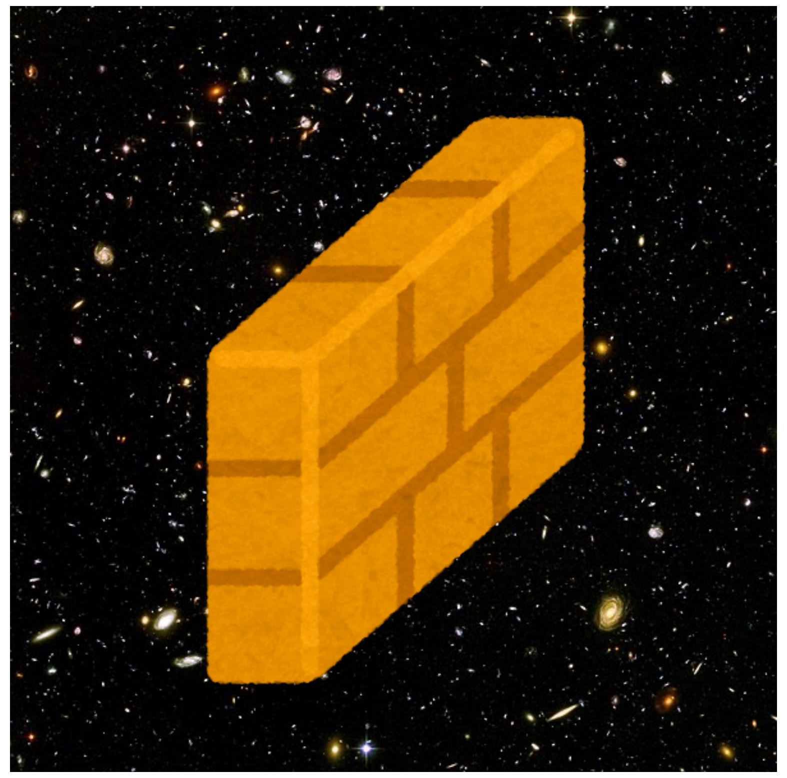
The evolution of the domain wall network with inflationary fluctuations under the asymmetric potential

Mar 28, 2023

@Workshop on Very Light Dark Matter 2023



Junseok Lee (Tohoku U.)

Based on 2304.xxxx (in progress)

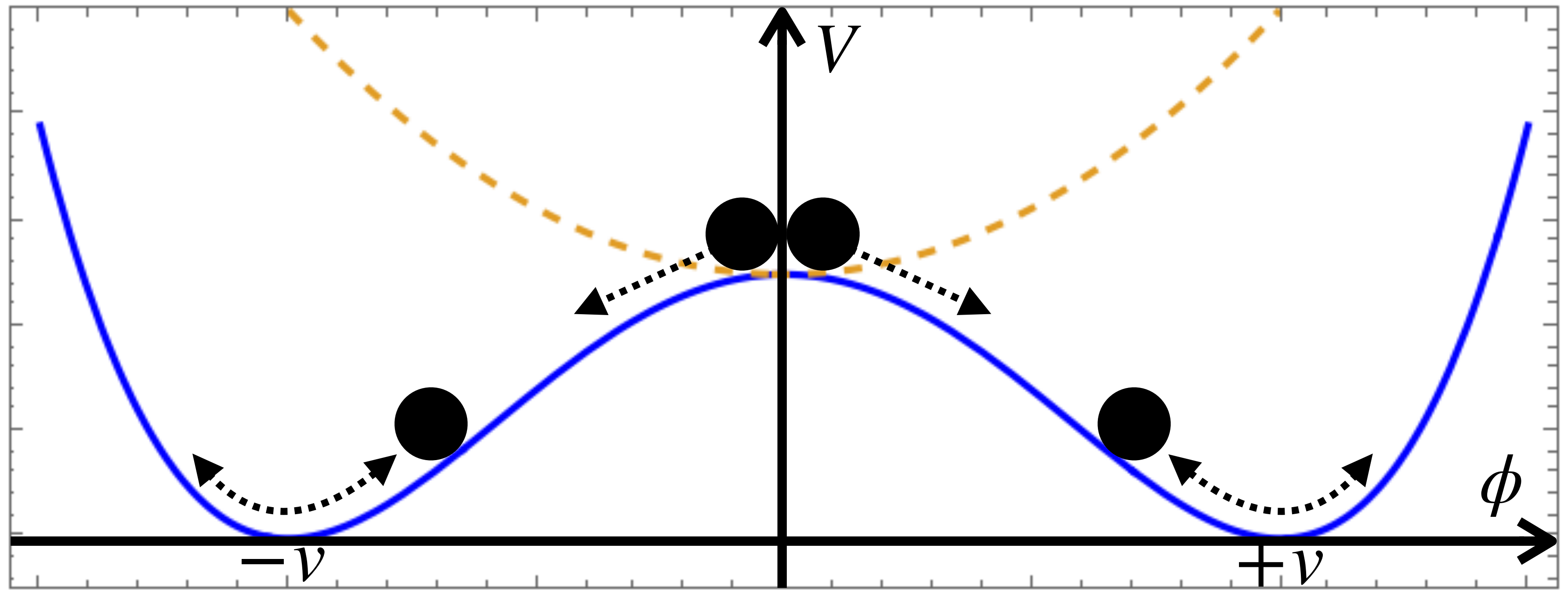
in collaboration with Naoya Kitajima, Fuminobu Takahashi, and Wen Yin

See talk by Diego Gonzalez

Cosmological domain wall

If there are multiple disconnected degenerate vacua, domain walls (DW), a type of topological defects, appear during the phase transition.

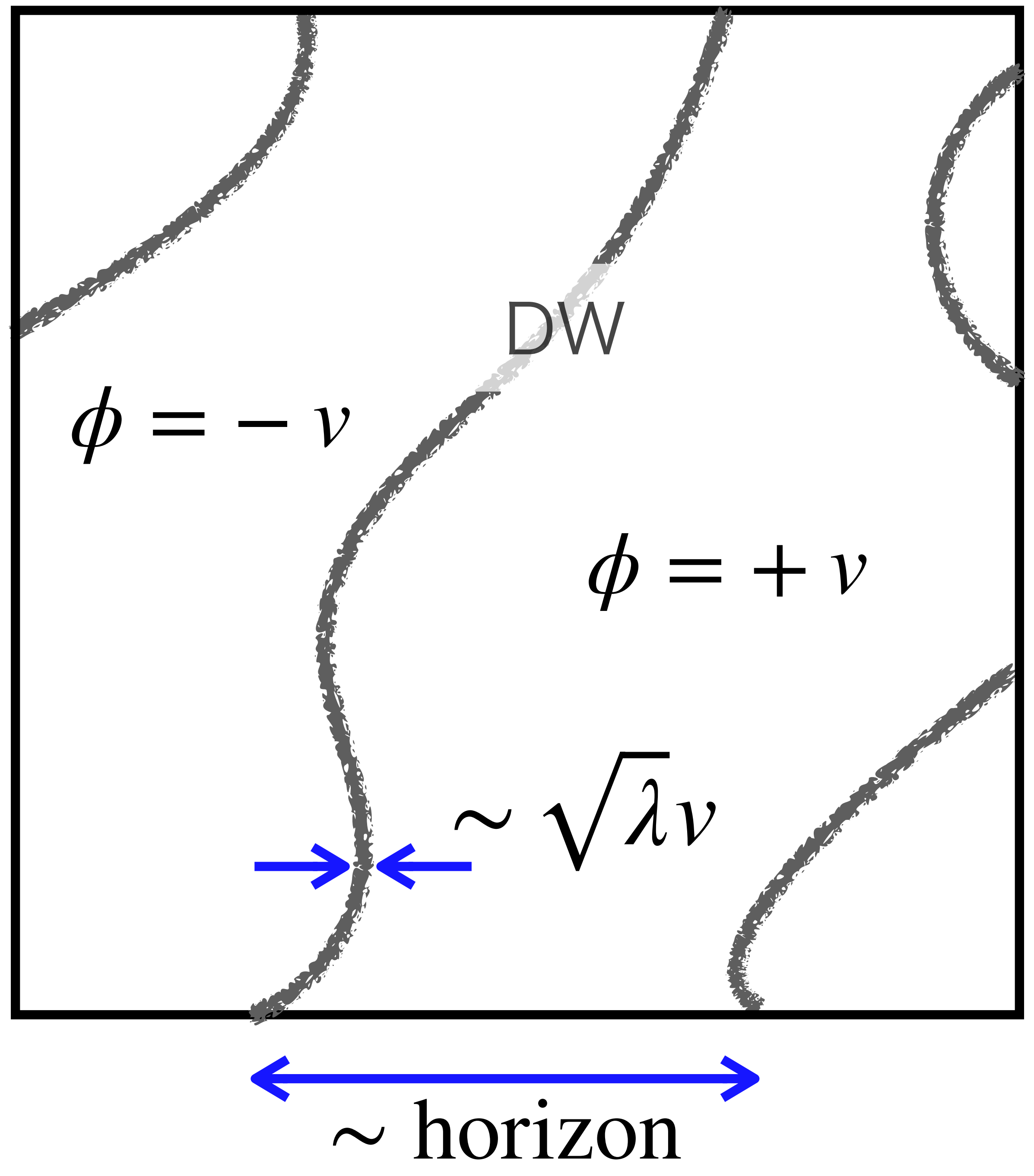
Zel'dovich, Kobzarev, Okun `74, Kibble `76, ⋯



For concrete discussion, we assume the system that undergoes the Z_2 phase transition.

$$V_0(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

We assume this



Each Hubble horizon (H^{-1}) contains $\mathcal{O}(1)$ DW, known as the scaling solution

Sikivie `82, Vilenkin `85, Press, Ryden, Spergel `89, ⋯

DWs cause a **cosmological DW problem**

Zel'dovich, Kobzarev, Okun `74

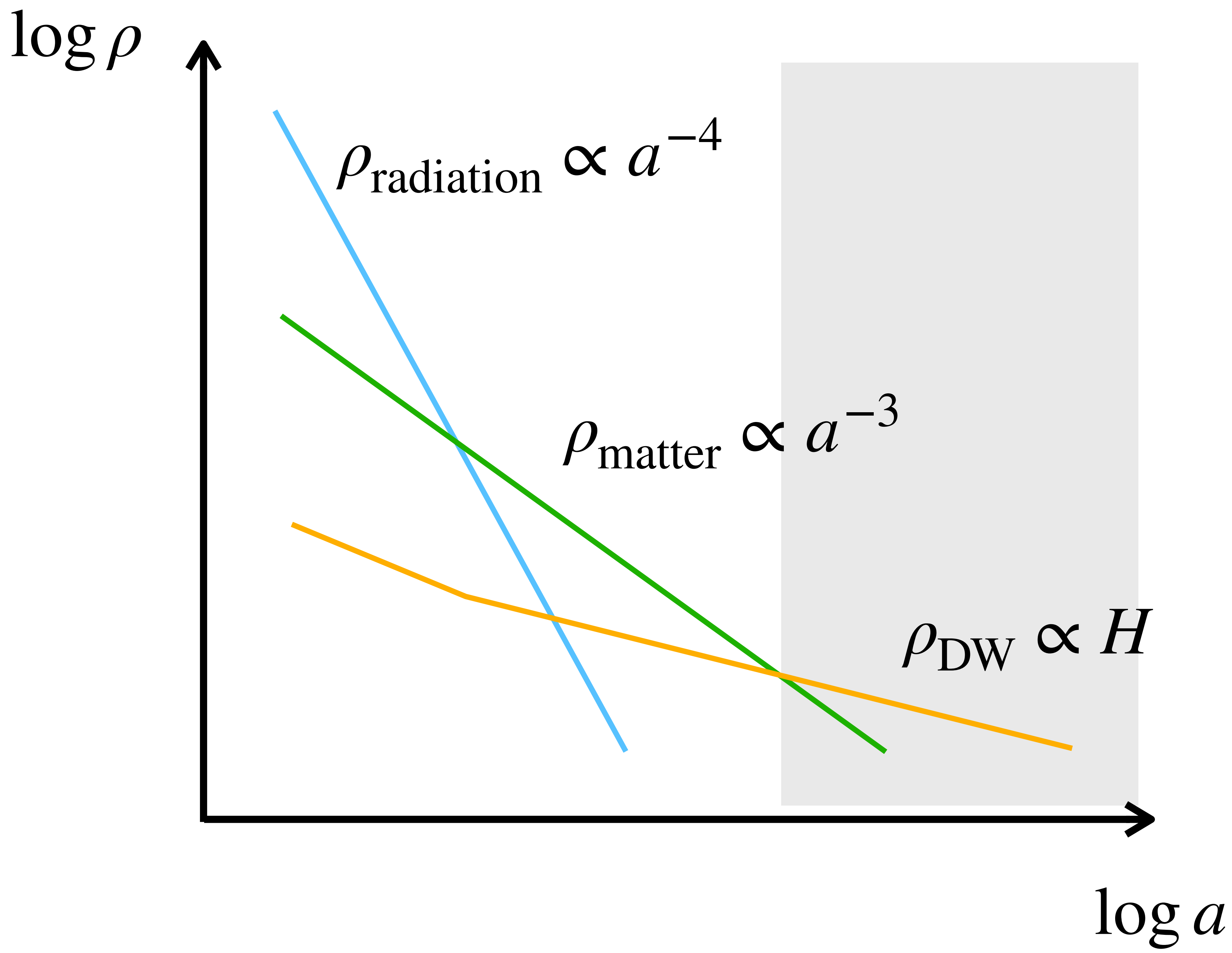
Cosmological DW problem

Zel'dovich, Kobzarev, Okun `74

The energy density of DW network falls slowly compared to other components as the universe expands.

