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Cosmological problems in axion models

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Based on
MK, Yanagida, Yoshino, arXiv:1305.5338
also
Hiramatsu, MK, Saikawa, Sekiguchi, arXiv:1202.5851
Hiramatsu, MK, Saikawa, Sekiguchi, arXiv:1207.3166
Hikage, MK, Sekiguchi, Takahashi, arXiv:1211.1095

1. Axion

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

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

- Axion acquires mass through QCD non-perturbative effect

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

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

- Axion is a good candidate for dark matter of the universe
- However, there exist serious domain wall and isocurvature perturbation problems in axion models

2. Cosmological Evolution of Axion

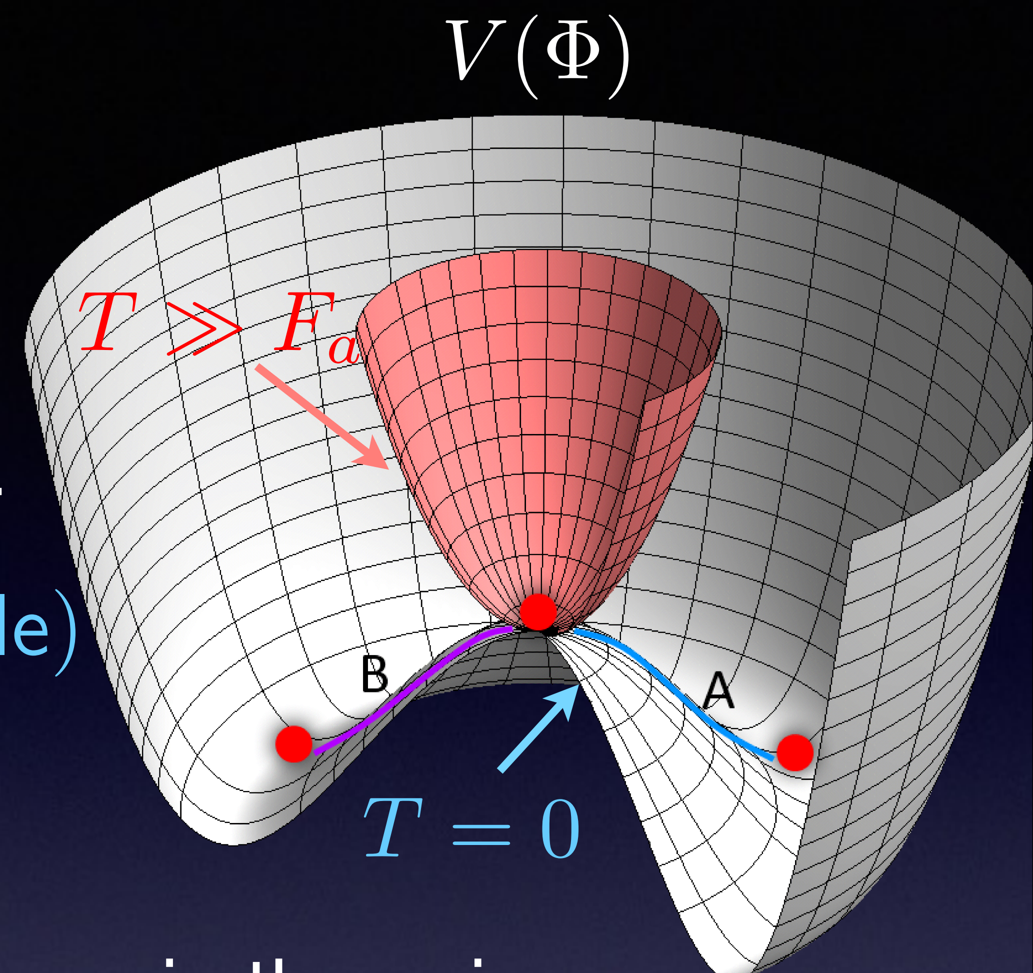
$T \simeq F_a (= v/N_{\mathrm{DW}})$

- $U_{PQ}(1)$ symmetry is broken
  - axion is a phase direction of PQ scalar

    $\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/v}$ (v breaking scale)

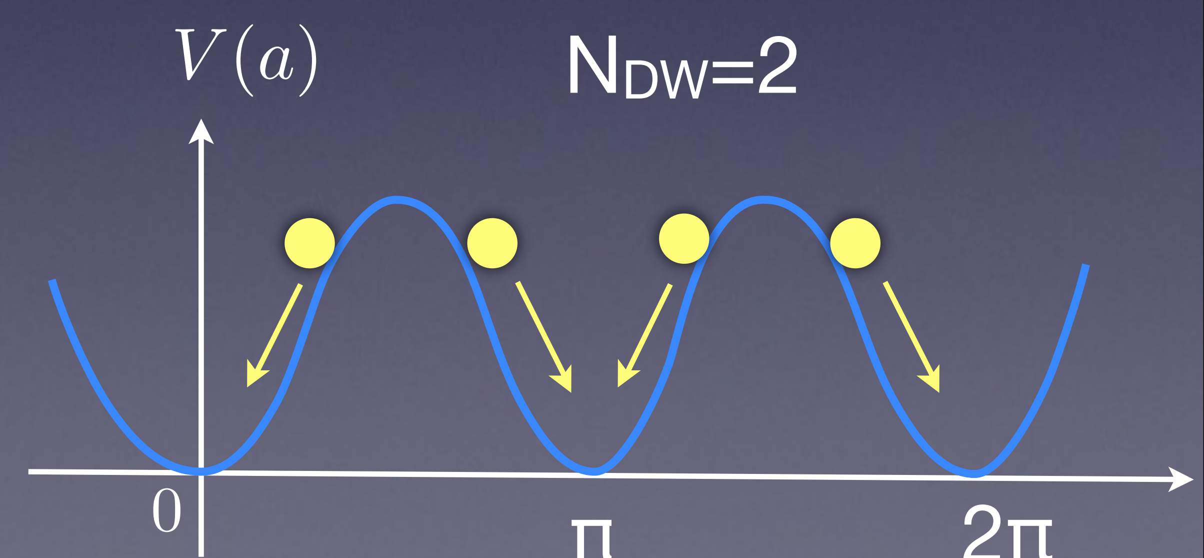
    $m_a = 0$
  - Formation of Cosmic Strings

