

宇宙の進化と素粒子模型

宇宙線研理論グループ

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神奈川大：粕谷

佐賀大：高橋

国内旅費：20万円

Axionic Strings and Domain Walls

東大宇宙線研：関口、川崎、齊川

東大ビッグバン：横山

東工大：山口

京大基研：平松

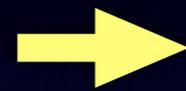
1.1 Axion

- QCD Strong CP Problem

QCD

$$\mathcal{L} = \mathcal{L}_{\theta=0} + \theta \frac{g^2}{32\pi^2} F^{a\mu\nu} \tilde{F}_{\mu\nu}^a$$

Experiment



$$\theta \lesssim 10^{-10}$$

~~CP~~

Why is θ so small?



strong CP problem

- Solution of Strong CP Problem

Peccei-Quinn Mechanism

Peccei, Quinn (1977)

$U(1)_{PQ}$



~~$U(1)_{PQ}$~~

at

F_a : PQ scale

Nambu-Goldstone boson



AXION

- Axion is a candidate for Dark Matter

2.2 Cosmological Evolution of Axion

- PQ scalar Φ_a

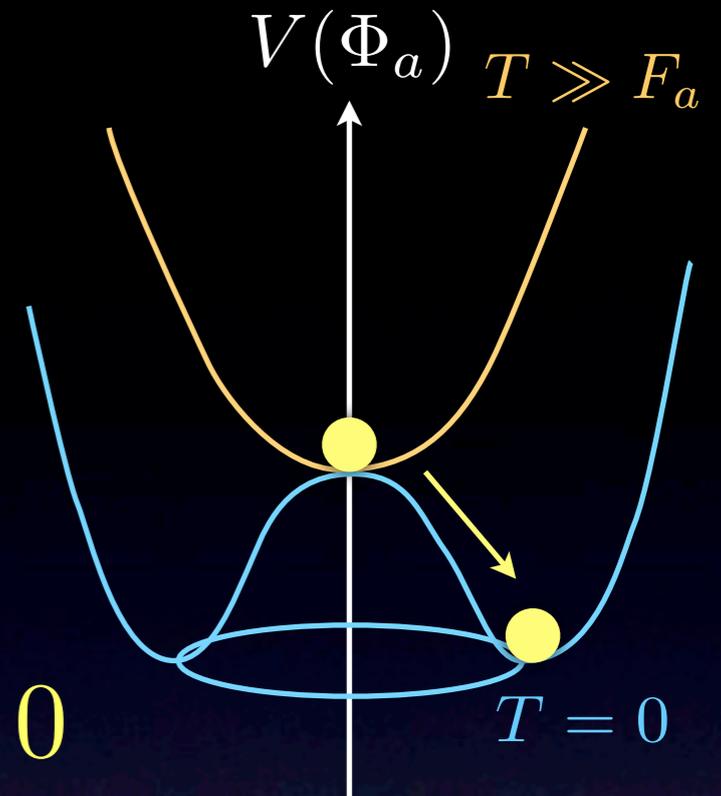
- $T \simeq F_a$ symmetry breaking of $U(1)_{\text{PQ}}$

$$\Phi_a = |\Phi_a| e^{i\theta_a} = |\Phi_a| e^{ia/F_a}$$

axion is a phase direction of PQ scalar

➔ Axionic String

$$m_a = 0$$



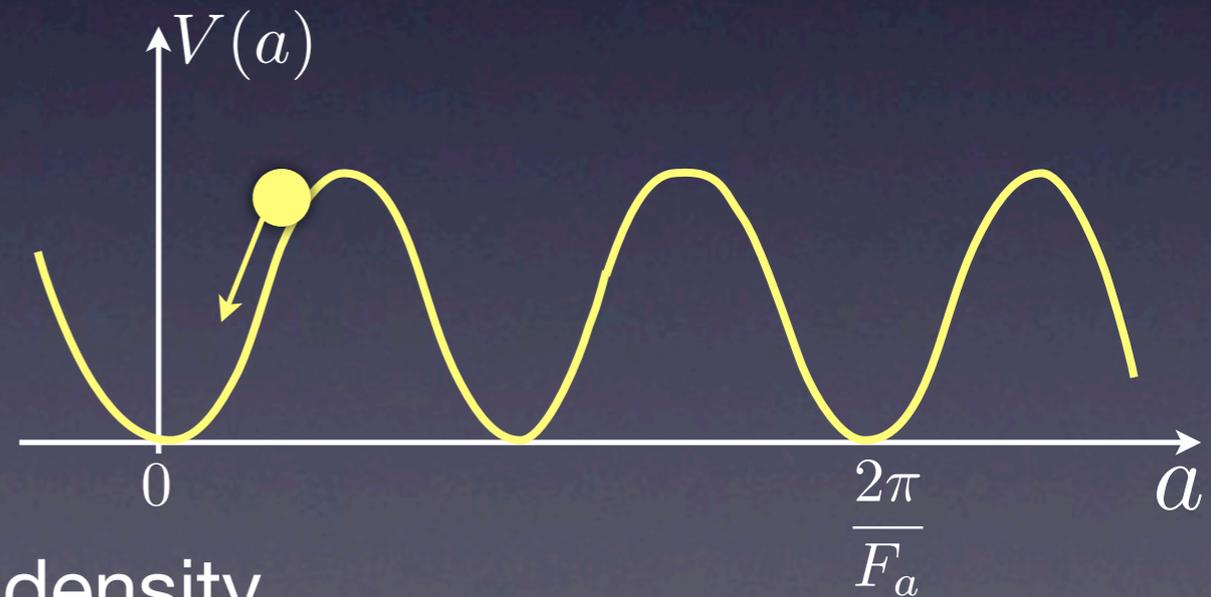
- $T \sim \Lambda_{\text{QCD}}$ axion acquires mass through QCD instanton effect

