複数場模型におけるアクシオンの位相欠陥とドメインウォール問題

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Axion

- **QCD axion** Peccei & Quinn (1977), Weinberg (1978), Wilczek (1978)

  a solution to the strong CP problem

  a (pseudo-)Nambu-Goldstone boson arising at spontaneous breaking of a U(1) symmetry

$$\Phi = \frac{f_\phi}{\sqrt{2}} e^{i\phi/f_\phi} \rightarrow \bar{\theta}_s \rightarrow \bar{\theta}_s + N\frac{\phi}{f_\phi}$$

(ϕ has a periodicity of $\phi \sim \phi + 2\pi f_\phi$)

After a redefinition of ϕ, $\phi = 0$ corresponds to the CP conserving point.

The QCD axion acquires a potential from non-perturbative effects of QCD:

$$V_{\rm QCD} = \chi(T)\left[1 - \cos\left(\frac{\phi}{F_\phi}\right)\right]$$

QCD axion

Decay constant: $F_\phi \equiv f_\phi/N$

CP is conserved in QCD thanks to the axion dynamics.

Axion

- **QCD axion** Peccei & Quinn (1977), Weinberg (1978), Wilczek (1978)

The QCD axion potential depends on temperature:

$$V_{\rm QCD} = \chi(T)\left[1 - \cos\left(\frac{\phi}{F_\phi}\right)\right]$$

$$\chi(T) = m_\phi^2(T)\,F_\phi^2 = \begin{cases} \chi_0 & (T < T_{\rm QCD}) \\ \chi_0\left(\dfrac{T}{T_{\rm QCD}}\right)^{-n} & (T \geq T_{\rm QCD}) \end{cases}$$

Lattice results:

$$\chi_0 \simeq (75.6\,\mathrm{MeV})^4$$
$$n \simeq 8.16$$
$$T_{\rm QCD} \simeq 153\,\mathrm{MeV}$$

Borsanyi *et. al.* (2016)

At high temperatures, the QCD axion is effectively massless.

Below the QCD scale, the axion mass becomes constant.

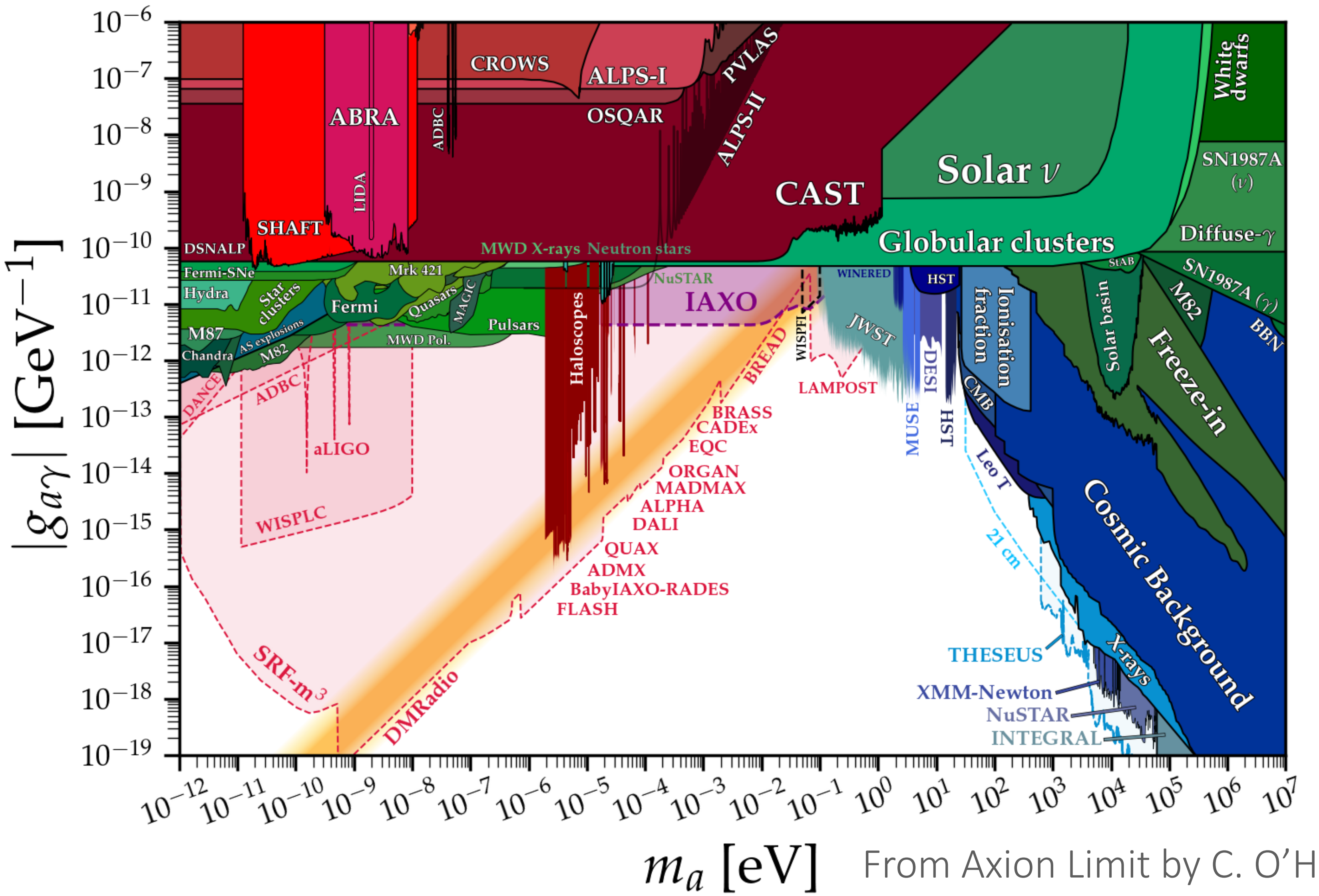
→ The QCD axion is a candidate for dark matter.

Axion

- Axion-Like Particle (ALP)

In addition to the QCD axion, axion-like particles are also studied:

Periodicity and couplings to the Standard Model as the QCD axion
Wide range of mass and decay constant



From Axion Limit by C. O'Hare

- **Pre-inflationary PQ breaking**

The axion does not exist when $\Phi = 0$. (An axion is ϕ of $\Phi = \dfrac{f_\phi}{\sqrt{2}} e^{i\phi/f_\phi}$)

To consider the axion in cosmology,
it is important to determine when Φ acquires a nonzero expectation value.

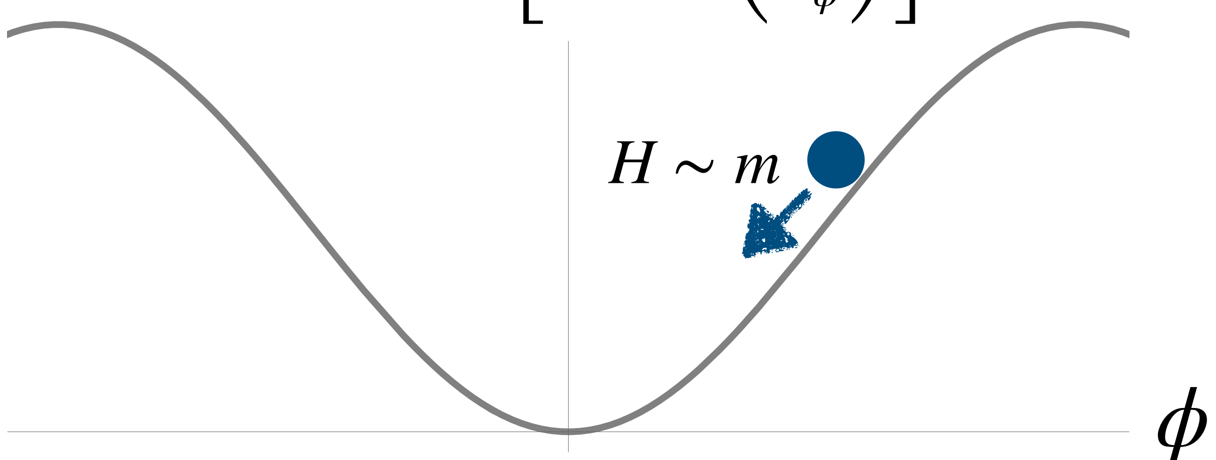
If the axion exists before the end of inflation,
the axion field becomes (nearly) uniform.

$$\phi(t, \mathbf{x}) = \phi_0 \quad \text{(const.)}$$

The homogeneous axion evolves following

$$V = m_\phi^2 F_\phi^2 \left[1 - \cos\left(\frac{\phi}{F_\phi}\right)\right]$$

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = 0$$



When $H \sim m_\phi$, ϕ starts to oscillate:

$$\rho_\phi \propto a^{-3} \quad \text{(matter-like)}$$

The axion can be dark matter via the “misalignment mechanism”.

