TOHOKU UNIVERSITY

Axion domain walls, and cosmic birefringence

November 27. 2022@ YU Workshop 2022
— Frontiers in Gravity and Fundamental Physics —

Fumi Takahashi (Tohoku)

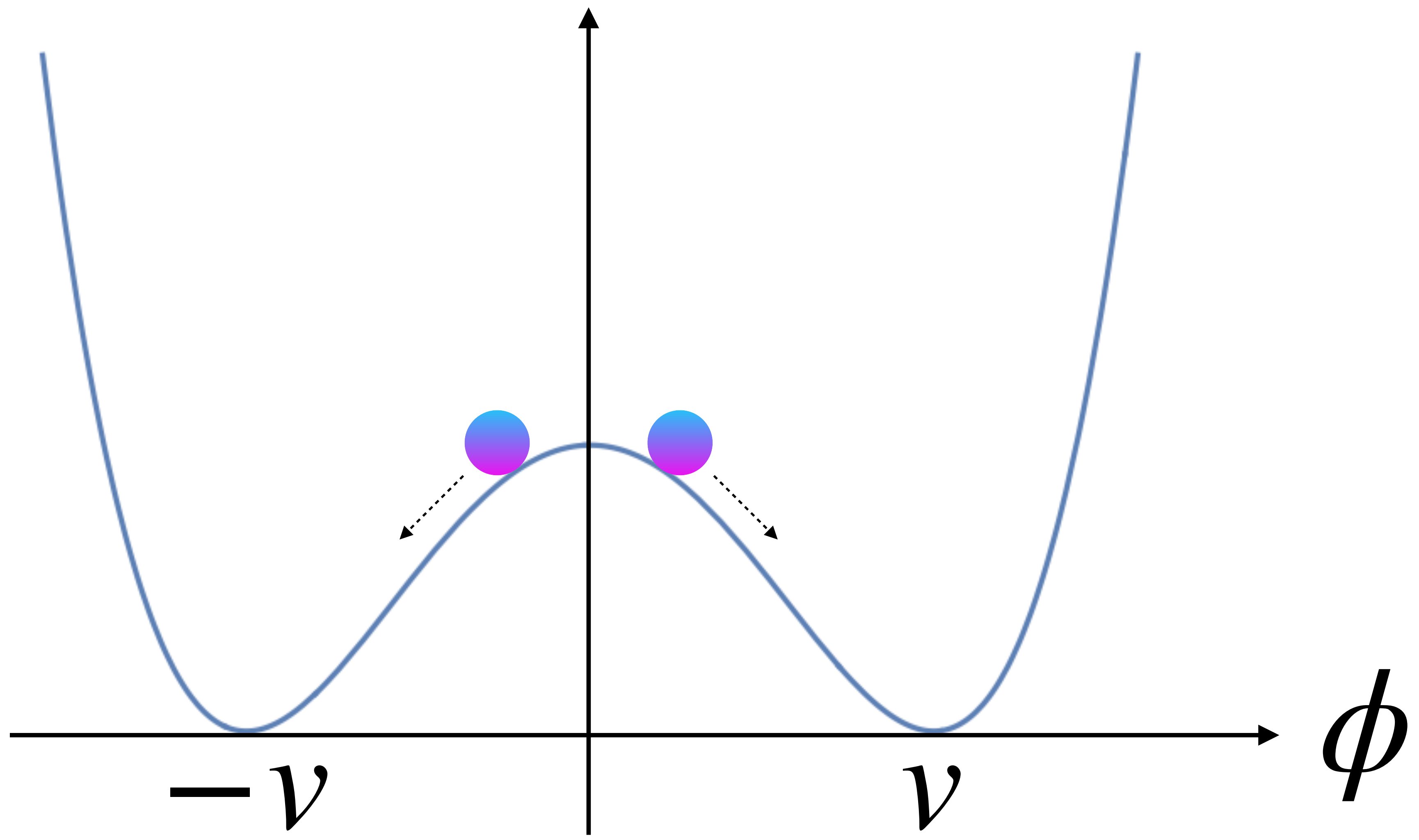
Based on 2012.11576 with Wen Yin, 2205.05083 with Naoya Kitajima, Fumiaki Kozai, and Wen Yin
2211.06849 with Diego Gonzalez, Naoya Kitajima, and Wen Yin

1. Introduction

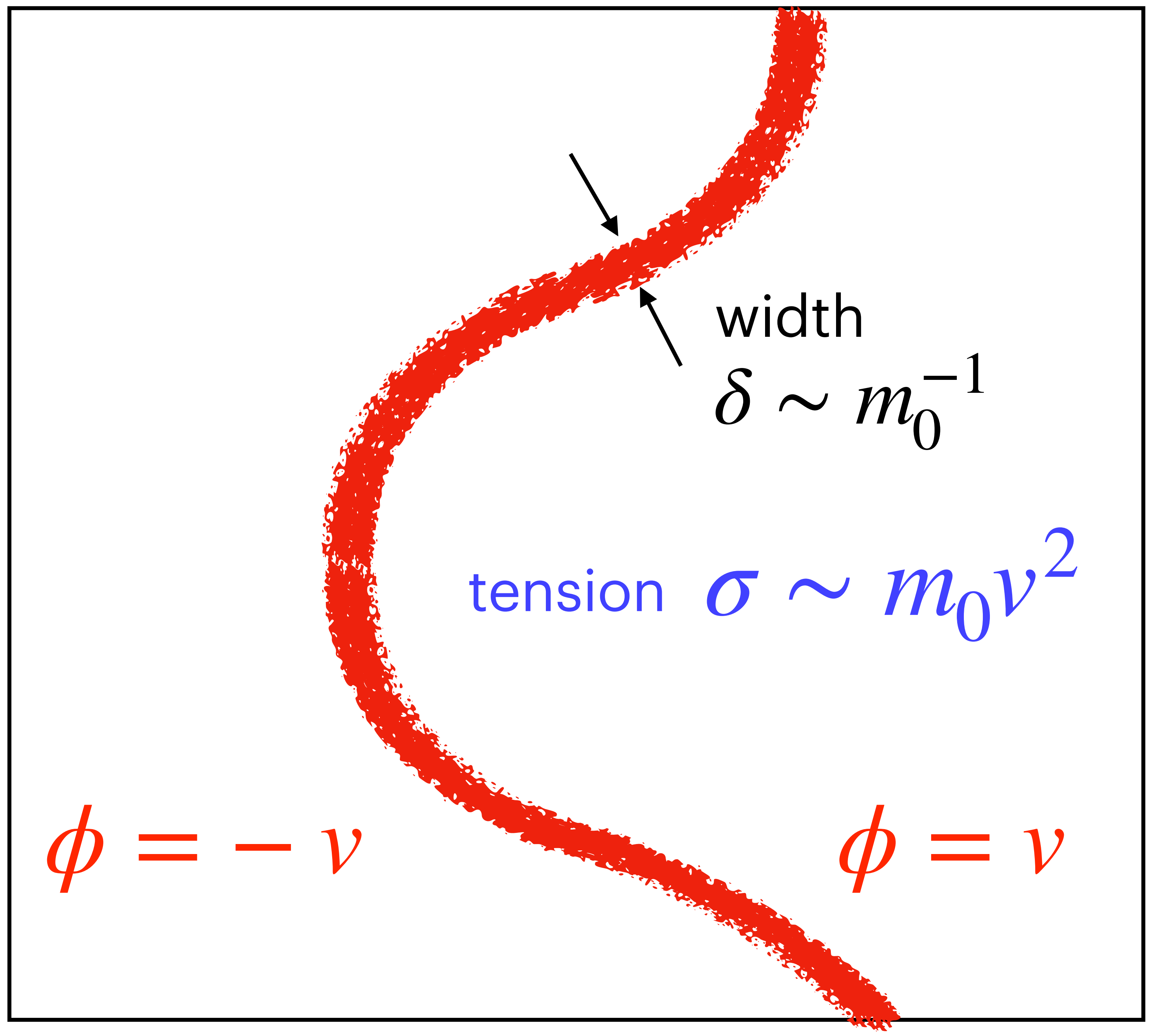
Domain walls (DWs) are produced when discrete symmetry is spontaneously broken. Zeldovich, Kobzarev, and Okun `74, Kobzarev, Oku, Voloshin `74, Kibble `76 see also Bogolyubov `66

e.g.) Z_2 symmetry

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 = \frac{\lambda}{4}v^4 - \frac{1}{2}m_0^2\phi^2 + \frac{\lambda}{4}\phi^4$$



Domain wall



Scaling regime

Press, Ryden, and Spergel `89, Hindmarsh `96, Garagounis and Hindmarsh `03, + many

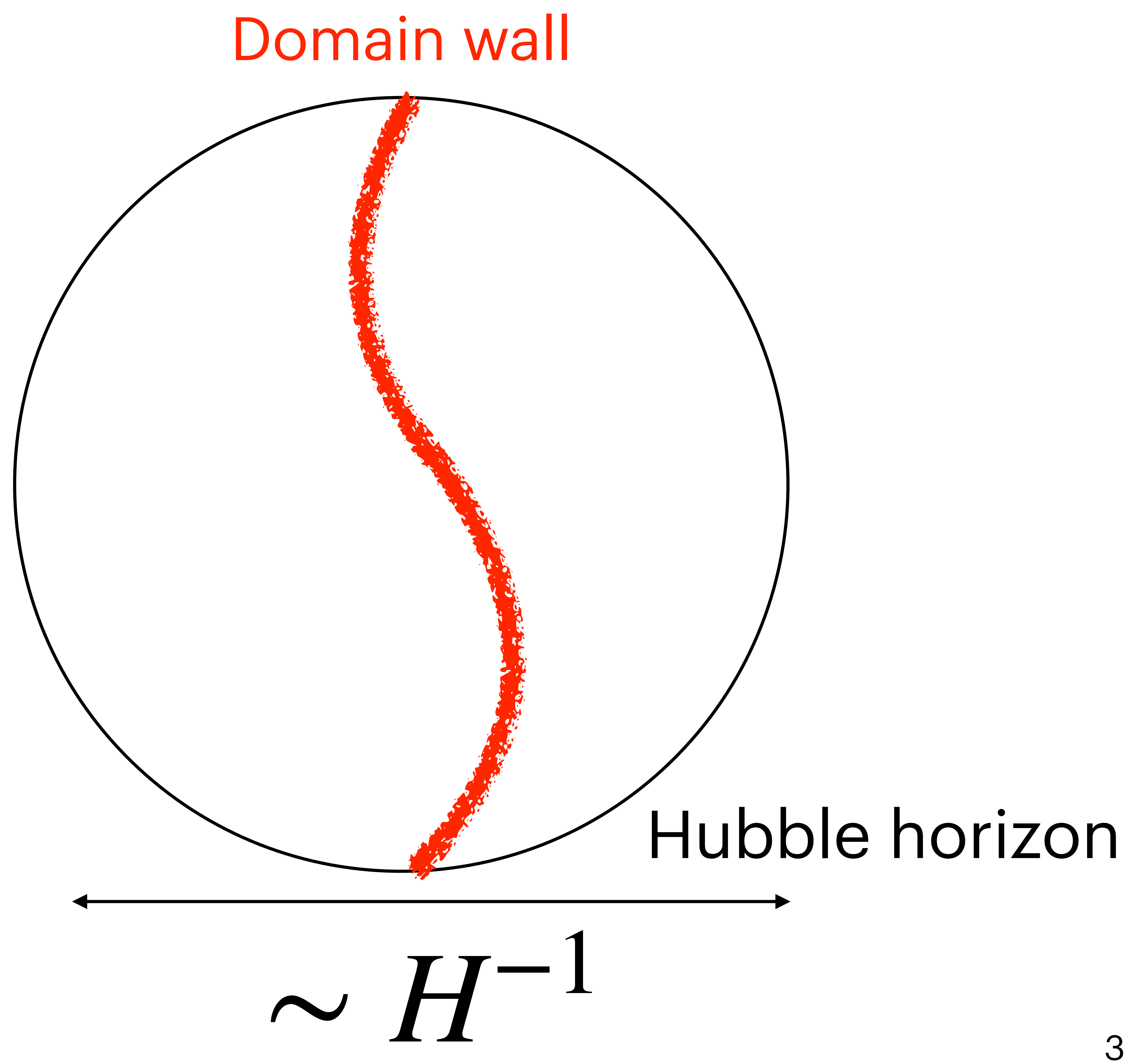
Once formed, the DW network soon converges to the so-called scaling solution, a situation where there is on average about one DW per the Hubble horizon.

Scaling solution: $$\boxed{\rho_{\rm DW} \sim \sigma H}$$

$$\left(\propto a^{-2} \quad \text{for RD}\right)$$

The scaling solution has been usually regarded as an attractor.

This is true for at least the cases that have been studied numerically so far.



Cosmological DW problem

Zeldovich, Kobzarev, and Okun `74

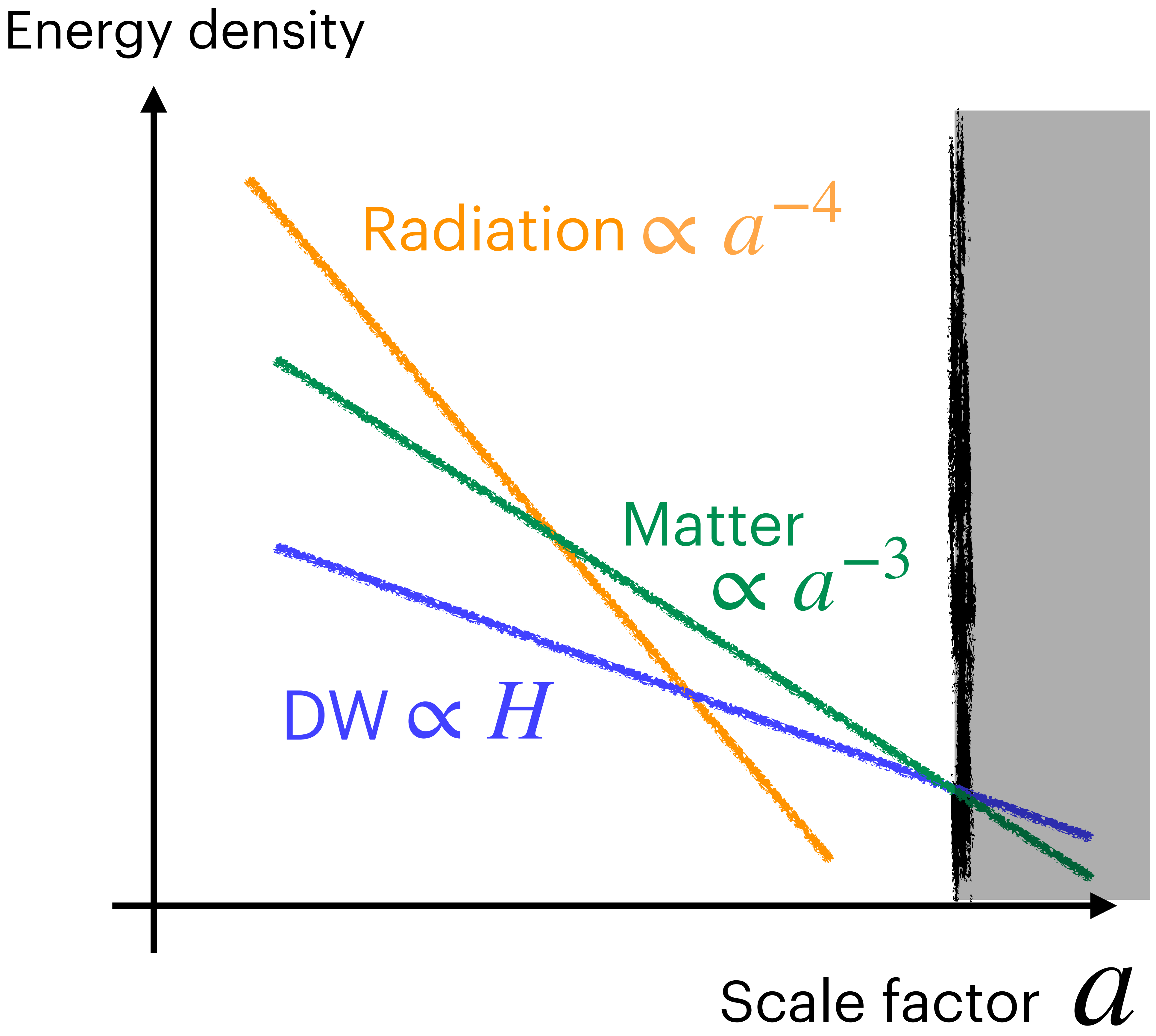
DWs can easily dominate the universe, which makes it anisotropic and inconsistent with observations.