$$m_a \sim 10^{-5} \text{eV} \left(\frac{F_a}{10^{12} \text{GeV}} \right)^{-1}$$

➔ Domain Wall

- $H \lesssim m_a$ axion oscillation

significant contribution to cosmic density



3 Axionic String

- Global strings are produced when $U(1)_{PQ}$ symmetry is spontaneously broken
- After production string network obeys scaling solution
O(1) strings in a horizon volume

$$\rho_{\text{string}} = \xi \frac{\mu}{t^2} \quad (\mu : \text{string tension})$$

- Strings lose their energy by emitting axions

Energy spectrum of axions?

Controversy

$$P(k) \sim \begin{cases} k_{\text{horizon}} & (\text{Devis, Shellard}) \\ 1/k & (\text{Sikivie}) \end{cases}$$

- New Simulation (Hiramatsu et al 2010)

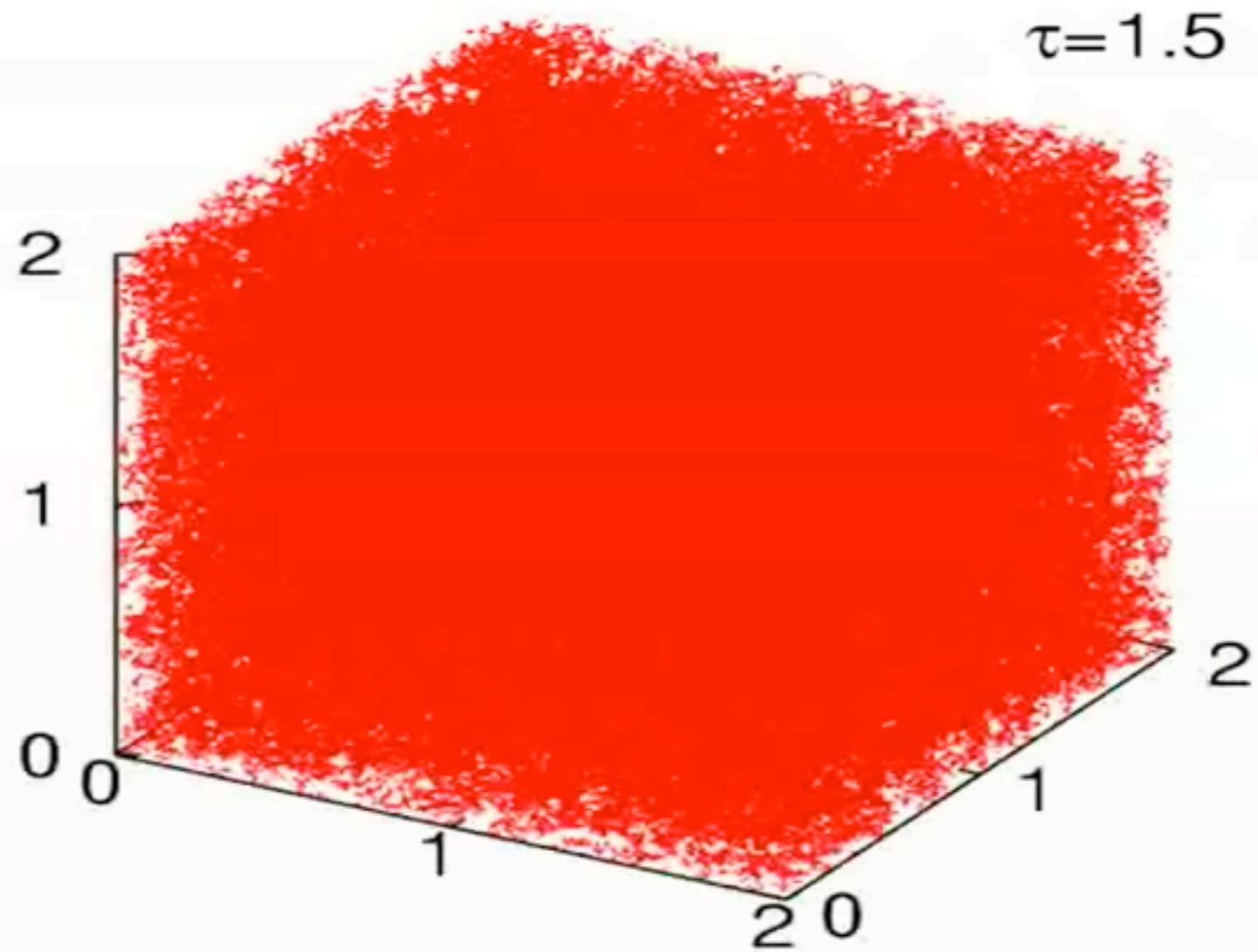
Simulation

Hiramatsu, MK, Sekiguchi, Yamaguchi, Yokoyama (2010)