Preskill, Wise, Wilczek (1983), Abbott & Sikivie (1983), Dine & Fischler (1983)

Axion

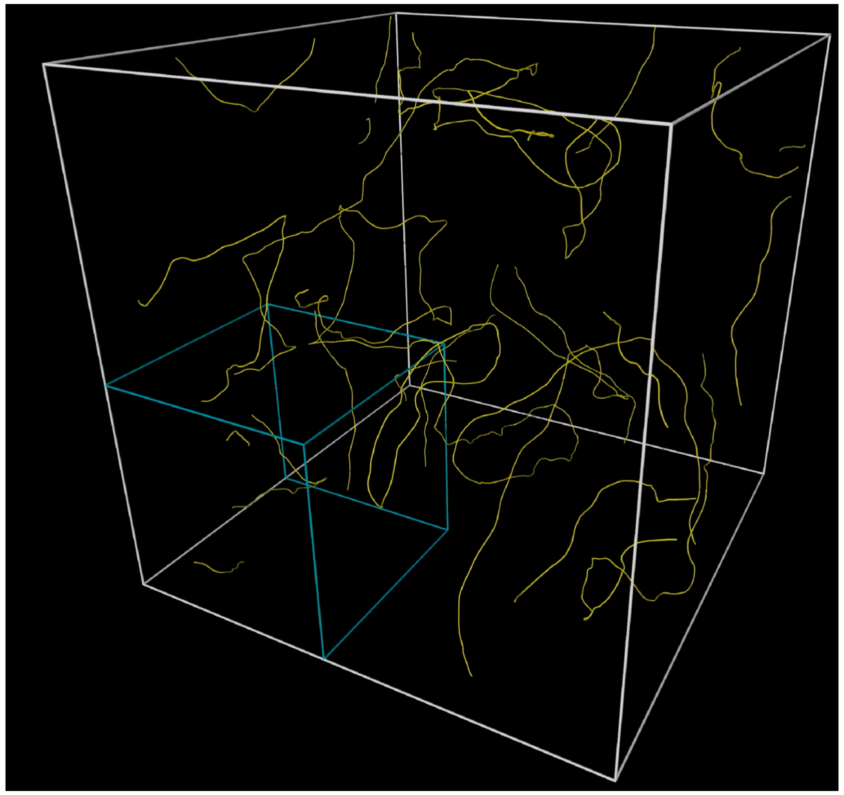
- Post-inflationary PQ breaking

If the axion arises after inflation,
the axion field value is randomly determined at that time.

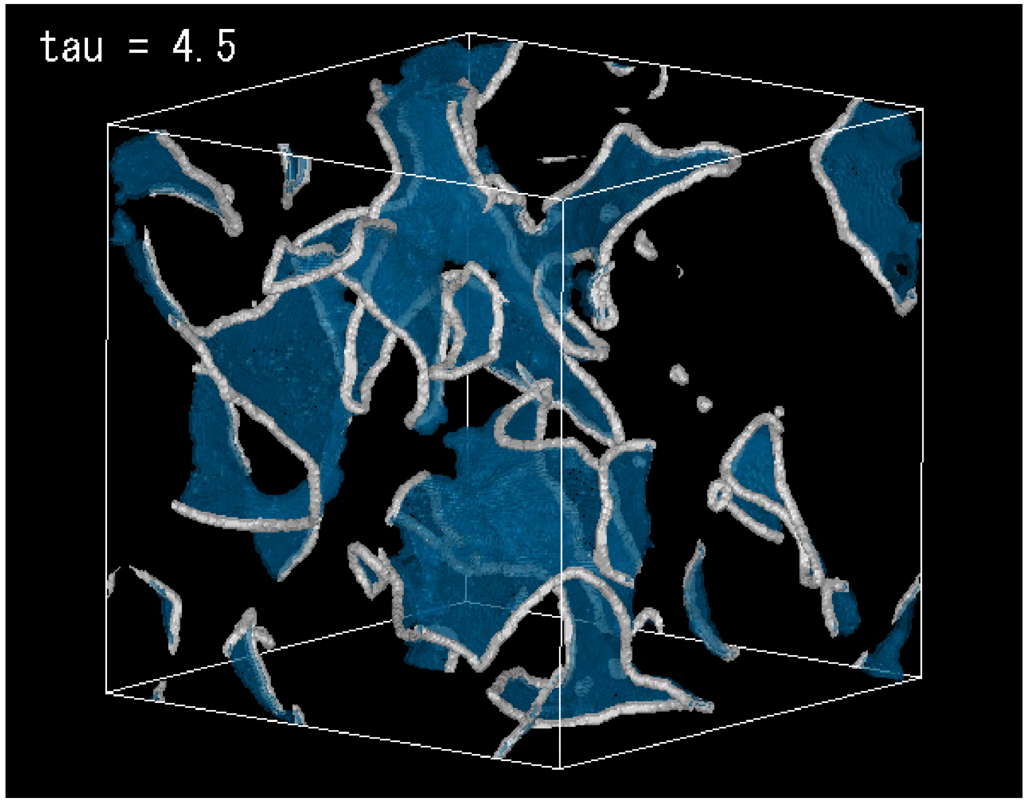
→ Cosmic strings and domain walls are formed.

topological defects

"Domain wall problem" or DM from collapse of defects Davis (1986)



Buschmann et al. (2021)



Hiramatsu et al. (2012)