$$\rho_{\mathrm{DW}} = \frac{\sigma H^{-2}}{H^{-3}} = \sigma H$$

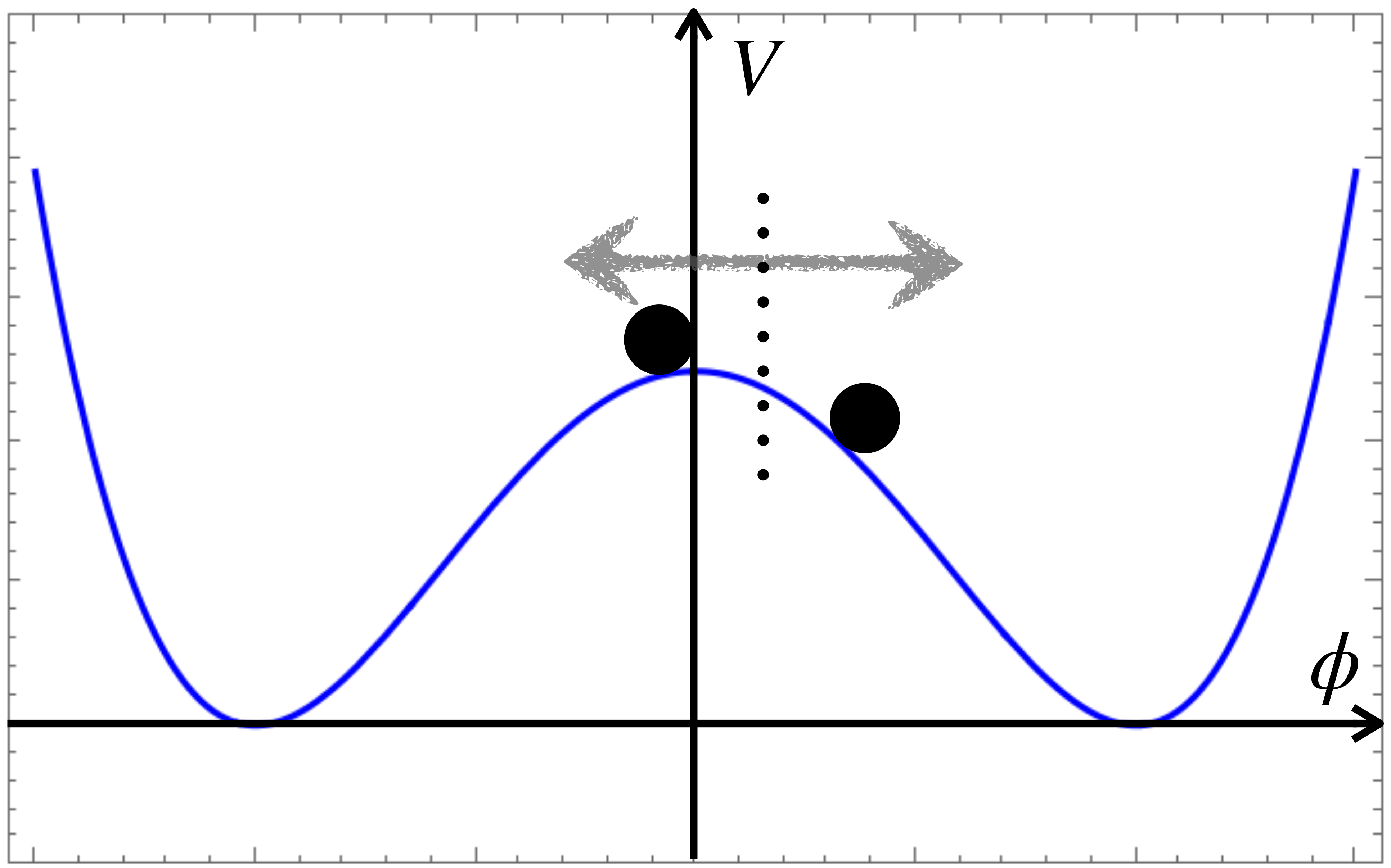
This easily makes DWs to dominate the universe which contradicts the isotropy of CMB observations.



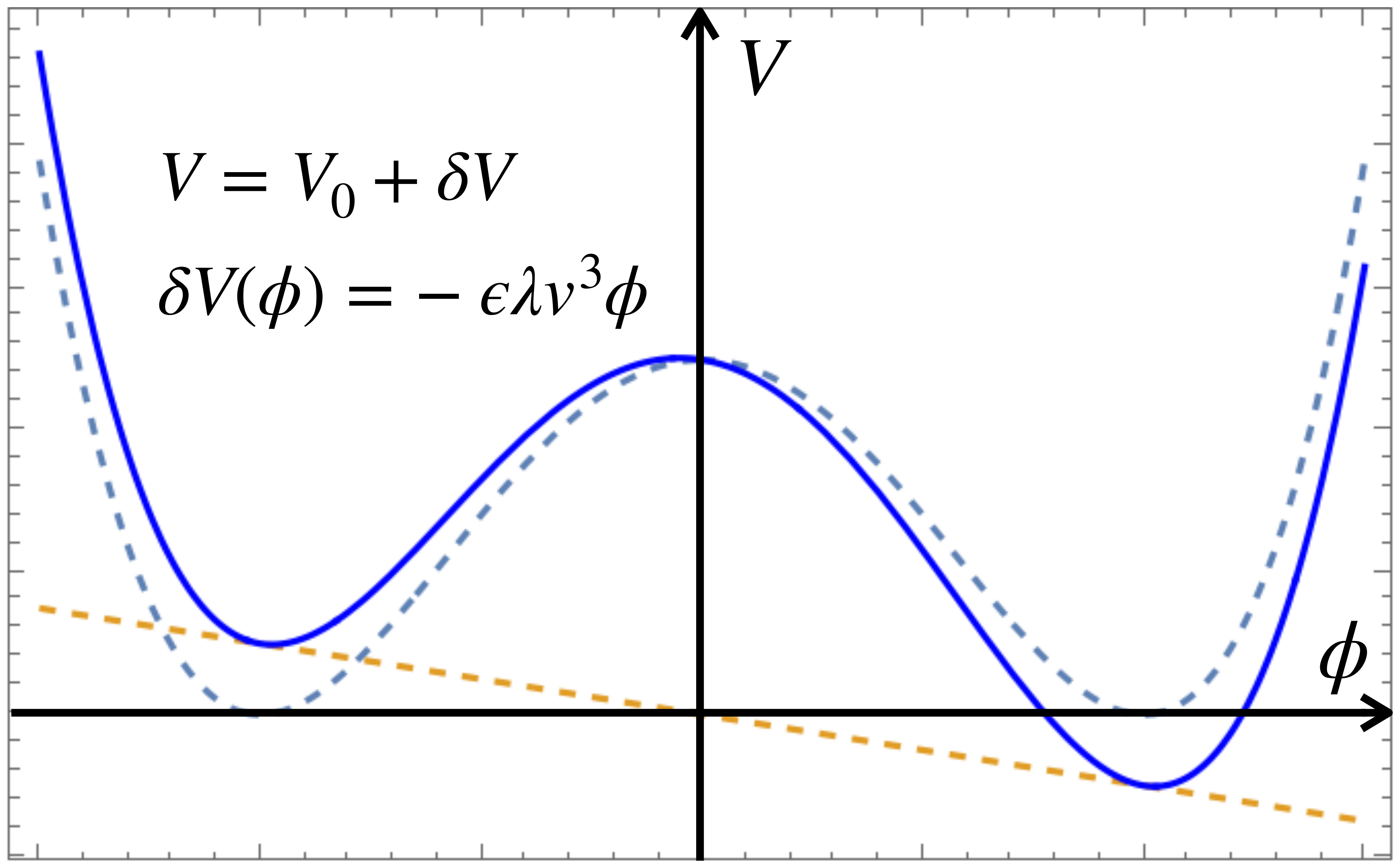
We need small DW tension $\sigma < (\mathrm{MeV})^3$ or <u>asymmetry which makes DW unstable</u>.