- Field theoretical simulation
- Pseudo Power Spectrum Estimator (PPSE)
- New string identification scheme
- $N(\text{grid}) = (512)$
- At the end of simulation
 - (space resolution) = 1.4 (string width)
 - (simulation box) = 1.6 (horizon)

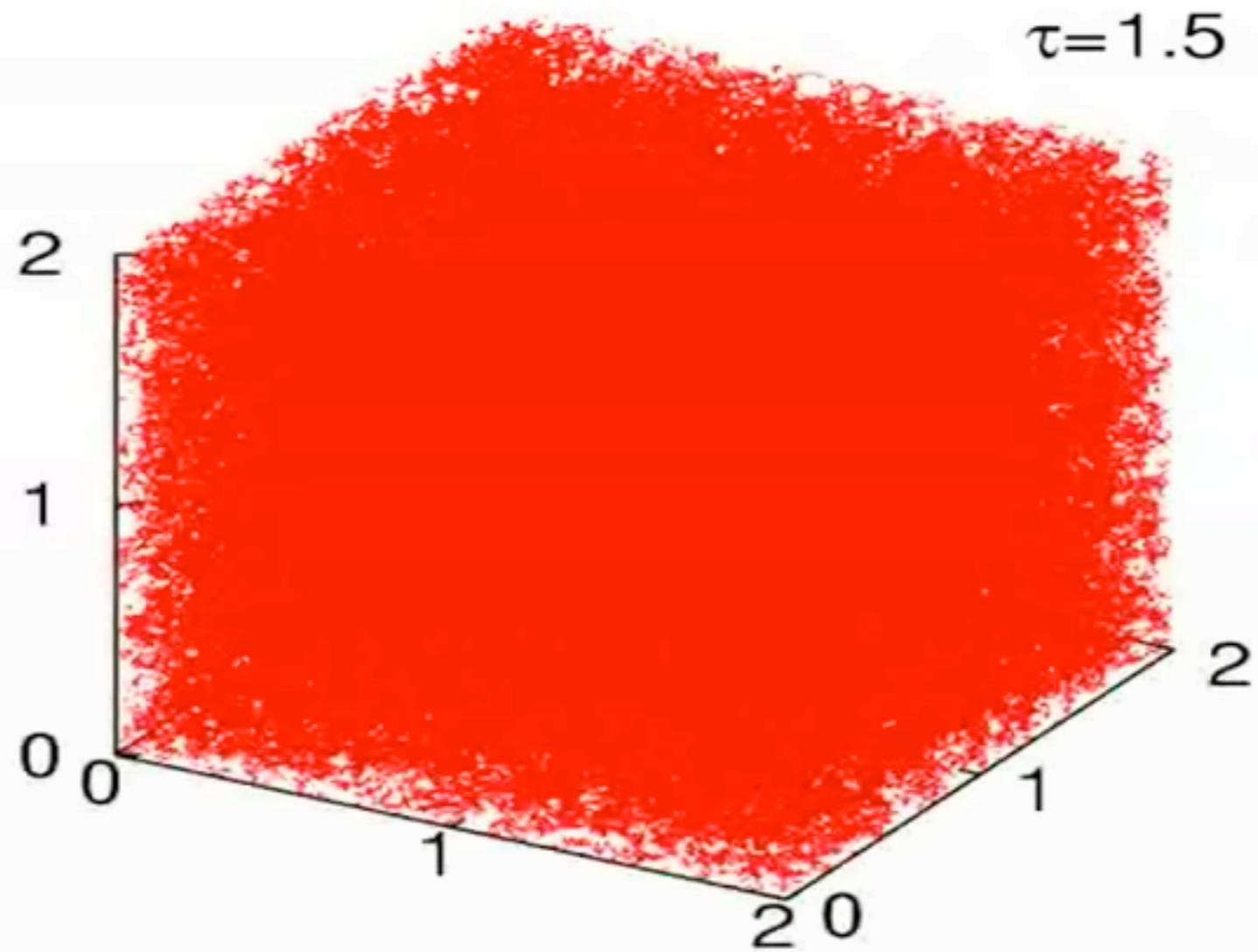
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● Scaling solution