    θ takes differentt values at different places in the universe



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

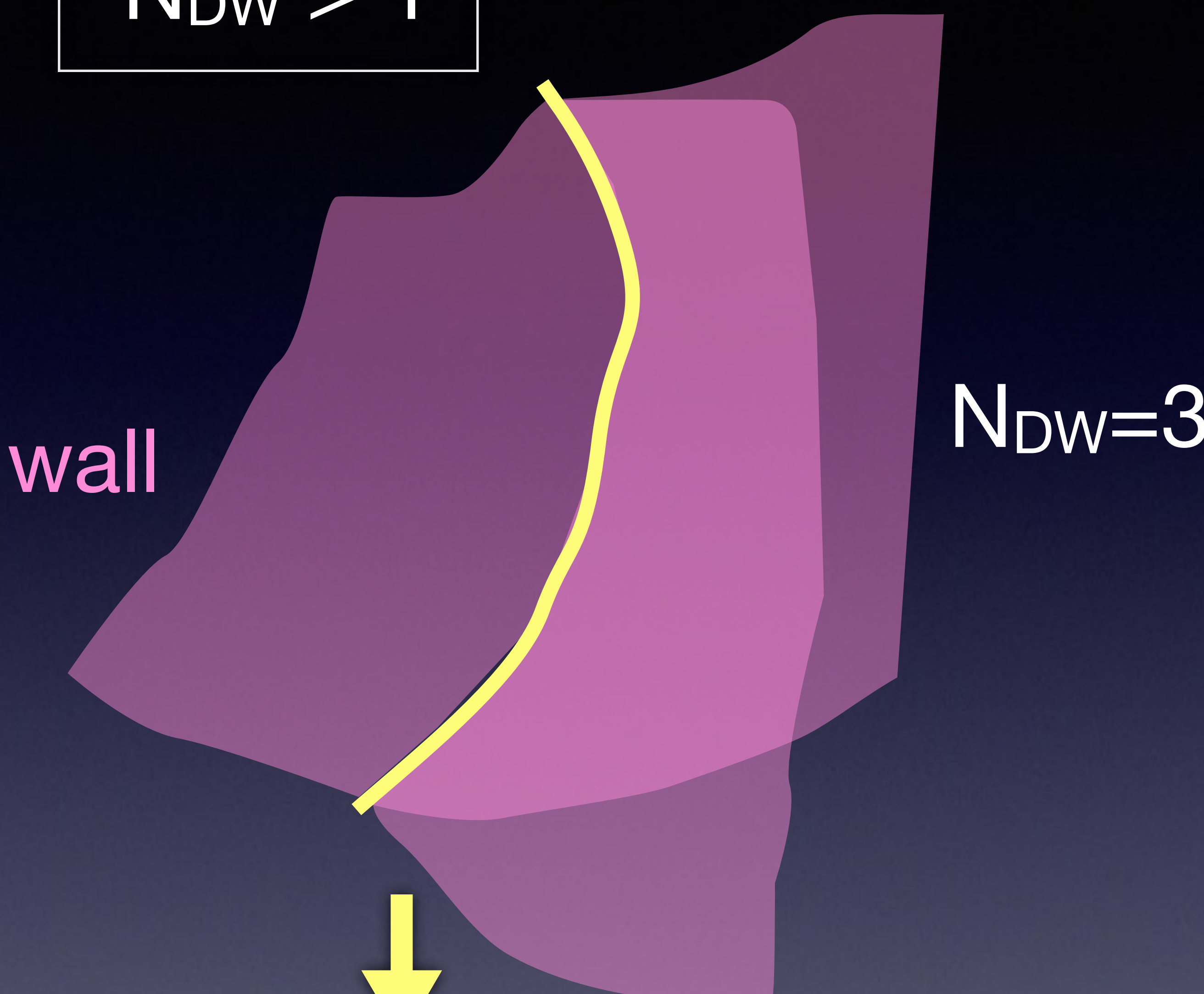
- Axion acquires mass through non-perturbative effect
  - $U_{PQ}(1)$ is broken to $Z_{N_{DW}}$
  - Formation of Domain Walls
  - Coherent oscillation ⟹ dark matter



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

- Domain walls attach to strings

$N_{DW} > 1$



↓

Stable and dominate the universe

↓

Domain Wall Problem

$N_{DW}=1$

↓

Collapse

↓

Axion overproduction

Cosmic Axion Density

- Coherent oscillation

$$\Omega_{a,\text{osc}} \simeq 0.19 \, \langle \theta_*^2 \rangle \left(\frac{F_a}{10^{12}\text{GeV}} \right)^{1.19}$$

$$\langle \theta_*^2 \rangle \simeq 6$$

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

- Axions from axionic strings

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

$$\Omega_{a,\text{str}} \simeq (4.0 \pm 2.0) \left(\frac{F_a}{10^{12}\text{GeV}} \right)^{1.19}$$

- Axions from domain walls
  - $N_{DW} = 1$

Hiramatsu, MK, Saikawa, Sekiguchi (2012)

$$\Omega_{a,\text{wall}} \simeq (11.8 \pm 5.7) \left(\frac{F_a}{10^{12}\text{GeV}} \right)^{1.19}$$

Dominant contribution

- Constraint

$$F_a \lesssim (2.0 - 3.8) \times 10^{10} \text{ GeV}$$

Domain Wall Problem

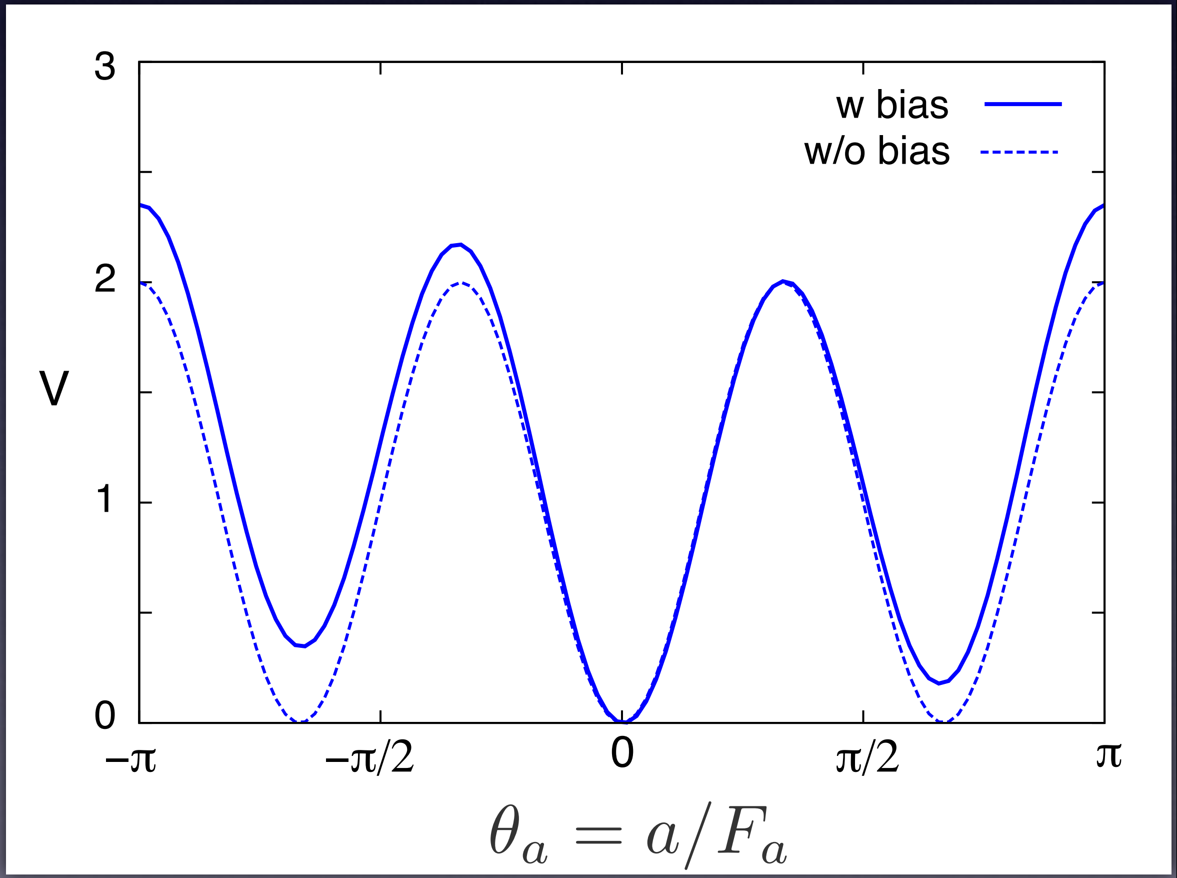
- For $N_{DW} > 1$
  - Produced domain walls are stable and soon dominate the universe, which causes a serious cosmological problem