Two kind of the bias

initial population bias



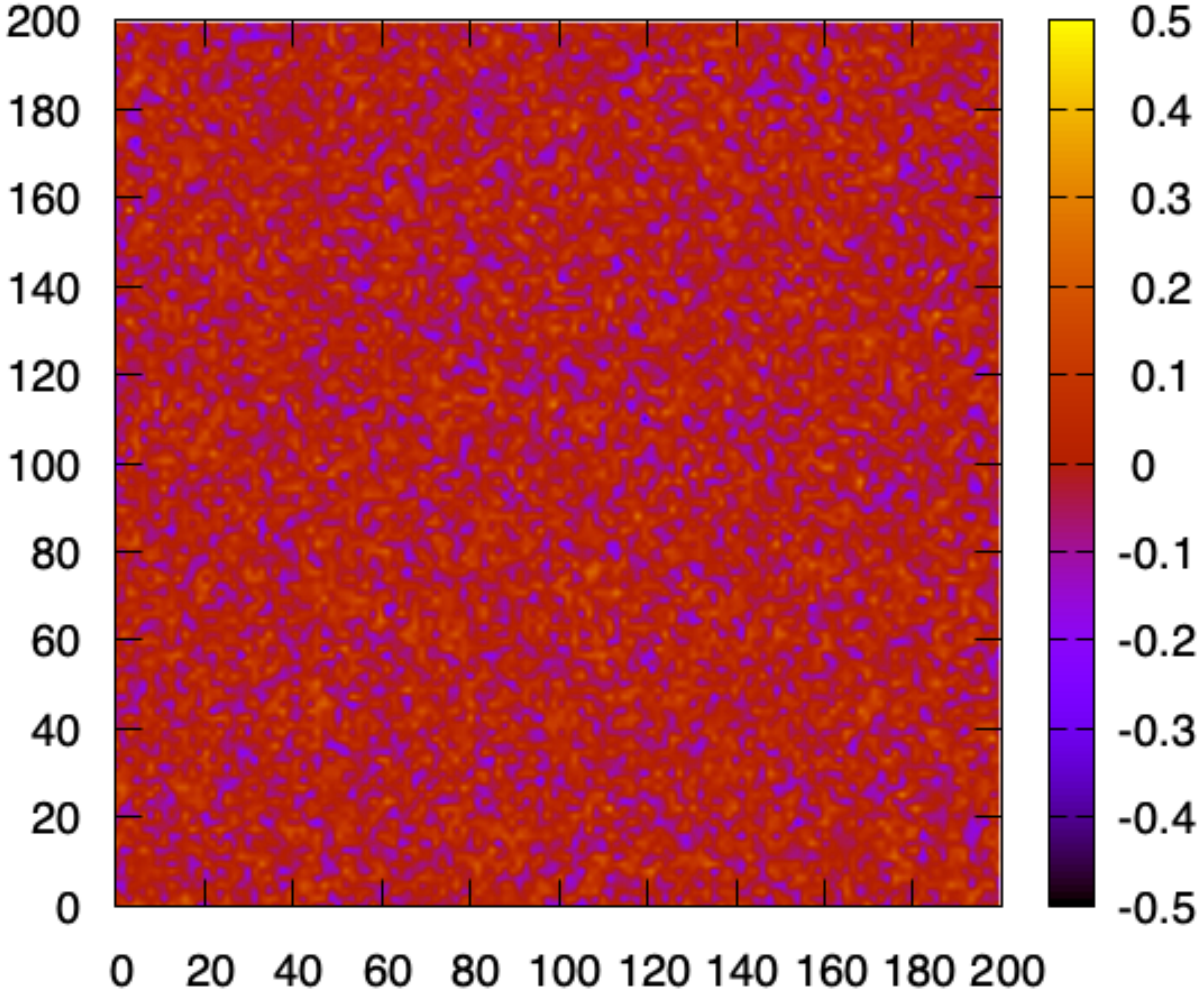
potential bias



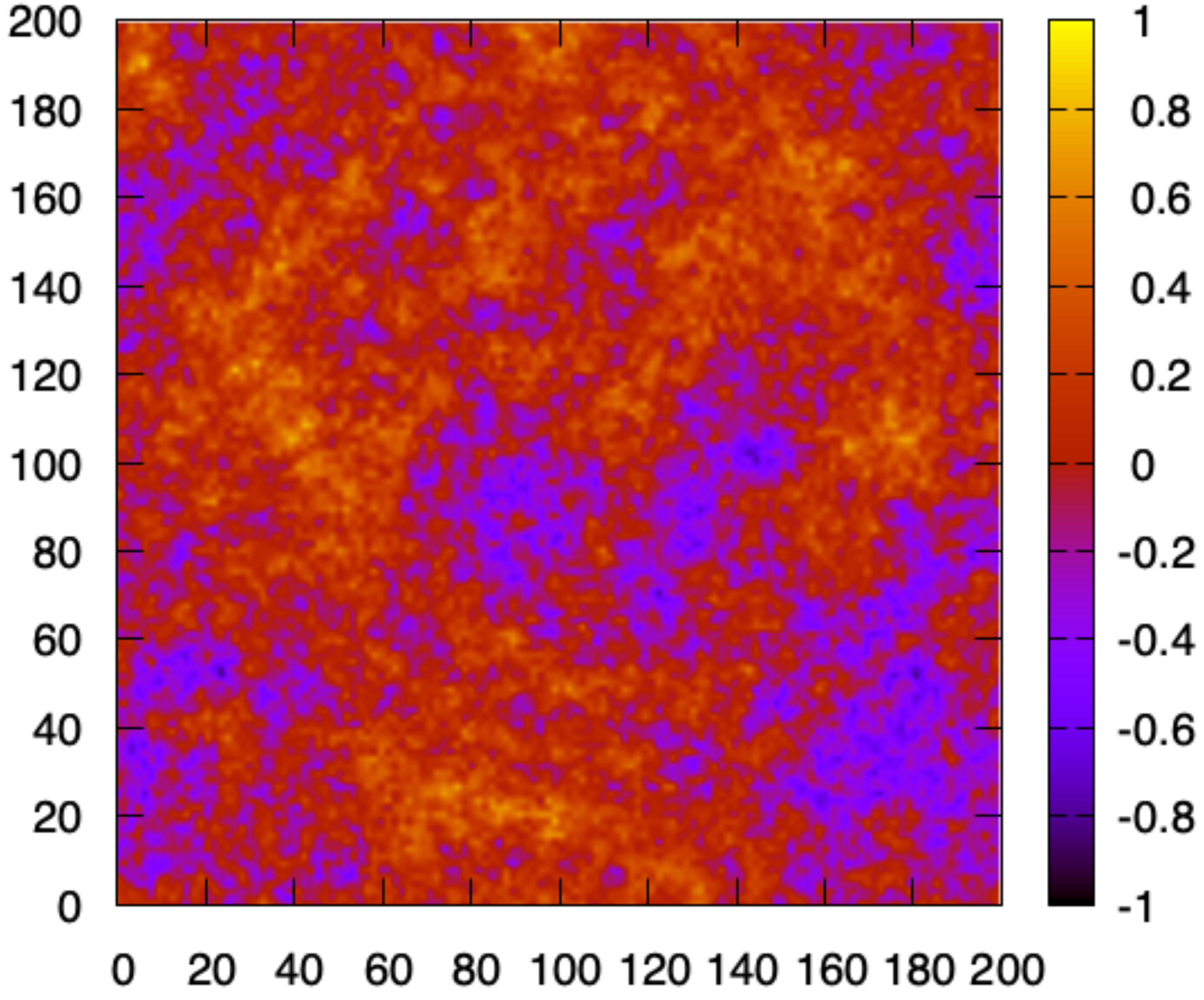
pressure $\quad F_{\text{killing}} = \dfrac{dP_{\text{killing}}}{dt} \sim \epsilon \lambda v^4$

Two different initial distributions

Thermal fluctuations
(No large scale correlations)



Inflationary fluctuations
(correlations on superhorizon)



What has been thought

initial condition

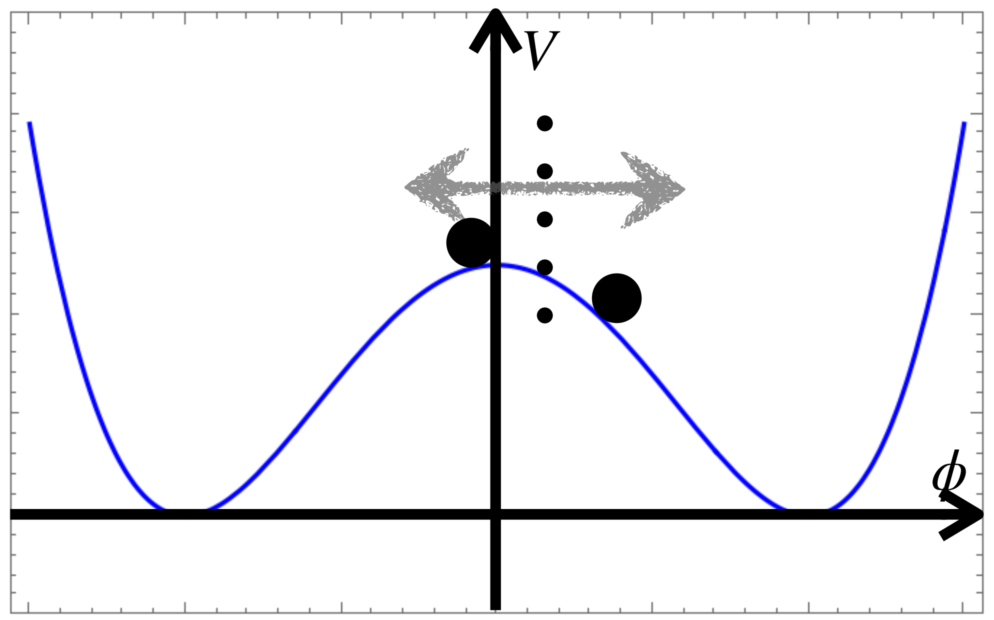
Thermal fluctuations
(No large scale correlations)

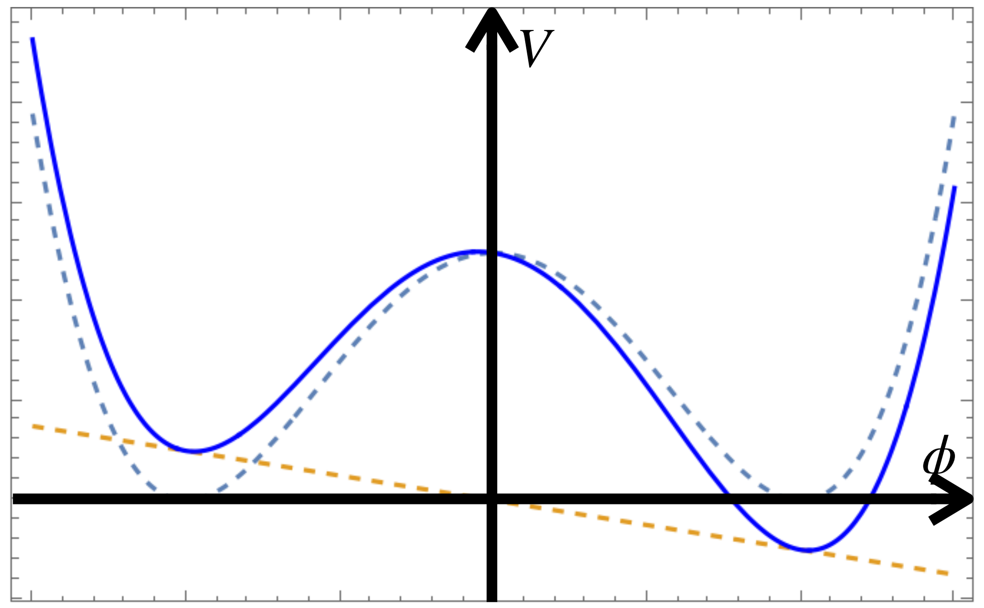
Inflationary fluctuations
(correlations on superhorizon)

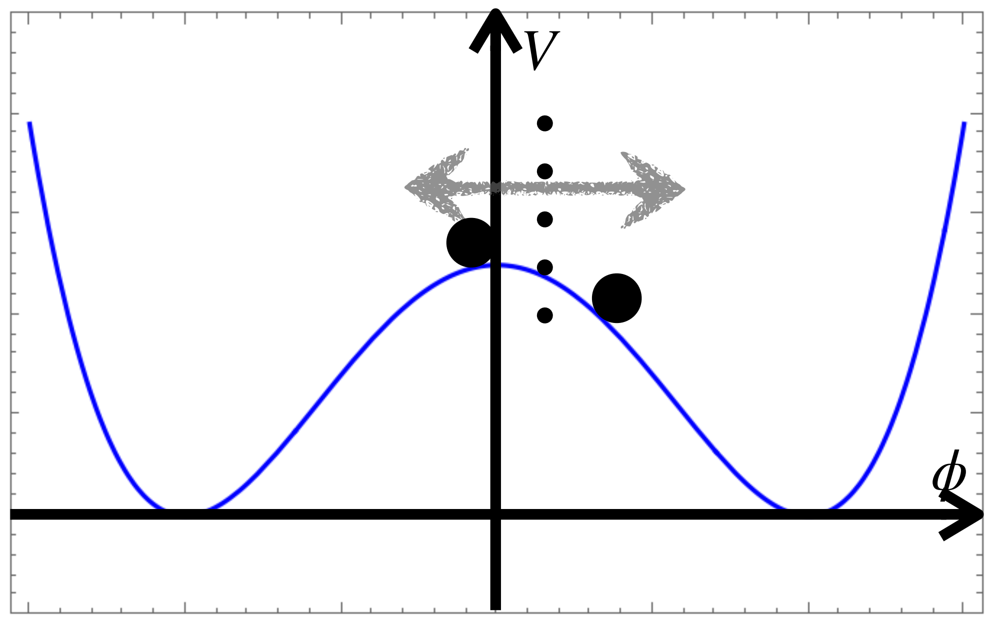
under

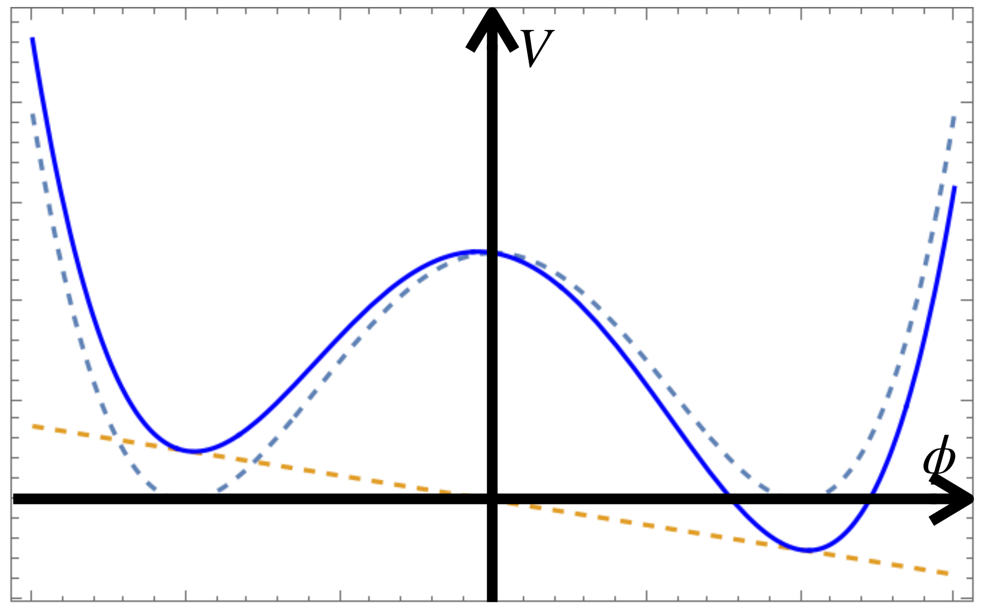
bias

Population bias	Potential bias	Population bias	Potential bias
unstable	unstable	unstable	unstable