Topological defects

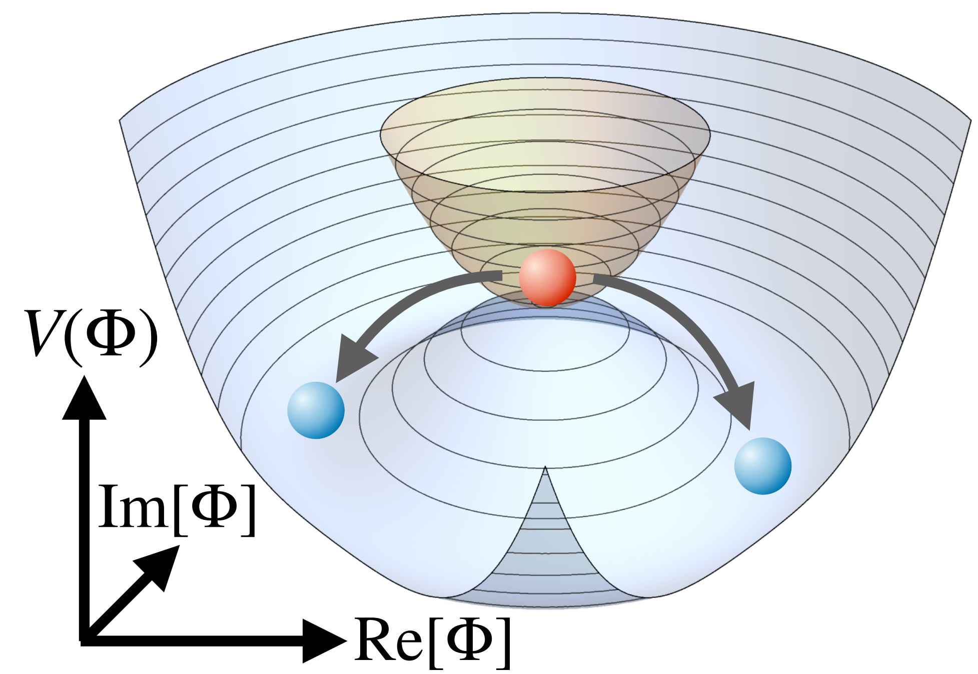
- Cosmic string

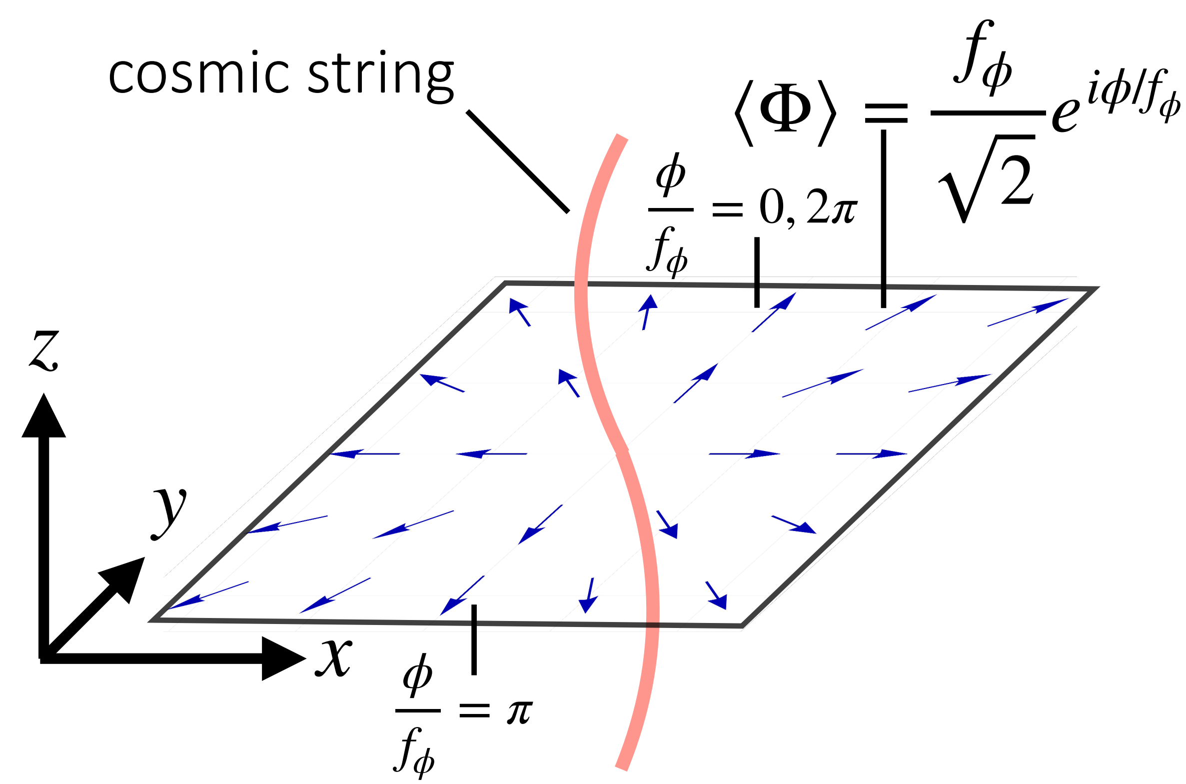
A complex scalar Φ with a wine-bottle $V(\Phi)$

At high temperatures,
Φ is stabilized at the origin.

At low temperatures,
the VEV, $\langle\Phi\rangle$, becomes nonzero.
An axion arises as a NG boson.

→ Formation of cosmic string at the SSB of U(1)





Topological defects

- Domain wall

Explicit breaking of U(1) symmetry

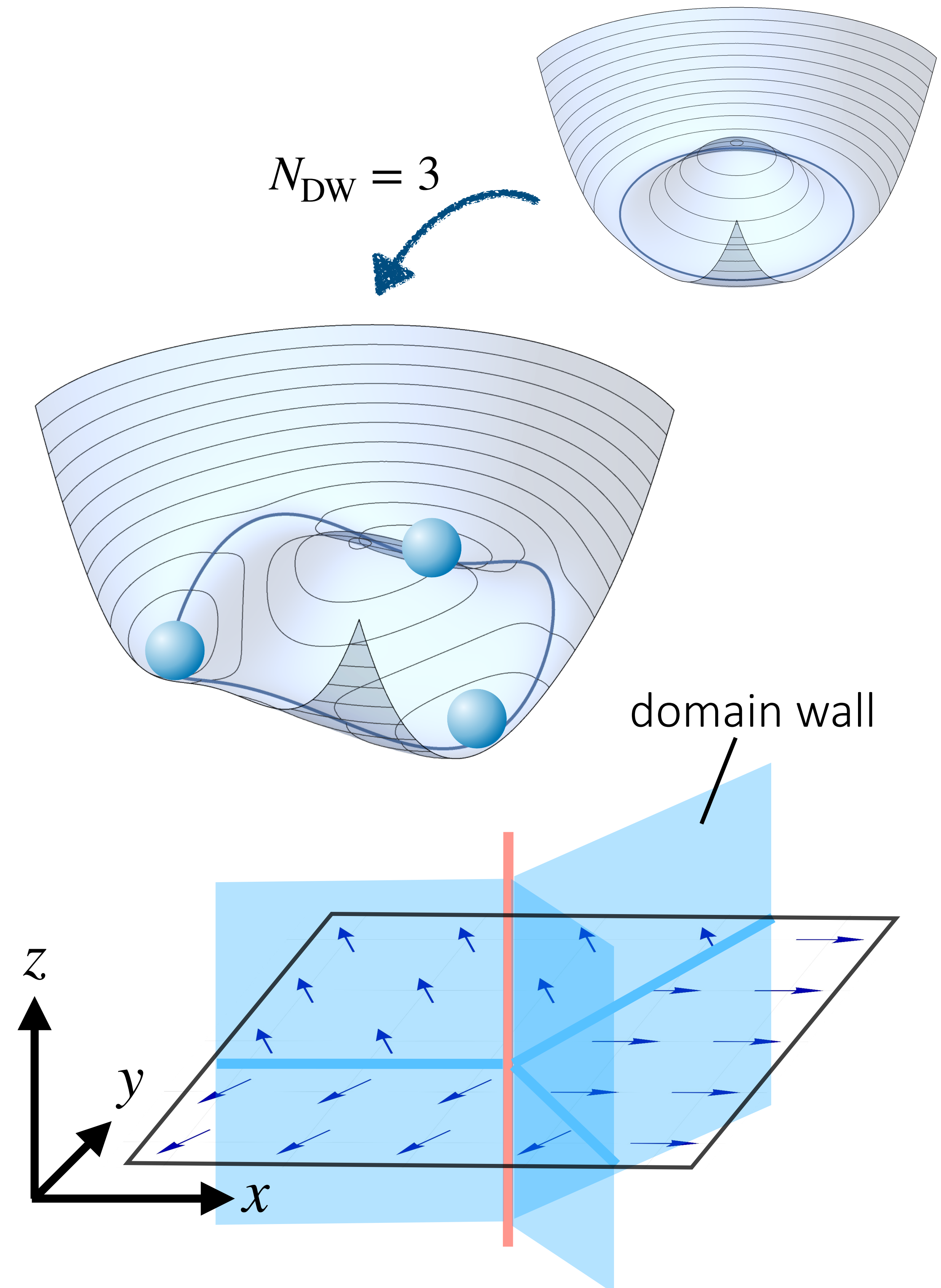
$$\mathrm{U}(1) \rightarrow \mathbb{Z}_{N_{\mathrm{DW}}}$$

➜ Potential for the axion, $m_a \neq 0$

$$V_{\mathrm{QCD}} = \chi \left[1 - \cos\left(N_{\mathrm{DW}} \frac{\phi}{f_\phi} \right) \right]$$

When $m_a > H$,
the axion rolls down the potential.

➜ A network of cosmic strings and domain walls is formed.

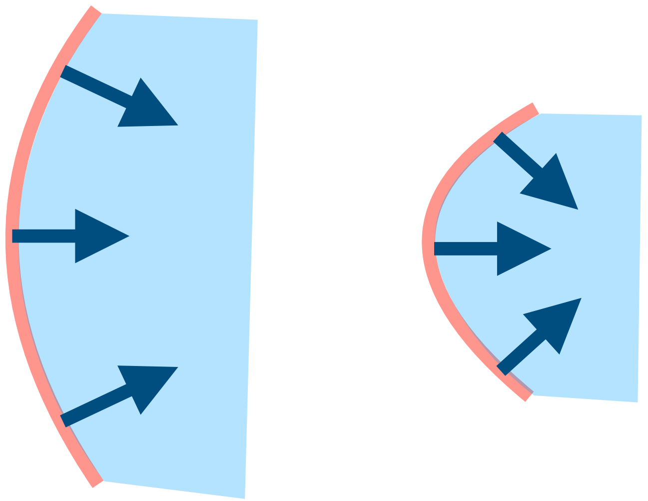


Domain wall number

- $N_{\mathrm{DW}} = 1$

  The network rapidly decay due to the DW tension.