    → Domain Wall Problem

  - The problem might be avoided by introducing "bias" which explicitly breaks PQ symmetry

$$\delta V = -\Xi v^3 (\Phi e^{-i\delta} + \text{h.c.})$$

Sikivie (1982)

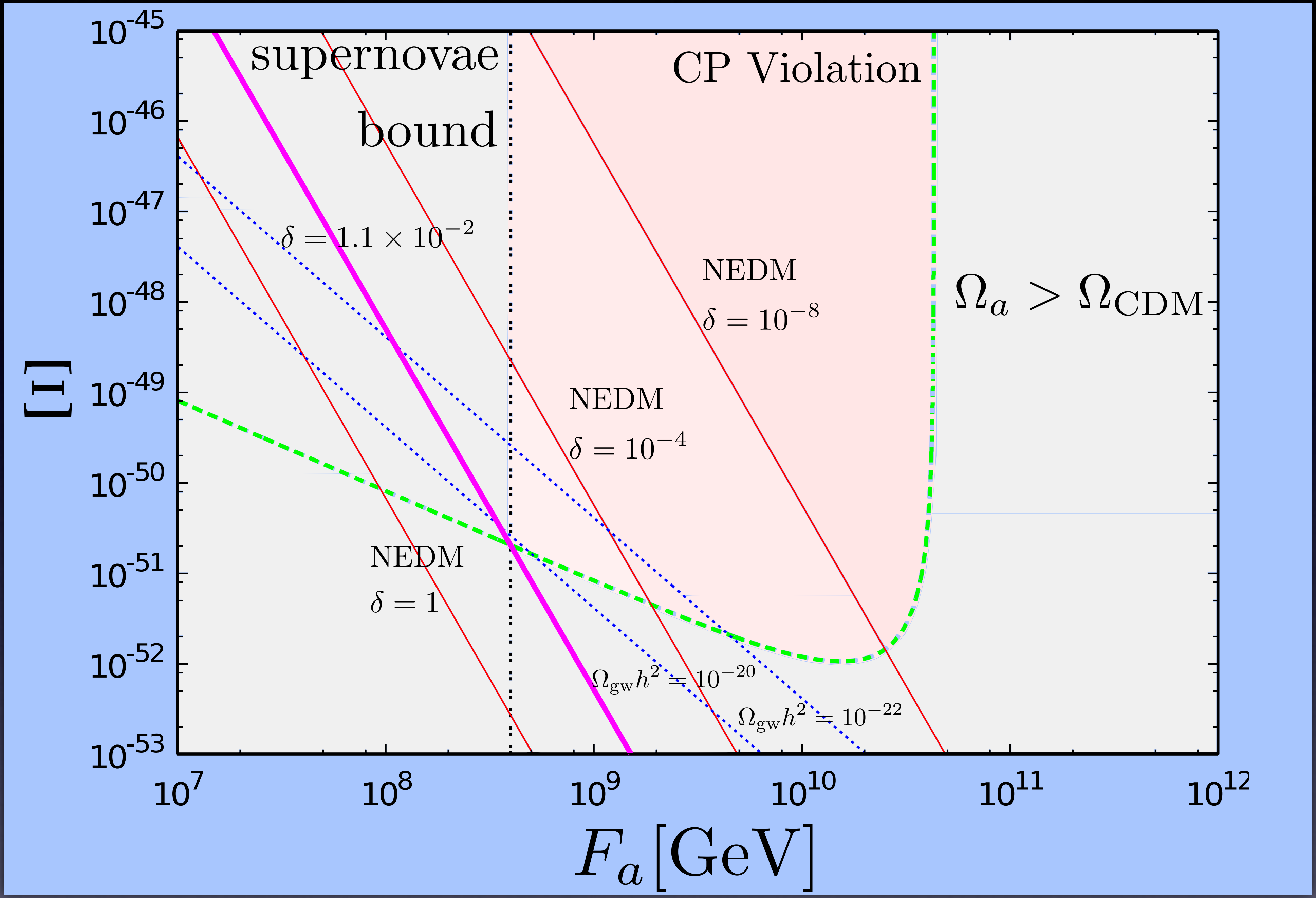


- Large bias
  Bias term shifts the minimum of the potential and might spoil the original idea of Peccei and Quinn

- Small bias
  Long-lived walls emit many axions

Constraints

Hiramatsu, MK, Saikawa, Sekiguchi (2012)



- Axion models with $N_{DW} > 1$ are excluded if δ > 0.01
  (δ: phase of the bias term ~ O(1))
- This applies when PQ symmetry is broken after inflation

3. Axion in the Inflationary Universe

- If PQ symmetry is broken after inflation

  The previous arguments about cosmological evolution of axion are applicable without modifications

- If PQ symmetry is broken before inflation

  - Strings and domain walls are diluted away by inflation
    No domain wall problem

  - Only coherent oscillation gives a significant contribution to the cosmic density

$$\Omega_{a,\mathrm{osc}} \simeq 0.19\ \theta_*^2 \left(\frac{F_a}{10^{12}\mathrm{GeV}} \right)^{1.19}$$

  Inflation makes θ_* the same in the whole observable universe (θ_* is a kind of free parameter)

  - Isocuravture perturbation problem

Axion Fluctuations during Inflation

- Axion acquires fluctuations during inflation

$$\delta a = F_a \delta\theta_a \simeq \frac{H_{\rm inf}}{2\pi}$$

$$\rho_a = \rho_a(t) + \delta\rho_a(t,\vec{x}) = m_a^2[a(t) + \delta a(t,\vec{x})]^2/2$$

$$= m_a^2 F_a^2[\theta_* + \delta\theta_a(\vec{x})]^2/2$$

- Small fluctuation

$$\theta_* > \delta\theta_a \quad \Rightarrow \quad \frac{\delta\rho_a}{\rho_a} \simeq 2\frac{\delta\theta_a}{\theta_*} + \left(\frac{\delta\theta_a}{\theta_*}\right)^2$$

