IBS-MultiDark Joint Focus Program:
WIMPs and axions
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Axion Dark Matter from Topological Defects

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Talk is based on

Hiramatsu, MK, Sekiguchi, Yamaguchi, Yokoyama 1012.5502 (2011)
Hiramatsu, MK, Saikawa 1012.4558 (2011)
Hiramatsu, MK, Saikawa, Sekiguchi 1202.5851 (2012)
Hiramatsu, MK, Saikawa, Sekiguchi 1207.3166 (2012)
Hiramatsu, MK, Saikawa, Sekiguchi to be appeared (2014)

1. Axion

- Axion is a scalar particle predicted in Peccei-Quinn(PQ) mechanism which solves the strong CP problem in QCD
- In PQ mechanism there exists a complex scalar field Φ (PQ scalar) with $U(1)_{PQ}$ which is spontaneously broken at scale η
- Axion is the Nambu-Goldstone boson associate with $U(1)_{PQ}$ breaking and can be identified with the phase of PQ scalar

$$\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/\eta}$$

- Axion acquires mass through QCD non-perturbative effect

$$m_a \simeq 0.6 \times 10^{-5} \text{eV} \left(\frac{F_a}{10^{12} \text{GeV}} \right)^{-1}$$

$$F_a = \eta / N_{\text{DW}}$$

- Axion coherent oscillation accounts for dark matter of the universe
- Axions are produced not only from coherent oscillation but also from topological defects (strings and domain walls)

Today's Talk

- Introduction
- Cosmological evolution of axion
- Axions from axionic strings
- Axions from axion domain walls
    - $N_{DW} = 1$
    - $N_{DW} \geq 2$
- Conclusion

2. Cosmological Evolution of Axion

$T \simeq \eta$

- Spontaneous symmetry breaking of $U(1)_{\rm PQ}$

$$\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/\eta}$$

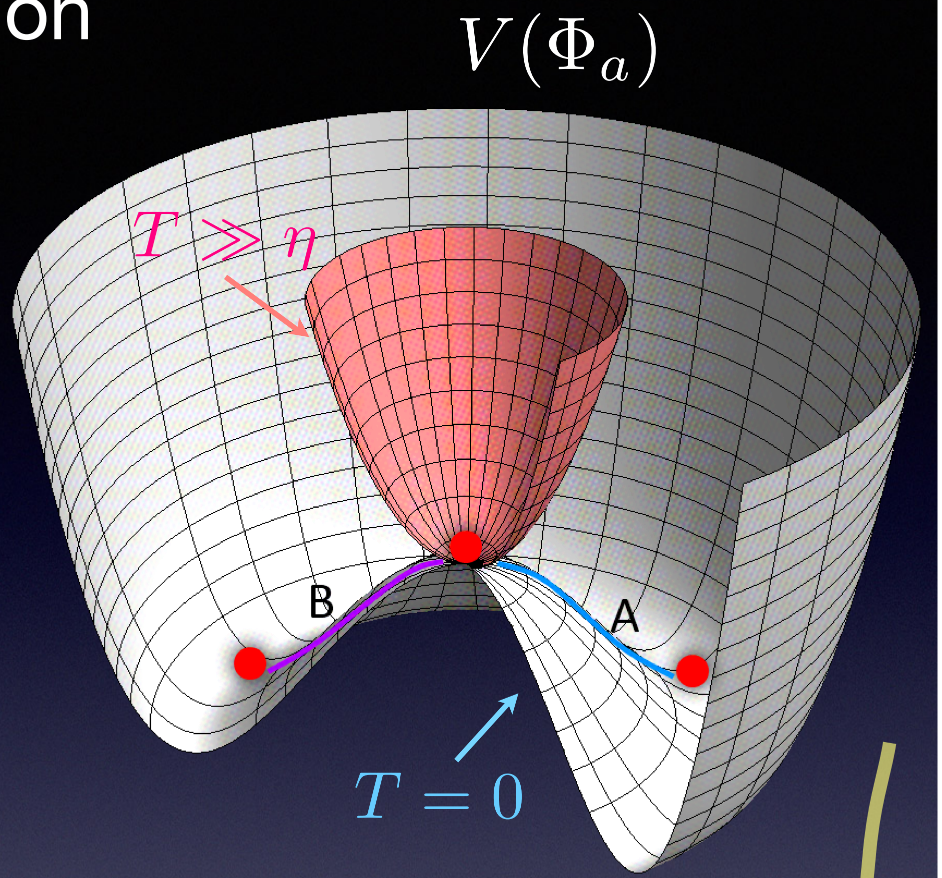
axion is a phase direction of PQ scalar and massless $m_a = 0$

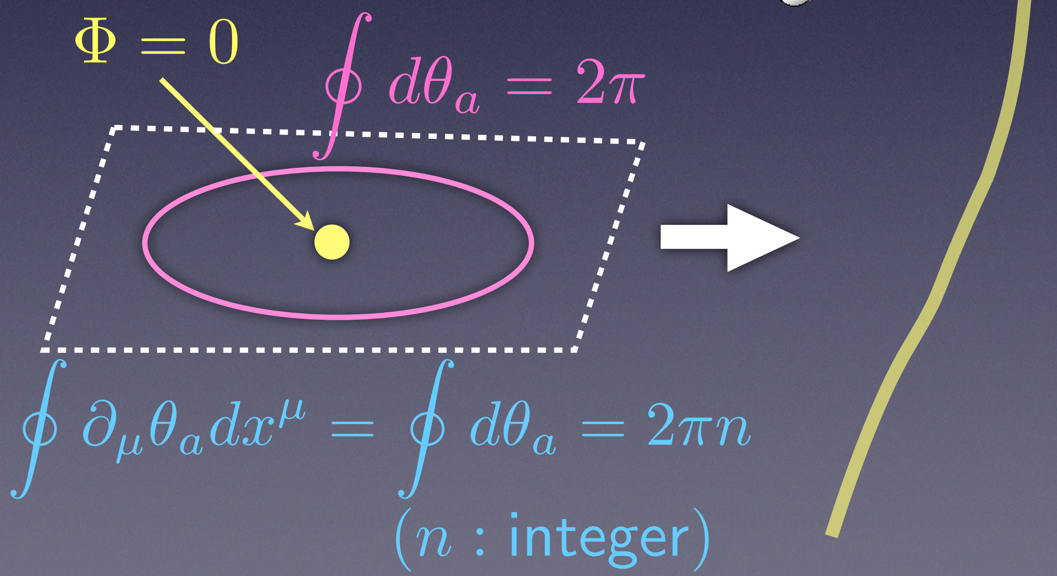
- Formation of Cosmic Strings

θ_a takes different values at different places in the Universe

1 dim. Topological Defect

→ **Axionic String**

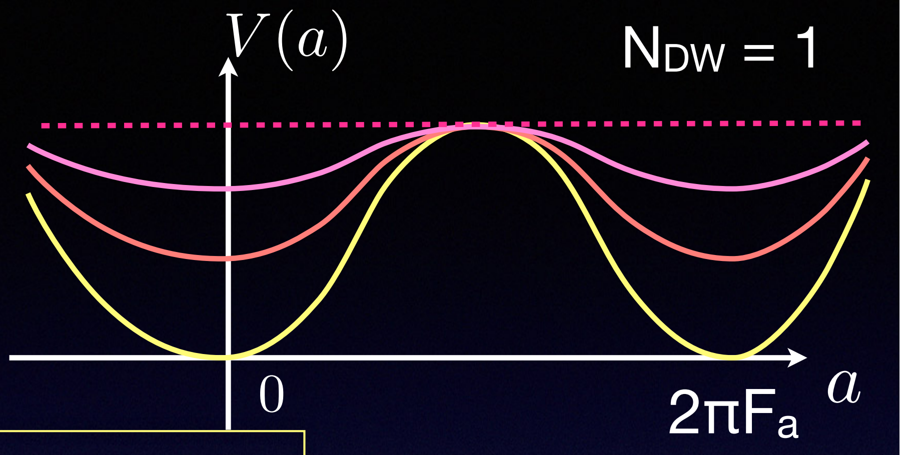




$T \simeq \Lambda_{\rm QCD}$

- Axion acquires mass through QCD non-perturbative effect

  axion mass depends on temperature



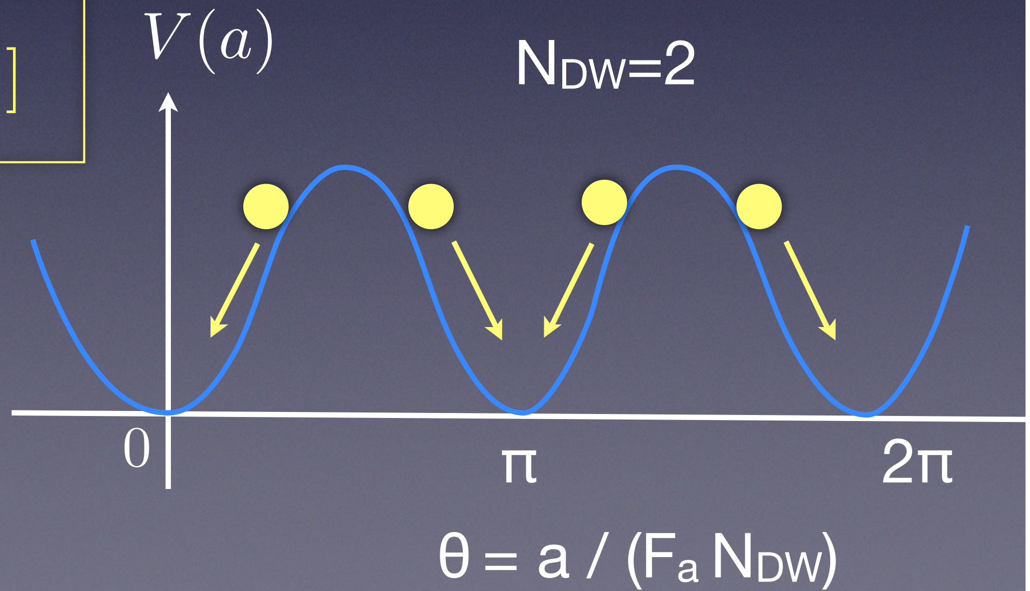
$$m_a \simeq 0.7 \times 10^{-3}\text{eV} \left(\frac{F_a}{10^{10}\text{GeV}}\right)^{-1} \left(\frac{T}{0.1\text{GeV}}\right)^{-3.34}$$

$F_a \equiv \eta / N_{\rm DW}$ [$N_{\rm DW}$: Domain wall number]

- Axion Potential

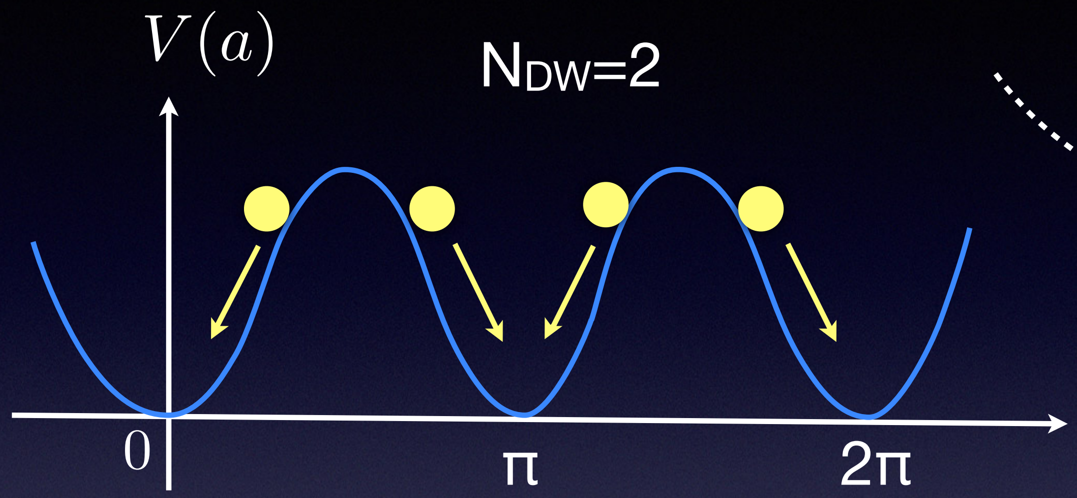
$$V(a) = m_a^2 F_a^2 \left[1 - \cos(a/F_a)\right]$$