  The emitted axions can account for DM. Davis (1986)



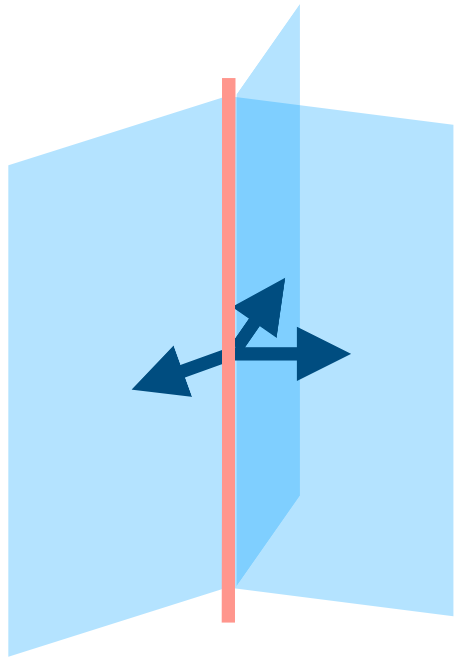
- $N_{\mathrm{DW}} > 1$

  The DW tension balance with each other.

  The network becomes long-lived.

  DWs follow the scaling solution:

  $\mathcal{O}(1)$ DWs in each Hubble volume.

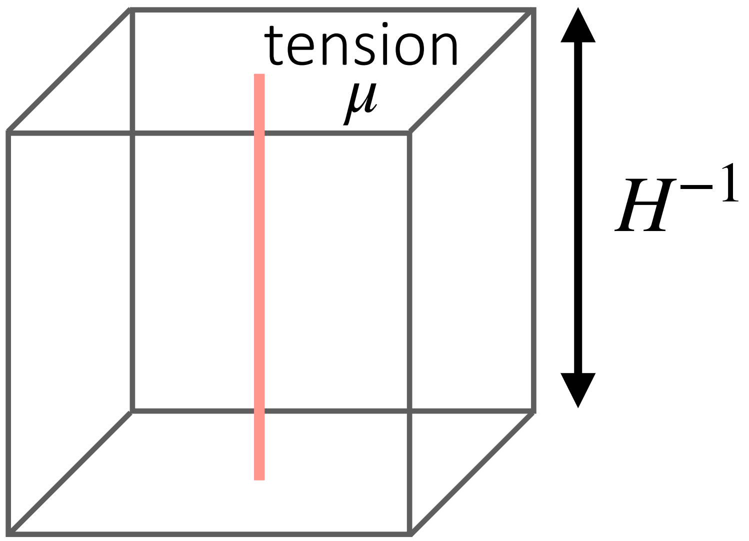


If the vacuum is unique, the universe is filled with that vacuum.

Topological defects

- Scaling solution

For $N_{\mathrm{DW}} > 1$, string-wall network is long-lived.

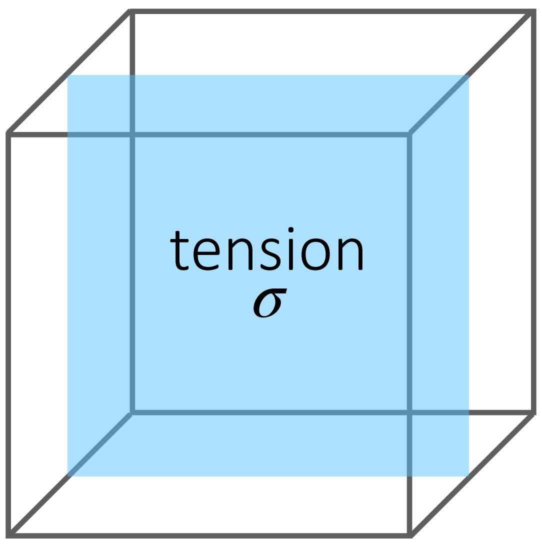


→ Scaling solution:

$\mathcal{O}(1)$ strings/walls in a Hubble volume

$$\rho_{\mathrm{str}} \sim \mu H^2 \propto \rho_{\mathrm{tot}}$$

$$\rho_{\mathrm{wall}} \sim \sigma H$$



→ DWs dominates the universe,
which is inconsistent with the CMB anisotropies.

"Domain wall problem"

We can introduce a potential bias to avoid the domain wall problem.

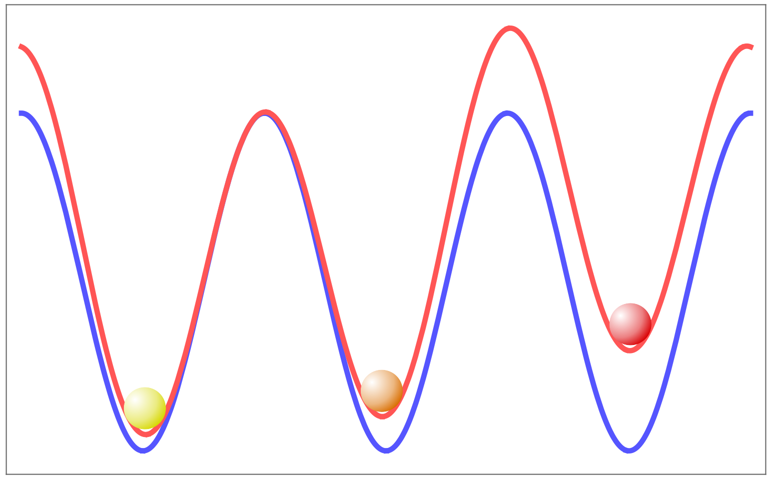
Topological defects

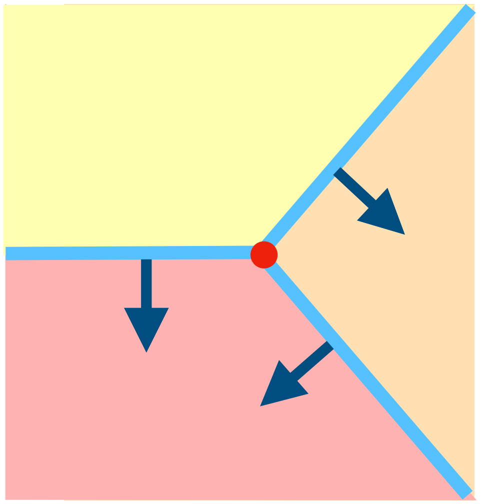
- Domain wall collapse

Let us introduce a bias term:

$$V(a) = \underbrace{\chi\left[1-\cos\left(N_{\rm DW}\frac{a}{f_a}\right)\right] + \epsilon\chi\left[1-\cos\left(N_{\rm b}\frac{a}{f_a}+\theta\right)\right]}$$

➜ DWs collapse when the bias overcomes the DW tension.





When the DWs disappear, axions and gravitational waves are emitted.

Due to the shift of the potential minimum, the PQ solution is spoiled.

Topological defects

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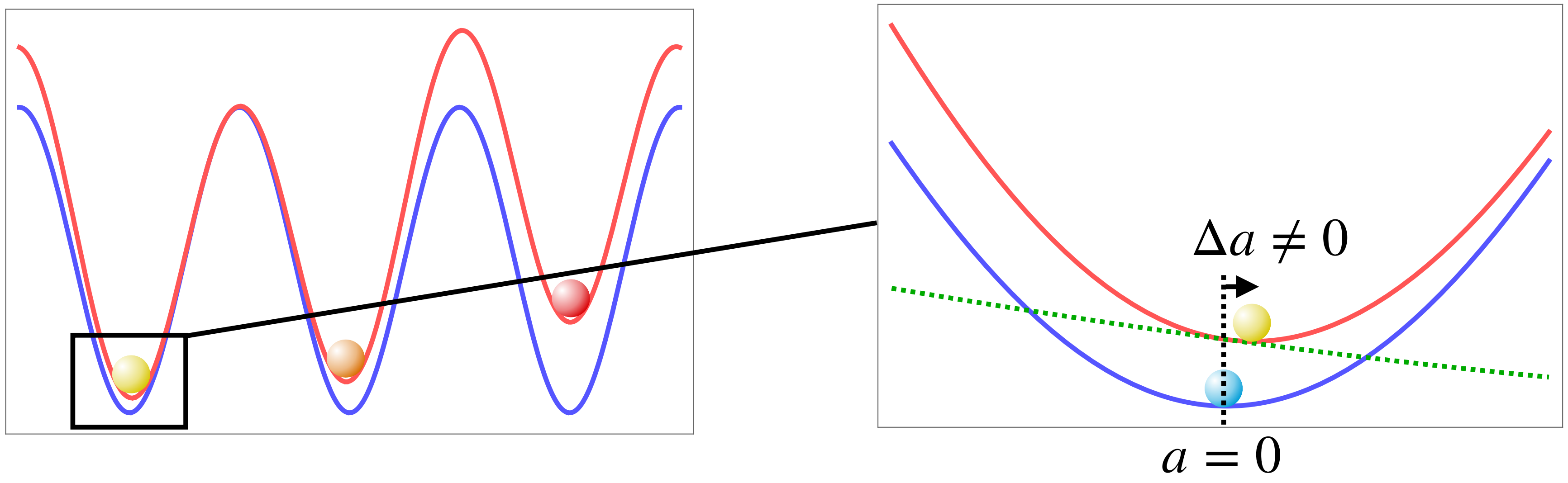

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Due to the shift of the potential minimum, the PQ solution is spoiled.

