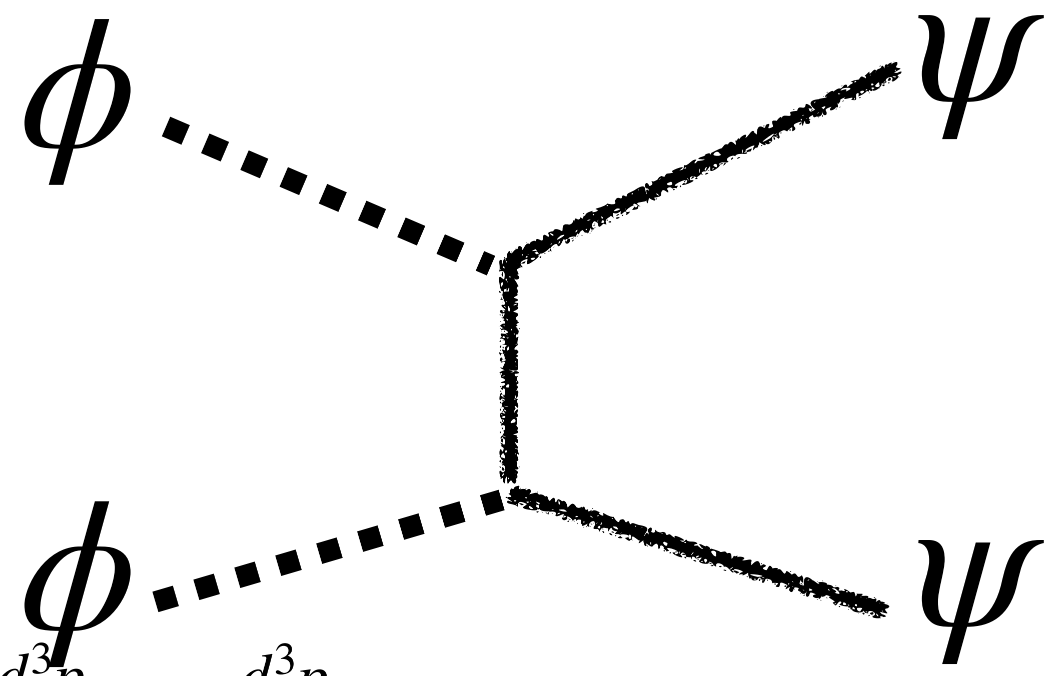

e.g. $C^\phi \supset$

$$C^\phi_{\phi\leftrightarrow\psi\psi} = -\frac{1}{S_\psi}\frac{1}{g_\phi}\frac{1}{2E_\phi}\sum_{\text{spins}}\int\frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2}(2\pi)^4\delta^4(p_\phi - p_1 - p_2)\,|\mathscr{M}|^2 \times \left\{f_\phi(p_\phi)[1-f_\psi(p_1)][1-f_\psi(p_2)] - [1+f_\phi(p_\phi)]f_\psi(p_1)f_\psi(p_2)\right\}.$$

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Pauli-blocking, Bose-enhancement factors are very important

Life-time of the DM

We solve the Boltzmann equation by neglecting Hubble expansion with some approximations.

Initial conditions:

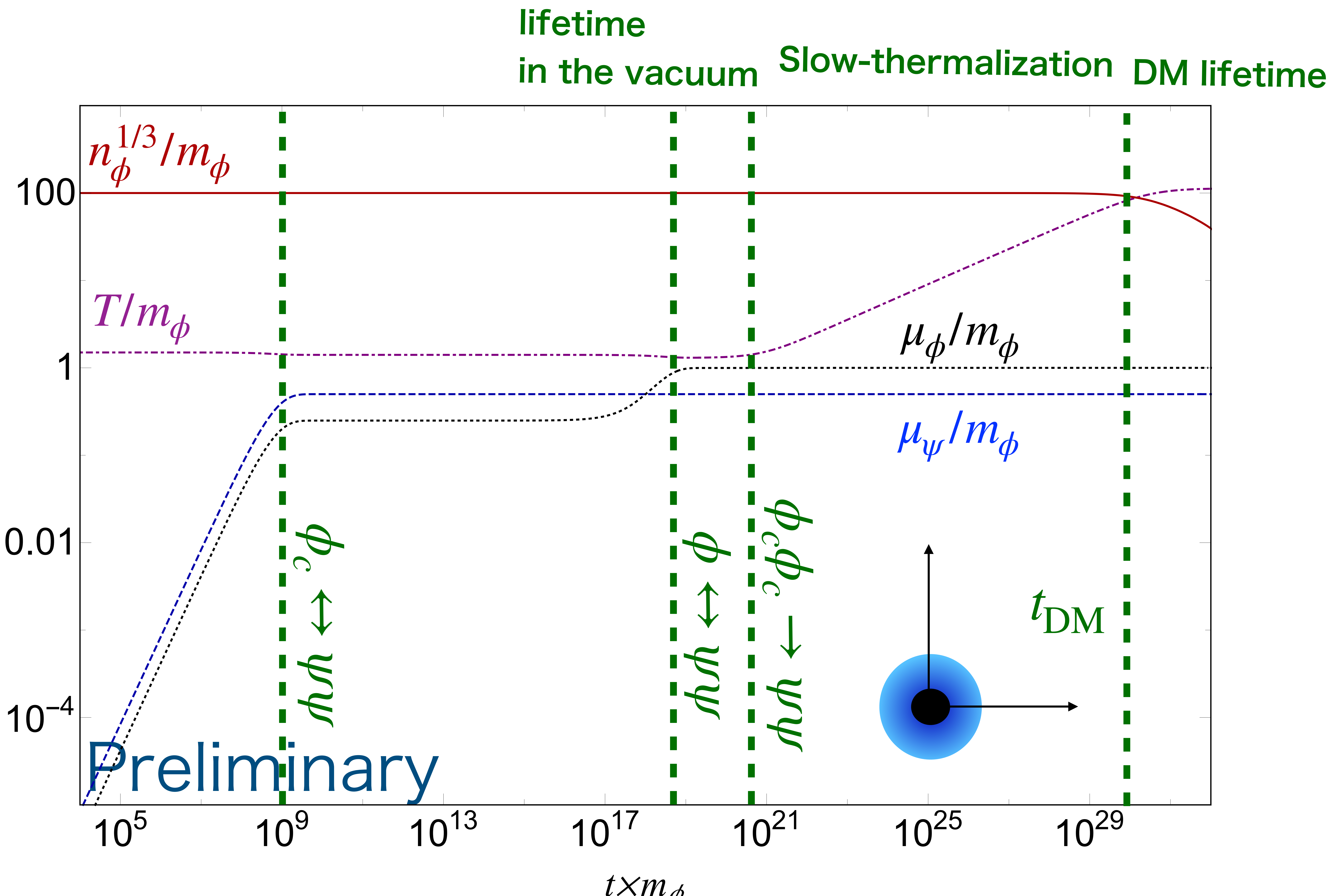
$n_\phi[0]/m_\phi^3 = 10^8$,

$T[0] = 3/2 m_\phi$,

$\mu_\psi[0] = \mu_\phi[0] = 0$,

$y = 10^{-8}$

$M_\psi = m_\phi/50$



Life-time of the DM

We solve the Boltzmann equation by neglecting Hubble expansion with some approximations.

Initial conditions:

$n_\phi[0]/m_\phi^3 = 10^8,$

$T[0] = 3/2m_\phi,$

$\mu_\psi[0] = \mu_\phi[0] = 0,$

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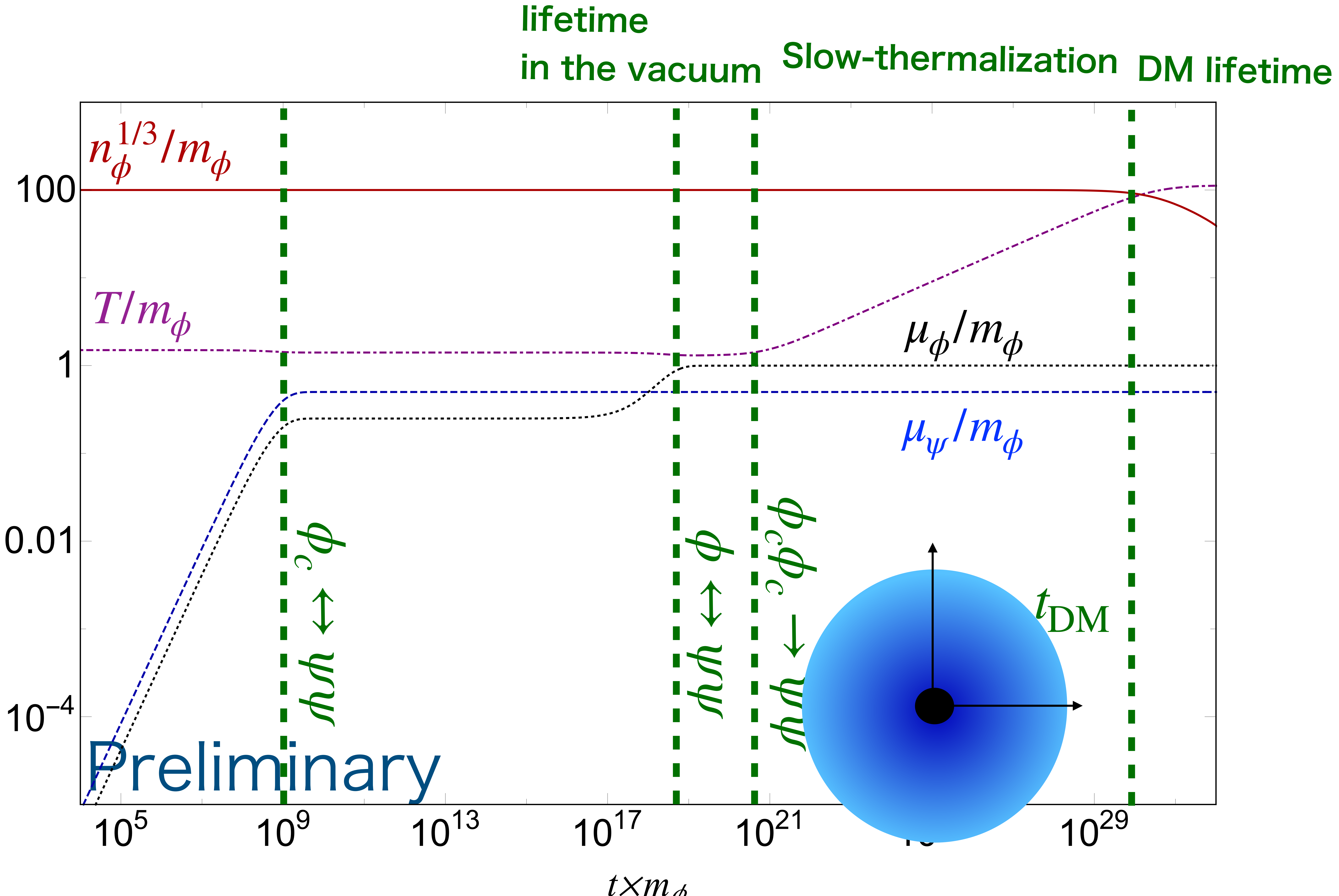
$M_\psi = m_\phi/50$