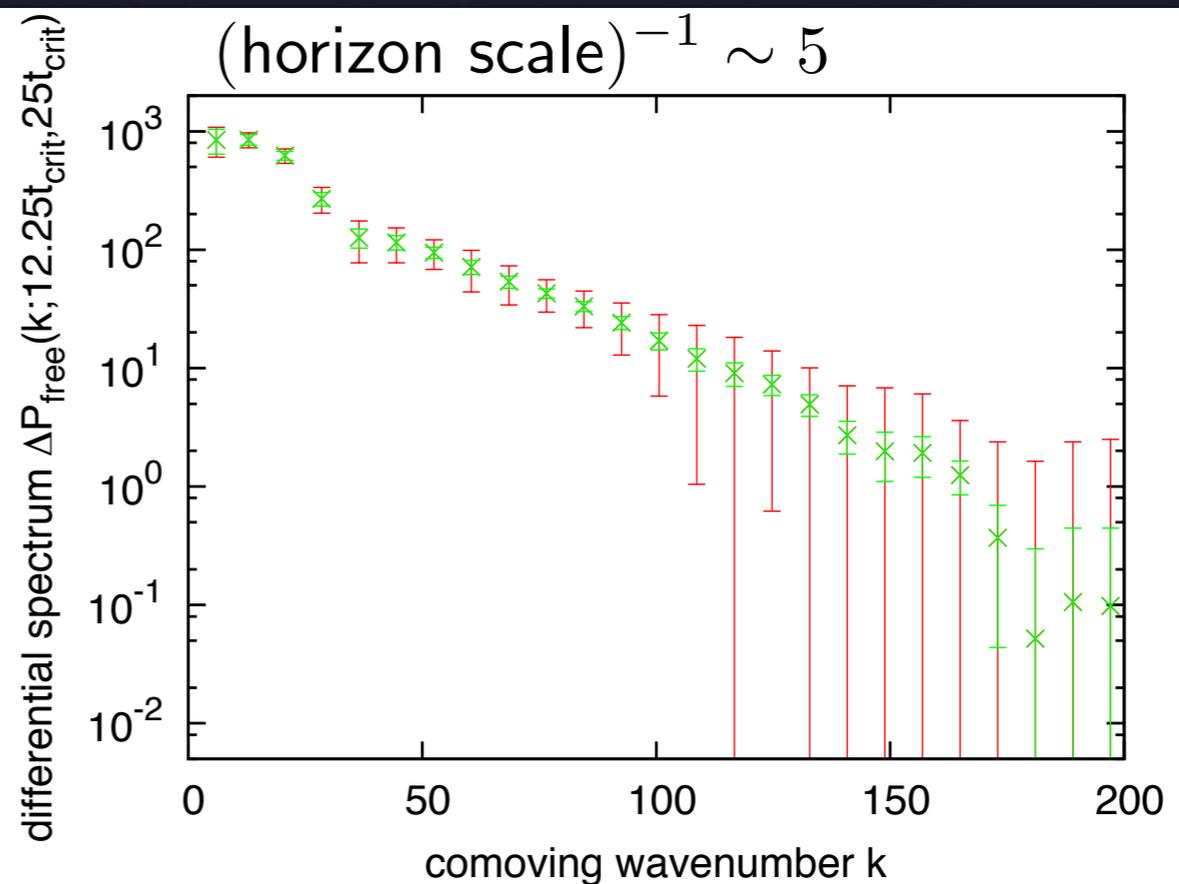
