Topological Defects and Gravitational Waves from Aligned Axions

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1512.05295, 1603.02090, 1606.05552

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Strong CP problem

CP violating phase

QCD Lagrangian: $\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \frac{g_s^2}{32\pi^2} \theta G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$

CP violation

neutron electric dipole moment

$$d_n \simeq 4.5 \times 10^{-15} \theta e \ {\rm cm}$$

experimental constraint: $|d_n| < 2.9 \times 10^{-26} e \ {\rm cm}$

$\Rightarrow$ $|\theta| < 0.7 \times 10^{-11}$ "strong CP problem"

Why is it extremely small? Fine tuning is necessary!

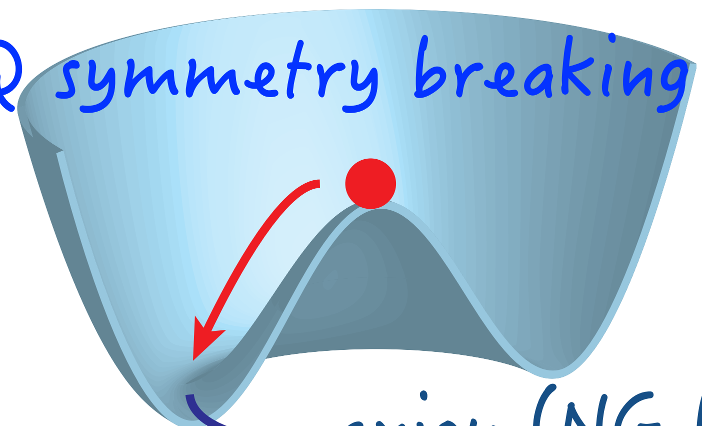
Solution : Peccei-Quinn mechanism

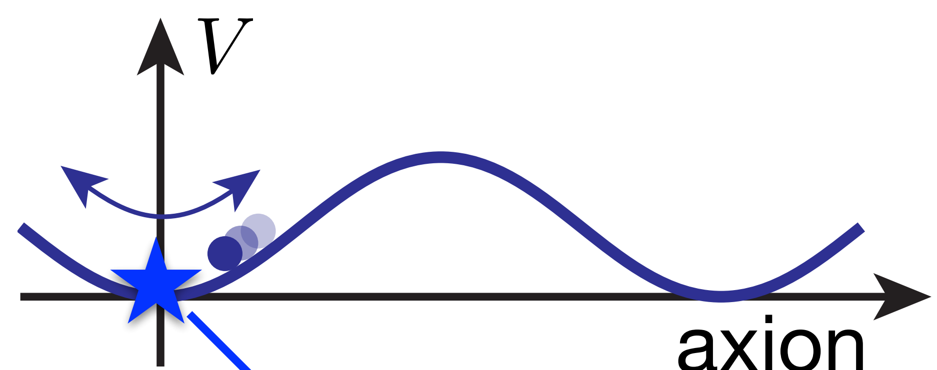
Peccei, Quinn (1977)

Complex scalar field (PQ field): $\Phi = |\Phi| e^{ia/f_a}$ ← axion

\+

U(1) symmetry (PQ symmetry)





$$\mathcal{L} \ni \frac{g_s^2}{32\pi^2}\left(\theta + \frac{a}{F_a}\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$$

$\left(\theta + \frac{a}{F_a}\right)$ → dynamical field

$$\theta + \frac{a}{F_a} = 0$$

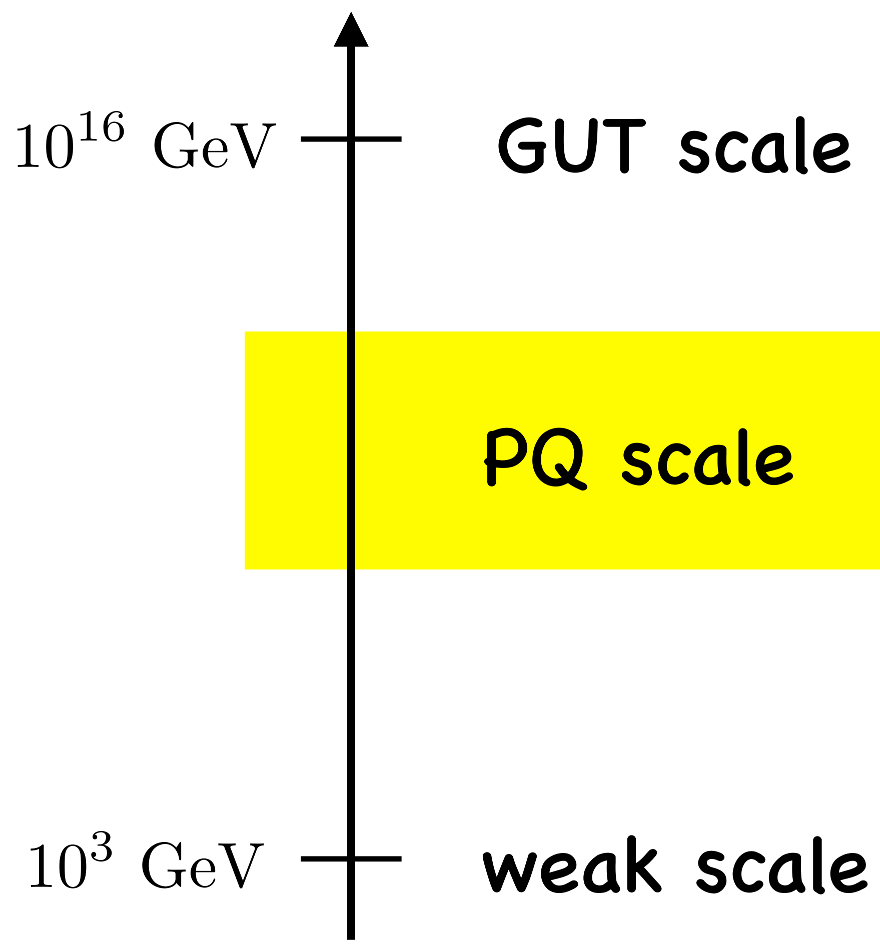
CP conserving minimum

- Strong CP phase is dynamically cancelled!
- New particle "axion" is predicted! —> contribute to CDM

Axion puzzle -1-

Axion window : $10^9 \text{ GeV} \lesssim F_a \lesssim 10^{12} \text{ GeV}$

SN1987A ↑ (lower bound) DM abundance ↑ (upper bound)



Q1. PQ scale must be in some intermediate scale. Why??

Axion puzzle -2-

Global symmetries must be explicitly broken

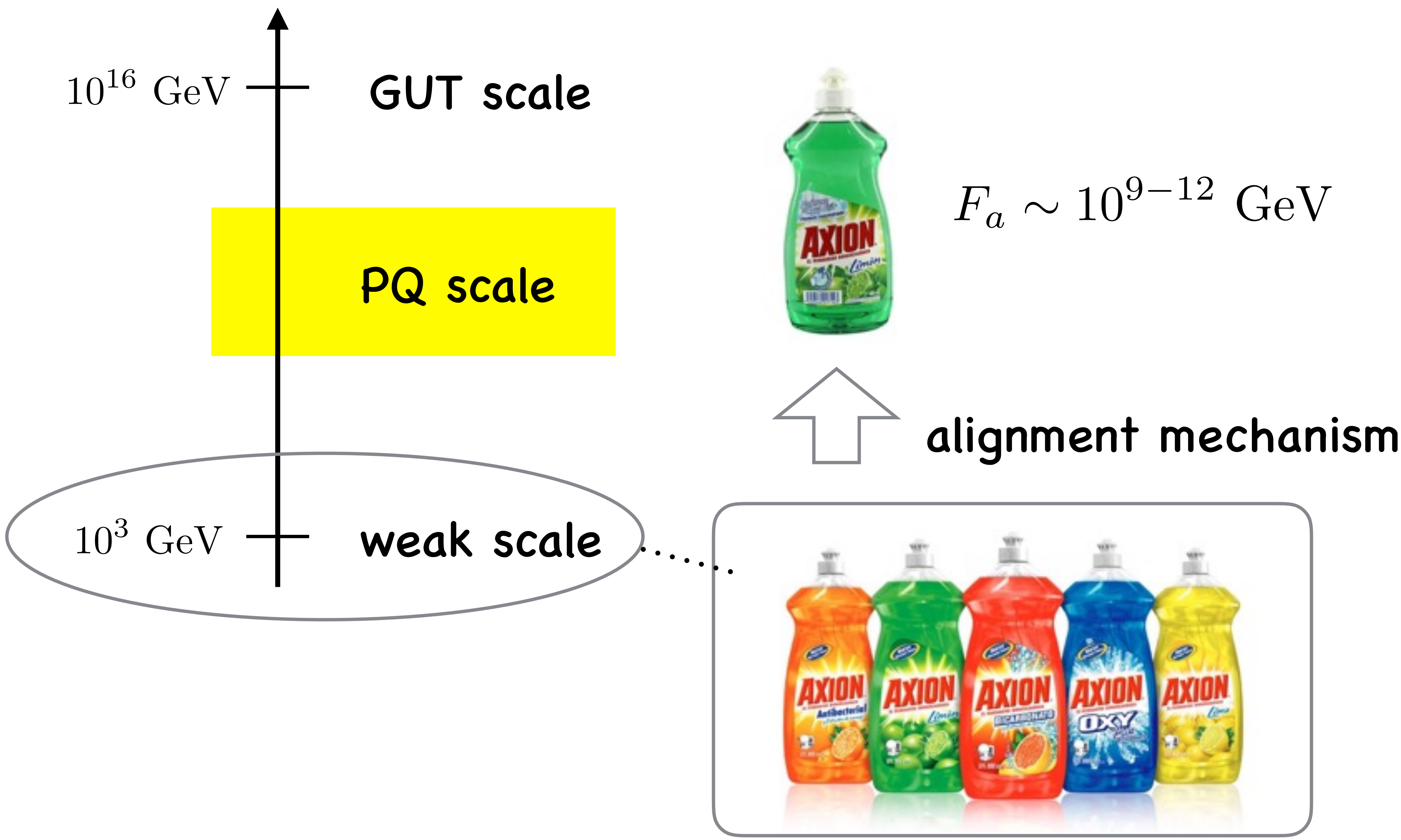
by, e.g., Planck suppressed operators : $\mathcal{L} \ni \frac{\Phi^5}{M_P}, \frac{\Phi^6}{M_P^2}, \ldots$

contribute to CP phase

!! PQ mechanism would be broken down

Q2. High quality of PQ symmetry is required. How come?