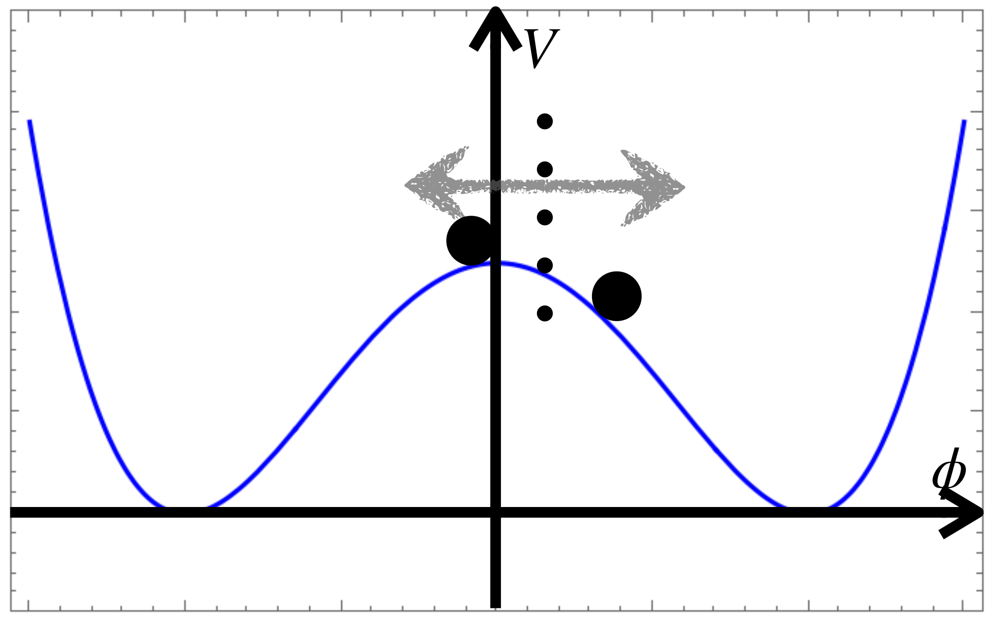


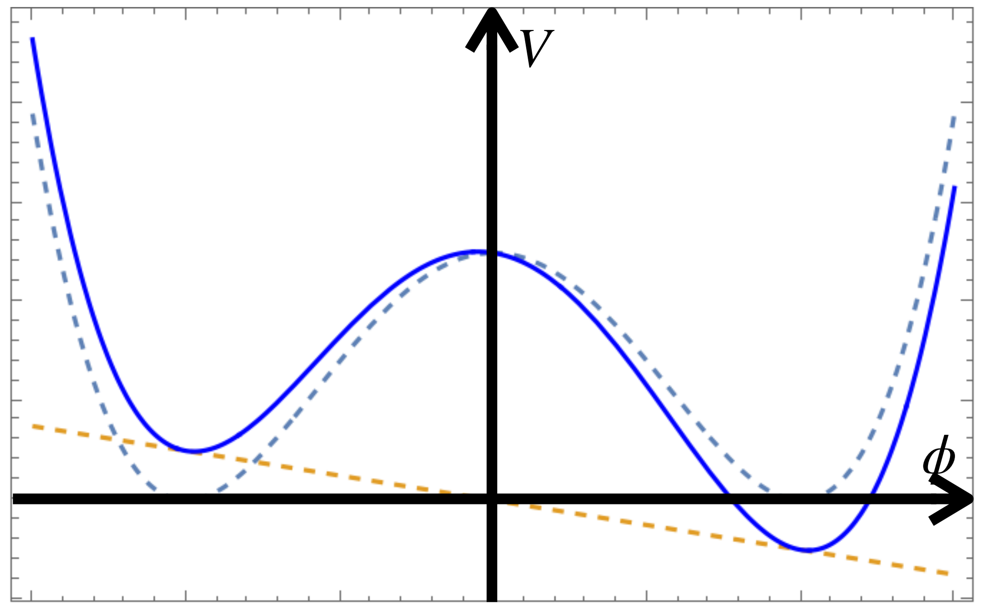
Coulson, Lalak, Ovrut `96, Larsson, Sakar, White `97, Correia, Leite, Martins `14, …

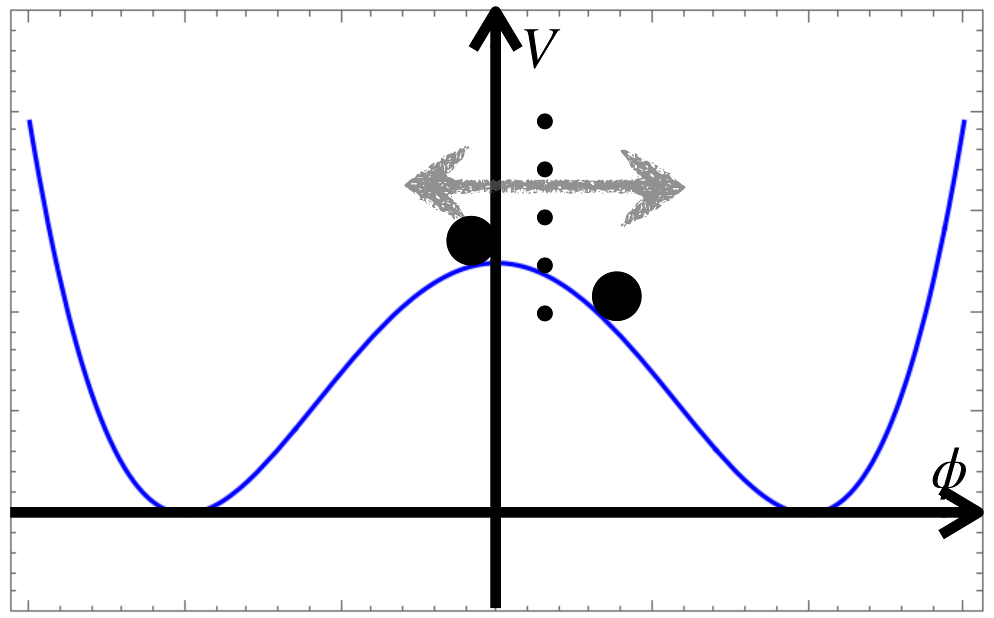
HOWEVER…

What has been found recently

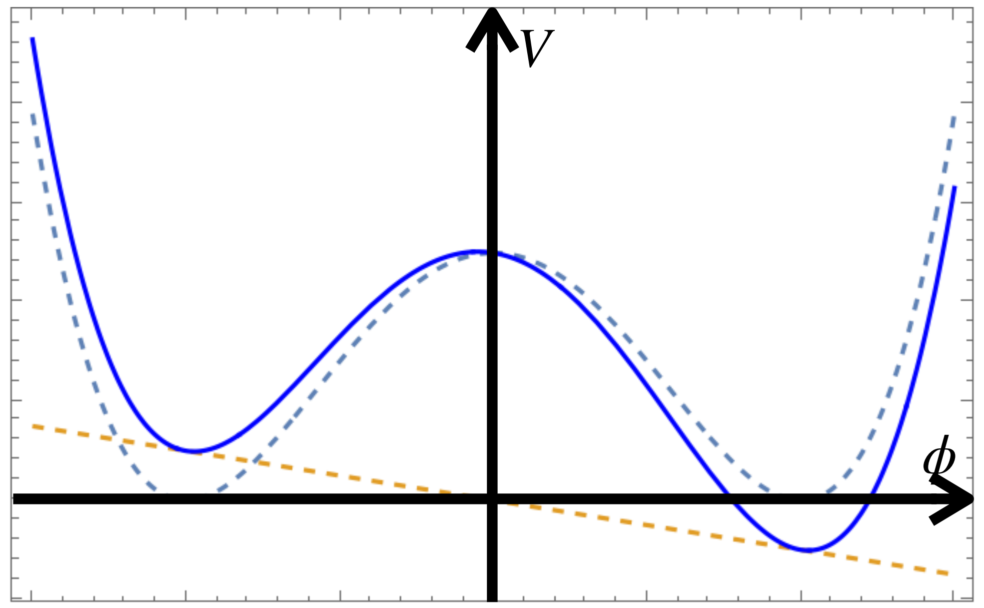
initial condition	**Thermal fluctuations** (No large scale correlations)		**Inflationary fluctuations** (correlations on superhorizon)	
under				
bias	**Population bias**	**Potential bias**	**Population bias**	**Potential bias**
	unstable	unstable	stable	??







Kitajima, Diego, Takahashi, Yin `22



What has been found recently

initial condition

Thermal fluctuations
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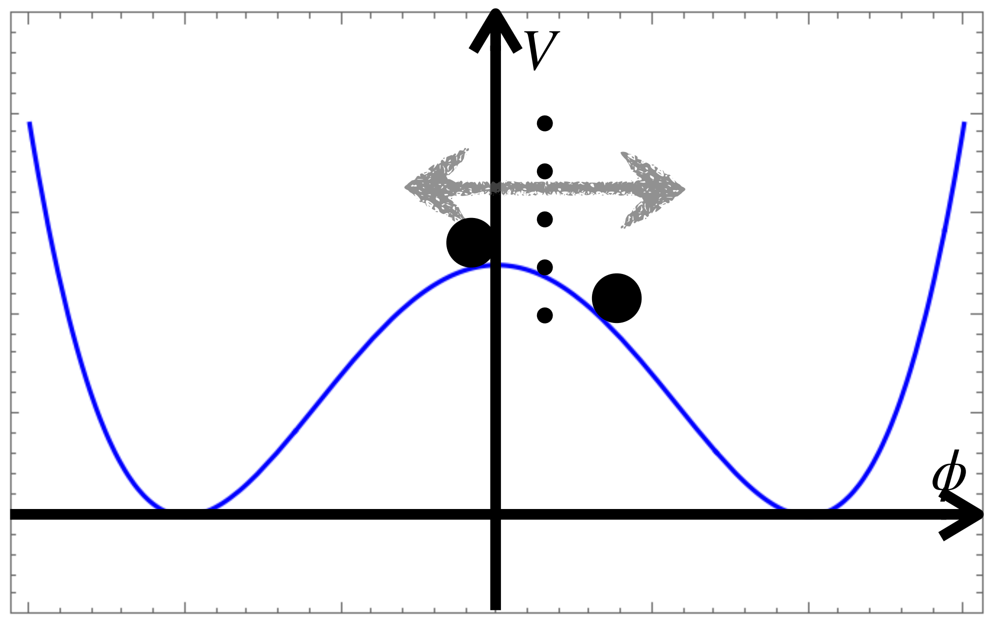
Inflationary fluctuations
(correlations on superhorizon)