Topological defects

- Multi-axion system

In the string axiverse, many axion-like particles are expected.
Arvanitaki et al. (2009)

They have mixings in the potential in general,
and one linear combination can work as the QCD axion.

Topological defects have been well studied for a single-axion setup.

Q. How about multiple axions?

Can we integrate out the heavier axions?

→ No.

We find new phenomena of defects in two-axion models.

Two-axion system

- General setup

We consider two axions with two potentials:

e.g.

$$V \supset \Phi_1^{n_1}\Phi_2^{n_2} + \mathrm{h.c.}$$

$$V(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}\right)\right]$$

Each axions follows either of pre- or post-inflationary scenarios.

homogeneous   defects

We can consider pre-pre, pre-post, post-post initial conditions.

→ We classify the evolution of defects by n's and the initial conditions.

n_1	n_2	N_{DW}	V_1	V_2
1	0	-	decay of ϕ_1 strings	ϕ_2 strings with $\lvert n_2' \rvert$ DWs
≥ 2	0	-	ϕ_1 network & ϕ_2 strings	stable network
≥ 1	1	0	θ_L string bundles	θ_L string bundles
		1		decay of network
		≥ 2		stable network
≥ 2	≥ 2	-	stable network	stable network with induced DWs or collapse by transient bias

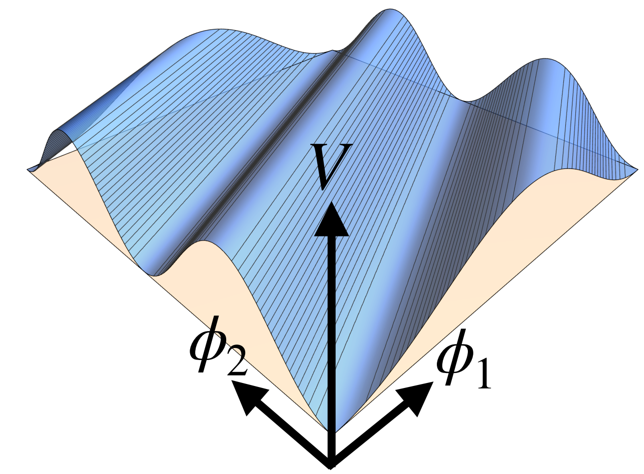
(See our paper for details.)

String bundles

- **Post-post scenario**

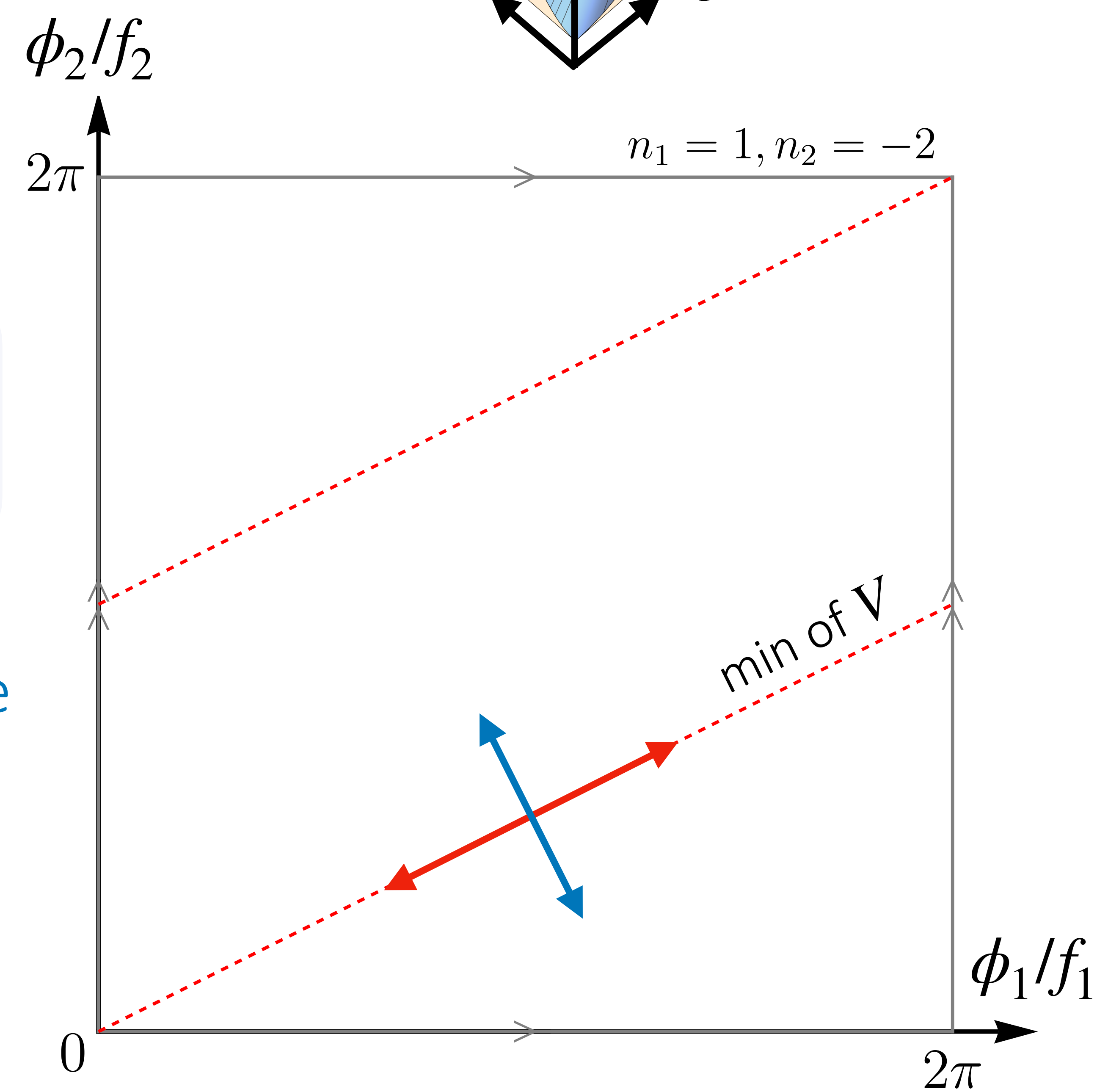
  Let us consider the post-post scenario.

  → Cosmic strings of ϕ_1 and ϕ_2



With the larger potential:

$$V(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$



One linear combination becomes massive while the other remains massless.

String bundles

Post-post scenario

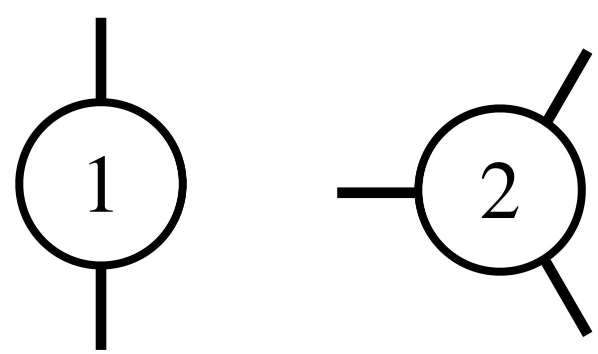
Let us consider the post-post scenario.