Our strategy



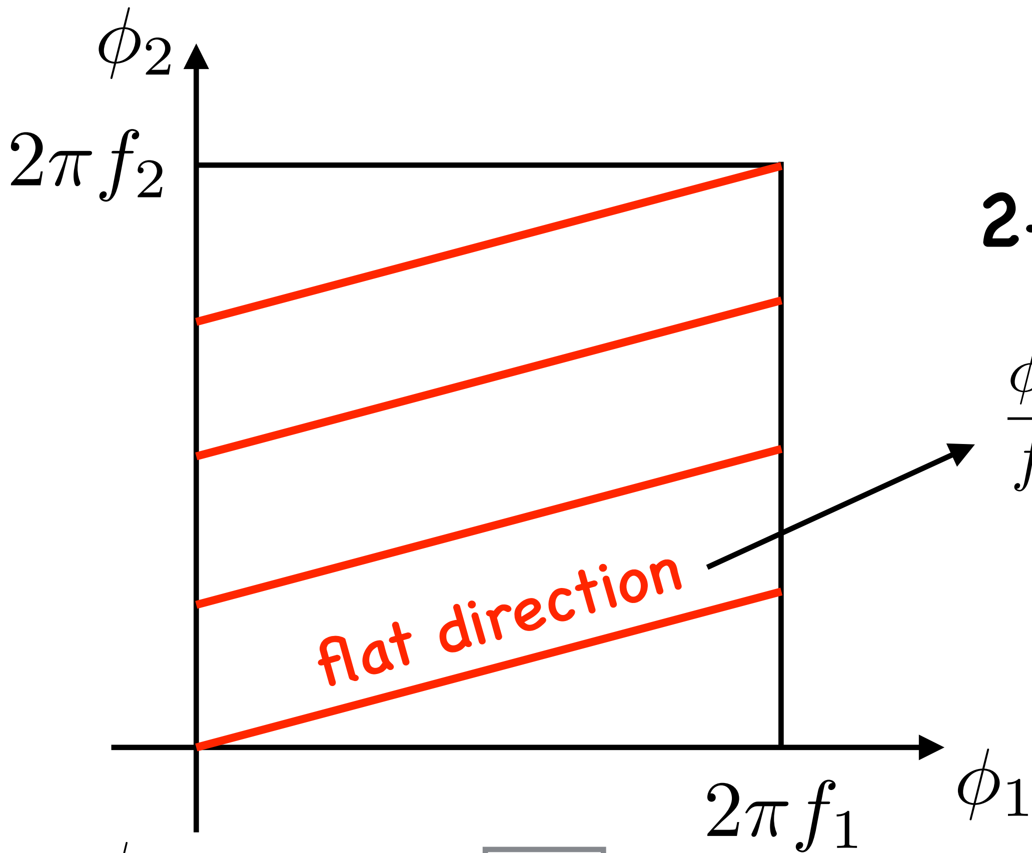
multiple axions with $\langle \Phi_i \rangle = f_i \sim \mathrm{TeV}, \quad i = 1, 2, 3, ..$

Aligned QCD axion model

T. Higaki, K.S. Jeong, NK, F. Takahashi, 1512.05295; 1603.02090

Alignment mechanism — basic picture

Kim, Niles, Peloso, hep-ph/0419138



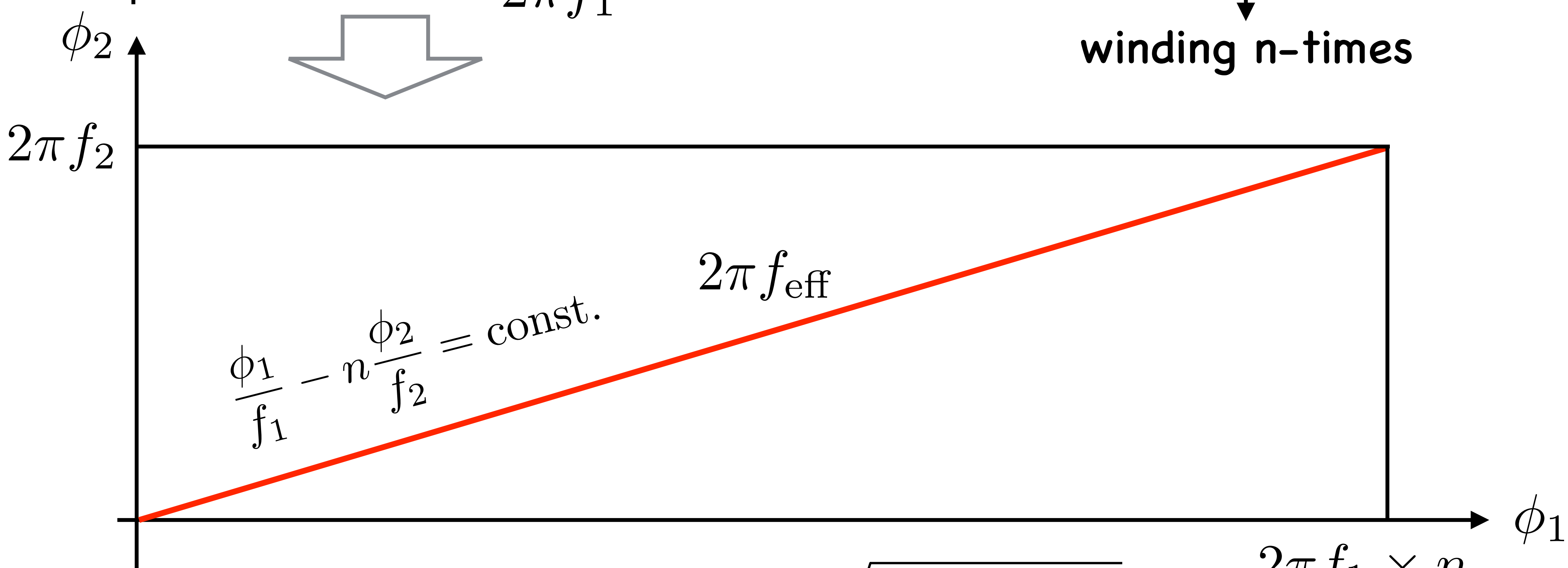
2-axion case $V = \Lambda^4\left[1 - \cos\left(\frac{\phi_1}{f_1} - \frac{n\phi_2}{f_2}\right)\right]$

$$\frac{\phi_1}{f_1} - n\frac{\phi_2}{f_2} = \text{const.}$$

period of flat direction

$$\phi_1 \to \phi_1 + 2\pi f_1 \times n, \quad \phi_2 \to \phi_2 + 2\pi f_2$$

winding n-times



effective decay constant : $f_{\rm eff} = \sqrt{n^2 f_1^2 + f_2^2}$

Clockwork axion model

K. Choi, H. Kim, S. Yun, 1404.6209
K. Choi, S.H. Im, 1511.00132
D.E. Kaplan, R. Rattazzi, 1511.01827

N-axions: $\phi_i = \phi_i + 2\pi f_i \quad (i = 1, 2, \ldots, N)$

potential : $$V = -\sum_{i=1}^{N-1} \Lambda_i^4 \cos\left(\frac{\phi_i}{f_i} + n_i \frac{\phi_{i+1}}{f_{i+1}}\right)$$

flat direction :

$$\phi_{\rm flat} = \sum_{i=1}^{N} (-1)^{i-1} \left(\prod_{j=i}^{N} n_j\right) \frac{f_i \phi_i}{f_{\rm eff}} \quad \textbf{with} \quad f_{\rm eff} = \sqrt{\sum_{i=1}^{N} \left(\prod_{j=i}^{N} n_j^2\right) f_i^2}$$

$(n_N \equiv 1)$

Aligned "QCD" axion model

T. Higaki, K.S. Jeong, NK, F. Takahashi, 1512.05295

$$\mathcal{L} = \sum_{i=1}^{N-1} \Lambda_i^4 \cos\left(\frac{\phi_i}{f_i} + n_i \frac{\phi_{i+1}}{f_{i+1}}\right) + \frac{g_3^2}{32\pi^2}\frac{k_s \phi_N}{f_N} G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{g_1^2}{32\pi^2}\frac{k\phi_N}{f_N} B^{\mu\nu}\tilde{B}_{\mu\nu}$$

flat direction = QCD axion

$$a = \sum_{i=1}^{N} (-1)^{i-1} \left(\prod_{j=i}^{N} n_j\right) \frac{f_i \phi_i}{f_a} \quad \textbf{with} \quad f_a = \sqrt{\sum_{i=1}^{N}\left(\prod_{j=i}^{N} n_j^2\right) f_i^2}$$

$$f_i \sim f_N \sim f \quad \text{and} \quad |n_i| \sim n > 0 \quad (i = 1, 2, \ldots, N-1)$$

(TeV scale)

$$\longrightarrow f_a \sim e^{N \ln n} f \sim 10^{9-12}\ \text{GeV}$$

$f \sim \text{TeV}, \quad f_a \sim 10^{10}\ \text{GeV}, \quad n = 3$ → **we need more than 10 axions**

Possible UV completion

N-complex scalar fields with global U(1)^N symmetry

U(1)^N symmetry breaking $\Downarrow$ $V = \sum_{i=1}^{N} \left(- m_i^2 |\Phi_i|^2 + \frac{\lambda_i}{4} |\Phi_i|^4 \right)$

$$\Phi_i = \left(\rho_i + \frac{f_i}{\sqrt{2}} \right) e^{i\phi_i/f_i} \quad \textbf{with} \quad f_i = \sqrt{2}\langle|\Phi_i|\rangle$$

$$\Delta\mathcal{L} = \sum_{i=1}^{N-1} \left(\Phi_i \bar{\psi}_i \psi_i + \sum_{a=1}^{n_i} \Phi_{i+1} \bar{\Psi}_{ai} \Psi_{ai} \right) + \text{h.c.}$$

K. Choi, H. Kim, S. Yun, 1404.6209

$$\Delta V = \sum_{i=1}^{N-1} \epsilon_i \Phi_i \Phi_{i+1}^3 + \text{h.c.} \longrightarrow n_i = 3 \ \text{ and } \ \Lambda_i = \left(\frac{\epsilon_i}{2} f_i f_{i+1}^3 \right)^{1/4}$$

D.E. Kaplan, R. Rattazzi, 1511.01827

Quality of the PQ symmetry

T. Higaki, K.S. Jeong, NK, F. Takahashi, 1603.02090

Quality of the PQ symmetry

Carpenter, Dine, Festuccia 0906.1273

potential for QCD axion : QCD instanton + quantum gravity

$$V_{\rm QCD} = -m_{\rm QCD}^2 F_a^2 \cos\left(\frac{a}{F_a}\right) - m_{\cancel{\rm PQ}}^2 \mu^2 \cos\left(\frac{a}{\mu} - \alpha\right)$$

QCD instanton

explicit PQ breaking from quantum gravity

axion mass : $m_a^2 \simeq m_{\rm QCD}^2 + m_{\cancel{\rm PQ}}^2 \cos\alpha$

QCD instanton — $m_{\rm QCD} \simeq 6 \times 10^{-4}\ {\rm eV} \left(\frac{\Lambda_{\rm QCD}}{400\ {\rm MeV}}\right)^2 \left(\frac{F_a}{10^{10}\ {\rm GeV}}\right)^{-1}$

Strong CP phase is modified by the second term

$$\frac{\langle a \rangle}{F_a} \equiv \bar{\theta} \simeq \frac{m_{\cancel{\rm PQ}}^2 \sin\alpha}{m_{\rm QCD}^2 + m_{\cancel{\rm PQ}}^2 \cos\alpha} \frac{\mu}{F_a}$$

1. Planck-suppressed dimension-5 operator (conventional case)

$$\Delta V_5 = \frac{\kappa_5}{5}\frac{\Phi_1^5}{M_P} + \mathrm{h.c.}$$

no alignment mechanism $\quad \langle \Phi_1 \rangle \sim F_a \sim \mu$

$$m_{\cancel{\mathrm{PQ}}} \sim 10^6\ \mathrm{GeV}\left(\frac{F_a}{10^{10}\ \mathrm{GeV}}\right)^{3/2} \gg m_{\mathrm{QCD}}$$

& $\bar{\theta} \sim \tan\alpha$

QCD instanton — $m_{\mathrm{QCD}} \simeq 6\times 10^{-4}\ \mathrm{eV}\left(\frac{\Lambda_{\mathrm{QCD}}}{400\ \mathrm{MeV}}\right)^2\left(\frac{F_a}{10^{10}\ \mathrm{GeV}}\right)^{-1}$

too large strong CP phase unless tan(α) is extremely small...

n.b. $\bar{\theta} \lesssim 10^{-10}$ by NEDM constraint

1. Planck-suppressed dimension-5 operator

$$\Delta V_5 = \frac{\kappa_5}{5}\frac{\Phi_1^5}{M_P} + \text{h.c.}$$

aligned QCD axion

$$m_{\not{\rm PQ}}^2 = \frac{5|\kappa_5|}{2\sqrt{2}}\frac{f_1^3}{M_P}, \quad \mu = \frac{f_1}{5} \quad \text{and} \quad \alpha = \arg(\kappa_5)$$

$$\longrightarrow \quad m_{\not{\rm PQ}} \simeq 0.03 \text{ MeV}\sqrt{|\kappa_5|}\left(\frac{f_1}{10^3 \text{ GeV}}\right)^{3/2}$$

$$\bar{\theta} \approx 2 \times 10^{-10}\left(\frac{\alpha}{0.1}\right)\left(\frac{F_a/f_1}{10^8}\right)^{-1} \quad \text{for} \quad m_{\not{\rm PQ}} \gg m_{\rm QCD}$$

Experimental bound can be satisfied if alignment mechanism enhances effective decay constant $\sim 10^8$

