位相欠陥によるアクシオン暗黒物質生成

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Collaborate with T. Hiramatsu (YITP), M. Kawasaki (ICRR) and T. Sekiguchi (Nagoya U.)

References:
[1] T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, hep-ph/1202.5851. (PRD85, 105020 (2012))
[2] T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, hep-ph/1207.3166. (prepared for submission to JCAP)

Abstract

- Numerical simulation of topological defects (strings & domain walls) which arise in axion models
  - Energy spectrum of axions radiated from collapse of defects
  - Contribution to CDM abundance
- Consider two different scenarios
  - $N_{DW}=1$ (KSVZ-like) unstable domain walls
  - $N_{DW}>1$ (DFSZ-like) long-lived domain walls

Strong CP problem and axion

- θ term in QCD Lagrangian

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

- violates CP
  - observation (neutron electric dipole moment)

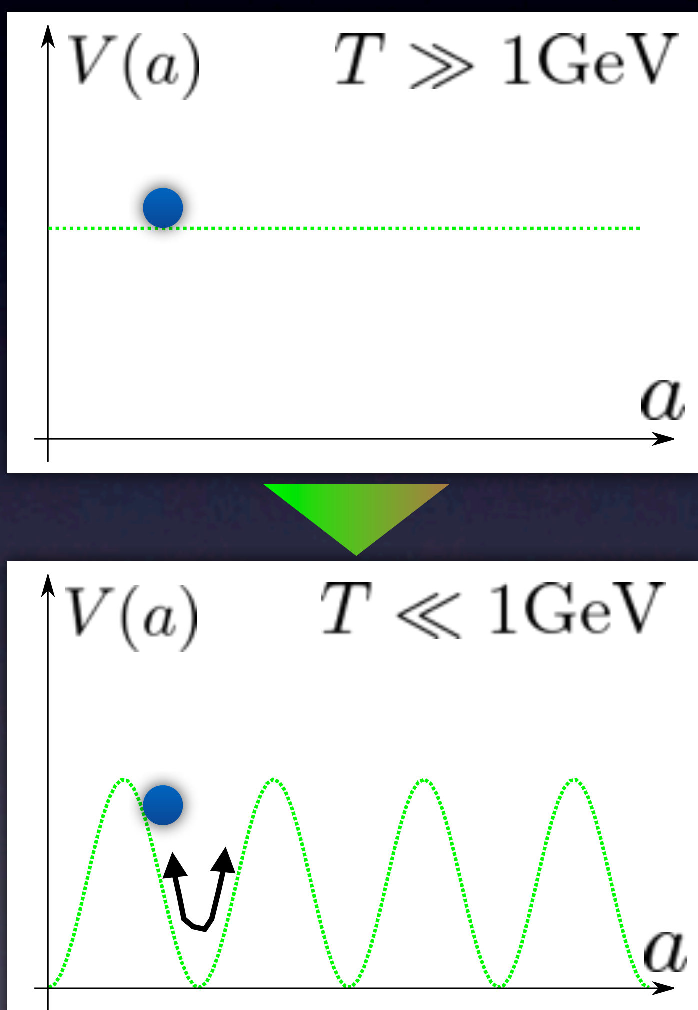
$$\theta \lesssim 10^{-10}$$

  - why θ is so small ?
- Solution : introduce U(1) symmetry (Peccei-Quinn mechanism) Peccei & Quinn, PRL38, 1440 (1977); PRD16, 1791 (1977)
  - Spontaneous breaking of $U(1)_{PQ}$
  - (pseudo) Nambu-Goldstone boson = axion
  - Good candidate of cold dark matter

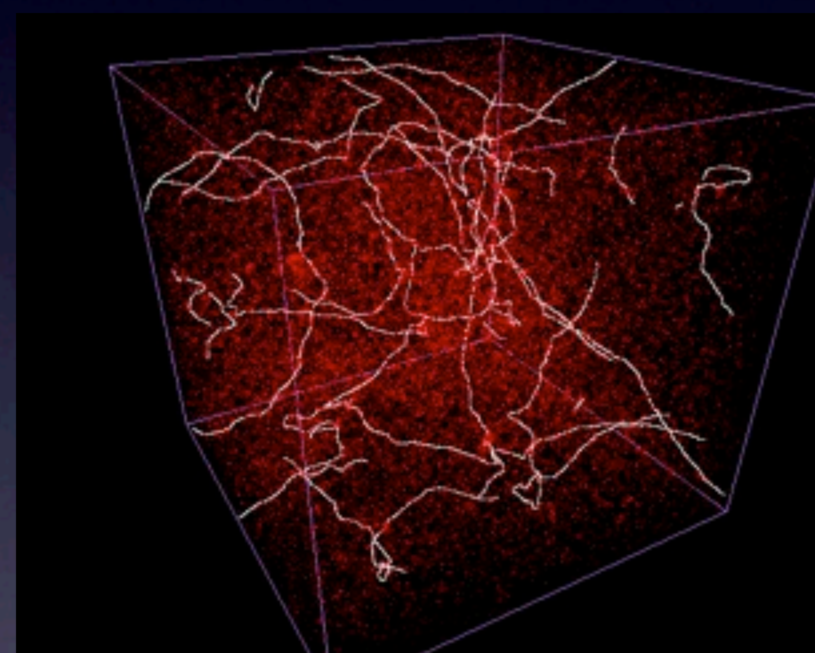
How axions are produced ?

Three mechanisms

(1) coherent oscillation

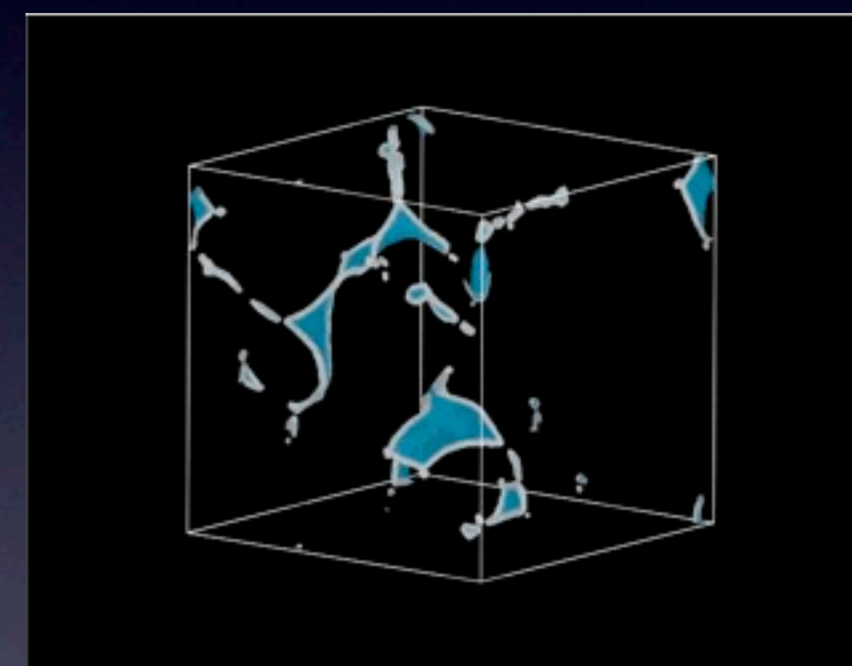


(2) radiation from strings



http://theory.physics.unige.ch/~ringeval/strings.html

(3) collapse of string-wall systems



- Total abundance is sum of three contributions
- We investigate the process (3)

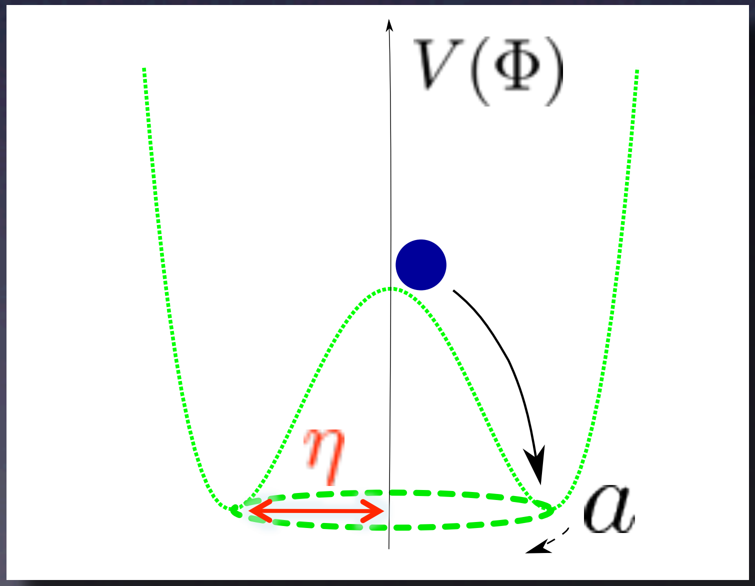
Axionic string

- Peccei-Quinn field (complex scalar field)