  - $U_{PQ}(1)$ is broken to Z_N
  - Formation of Domain Walls
  - Coherent oscillation

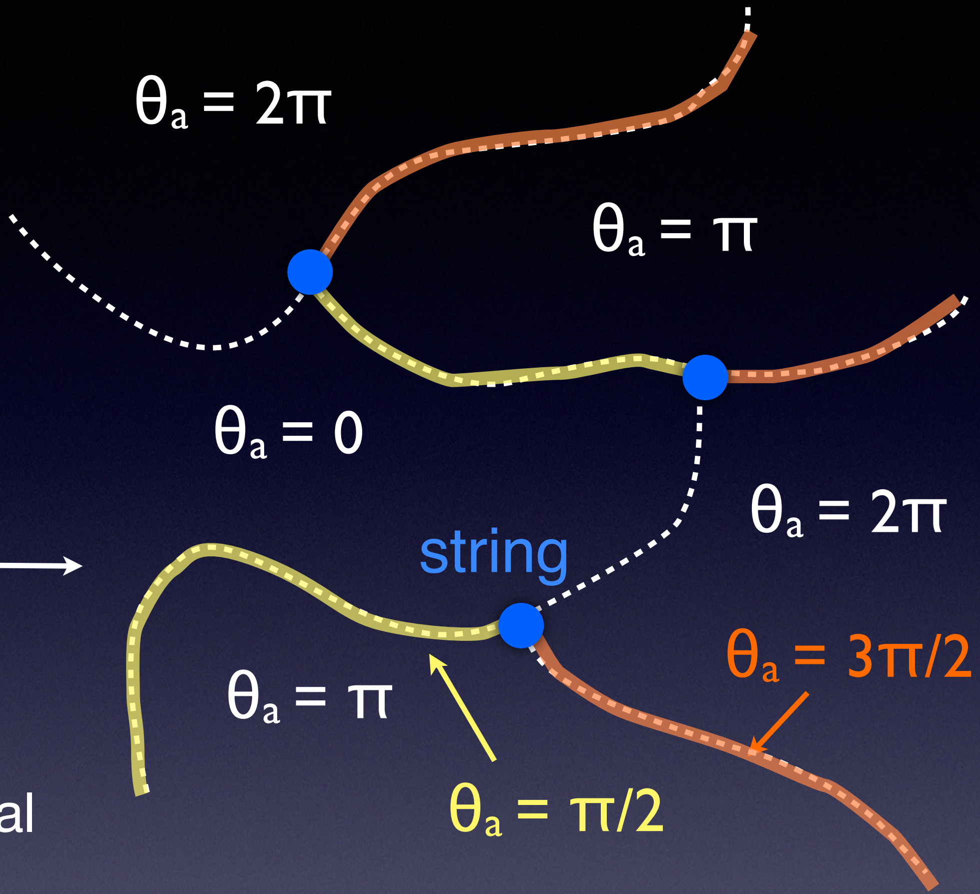


Formation of domain wall

- Axion potential



$\theta = a / (F_a N_{DW})$



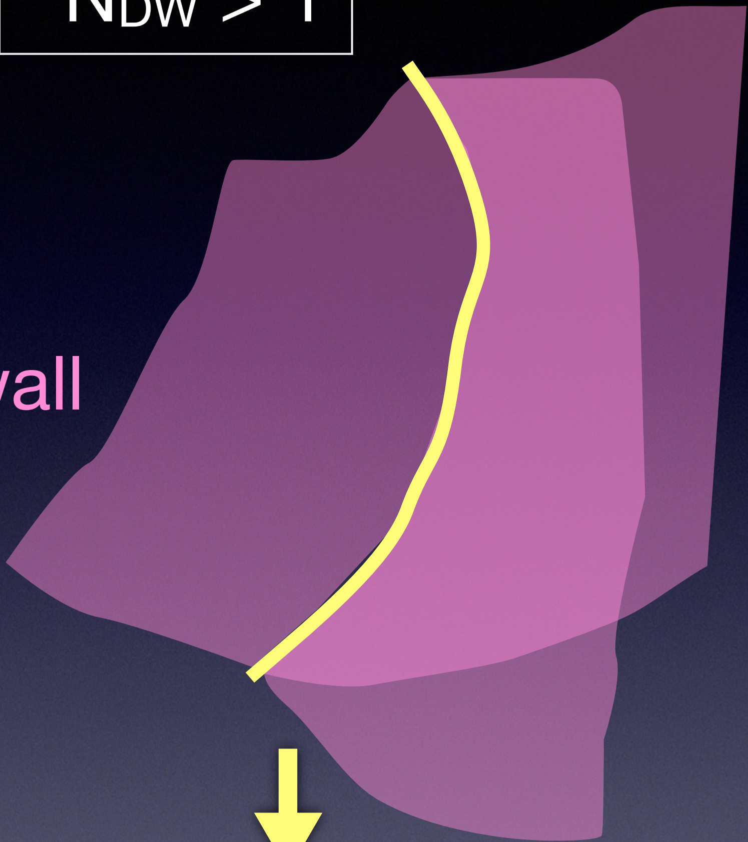
- Axion field begins to feel the potential

$H \simeq m_a(T_*)$ ⟵ $t_* \simeq m_a^{-1}$

➡ **Axion Domain Wall**

- Domain walls attach to strings

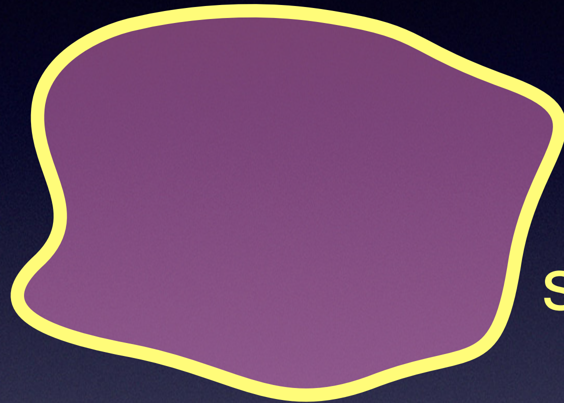
$N_{DW} > 1$



Stable and dominate the universe

Domain Wall Problem

$N_{DW}=1$



Collapse

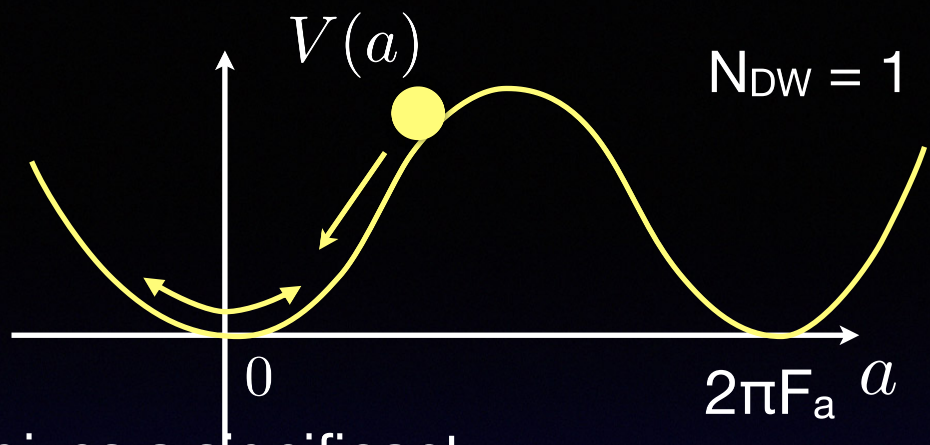
Virenkin Everett (1982)
Barr Choi Kim (1986)

no domain wall problem

Axion overproduction

Coherent Axion oscillation

$$H \simeq m_a(T_*)$$



- Axion field starts to oscillate
- Coherent oscillation of axion field gives a significant contribution to the cosmic density

$$\Omega_{a,\mathrm{osc}}h^2 \simeq 7\times 10^{-4}\langle\theta_*^2\rangle\left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19} \quad \Longleftrightarrow \quad \Omega_{\mathrm{CDM}}h^2 \simeq 0.12$$

WMAP, Planck

$\theta_* = a_*/F_a$: misalighnment angle at T_*

$\langle\theta_*^2\rangle \simeq 6$ including anharmonic effect

- Axion is a good candidate for dark matter if

$$F_a \simeq 2\times 10^{11}\ \mathrm{GeV}$$

Axion solves not only strong CP problem but also dark matter problem

3 Axionic String and Axion Emission

- Axionic 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

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

$$\mu \simeq \pi \eta^2 \ln\left(\frac{t}{\delta_s \xi}\right)$$

- Strings lose their energy by emitting axions ξ : length parameter
  Controversy about energy spectrum of axions

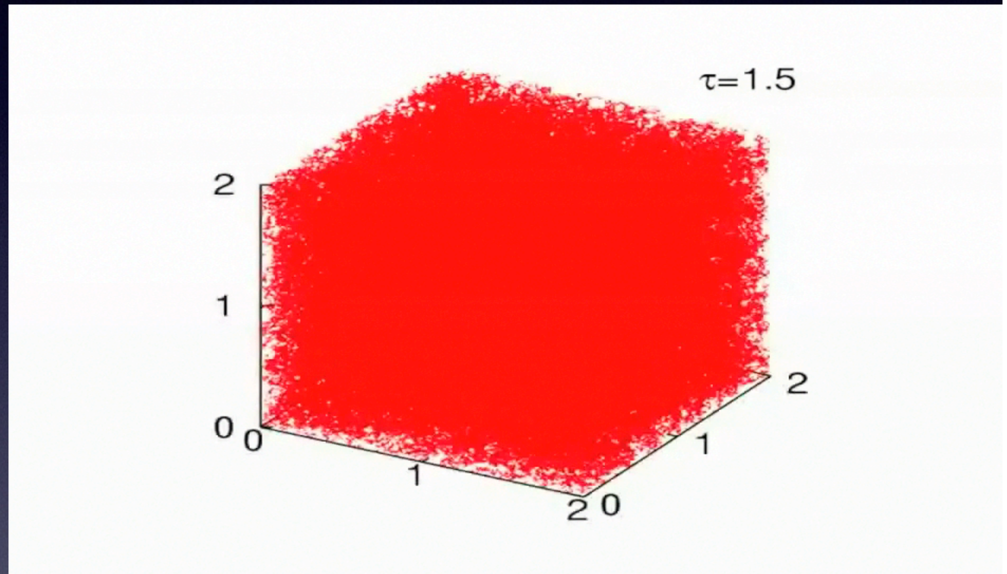
$$P(k) \sim \begin{cases} \text{peak at } k_{\text{horizon}} & (\text{Davis, Shellard}) \\ & \text{or} \\ 1/k & (\text{Sikivie}) \end{cases}$$

Knowledge of precise energy spectrum is crucial in estimating axion density from strings