under

bias

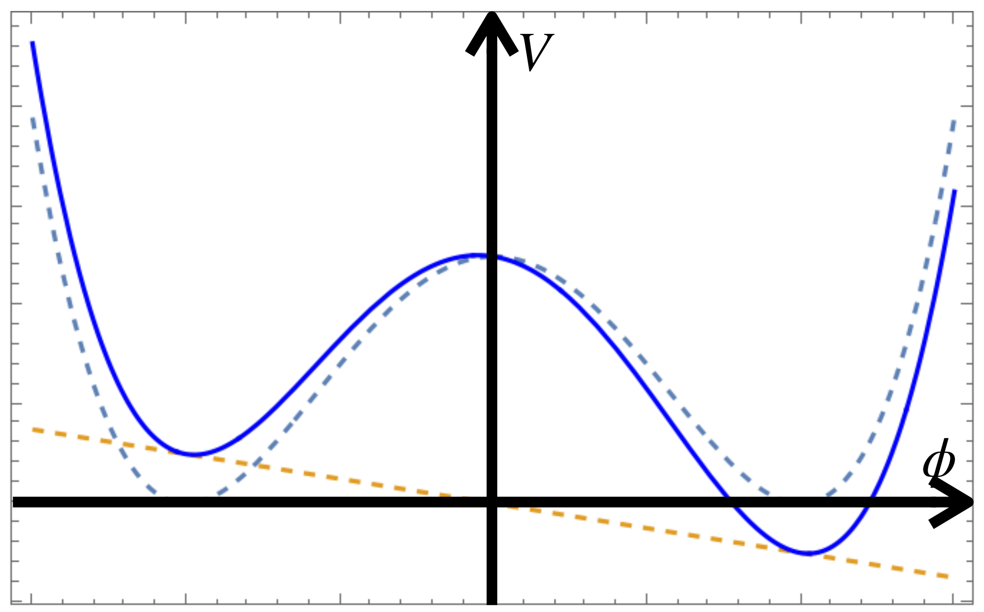
Population bias

unstable



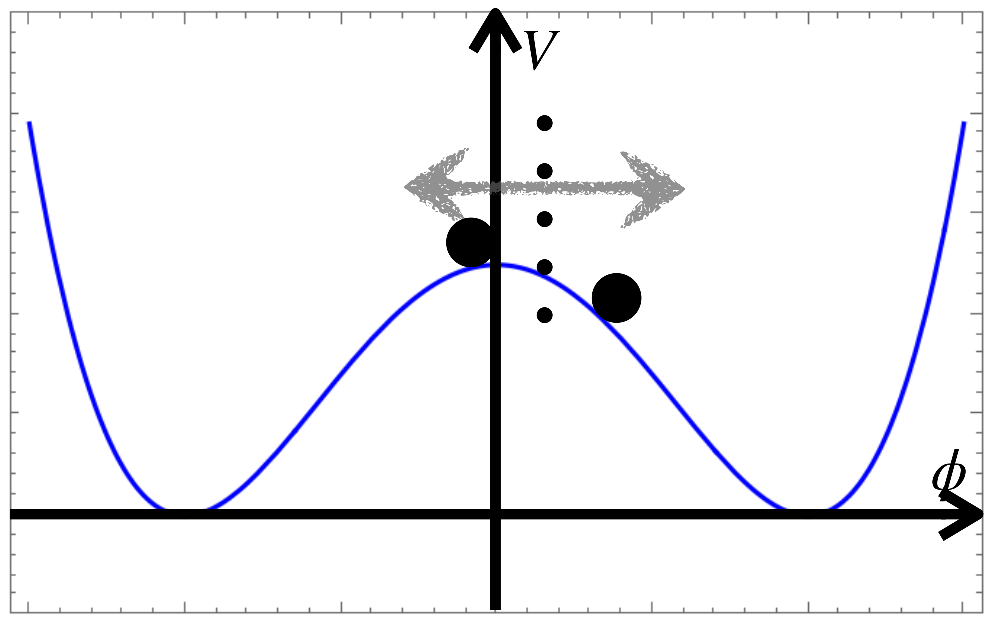
Potential bias

unstable



Population bias

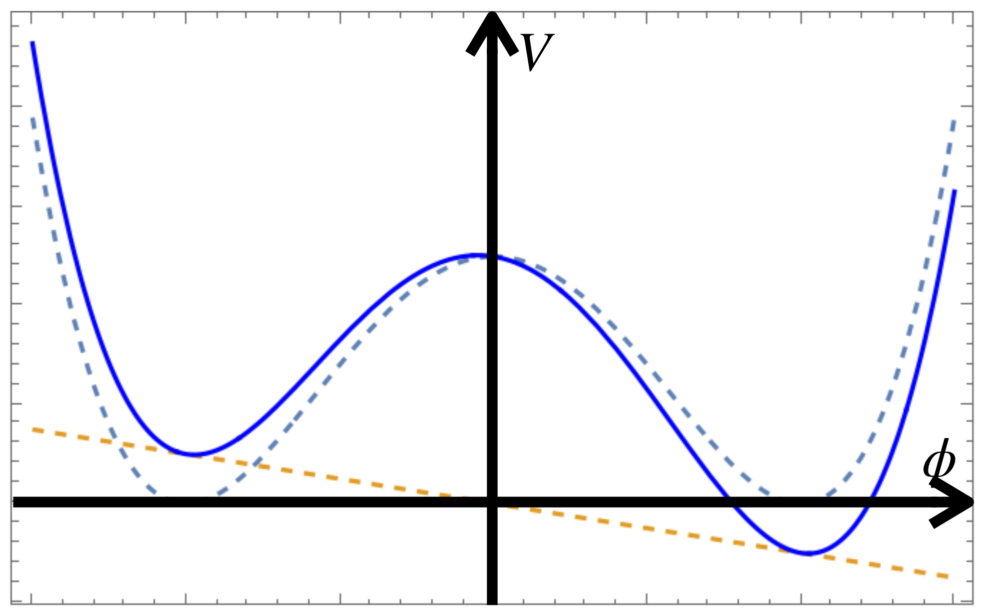
stable



Kitajima, Diego, Takahashi, Yin `22

Potential bias

??



This work

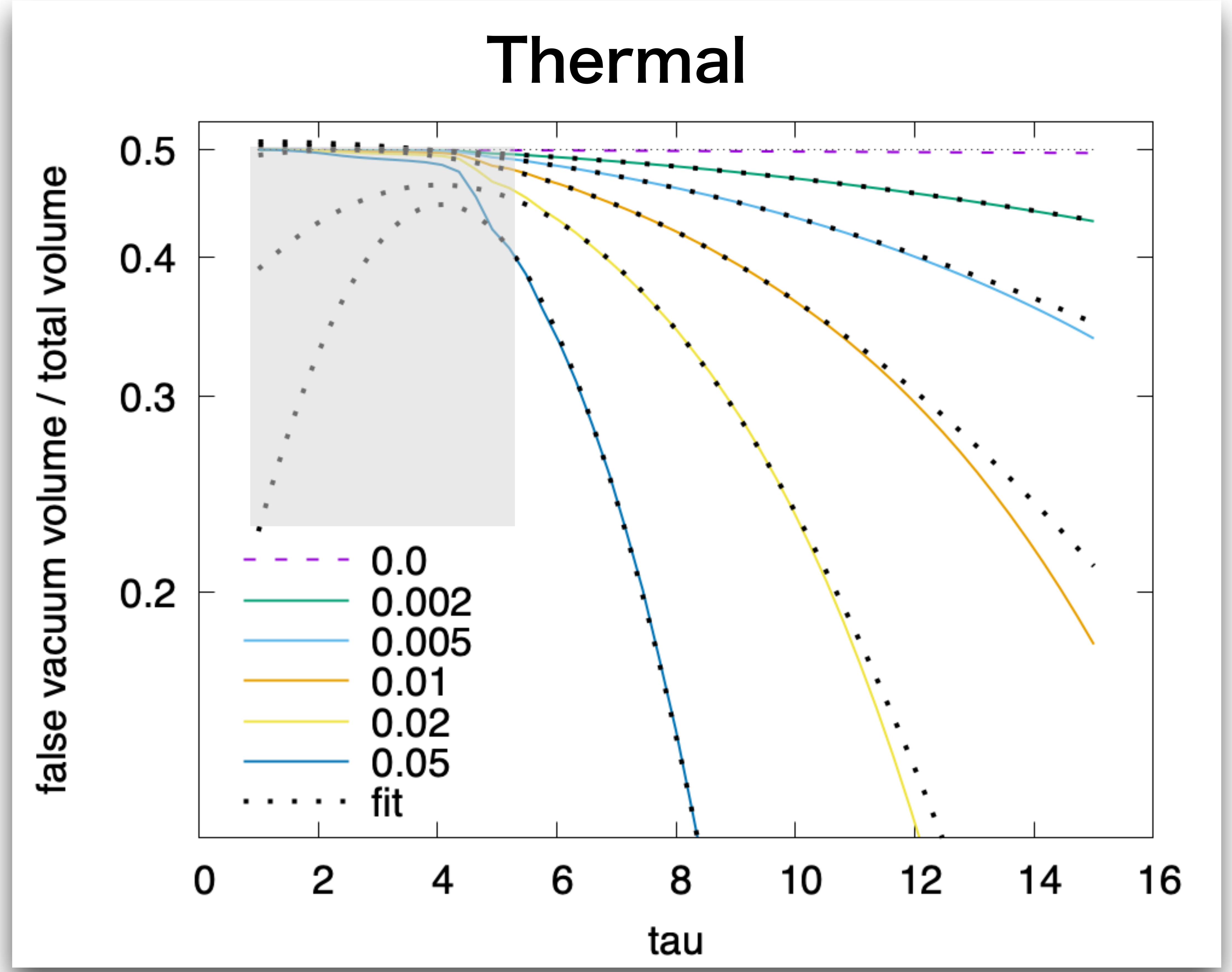
What we did

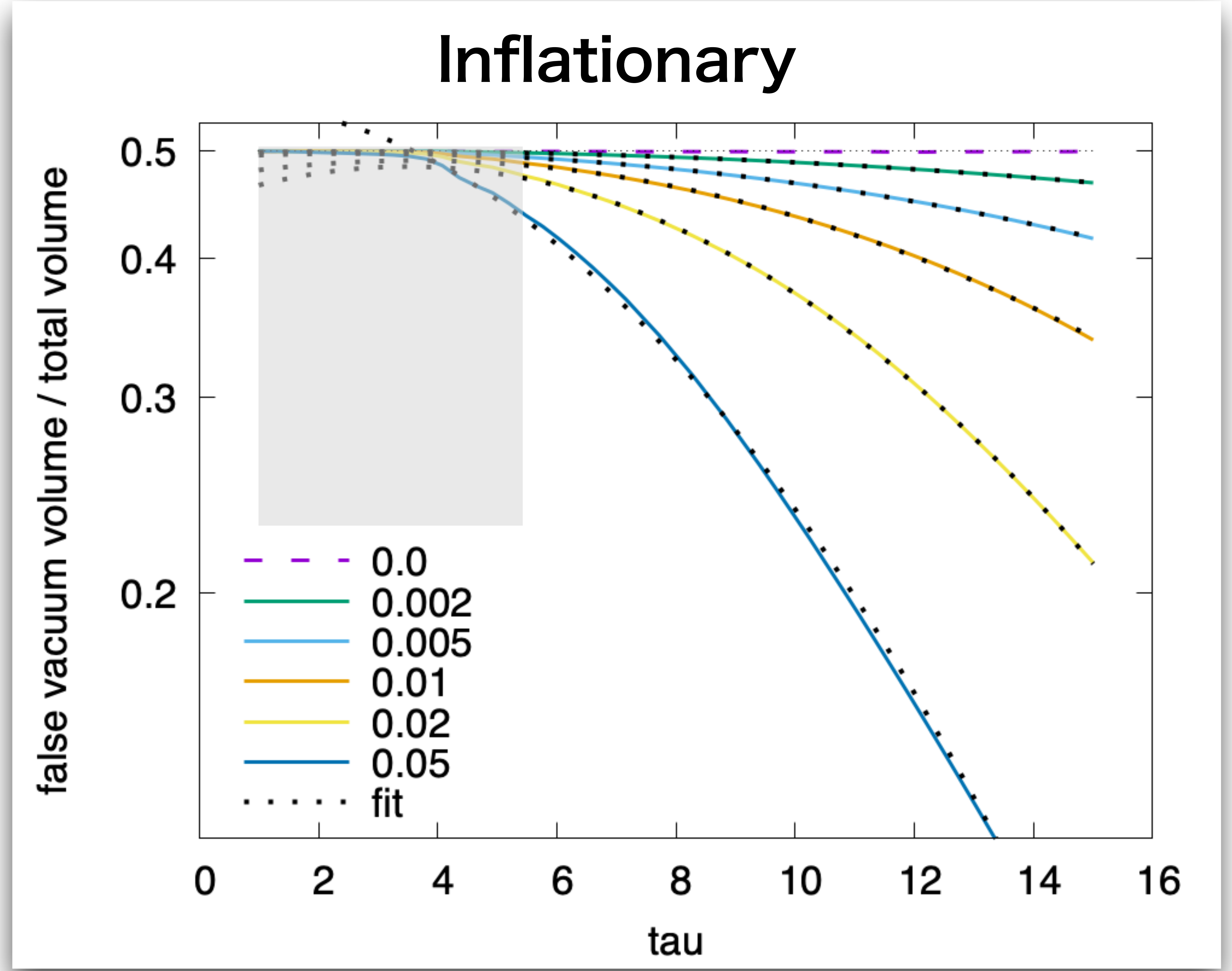
- The first study on the evolution of DW network under the potential bias, based on the lattice simulations with initial inflationary fluctuations

- As the initial conditions, we generated random numbers properly on the momentum space and Fourier transformed them.

- We focused on the ratio of the volume of false vacuum domain against the total volume of the system to evaluate the lifetime.