Even if DW is subdominant, its energy density is bounded above due to the CMB observations.

$$\rho_{\mathrm{DW}} \underset{\uparrow}{\sim} \sigma H < 10^{-5} H_0^2 M_p^2$$

Scaling solution

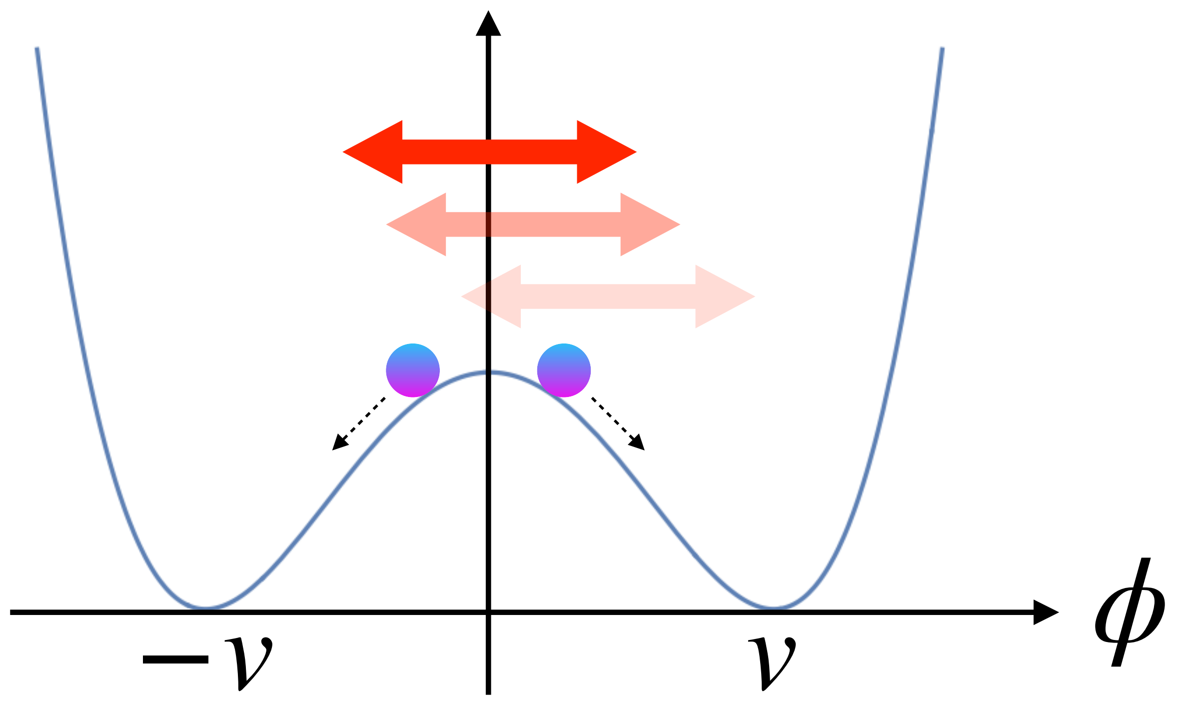
$$\boxed{\sigma < (\mathrm{MeV})^3}$$



I will talk about the two recent topics related to DWs;

- Stability of the DW network with inflationary fluctuations

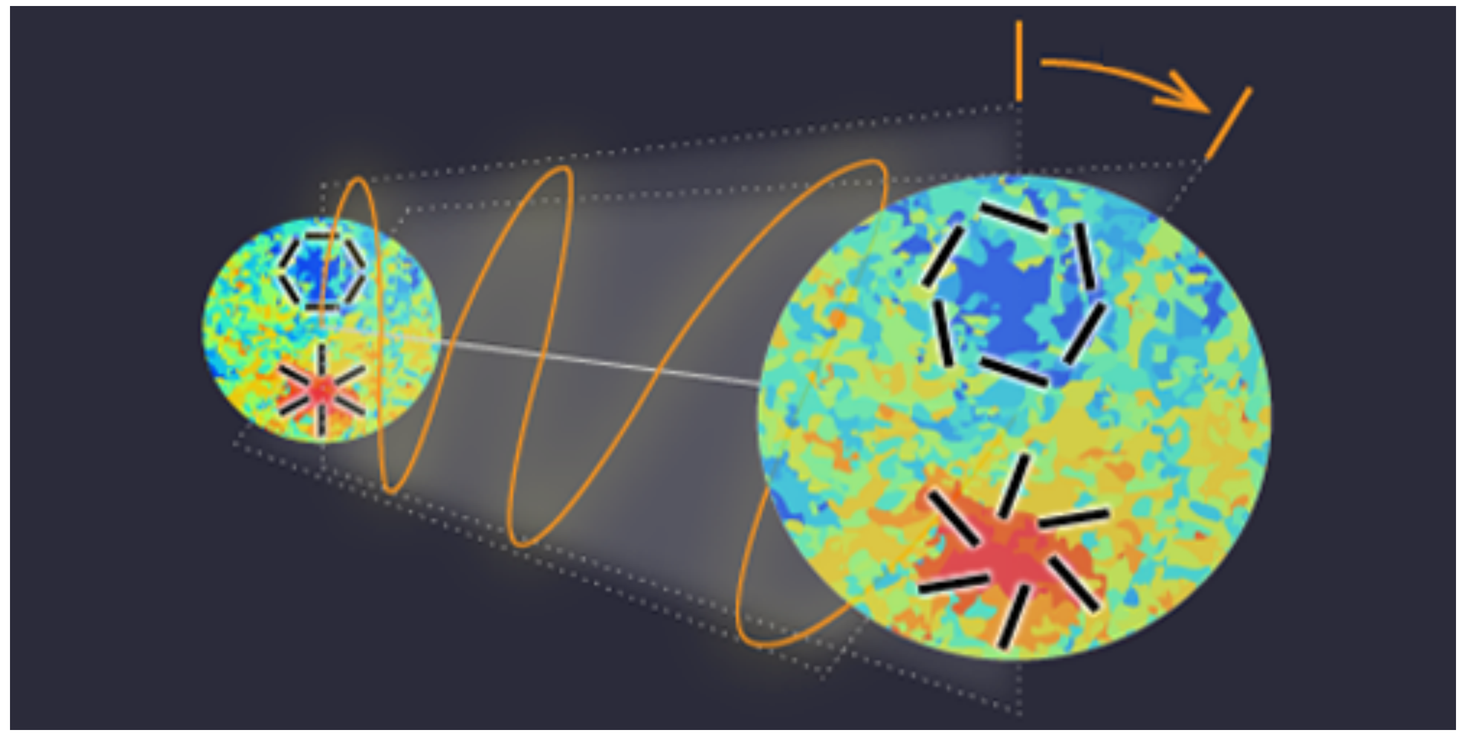
Gonzalez, Kitajima, FT and Yin 2211.06849



- Thermal or non-thermal fluctuations?
- Decay fast in the presence of bias?

- Cosmic birefringence caused by axion DWs

FT and Yin 2012.11576, Kitajima, Kozai, FT and Yin 2205.05083,
Gonzalez, Kitajima, FT and Yin 2211.06849



- The field value, not the energy, of the scalar field that constitutes DW can be probed by cosmic birefringence.

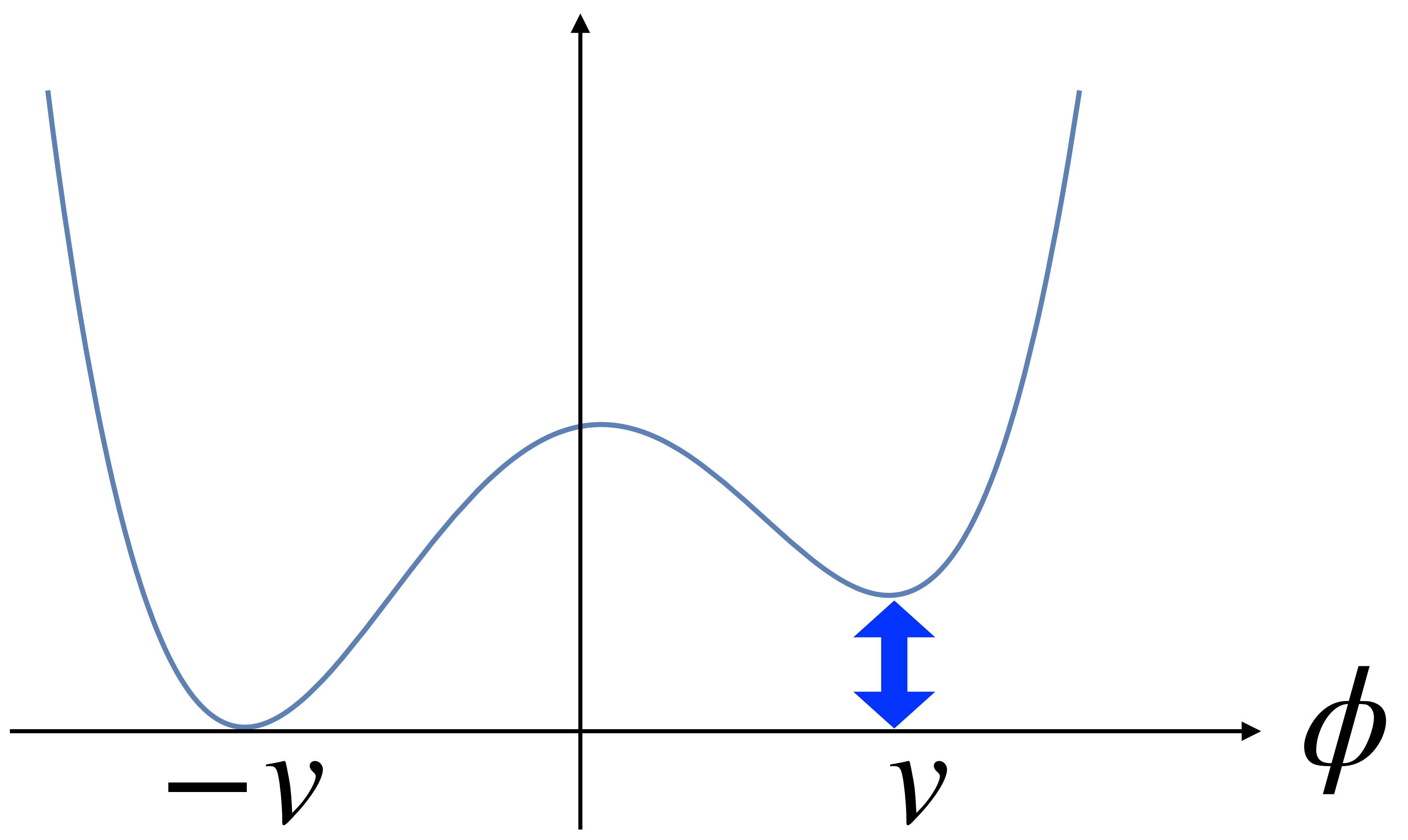
https://physics.aps.org/articles/v13/s149

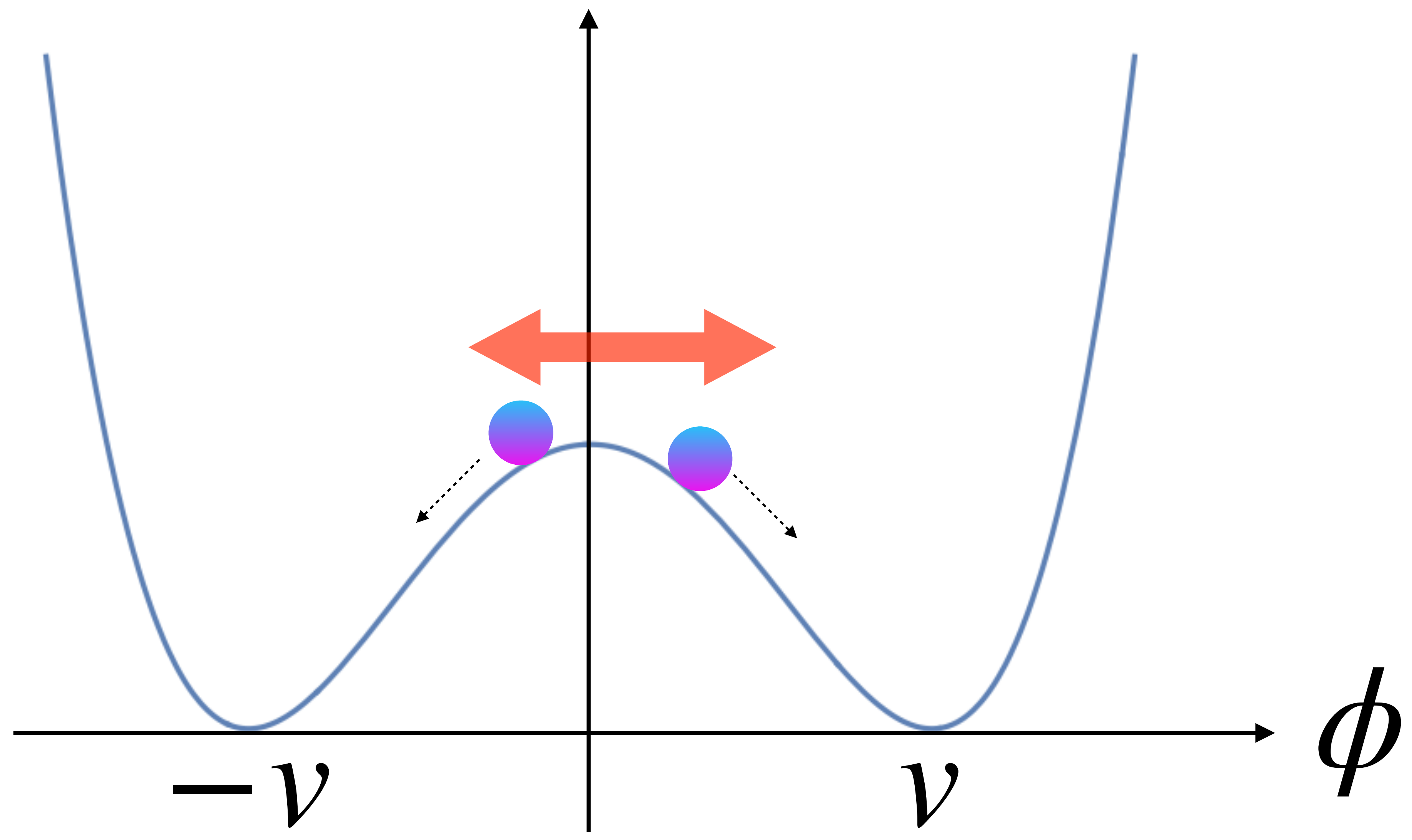
2. Stability of the DW network

Destabilization of DW network

One way to avoid the cosmological DW problem is to destabilize the DW network and make it disappear in the early Universe.

To this end, we need to introduce a small bias either in the potential or in the initial distribution. Vilenkin `81, Sikivie `82, Mohanty and Stecker `84, Gelmini, Gleiser and Kolb `89, Lalak and Thomas `93, + many





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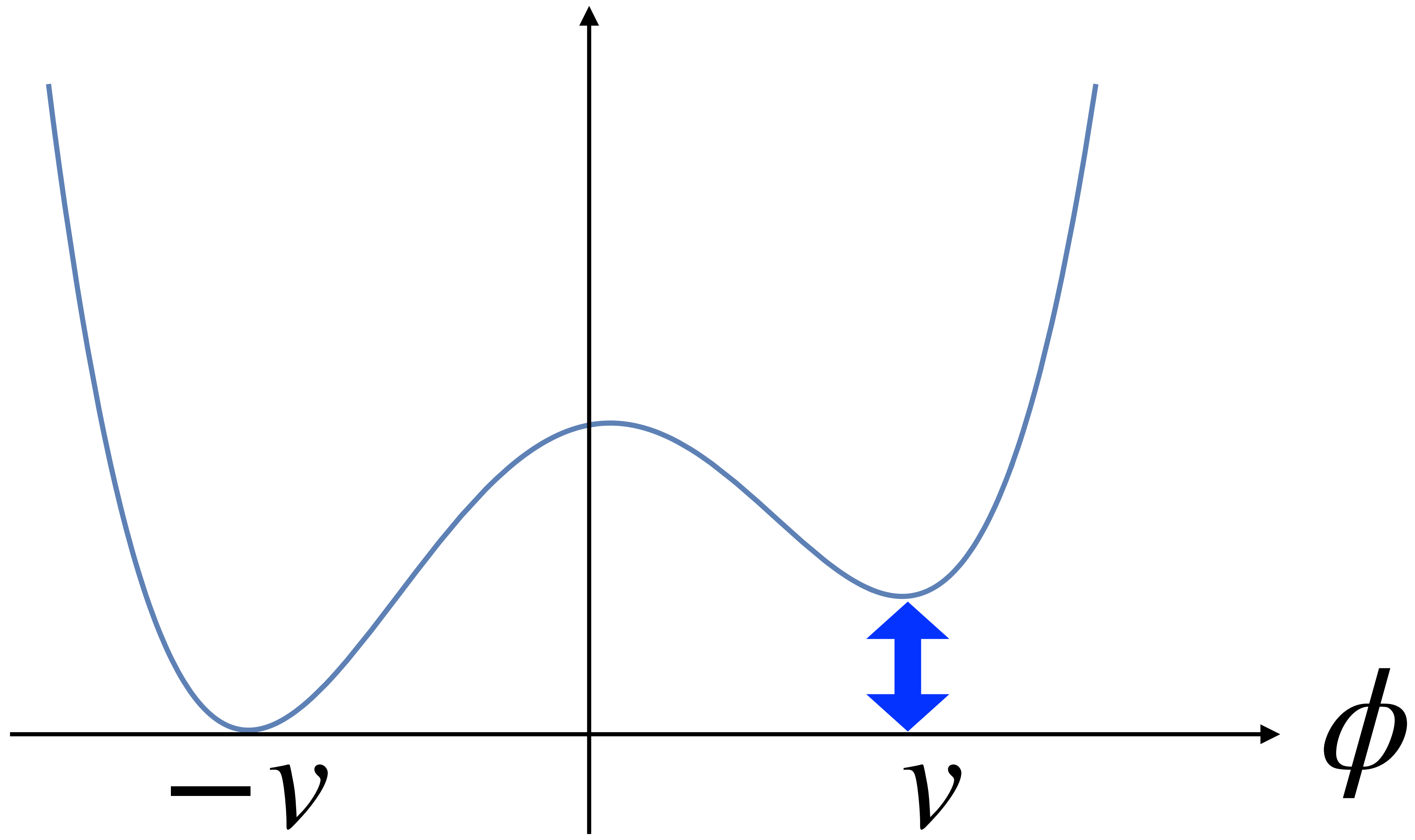
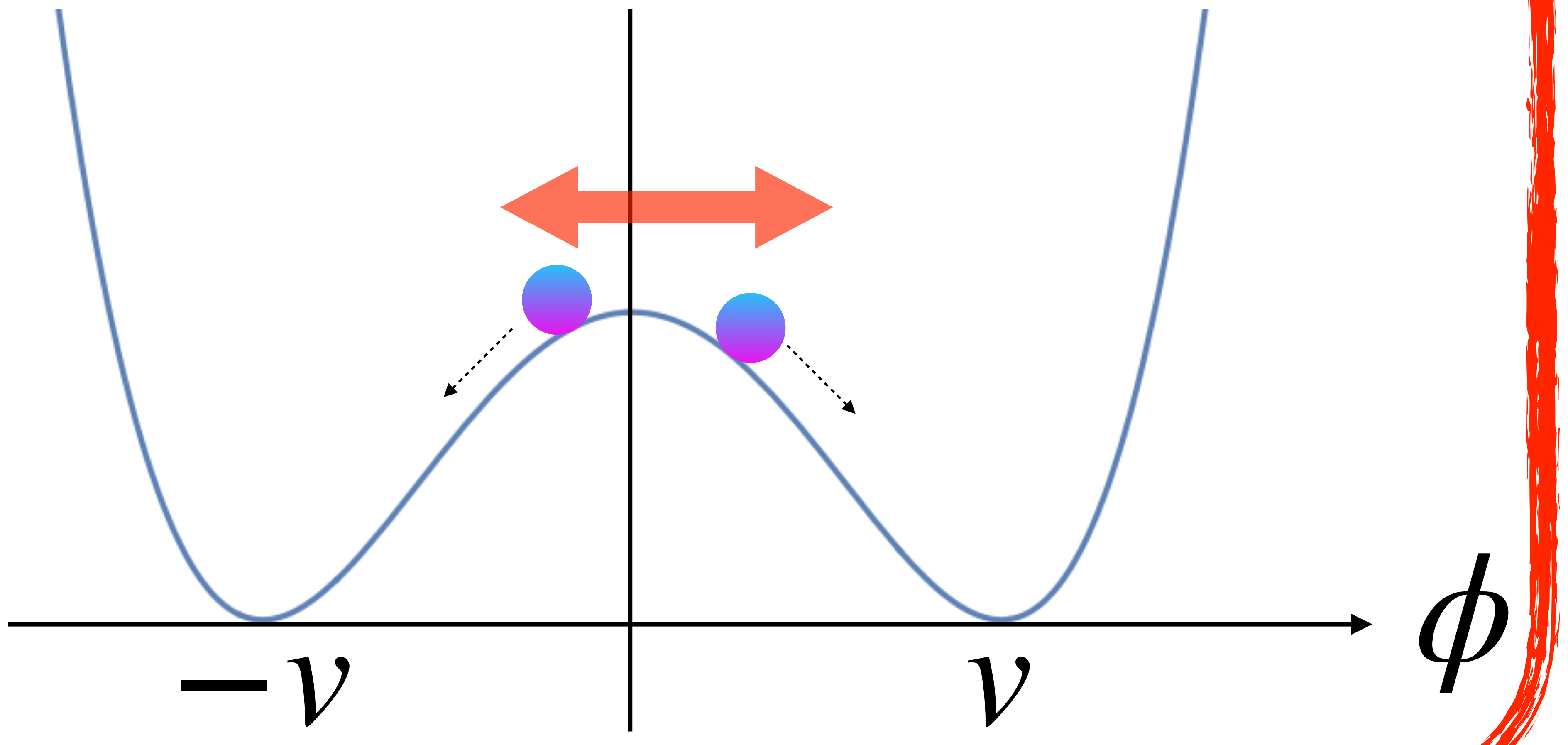