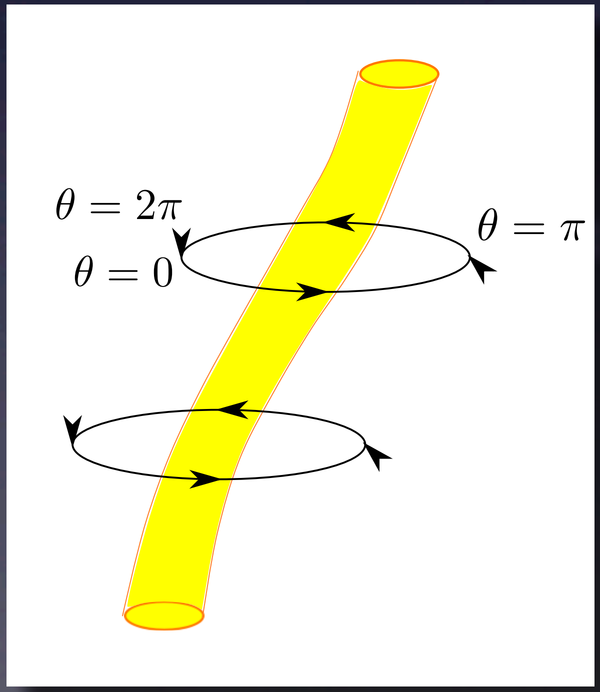
$$\Phi = |\Phi| e^{ia(x)/F_a} \qquad a(x) \text{ : axion field}$$

- breaks global U(1) symmetry

$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - \eta^2)^2$$



field space

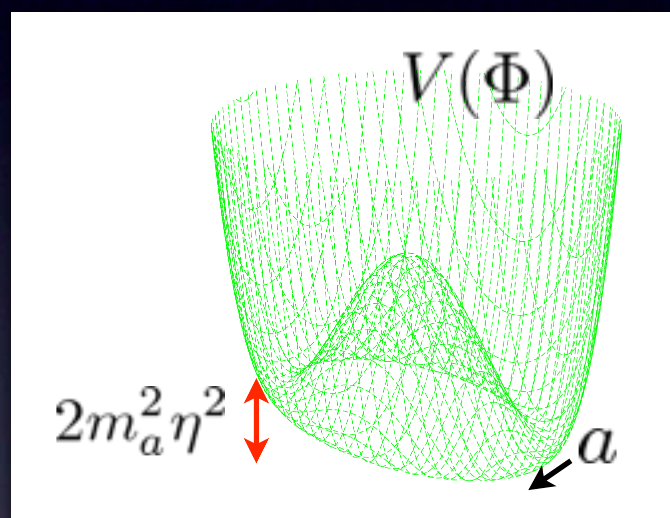


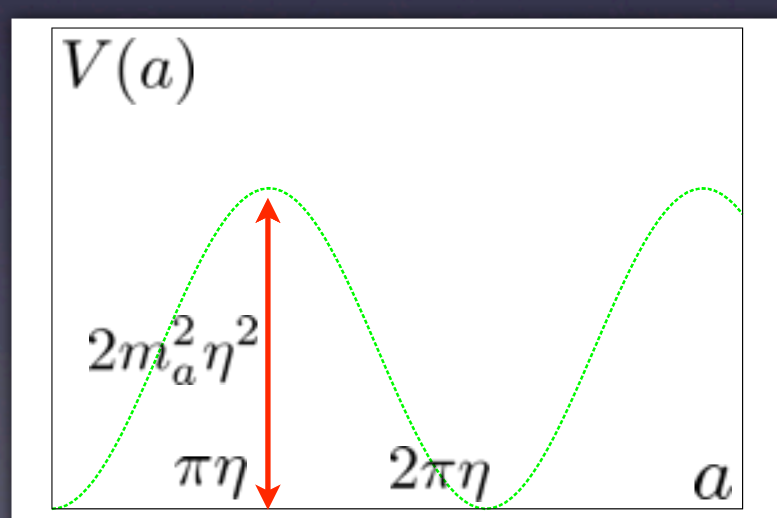
coordinate space

Axionic domain wall

- mass of the axion (QCD effect ; $T \lesssim 1\mathrm{GeV}$)

$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - \eta^2)^2 + m_a^2\eta^2(1 - \cos(a/\eta))$$





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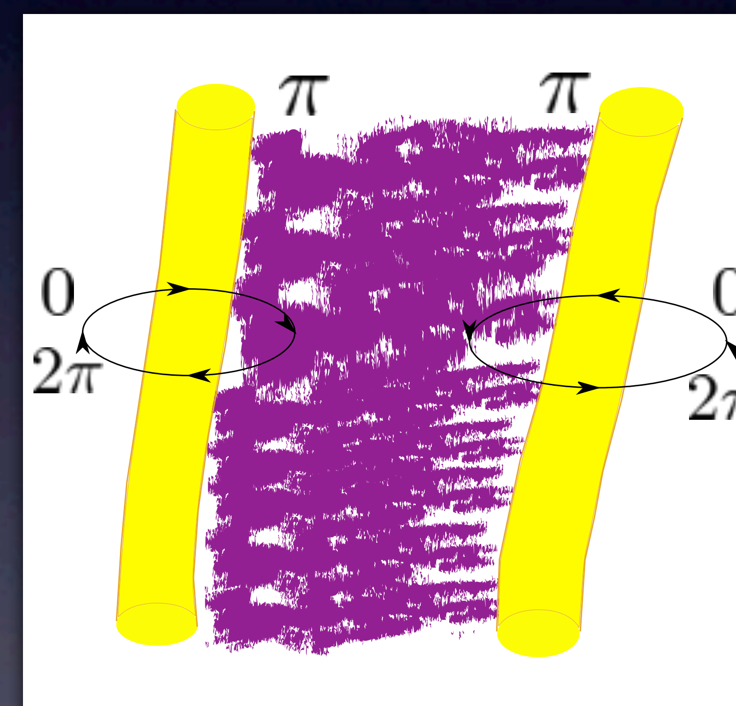


coordinate space

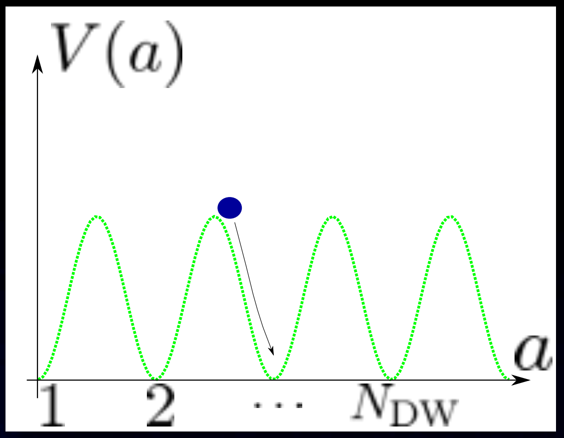
- strings attached by domain walls

Axionic domain wall problem

- Domain wall number N_{DW}

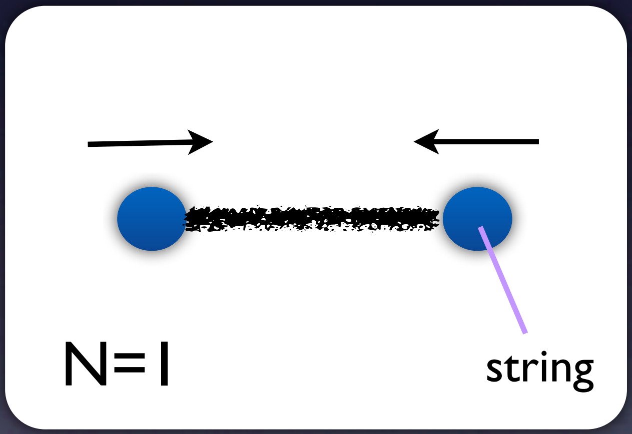
$$N_{\rm DW} = {\rm Tr}[Q_{\rm PQ}(q) I(q)]$$

: depend on models (QCD anomaly)



$$V(a) = \frac{m^2 \eta^2}{N_{\rm DW}^2}(1 - \cos(N_{\rm DW} a/\eta))$$

- If N_{DW}=1,
  string-wall networks are unstable
  - Decay → production of axions



