Induced domain walls of QCD axion, and gravitational waves

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Gravitational Waves and the Early Universe
@KMI Nagoya

Junseok Lee
Particle Theory and Cosmology Group, Tohoku U.

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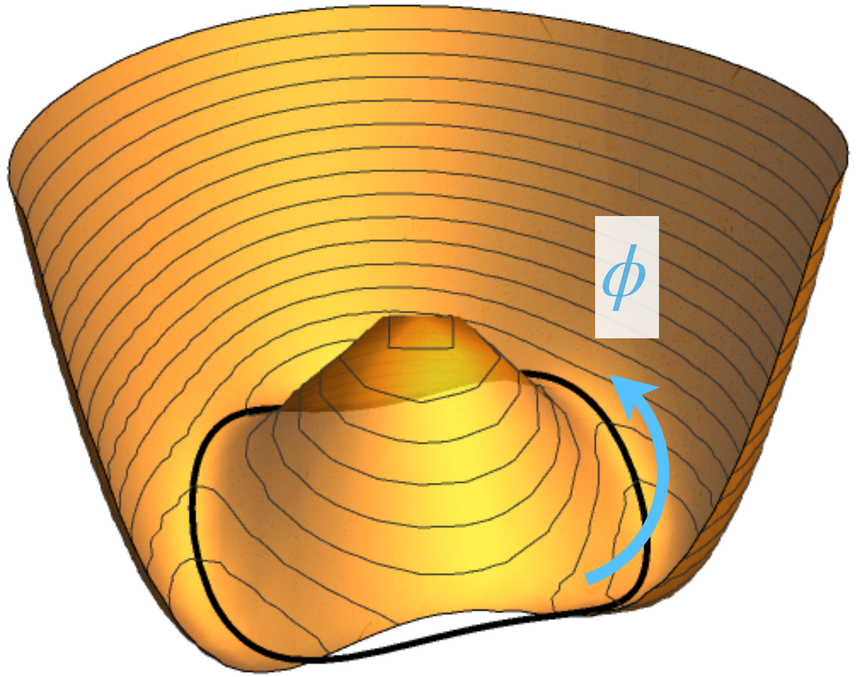
collaboration with **Kai Murai, Fuminobu Takahashi, and Wen Yin**

Axion

The axion is the pseudo-Nambu-Goldstone boson that arises from the spontaneous breaking of global U(1) symmetry.



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

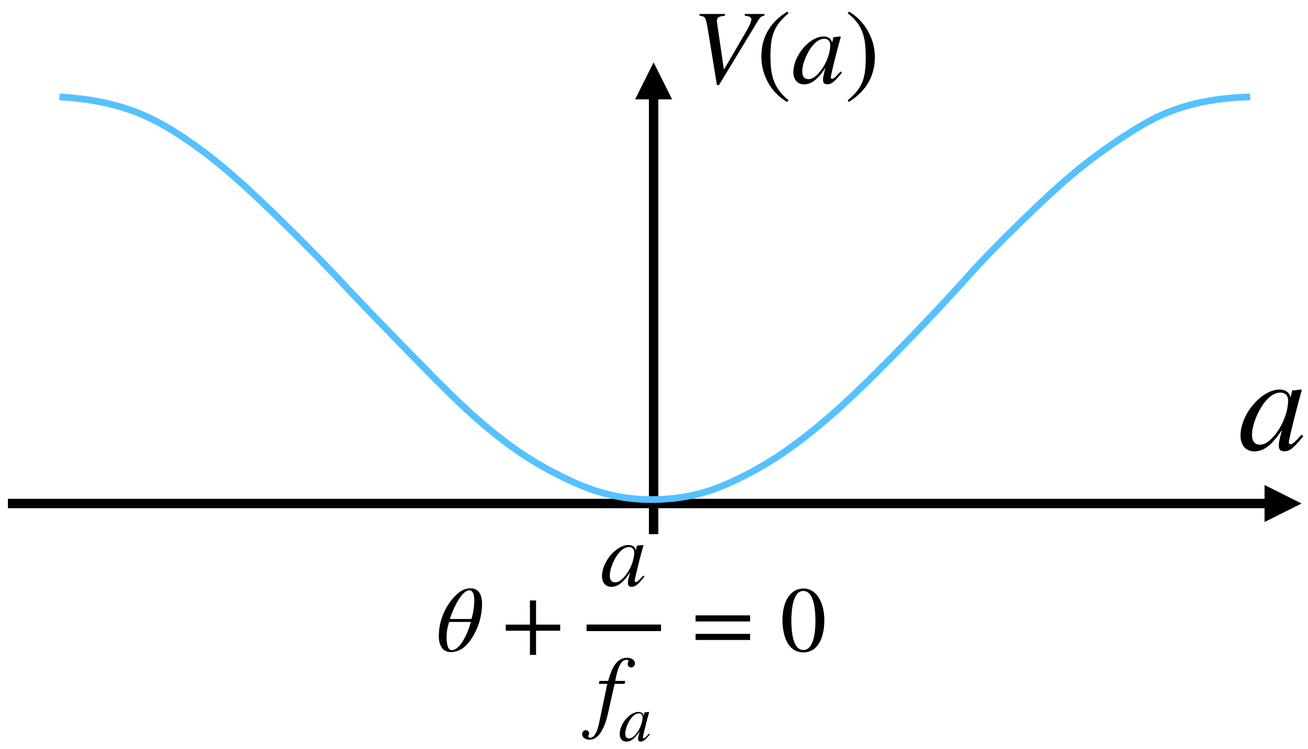
QCD Axion

QCD axion dynamically solves the strong CP problem.

Peccei, Quinn `77, Weinberg `78, Wilczek `78

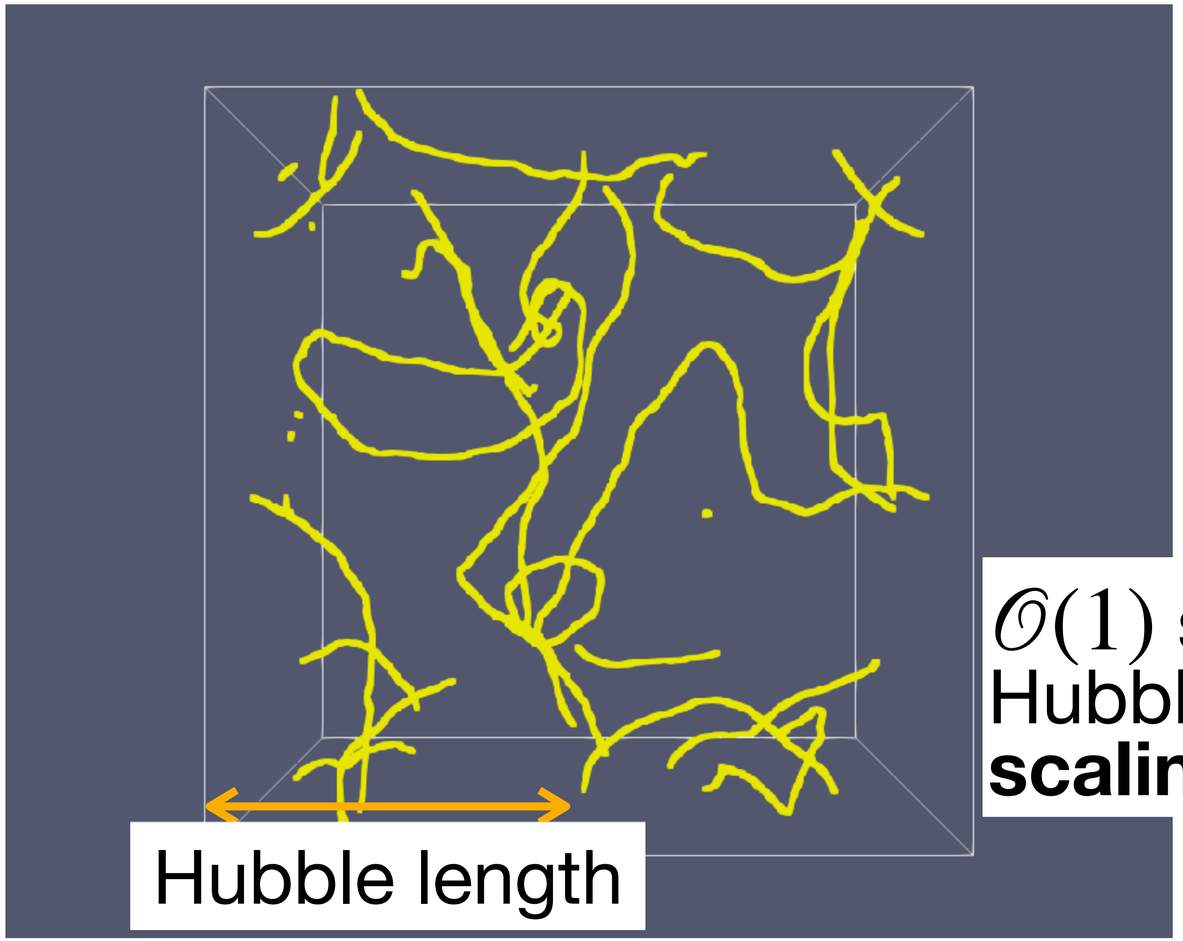
QCD axion obtains a periodic potential by the non-perturbative effect of QCD such that the combination $\theta + a/f_a$ vanishes at the potential minimum.