2. Planck-suppressed dimension-6 operator

$$\Delta V_6 = \frac{\kappa_6}{6}\frac{\Phi_1^6}{M_P^2} + \text{h.c.}$$

$$Z_2 : \ \Phi_i \to -\Phi_i$$

aligned QCD axion ⇩

$$m^2_{\not{\rm PQ}} = \frac{3|\kappa_6|}{2}\frac{f_1^4}{M_P^2}, \quad \mu = \frac{f_1}{6} \quad \text{and} \quad \alpha = \arg(\kappa_6)$$

$$\longrightarrow \ m_{\not{\rm PQ}} \simeq 0.5\times 10^{-3}\ \text{eV}\sqrt{|\kappa_6|}\left(\frac{f_1}{10^3\ \text{GeV}}\right)^2$$

$$\bar\theta \simeq 1.7\times 10^{-10}\frac{m^2_{\not{\rm PQ}}\cos\alpha}{m^2_{\rm QCD} + m^2_{\not{\rm PQ}}\cos\alpha}\left(\frac{\tan\alpha}{0.1}\right)\left(\frac{F_a/f_1}{10^8}\right)^{-1}$$

Experimental bound can be satisfied if alignment mechanism enhances effective decay constant $\sim 10^8$

Topological defects in aligned axion models

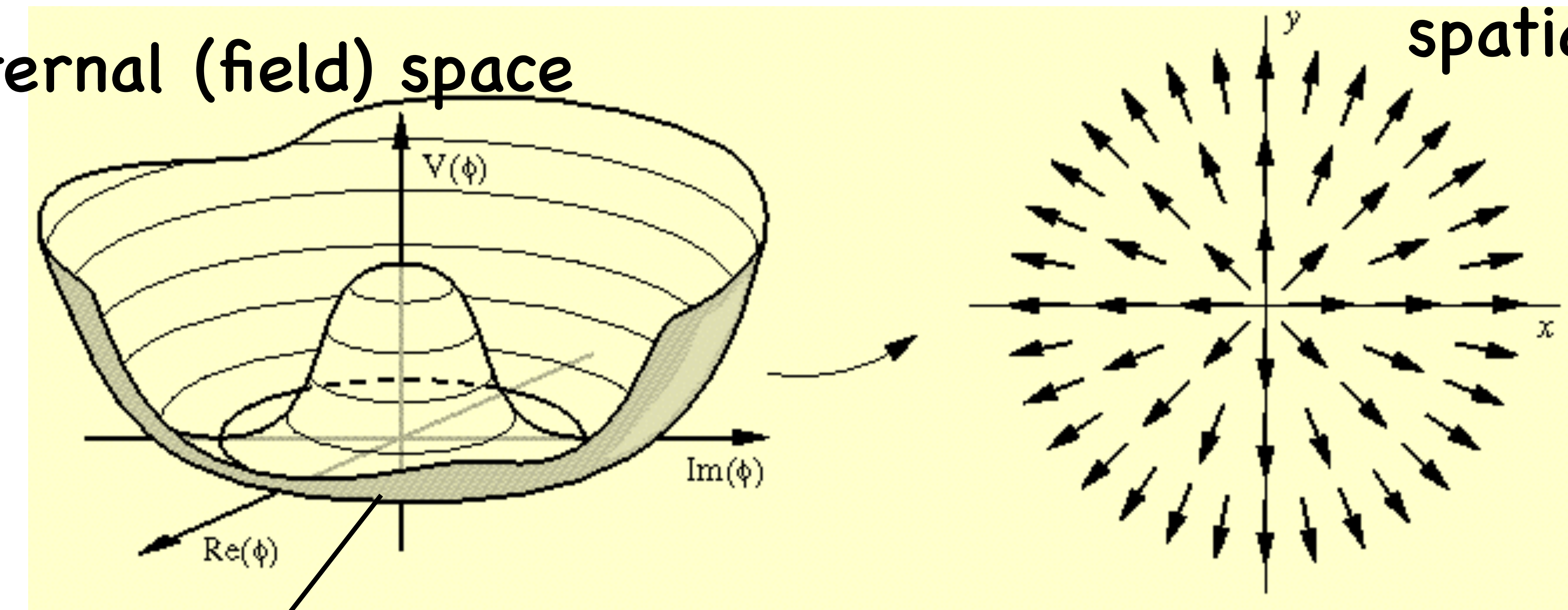
T. Higaki, K.S. Jeong, NK, T. Sekiguchi F. Takahashi, 1606.05552

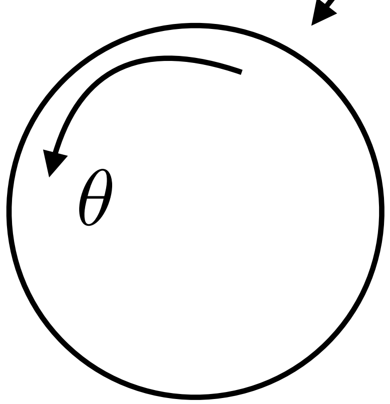
Topological defect 1 : Cosmic string

spontaneous breaking of U(1) symmetry —> cosmic string

internal (field) space

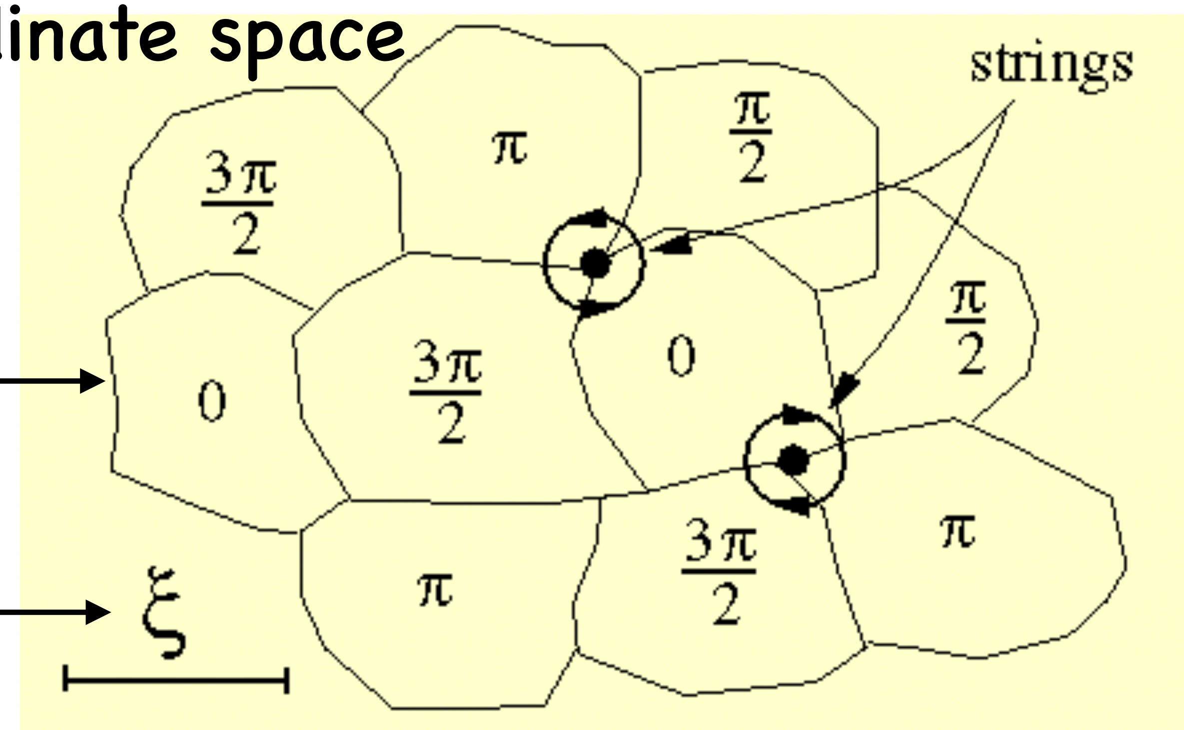
spatial coordinate





"vacuum circle"

