Large entropy production induced by domain walls

Windows to New Paradigm in Particle Physics,
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M. Kawasaki and F.T., hep-ph/0410158

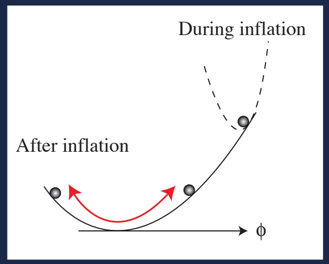
1.Introduction

New particles with long lifetimes are predicted in particle theories beyond the standard model.

→ These particles might either spoil the BBN or overclose the universe.

- Gravitino problem: → $T_{RH} < 10^6 \mathrm{GeV}$

  (Kawasaki, Kohri and Moroi `04)
- Moduli problem: (severer than the gravitino problem)



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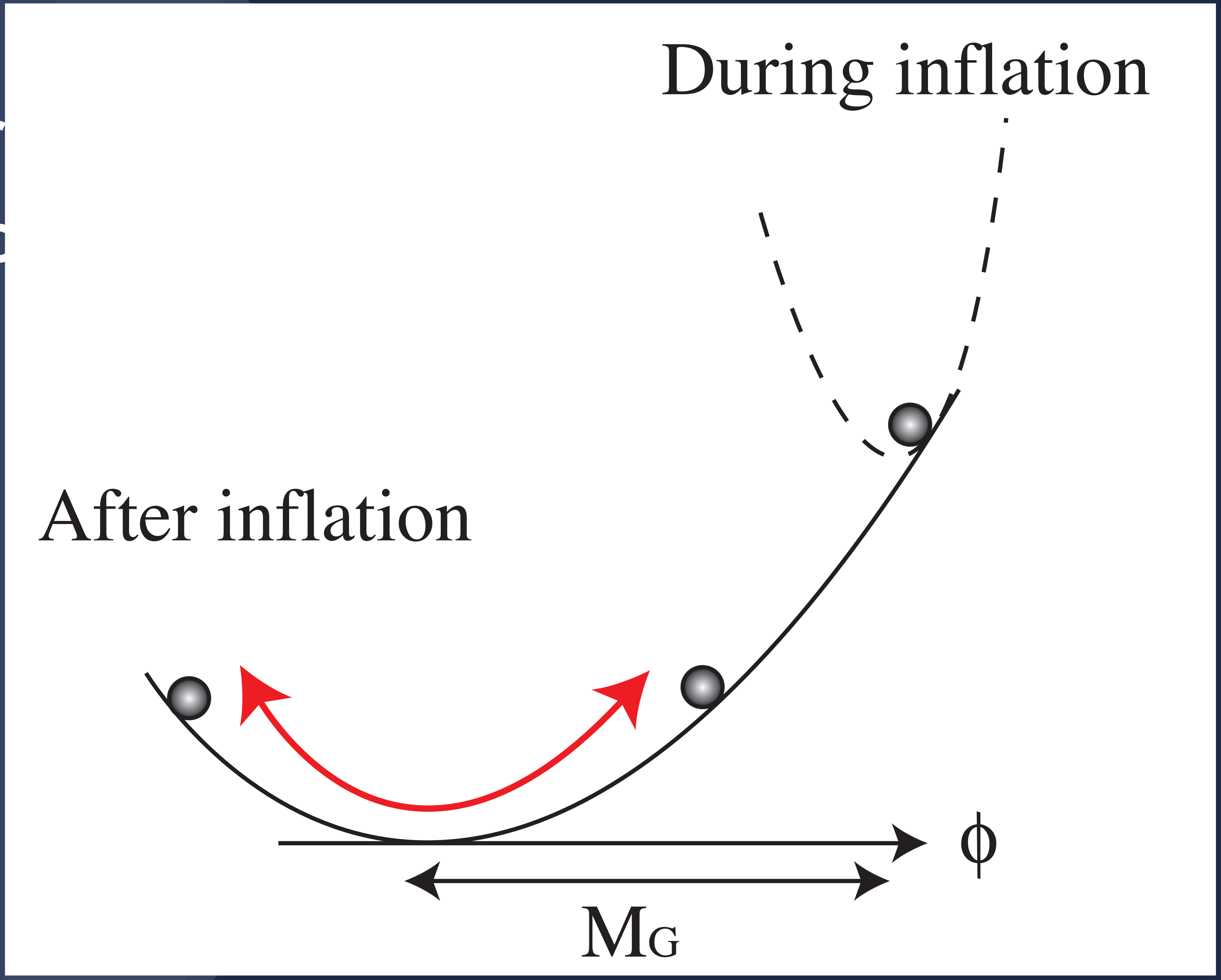
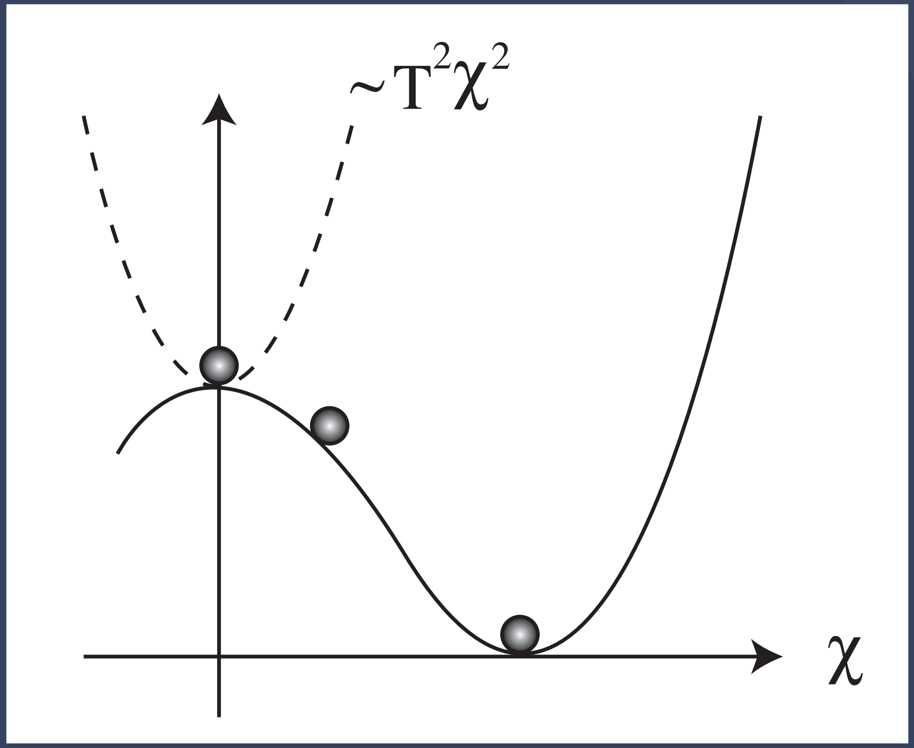
- Gravitino problem
- Moduli problem:



- The simplest solution is **to dilute those unwanted relics!**

Ex.) thermal inflation (Lyth and Stewart, `95)



The moduli can be successfully diluted. (Asaka and Kawasaki, `99)

However, incompatible with the AD baryogenesis!
(Kasuya, Kawasaki and F.T. `02)

- We would like to propose another model for late-time entropy production.

What we did:

- ✓ We have shown that domain walls (DWs) can dilute moduli, if the walls dominate the universe and decay at relatively low temperature.

$$\sigma = (1 \sim 100\,\mathrm{TeV})^3$$

$$T_d = 10\mathrm{MeV} \sim 10\mathrm{GeV}$$

- ✓ It is compatible with the Affleck-Dine baryogenesis.

2. Scenario

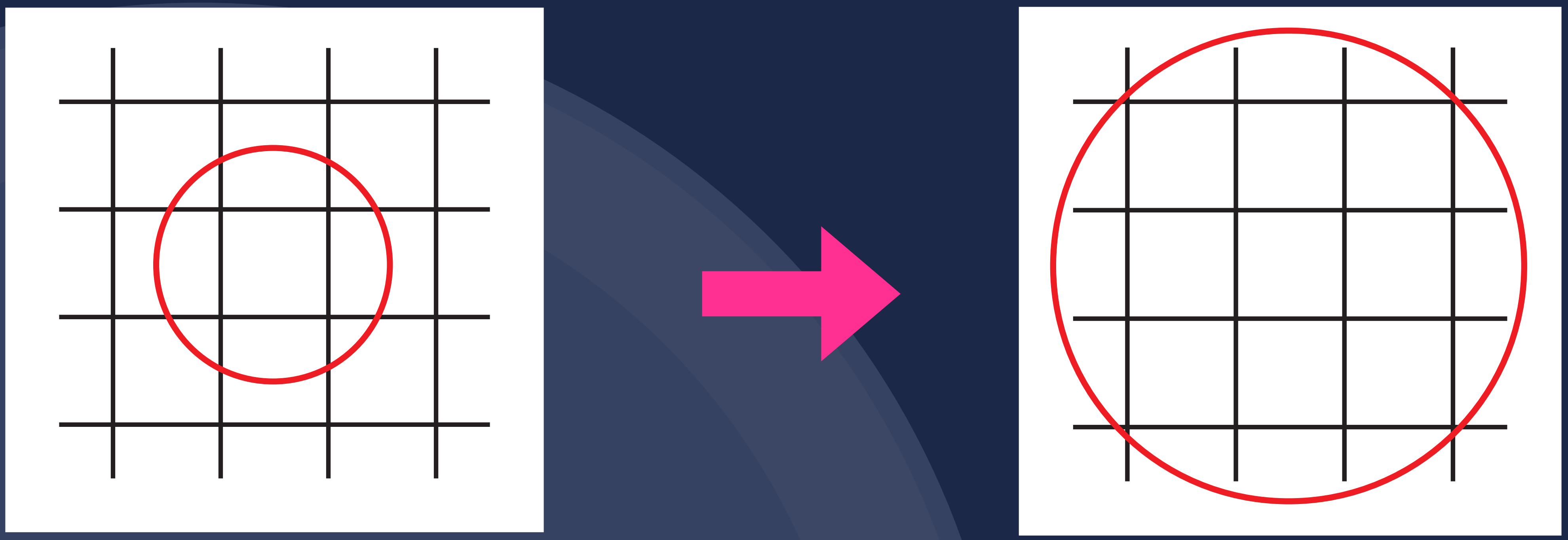
When some discrete symmetries are spontaneously broken, domain walls are produced.