$$\mathscr{L} \supset -\frac{\alpha_s}{8\pi}\left(\theta + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$$



Network of strings

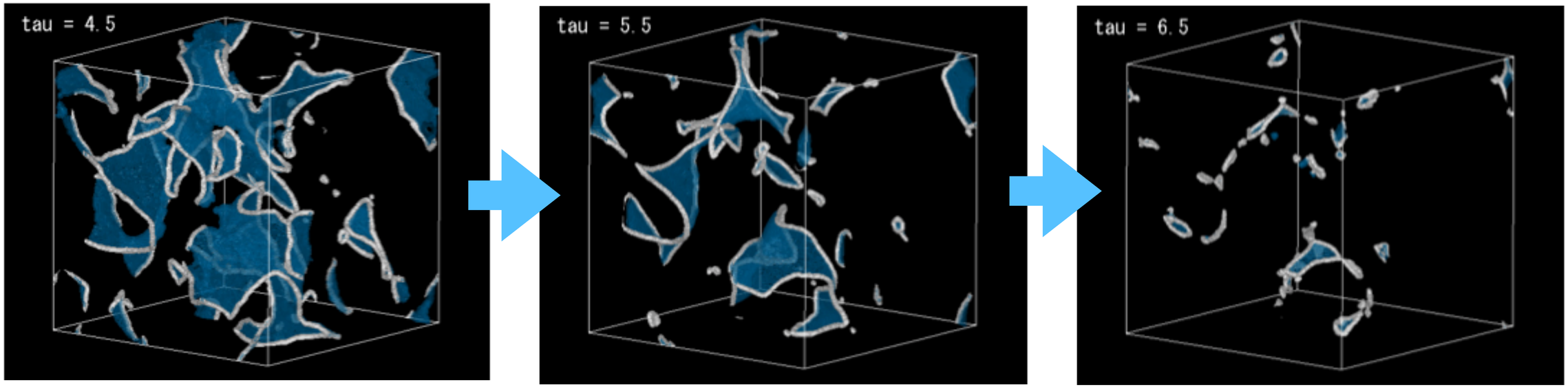
If the U(1) symmetry is spontaneously broken **after** inflation, a network of cosmic strings is formed.



$\mathcal{O}(1)$ strings in each Hubble horizon: **scaling solution**

Collapsing strings and domain walls

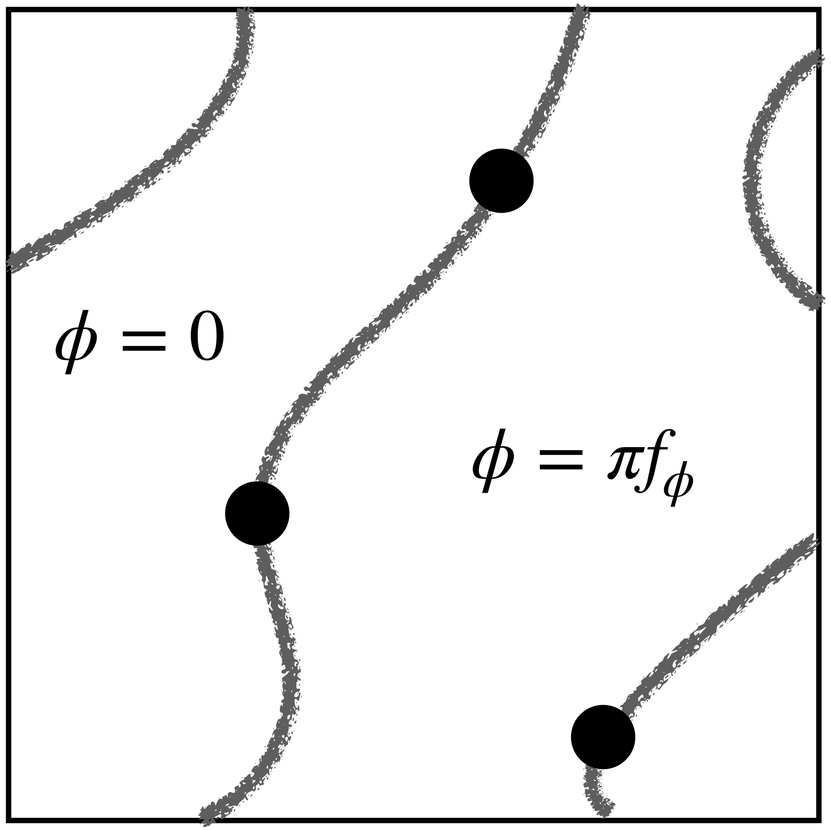
If $N_{\rm DW} = 1$, the network of cosmic strings rapidly decays due to the domain wall tension.



Taken from Hiramatsu, Kawasaki, Saikawa, Sekiguchi `12

Stable string-wall network

If $N_{\rm DW} > 1$, the network of cosmic strings and domain walls is long-lived.