coordinate space

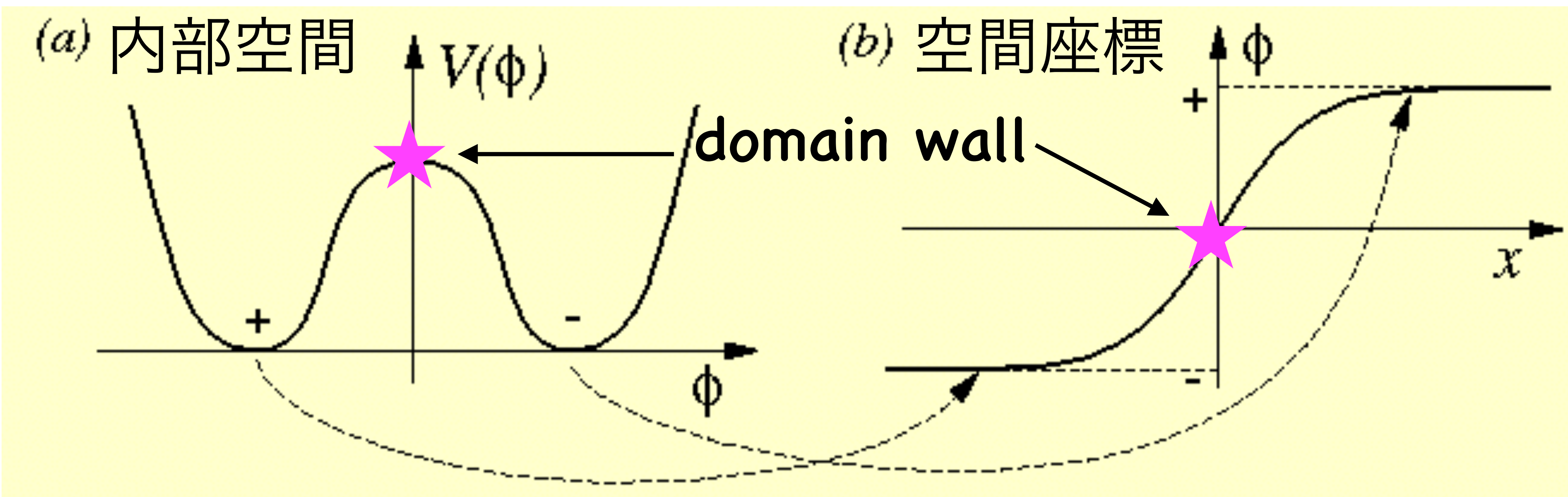


domain wall

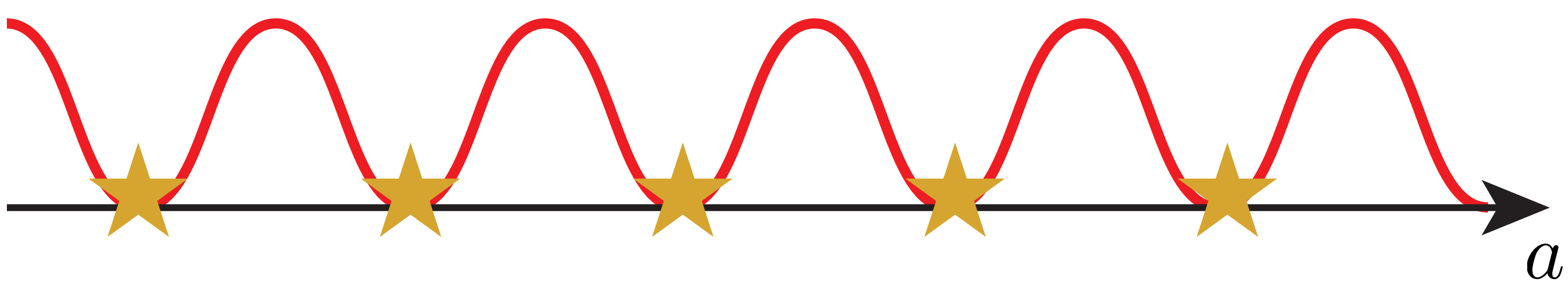
horizon scale

Topological defect 2 : Domain wall

discrete minima (vacuum) —> domain wall formation



Axion potential



Topological defects in conventional axion scenario

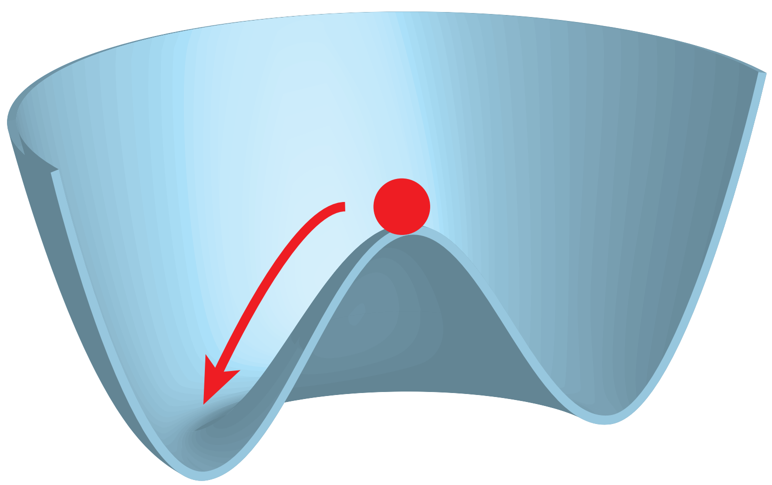
PQ symmetry breaking after inflation

↓

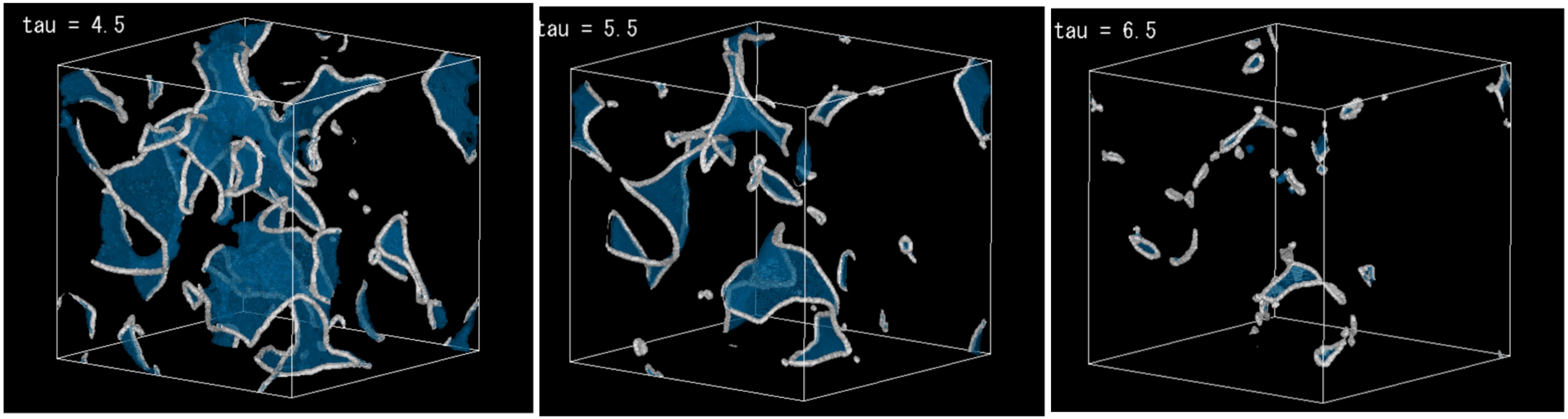
Cosmic string

↓

Domain walls with cosmic strings



$N_{DW}=1$ ⟶ string-wall network decays into axions



Hiramatsu, Kawasaki, Saikawa, Sekiguchi 1202.5851

Axion abundance (conventional scenario)

coherent oscillation : $\Omega_{a,\mathrm{osc}}h^2 = 0.18\,\theta_i^2\left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}$

with $\langle\theta_i^2\rangle = \frac{c_{\mathrm{anh}}\pi^2}{3}$

cosmic string : $\Omega_{a,\mathrm{str}}h^2 = 2.0\xi\left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}\left(\frac{\Lambda}{400\ \mathrm{MeV}}\right)$

domain wall : $\Omega_{a,\mathrm{dw}}h^2 = (5.8\pm 2.8)\left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}\left(\frac{\Lambda}{400\ \mathrm{MeV}}\right)$

total : $\Omega_{a,\mathrm{tot}}h^2 = (8.4\pm 3.0)\left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}\left(\frac{\Lambda}{400\ \mathrm{MeV}}\right)$

Defect formation in aligned axion model

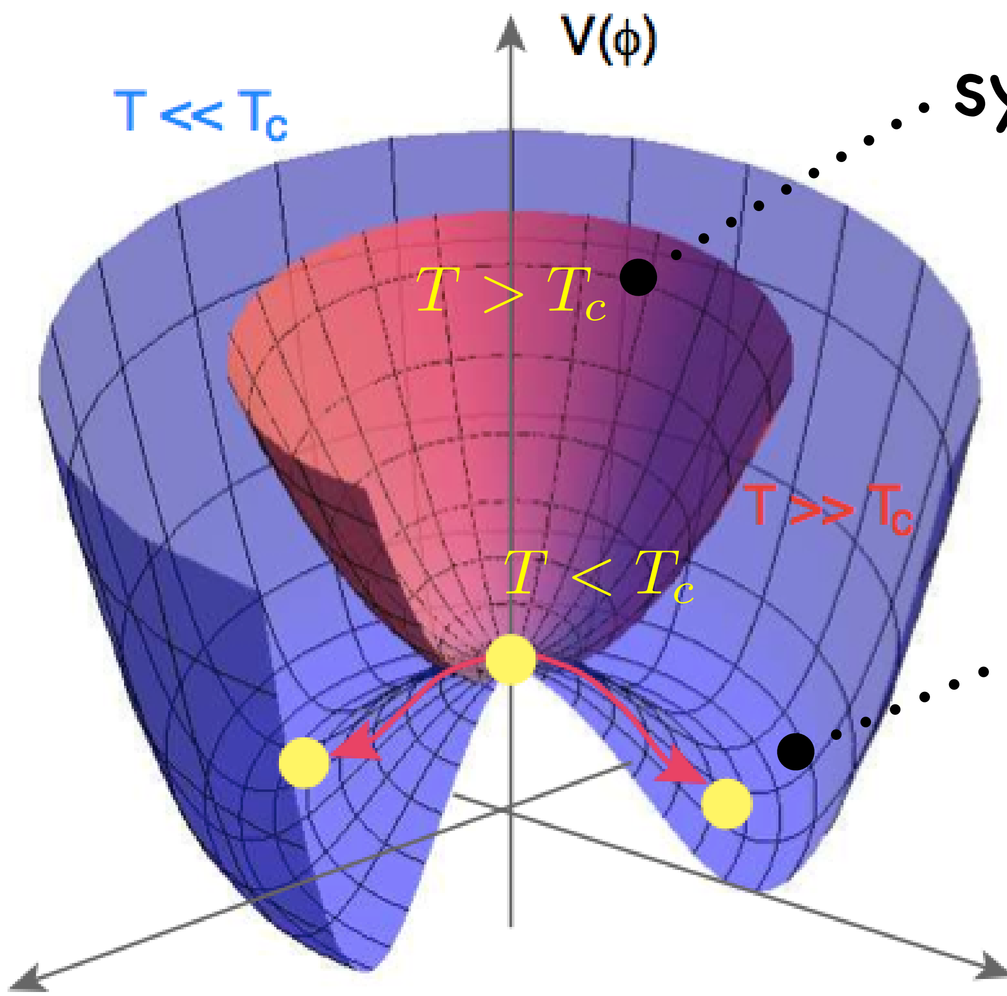


Fig. in Kawasaki, Nakayama 1301.1123

$T_c \sim f \sim$ weak scale for n-axions

⇩

PQ symmetries $U(1)^N$ can easily be restored in a hot universe

(no isocurvature perturbations)

Defect formation in aligned axion model

Re-breaking of $U(1)^N$

⇩

N cosmic strings are formed
each string has a tension f^2

⇩ ~~shift symmetry~~

N-1 domain walls are formed
(bounded by cosmic strings)

"string-wall network"

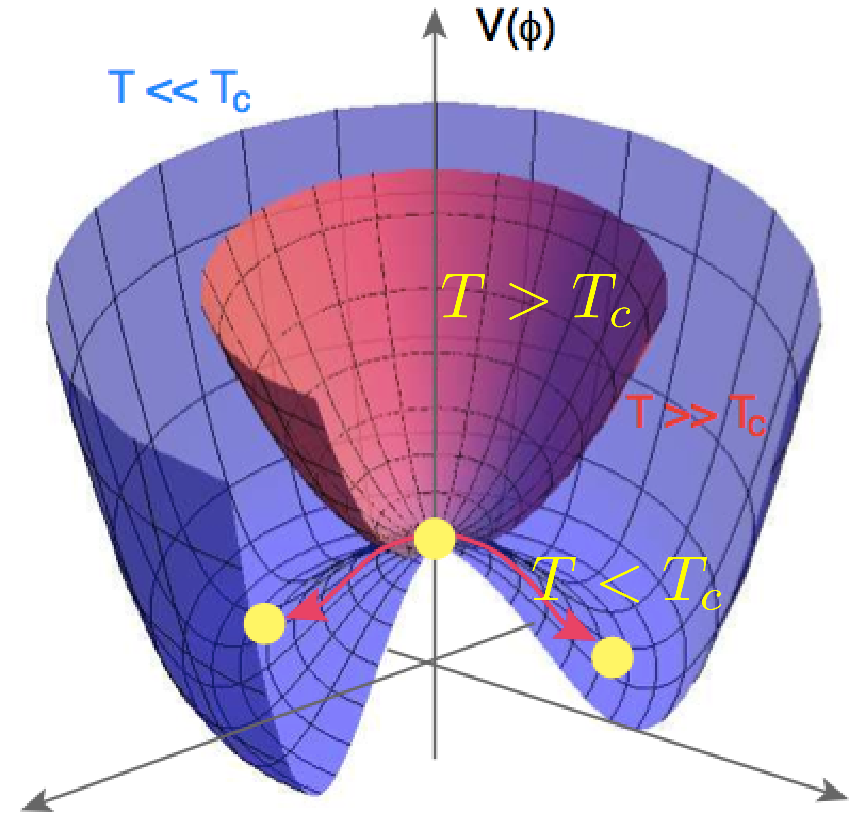


Fig. in Kawasaki, Nakayama 1301.1123

$$V = \sum_{i=1}^{N} \left(-m_i^2 |\Phi_i|^2 + \lambda_i |\Phi_i|^4 \right)$$

$$\Delta V = \sum_{i=1}^{N-1} \epsilon_i \Phi_i \Phi_{i+1}^3 + \text{h.c.}$$

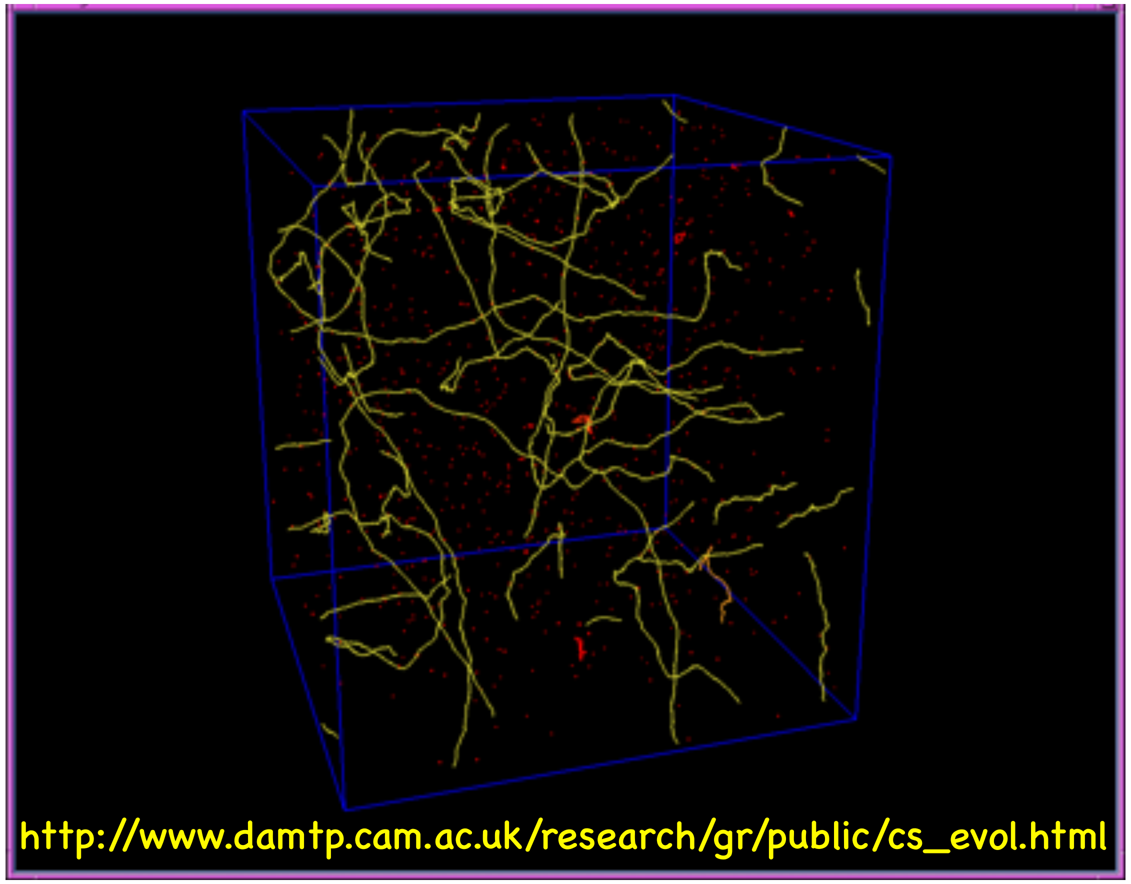
Cosmic strings of N-axions

Cosmic string solution : $\Phi_i = \frac{f_i}{\sqrt{2}} e^{i\phi_i/f_i} = \frac{f_i}{\sqrt{2}} e^{iw_i\theta}$

w_i : winding number for each axion string

θ : angular coordinate in real space

tension : $\mu_i \sim \mu_{\rm core} + \int_\delta^R \left| \frac{1}{r}\frac{\partial \Phi_i}{\partial \theta_i} \right|^2 2\pi r dr \approx \pi w_i^2 f_i^2 \ln\left(\frac{R}{\delta}\right)$