Kitajima, Lee, FT, and Yin, in preparation

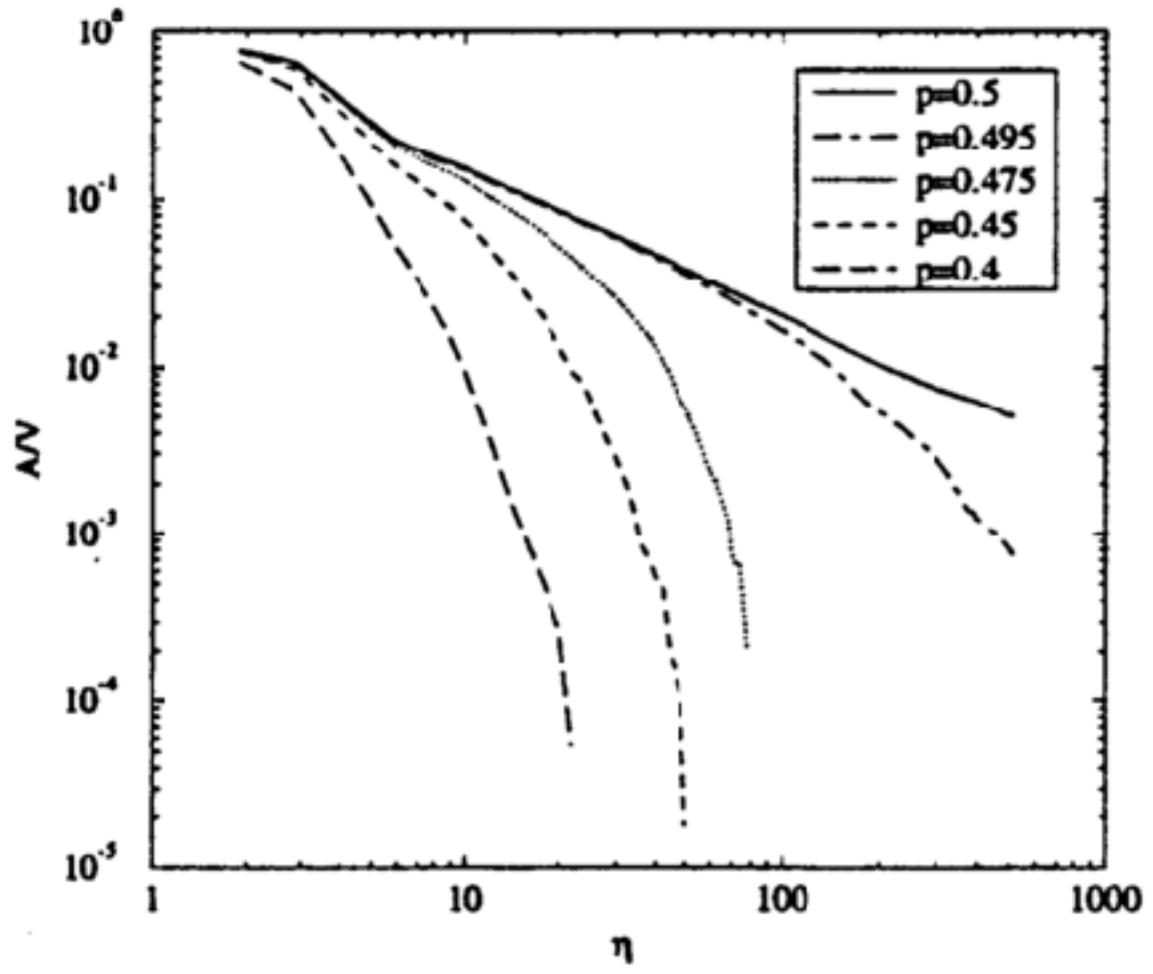
I will talk about this case today.



DW network vulnerable to bias in the initial distribution?

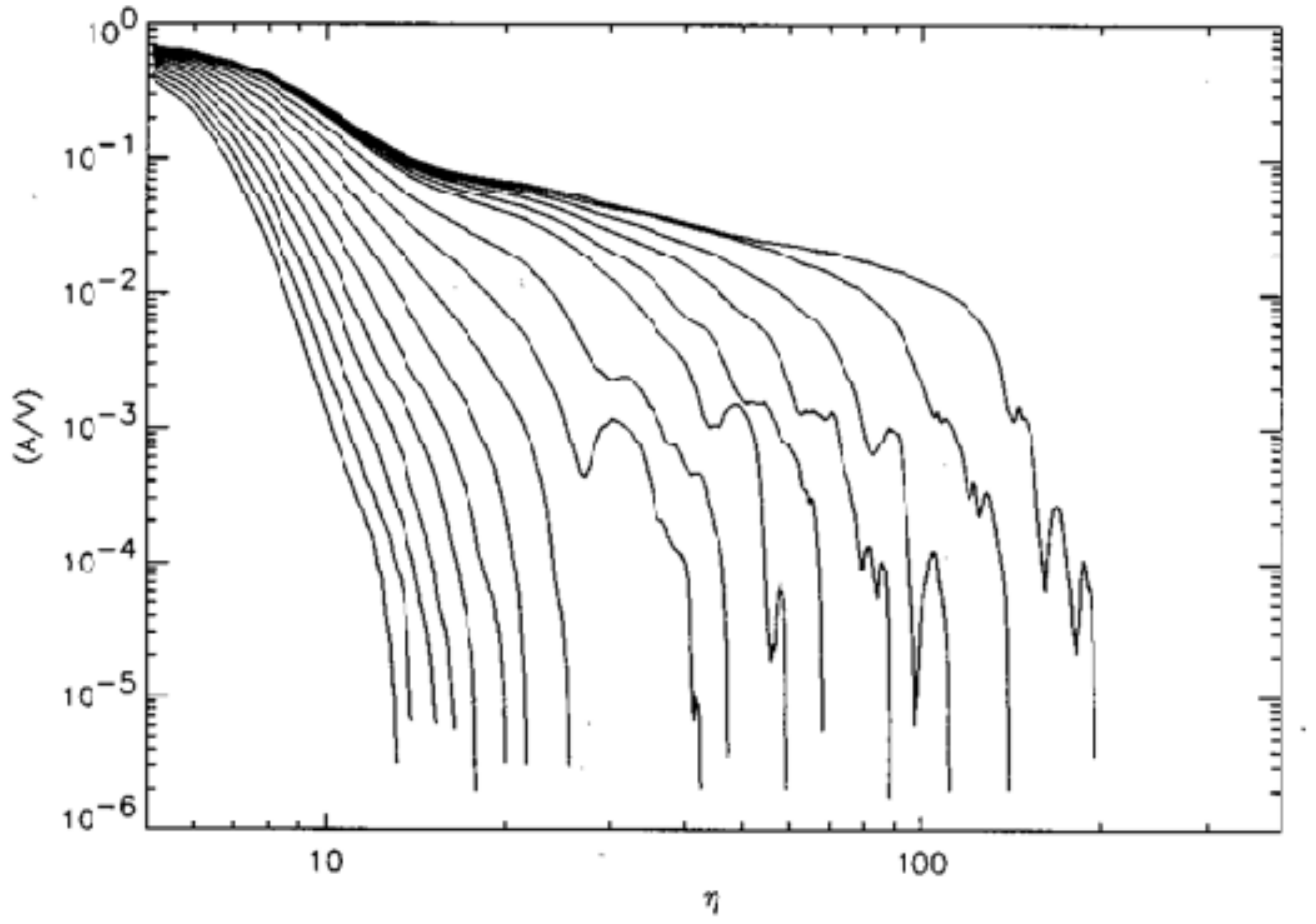
According to numerical simulations in the literature, the DW network quickly disappears when the initial distribution is only slightly biased.

Coulson, Lalak, and Ovrut, PRD 53, 4237 (1996), Larsson, Sarkar, and White PRD 55, 5129 (1997), Correia, Leite, and Martins, PRD 90, 023521 (2014), Correia, Leite, and Martins, PRD 97, 083521 (2018).



Coulson, Lalak, and Ovrut, PRD 53, 4237 (1996)

FIG. 7. Evolution of the comoving area, A, of domain walls per volume, V, with conformal time, η, in two dimensional runs. For each bias, p, we show the evolution of one realization.



Larsson, Sarkar, and White PRD 55, 5129 (1997)

FIG. 5. Comoving area against conformal time in three dimensions with the bias ε in the range $0-0.03$.

White noise (random) initial distribution was assumed.

It was claimed that a random distribution with correlation length of $O(H^{-1})$ can mimick the inflationary fluctuations.

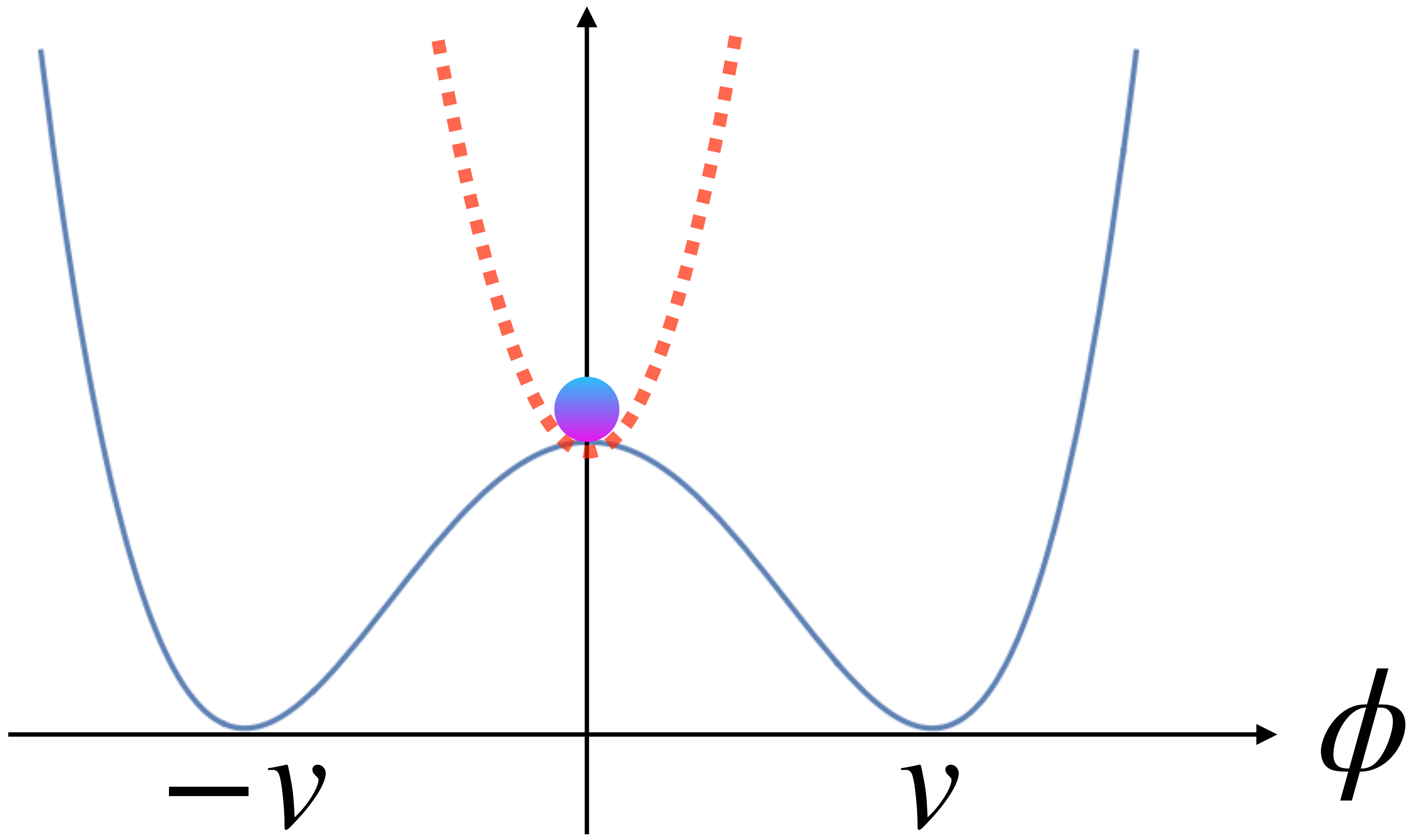
e.g. Lalak and Thomas, Phys. Lett. B 306, 10 (1993), Lalak, Ovrut, and Thomas, Phys. Rev. D 51, 5456 (1995), Larsson, Sarkar, and White Phys. Rev. D 55, 5129 (1997), Correia, Leite, and Martins, PRD 90, 023521 (2014)

Initial distributions

Initial distributions are broadly classified into thermal and non-thermal fluctuations.

Thermal fluctuations/white noise

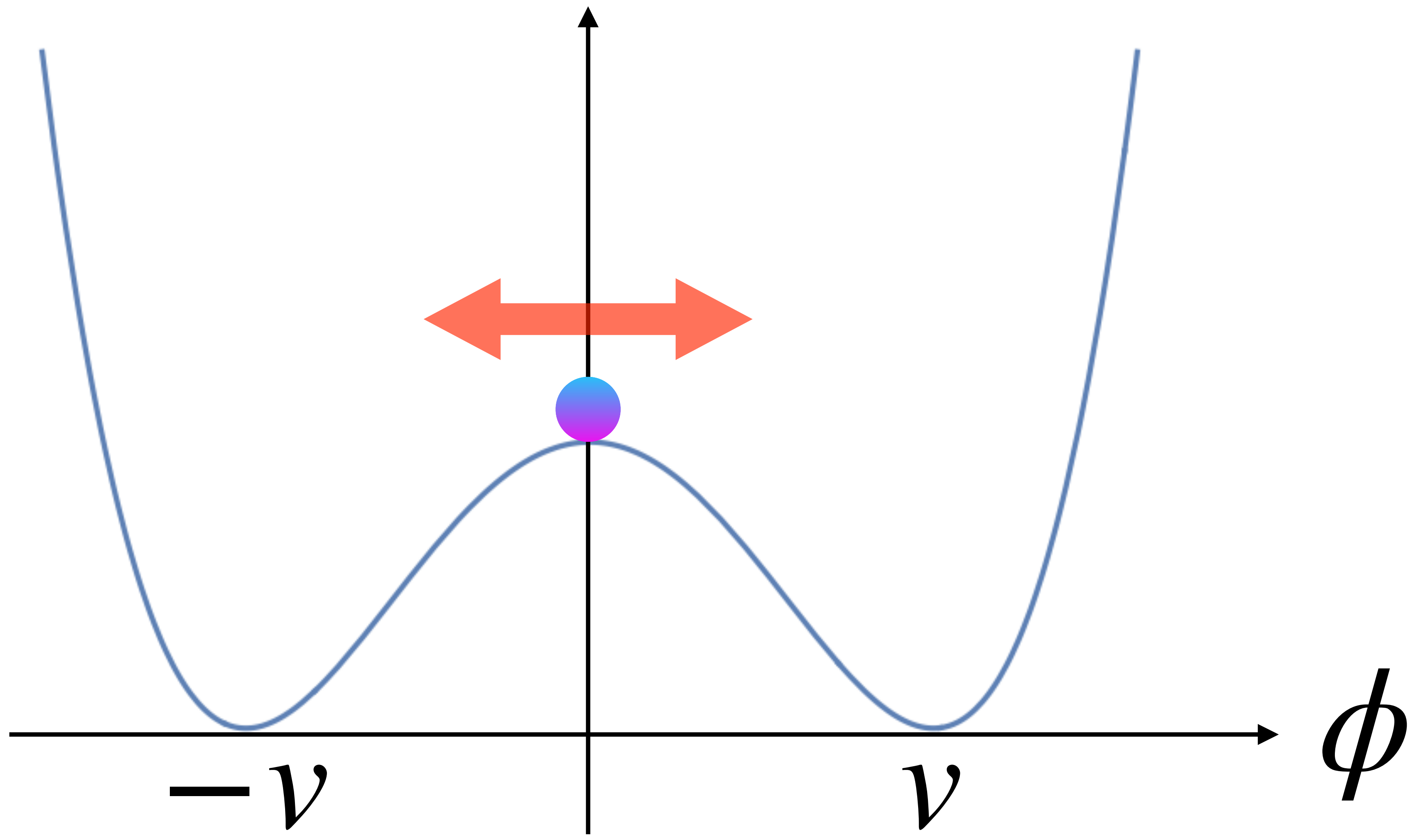
No large-scale correlations



$$\delta V = T^2\phi^2 \text{ or } H^2\phi^2$$

Inflationary fluctuations

Correlation on superhorizon scales



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

Linde and Lyth `90,
Nagasawa and Yokoyama `92

Initial distributions

During inflation, a massless (or light) scalar acquires almost scale-invariant fluctuations;

(Here the bias is set to be zero)

$$\langle \phi(\mathbf{k})\phi(\mathbf{k}')\rangle = (2\pi)^d \delta^{(d)}(\mathbf{k}+\mathbf{k}')P(k) \qquad d = 2 \text{ or } 3$$

$$\boxed{\mathscr{P}(k) \simeq \left(\frac{H_{\rm inf}}{2\pi}\right)^2} \quad \text{with} \quad \mathscr{P}(k) = \frac{k^d}{2\pi^{d-1}}P(k)$$

$$\langle \phi(\mathbf{x})^2\rangle = \int \frac{d^d\mathbf{k}}{(2\pi)^d}P(k) = \int d\ln k\, \mathscr{P}(k),$$

Correlation on large scales

Standard lore about DWs?