- If N_{DW}>1,
  string-wall networks are stable
  - come to overclose the universe
    (domain wall problem) Zel'dovich, Kobzarev and Okun, JETP 40, 1 (1975)
  - we may avoid this problem by introducing a explicit symmetry breaking term (will be discussed later) Sikivie, PRL 48, 1156 (1982)

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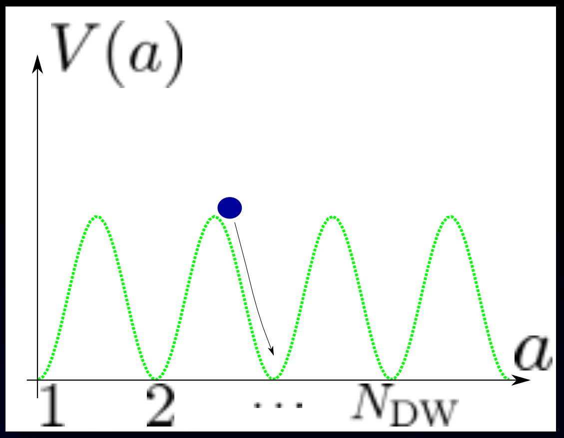

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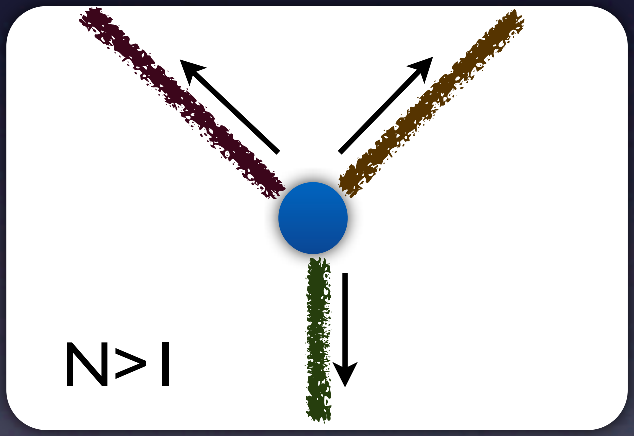

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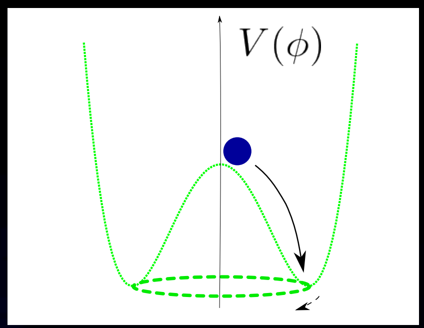
$N_{DW} = 1$

T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, hep-ph/1202.5851.

Production of axions in the universe

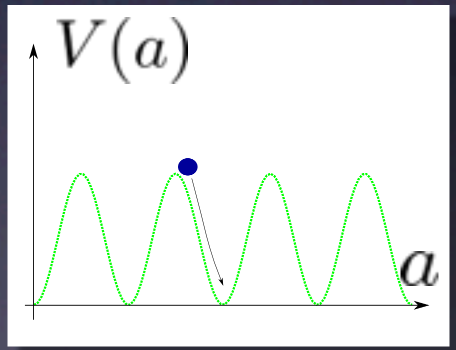


$T \simeq 10^{10-11}\text{GeV}$

$(\simeq F_a \equiv \eta / N_{\rm DW})$

"axion decay constant"

$T \lesssim 1\text{GeV}$



Inflation

↓

PQ symmetry breaking
- formation of strings

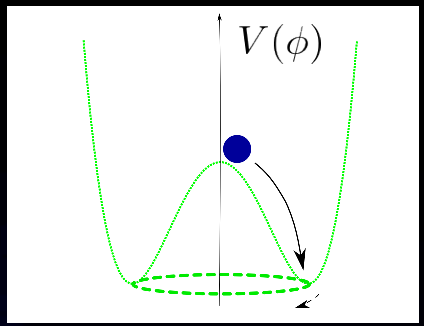
↓

QCD phase transition
- axions acquire a mass
- formation of domain walls

↓ immediately after formation ...

- collapse of string-wall networks

Production of axions in the universe



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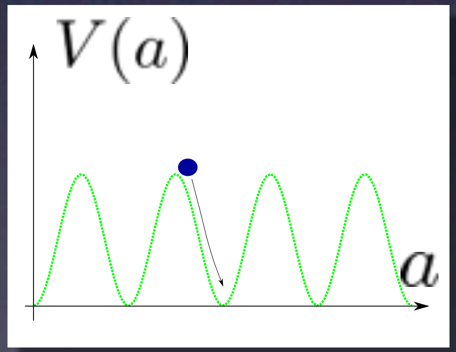

QCD phase transition
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(i) coherent oscillation

Preskill & Wise (1983)
Abbott & Sikivie (1983)
Dine & Fischler (1983)
etc.

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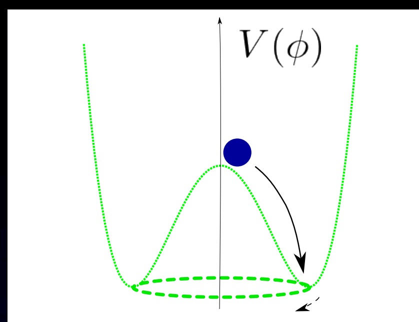

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(ii) string decay

Davis (1986)
Harari & Sikivie (1987)
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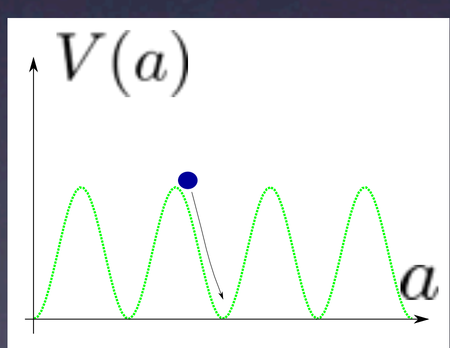

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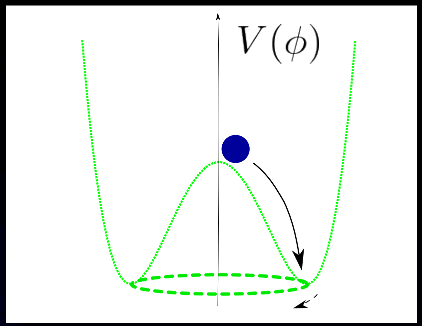

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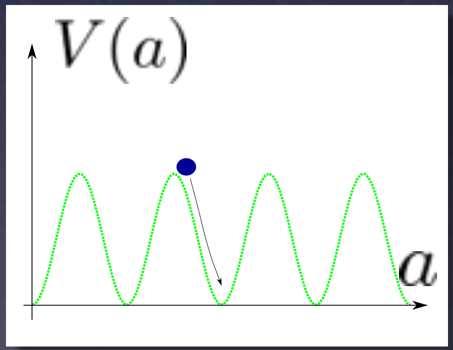

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(i) coherent oscillation

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Dine & Fischler (1983)
etc.

(iii) wall decay

Lyth (1992)
Nagasawa & Kawasaki (1994)
Chang, Hagmann & Sikivie (1998)

Wall decay contribution to CDM abundance

- On the mean energy of axions radiated from domain wall decay

Scenario A

$$\langle\omega\rangle \sim m_a$$

Nagasawa & Kawasaki (1994)

- Radiated axion is mildly relativistic
- Contribution for DM abundance can be large

Scenario B

$$\langle\omega\rangle \sim m_a \log(F_a/m_a)$$

Chang, Hagmann & Sikivie (1999)