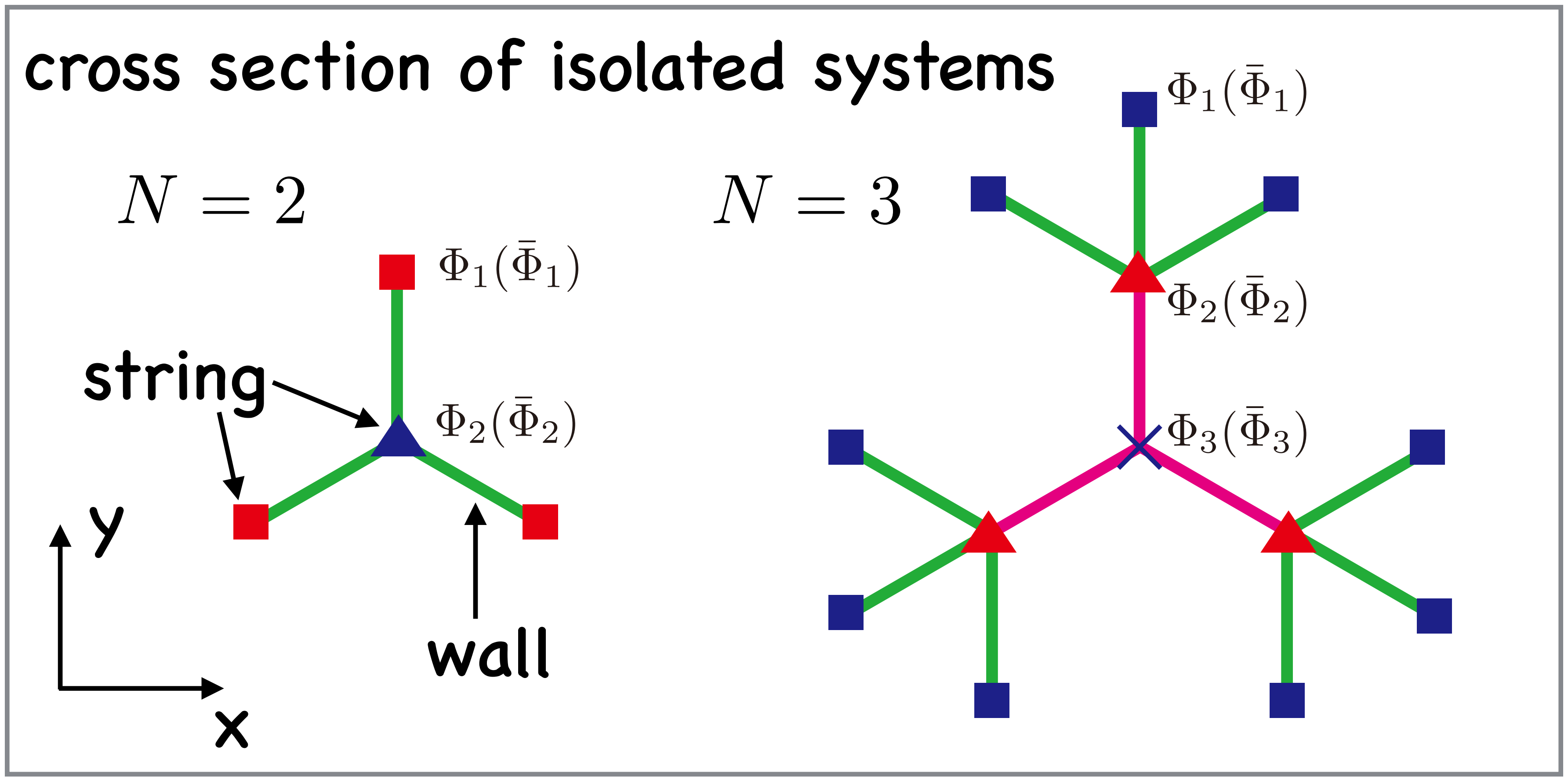


n.b. $f_i \ll F_a$

Each string tension is
much smaller than
that of the QCD axion string

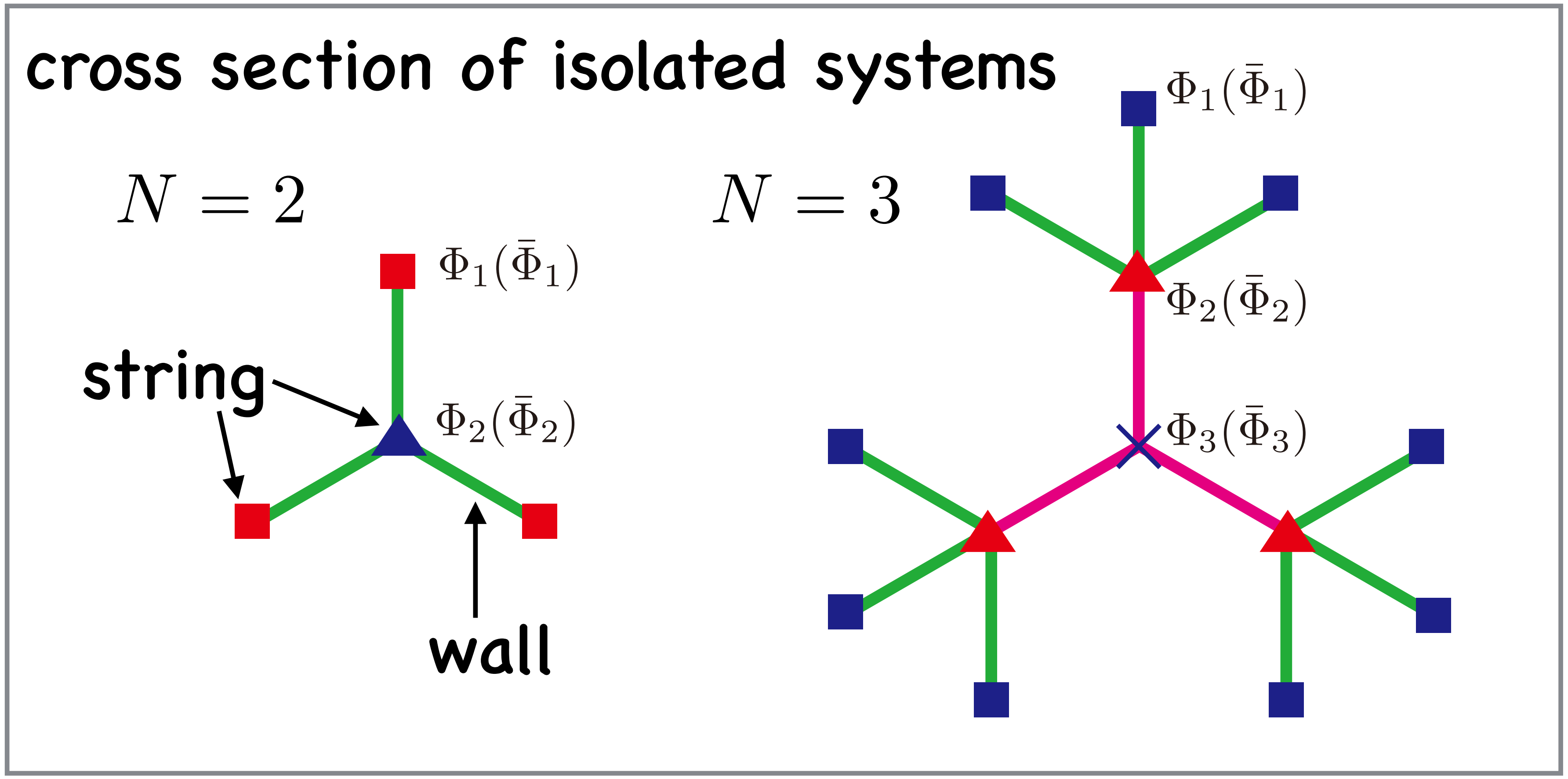
Cosmic string "Bundle"

$$\Delta V = \sum_{i=1}^{N-1} \epsilon_i \Phi_i \Phi_{i+1}^3 + \text{h.c.}$$



Aligned structure in the field (internal) space appears in the real space!

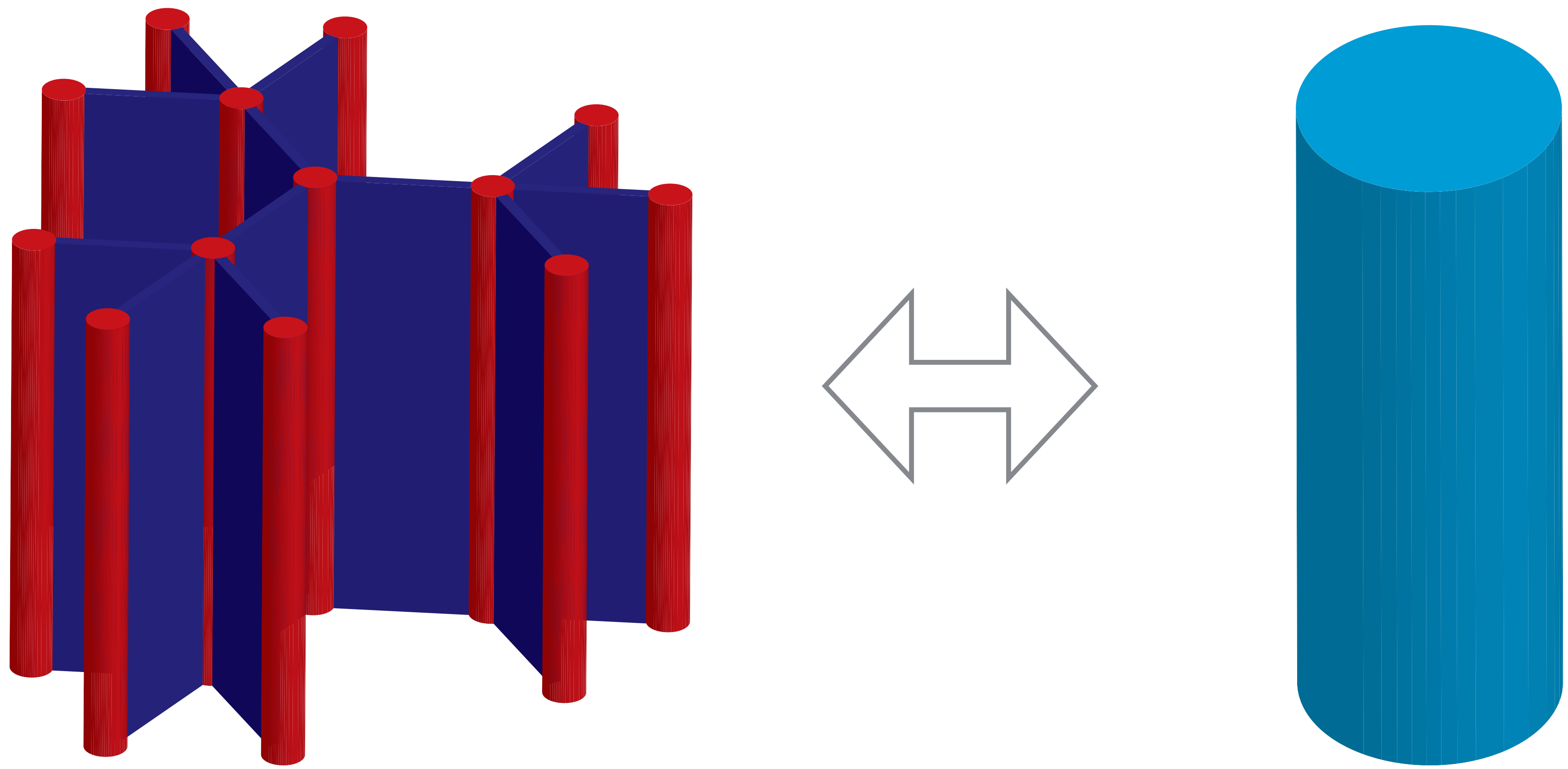
Cosmic string "Bundle"



$$F_a = \sqrt{\sum_{i=1}^{N} f_i^2 \left(\prod_{j=i}^{N} n_j^2 \right)}$$

"effective" tension : $\mu_{\text{eff}} \simeq \pi(3^2 f_1^2 + f_2^2) \ln\left(\frac{R}{\delta}\right) = \pi F_a^2 \ln\left(\frac{R}{\delta}\right)$ **(N=2)**