- *The scaling solution is an attractor.*
- *DW is a nonlinear object, and so, the dynamics is determined locally.*

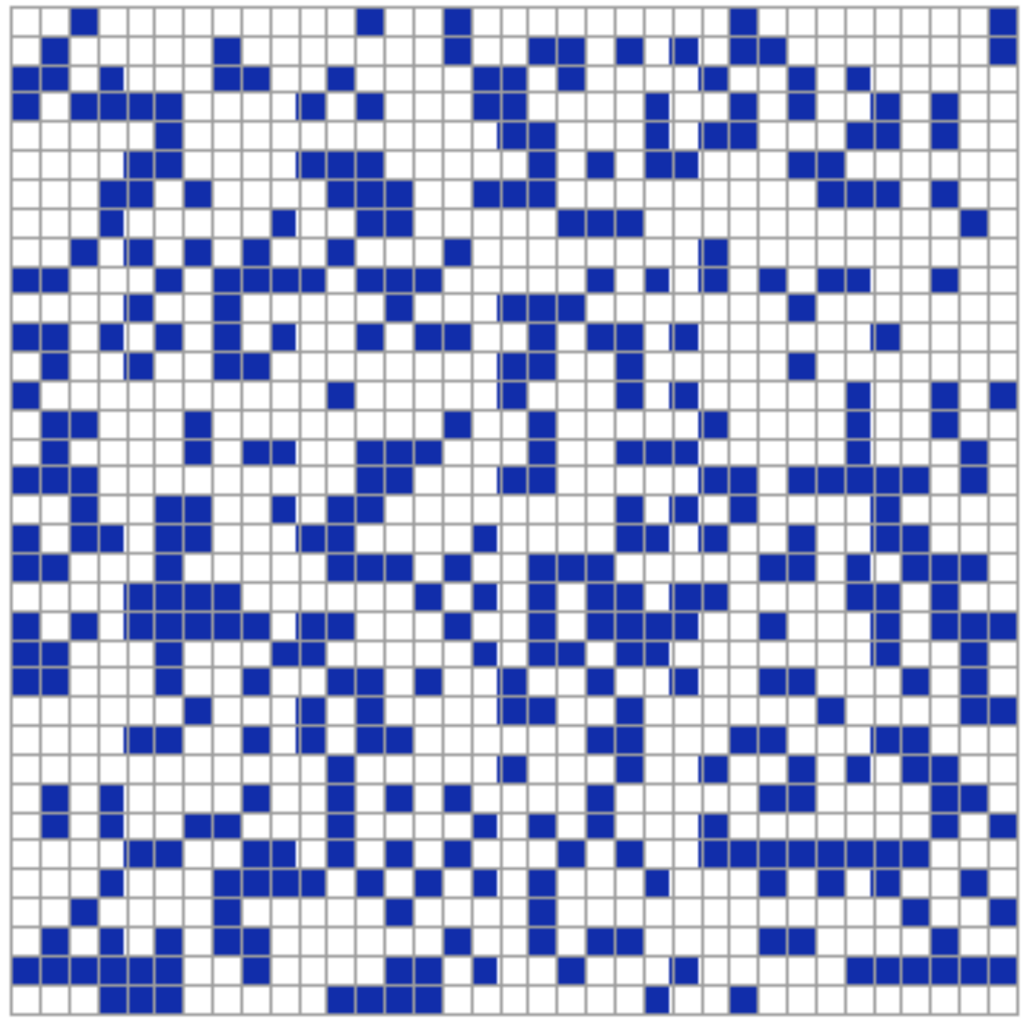
   ➡ *Thus, the DW network forgets the initial condition soon.*

- *One can use the percolation theory to see if infinitely large DWs are formed or not.*

however that this situation will change if we take into account the effect of the cosine potential on the values of χ. We will then find that the gaussian distribution will evolve into one which is non-gaussian, displaying peaks near the two minima $\chi = \pm\pi$ of the potential. In this way we have a situation which is much closer to the one relevant to percolation theory.

from Lalak and Thomas, Phys. Lett. B 306, 10 (1993)

For the inflationary fluctuations, based on percolation theory, it was assumed that for each Hubble horizon, the scalar field randomly falls into one of the two vacua, which is the same as the case of white noise, without proper numerical simulations.



https://faculty.math.illinois.edu/~kkirkpat/percolation.html

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These do not apply to DWs with inflationary fluctuations!

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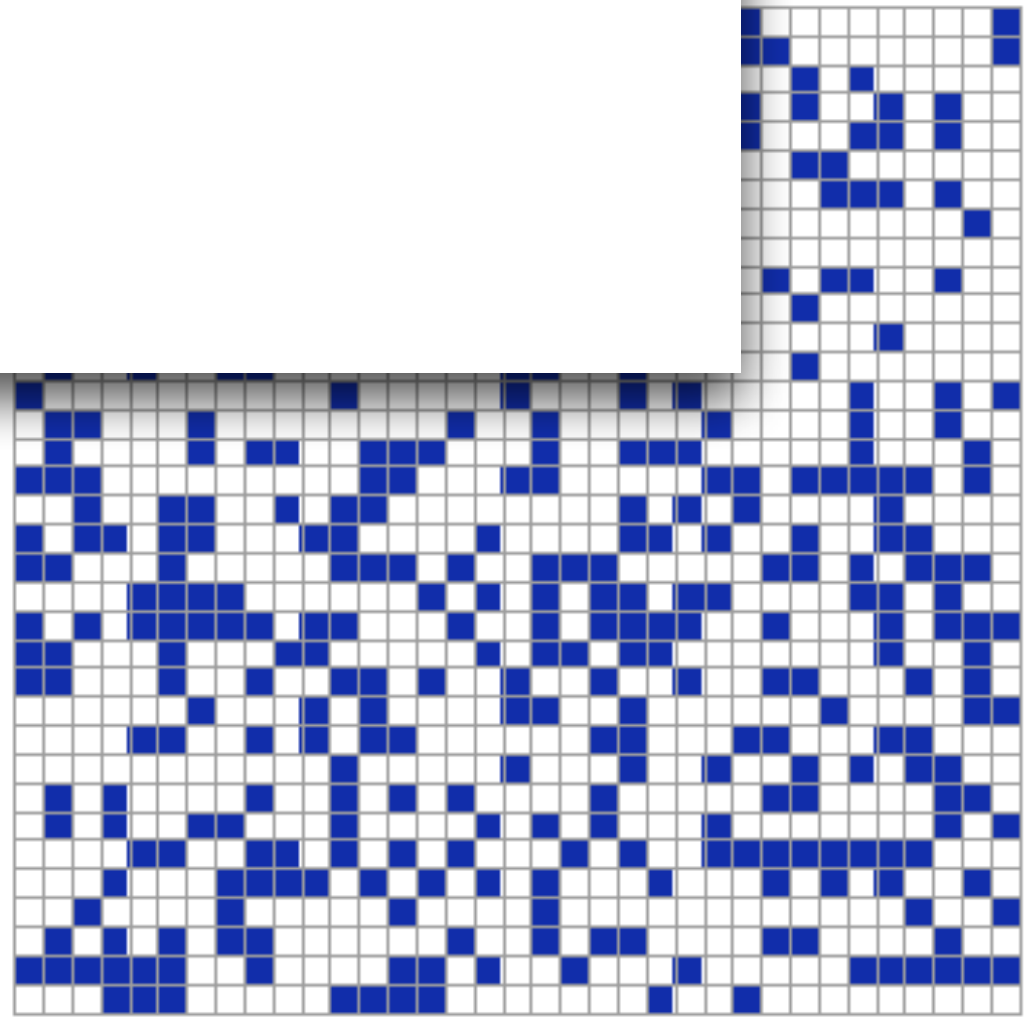


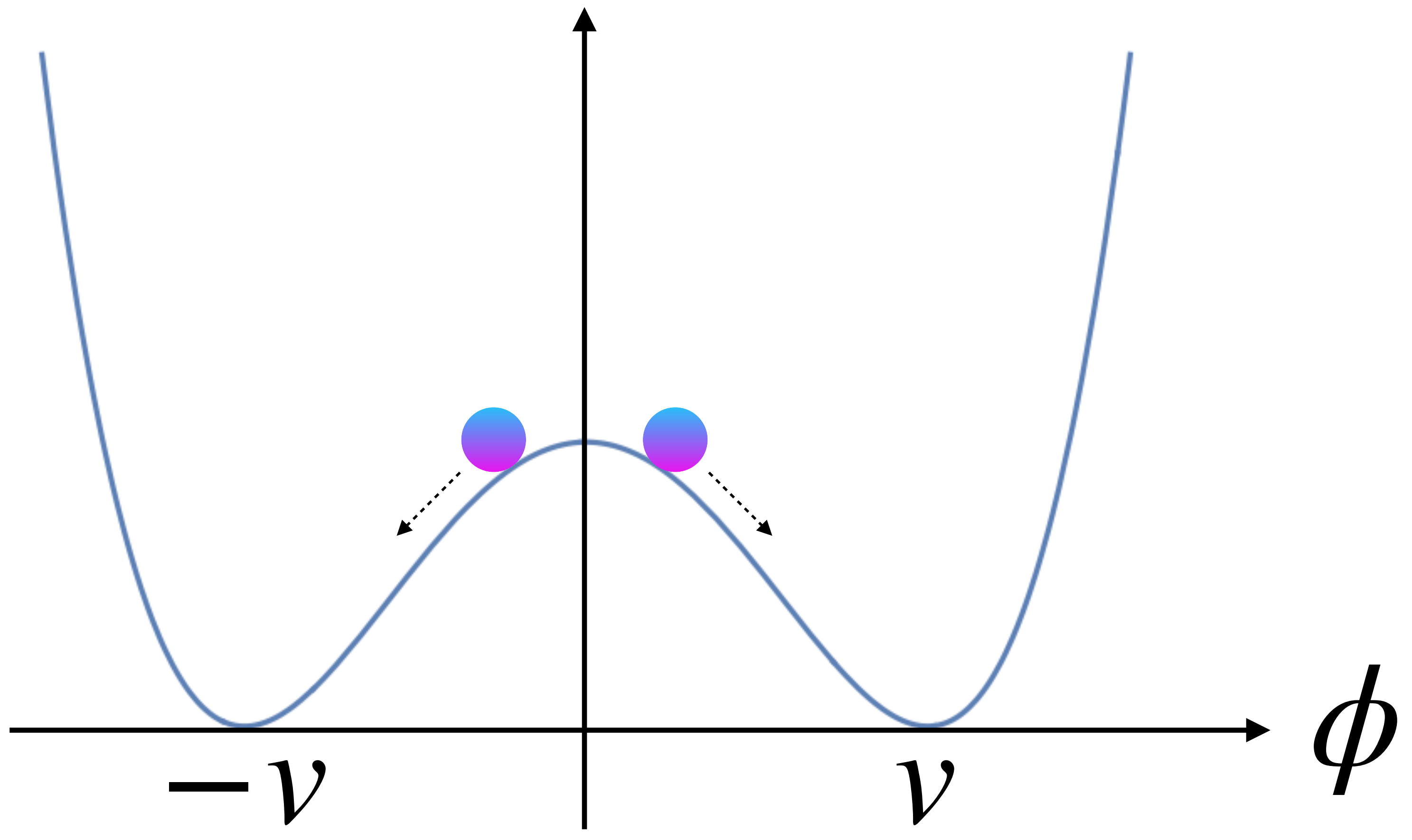
https://faculty.math.illinois.edu/~kkirkpat/percolation.html

Numerical lattice simulations

Gonzalez, Kitajima, FT and Yin 2211.06849

- EOM: $\dfrac{\partial^2\phi(\mathbf{x},t)}{\partial t^2} + 3H\dfrac{\partial\phi(\mathbf{x},t)}{\partial t} - \dfrac{\partial_i^2\phi(\mathbf{x},t)}{a^2} + \dfrac{\partial V}{\partial\phi} = 0,$

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 = \frac{\lambda}{4}v^4 - \frac{1}{2}m_0^2\phi^2 + \frac{\lambda}{4}\phi^4$$



- Conformal time: $\tau = \sqrt{2t/m_0}$
- Set-up

  -2D lattice with a grid size of 4096 x 4096 (or 16384 x 16384)

  -Initial fluctuations are set with white noise and inflationary fluctuations.

  -The bias parameter: $$b_d \equiv \frac{\langle\phi(\mathbf{x})\rangle}{\sqrt{(\langle\phi(\mathbf{x} - \langle\phi(\mathbf{x})\rangle)^2\rangle}}$$

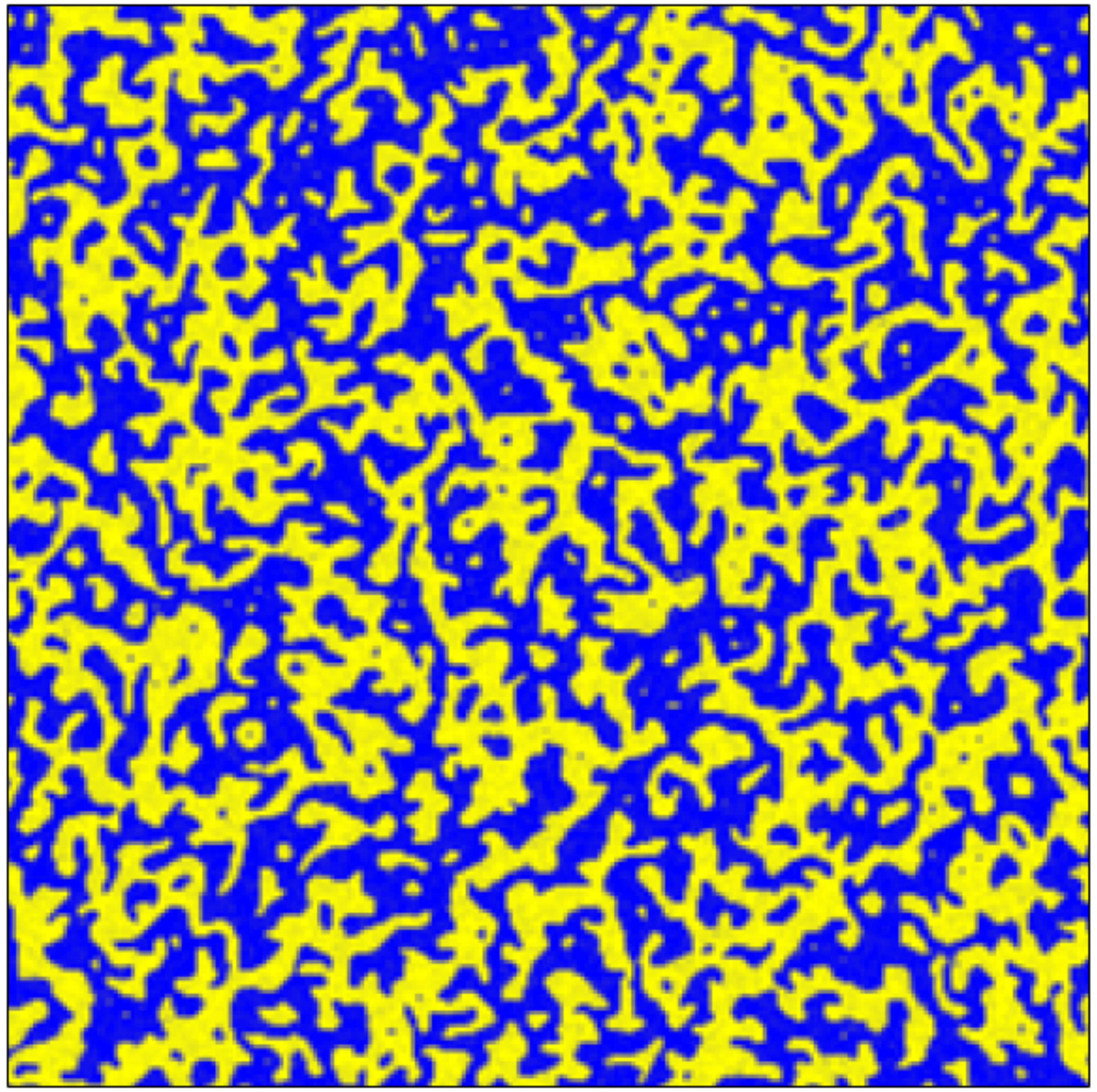
Note: for the inflationary fluctuations, we use $\sqrt{\mathscr{P}(k)}$ for the denominator to avoid the logarithmic dependence on the box size.