- Spectrum is hard

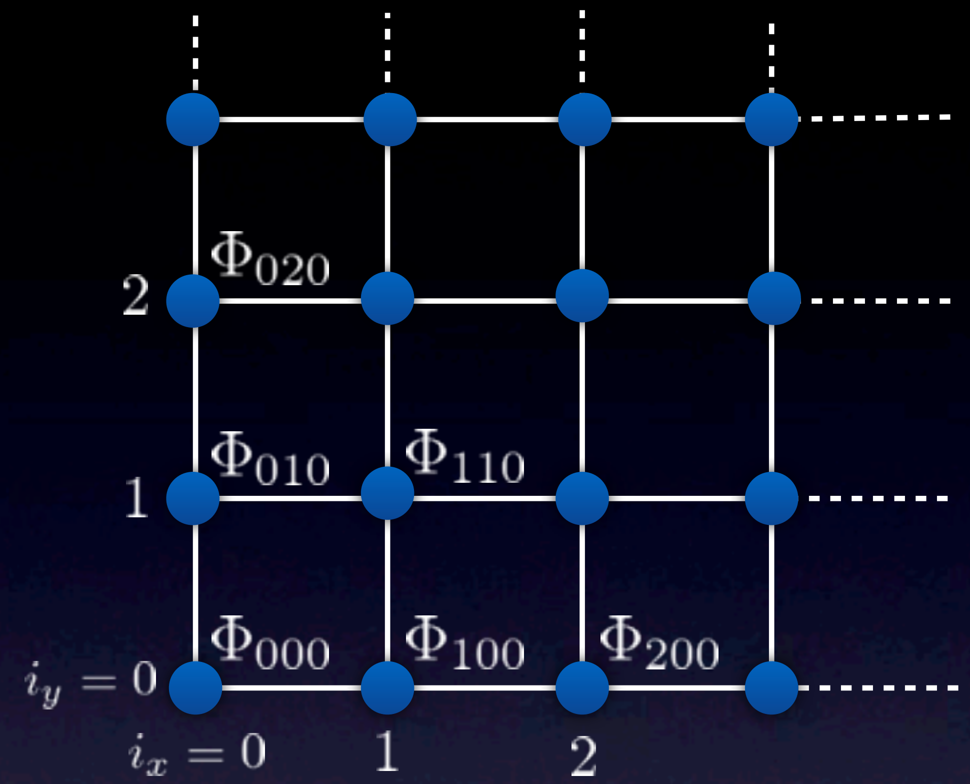
$$dE/dk \sim 1/k$$

- Contribution for DM abundance is subdominant

$$\rho_a(t_{\text{today}}) = m_a n_a(t_{\text{today}}) = m_a \frac{\rho_a(t_{\text{decay}})}{\langle\omega\rangle}\left(\frac{a(t_{\text{decay}})}{a(t_{\text{today}})}\right)^3$$

- This controversy can be resolved by simulation of defect networks

Numerical simulation



- Discretize the spatial coordinate

$$\vec{\mathbf{x}} \quad \rightarrow \quad (i_x, i_y, i_z)$$

$$\Phi(\vec{\mathbf{x}}) \quad \rightarrow \quad \Phi_{i_x i_y i_z}$$

$$i_x, i_y, i_z = 0, 1, \ldots, N-1$$

- Solve the classical EOM for complex scalar $\Phi = \phi_1 + i\phi_2$ on 3D lattice

$$\ddot{\phi}_1 + 3H\dot{\phi}_1 - \frac{\nabla^2}{a^2}\phi_1 = -\lambda\phi_1(|\Phi|^2 - \eta^2) - \frac{\lambda}{3}T^2\phi_1 + m_a^2\eta$$

$$\ddot{\phi}_2 + 3H\dot{\phi}_2 - \frac{\nabla^2}{a^2}\phi_2 = -\lambda\phi_2(|\Phi|^2 - \eta^2) - \frac{\lambda}{3}T^2\phi_2$$

- Number of grids in simulation box : $N^3 = 512^3$

- Numerical computation is carried out in SR16000 at the Yukawa Institute Computer Facility

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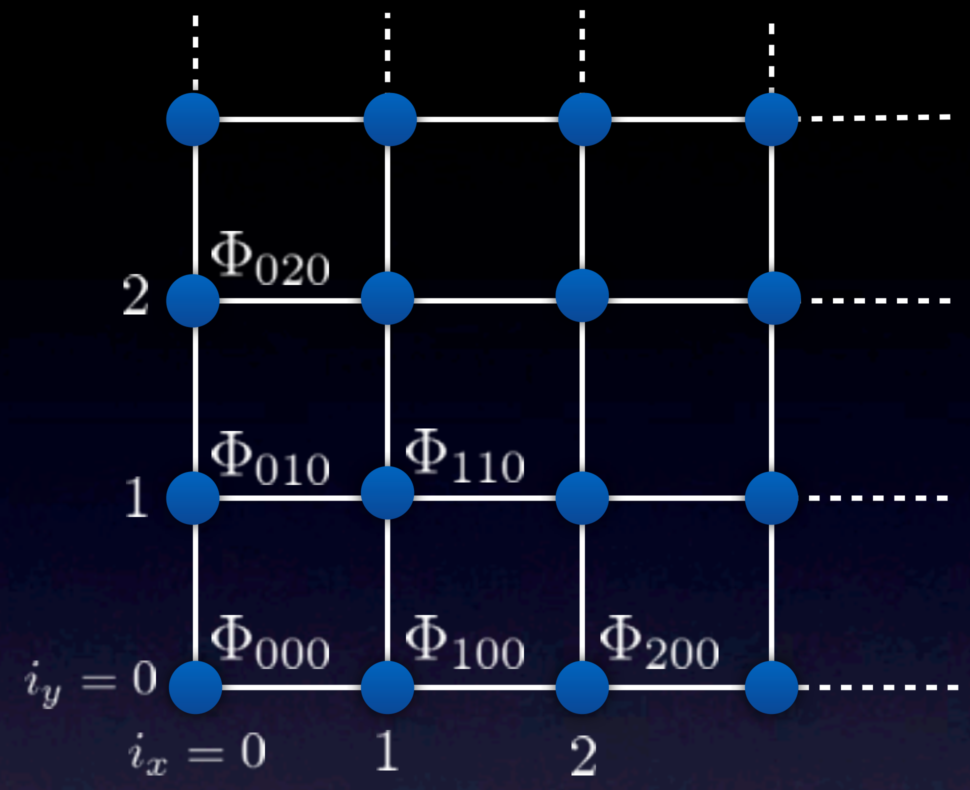