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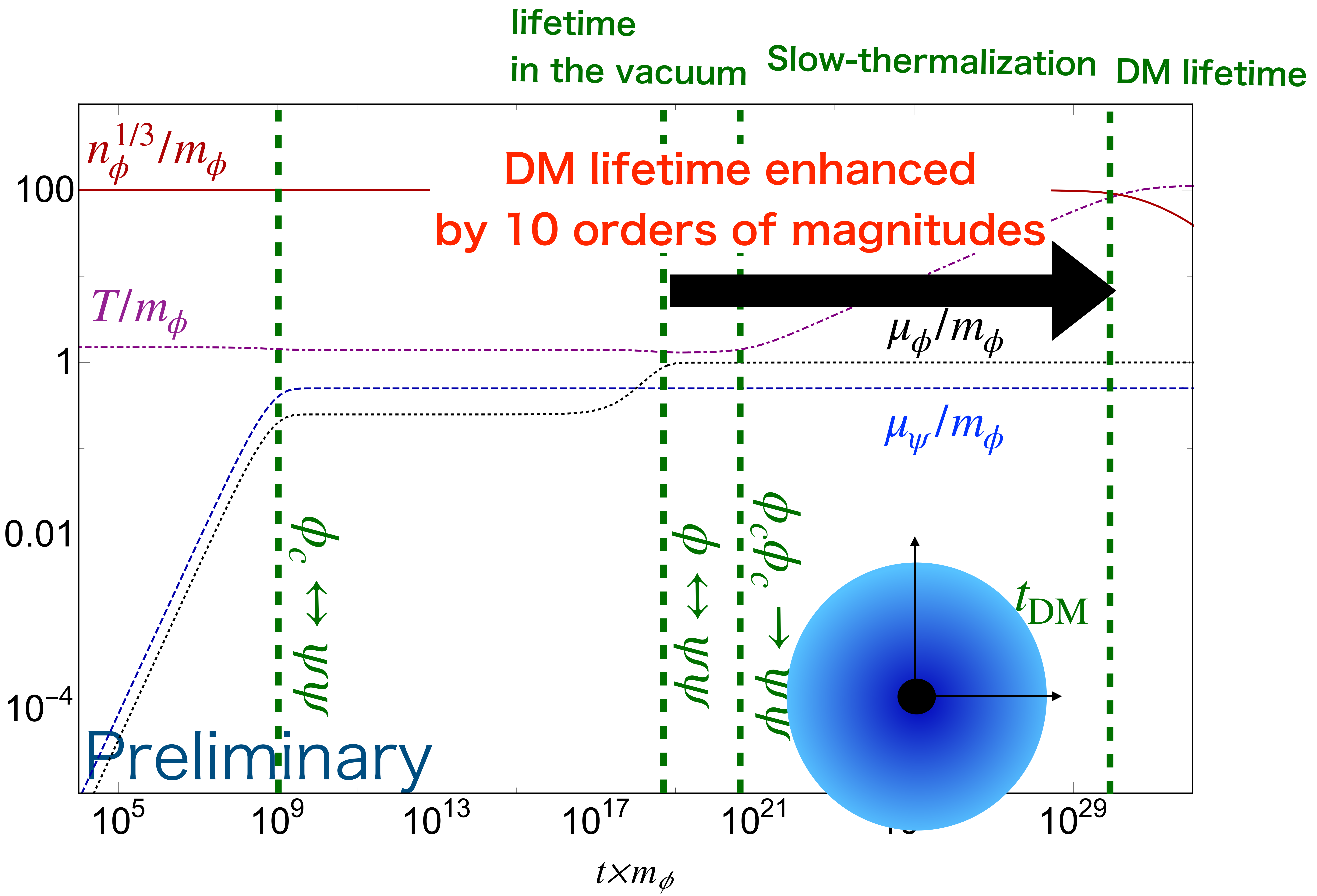

Dark radiation self-interaction prevents DM from decay.

Initial conditions:

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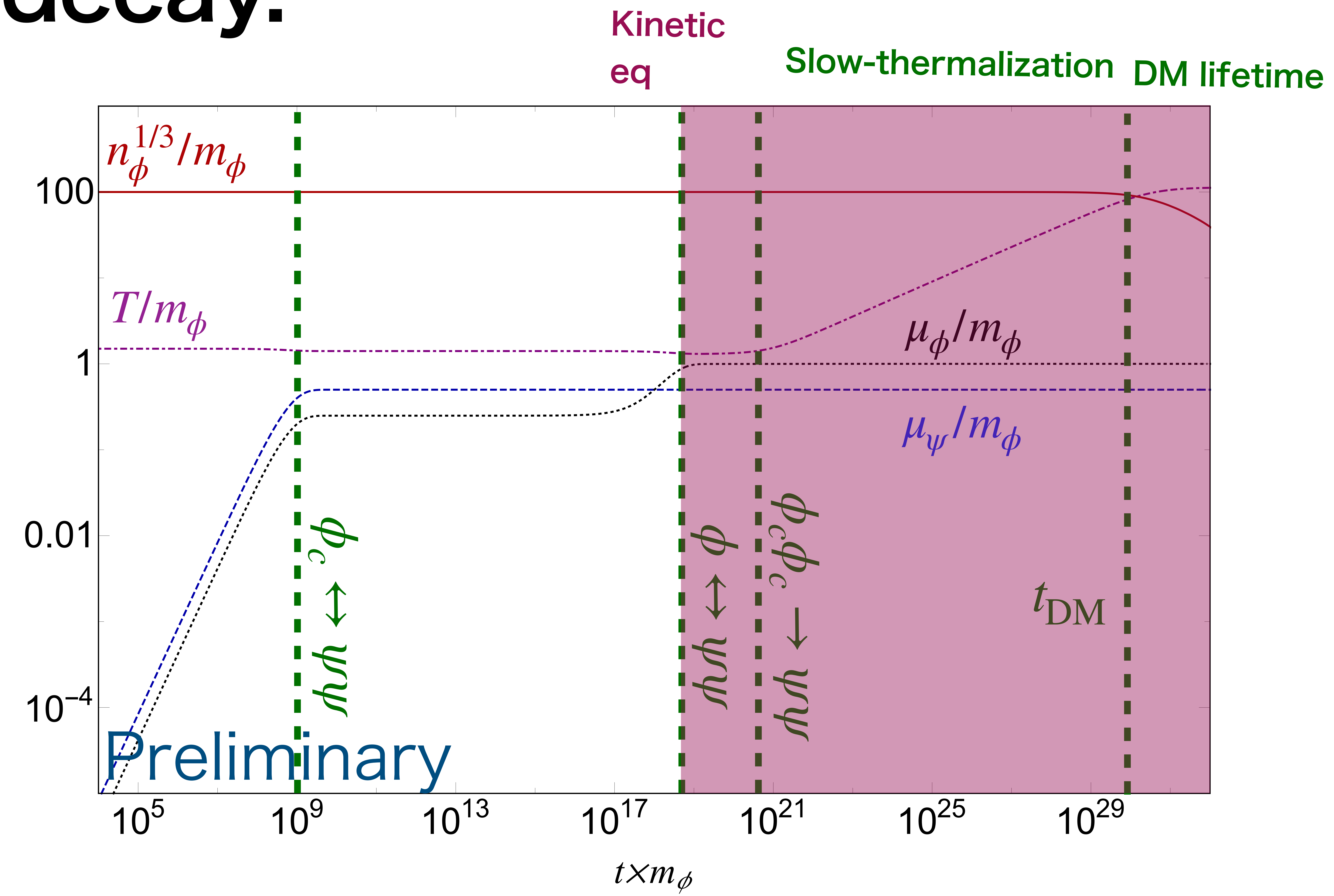
$T[0] = 3/2 m_\phi$,

$\mu_\psi[0] = \mu_\phi[0] = 0$,

$y = 10^{-8}$

$M_\psi = m_\phi/50$



Produced Dirac sea is self-interacting!