- Large fluctuation

$$\theta_* < \delta\theta_a \quad \Rightarrow \quad \frac{\delta\rho_a}{\rho_a} \simeq \left(\frac{f_a\delta\theta_a}{H_{\rm inf}/2\pi}\right)^2$$

non-Gaussianity

Fluctuations determine the density

$$\Omega_a \simeq 0.19\left(\frac{F_a}{10^{12}{\rm GeV}}\right)^{-0.81}\left(\frac{H_{\rm inf}/2\pi}{10^{12}{\rm GeV}}\right)^2$$

Lyth (1992)

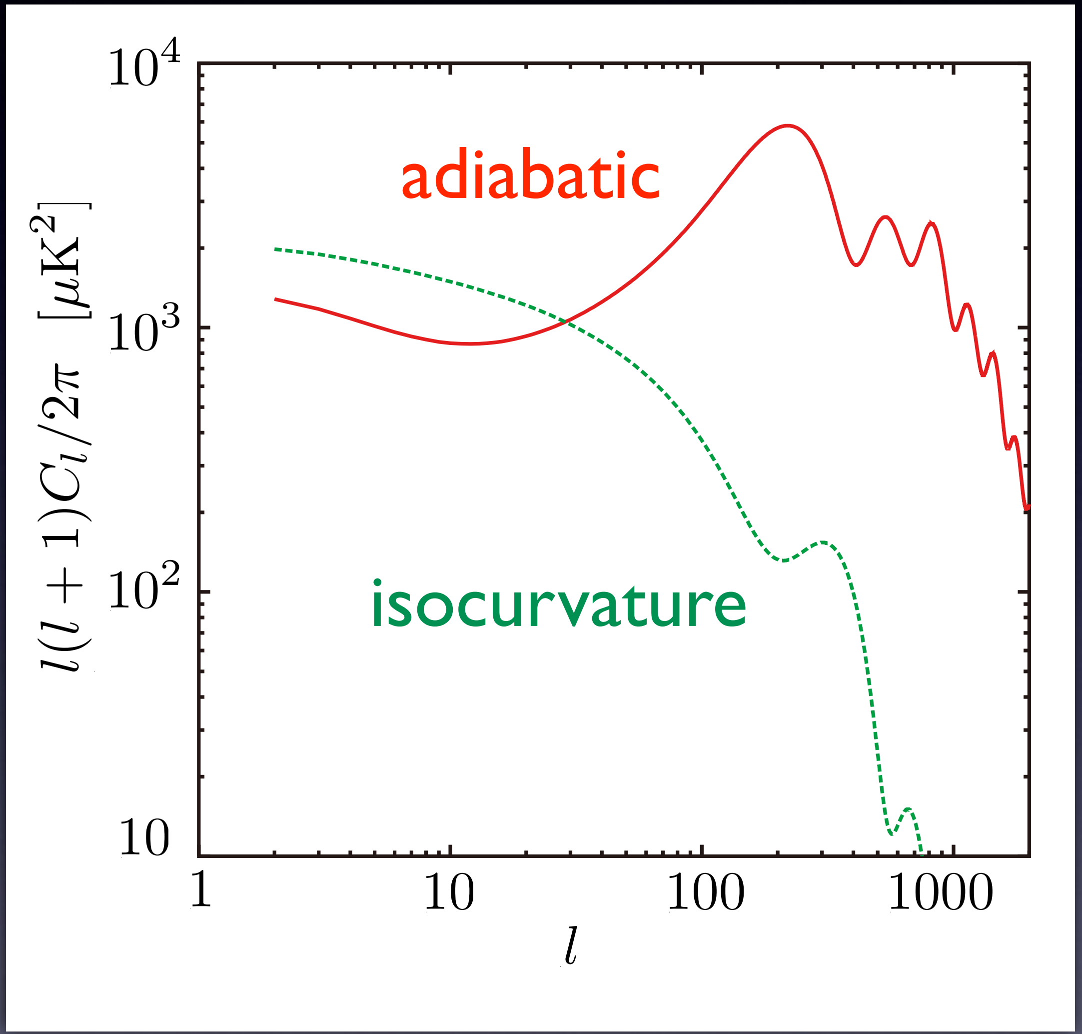
4. Axion Isocurvature Fluctuations

- Axion fluctuations produced during inflation contribute to CDM isocurvature density perturbation

$$S = \frac{\delta\rho_{\mathrm{CDM}}}{\rho_{\mathrm{CDM}}} - \frac{3\delta\rho_\gamma}{\rho_\gamma} = \frac{\Omega_a}{\Omega_{\mathrm{CDM}}}\frac{\delta\rho_a}{\rho_a}$$