→ Cosmic strings of ϕ_1 and ϕ_2

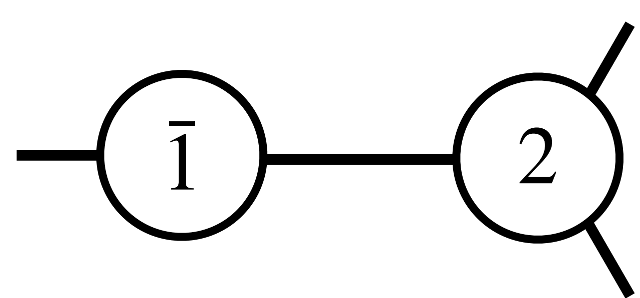
With the potential: $$V(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}\right)\right]$$

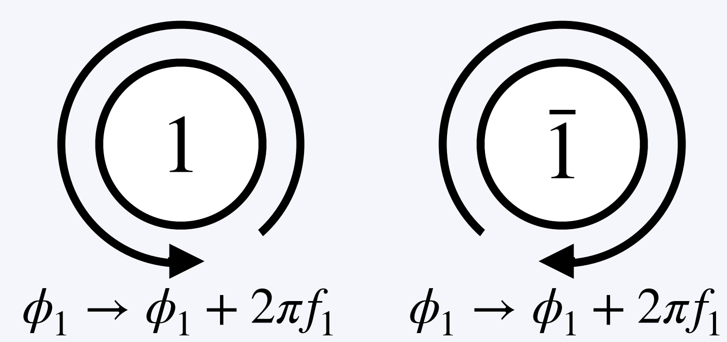
ϕ_1, ϕ_2 string has n_1, n_2 domain walls, respectively.

$(n_1, n_2) = (2,3)$:



The strings can be connected by domain walls.





String bundles

Memo: $V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$

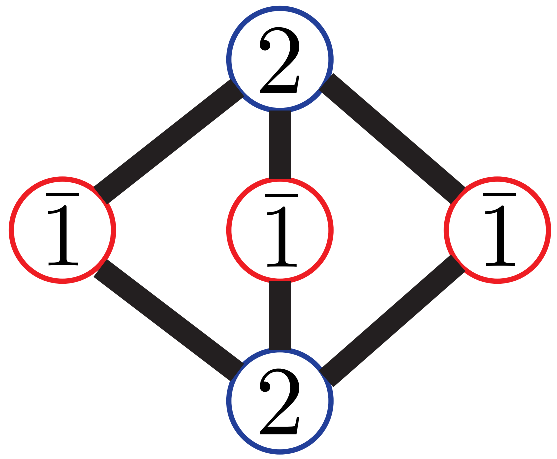
- String bundles or network

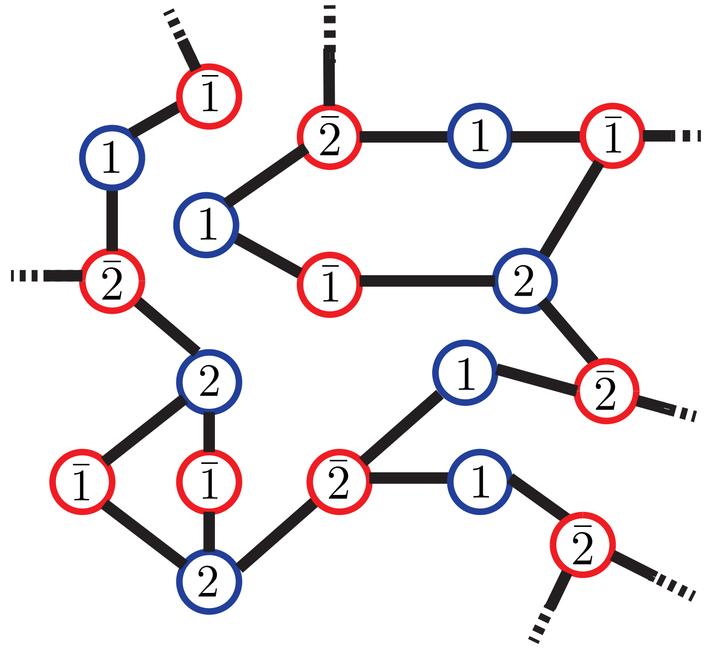
If n_2 strings of ϕ_1 and n_1 anti-strings of ϕ_2 composes a closed network, it shrinks and behaves as a string associated with the massless axion.

"String bundle"

However, we expect the complex network expanding infinitely for $|n_1| > 1$ and $|n_2| > 1$.
(cf. We know a complex network for a single-axion with $N_{\mathrm{DW}} > 1$.)

$(n_1, n_2) = (2,3)$:





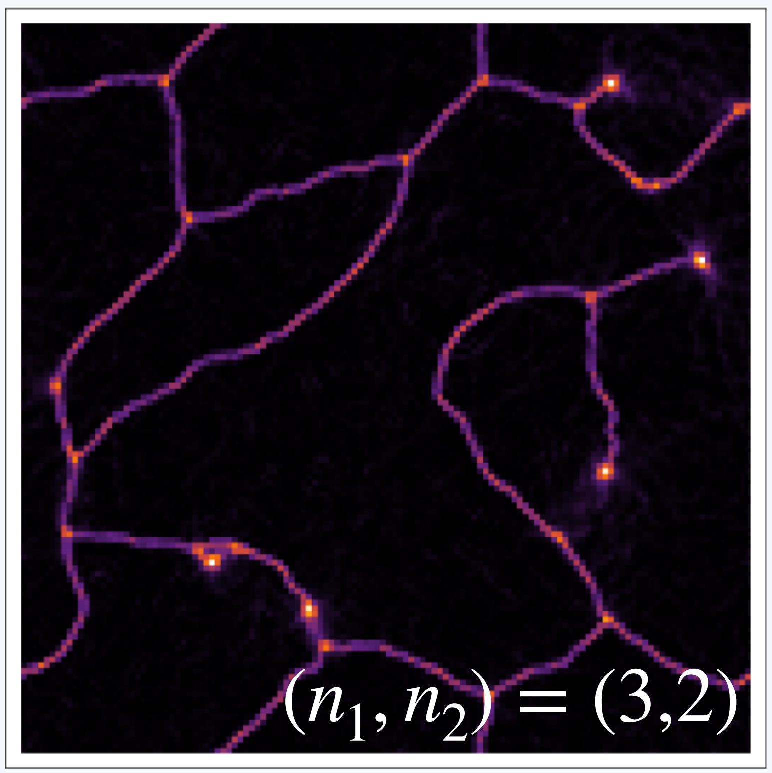
See also Higaki et al. (2016), Eto et al. (2023)

String bundles

Memo: $V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$

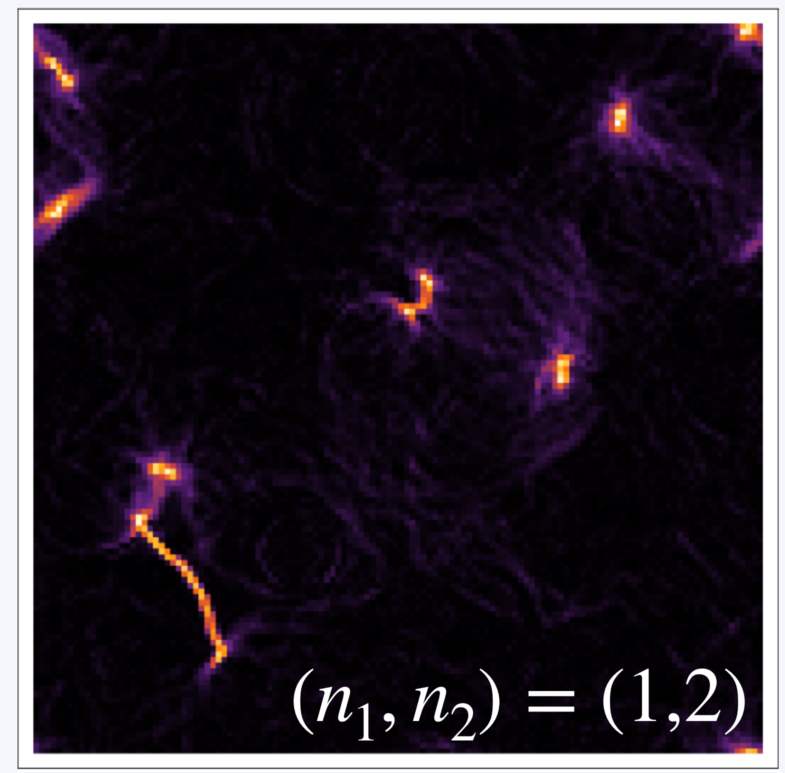
- Formation of string bundles

We simulate the formation of string bundles in 2D and 3D lattice.



Complex network remains.

→ Domain wall problem



“String bundles” are formed.