Simulation

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

- Field theoretical lattice simulation
- N(grid) = $(512)^3$
- enough spatial resolution and large simulation box



horizon = 0.8 at τ=4

Simulation

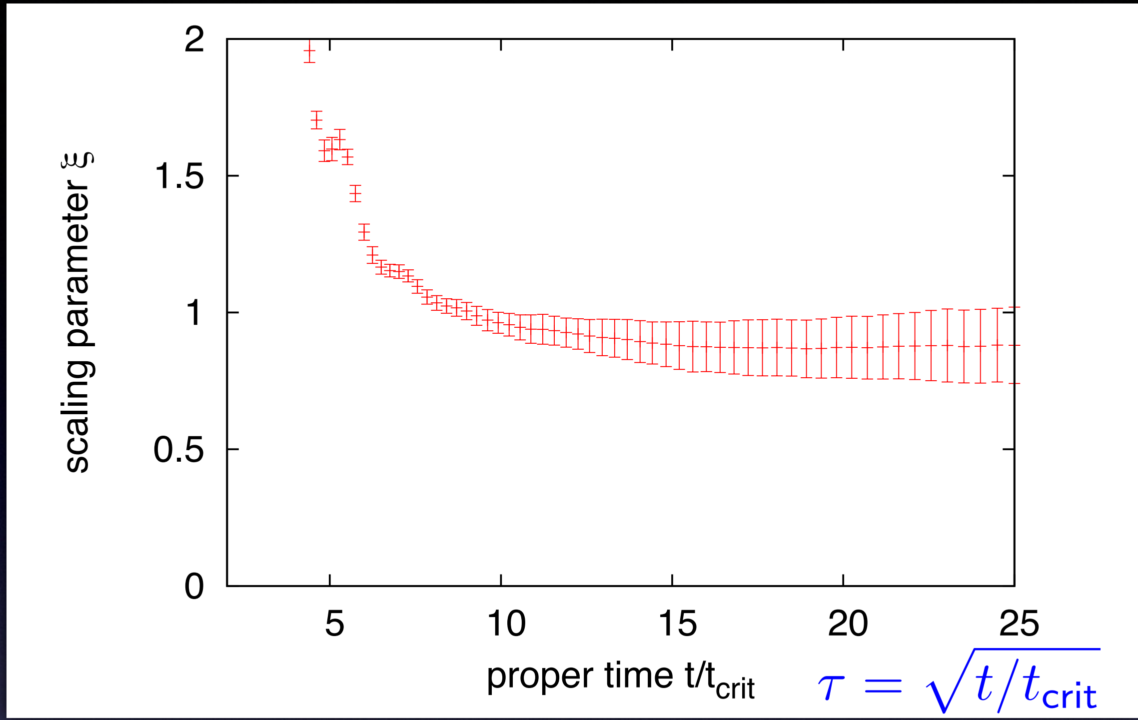
Hiramatsu, MK, Sekiguchi, Yamaguchi, Yokoyama (2010)

- Scaling solution

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

$$\xi = 1.0 \pm 0.5$$

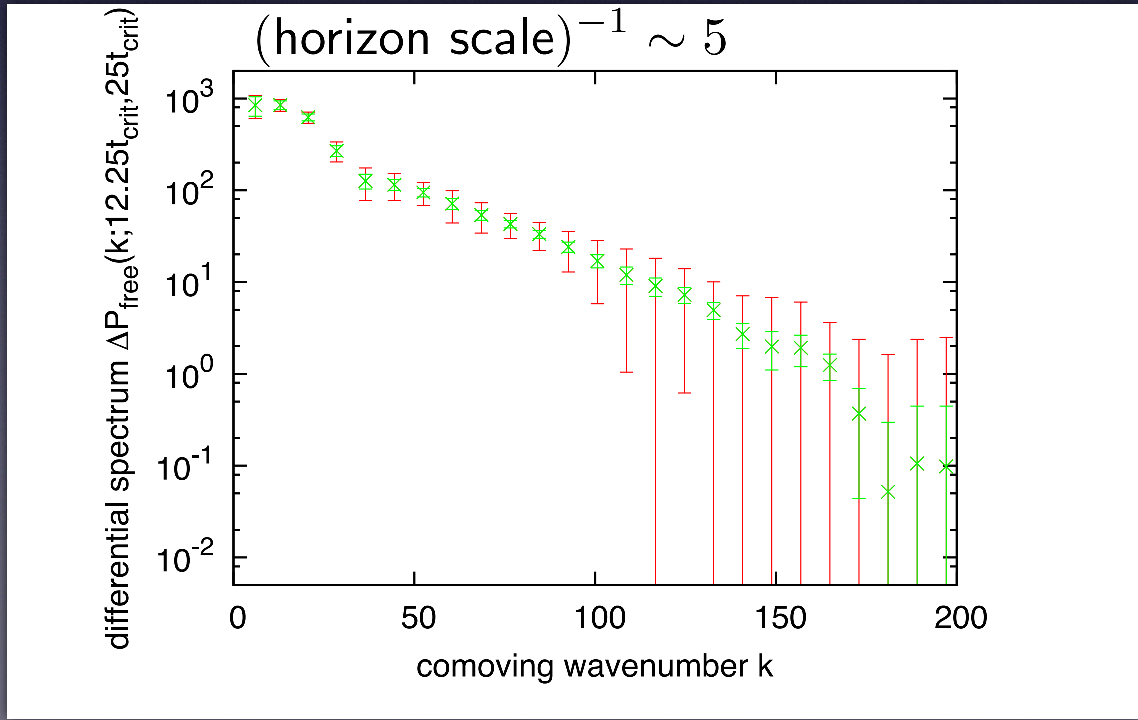
including sys. errors



- Energy Spectrum

peaked at horizon scale

exponentially suppressed at higher wavenumber



- Mean energy

$$\bar{\omega}_a = \epsilon \frac{2\pi}{t}$$

$$\epsilon = 4.3 \pm 0.4$$

Density of Axions from Strings

- Cosmic density of produced axion

$$\Omega_{a,\mathrm{str}}h^2 = (5.9 \pm 4.2) \times 10^{-3} N_{\mathrm{DW}}^2 \left(\frac{F_a}{10^{10}\mathrm{GeV}} \right)^{1.19}$$

- Axions from strings gives at least comparable contribution to the cosmic density with those from the coherent oscillation

$$\Omega_{a,\mathrm{osc}}h^2 \simeq 4 \times 10^{-3} \left(\frac{F_a}{10^{10}\mathrm{GeV}} \right)^{1.19}$$

- Large uncertainty comes from estimation of ξ

4. Domain Wall and Axion Emission

- QCD scale

  $U(1)_{PQ}$ → discrete Z_N

  Domain wall formation

- $N_{DW} > 1$

  Produced domain walls are stable and soon dominate the universe, which causes a serious cosmological problem

  Domain Wall Problem

- $N_{DW} = 1$

  Produced domain walls are disk-like, collapse by their tension and disappear in the universe

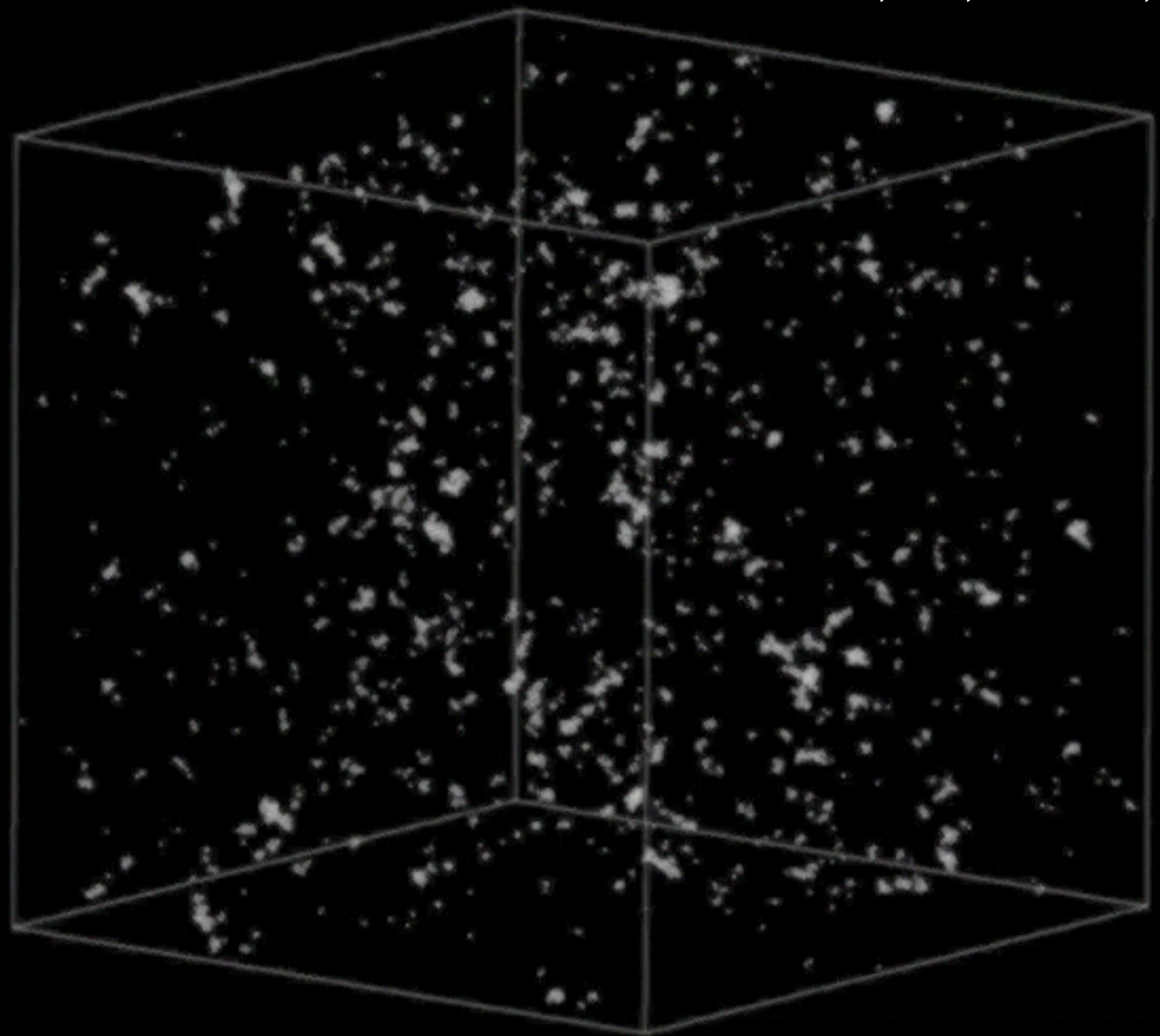
  No Cosmological Domain Wall Problem

  However, axions are produced in the collapse, which may affect the cosmic axion density

4.1 Axion domain wall (N_{DW} =1)

- Lattice simulation with N(grid) = $(512)^3$
- Time evolution of string-wall network

Hiramatsu, MK, Saikawa, Sekiguchi (2012)