- Isocurvature perturbation leads to characteristic CMB angular power spectrum

CMB angular Power spectrum



- Stringent constraint on amplitude of isocurvature perturbation

$$\beta_{\mathrm{iso}} \equiv \frac{P_S(k_0)}{P_\zeta(k_0) + P_S(k_0)}$$

$k_0 = 0.002\ \mathrm{Mpc}^{-1}$

- WMAP9

$$\beta_{\mathrm{iso}} < 0.047\ (95\%\ \mathrm{CL})$$

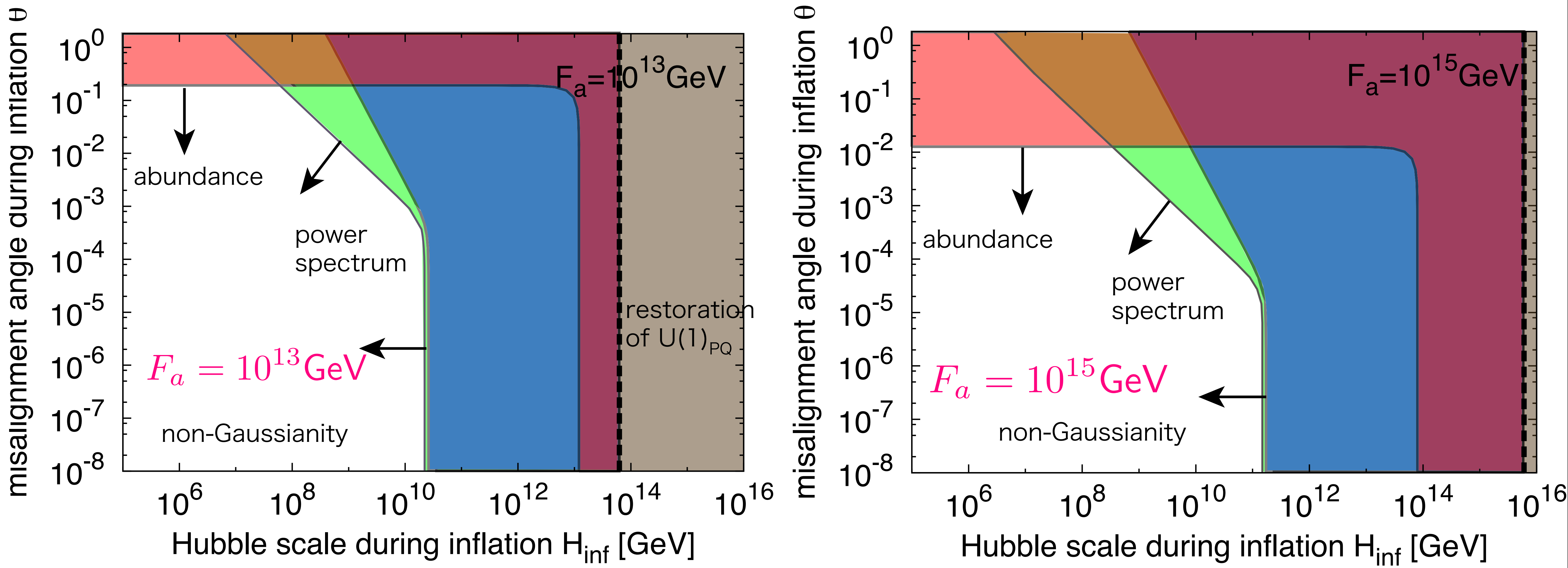
- PLANCK

$$\beta_{\mathrm{iso}} < 0.036\ (95\%\ \mathrm{CL})$$

Axion isocurvature fluctuations

- Stringent constraints from CMB

Hikage, MK, Sekiguchi, T.Takahashi (2012)



Constraint from power spectrum is updated including Planck data

- Only low energy scale inflation models are allowed
  Chaotic inflation is inconsistent with axion

- If axion is dark matter

$$H_{\rm inf} < 2.2 \times 10^{7}\,{\rm GeV} \left(\frac{F_a}{10^{12}\,{\rm GeV}}\right)^{0.41}$$

5. Suppress Isocurvature Perturbations

- Amplitude of isocurvature perturbations is determined by fluctuations of misalignment angle

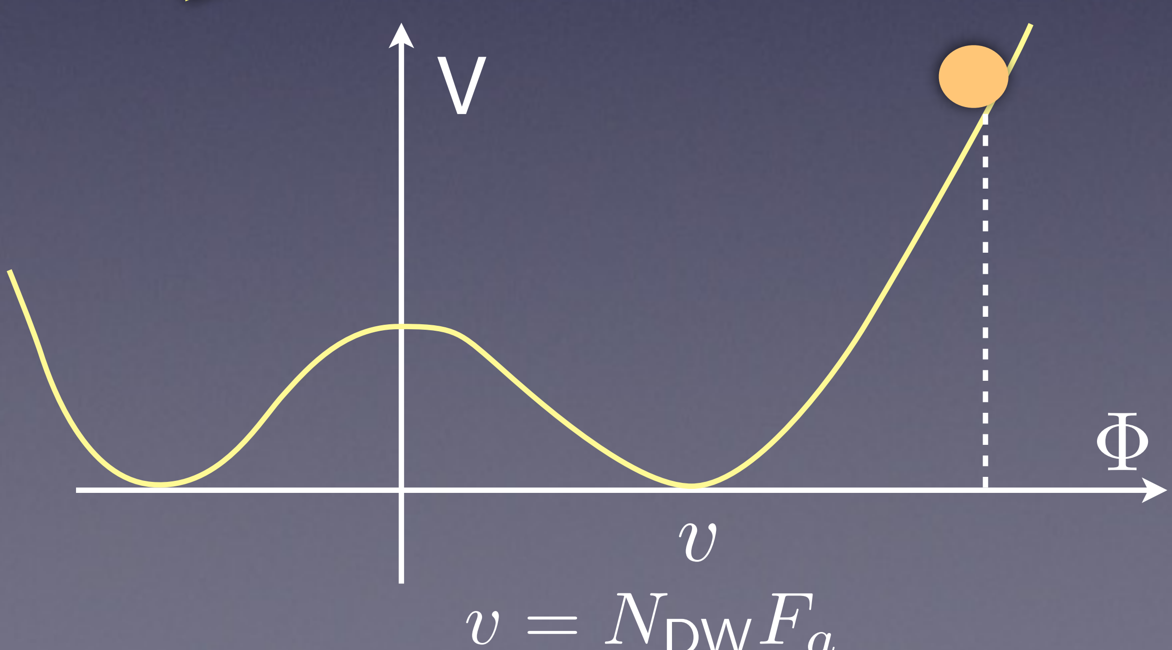
$$\delta\theta_a \simeq \frac{N_{\rm DW}}{F_a}\frac{H_{\rm inf}}{2\pi}$$

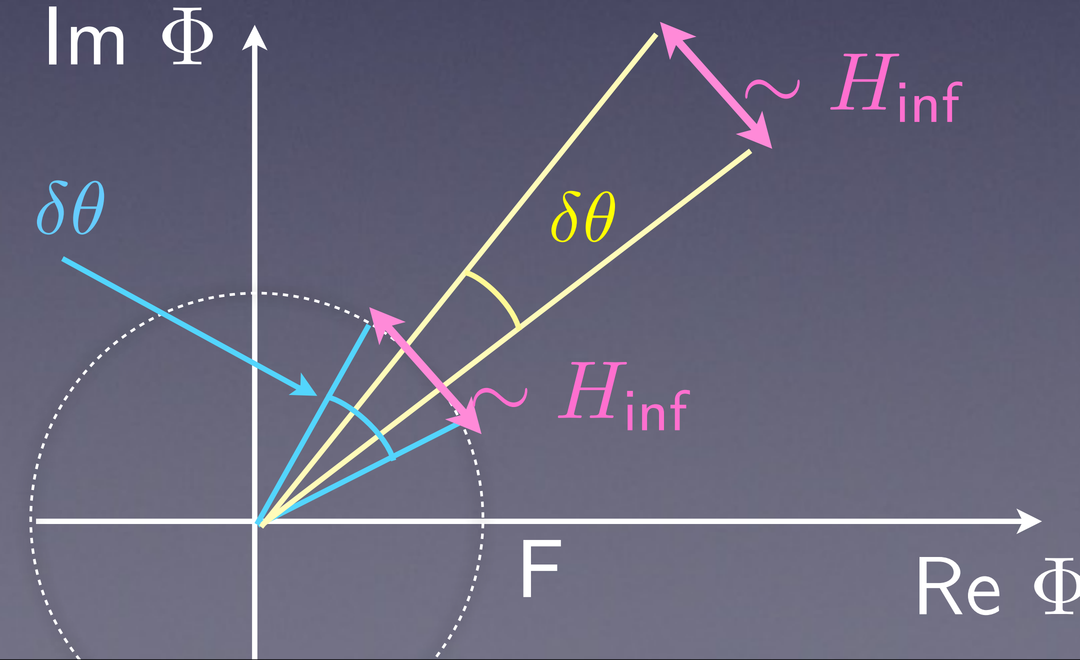
- If PQ field has a large value during inflation effective PQ scale becomes large

→ $$\delta\theta_a \simeq \frac{N_{\rm DW}}{|\Phi|}\left(\frac{H_{\rm inf}}{2\pi}\right)$$ → $$|\Phi| \gg F_a \;\Rightarrow\; \delta\theta_a \searrow$$