The energy density of the domain walls evolves as

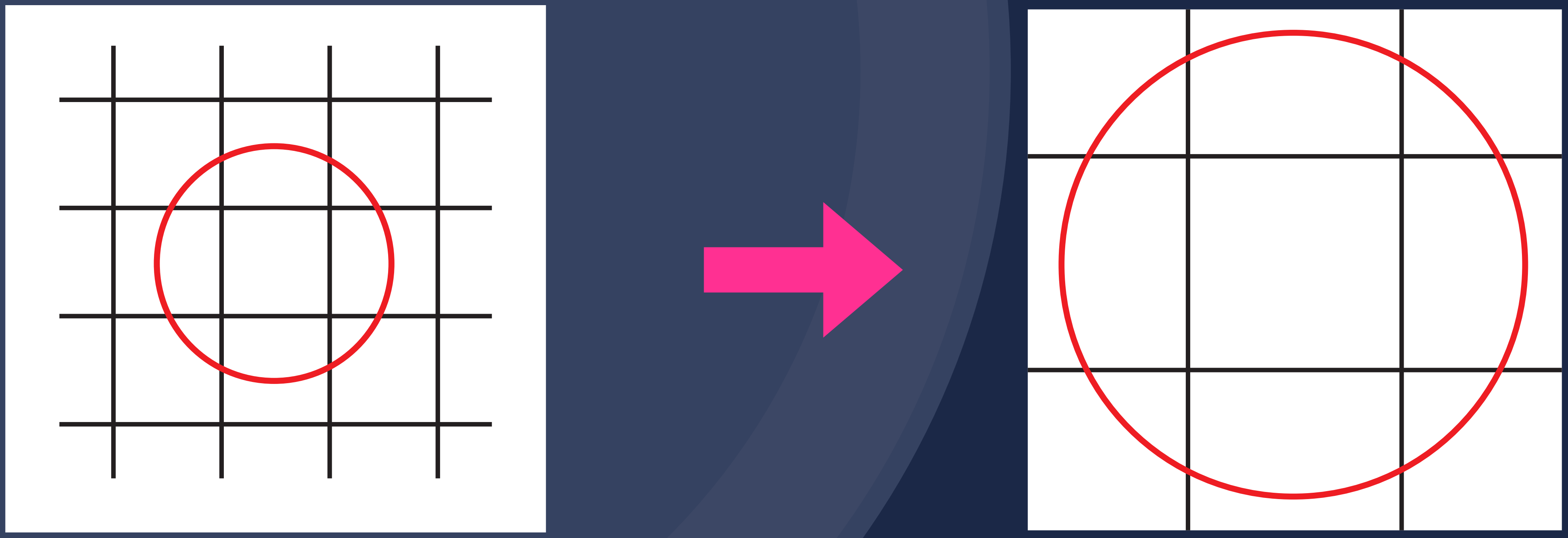
$$\rho_{DW} \propto \begin{cases} a^{-1} & \text{; fully frustrated DW} \\ a^{-3/2} & \text{; the scaling solution} \end{cases}$$

depending on the structure of vacua.