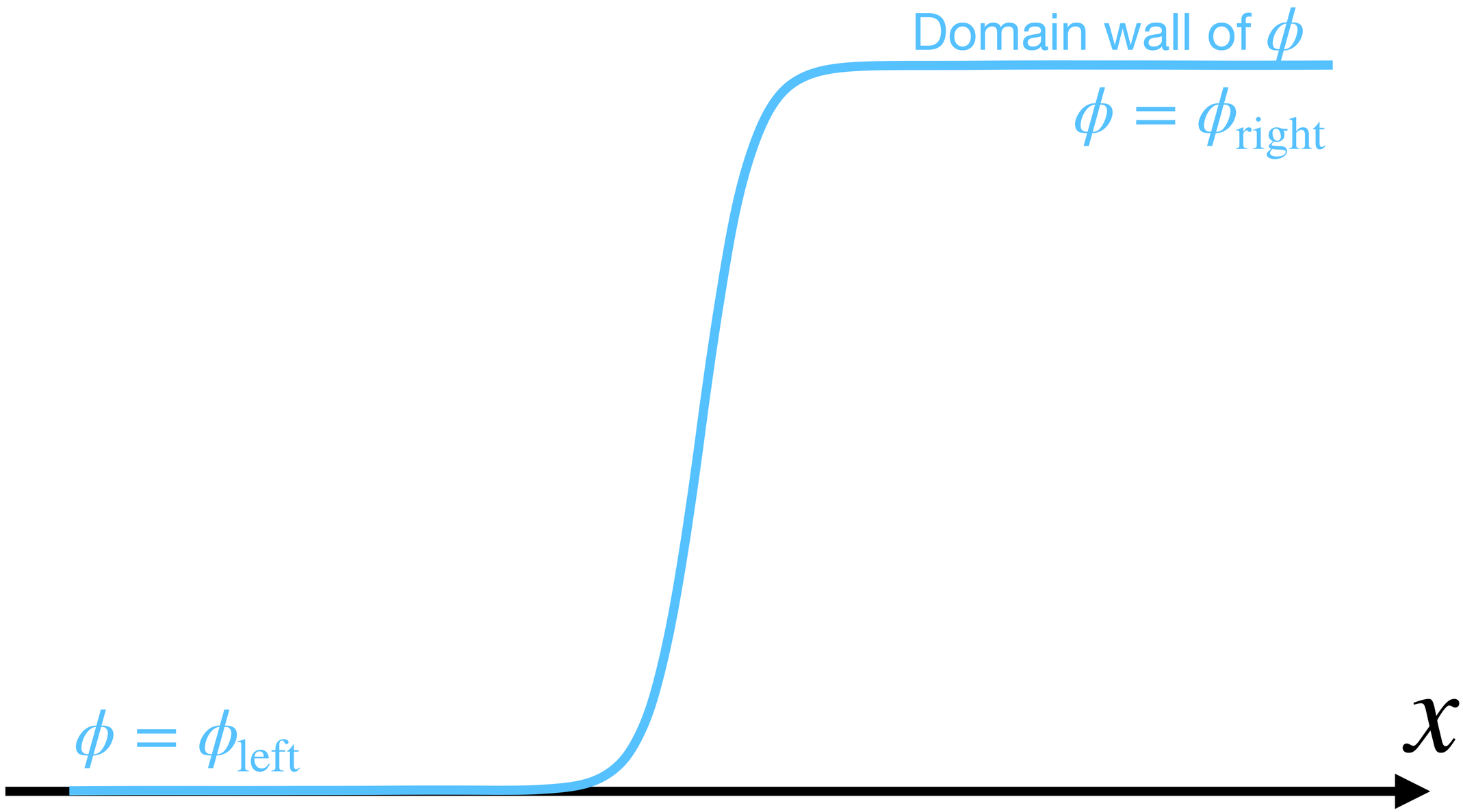


e.g., $N_{\rm DW} = 2$

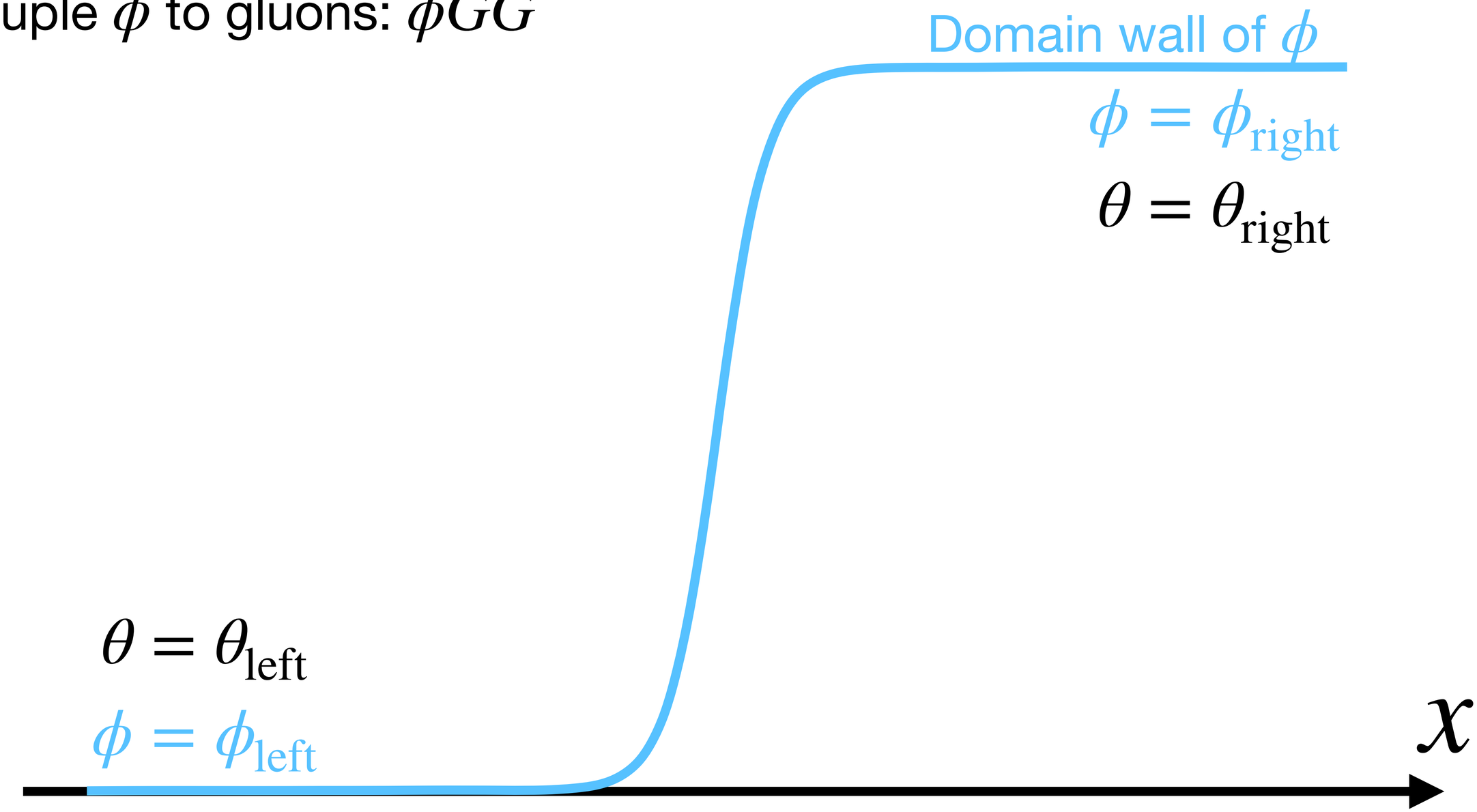
$\mathcal{O}(1)$ walls in each Hubble horizon

Axion domain walls generate domain-wall-like structures via mixing with another axion.

“Induced domain wall”