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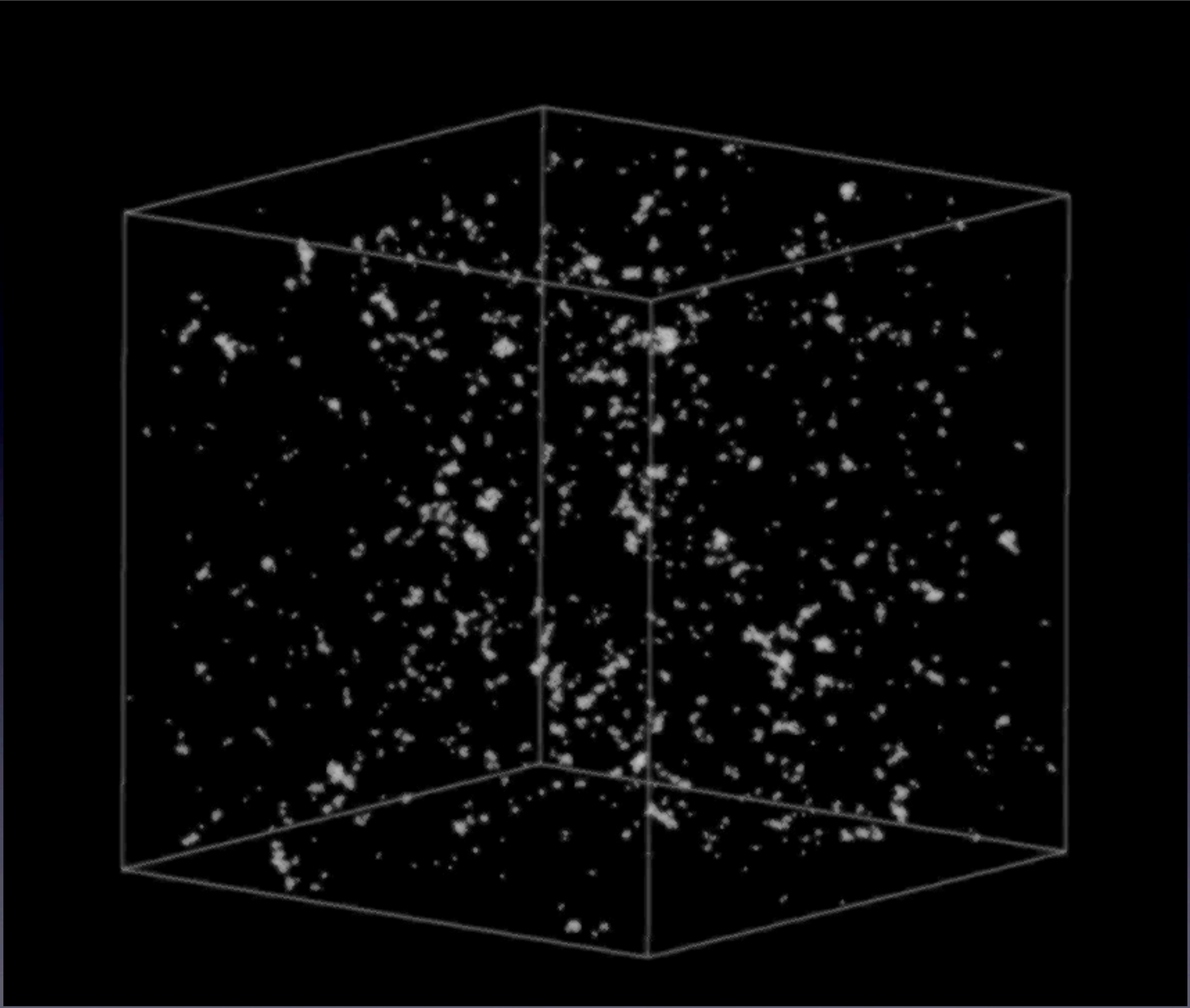
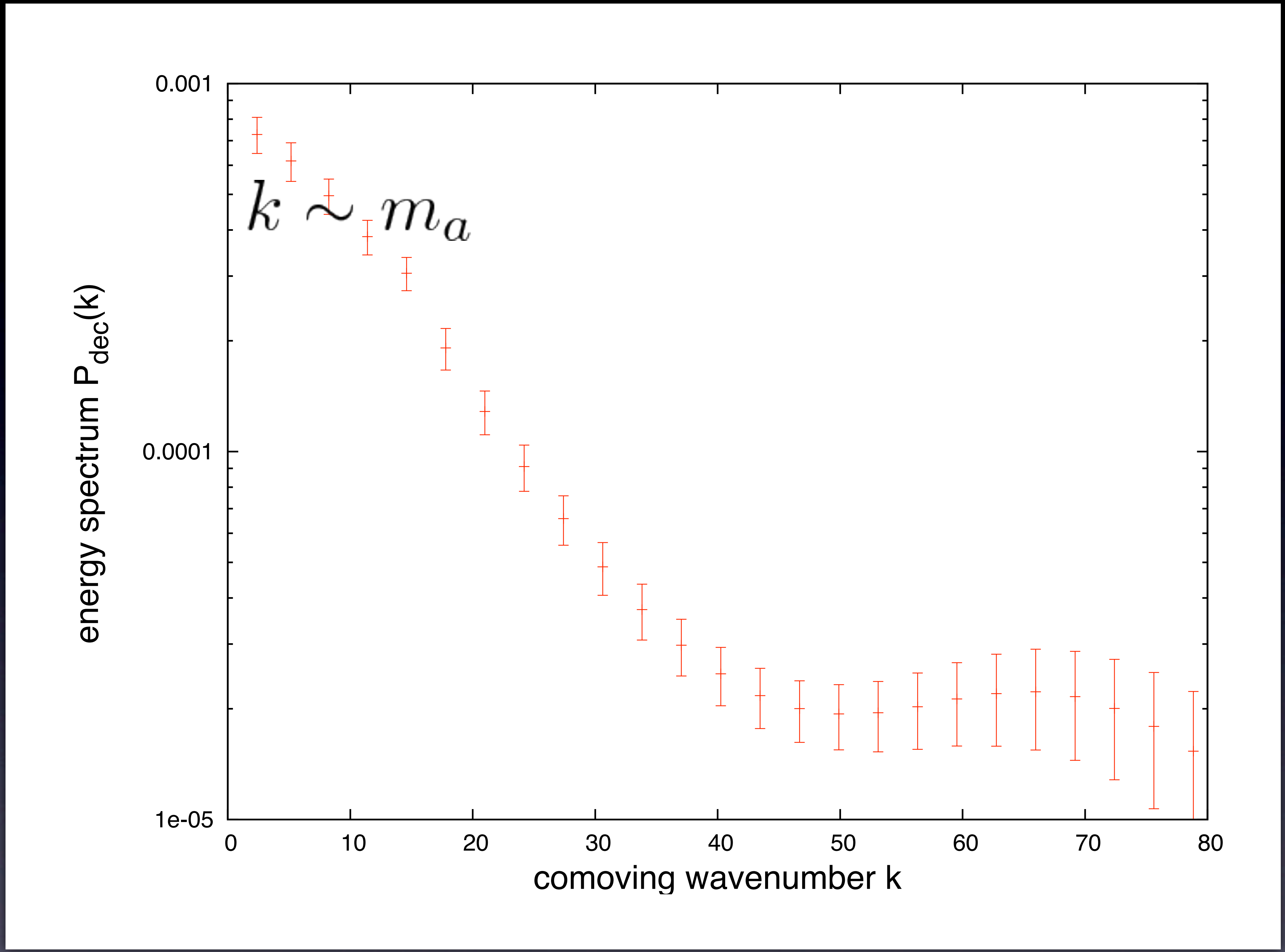




Radiated axions are mildly relativistic. $\langle \omega \rangle \simeq 3m_a$

Nagasawa & Kawasaki (1994)

Contribution to CDM abundance

$$\Omega_{a,(\mathrm{wall\ decay})}h^2 \simeq 11 \times \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19}\left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right)$$

cf. $$\Omega_{a,(\mathrm{coherent\ osc.})}h^2 \simeq 0.58 \times \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19}\left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right)$$

$$\Omega_{a,(\mathrm{string})}h^2 \simeq 4.0 \times \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19}\left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right)$$

$$\Omega_{a,(\mathrm{total})}h^2 = \Omega_{a,(\mathrm{coherent\ osc.})}h^2 + \Omega_{a,(\mathrm{string})}h^2 + \Omega_{a,(\mathrm{wall\ decay})}h^2$$

$$< \Omega_{\mathrm{CDM}}h^2 = 0.11$$

→ $F_a \lesssim 2 \times 10^{10}\mathrm{GeV}$ $(\, m_a > 10^{-4} - 10^{-3}\mathrm{eV}\,)$

- Tighter constraint than coherent oscillation ($F_a \lesssim 10^{12}\mathrm{GeV}$)
- cf. bound from astrophysics : $F_a \gtrsim \mathrm{a\ few} \times 10^{8}\mathrm{GeV}$ $(m_a < 10^{-2}\mathrm{eV})$

$N_{DW} > 1$

T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, hep-ph/1207.3166.