Lifetime of DW





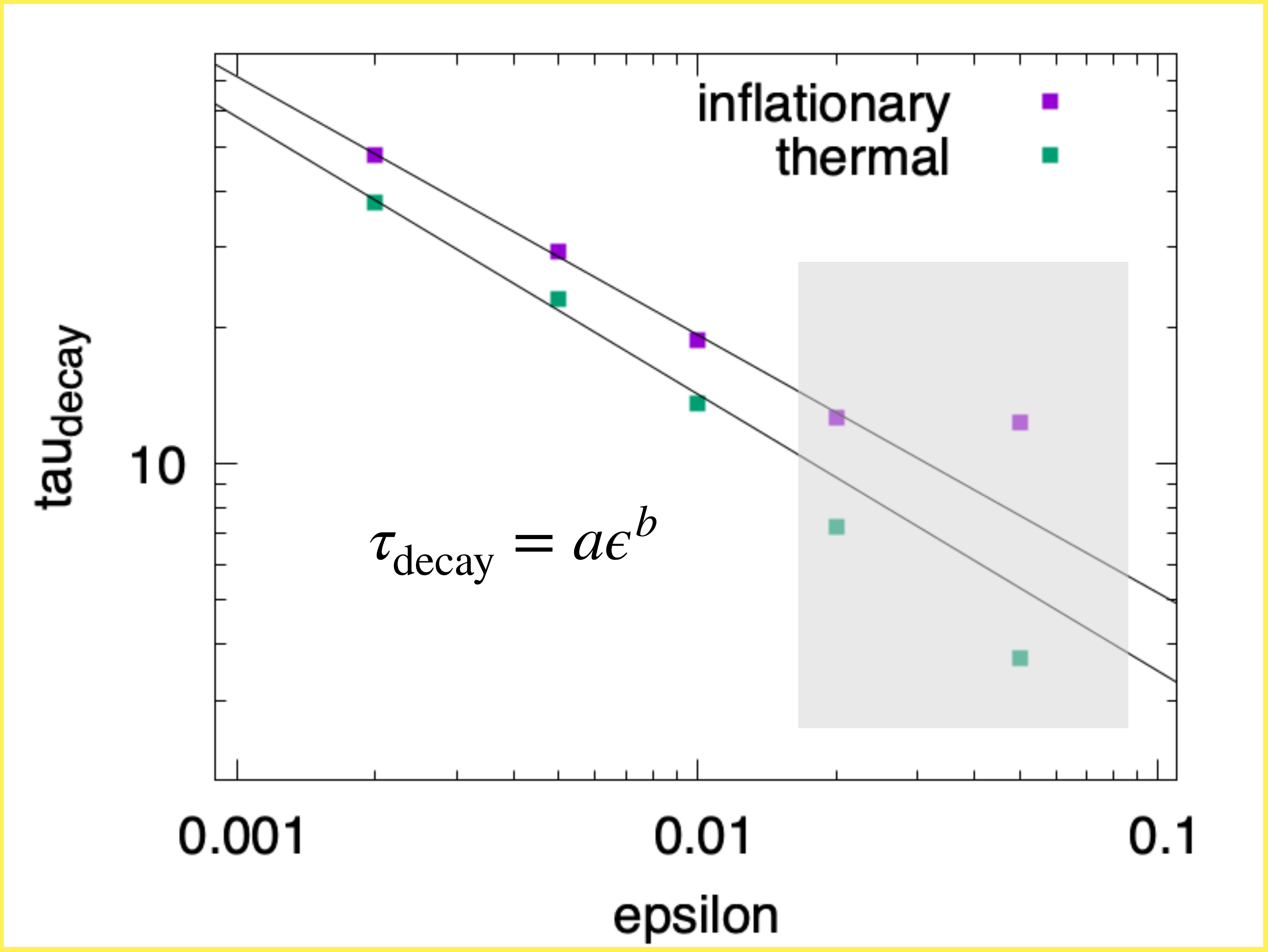
Both show the same decaying pattern as $r_{\mathrm{vol}} = C \exp\left[-\left((\tau - \tau')/\tau_{\mathrm{decay}}\right)^2\right]$

Bias dependency of lifetime

The lifetime of the DW network of both shows same bias dependency which can be predicted by

$$\sigma H_{\rm decay} \sim p \quad \rightarrow \quad \tau_{\rm decay} \propto \epsilon^{-1/2}$$

in radiation dominated era. It means that DW collapse when the pressure p overwhelms its energy density σH.



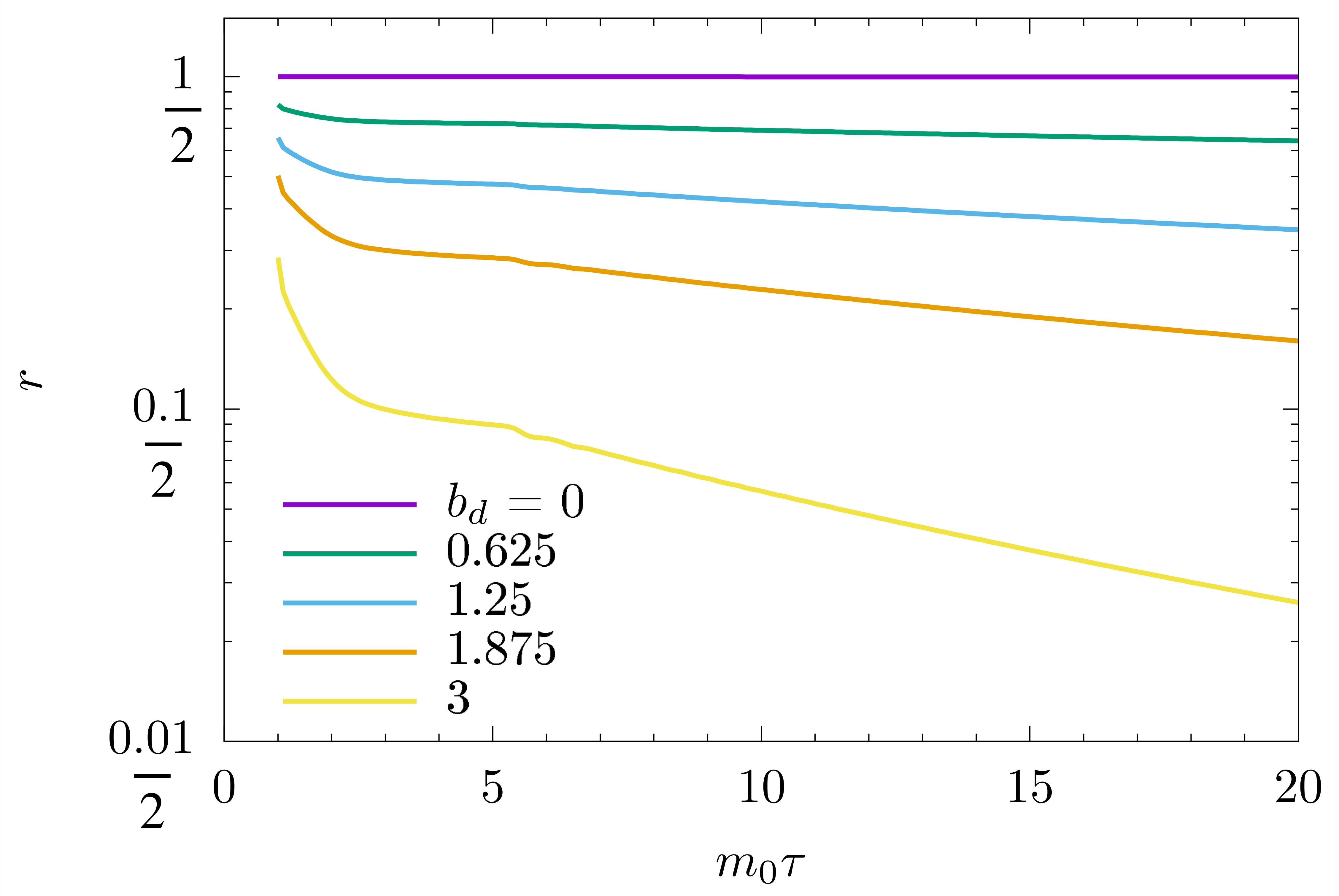
$a \simeq 0.9 \qquad b \simeq -0.6 \qquad \text{(thermal)}$

$a \simeq 1.4 \qquad b \simeq -0.6 \qquad \text{(inflationary)}$

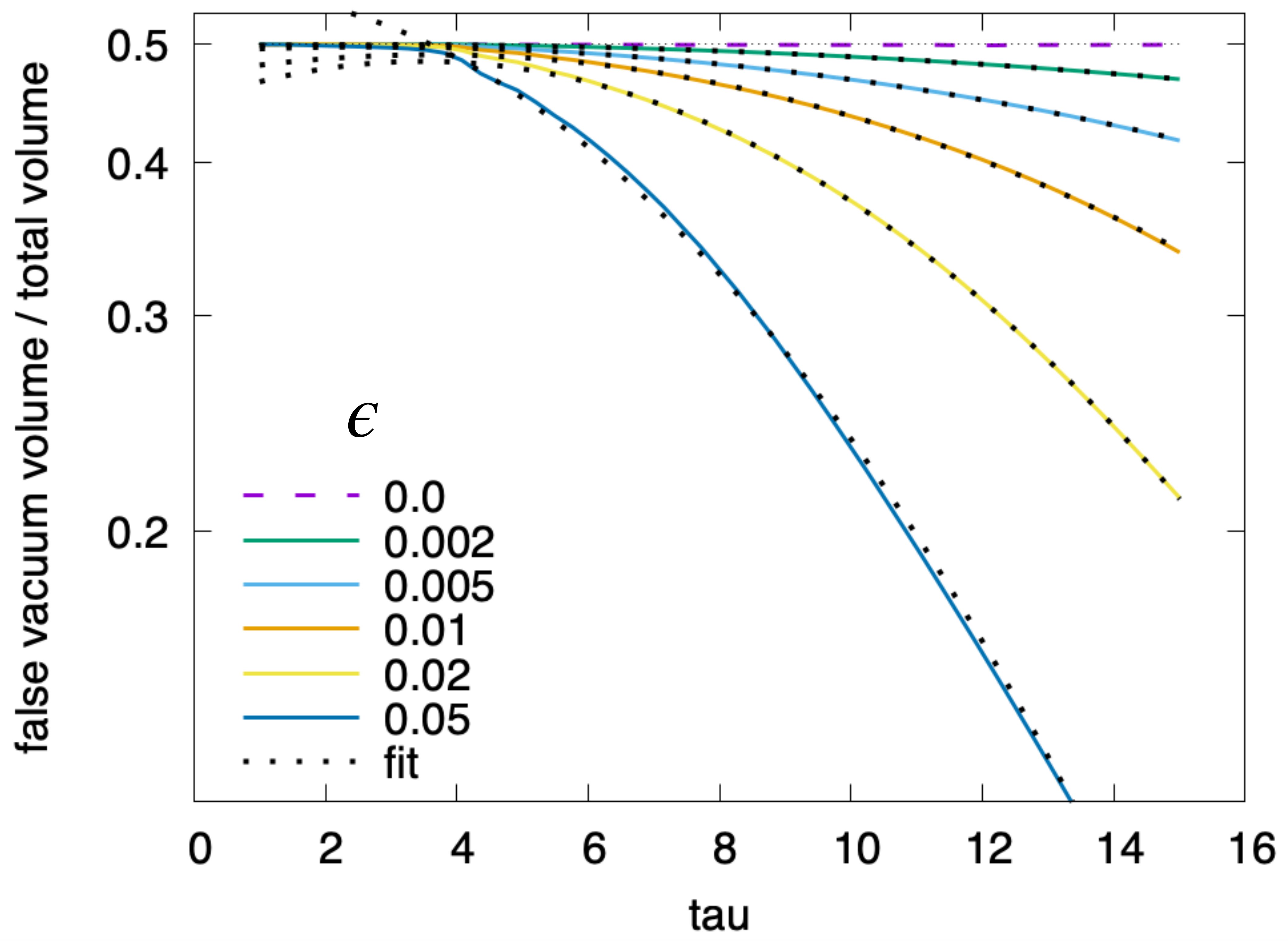
Comparison with the population biased case

Kitajima, Diego, Takahashi, Yin `22

Inflationary, Population biased



Inflationary, Potential biased



Essential differences between them exist.