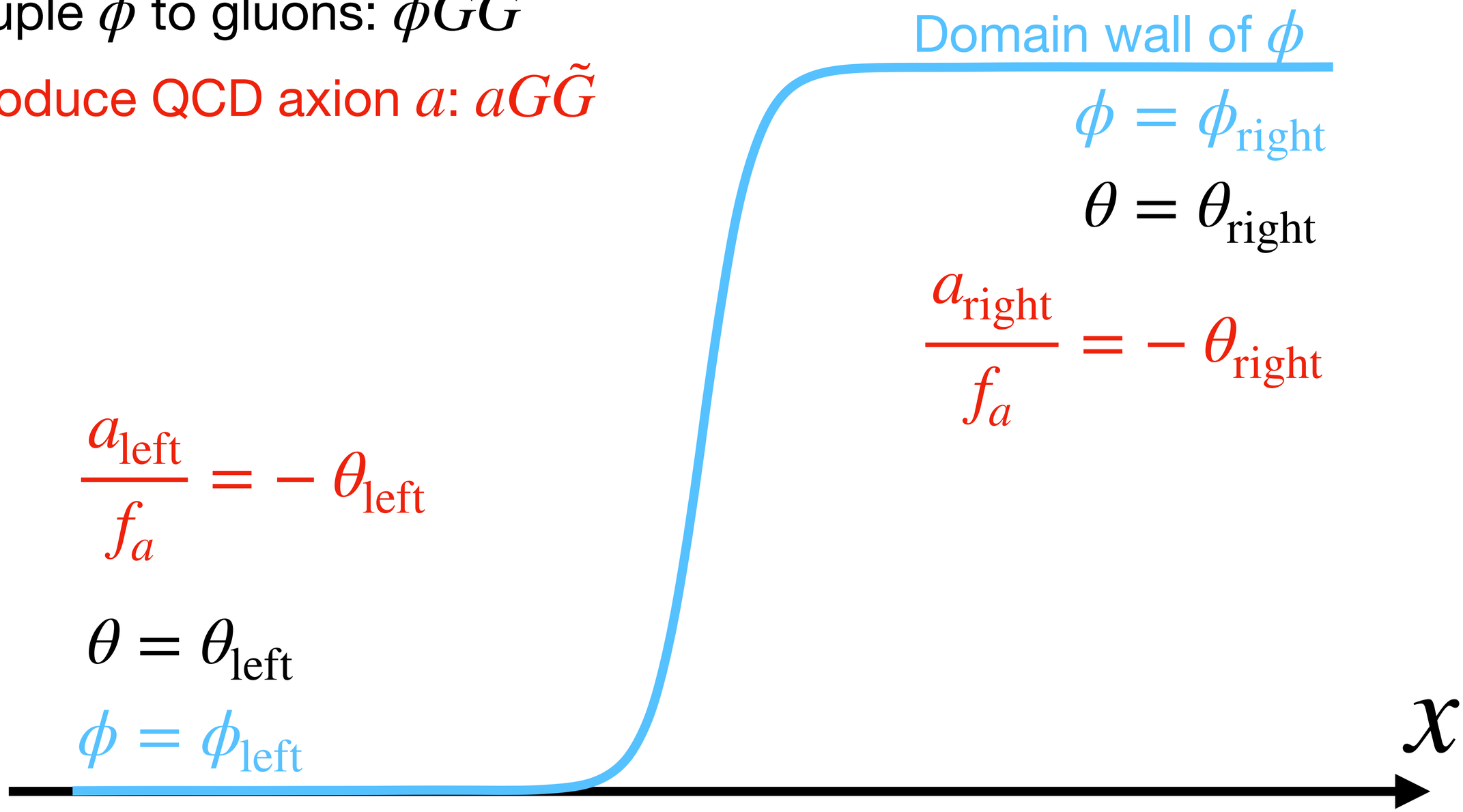

Domain wall of ϕ
$\phi = \phi_{\mathrm{right}}$
$\phi = \phi_{\mathrm{left}}$
x

Couple ϕ to gluons: $\phi G\tilde{G}$



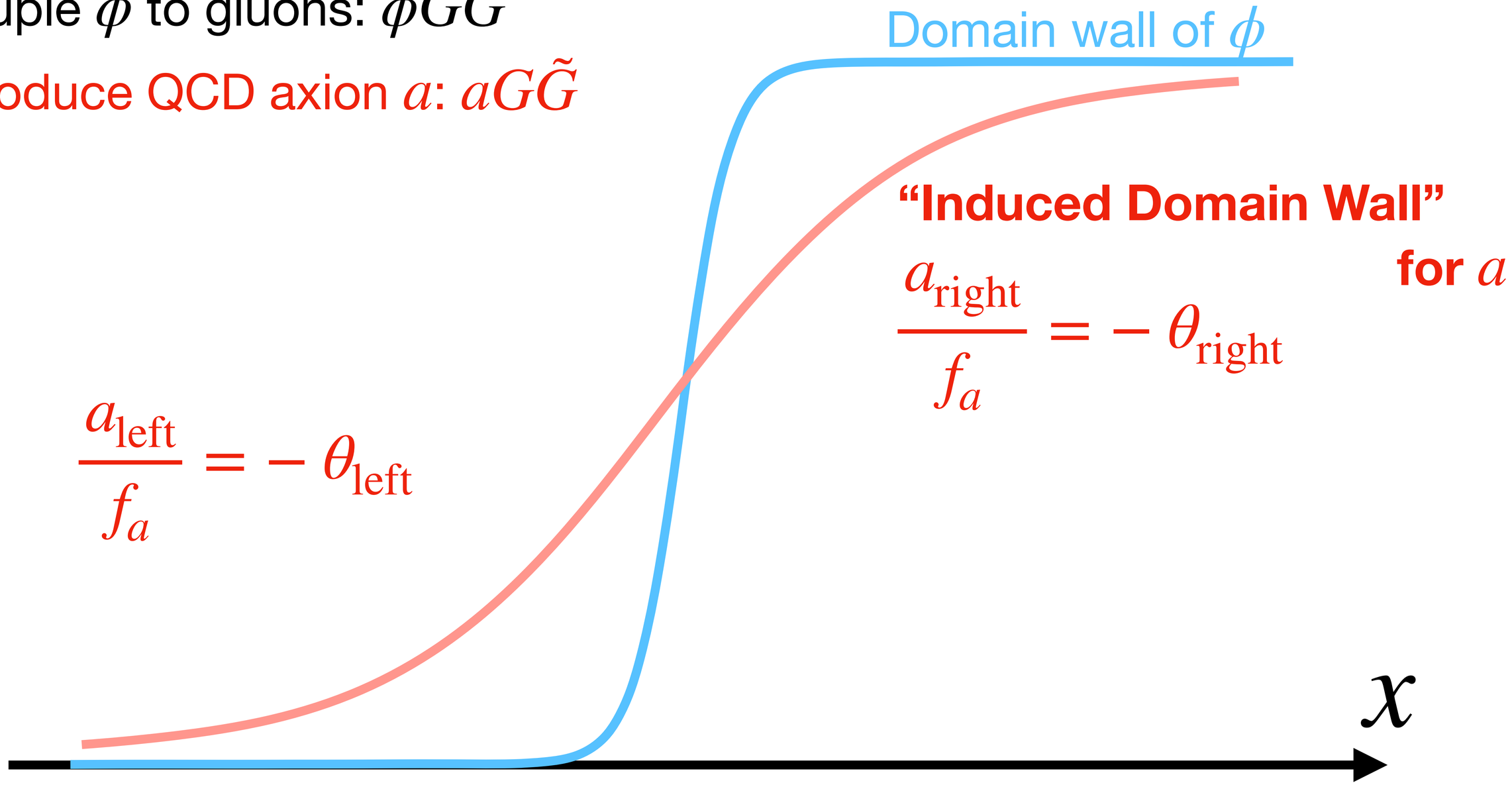
Couple ϕ to gluons: $\phi G\tilde{G}$

Introduce QCD axion a: $aG\tilde{G}$

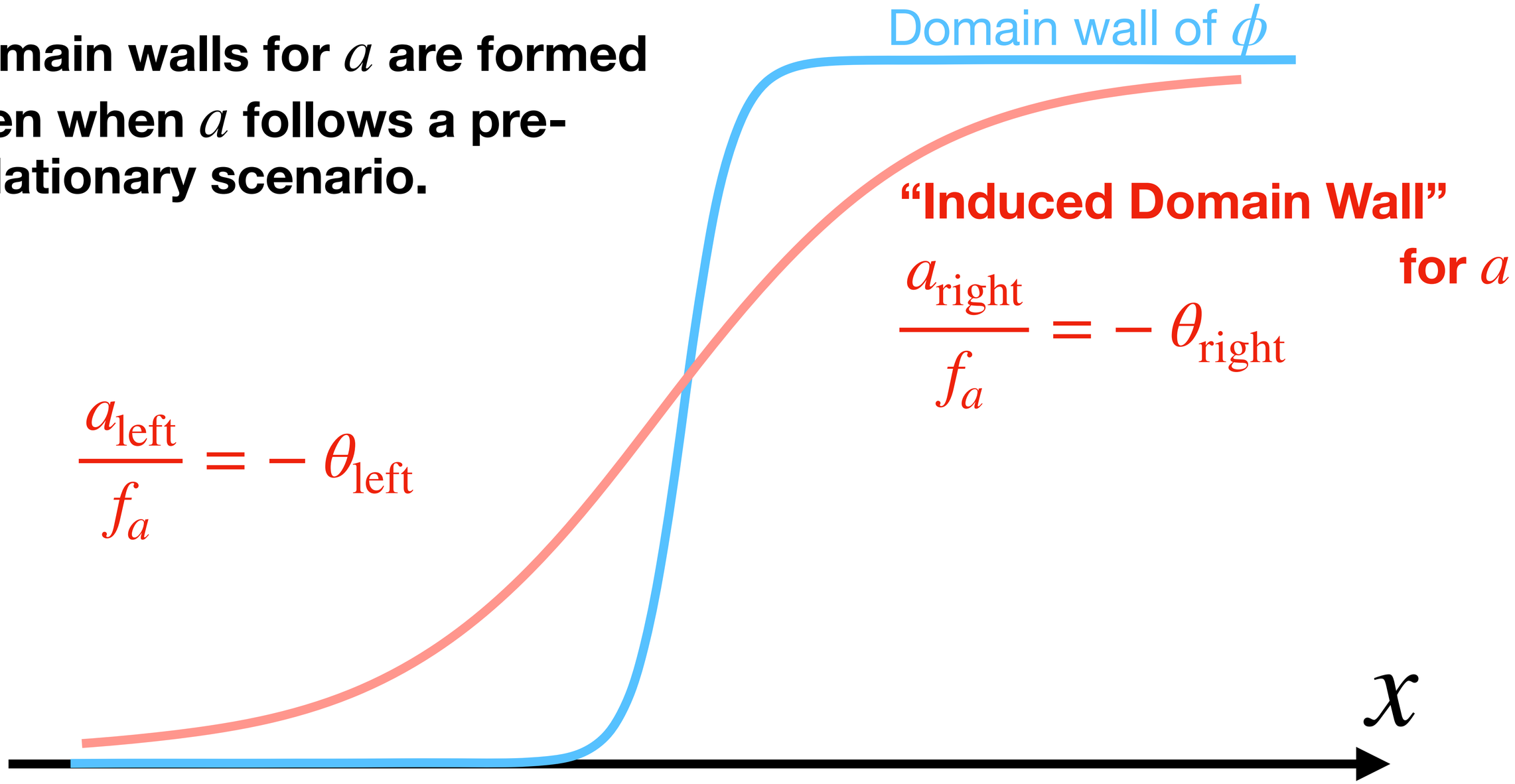


Couple ϕ to gluons: $\phi G\tilde{G}$

Introduce QCD axion a: $aG\tilde{G}$



Domain walls for a are formed even when a follows a pre-inflationary scenario.



Two axions and mixed initial conditions

We consider two axions

Heavy axion

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

QCD axion