Scaling Parameters

- Strings

  Strings obey scaling solution

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

- Walls

  Walls also obey scaling solution

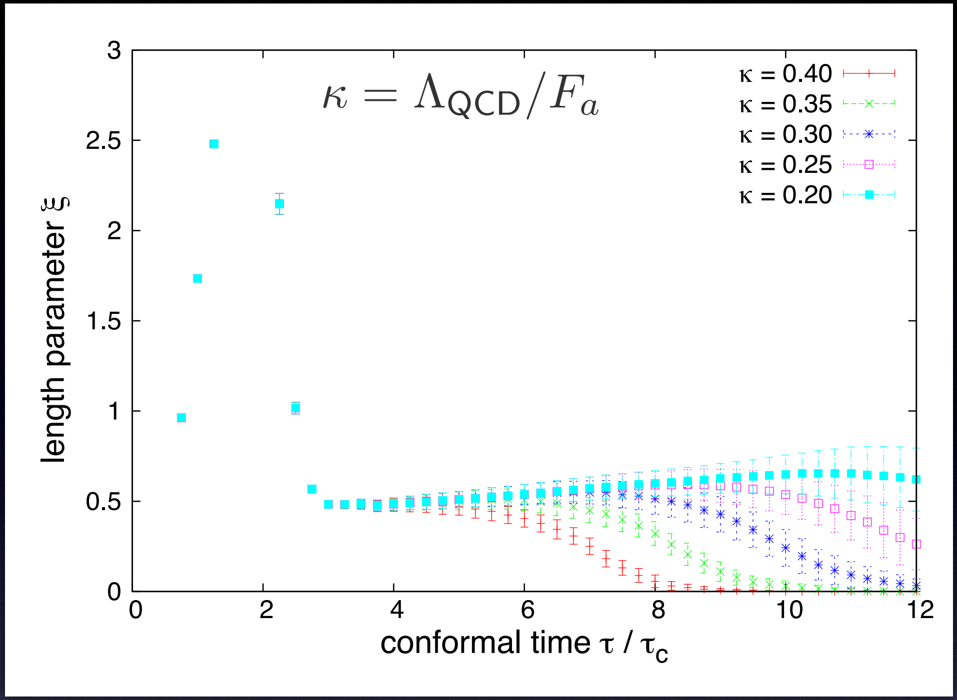
  O(1) walls in a horizon volume

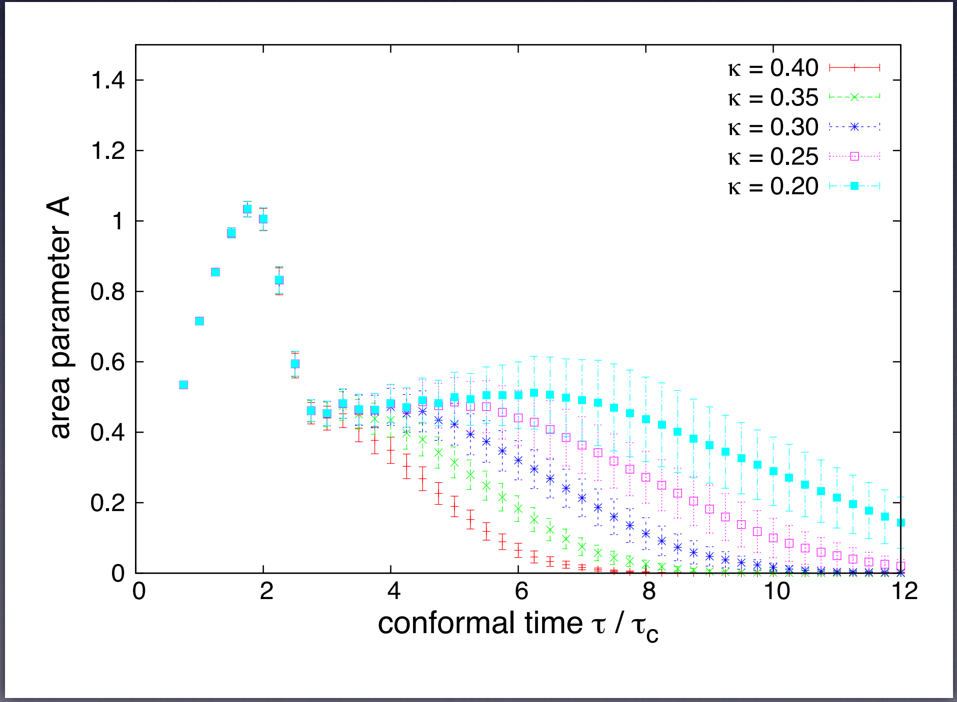
$$\rho_{\text{wall}} = \mathcal{A} \frac{\sigma}{t}$$

$$(\sigma \sim F_a^2 m_a \;:\; \text{wall tension})$$

$\mathcal{A}$: area parameter

$$\mathcal{A} \simeq 1.0 \pm 0.25$$





Axion Emission

- Domain wall collapse when wall tension exceeds string tension

$$\sigma(t_c) \simeq \frac{\mu(t_c)}{t_c}$$

- Axions from collapsed domain walls

- Energy spectrum $P(k) \sim \begin{cases} \text{peak at } m_a & \text{(width of domain wall)} \\ & \text{or} \\ 1/k & \text{(Chang et al.)} \end{cases}$

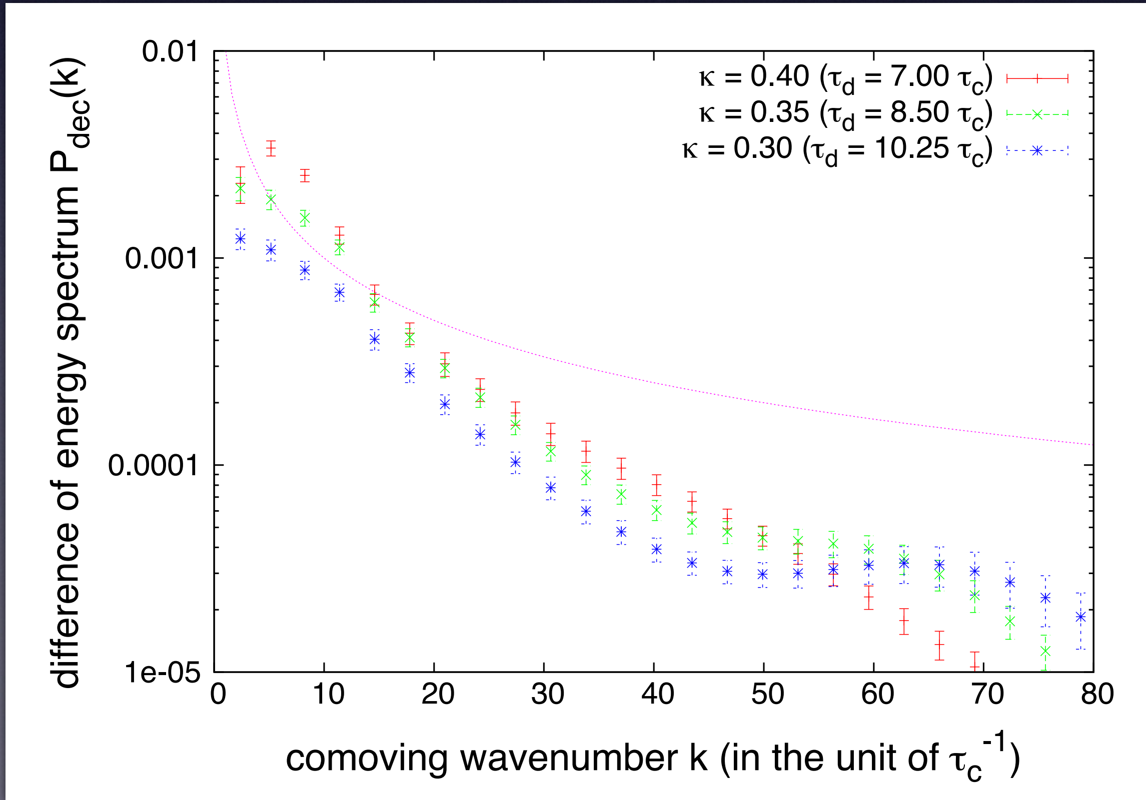
- Simulation

  peak at axion mass

$$\frac{E_a}{m_a}(t_{\text{decay}}) = \sqrt{1+\epsilon_w^2}$$

$$\boxed{\epsilon_w \simeq 2 \pm 1}$$

$$E_a \simeq (1.4 - 3.2) m_a$$

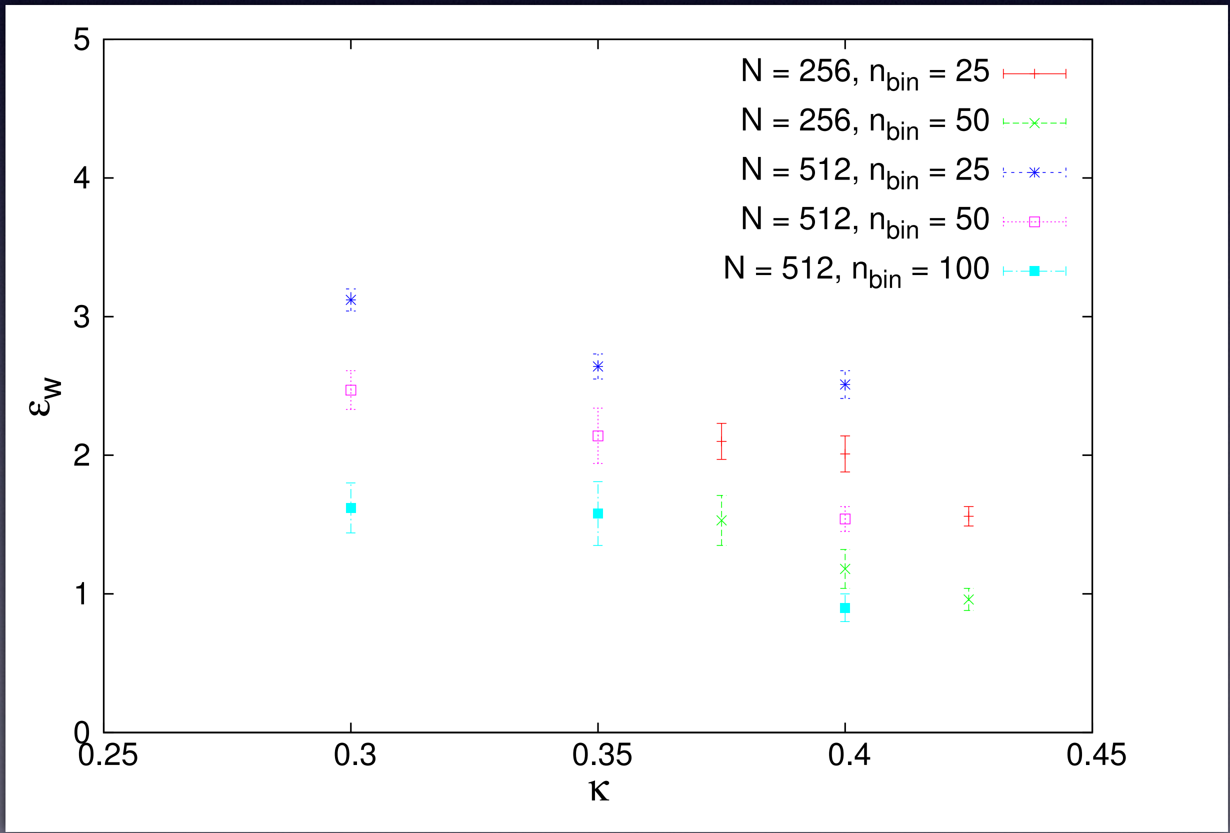


- Uncertainties in estimation of averaged axion energy
  - Dependence on κ=Λ_{QCD} / F_a
  - number of bins in power spectrum

  (resolution of P(k) is not good in low k)

$$\frac{E_a}{m_a}(t_{\rm decay}) = \sqrt{1+\epsilon_w^2}$$

$$\epsilon_w \simeq 2 \pm 1$$



Axions from string-wall systems

- Axion density from string-wall systems

$$\Omega_{a,\mathrm{wall}}h^2 \simeq (5.3 \pm 2.9) \times 10^{-3} \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19}$$

- For N_{DW} =1, axion density from string-wall systems is comparable to axion densities from other sources

$$\Omega_{a,\mathrm{osc}}h^2 \simeq 4 \times 10^{-3} \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19} \qquad \Omega_{a,\mathrm{str}}h^2 = 6 \times 10^{-3} \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19}$$

- Total axion density

$$\Omega_{a,\mathrm{tot}}h^2 \simeq (1.7 \pm 0.4) \times 10^{-2} \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19}$$

- Constraint on the PQ scale $\Omega_{a,\mathrm{tot}} \lesssim \Omega_{\mathrm{dark}}$

$$F_a \lesssim (4.3 - 6.7) \times 10^{10}\mathrm{GeV} \qquad m_a \lesssim (0.9 - 1.4) \times 10^{-4}\mathrm{eV}$$