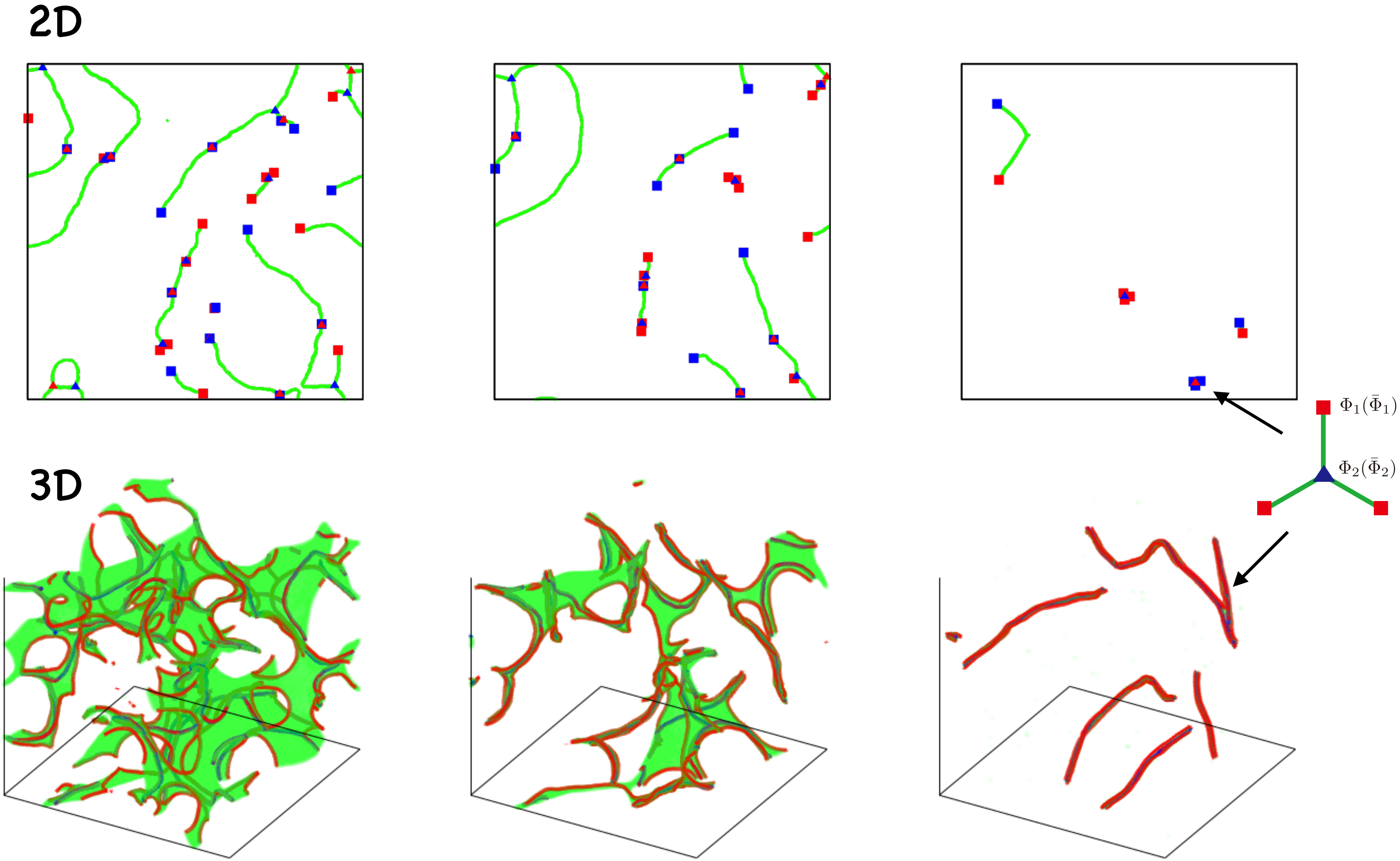
$$\mu_{\text{eff}} \simeq \pi(3^{2(N-1)} f_1^2 + \cdots + 3^2 f_{N-1}^2 + f_N^2) \ln\left(\frac{R}{\delta}\right) = \pi F_a^2 \ln\left(\frac{R}{\delta}\right)$$



string bundle QCD axion string

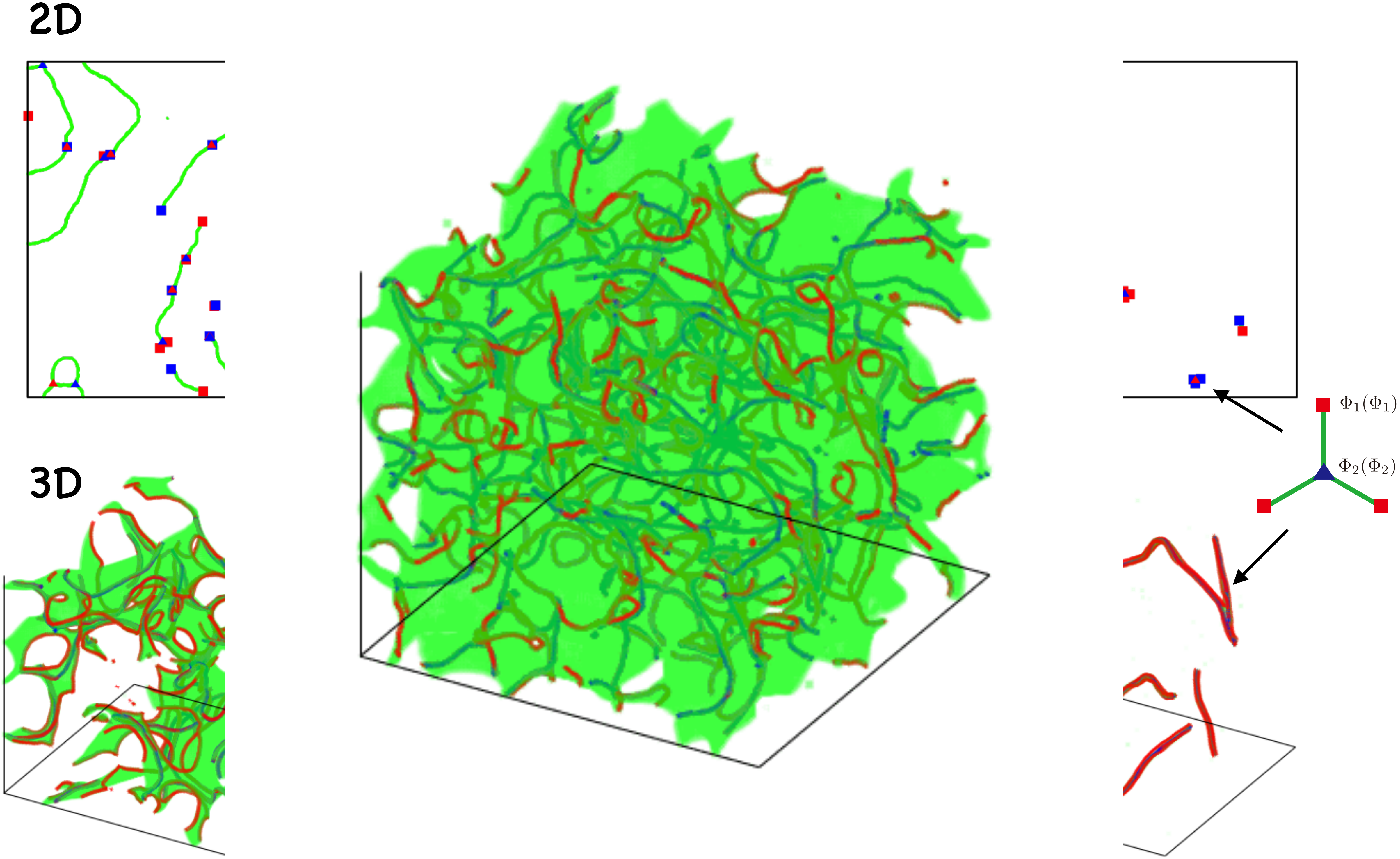
They are equivalent to the QCD axion string!!

Lattice simulation for N=2

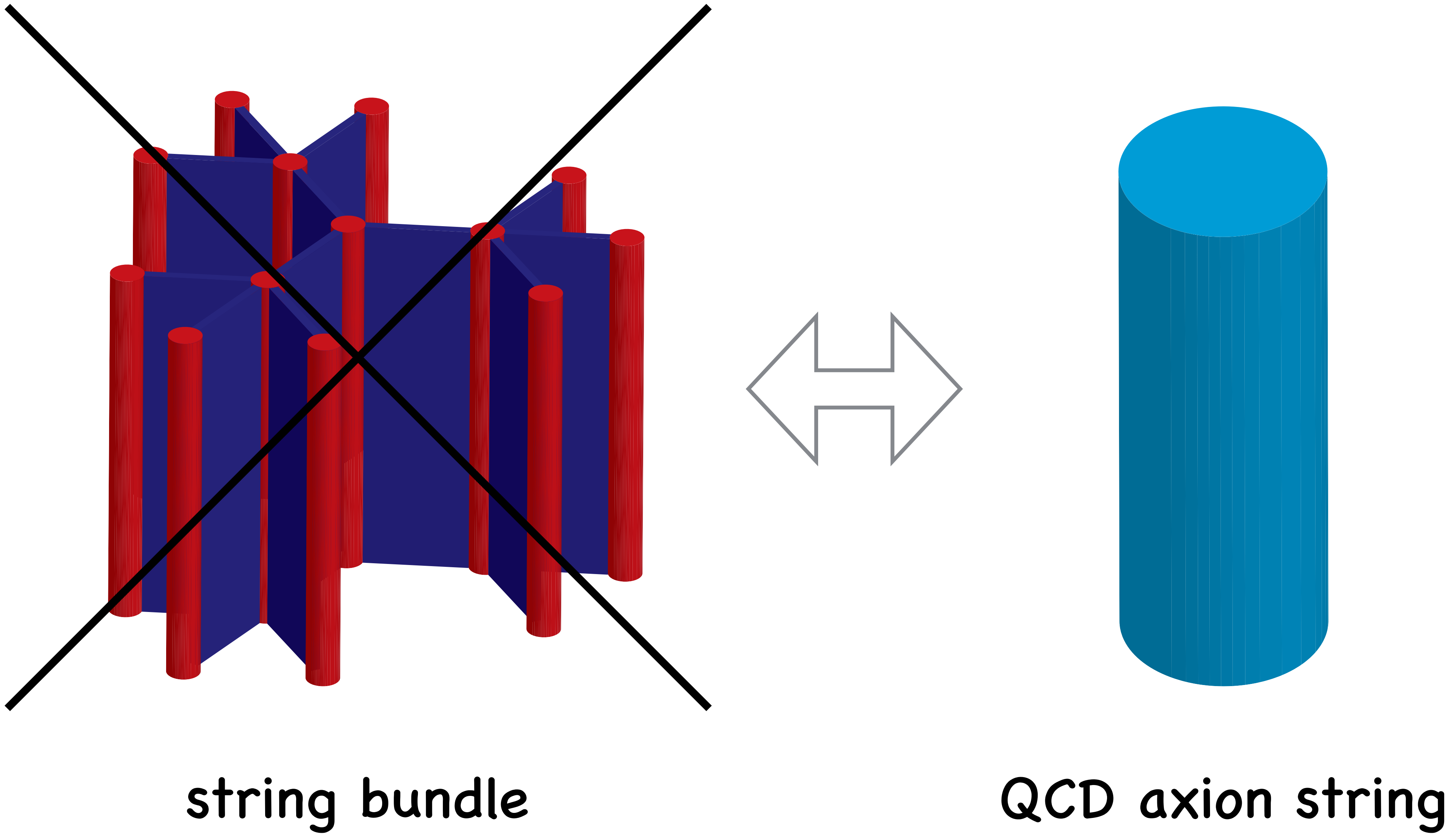


Domain walls disappear and string bundles are formed!!