$$A = \frac{f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

with the initial conditions:

$$\begin{cases} \text{post-inflationary condition for the heavy axion,} \\ \text{pre-inflationary condition for the QCD axion.} \end{cases}$$

Induced domain walls of QCD axion

JL, Murai, Takahashi, Yin `24

$$V(a,\phi) = V_{\rm DW}(\phi) + V_{\rm mix}(a,\phi)$$

$$= \Lambda^4 \left[1 - \cos\left(2\frac{\phi}{f_\phi}\right)\right] + \chi(T)\left[1 - \cos\left(\frac{a}{f_a} + \frac{\phi}{f_\phi}\right)\right]$$

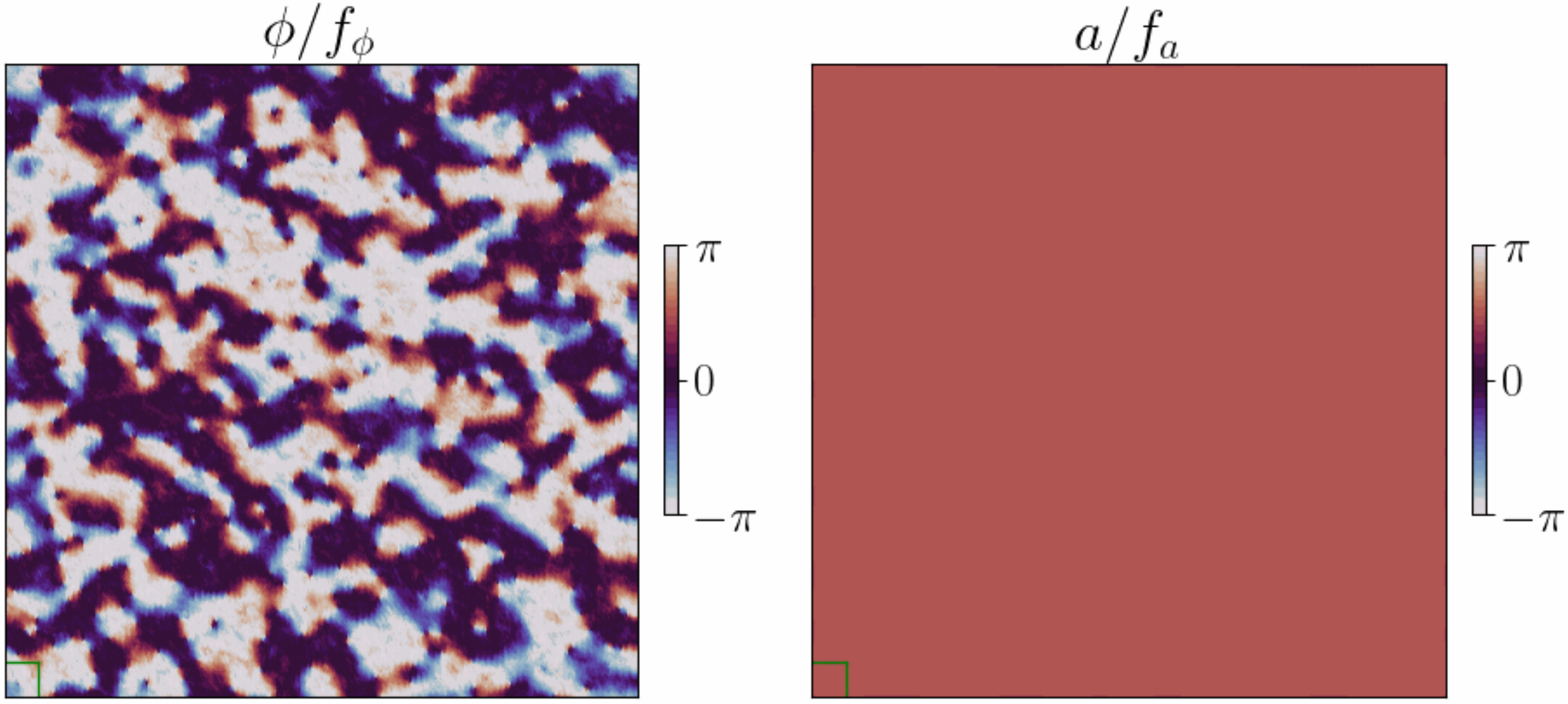
$\chi(T) \equiv m_a^2(T) f_a^2$: topological susceptibility

We assume a hierarchy in the mass and the domain wall tension for simplicity.