Dark radiation and deviation from ΛCDM

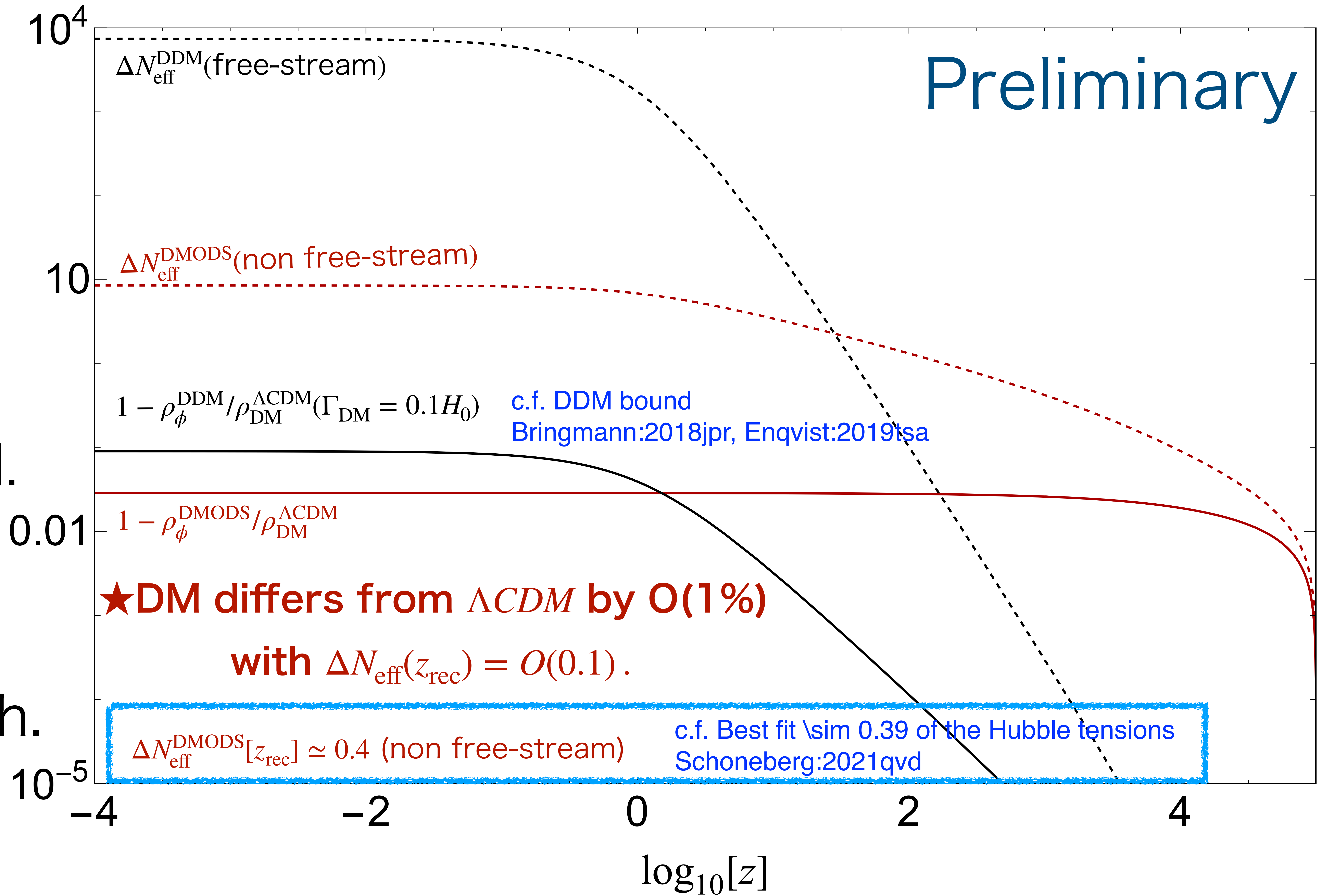
We solve (integrated) Boltzmann equation with Hubble expansion