$1 - \bar{2} - 1$

String bundles

Memo: $V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$

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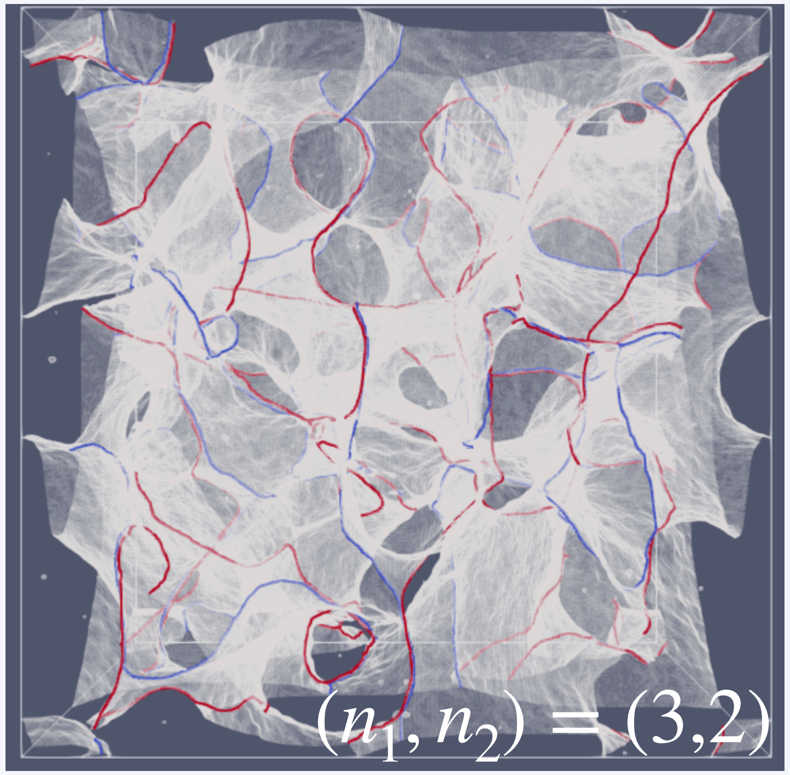
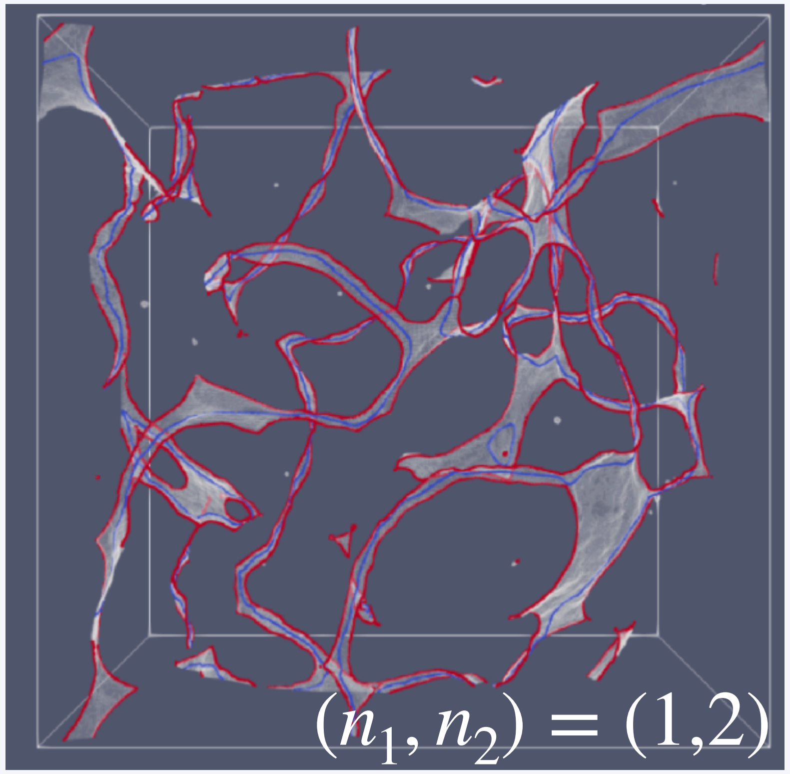


Complex network remains.

→ Domain wall problem



“String bundles” are formed.

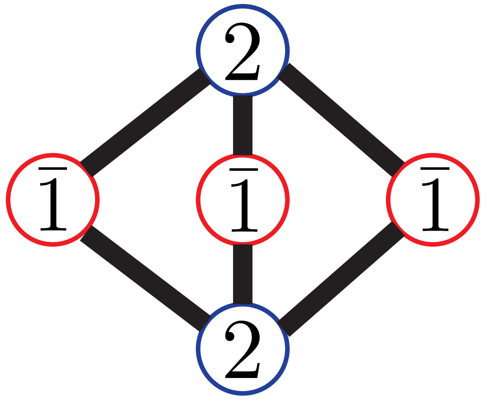
$1 - \bar{2} - 1$

String bundles

- Domain walls on a string bundle

With the second potential: $V_2(\phi_1, \phi_2) = \tilde{\Lambda}^4 \left[1 - \cos\left(n'_1 \frac{\phi_1}{f_1} + n'_2 \frac{\phi_2}{f_2} + \alpha\right)\right]$

Around a string bundle, ϕ_1/f_1 changes by $-2\pi n_2$, and ϕ_2/f_2 changes by $2\pi n_1$.



→ Each bundle has $N_{\rm DW}$ DWs with $N_{\rm DW} = |n_1 n'_2 - n_2 n'_1|$.

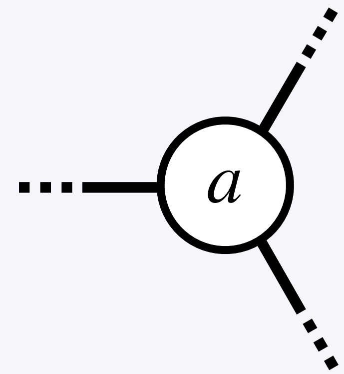
$$N_{\rm DW} \begin{cases} = 0 & \text{String bundles with no DWs remain.} \\ = 1 & \rightarrow \text{String bundles and DWs disappear.} \\ > 1 & \text{String bundle-DW network remains.} \end{cases}$$

Solving domain wall problem of QCD axion

- Idea of solution

In the conventional QCD axion models with $N_{\rm DW} > 1$:

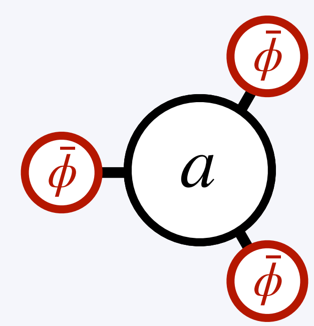
$$V_{\rm QCD} = \chi(T)\left[1 - \cos\left(N_{\rm DW}\frac{a}{f_a}\right)\right]$$



Stable network is formed.