Lattice simulation for N=2



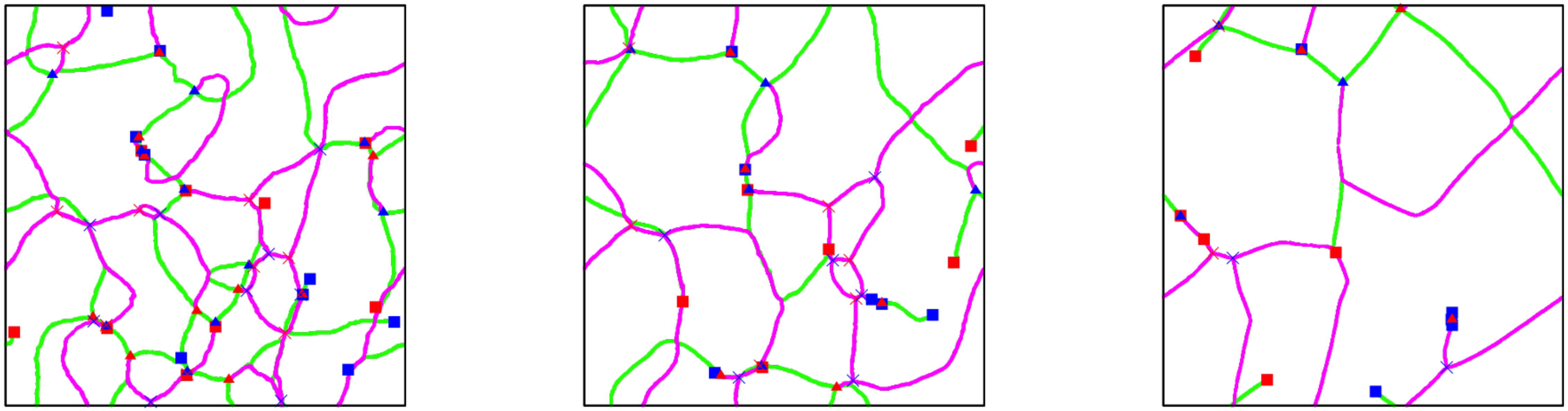
Domain walls disappear and string bundles are formed!!



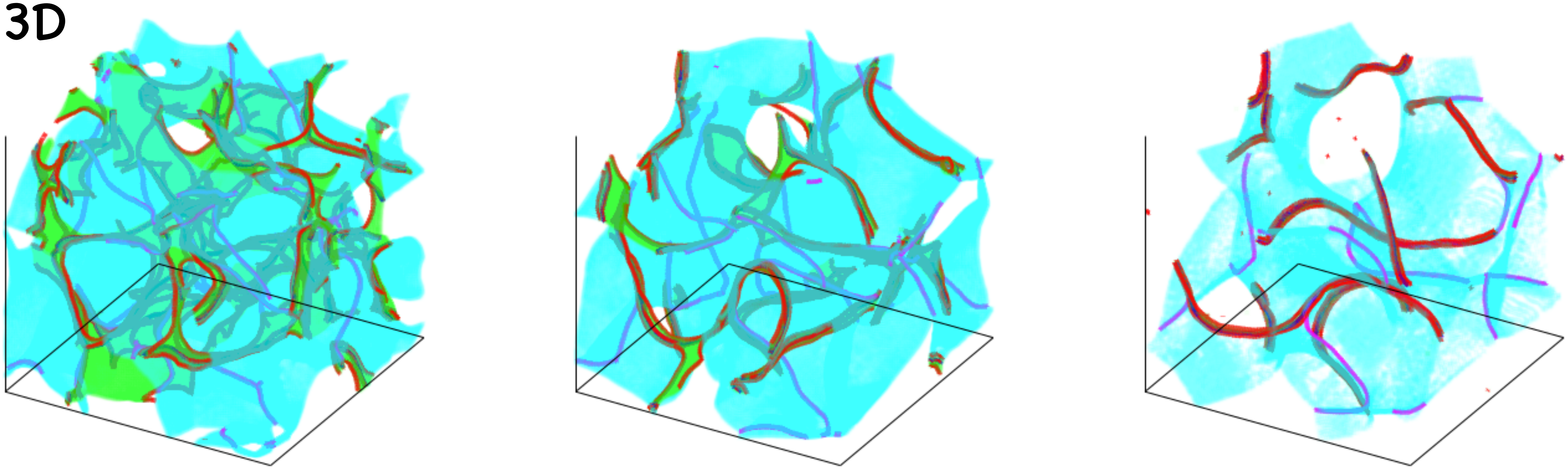
However, formation probability for such structure
is exponentially suppressed
(Φ_N string requires 3^N Φ_1 strings
but # of strings decreases by pair annihilation)

Lattice simulation for N=3

2D



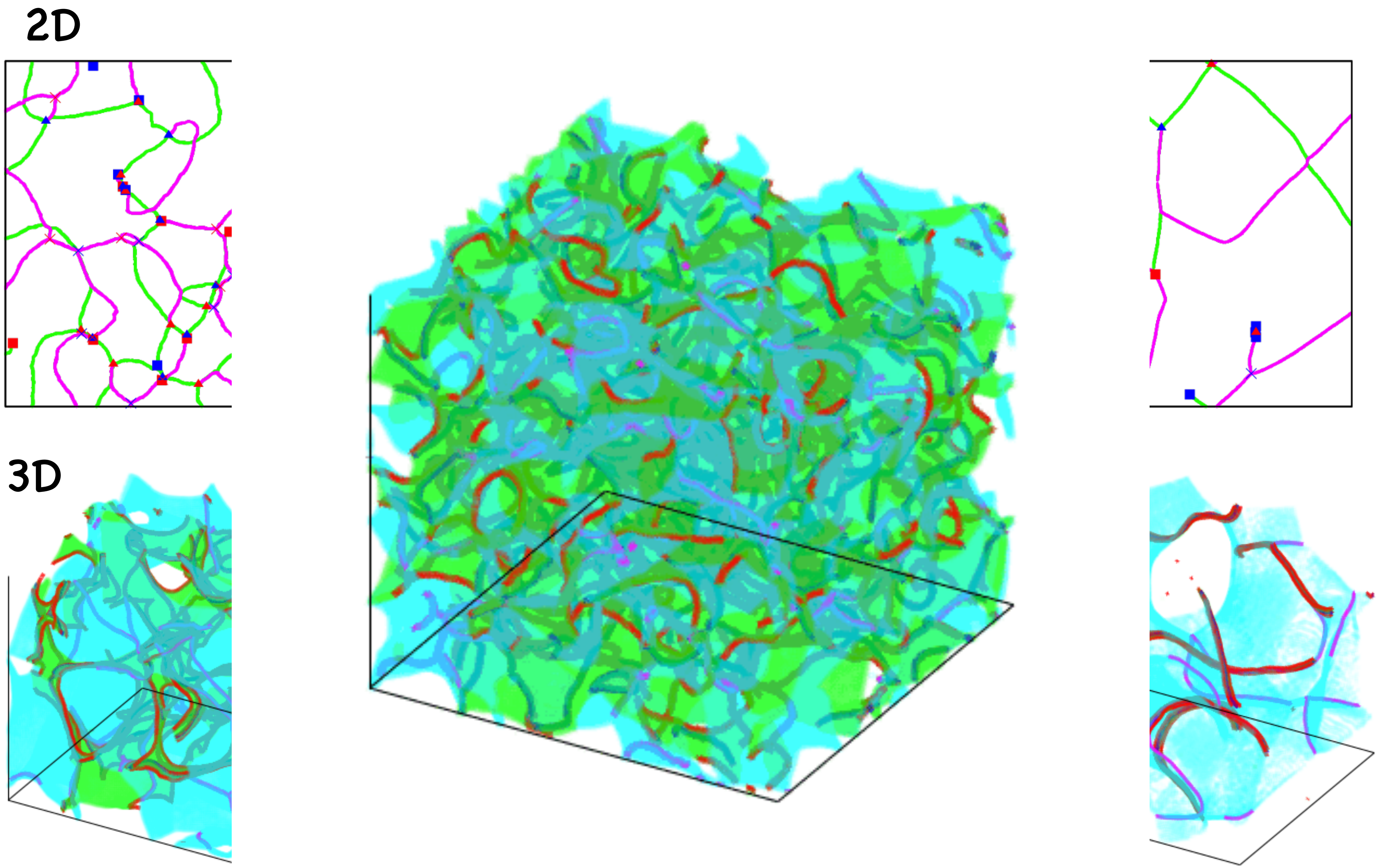
3D



String-wall network is long-lived

and they evolve under the scaling low

Lattice simulation for N=3

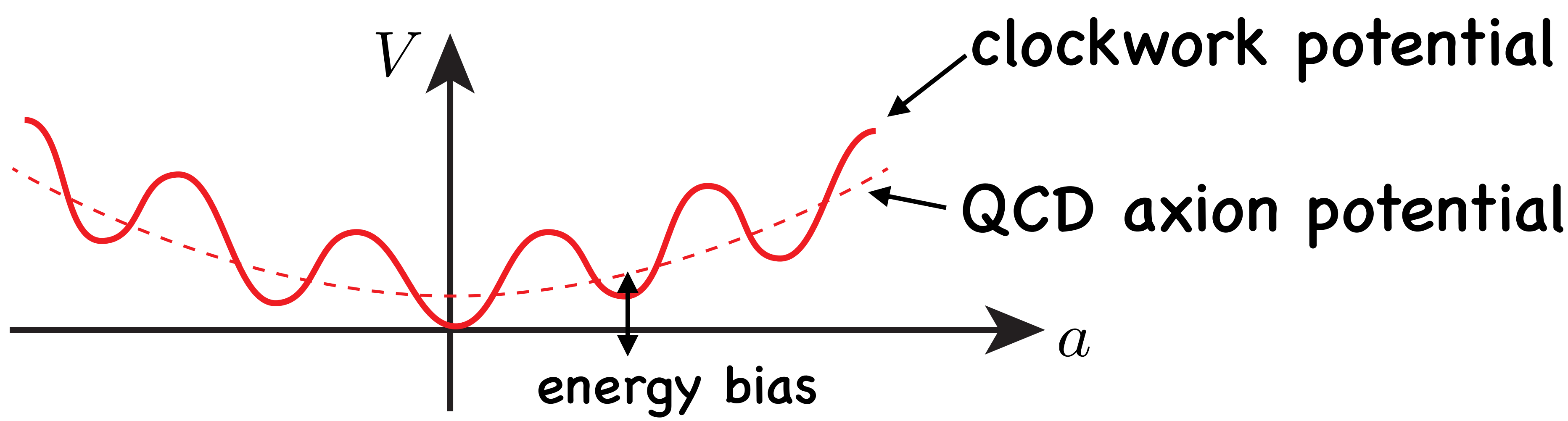


String-wall network is long-lived

and they evolve under the scaling low

Domain wall annihilation

$T \sim 1$ GeV → QCD axion potential arises & domain wall becomes unstable



Domain wall annihilates when $\rho_{\mathrm{DW}} \sim V_{\mathrm{bias}}$

To avoid domain wall domination before the annihilation :

$$f \lesssim 400 \text{ TeV } \epsilon^{-1/6} \left(\frac{\Lambda_{\mathrm{QCD}}}{400 \text{ MeV}} \right)^{4/3}$$