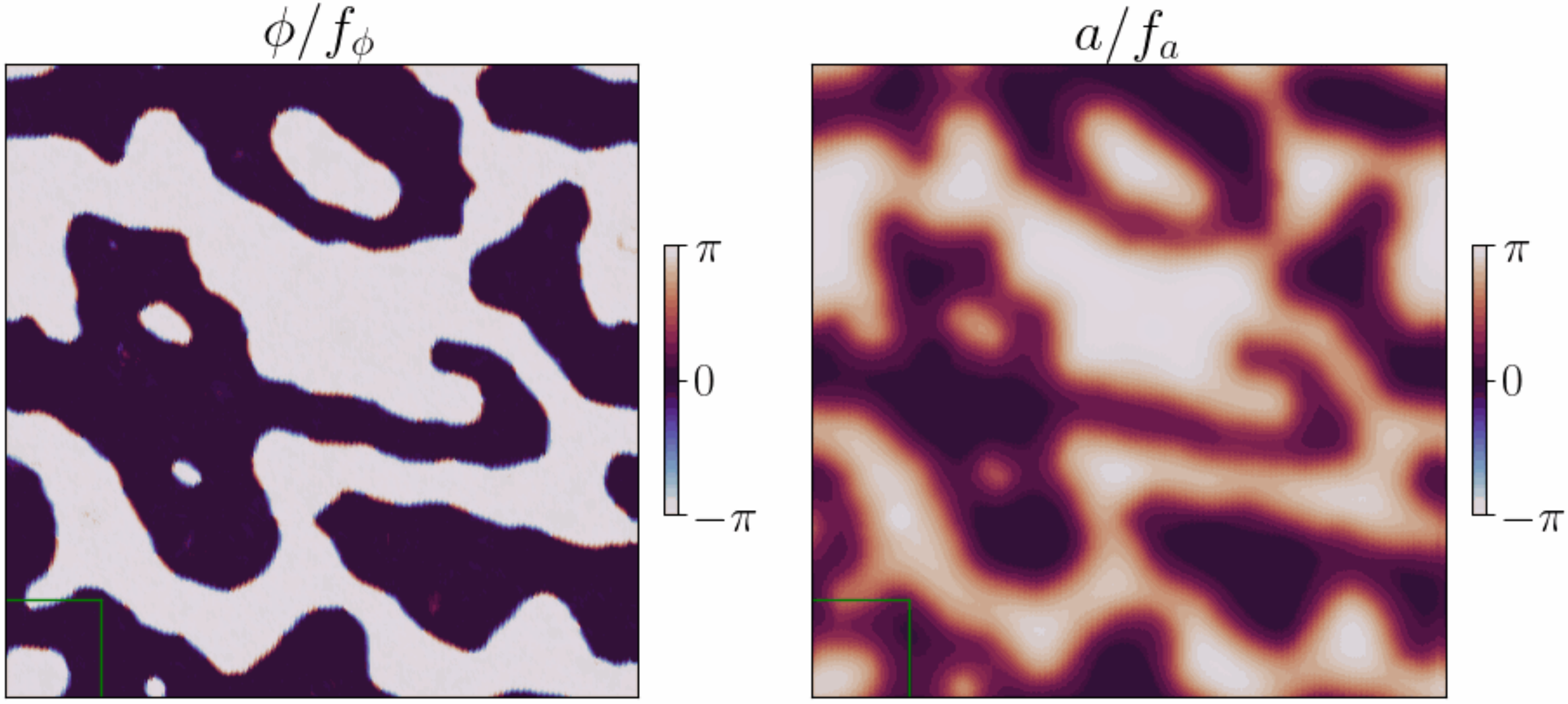
$$m_\phi \gg m_{a0} \equiv m_a(T=0)$$

$$m_\phi f_\phi^2 \gg m_{a0} f_a^2$$

$$m_\phi/H = 12.0,\ m_a/H = 1.2$$

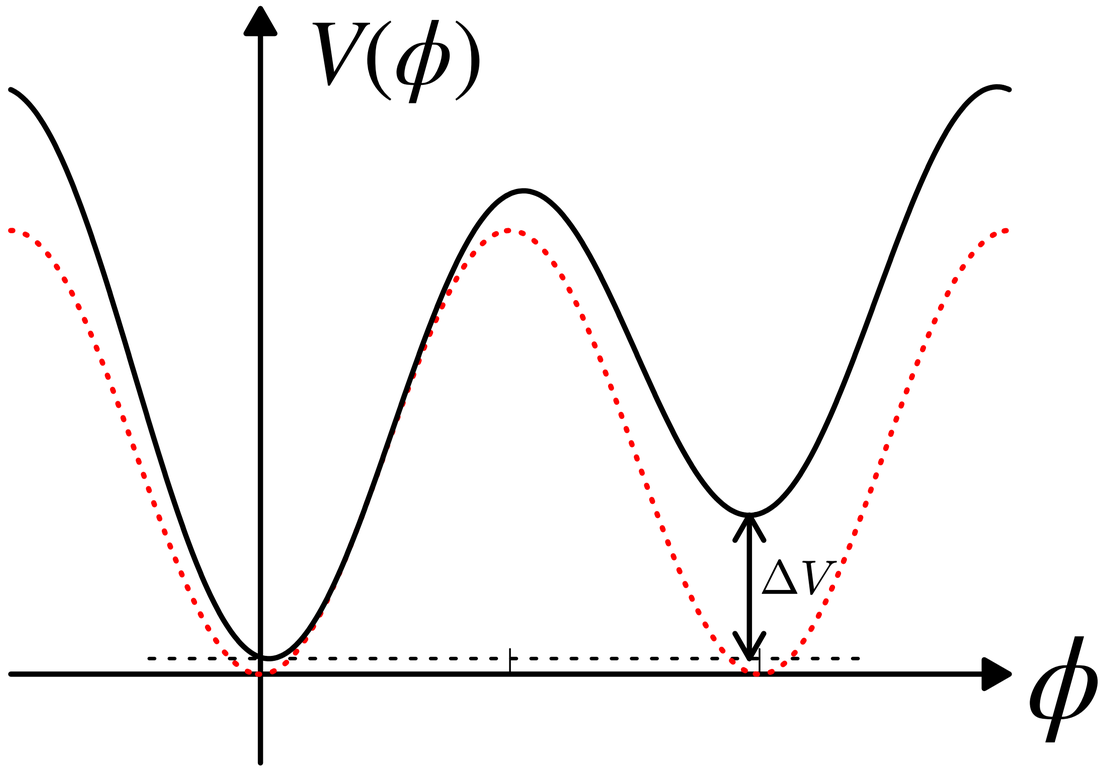


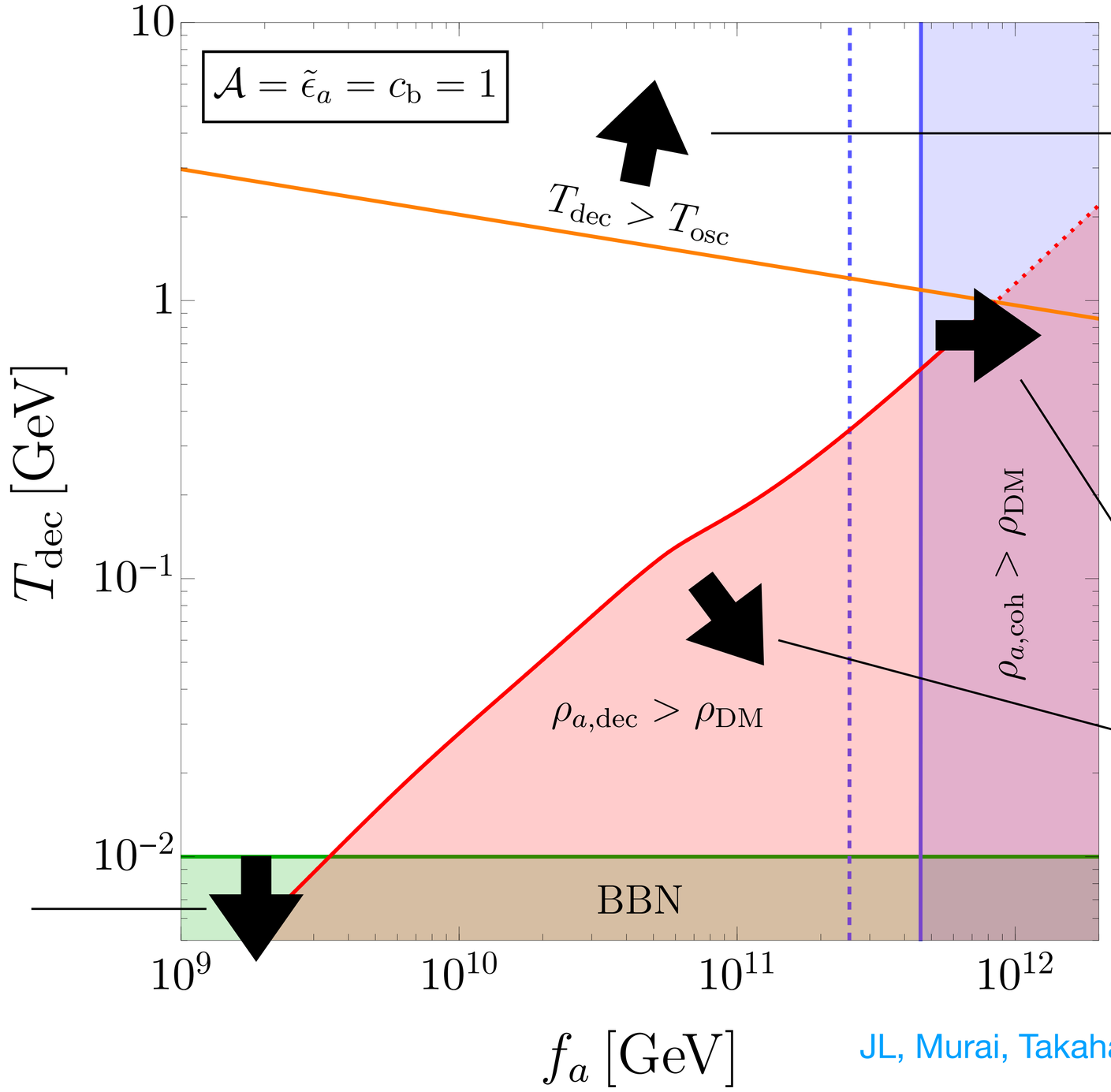