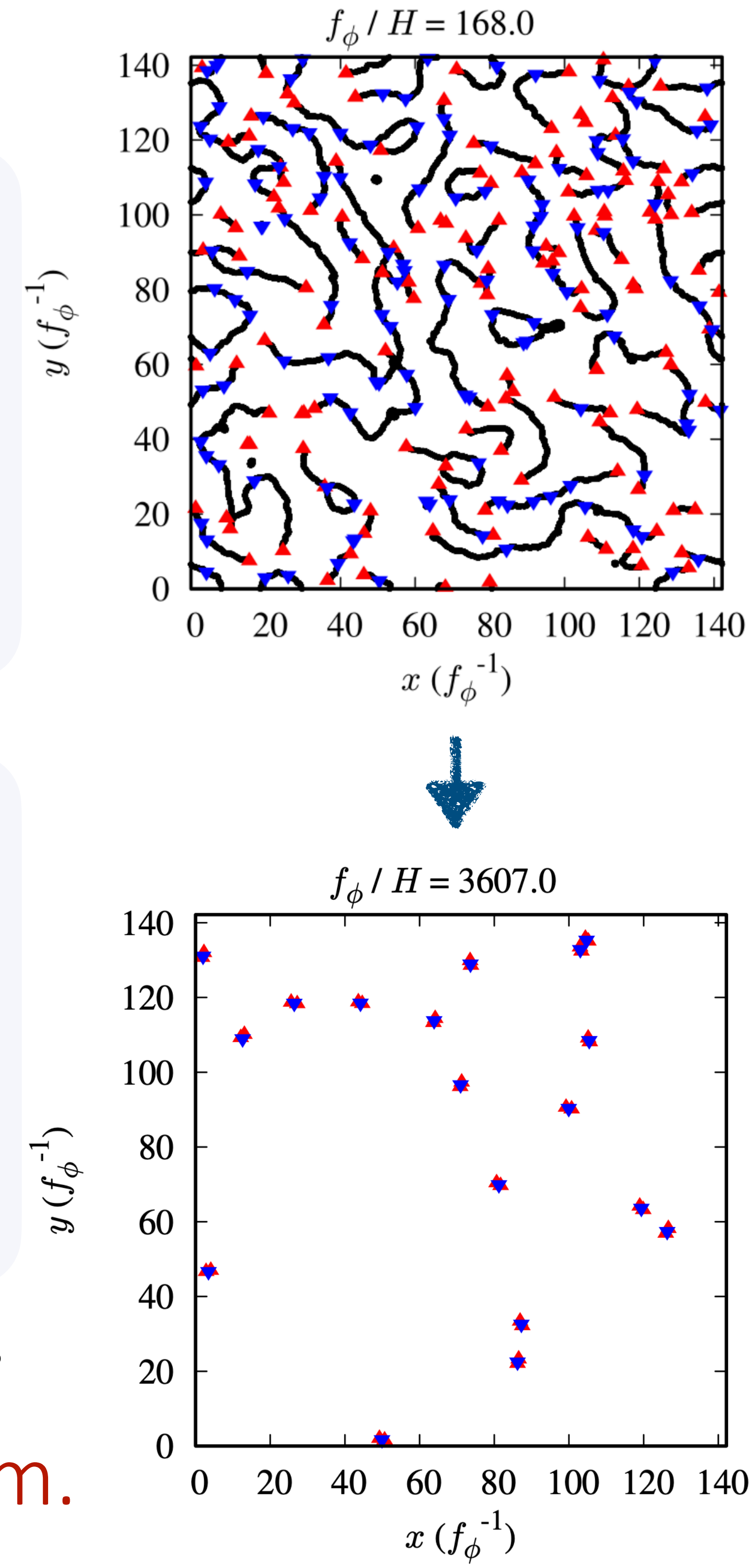
We introduce an additional axion ϕ with $N_{\rm DW} = 1$:

$$V_{\rm QCD} = \chi(T)\left[1 - \cos\left(N_{\rm DW}\frac{a}{f_a} + \frac{\phi}{f_\phi}\right)\right]$$



String bundles are formed, and domain walls disappear.

A light axion can solve the QCD axion DW problem.



Solving domain wall problem of QCD axion

Setup

The potential depends on the massive mode:

$$V_{\rm QCD} = \chi(T)\left[1 - \cos\left(N_{\rm DW}\frac{a}{f_a} + \frac{\phi}{f_\phi}\right)\right] = m_A(T)^2 F^2 \left[1 - \cos\left(\frac{A}{F}\right)\right]$$

$$A \equiv F\left(N_{\rm DW}\frac{a}{f_a} + \frac{\phi}{f_\phi}\right), \qquad F \equiv \frac{f_a f_\phi}{\sqrt{N_{\rm DW}^2 f_\phi^2 + f_a^2}}$$

In the following, we focus on $f_a \ll f_\phi$.

$$A \sim a, \qquad F \sim \frac{f_a}{N_{\rm DW}}$$

The QCD axion is almost a, which originally have domain wall problem.

Solving domain wall problem of QCD axion

$$\sigma_A(T) \simeq 8 m_A(T) F^2$$

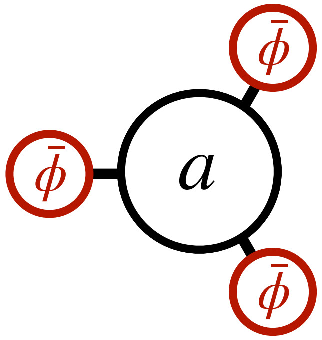
$$\mu_\phi \simeq \pi f_\phi^2 \gg \mu_a$$

- Bundle formation and axion production

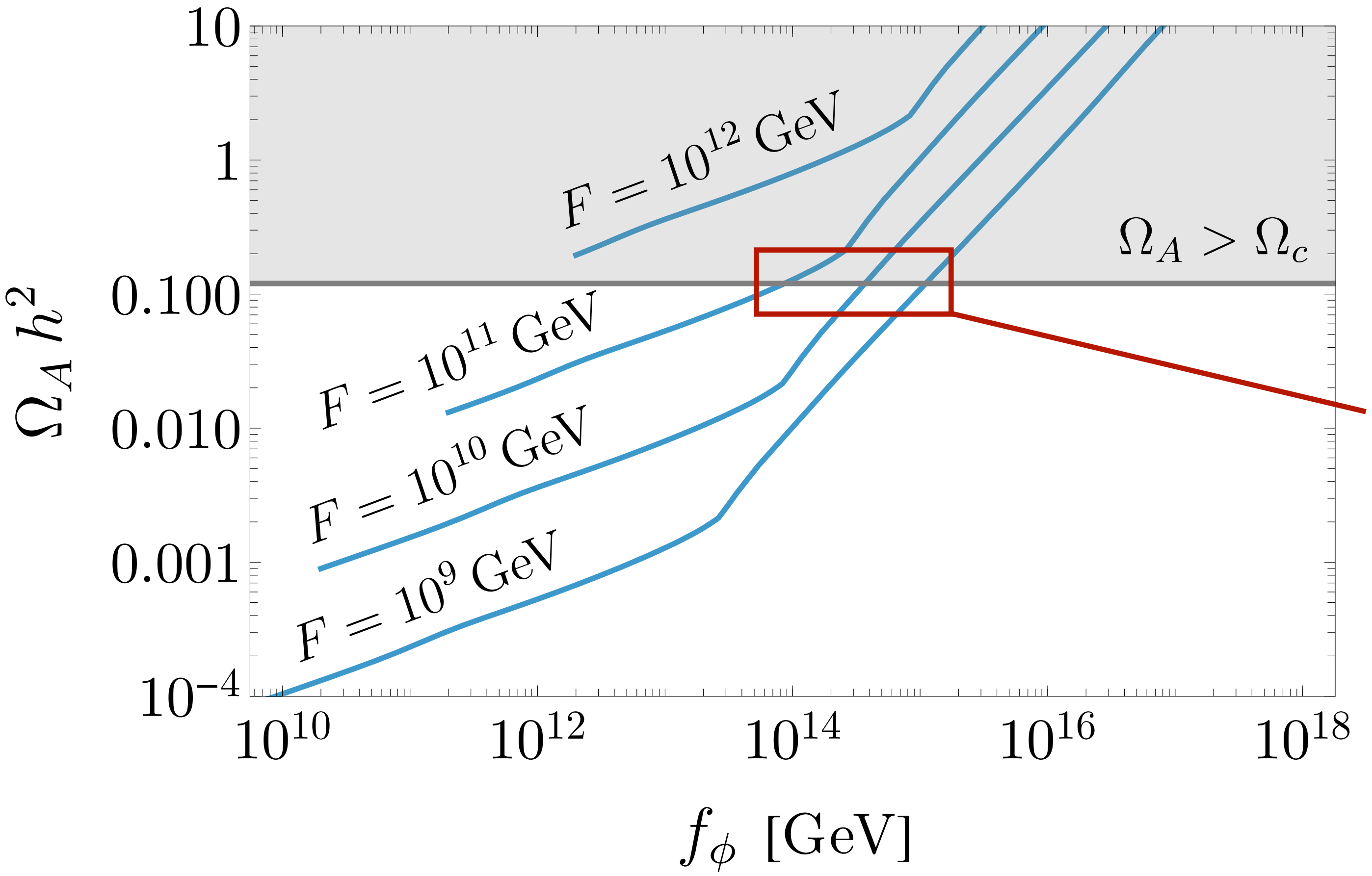
Domain wall formation: $m_A \sim H$

To form string bundles, walls must pull strings together.

String bundle formation: $\sigma_A \sim \mu_\phi H$



The energy stored in domain walls are emitted as QCD axions.



QCD axion dark matter with $F < 10^{12}\,\mathrm{GeV}$

Summary

We studied topological defects in two-axion system with mixings.

- DWs can be confined in string bundles depending on the DW numbers.
- QCD axion + light axion can solve the domain wall problem of the QCD axion via string bundles.
- QCD axion dark matter can be produced at bundle formation.

In two-axion systems,
the cosmology is very different from single-axion systems!