Snapshots of the DW network

$b_d = 0 \quad \tau = 10/m_0$

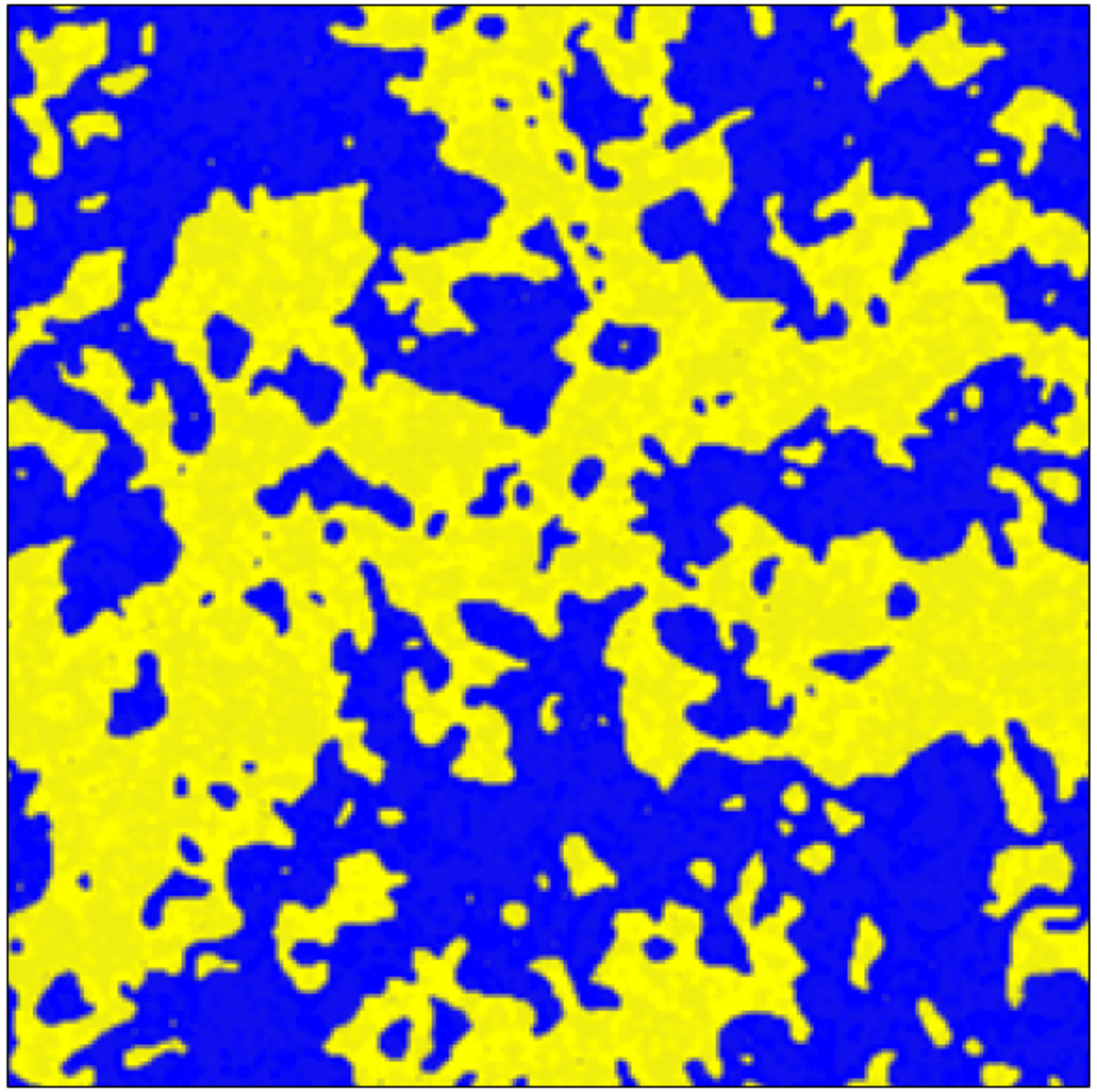
$\sim 40^2$ horizons

White noise



Typical structure of $\mathcal{O}(H^{-1})$

Inflationary fluctuations



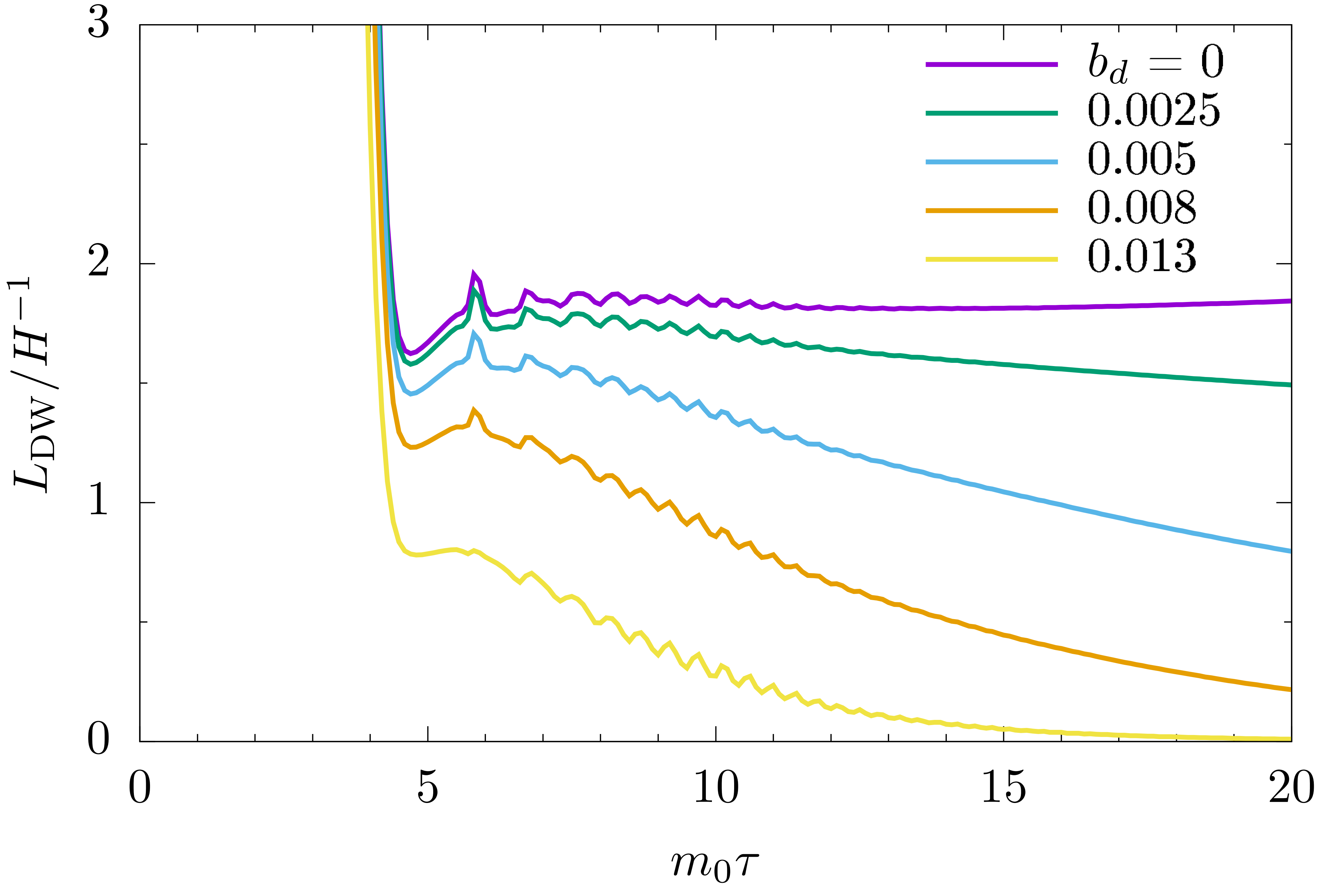
Structure of various scales

Gonzalez, Kitajima, FT and Yin 2211.06849

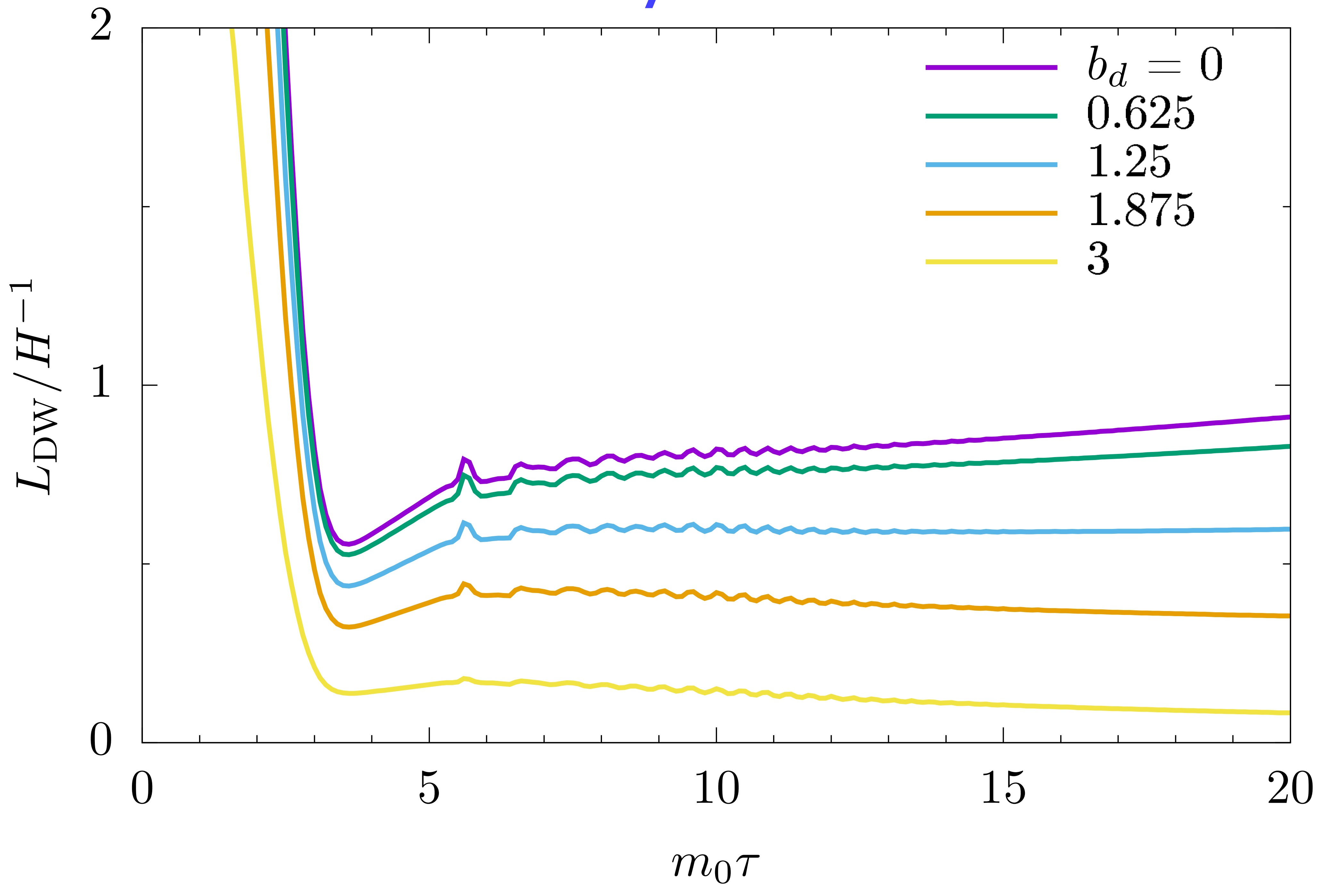
DW length per horizon

Scaling solution: $L_{\mathrm{DW}}/H^{-1} = \mathcal{O}(1)$ L_{DW} : the average DW length per horizon

White noise



Inflationary fluctuations



DW decays fast for small bias

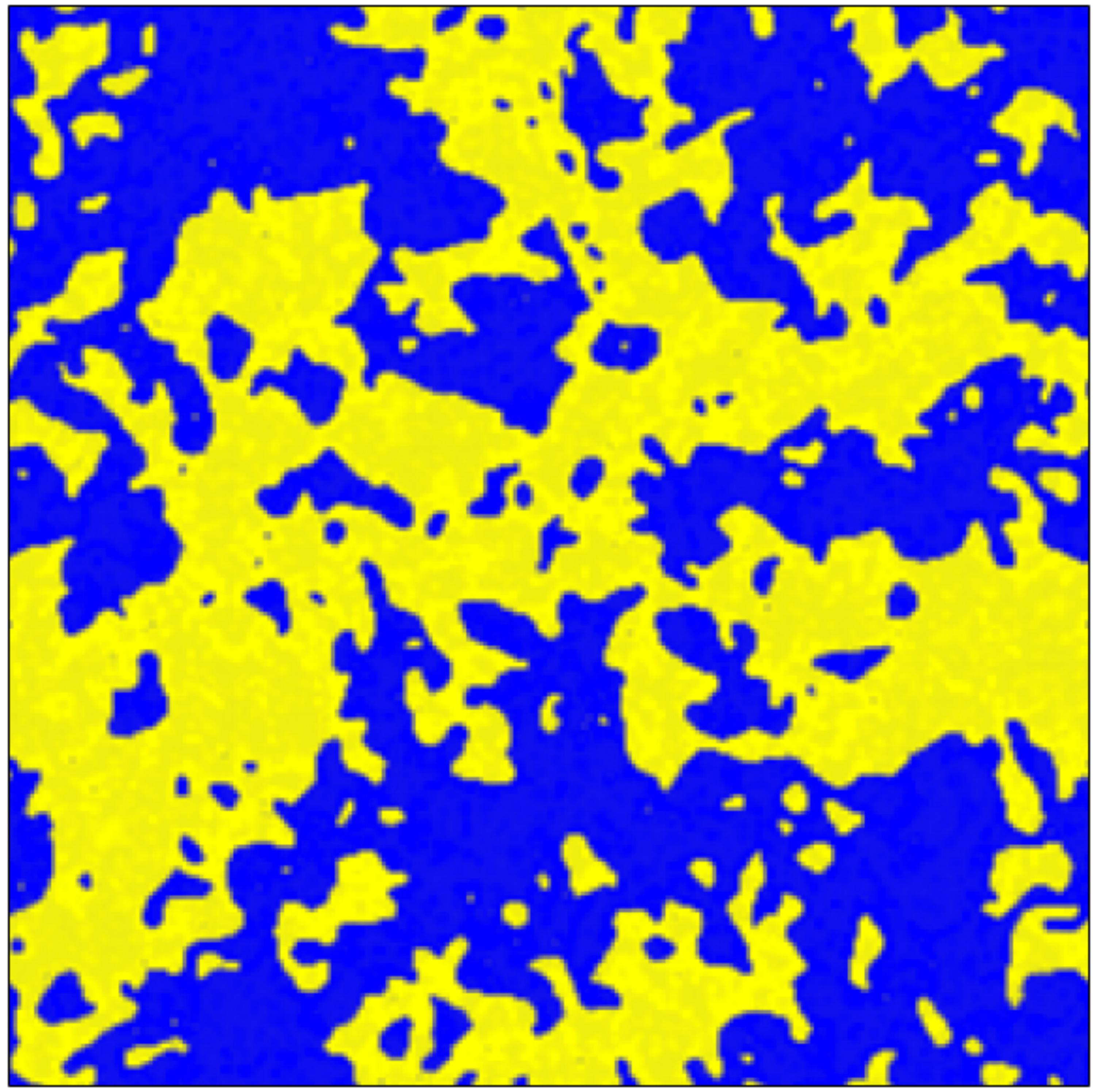
DW is rather stable for large bias

Why is the DW with inflationary fluctuations so stable?

The DW network retains information on the initial distributions, and in this sense, the scaling solution is not a local attractor.

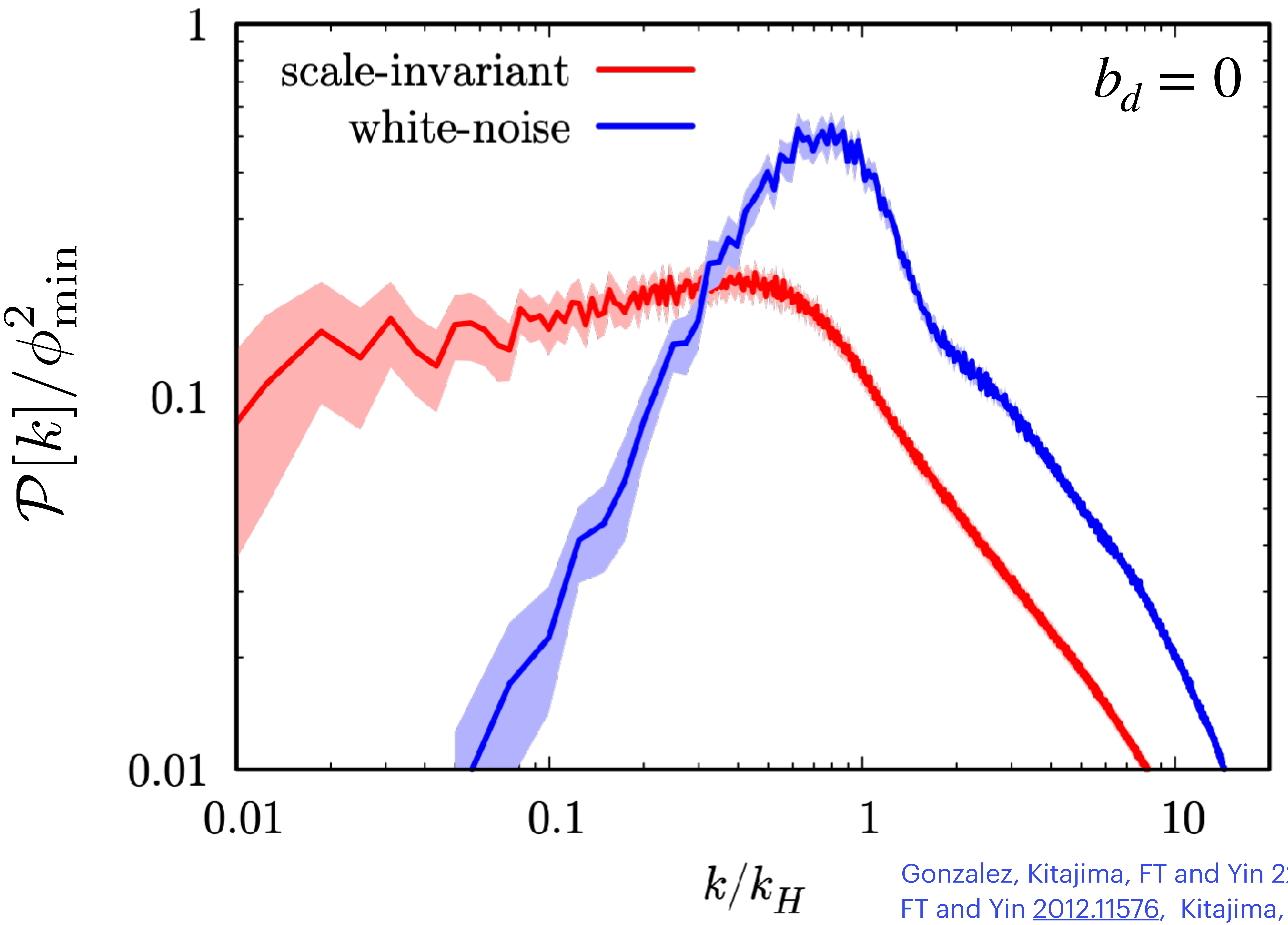
Clearly, the percolation theory is not applicable.

There are large voids without DWs, which remain until the Hubble horizon grows to their sizes.



It is the large-scale correlation that makes the DW network so stable!