$$m_\phi/H = 95.2,\ m_a/H = 9.5$$



Domain walls must decay

We introduce a potential bias along the heavy axion to destabilize domain walls while preserving the PQ mechanism



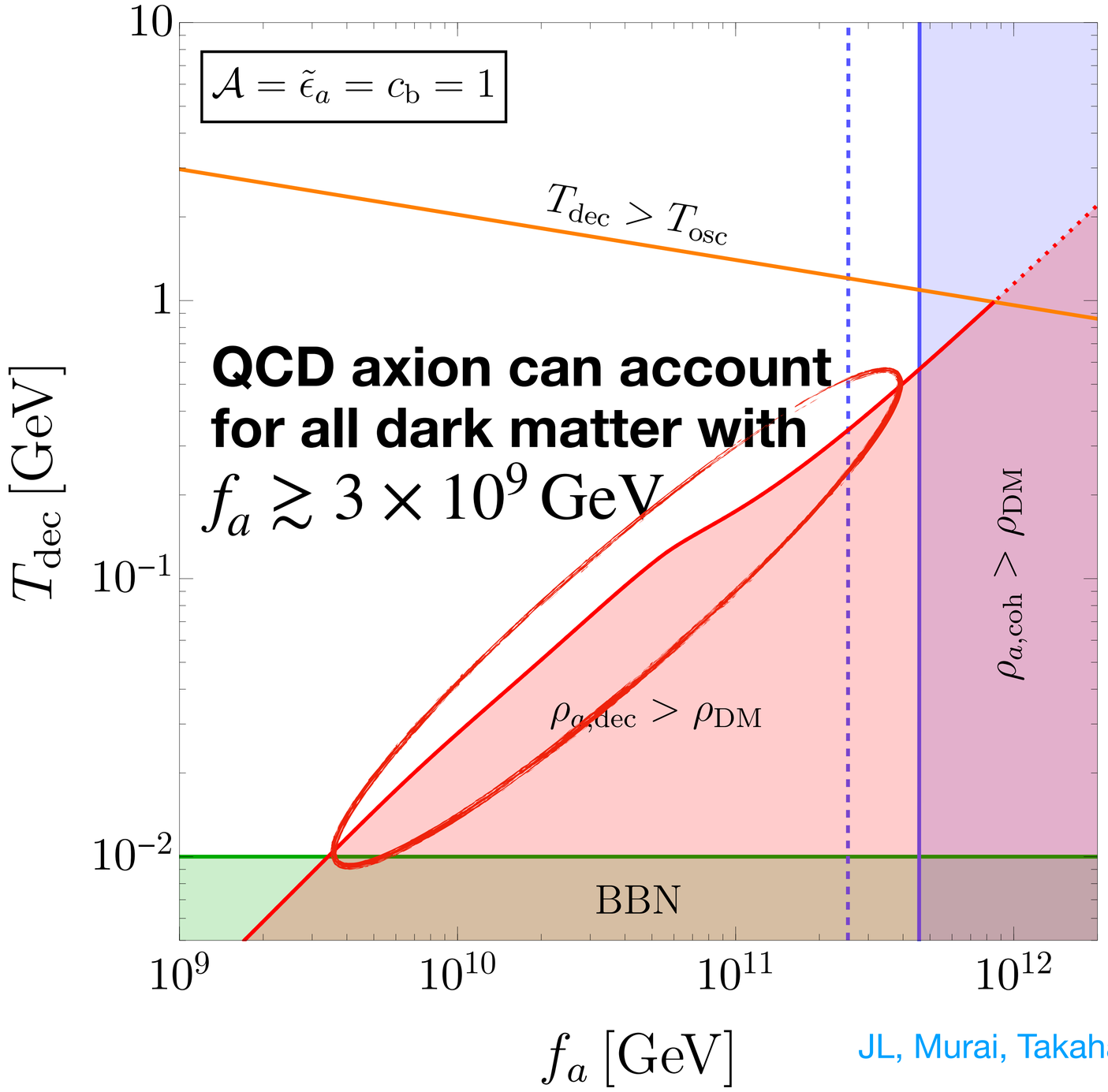


Induced walls are not formed.