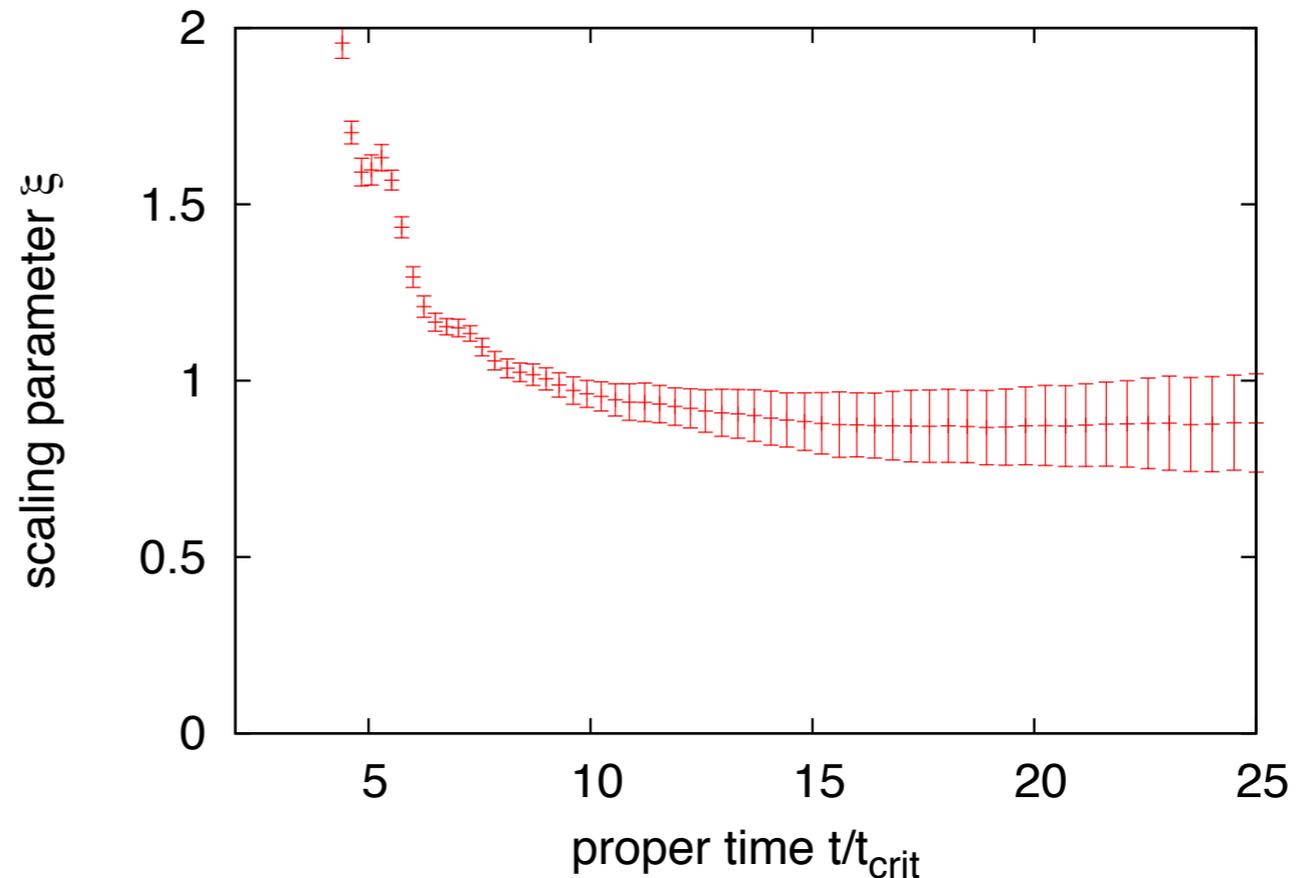
$$\xi = 0.87 \pm 0.14$$