Power spectrum



Gonzalez, Kitajima, FT and Yin 2211.06849
FT and Yin 2012.11576, Kitajima, Kozai, FT and Yin 2205.05083

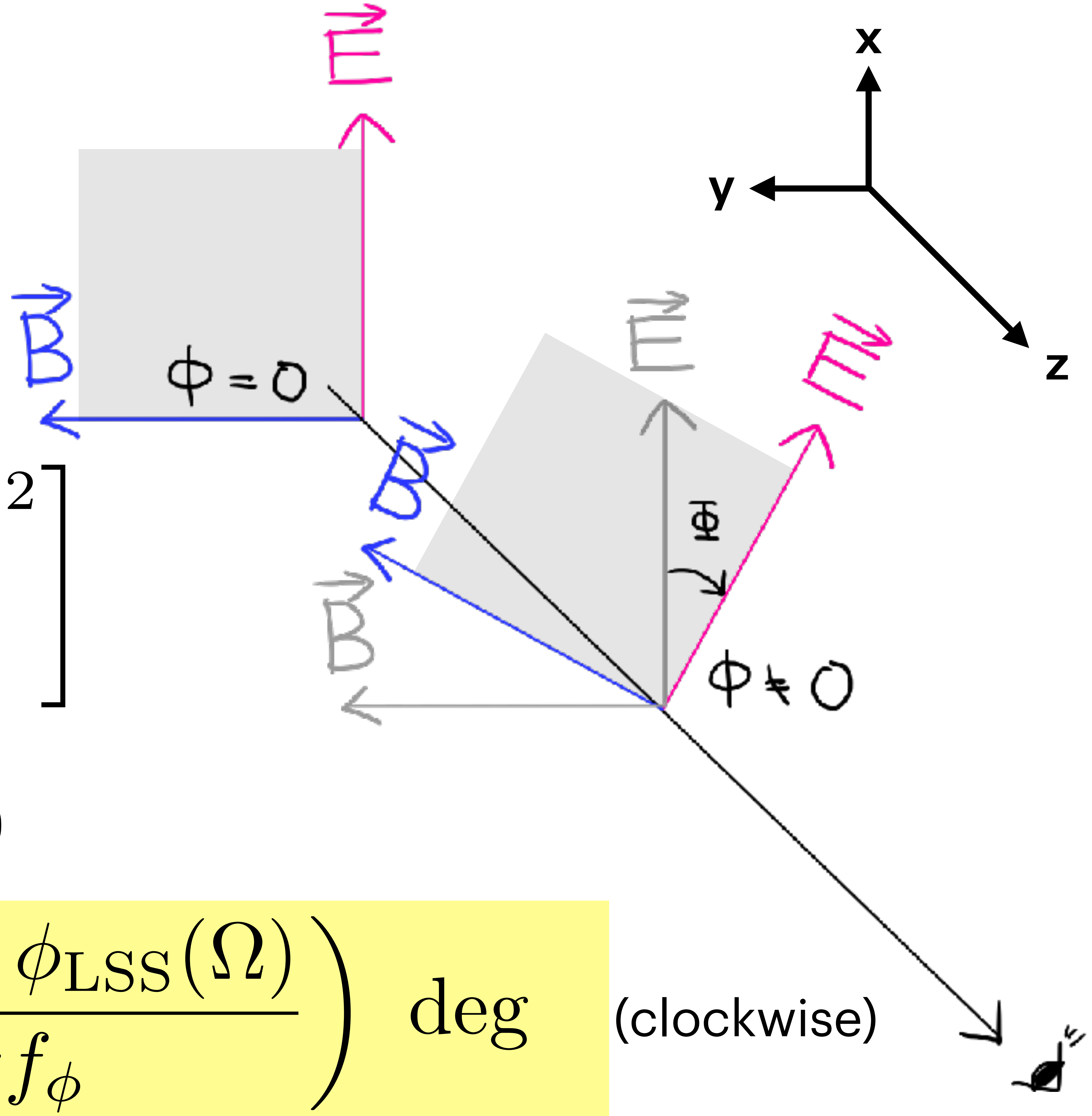
3. Axion DW and cosmic birefringence

Cosmic birefringence

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

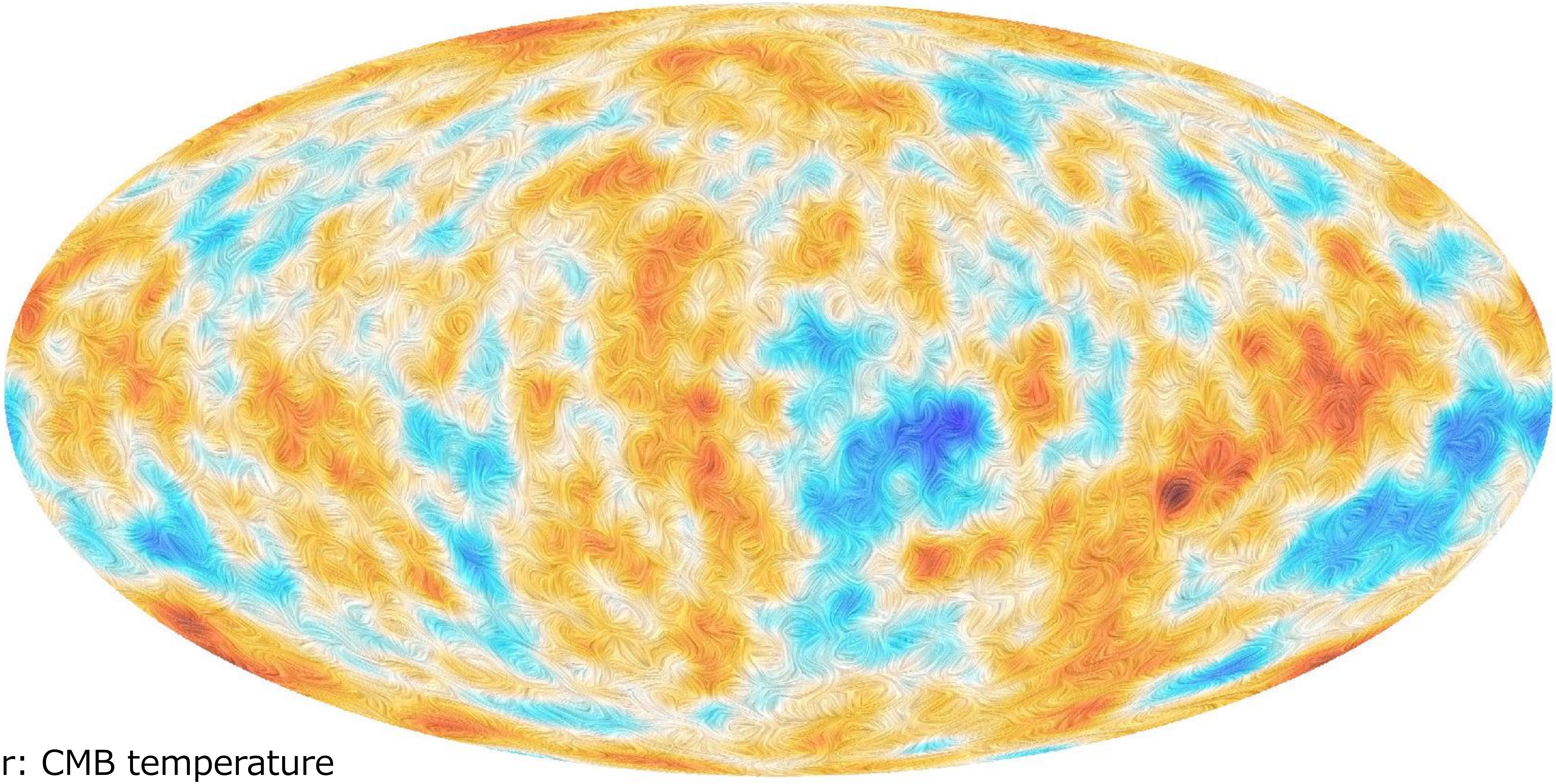
The axion dynamics rotates the polarization plane of linearly polarized light through the axion-photon coupling.

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



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

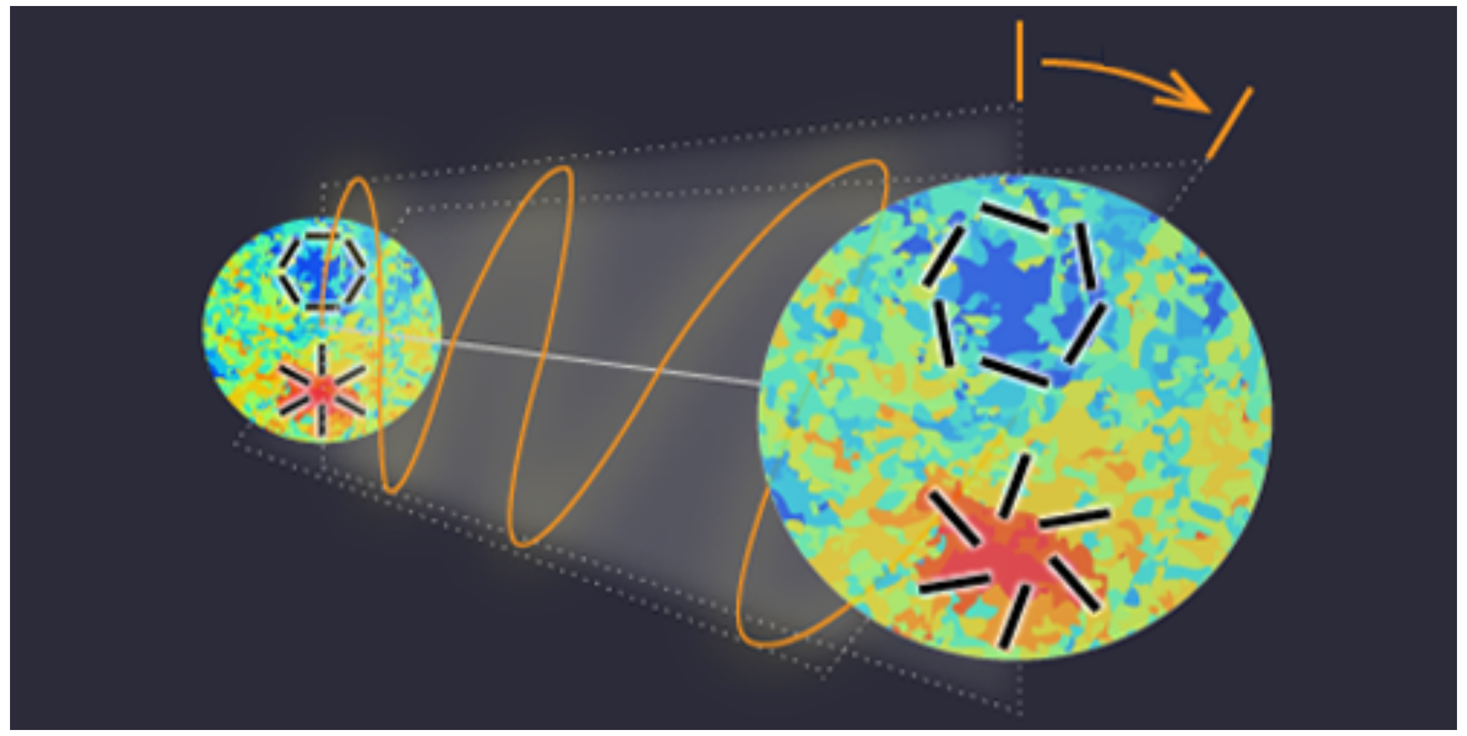
CMB photons are polarized (dominated by E-mode)



Color: CMB temperature

Texture: direction of polarization

CMB constraints on the CB



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

Isotropic CB

$$\beta = \frac{1}{4\pi}\int d\Omega\,\Phi(\Omega) = 0.36 \pm 0.11 \text{ deg}$$

from Planck 18 pol. data

Minami, Komatsu, Phys. Rev. Lett. **125**, 221301 (2020)
P. Diego-Palazuelos et al, Phys. Rev. Lett. **128**, 091302 (2022)

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

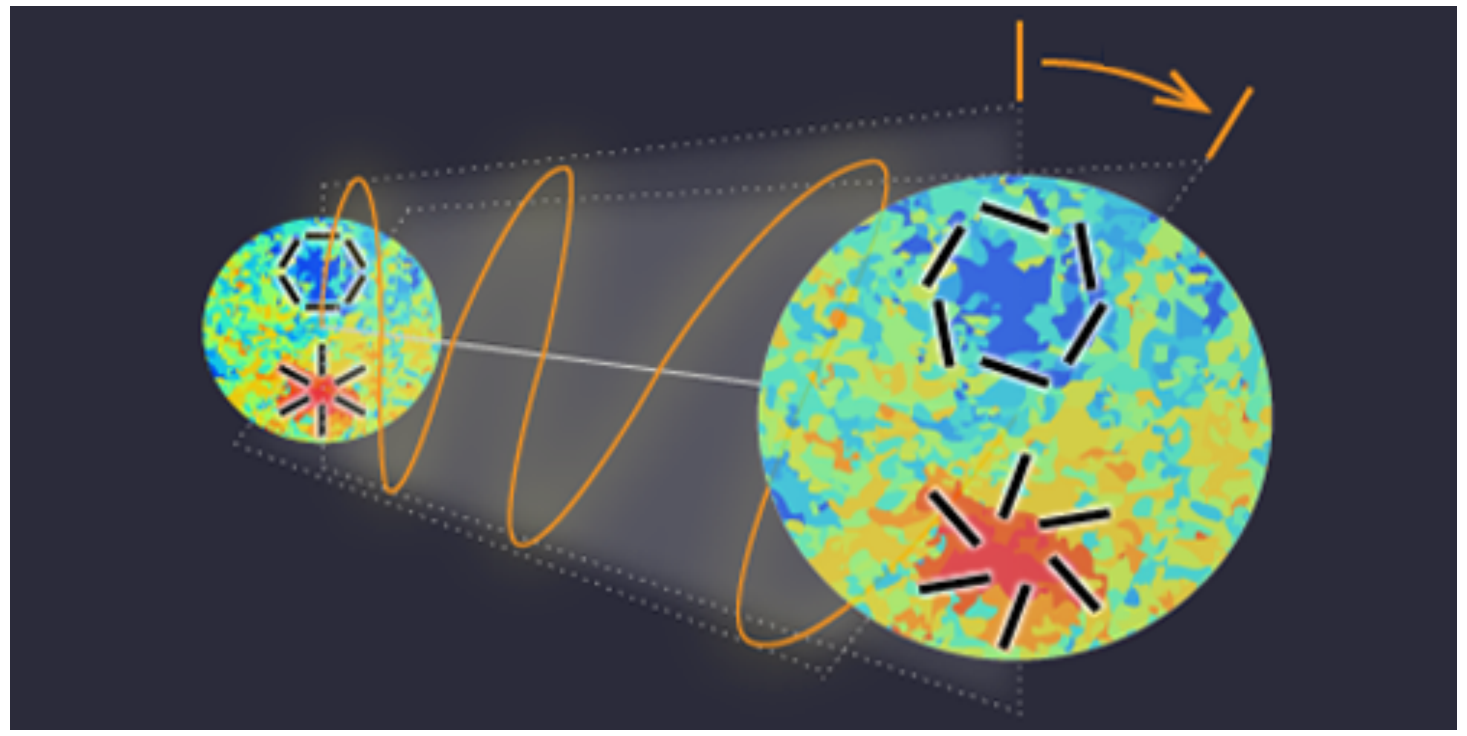
Minami et al, PTEP 2019 083E02 , Minami PTEP 2020 063E01, Minami and Komatsu PTEP 2020 103E02

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



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

Anisotropic CB

$$\sqrt{\frac{L(L+1)C_L}{2\pi}} \left(= \frac{g_{\phi\gamma\gamma}}{2}\frac{H_{\rm inf}}{2\pi} \right) < 0.12\,\mathrm{deg}$$

(95% CL)

Massless axion

BICEP/Keck Collaboration, arXiv:2210.08038

for a scale-invariant CB; e.g. a massless axion with fluctuations

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

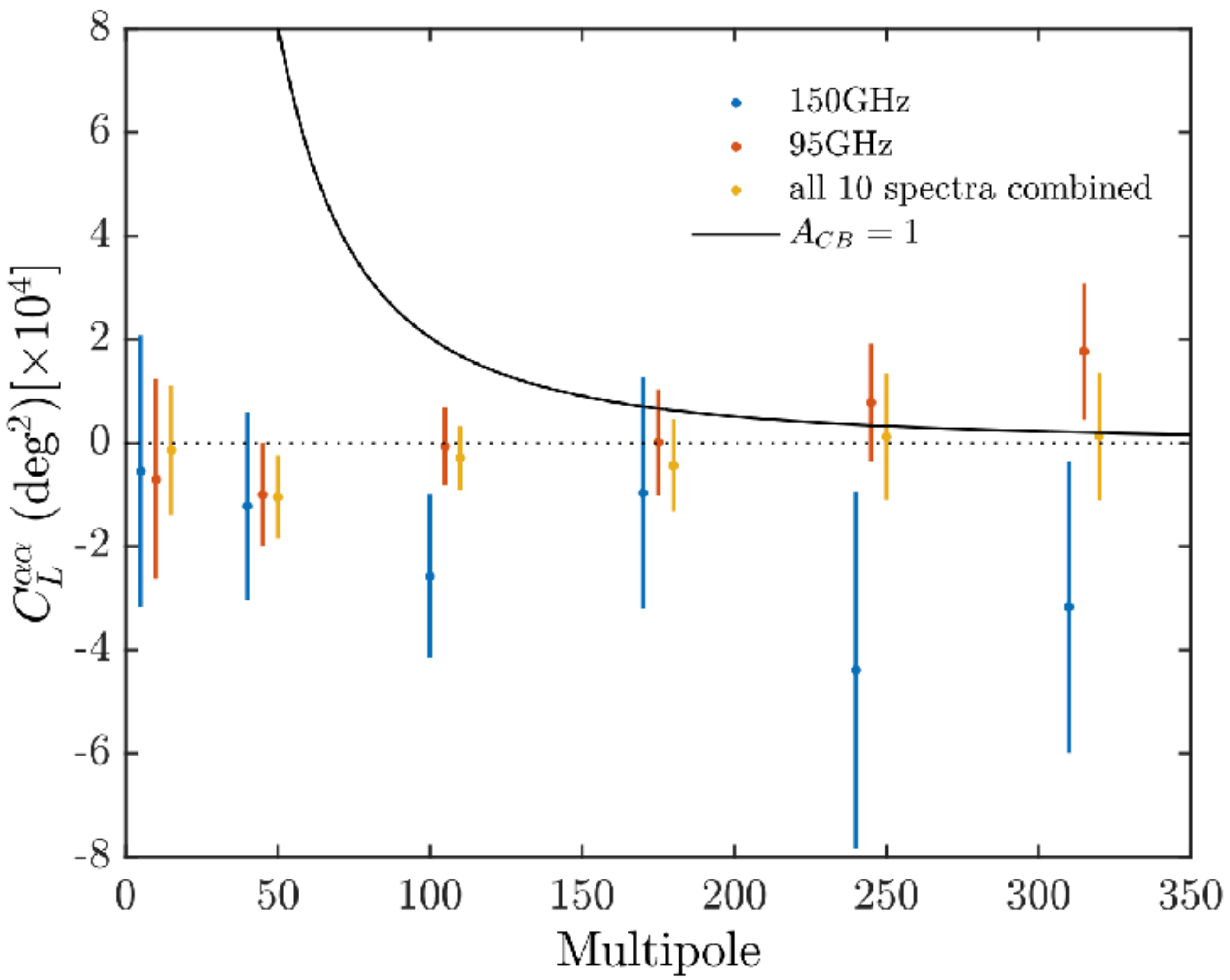
generated during inflation.