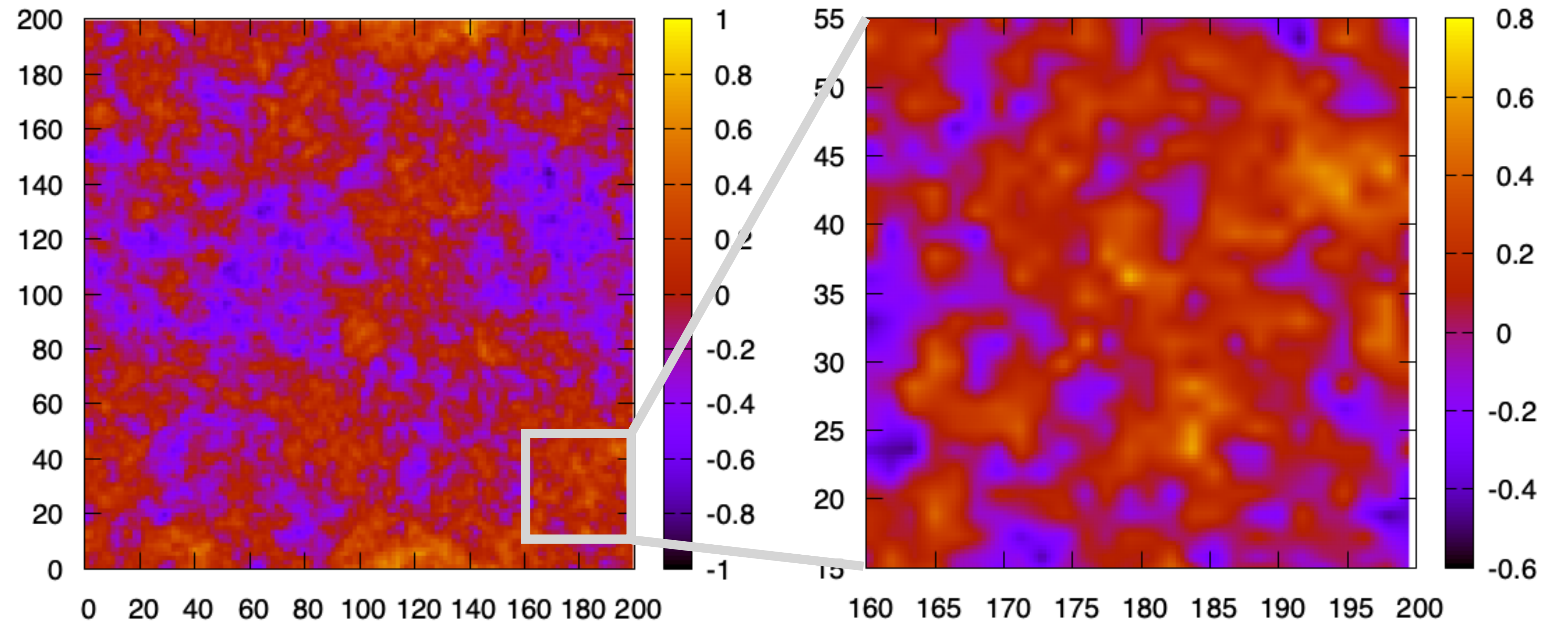
Difference between two biases

If fluctuations have scale invariance, it means that there is an inherent bias in population depending on the location or the size you focus on.

Population bias

Large voids act as obstacles to DWs collapsing and merging by tension.

Large minor voids are (comparably) stable with tension

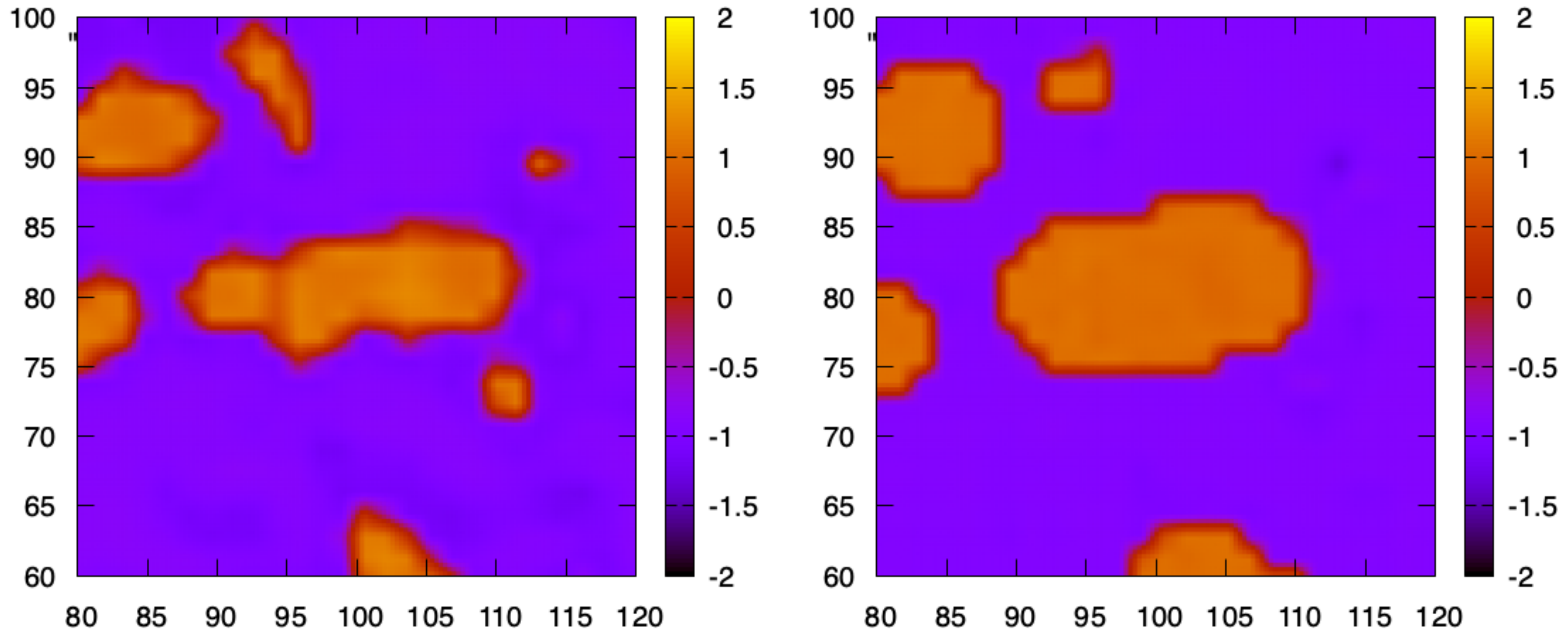


Potential bias

The small true vacuum bubbles survive and grow rather than collapse by its tension.

Large false vacuum voids shrink

Typical wall distance determines the lifetime



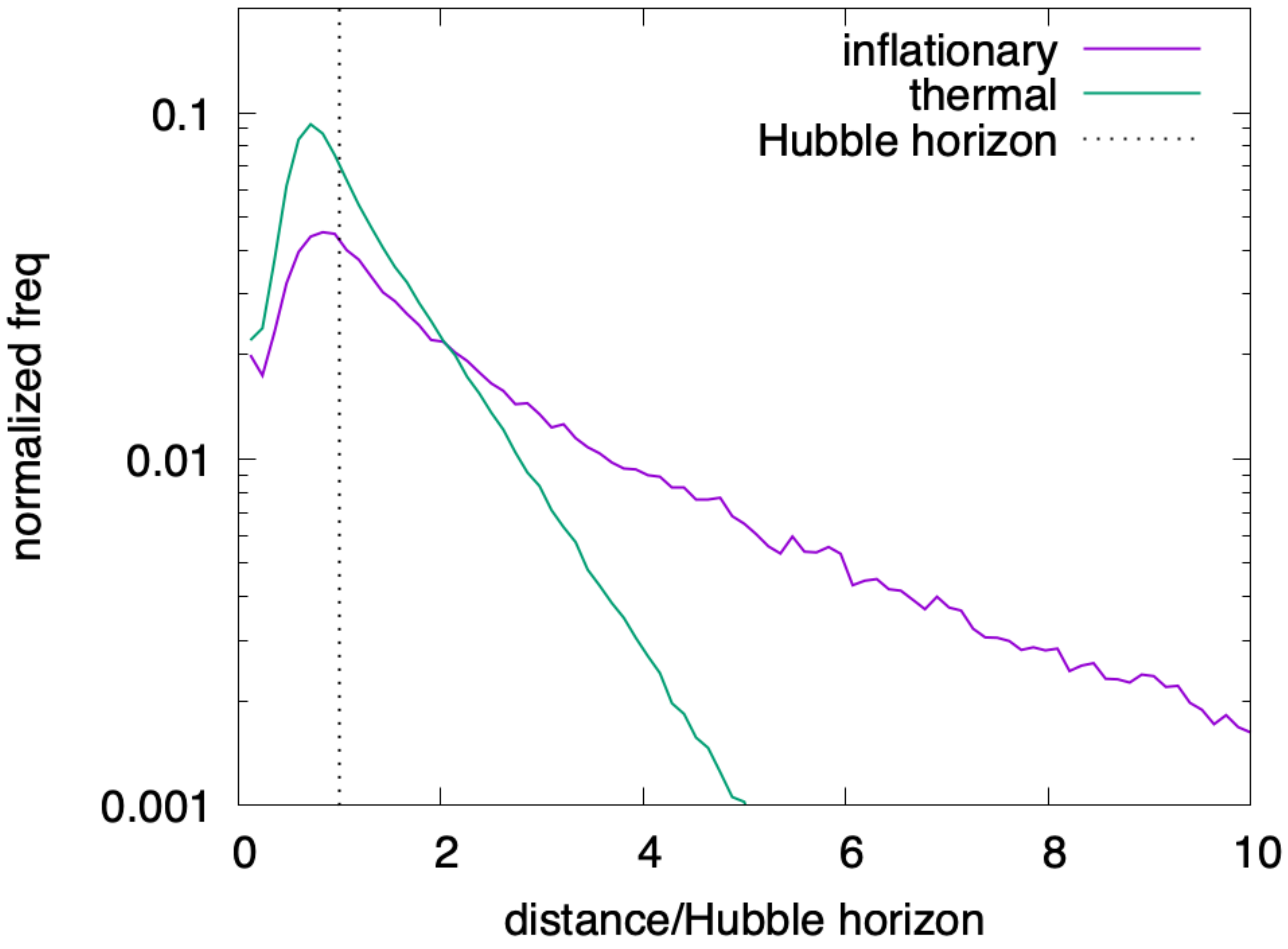
Typical DW distances

Unlike the population bias, the force which compress the false vacuum dominate the dynamics.

Typical distance between the wall determines the lifetime.

Both cases have near peaks and same order value of average distance $\mathcal{O}(H^{-1})$.

Wall distance (unbiased, tau = 6)



$$d \simeq 1.3H^{-1} \qquad \text{(thermal)}$$
$$d \simeq 3.0H^{-1} \qquad \text{(inflationary)}$$

It may also explain the $\mathcal{O}(1)$ difference on lifetime $a_{\text{inflationary}}/a_{\text{thermal}}$

Conclusion

initial condition

Thermal fluctuations
(No large scale correlations)

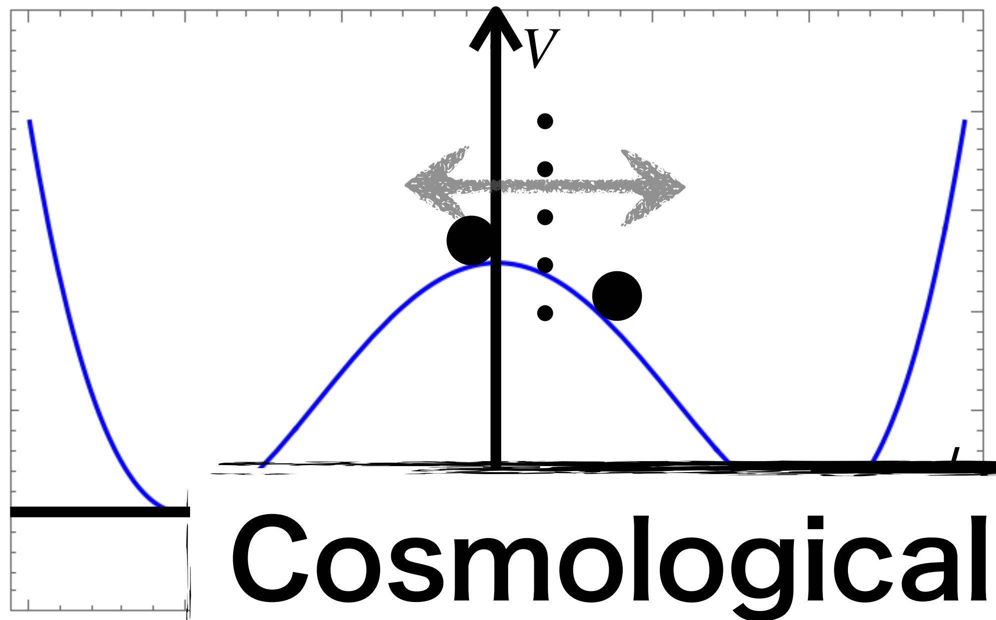
Inflationary fluctuations
(correlations on superhorizon)