4.2 Axion Domain Wall (N_{DW} > 1)

- Wall-string networks are stable and soon dominate the universe

→ Domain Wall Problem

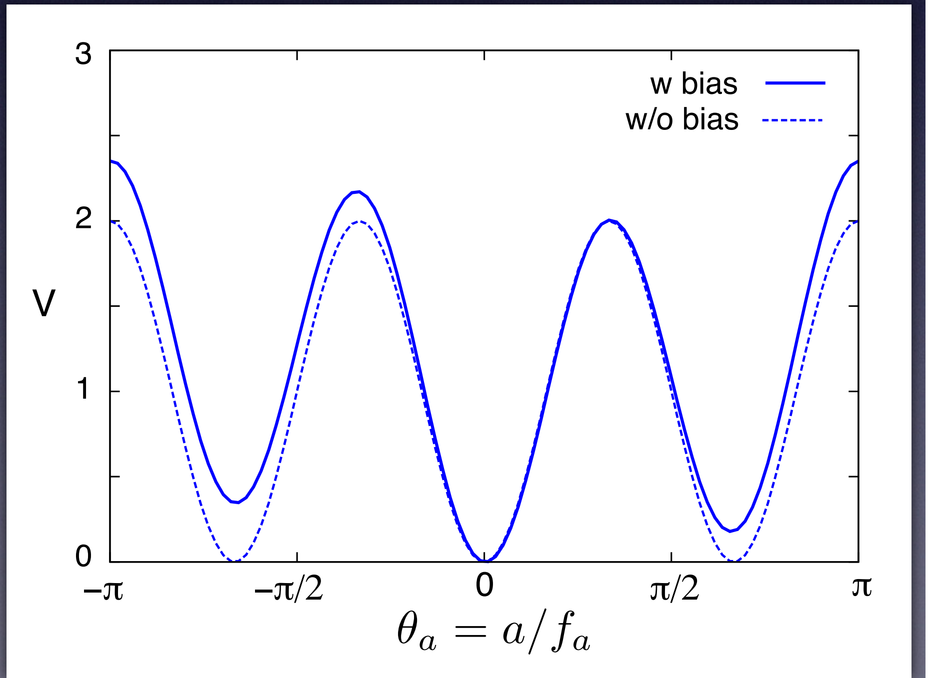
- The problem might be avoided by introducing a "bias" term which explicitly breaks PQ symmetr

$$V_{\text{bias}} = -\Xi\eta^3 \left(\Phi e^{-i\delta} + \text{h.c.}\right)$$

Sikivie (1982)

- Bias term lifts degenerated vacua

- Differences of the vacuum energy produce pressure on the walls and eventually annihilate domain walls



- For small bias
  - Long-lived domain walls emit a lot of axions which might exceed the observed matter density

    Large bias is favored

- For large bias
  - Bias term shifts the minimum of the potential and might spoil the original idea of Peccei and Quinn

$$\theta = \frac{2\Xi N_{\mathrm{DW}}^3 F_a^2 \sin\delta}{m_a^2 + 2\Xi N_{\mathrm{DW}}^2 F_a^2 \cos\delta} < 7 \times 10^{-12}$$

δ : phase of bias term

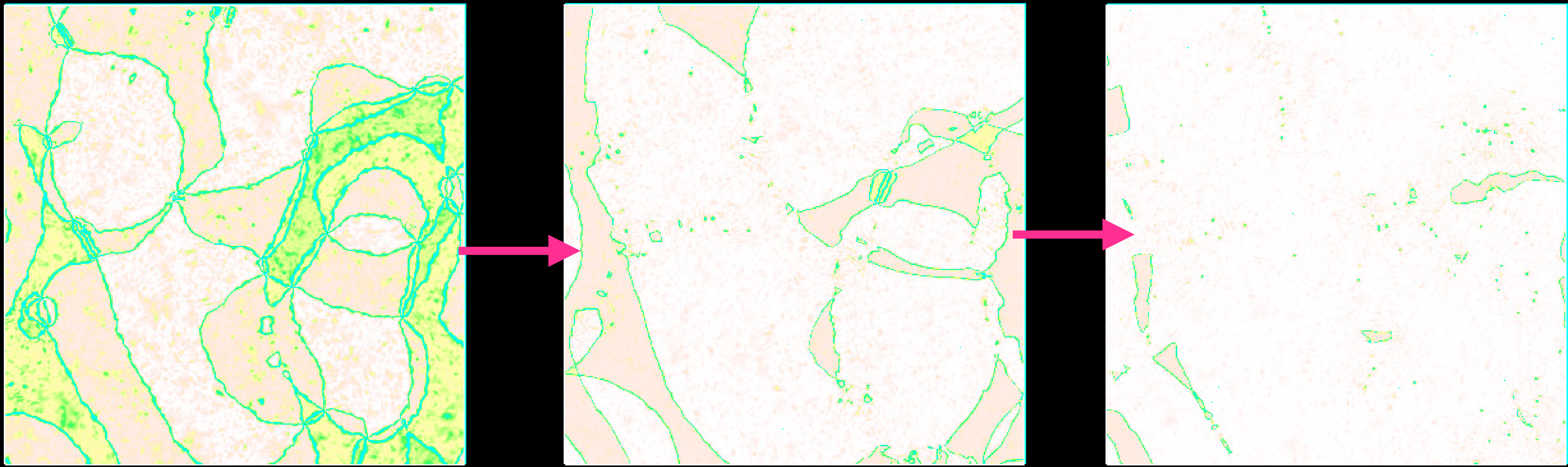
    Small bias is favored

- Consistent parameters?

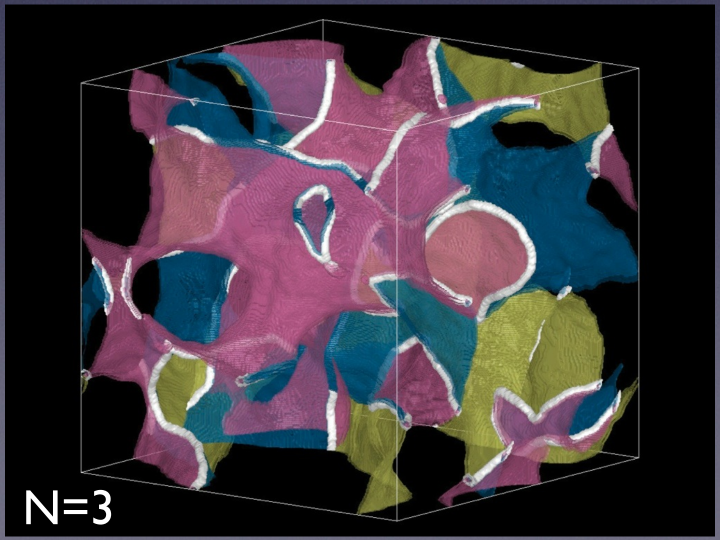
Numerical simulations

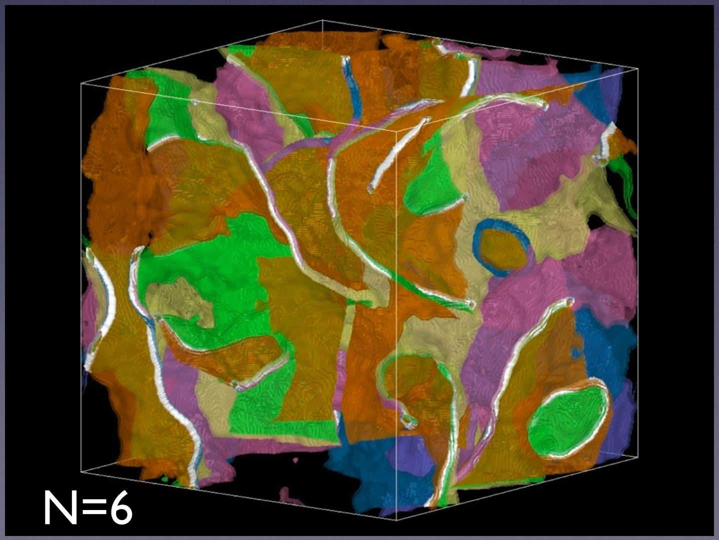
Hiramatsu, MK, Saikawa, Sekiguchi (2014)

- Lattice simulation with 8192^2 16384^2 32768^2 (2D) , 512^3 (3D)

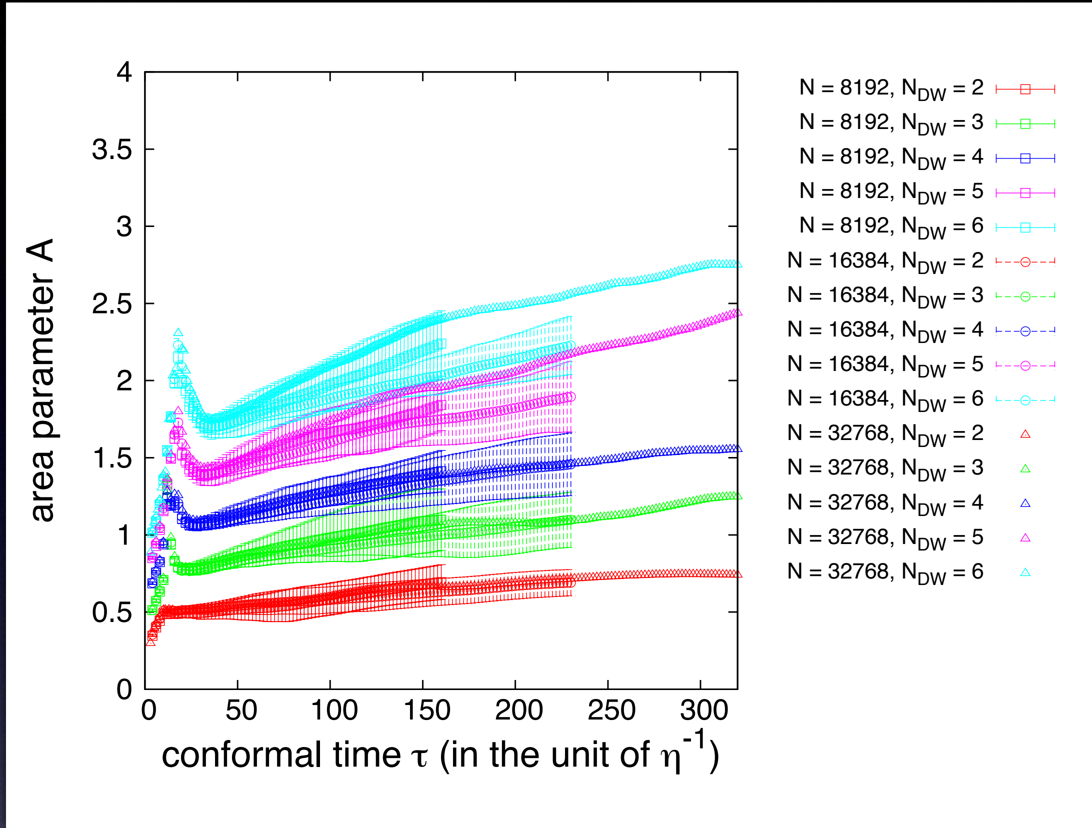


$N_{\rm DW} = 6 \quad \Xi = 6 \times 10^{-5}$





Area parameter $\rho_{\text{wall}} = \mathcal{A}\frac{\sigma}{t}$



- Area parameters increase for large N_{DW}

N_{DW}	$\mathcal{A}(\tau_f)$ $(N = 16384,\ \tau_f = 230)$
2	0.690 ± 0.085
3	1.10 ± 0.18
4	1.46 ± 0.20
5	1.90 ± 0.23
6	2.23 ± 0.19

- Slightly increase with time?

$$\mathcal{A}(\tau) = \mathcal{A}_{\text{form}}\left(\frac{\tau}{\tau_{\text{form}}}\right)^{2(1-p)}$$

$$p = 0.92 - 0.93$$

- It is not clear if the increase continues in later times, so we consider both two cases, “exact scaling” and “deviation from scaling”