→ suppress isocurvature perturbations

Linde (1991)





- However, PQ field oscillates after inflation

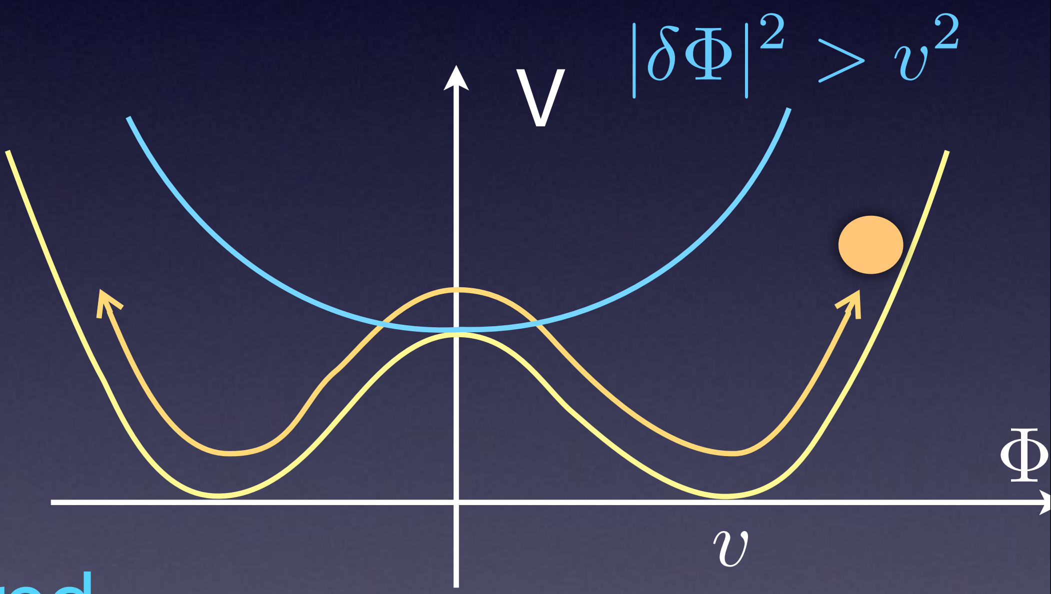
→ Production of large fluctuations of PQ field through parametric resonance

→ This leads to non-thermal restoration of $U(1)_{PQ}$ symmetry

Strings and domain walls are produced

- Potential of PQ field

$$V_{PQ} = \frac{\lambda}{2}\left(|\Phi|^2 - v^2\right)^2 + \lambda\langle|\delta\Phi|^2\rangle|\Phi|^2$$



$\langle|\delta\Phi|^2\rangle \gtrsim v^2 \;\Rightarrow$ symmetry is restored

- To avoid defect formation, PQ field must settle down to the minimum before the fluctuations fully develop

→ Lower bound on breaking scale v

Lattice Simulation

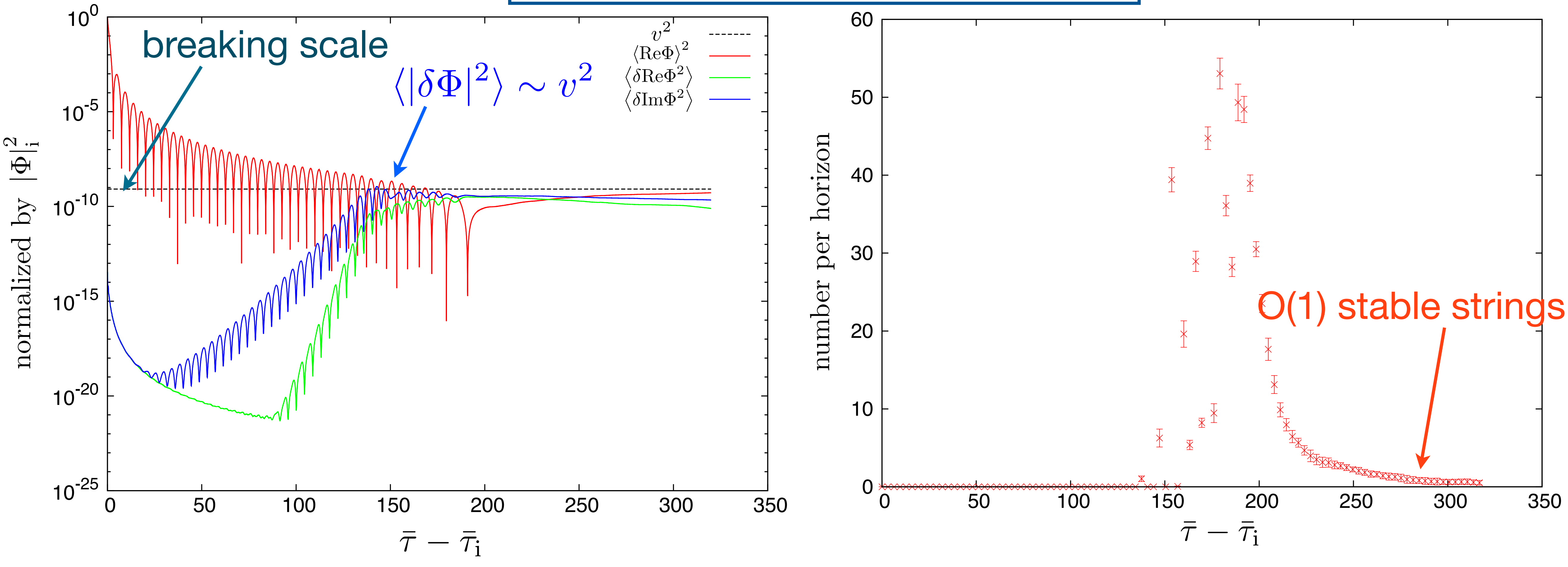
MK, Yanagida, Yoshino (2013)

- In order to examine whether strings are formed or not we performed lattice simulations with 1024X1024 lattice points
  - Model $$V = V_{\text{inf}} + V_{\text{PQ}} = \frac{M^2}{2}\chi^2 + \frac{\lambda}{2}\left(|\Phi|^2 - v^2\right)^2$$
  - Chaotic inflation with $H_{\text{inf}} = 10^{13}$GeV
  - Matter dominated universe