$y = 7.4 \times 10^{-10}, m_\phi = 10^{-4} eV$ and $M_\psi = m_\phi/5.$

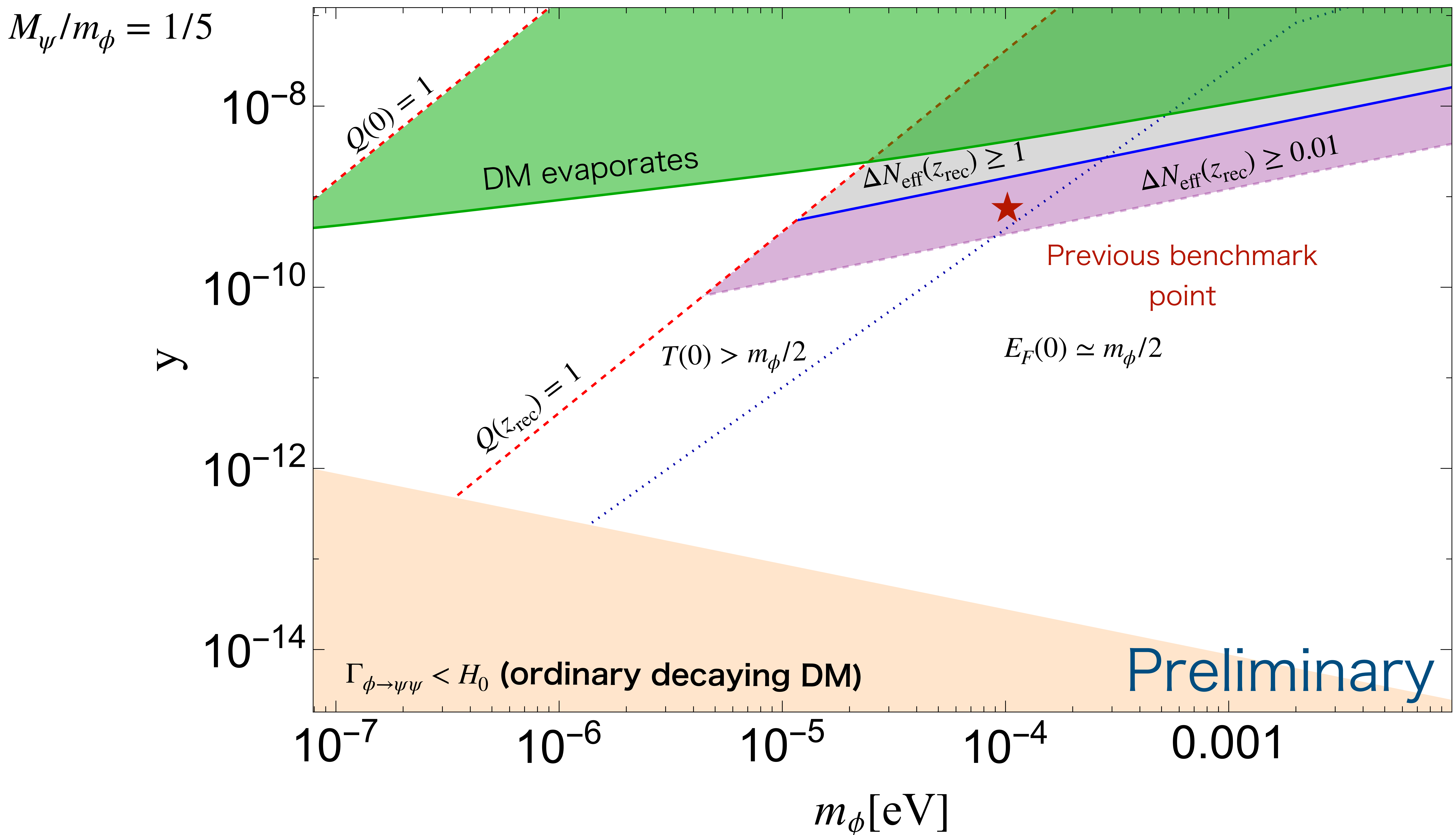
Initial conditions:

$\rho_\phi(z = 10^5) = \rho_{\rm DM}^{\Lambda\rm CDM}$ and $T[z = 10^5] = m_\phi\,.$

- Self-interacting DR significantly produced.
- DM comoving density does not change much.



Parameter region



Conclusions

1. ALP DW without a string following scaling solution naturally explains the isotropic CB. Takahashi, WY, 2012.11576
2. The scenario can be fully tested in the future observation of anisotropic CB. Takahashi, Kitajima, Kozai, WY, in progress

Batell, WY, in progress.

1. DM can be stabilized if $m_\phi < 0.01eV, y \lesssim 10^{-7}$, even if $\Gamma_{decay,vac} \gg H_0$.
2. The resulting dark radiation of the Fermi gas is self-interacting and may alleviate the Hubble tension.
3. The present Universe DM density has an upper bound. DM stabilized by CnuB may predict the enhancement of ν_e capturing rate by ~ 5 in PTOLEMY. (will appear in our paper)