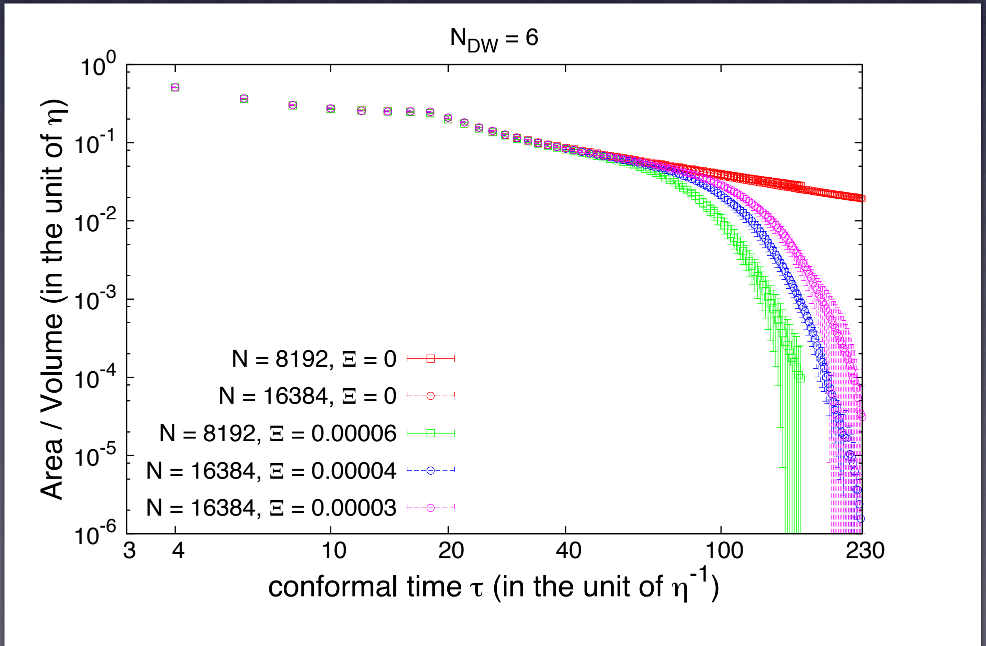
Decay time

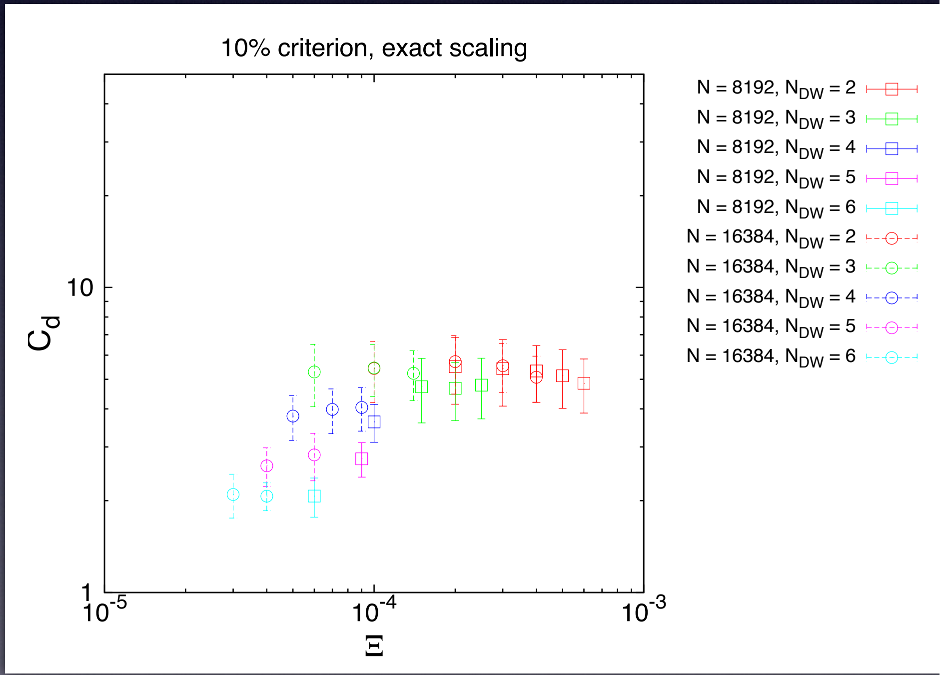
- Bias term produces pressure p_V acting on walls $\quad p_V \sim \Xi\eta^4$
- Walls decay when it becomes larger than wall tension $\quad p_T \sim \mathcal{A}\sigma/t$

$$\Rightarrow \quad t_{\text{dec}} = C_d \frac{\mathcal{A}\sigma}{\Xi\eta^4[1-\cos(2\pi/N_{\text{DW}})]}$$

- C_d should be determined by the numerical simulation

$$\left.\frac{A/V(\Xi)}{A/X(\Xi=0)}\right|_{t_{\text{dec}}} = 0.1$$





$$\Rightarrow \quad C_d \simeq 2-5$$

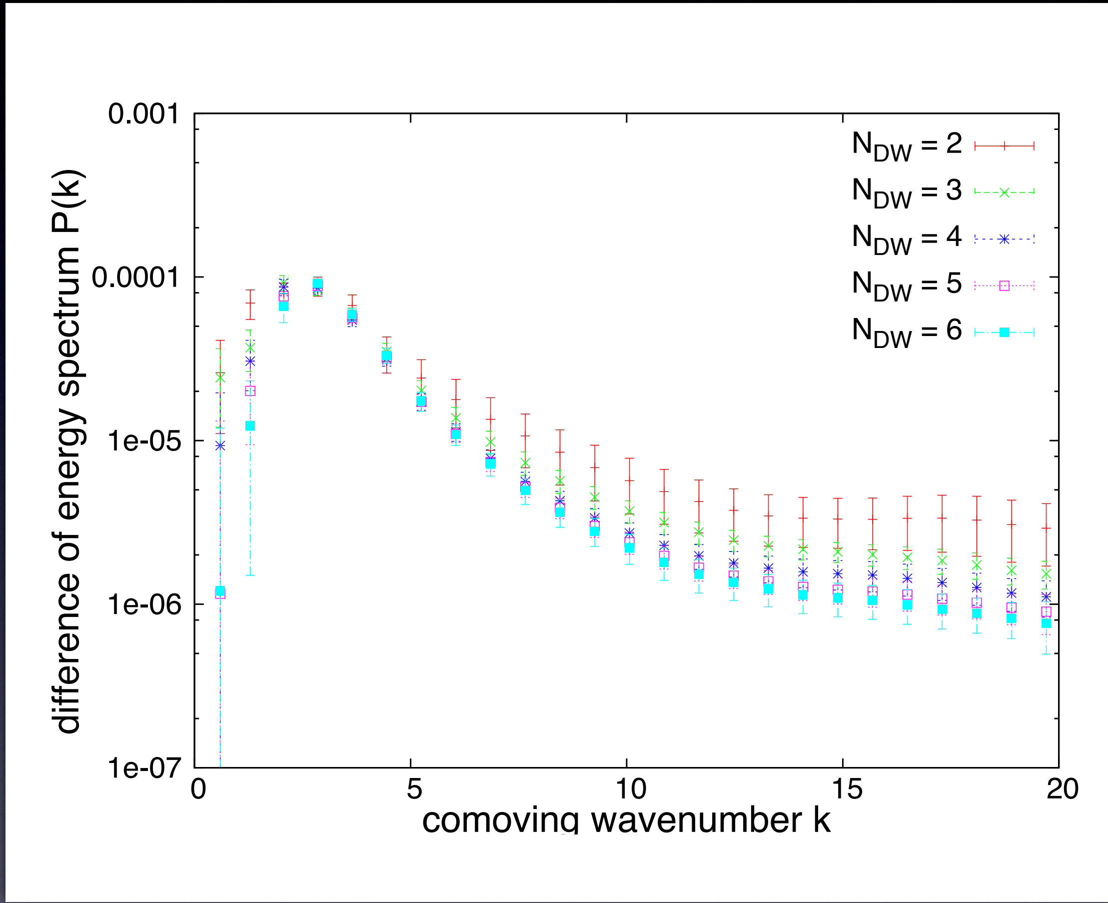
Emission of axions from domain walls

Hiramatsu, MK, Saikawa, Sekiguchi (2012)

- Axion spectrum
  - Peak at k ~ axion mass
  - Mean energy

$$\frac{E_a}{m_a}(t_{\rm dec}) = \sqrt{1+\epsilon_a^2}$$

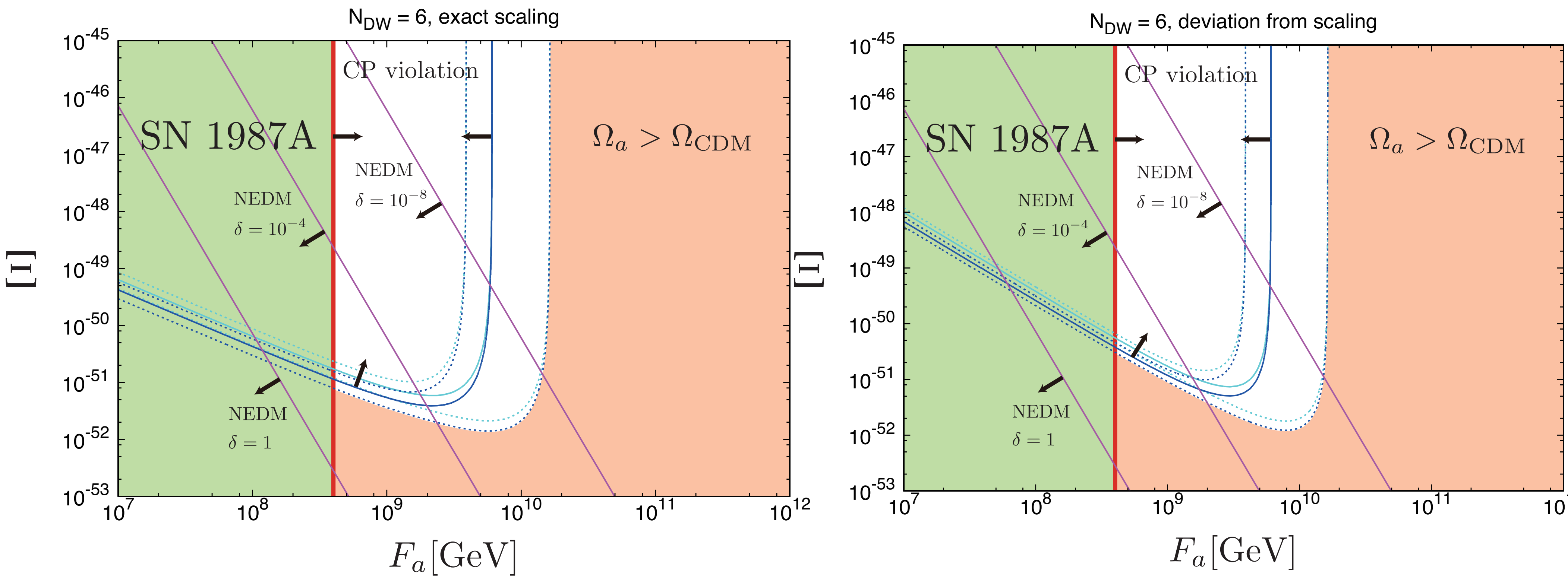
$N_{\rm DW}$	ϵ_a
2	1.19 ± 0.14
3	1.19 ± 0.12
4	1.31 ± 0.15
5	1.49 ± 0.22
6	1.54 ± 0.21



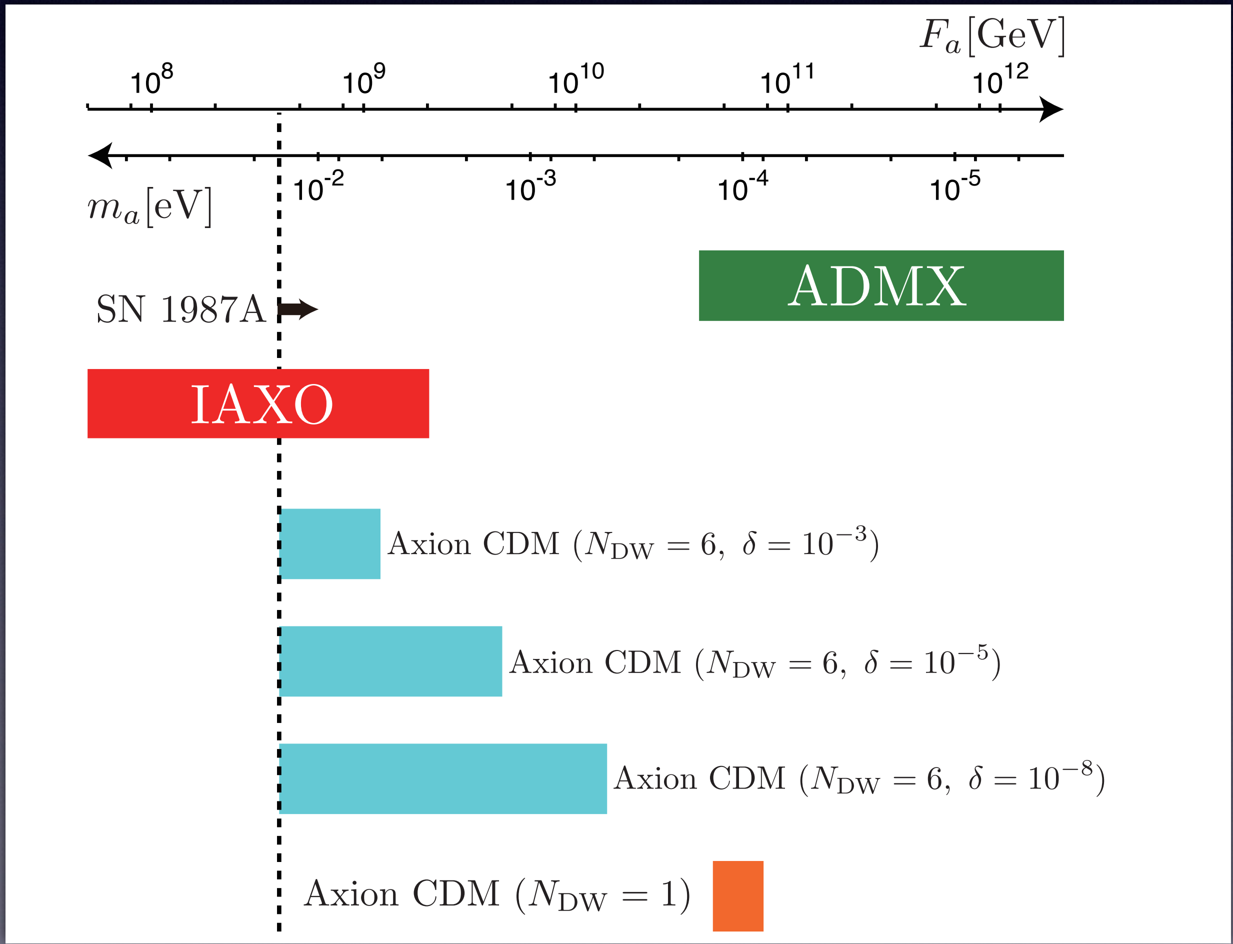
  - Mean energy does not depend on choice of number of bins because axion mass scale is much smaller than the horizon size