(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)



BICEP/Keck Collaboration, arXiv:2210.08038

Implications for ALP

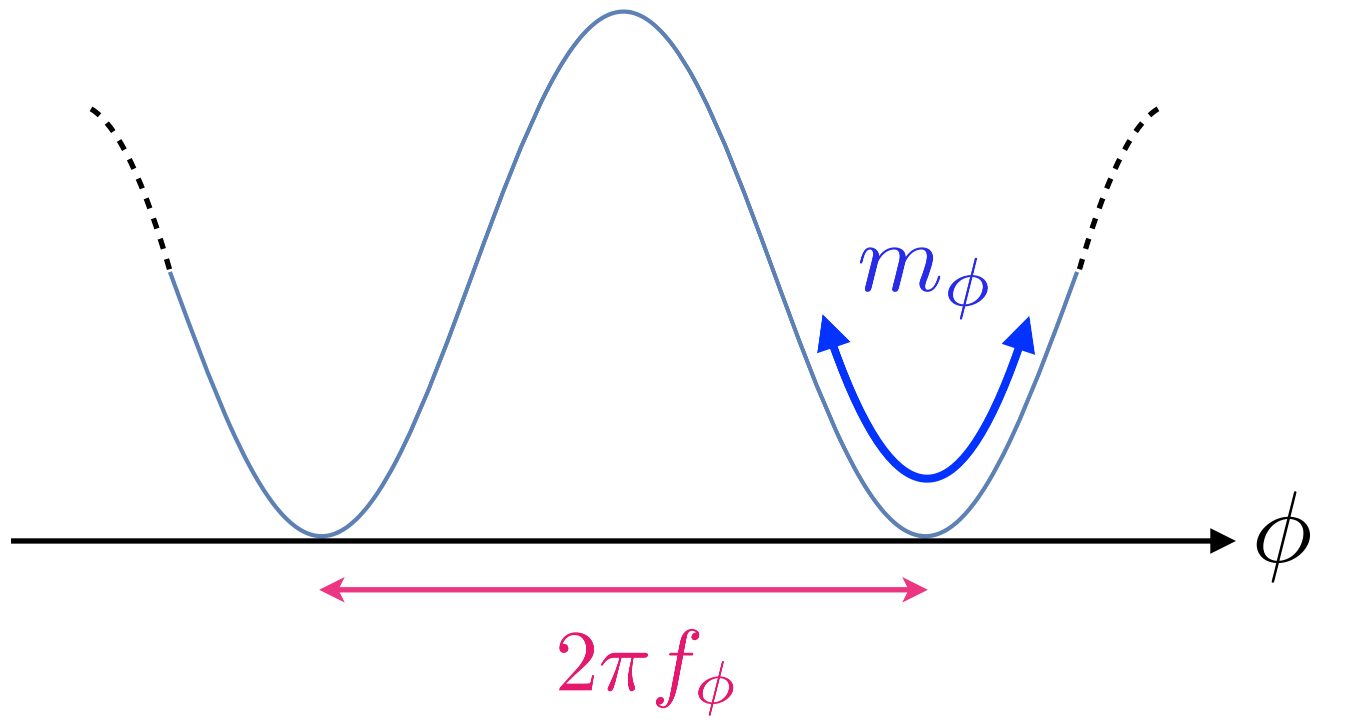
$$\mathcal{L}_{\phi\gamma} = -c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi}F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{4}g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

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

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

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



ALP domain walls without strings

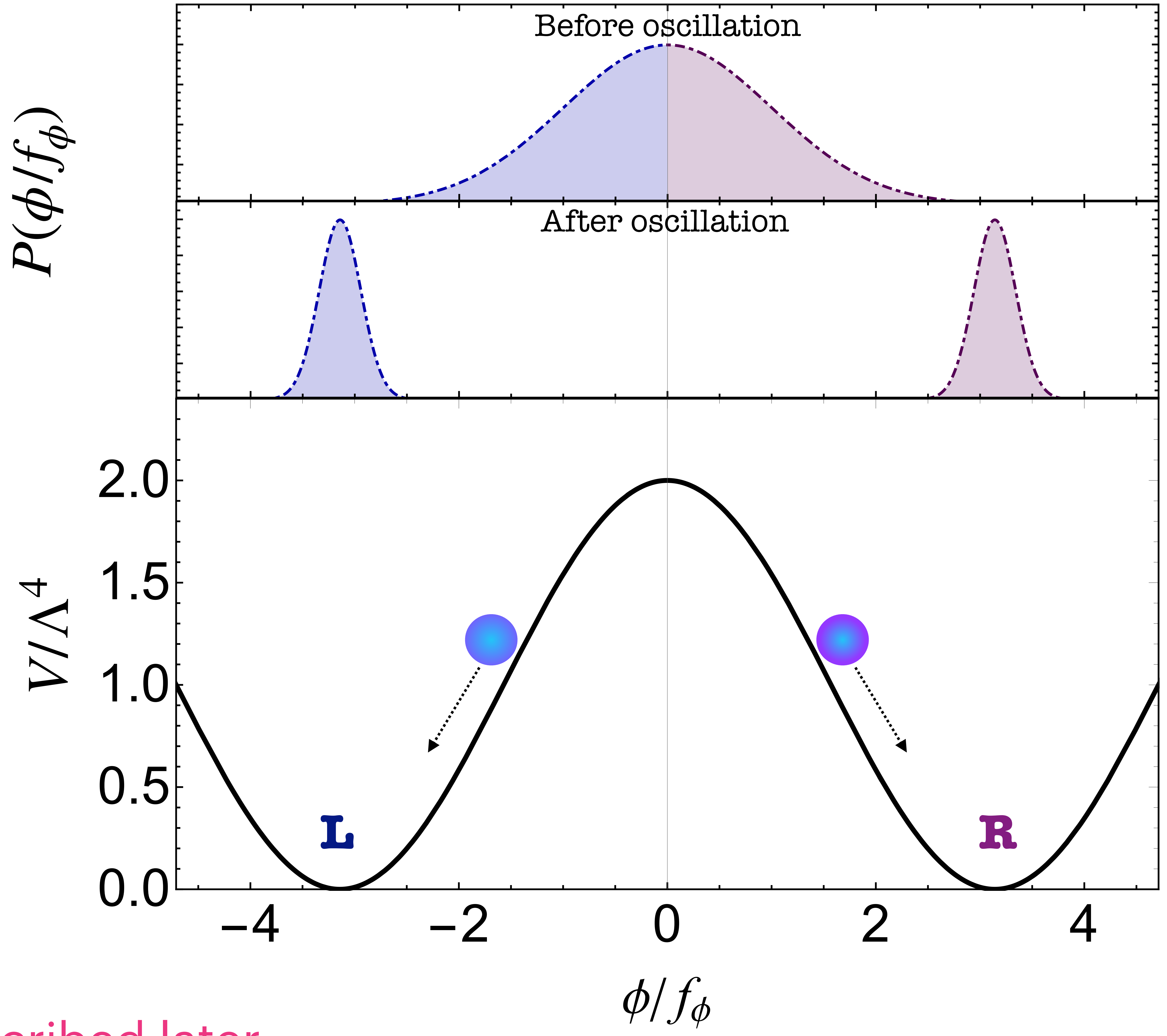
Let us consider the axion potential

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

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, 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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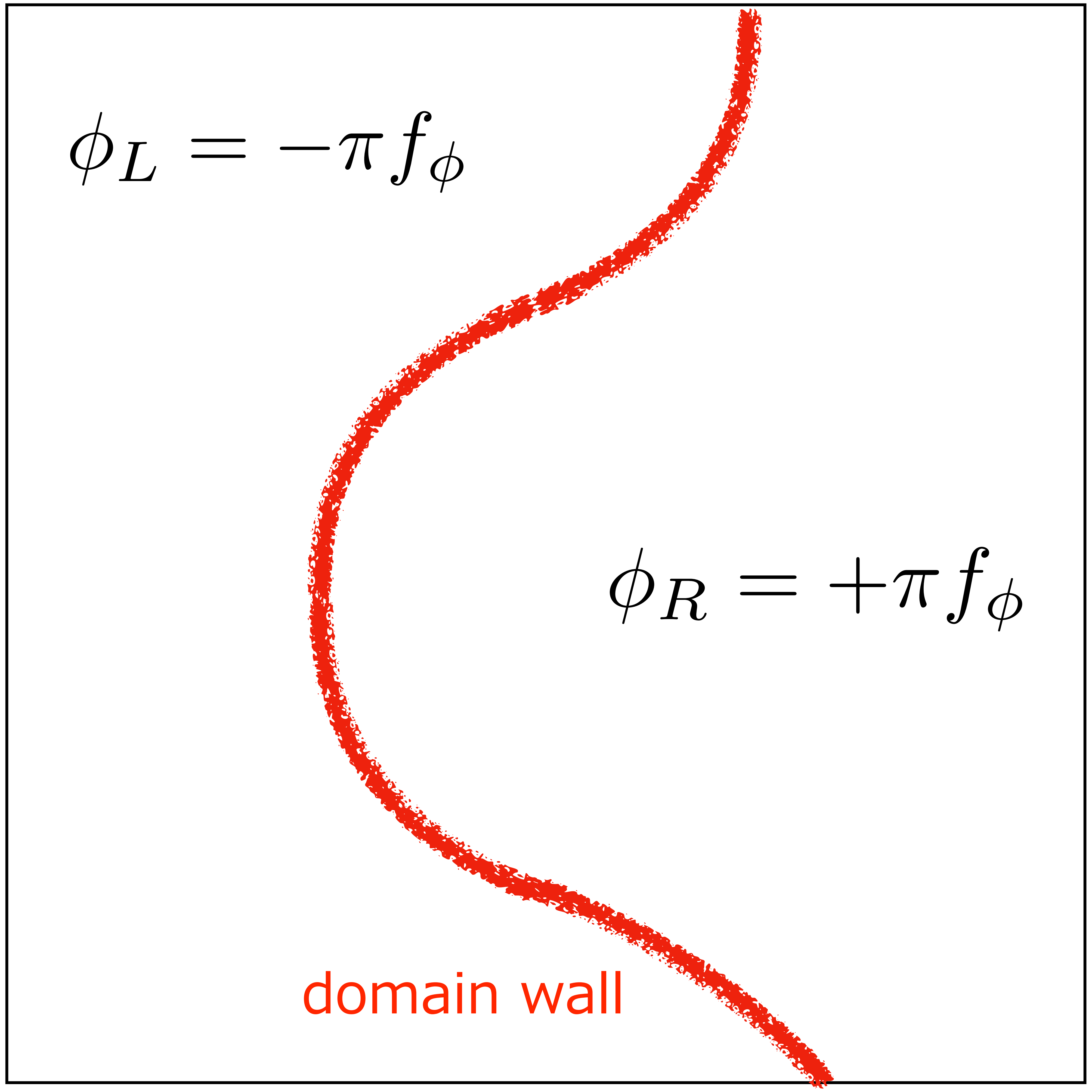
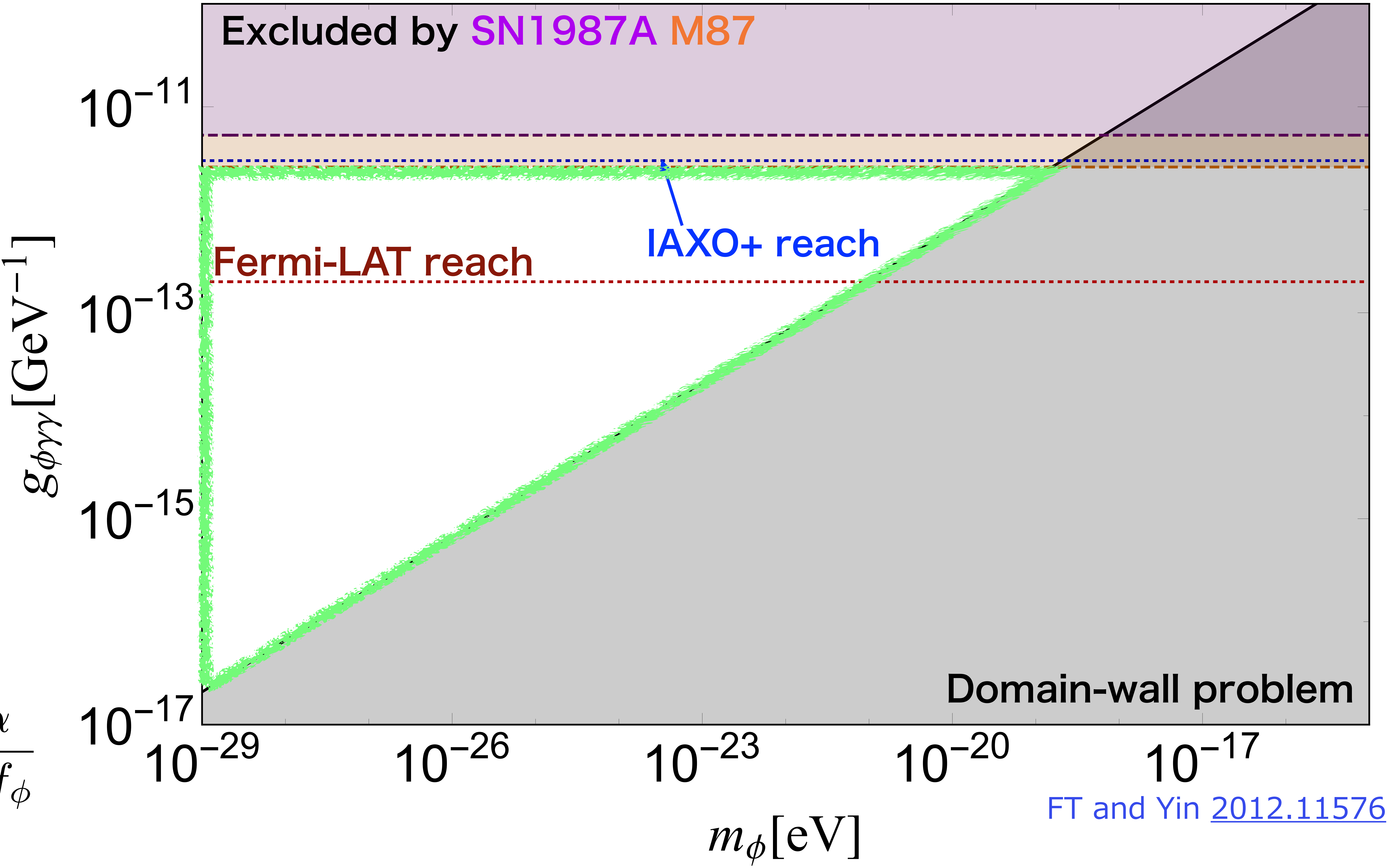