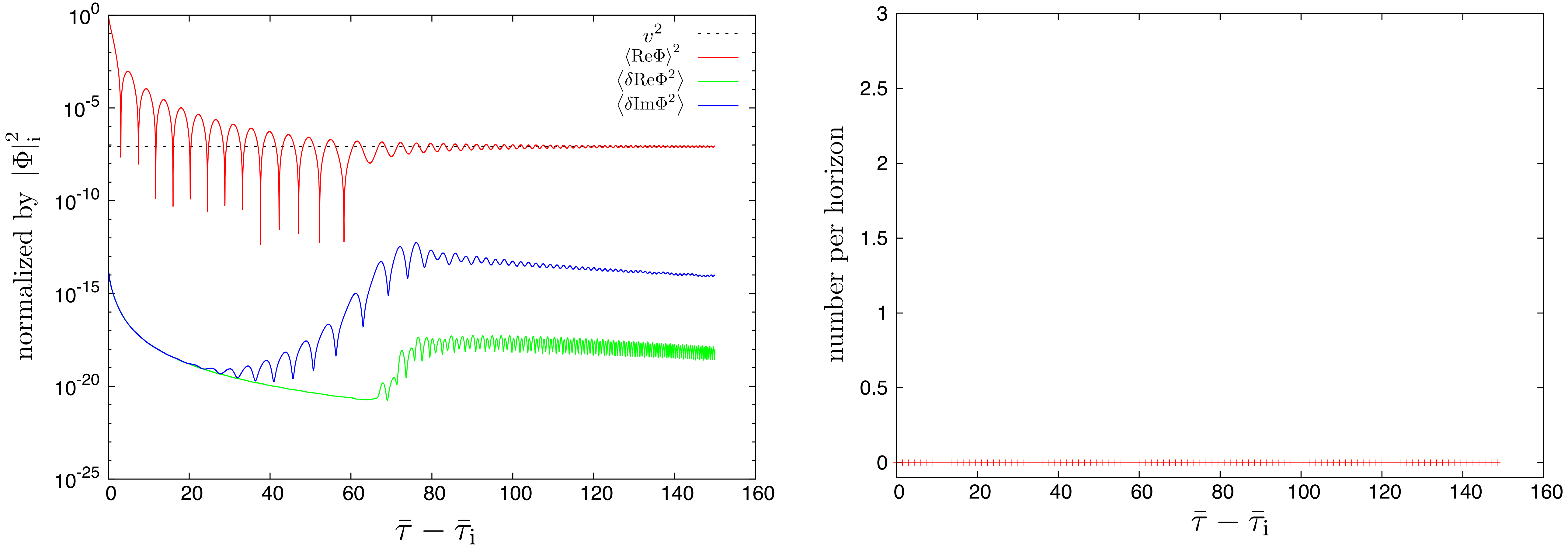
χ : inflaton

Φ_i : initial value

$$|\Phi|_i = M_p \quad v = 7\times 10^{13}\text{GeV}$$



$$|\Phi|_i = M_p \quad v = 7 \times 10^{14}\text{GeV}$$



- Lower bound on the breaking scale

$$v \gtrsim 1 \times 10^{-4} |\Phi|_i$$

  - The result almost independent of H_{inf}

$$v \gtrsim (1-2) \times 10^{-4} |\Phi|_i \quad \text{for} \quad H_{\text{inf}} = 10^{10}\text{GeV}$$

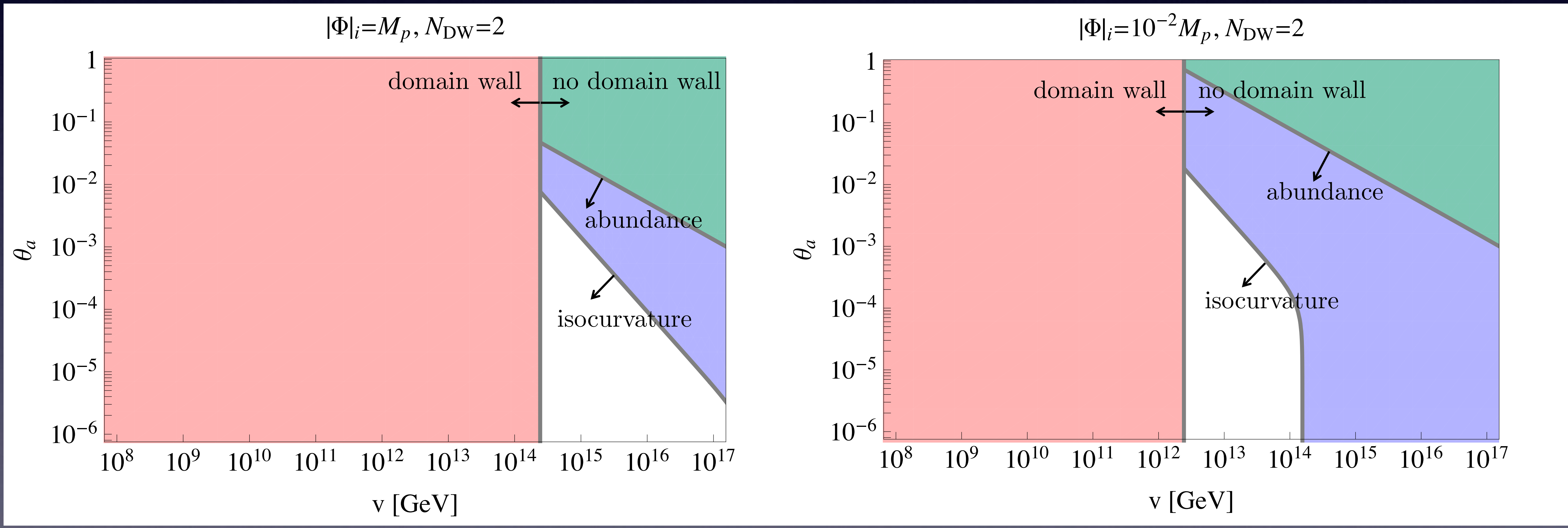
  - The constraint becomes much stringent if RD after inflation

$$v \gtrsim 1 \times 10^{-2} |\Phi|_i \quad (\text{RD})$$

Kasuya, MK (2000)

Chaotic Inflation

- No domain wall problem $v > 10^{-4}|\Phi|_i$
- No isocurvature pertubation problem $\beta_{\rm iso} < 0.0036$
- Axion density < CDM density $\Omega_a h^2 \simeq 0.2(\theta_a^2 + \langle\delta\theta_a^2\rangle)\left(\frac{F_a}{10^{12}\,{\rm GeV}}\right)^{1.19}$