Constraints

- Axion density $\Omega_{a,\text{wall}} + \Omega_{a,\text{str}} + \Omega_{a,\text{osc}} < \Omega_{\text{dark}}$
- Neutron electric dipole moment (NEDM) $\bar{\theta} < 0.7 \times 10^{-11}$
- Astrophysical constraint (SN1987A) $F_a > 4 \times 10^8$ GeV



- NEDM constraint depends on the phase of bias δ
- For allowed region δ should be
  δ < 0.03 (exact scaling) δ < 0.008 (deviation from scaling)
- With a mild tuning of the phase axion can be dark matter of the universe for $F_a = 4 \times 10^8$ GeV - 2×10^{10} GeV and can be probed in the next generation experiments

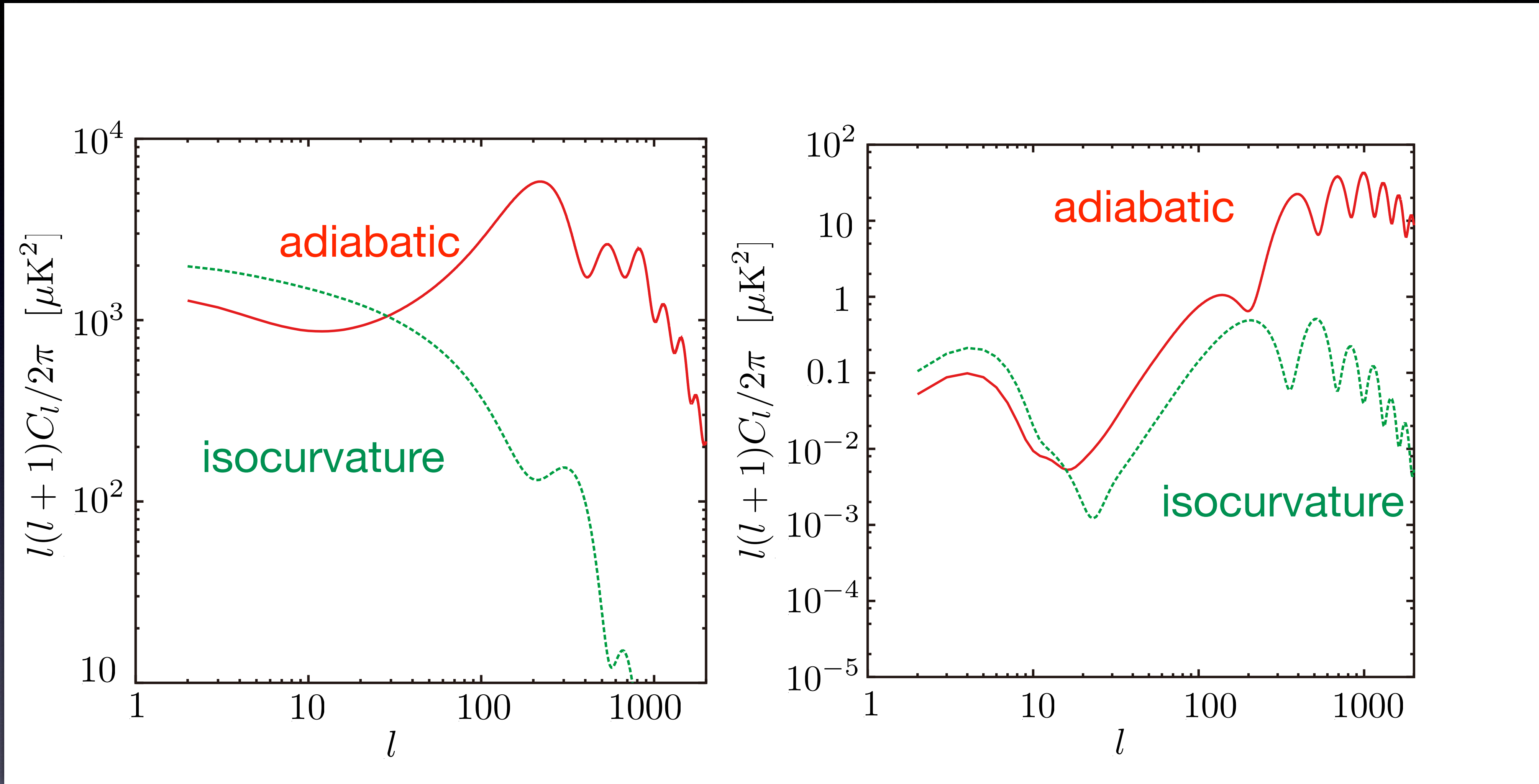


5. Conclusion

- We consider the scenario where PQ symmetry is broken after inflation
- Axion can be dominant component of dark matter if
  - $F_a \simeq (4.4 - 7.6) \times 10^{10}$ GeV for $N_{DW} = 1$
    $m_a \simeq (0.8 - 1.4) \times 10^{-4}$ eV
  - $F_a \simeq O(10^8 - 10^{10})$ GeV for $N_{DW} > 1$
    $m_a \simeq (10^{-4} - 10^{-2})$ eV
- These mass ranges may be probed in the next generation experiments such as IXAO

Backup

Isocurvature vs. adiabatic



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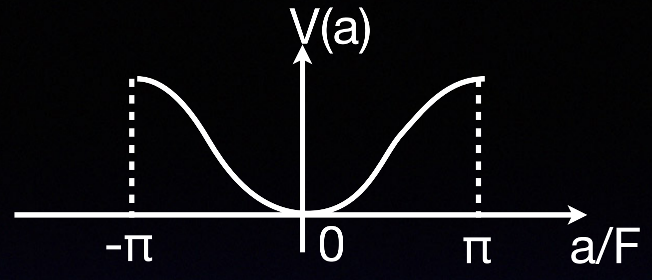
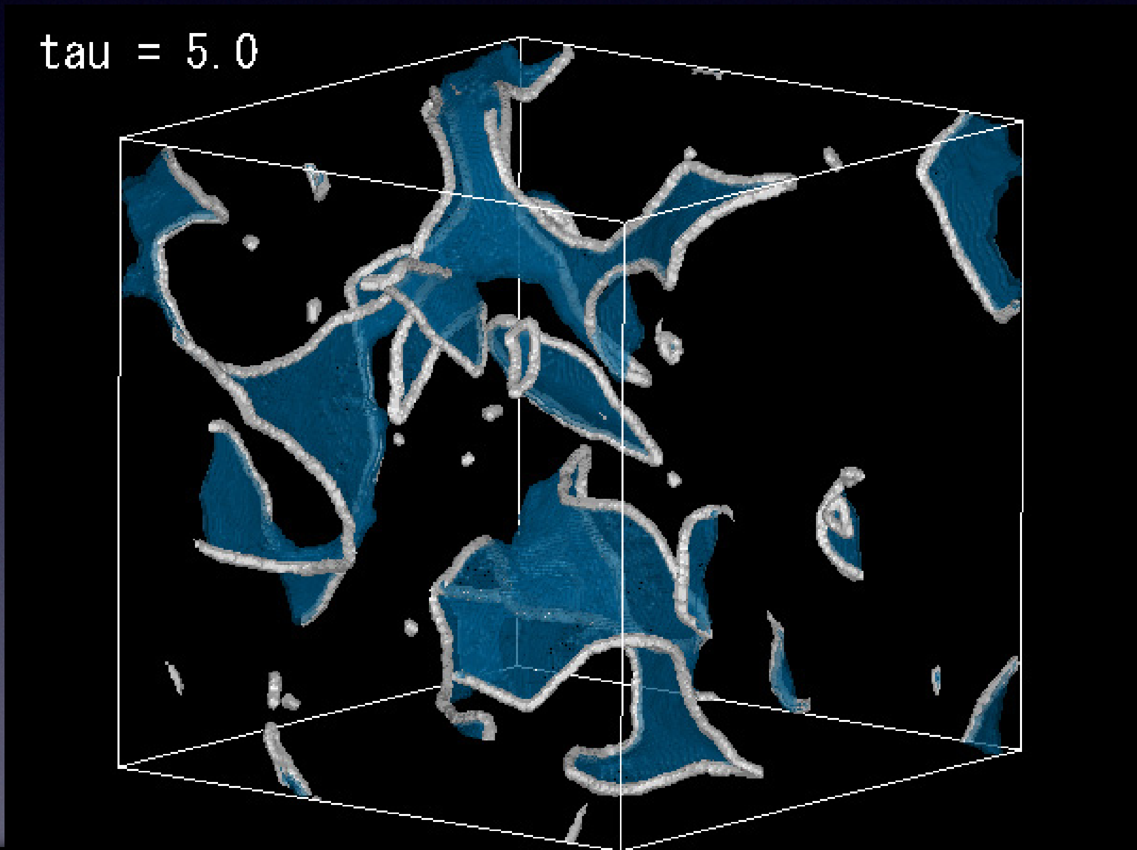
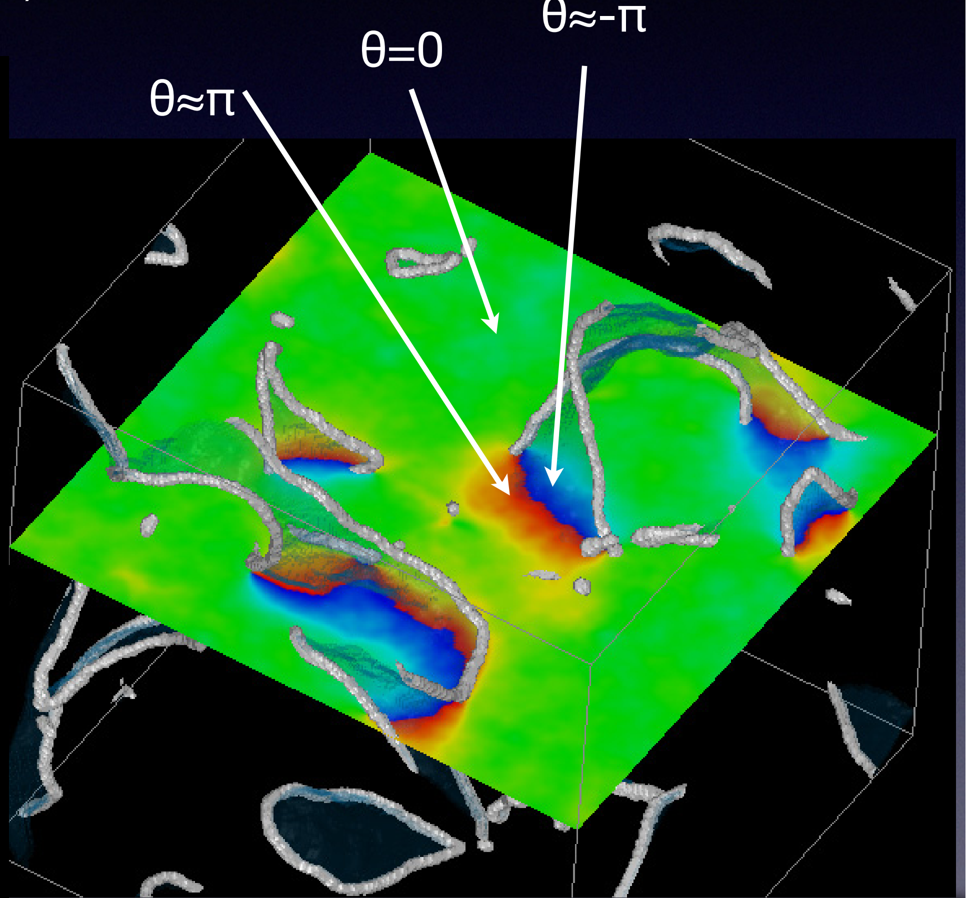
Axion Domain Wall (N=1)