$$\rho_{\text{string}} = \xi \frac{\mu}{t^2}$$

● Energy Spectrum

peaked at horizon scale

exponentially suppressed
at higher momentum



Constraint on PQ scale

- Cosmic density of produced axion

$$\Omega_{\text{axion}} h^2 = 1.66 \pm 0.25 \left(\frac{\Lambda_{\text{QCD}}}{400 \text{ MeV}} \right) \left(\frac{F_{\text{PQ}}}{10^{12} \text{ GeV}} \right)^{1.19}$$

- Constraint

$$F_{\text{PQ}} \leq 3 \times 10^{11} \text{ GeV}$$

4. Axion Domain Wall

- QCD scale

$U(1)_{PQ} \longrightarrow$ discrete Z_N

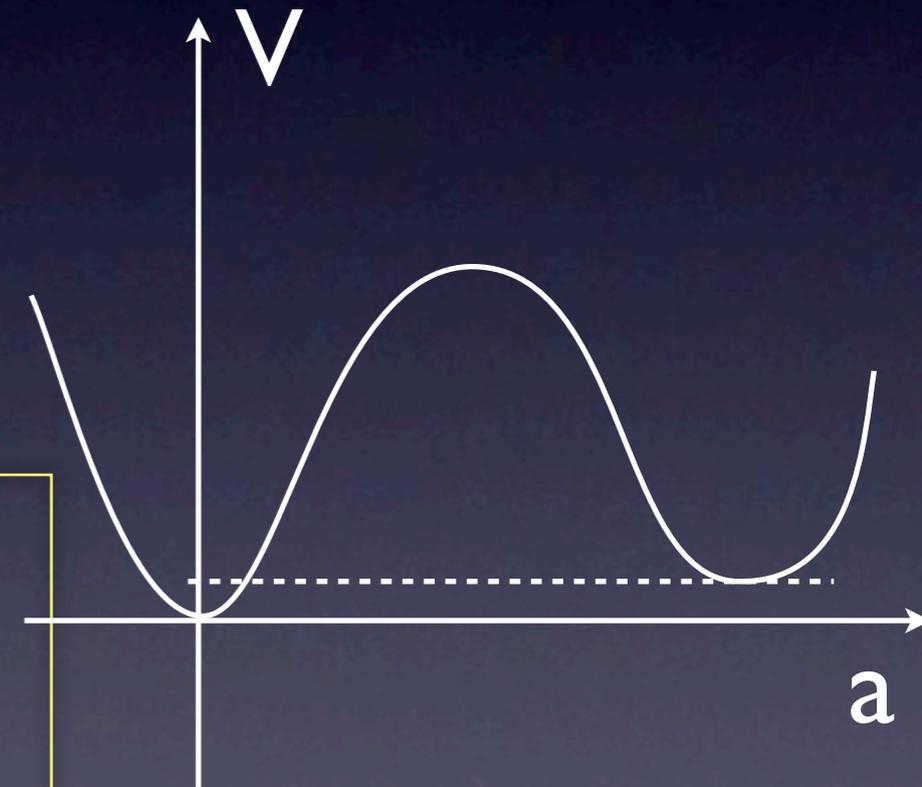
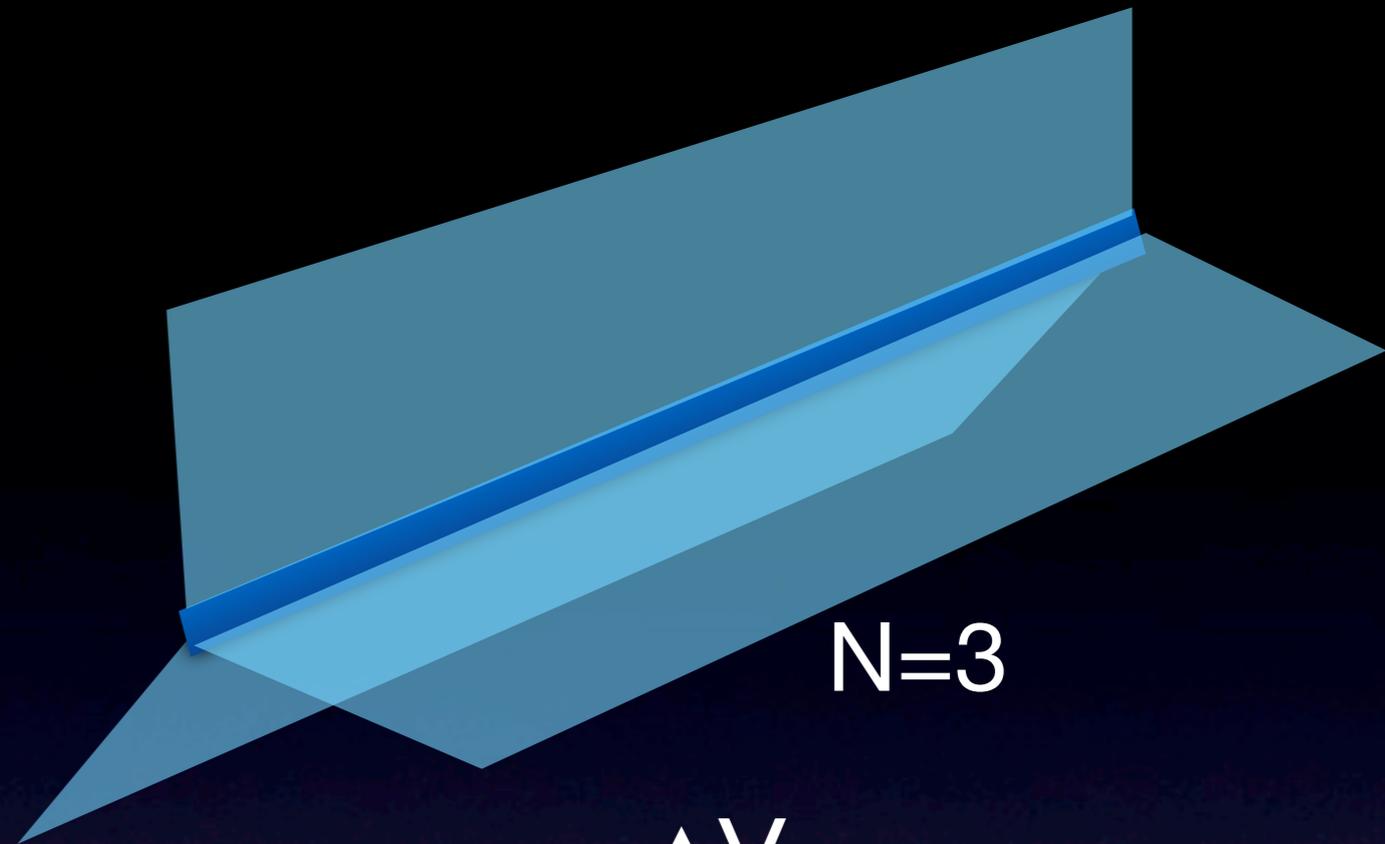
Domain Wall Formation