Cosmological evolution in the model with $N_{DW}>1$

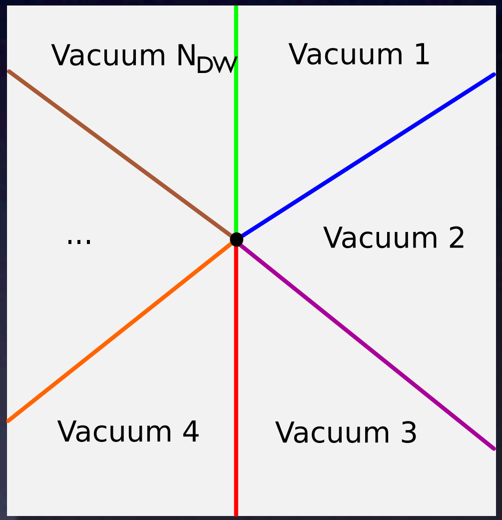
Inflation

$T \simeq 10^{10-11}\mathrm{GeV}$

PQ symmetry breaking
- formation of strings

$T \lesssim 1\mathrm{GeV}$

QCD phase transition
- axions acquire a mass
- formation of domain walls



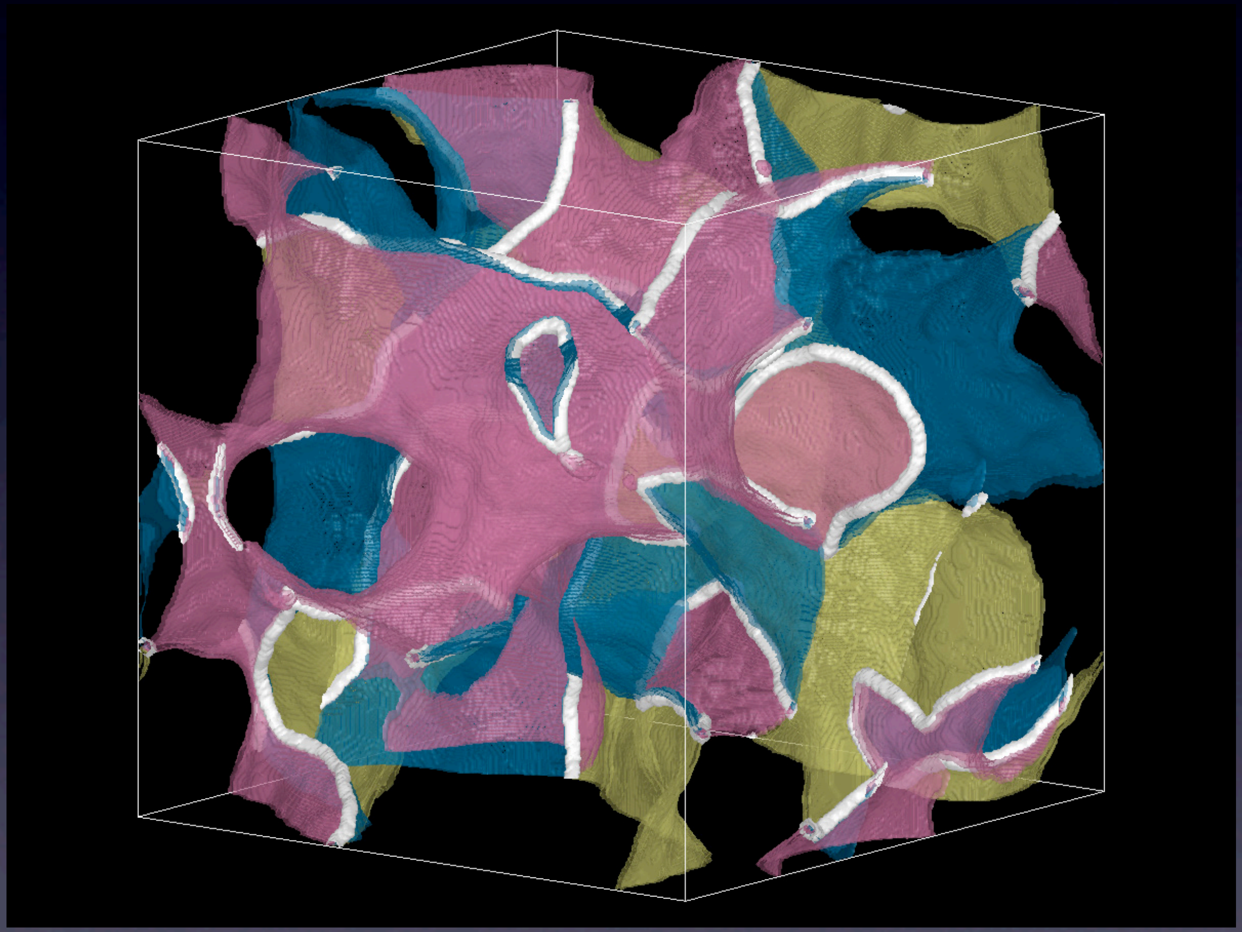
string-wall networks exist for a long time

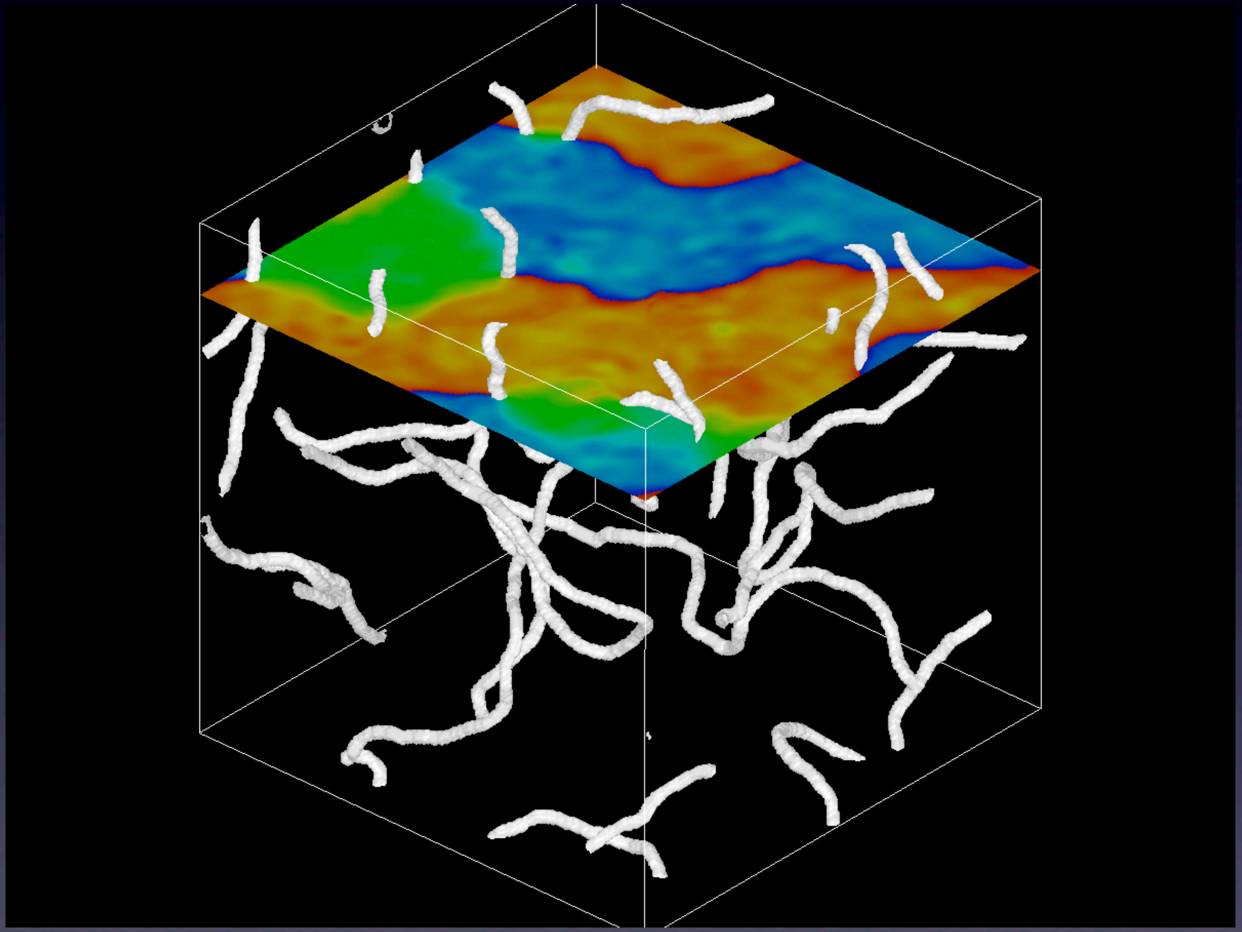
Production of
- axions
- gravitational waves

$T \gtrsim 1\mathrm{MeV}$

annihilation of domain walls before they overclose the universe

N_{DW}=3





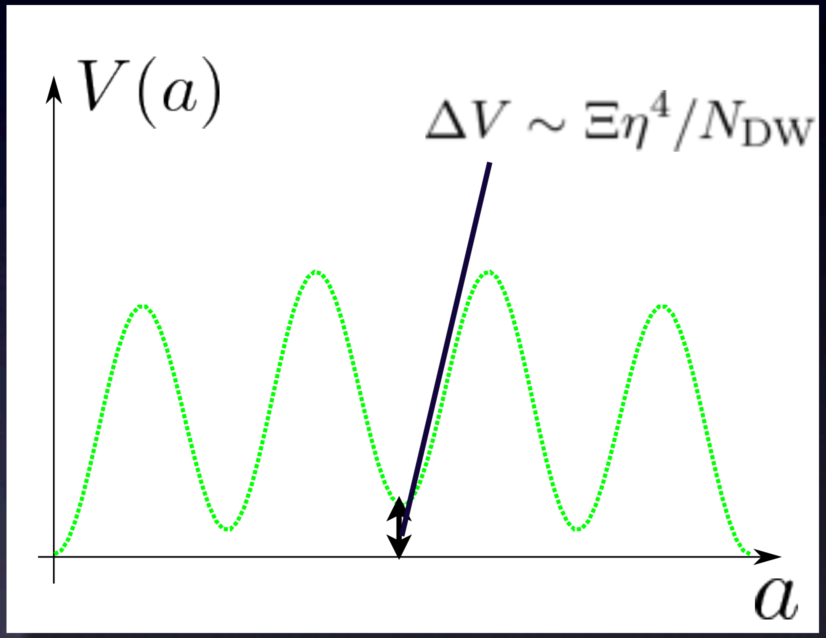
Avoiding wall domination

- The explicit $Z_{N_{DW}}$ breaking term (bias) Sikivie, PRL 48, 1156 (1982)

$$V(\phi) = \frac{m^2\eta^2}{N_{\rm DW}^2}(1-\cos N_{\rm DW}\theta) - \boxed{\Xi\eta^3(\phi e^{-i\delta} + \text{h.c.})}$$