- Field theoretical lattice simulation with N(grid) = $(512)^3$



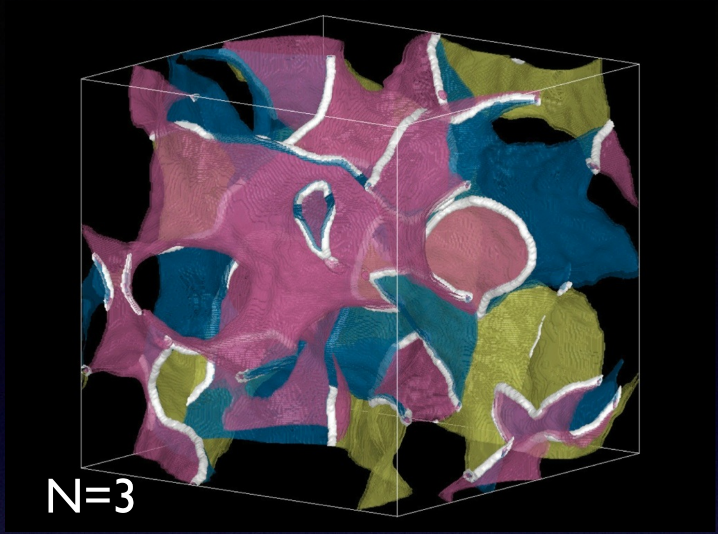
Hiramatsu, MK, Saikawa, Sekiguchi (2012)

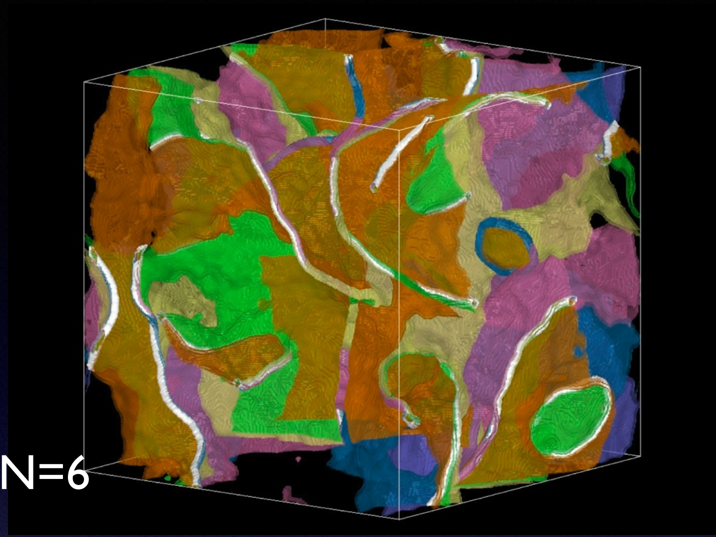


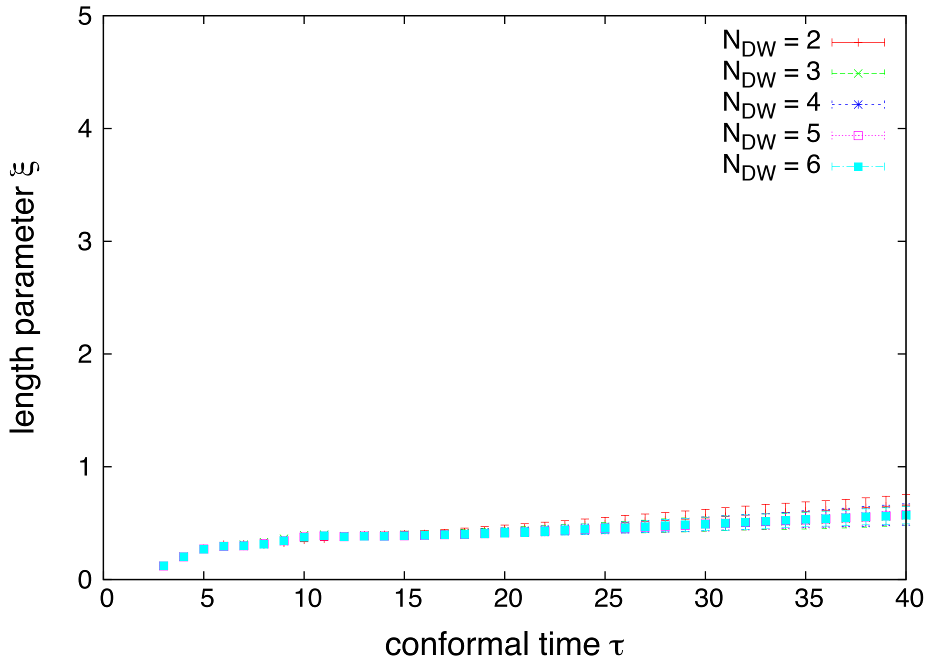


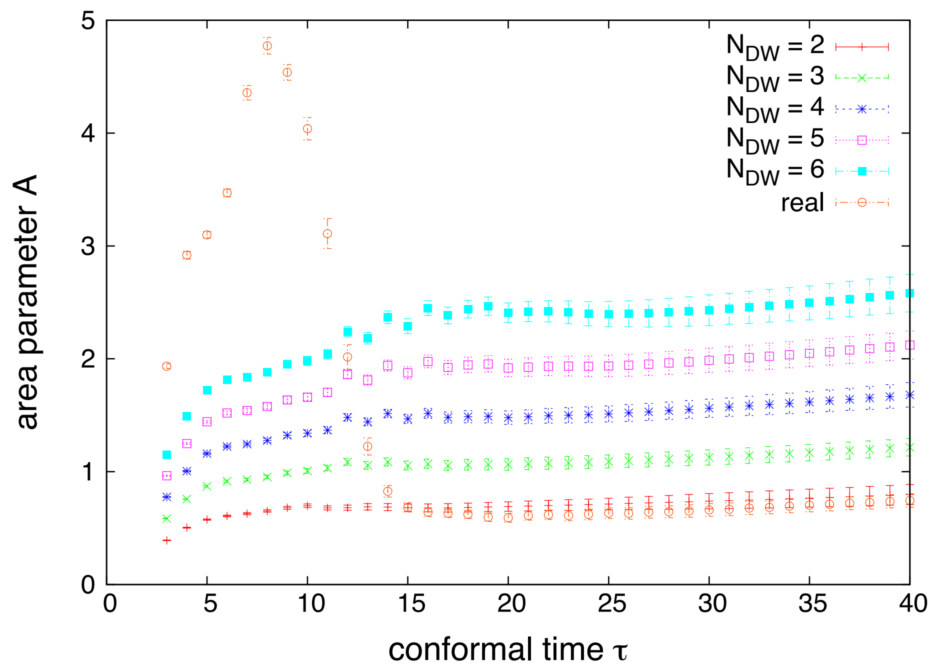
3D simulation

Hiramatsu, MK, Saikawa, Sekiguchi (2012)

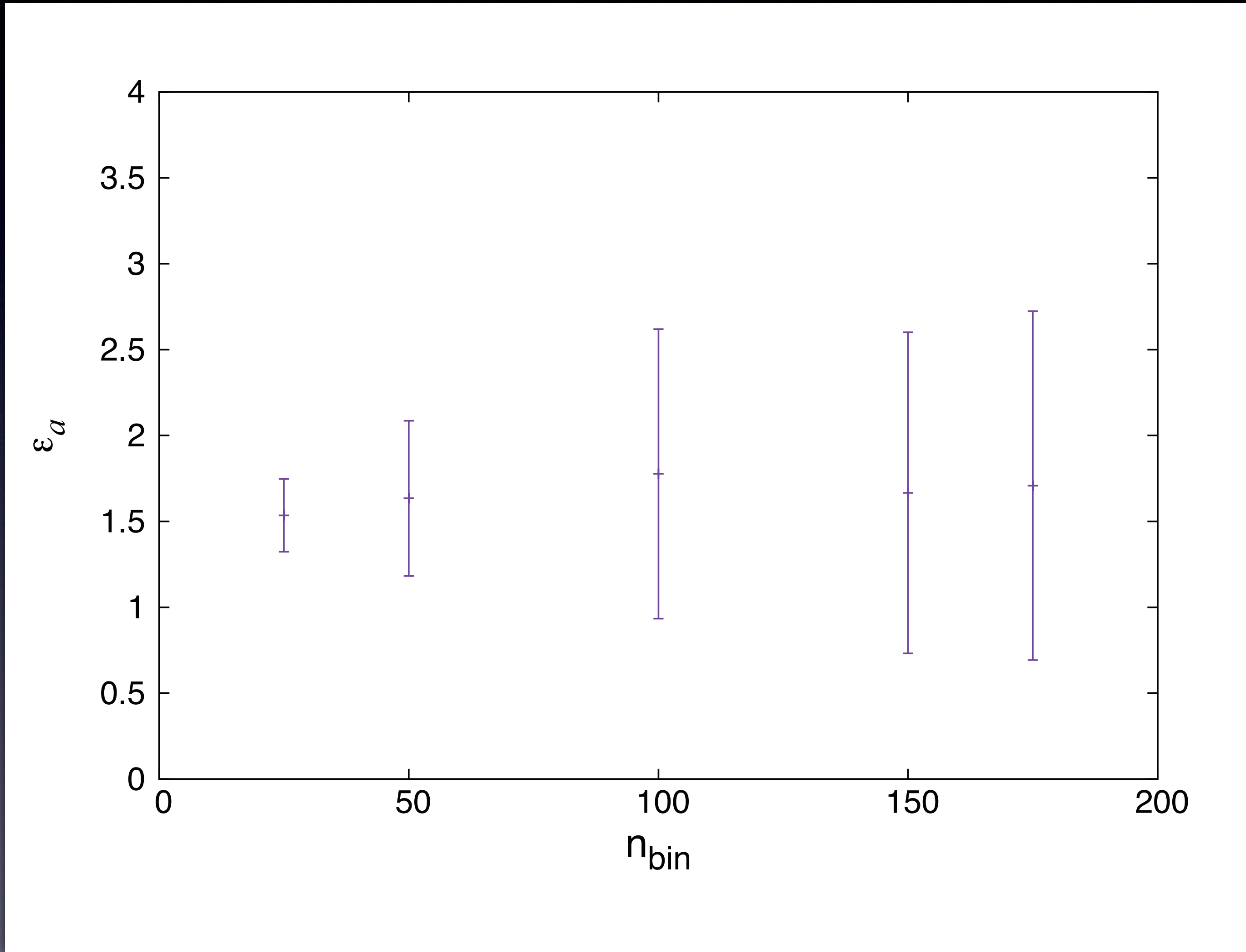








Dependence on number of bins ($N_{DW} \geq 2$)



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