under

bias

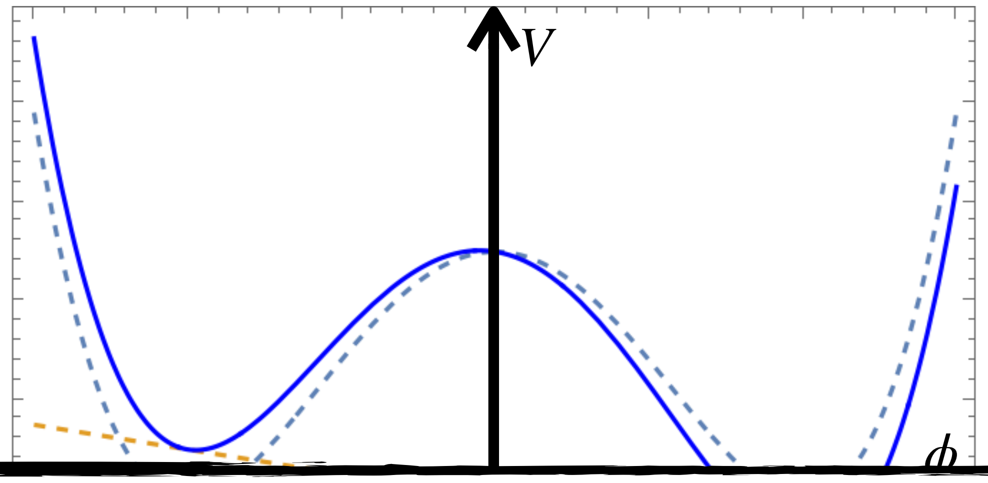
Population bias

unstable



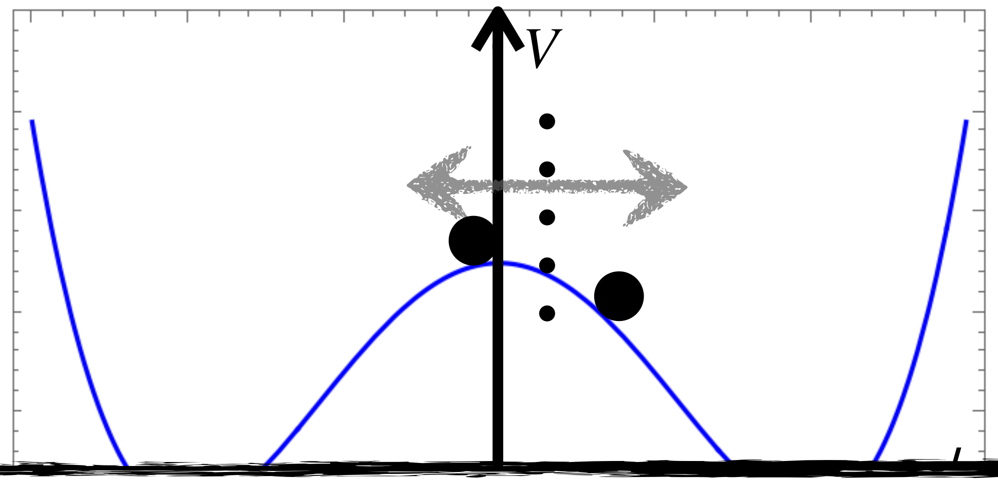
Potential bias

unstable



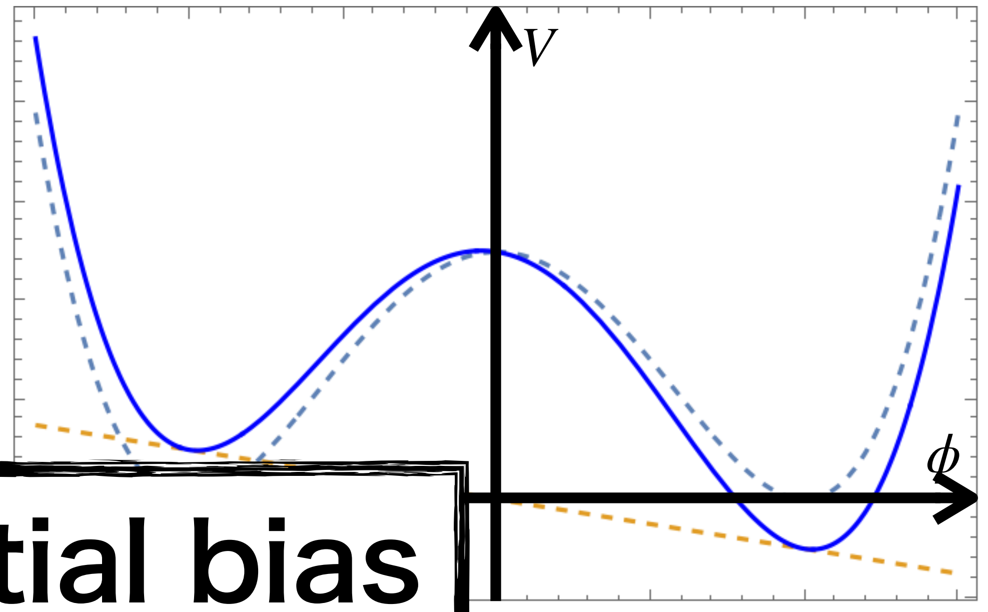
Population bias

stable



Potential bias

unstable

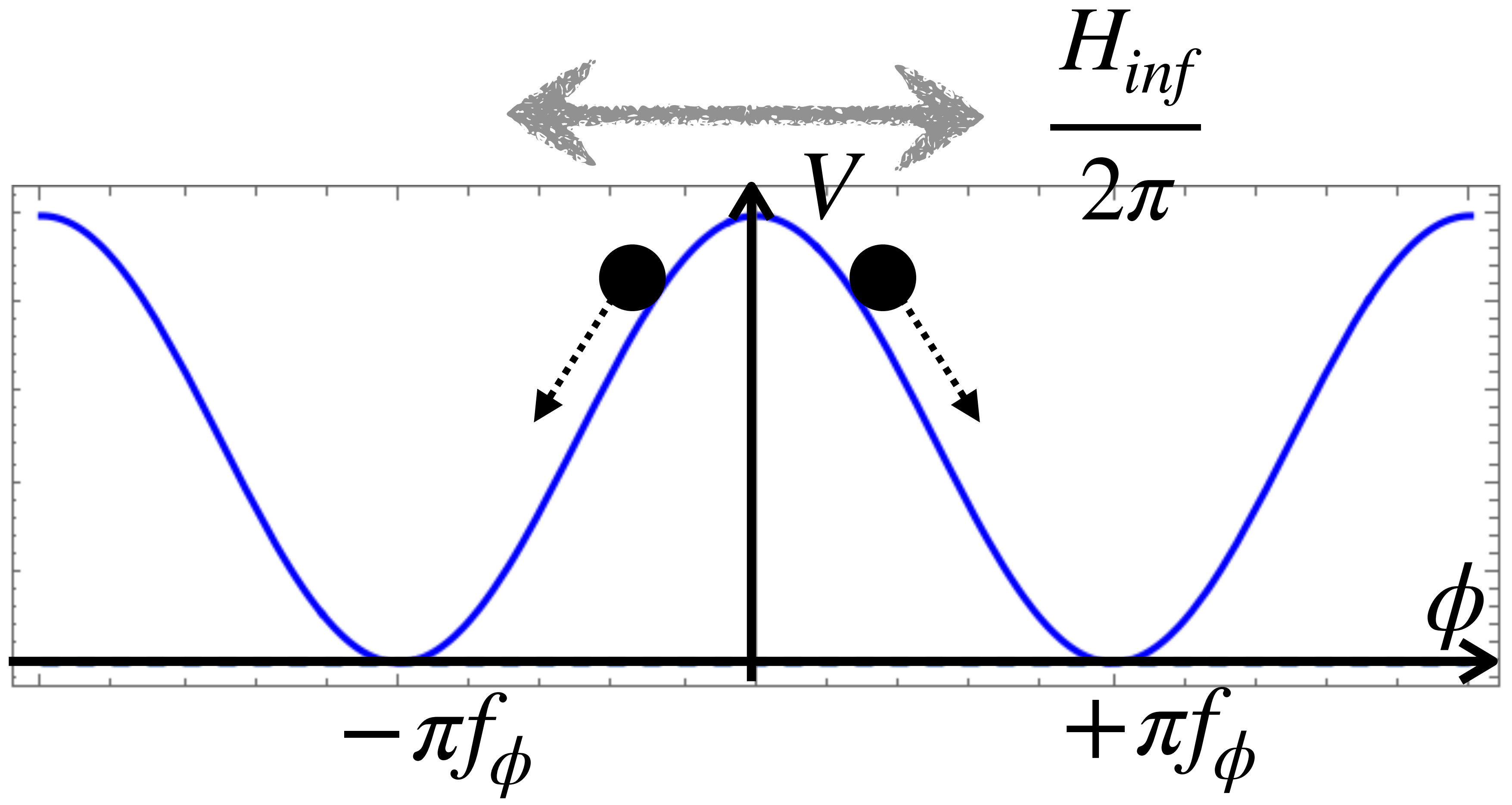


Cosmological DW problem is avoidable under the potential bias

Kitajima, JL, Takahashi, Yin, in preparation

Axion is a good target for the scenario

The breaking of Peccei-Quinn U(1) symmetry and the inflationary fluctuations lead to the formation of the axion DWs.

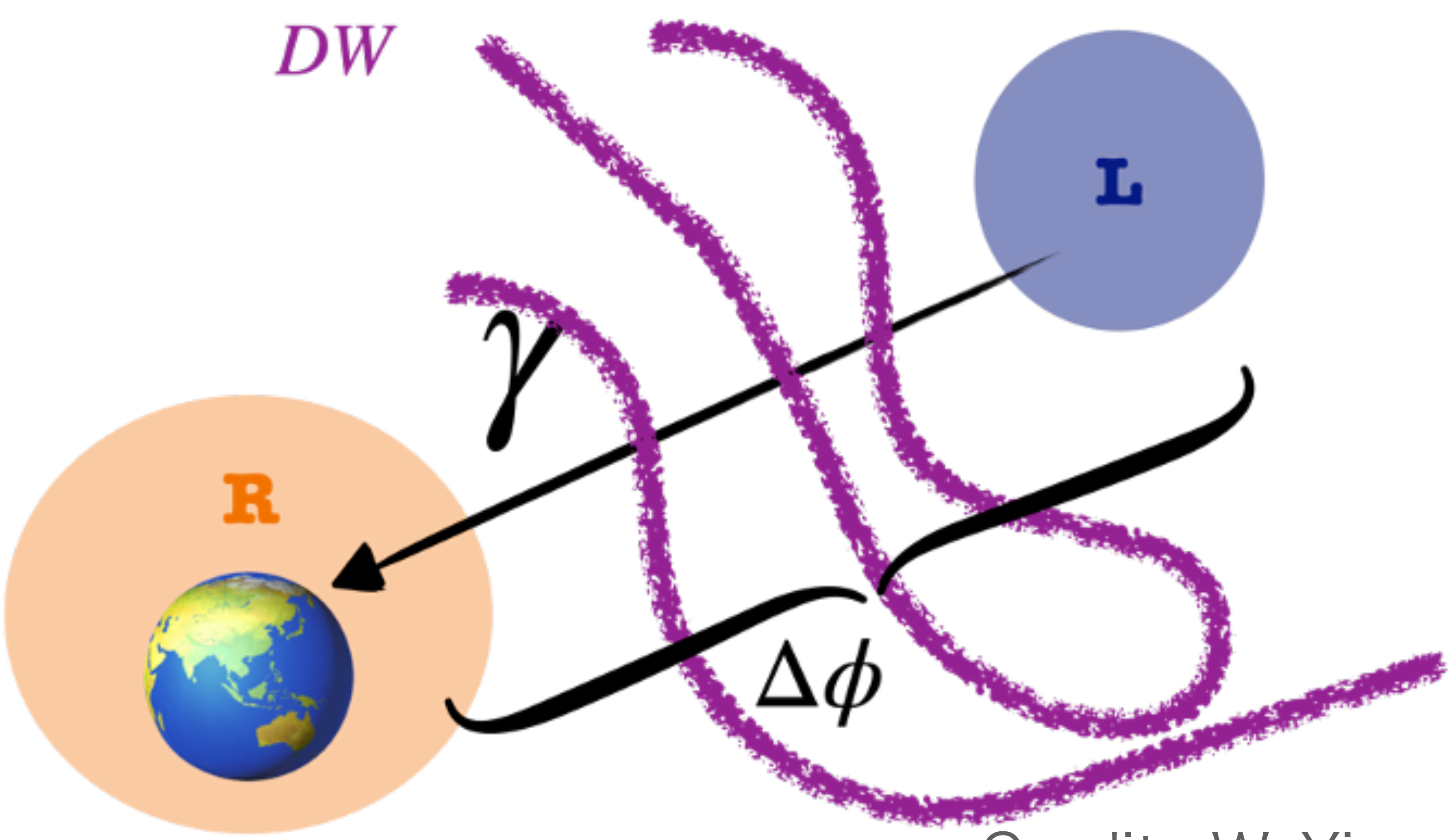


The collapse of DWs can produce the dark matter axions

Hiramatsu, Kawasaki, Saikawa, Sekiguchi `12

The axion DW gives implications on the anisotropic cosmic birefringence.

Takahashi, Yin `21, Kitajima, Diego, Takahashi, Yin `22



Credit : W. Yin