Domain wall collapse

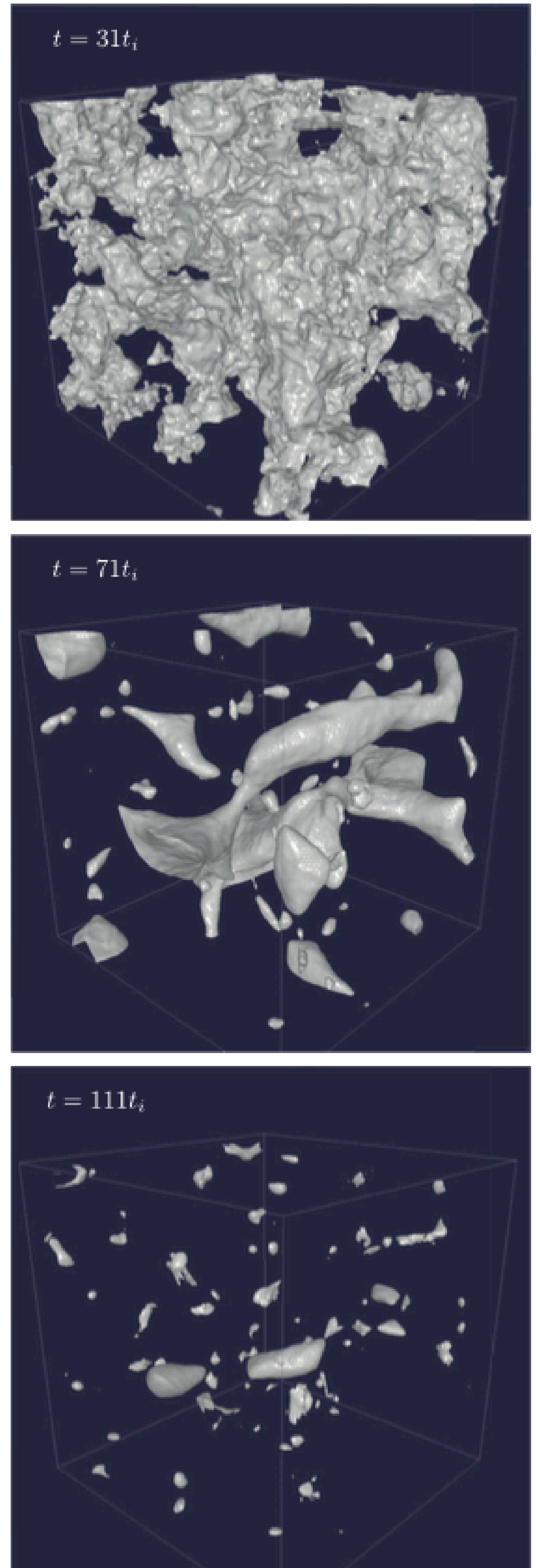
↓ ↓ ↓

Gravitational waves

Long-lived DW

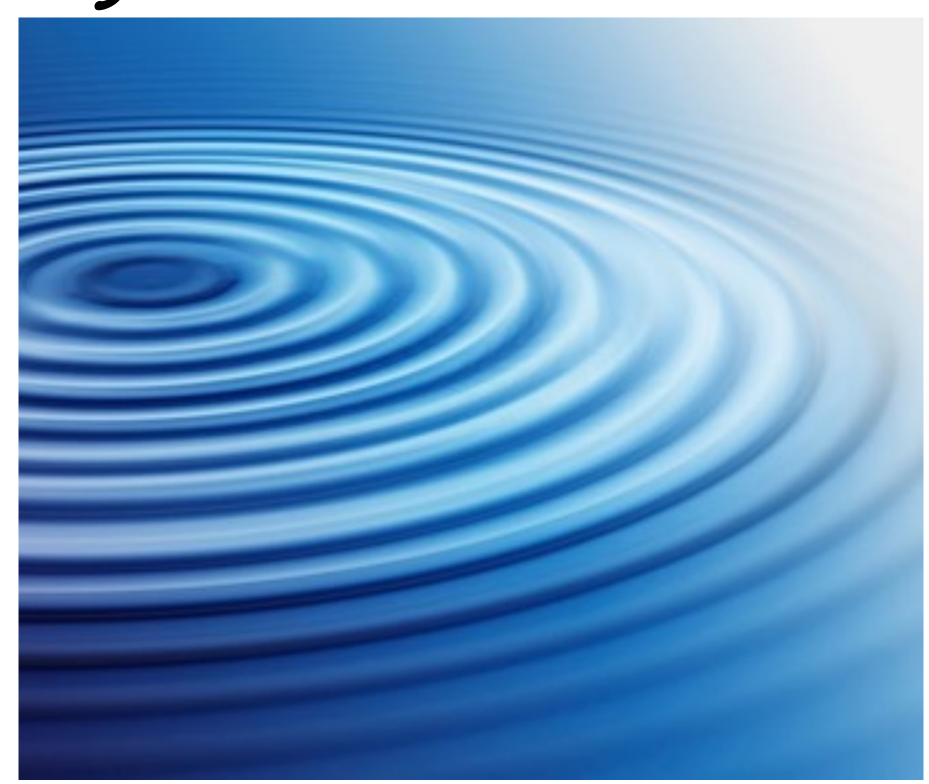
↓

A large amount of GW



Hiramatsu,Kawasaki,Saikawa (2010)

gravitational waves

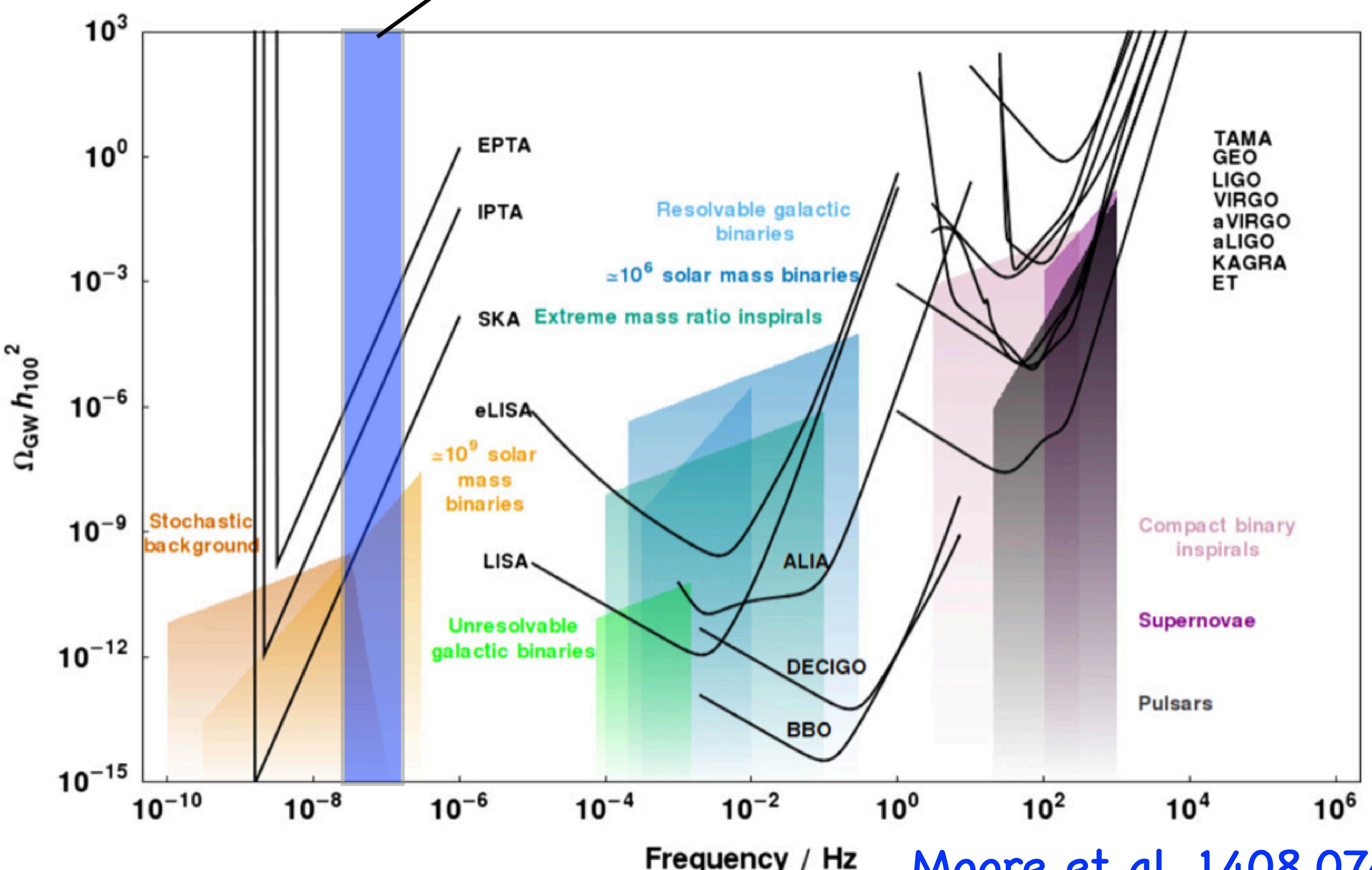


Gravitational waves from decaying domain walls

Peak frequency of GW – Hubble parameter at the annihilation

$$\nu_{\rm peak} \simeq 1.6 \times 10^{-7}\ {\rm Hz} \left(\frac{g_{*{\rm ann}}}{80}\right)^{1/6} \left(\frac{T_{\rm ann}}{1\ {\rm GeV}}\right)$$

pulsar timing obs.



Moore et al. 1408.0740

Constraints from pulsar timing observations

Intensity of GW by DW decay

$$\Omega_{\rm gw}(\nu_{\rm peak})h^2 \simeq 2\times 10^{-11}\epsilon\left(\frac{g_{*\rm ann}}{80}\right)^{-4/3}\left(\frac{T_{\rm ann}}{1\ \rm GeV}\right)^{-4}\left(\frac{f}{100\ \rm TeV}\right)^{6}$$

frequency dependence : $\Omega_{\rm gw}(\nu) \propto \nu^3 \quad \text{for} \quad \nu < \nu_{\rm peak}$

Hiramatsu, Kawasaki, Saikawa, 1309.5001

current constraint : $\Omega_{\rm gw}h^2 < 2.3\times 10^{-10}$ **at** $\nu_{\rm 1yr} \simeq 3\times 10^{-8}\ \rm Hz$

P. D. Lasky et al. 1511.05994

$$f \lesssim 200\ {\rm TeV} \times \epsilon^{-1/6}\left(\frac{\Lambda_{\rm QCD}}{400\ \rm MeV}\right)^{28/33}$$

$200\ \rm TeV \rightarrow 100\ \rm TeV$ **(future observation by SKA)**

Summary

- Intermediate scale for axion decay constant can be realized by alignment mechanism — aligned QCD axion model

N-axions w/ weak scale decay constant —> QCD axion

- High quality of PQ scale can be naturally realized
PQ mechanism works well w/o fine tuning / introducing extra Z_N

- Topological defects can easily formed in aligned axion model and it puts upper bound on the decay constant

$$\longrightarrow \quad f \lesssim O(100)\ \mathrm{TeV}$$

Aligned axion

Kim, Niles, Peloso, hep-ph/0419138; K. Choi, H. Kim, S. Yun, 1404.6209, …

$$V(\phi_1, \phi_2) = \Lambda_1^4 \left[1 - \cos\left(\frac{n_1\phi_1}{f_1} + \frac{n_2\phi_2}{f_2}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(\frac{m_1\phi_1}{f_1} + \frac{m_2\phi_2}{f_2}\right)\right]$$

$$V_{\text{eff}}(\phi_{\text{flat}}) = \Lambda_2^4 \left[1 - \cos\left(\frac{\phi_{\text{flat}}}{f_{\text{eff}}}\right)\right]$$

with

$$\phi_{\text{flat}} \propto \frac{n_2\phi_1}{f_2} - \frac{n_1\phi_2}{f_1}, \quad f_{\text{eff}} = \frac{\sqrt{n_1^2 f_2^2 + n_2^2 f_1^2}}{|n_1 m_2 - n_2 m_1|}$$

$f_1,\ f_2 < M_P$ but $f_{\text{eff}} > M_P$

: requirement for inflaton/relaxion excursion