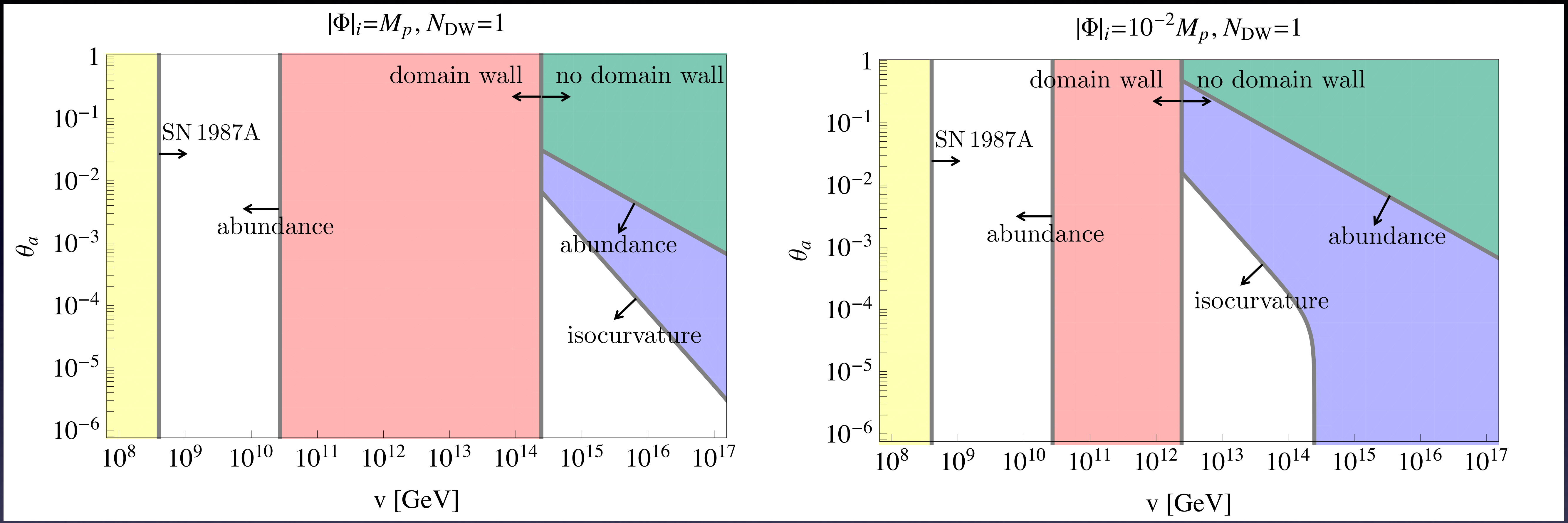


MK, Yanagida, Yoshino (2013) $v = N_{\rm DW} F_a$

- Chaotic inflation is consistent with axion for $\theta_a < O(10^{-2})$
- axion cannot be dark matter

Chaotic Inflation

- $N_{DW} = 1$ $v = N_{DW} F_a$



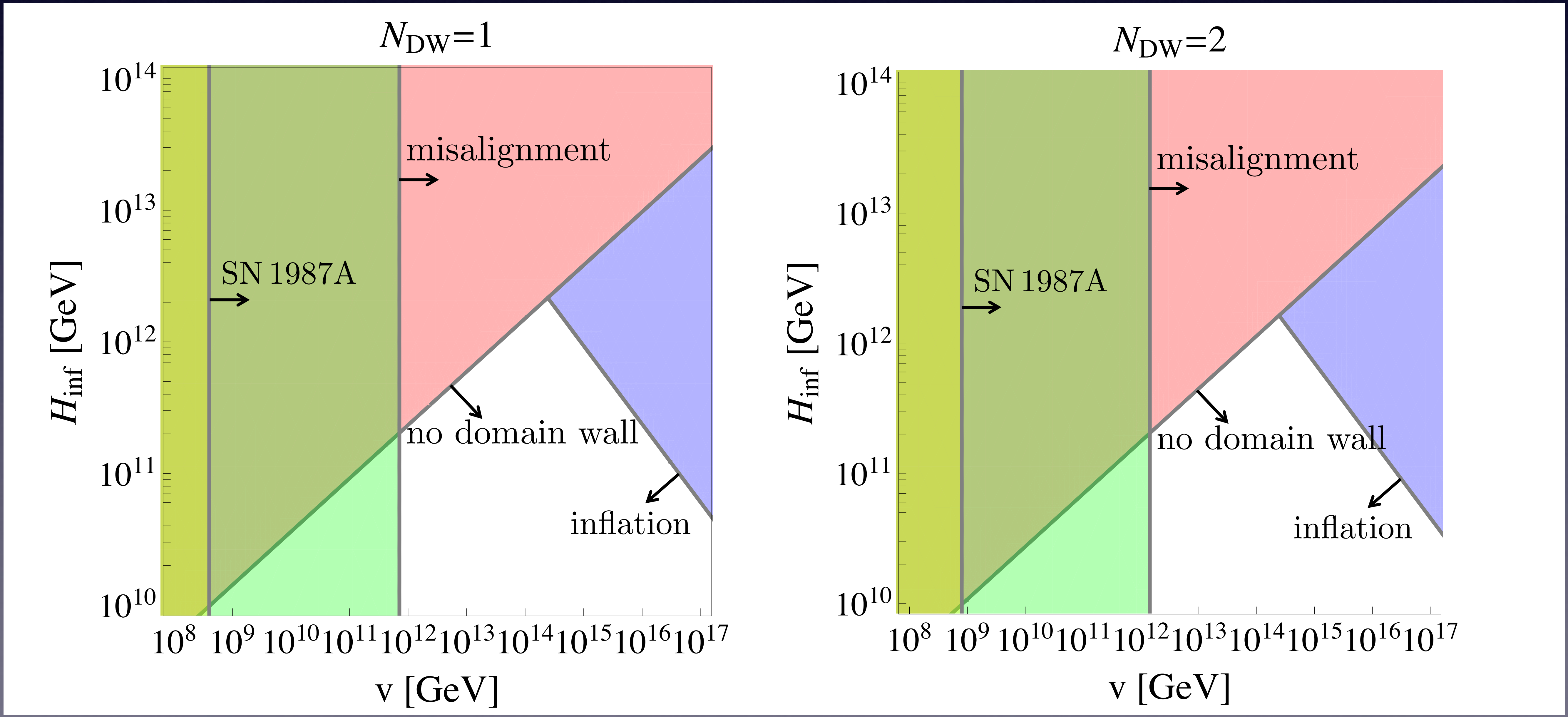
- $v \gtrsim 10^{-4} |\Phi|_i$
  - Same as $N_{DW} = 2$
- $v \lesssim 10^{-4} |\Phi|_i$
  - Unstable domain walls are formed and axions are emitted at collapse of domain walls (same as $U(1)_{PQ}$ breaking after inflation)
  - Axion can be dark matter for $v = 3 \times 10^{10}$ GeV

General Inflation Models

- Assuming axion is dark matter $\Omega_a = \Omega_{\mathrm{CDM}}$
- $|\Phi|_i < M_p$ and $\theta_a < 1$

■ No domain wall and isocurvature perturbation problems

if $H_{\mathrm{inf}} \lesssim 10^{11-12}\mathrm{GeV}$ for $v \simeq 10^{12-16}\mathrm{GeV}$



6. Conclusion

- Axion solves dark matter problem as well as strong CP problem in QCD. However, axion models with $N_{DW} > 1$ have serious domain wall problem
- In the inflationary universe, if PQ symmetry breaks during inflation, no domain wall problem exists
- However, axion has isocurvature density perturbations which are stringently constrained by CMB observations. As a result only low scale inflation models are allowed.
- If PQ scalar has a large field value during inflation, isocurvature perturbations can be suppressed, but a new domain wall problem arises due to parametric resonance
- We have found that both problems are solved and axion accounts for the dark matter if Hubble parameter $H_{\rm inf} \lesssim 10^{11-12}$GeV for breaking scale $v \simeq 10^{12-16}$GeV