Ξ term lifts degenerate vacua

→ decay of walls

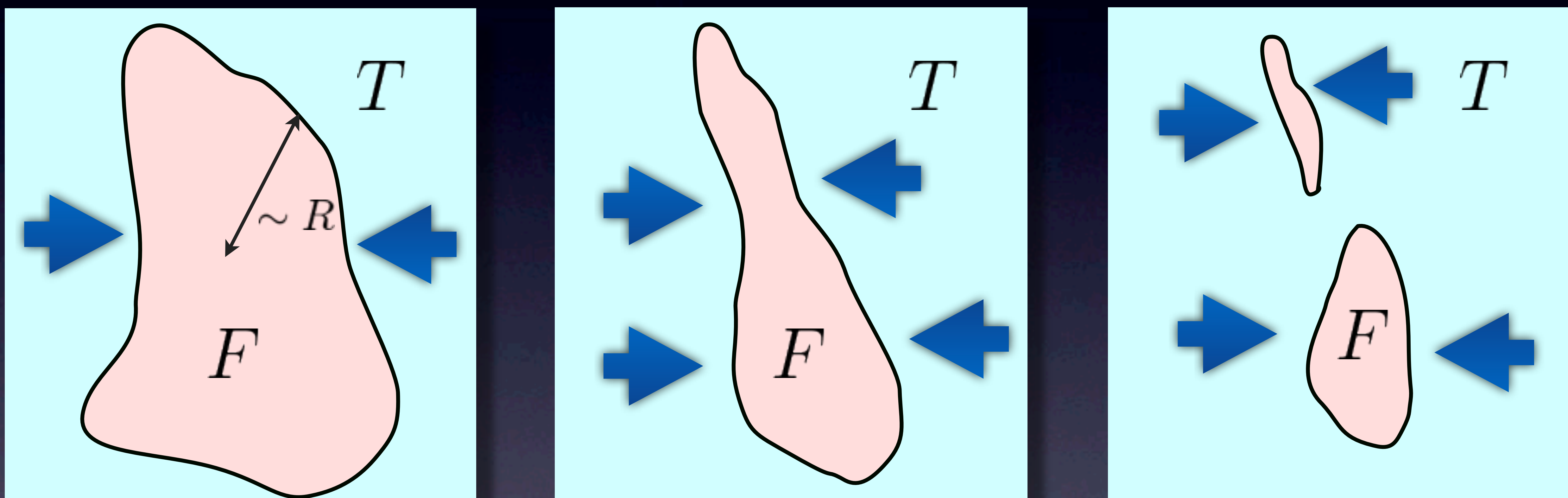


- Unstable but long-lived domain walls
  - copiously produce axions
  - Ξ term shifts CP conserving minimum