- $N > 1$

Domain Wall Problem

\longrightarrow Biased Potential

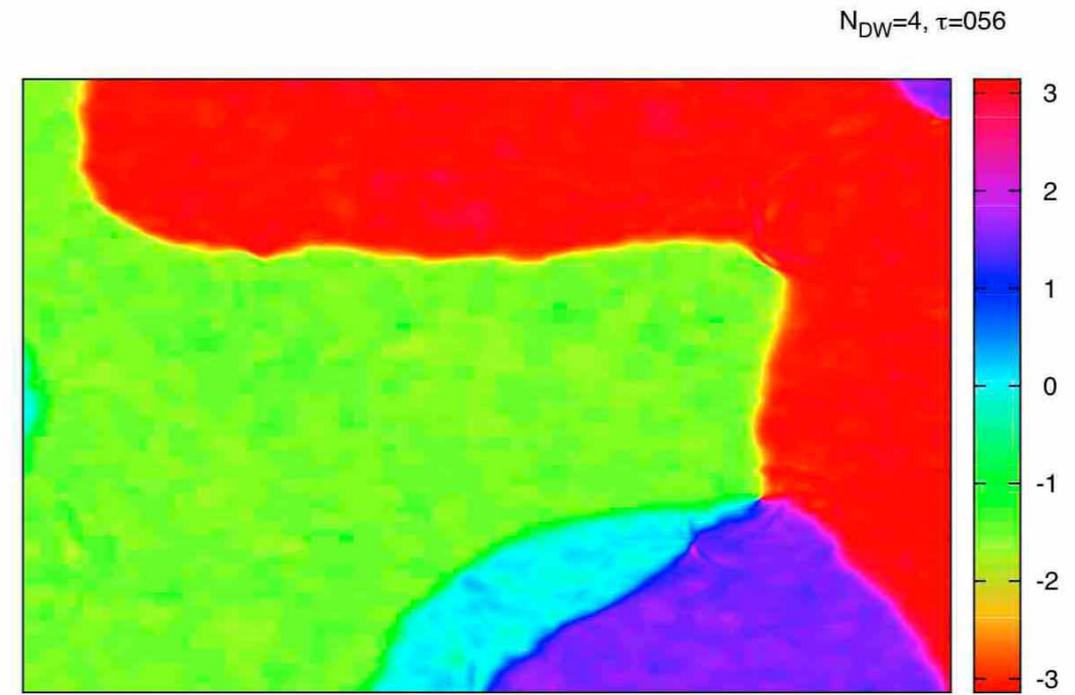
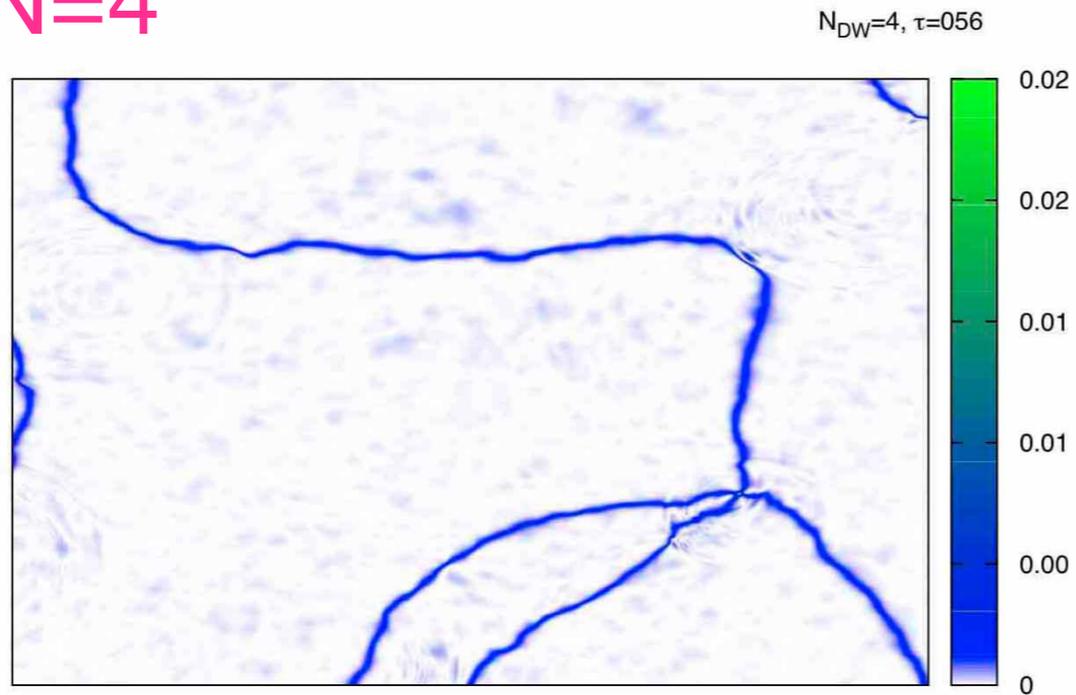
Domain wall decay