Too much dark matter

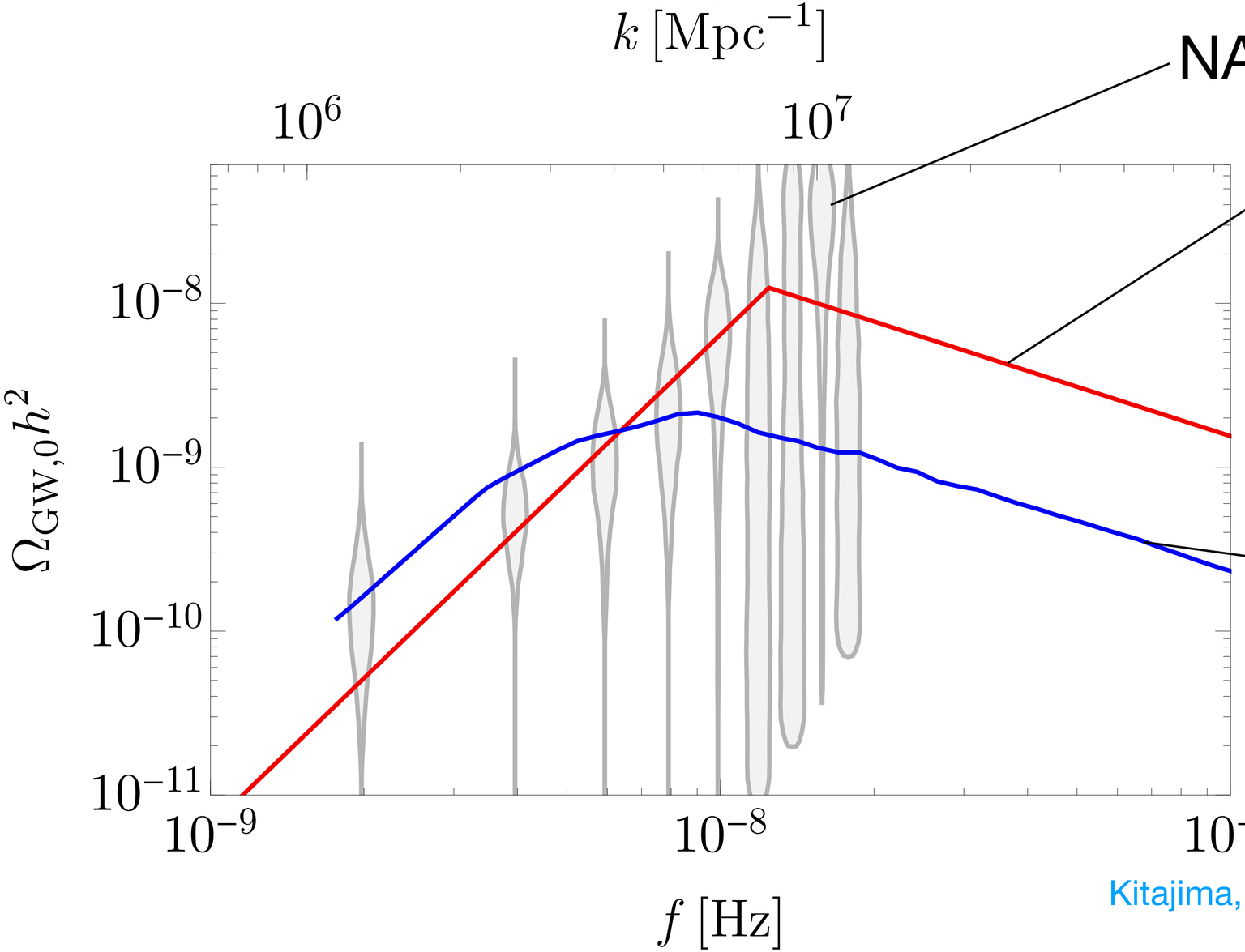
Too late decay affects BBN.

JL, Murai, Takahashi, Yin `24



JL, Murai, Takahashi, Yin `24

Gravitational wave spectrum



NANOGrav dataset

Analytic estimate with

$\sigma_\phi = 6 \times 10^{15}\,\mathrm{GeV}^3$

$T_{\mathrm{dec}} = 100\,\mathrm{MeV}$

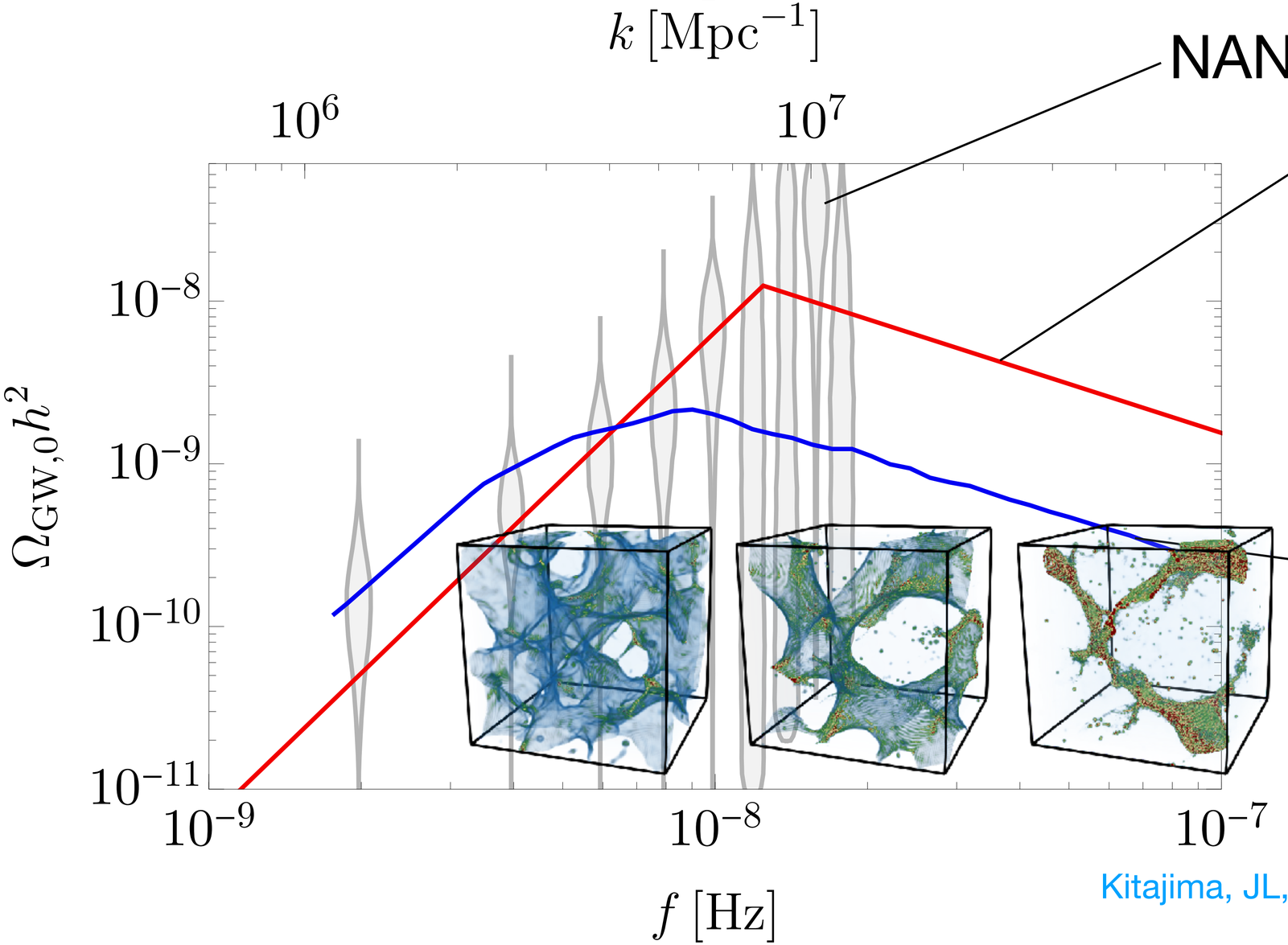
Numerical result with

$\sigma_\phi = 1.3 \times 10^{15}\,\mathrm{GeV}^3$

$T_{\mathrm{dec}} = 150\,\mathrm{MeV}$

Kitajima, JL, Murai, Takahashi, Yin `23

Gravitational wave spectrum



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Analytic estimate with

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$T_{\mathrm{dec}} = 100\,\mathrm{MeV}$

Numerical result with

$\sigma_\phi = 1.3 \times 10^{15}\,\mathrm{GeV}^3$

$T_{\mathrm{dec}} = 150\,\mathrm{MeV}$

Kitajima, JL, Murai, Takahashi, Yin `23

Summary

- We found a new type of domain-wall-like structure, called “induced domain walls,” arising from axion mixings.
- Heavy axion domain walls can induce domain walls of the QCD axion even with a pre-inflationary initial condition.
- The QCD axion can be produced from the decay of induced domain walls, and can explain dark matter even for $f_a \gtrsim 3 \times 10^9\,\mathrm{GeV}$.
- Gravitational waves from the collapse of heavy-axion domain walls can account for the Pulsar Timing Array results.