→ constraints on model parameters

Collapse of domain walls

Due to the volume pressure $p_V \sim \Delta V \sim \Xi\eta^4/N_{\rm DW}$



Annihilation occurs when

$$p_V \sim p_T$$

$$p_T \sim \sigma/R \sim m\eta^2/N_{\rm DW}^2 R$$

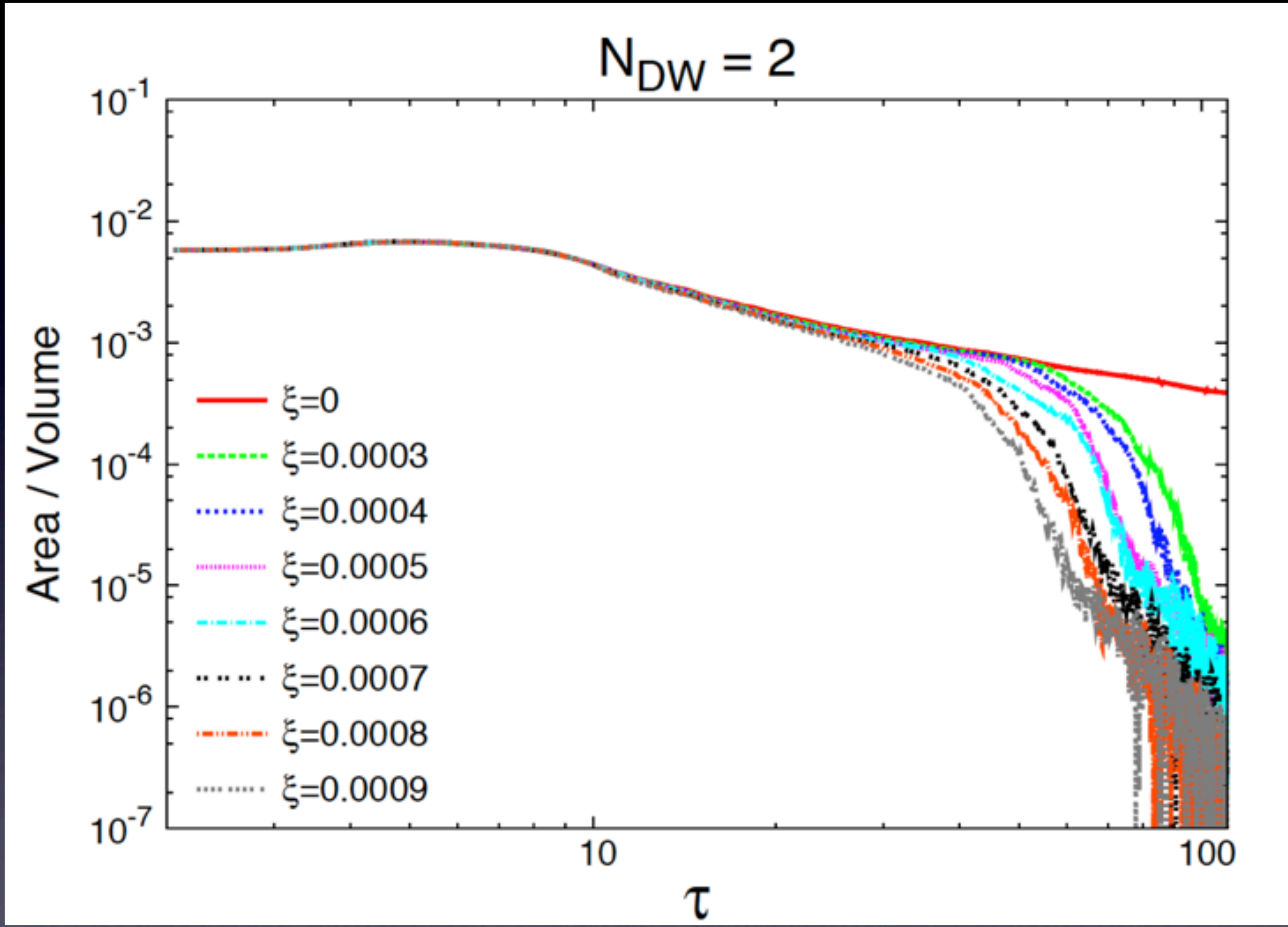
: tension of walls

R : curvature radius

Decay time

$$t_{\rm dec} \sim R \sim m/N_{\rm DW}\Xi\eta^2$$

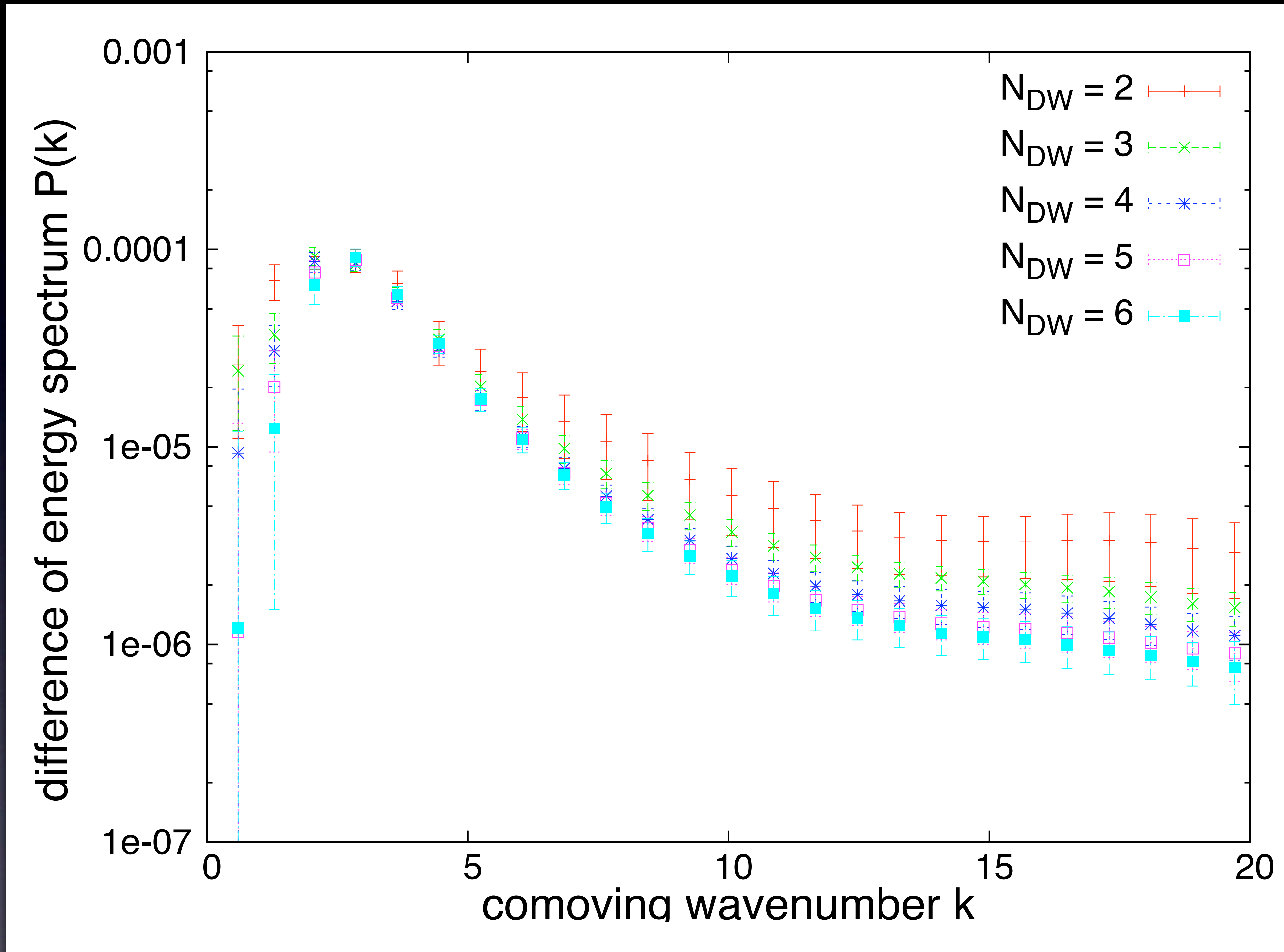
Annihilation time



T. Hiramatsu, M. Kawasaki and KS, JCAP08(2011)030

$$t_{\rm dec} \simeq 18 \times \left(\frac{m}{N_{\rm DW} \Xi \eta^2} \right)$$

Spectrum of radiated axions ($N_{DW}>1$)



$\langle\omega\rangle \simeq \mathrm{a\ few} \times m_a$: similar result with $N_{DW}=1$

Observational constraints

- Cold dark matter abundance

$$\rho_{\rm wall}(t_{\rm dec}) \begin{array}{l} \nearrow \rho_a \\ \searrow \rho_{\rm gw} \end{array} \Rightarrow \Omega_a h^2 \leq \Omega_{\rm CDM} h^2 \simeq 0.11$$

- Neutron electric dipole moment

Non zero value of Ξ

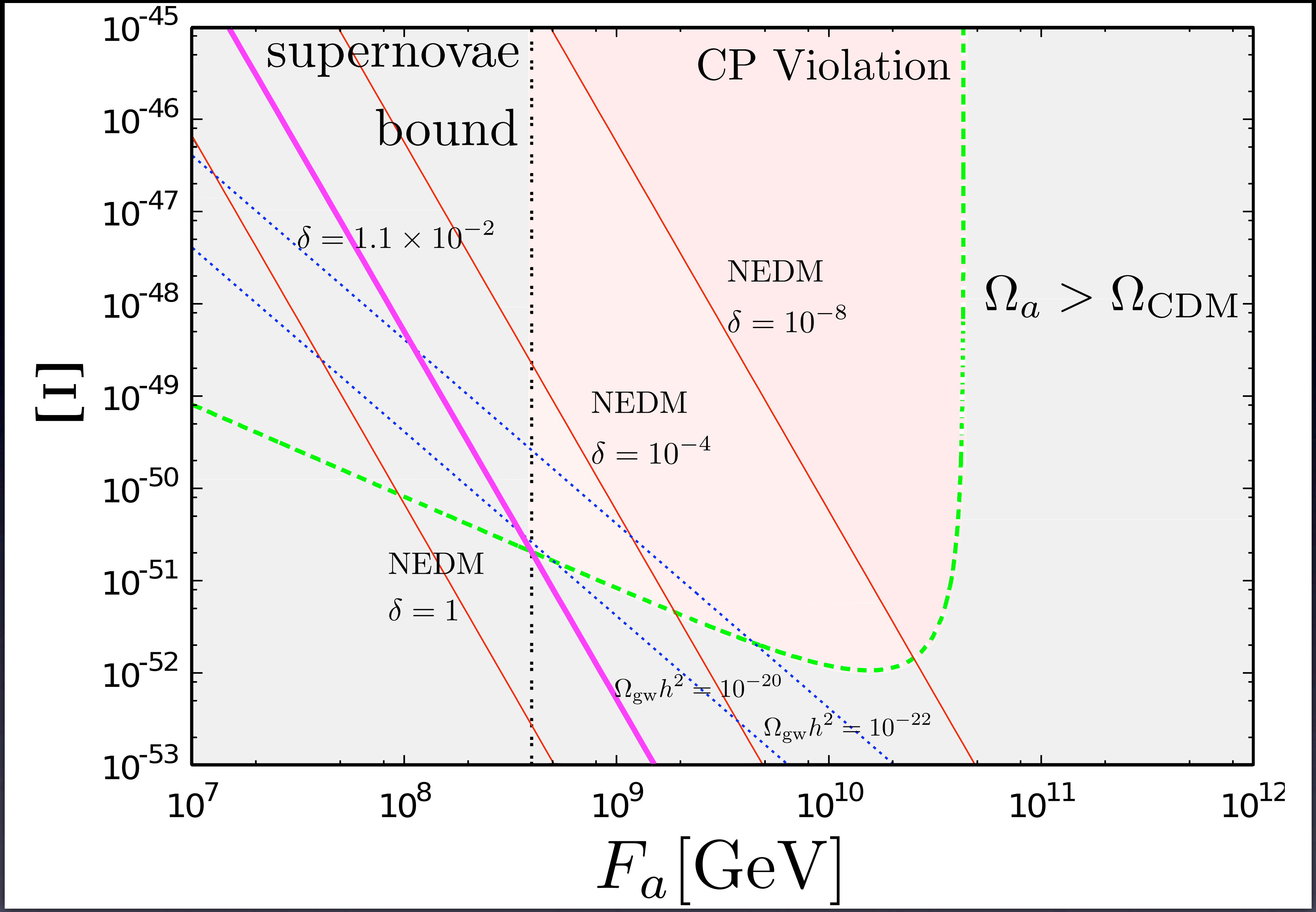
$\Rightarrow$ shift the CP conserving minimum

$$\bar{\theta} = \frac{\langle a \rangle}{F_a} = \frac{2N_{\rm DW}\Xi\eta^2 \sin\delta}{m_a^2 + 2\Xi\eta^2\cos\delta} < 0.7 \times 10^{-11}$$

- Cooling rate of Supernova 1987A

$$F_a > 4 \times 10^8 {\rm GeV}$$

Constraints for parameters



- Whole parameter region is excluded unless δ is highly suppressed

Summary

- axions produced from decay of walls give significant contribution to CDM abundance
  → severe constraint on axion models
- Three possibilities for cosmologically viable axion dark matter
  - $N_{DW}=1$: walls quickly disappear
    axion mass is constrained $m_a \simeq 10^{-3} - 10^{-2}\mathrm{eV}$
  - $U(1)_{PQ}$ is broken before(during) inflation:
    no domain wall problem but severe constraint from isocurvature fluctuations
  - $N_{DW}>1$ + Ξ term + highly suppressed δ
    (less attractive)