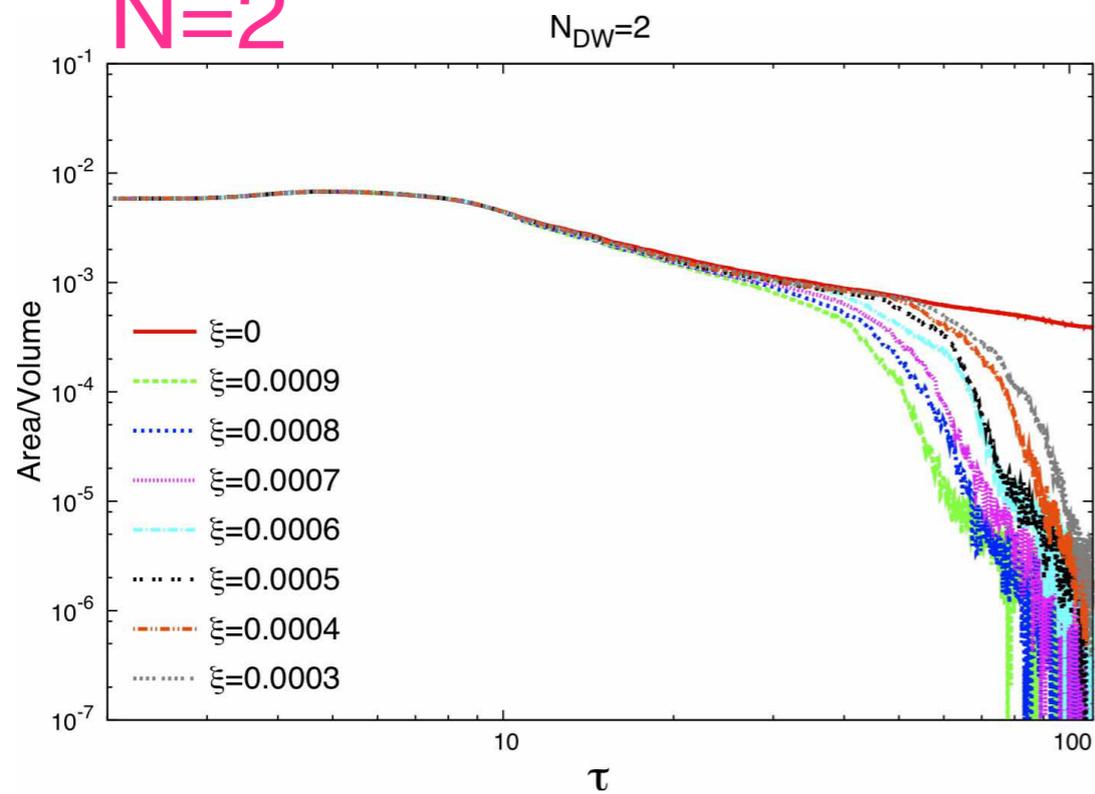
$$V(\phi) = \frac{\lambda}{4} (|\phi|^2 - \eta^2)^2 + \frac{m^2 \eta^2}{N^2} (1 - \cos N\theta) + \delta V$$
$$\delta V = -\xi \eta^3 (\phi e^{-i\delta} + \text{h.c.})$$

2D simulation

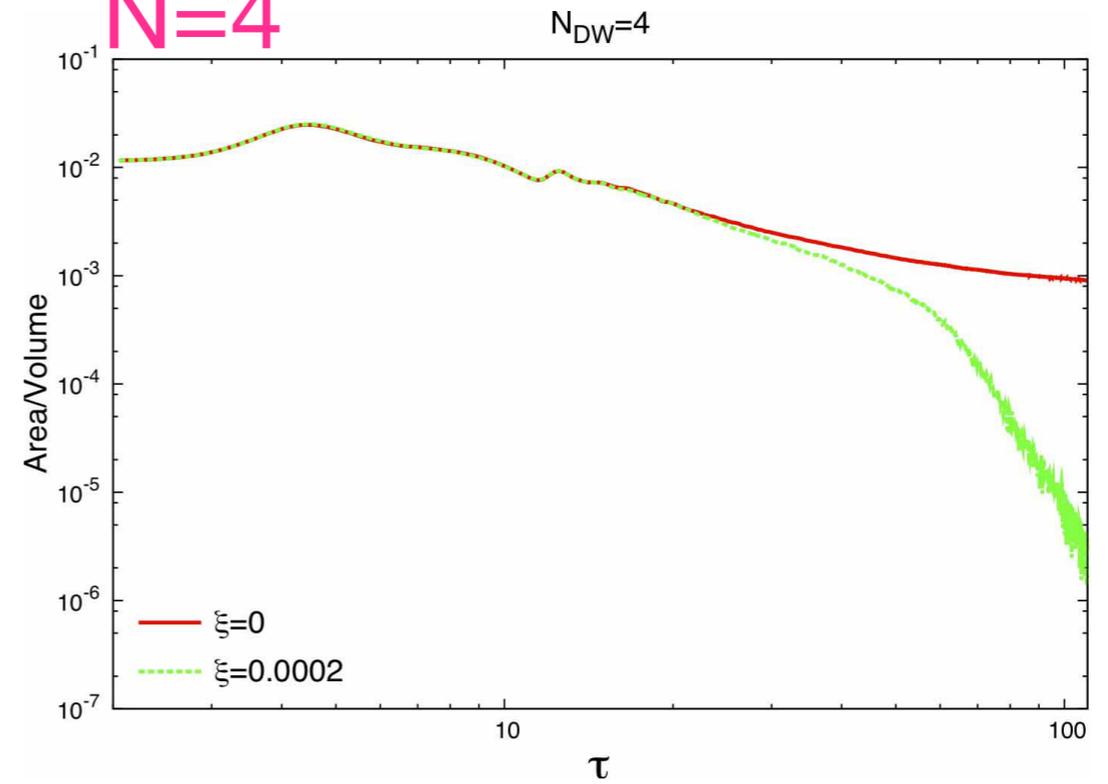
$N=4$



$N=2$



$N=4$



Constraints

- EDM

$$\bar{\theta} \simeq \frac{\xi \eta^2}{m^2} \lesssim 10^{-11}$$

- Decay before wall domination

$$\xi > 3 \times 10^3 N^{-3} \left(\frac{m}{M_p} \right)^2$$