$\delta \sim m_\phi^{-1}$

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

Various bounds and future sensitivity reach



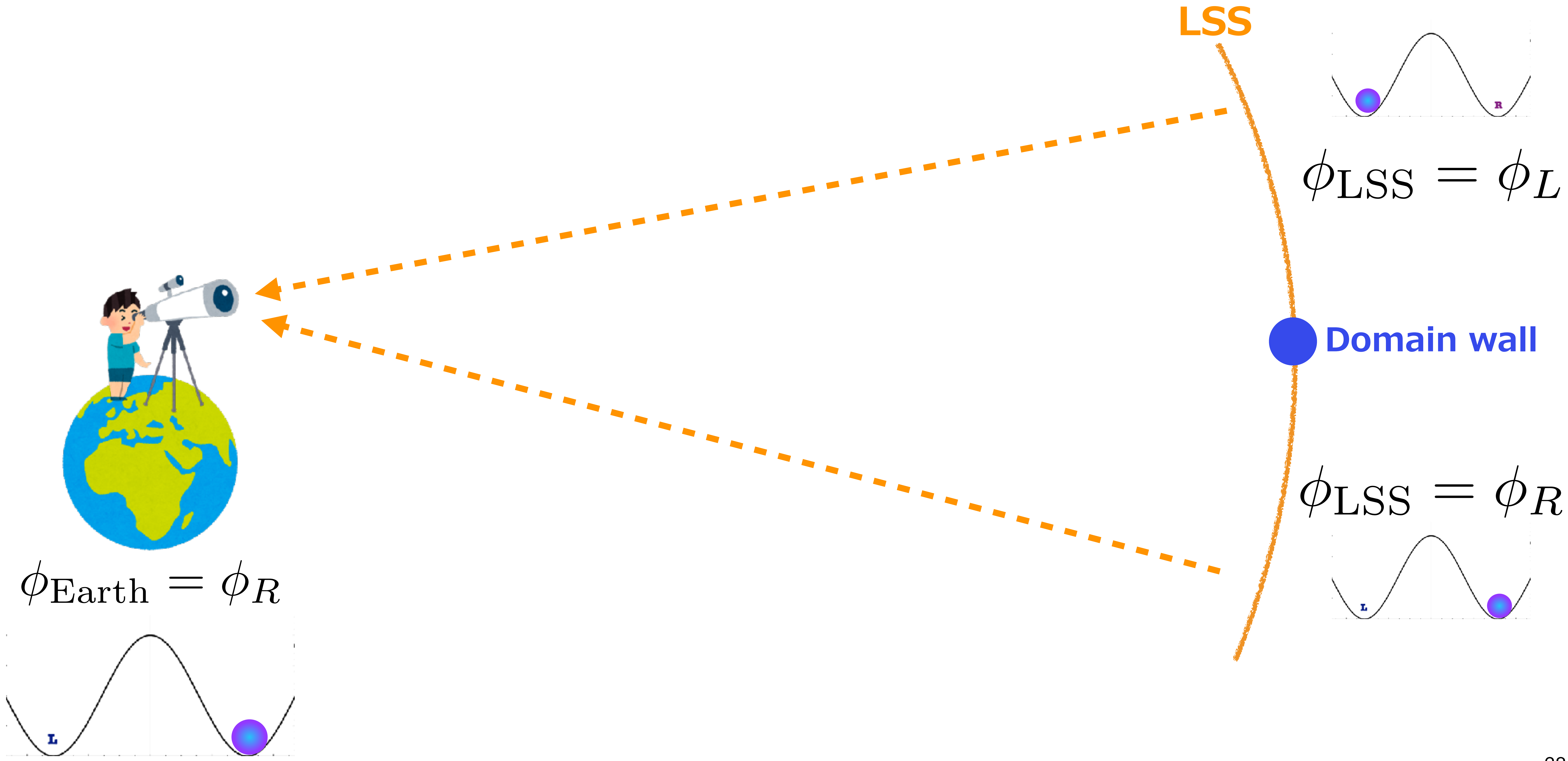
$c_\gamma = 1$

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

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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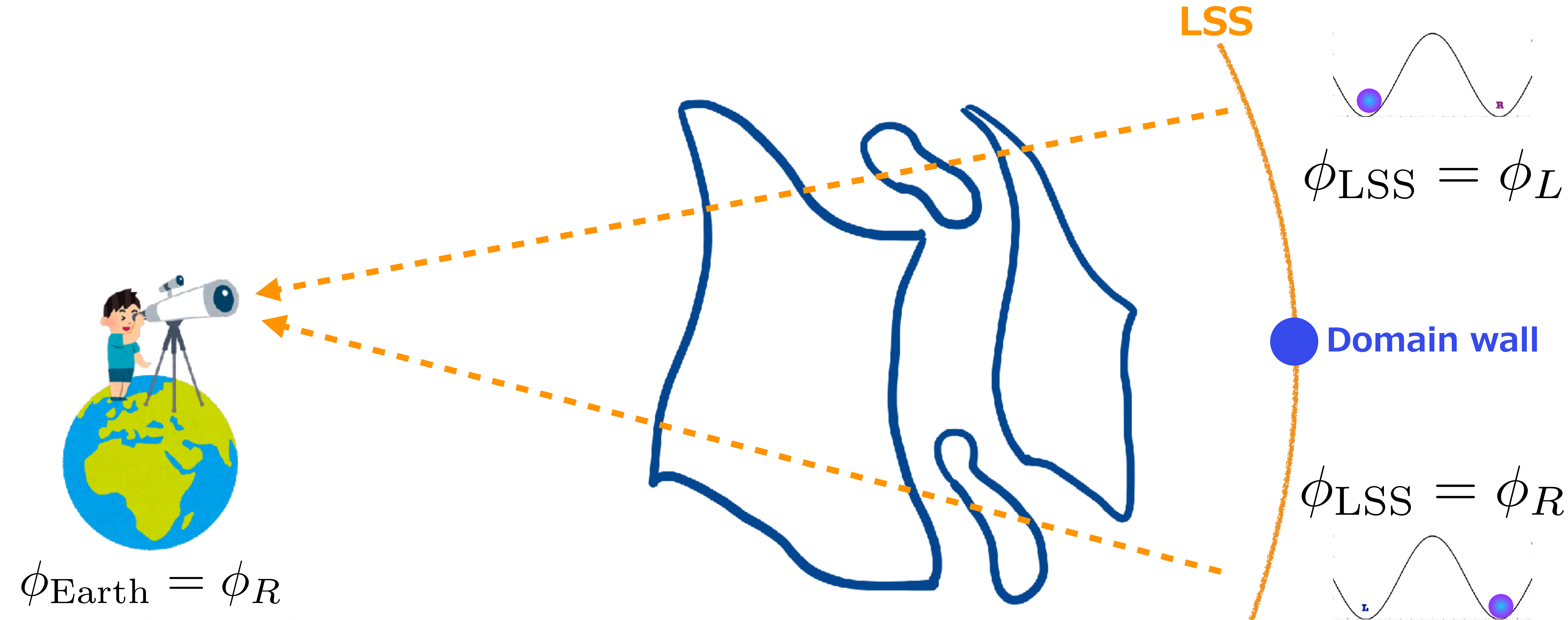
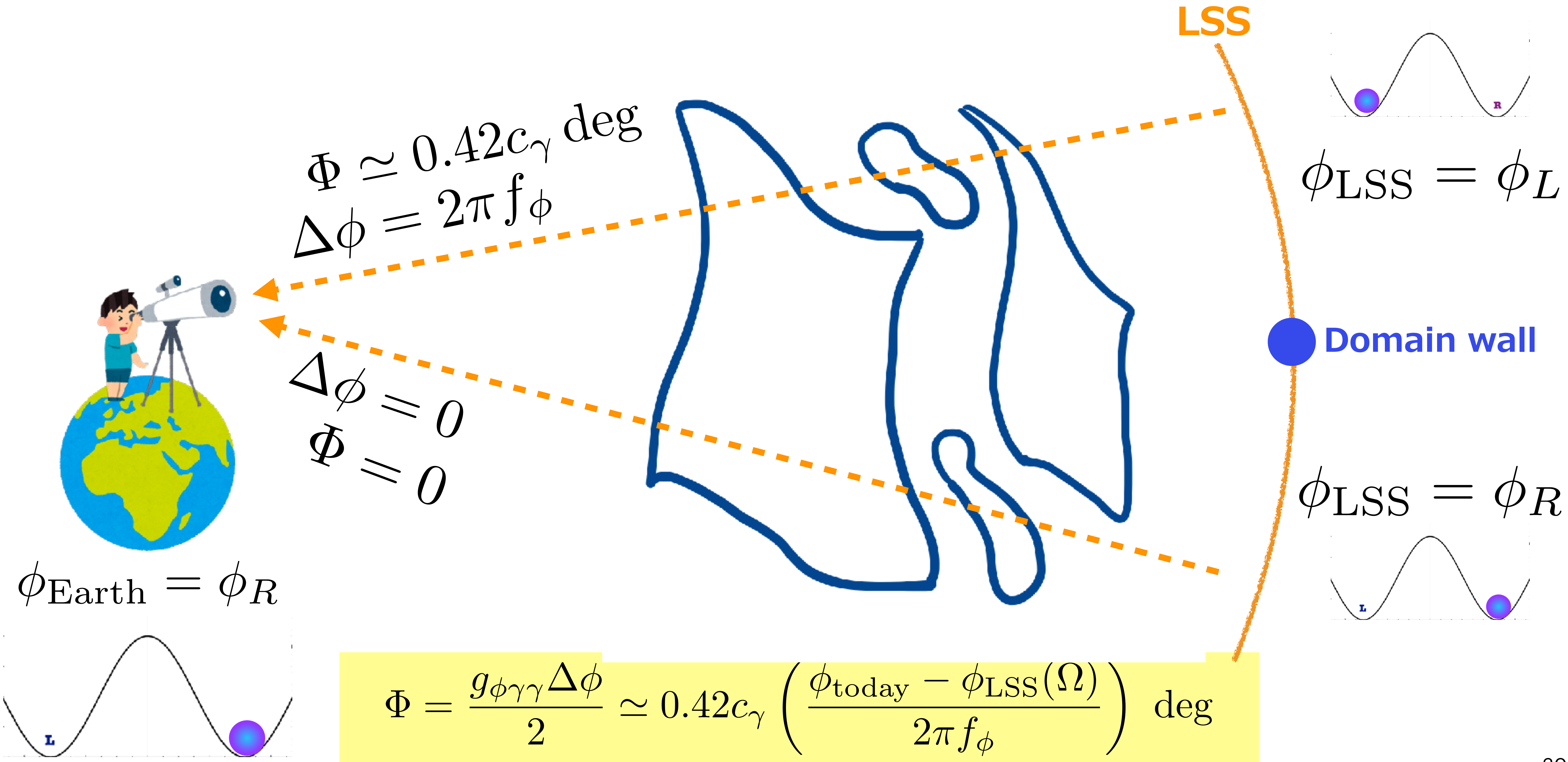


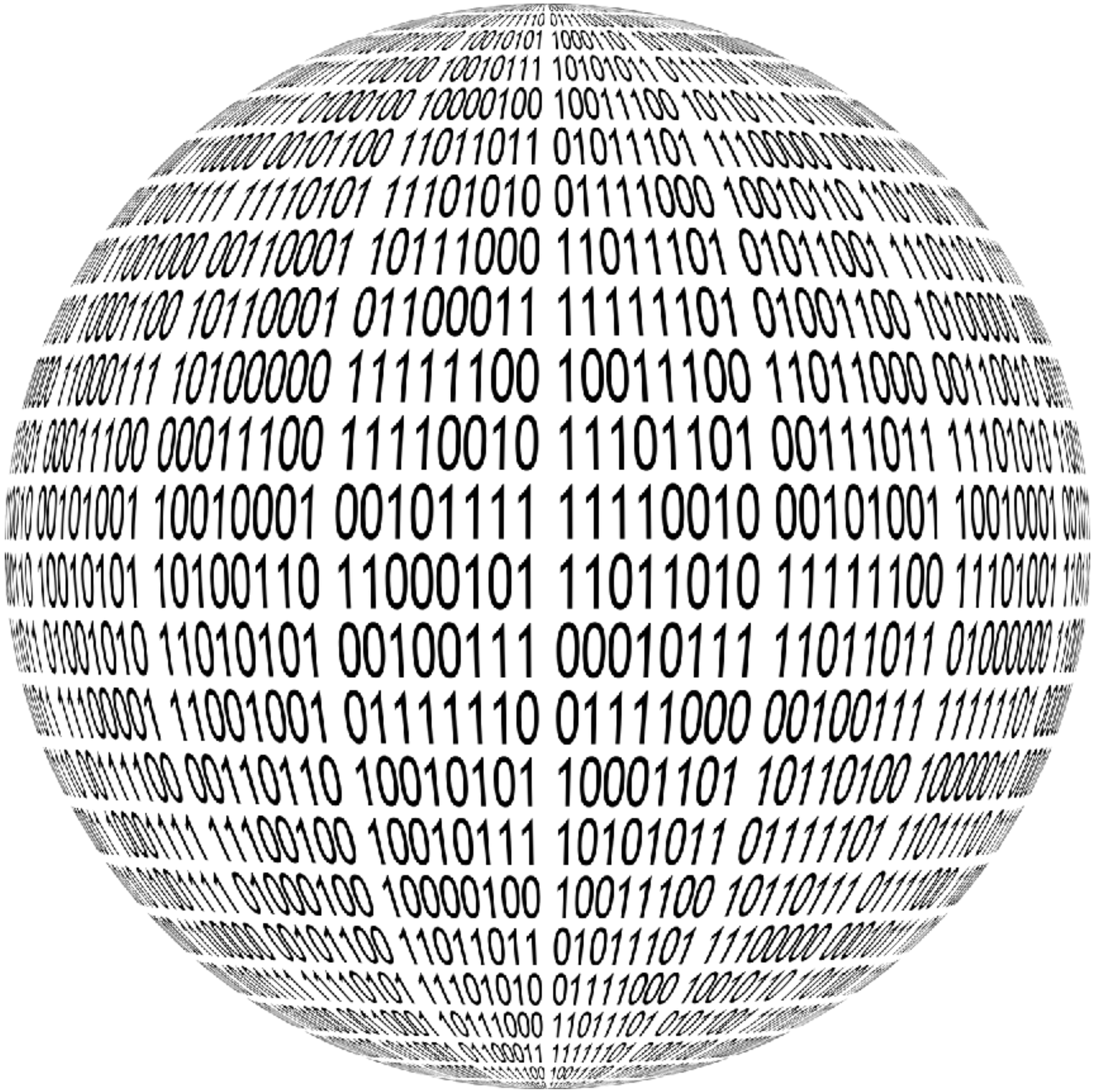
$$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi}\right) \,\mathrm{deg}$$

KiloByte CB from ALP domain walls



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

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)

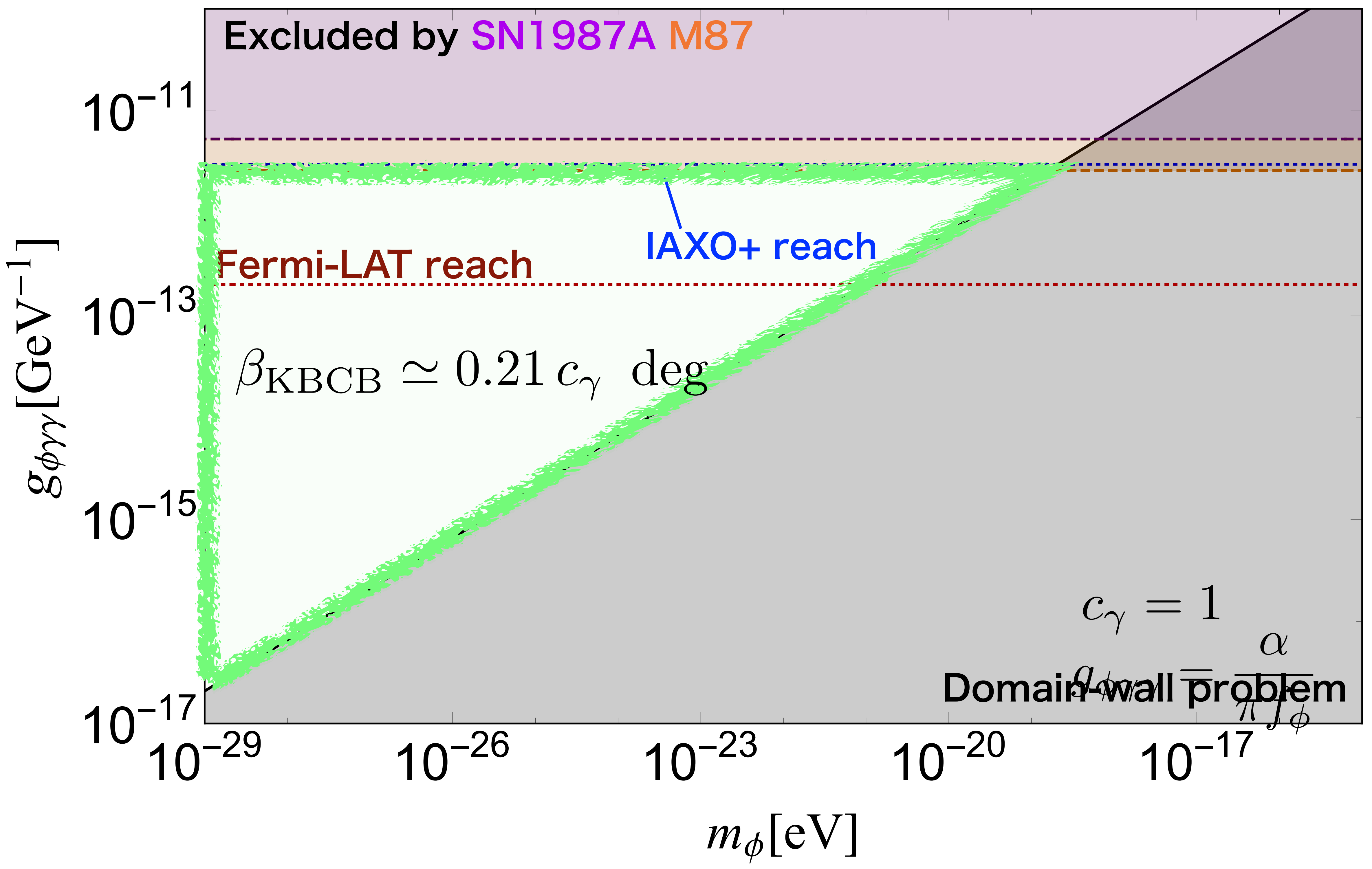
Predictions of KBCB: isotropic CB

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

independent of m_ϕ and f_ϕ.

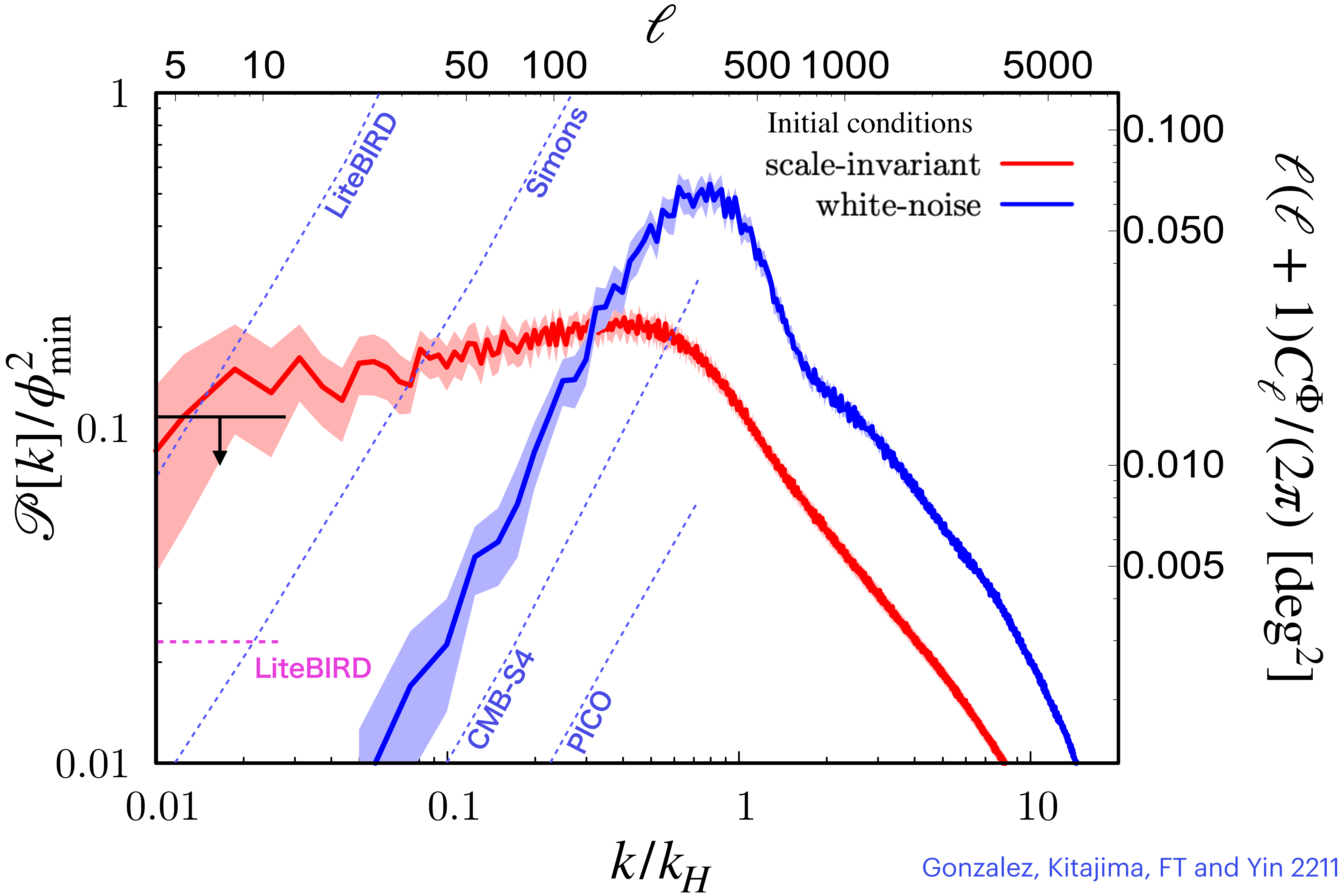
$\beta_{\rm obs} = 0.36 \pm 0.11$ deg. can be naturally explained for $c_\gamma = O(1)$.

N.B. This naturally explains the closeness of β and $\alpha \simeq 1/137\,[\mathrm{rad}] \simeq 0.42\,[\mathrm{deg}]$.



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

Predictions of KBCB: anisotropic CB



Gonzalez, Kitajima, FT and Yin 2211.06849

4. Summary

- DWs with initial inflationary fluctuations are much more stable than previously thought, due to the correlation on super-horizon scales. So, such DWs could play an important role in cosmology.

- The axion DW with inflationary fluctuations not only explains the isotropic CB, but also predicts anisotropic CB that is nearly scale-invariant at large-scales.