- fully frustrated DW;

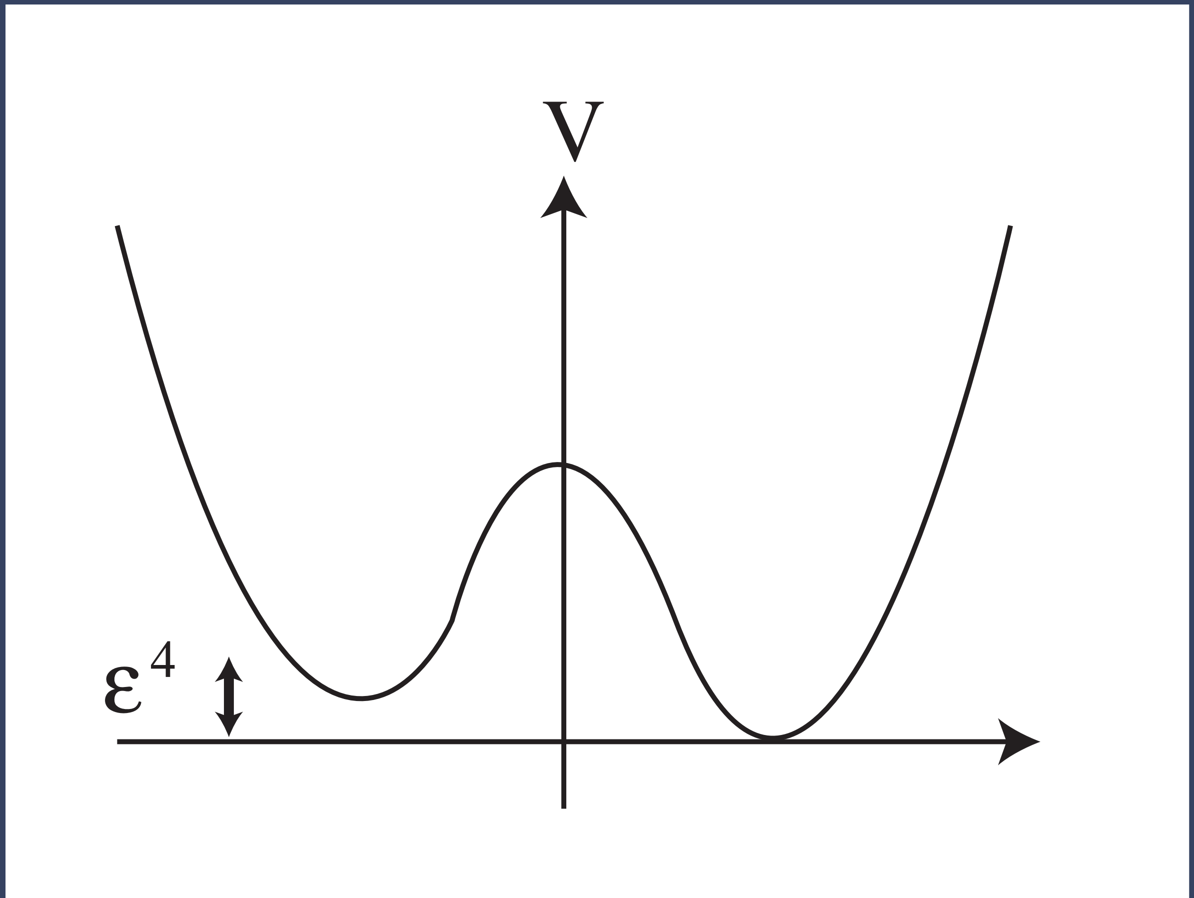


- scaling solution;



Decay of domain walls:

We assume that the spontaneously broken discrete symmetry is only approximate.



When the bias, ε^4, becomes comparable to the energy density of DWs, the decay occurs.

$$\varepsilon \sim T_d \gtrsim 10\mathrm{MeV}$$

- Requirements:
  i. DWs dominate the universe.
  ii. The decay of walls generate large enough entropy to dilute the moduli.
  iii. There are several walls inside the Hubble horizon, when they decay.

$$\Rightarrow \quad \sigma = (1 \sim 100\,\mathrm{TeV})^3$$

with $T_d \sim 10\mathrm{MeV}$ and $H_i \sim 1\mathrm{TeV}$.

(i) The initial energy density of the DWs is

$$\rho_{DW,i} \sim \sigma H_i$$

where σ is the tension of the walls.
The walls come to dominate the universe when

$$H_{eq} \sim \sigma^{\frac{3}{4}} H_i^{\frac{1}{4}} M_G^{-\frac{3}{2}}.$$

The domination should occur before the decay:

$$H_{eq} > H_d \sim \frac{T_d^2}{M_G},$$

which leads to

$$\sigma > (100\,\mathrm{GeV})^3 \left(\frac{T_d}{10\,\mathrm{MeV}}\right)^{\frac{8}{3}} \left(\frac{H_i}{1\,\mathrm{TeV}}\right)^{-\frac{1}{3}}.$$

(ii) The modulus-to-entropy ratio after the decay of DWs is

$$\frac{\rho_{mod}}{s} \sim \frac{T_d^9 M_G^2}{\sigma^3 H_i} < \kappa \frac{\rho_c}{s_0} ,$$

where κ varies from 10^{-10} to 0.2, depending on the modulus mass. Therefore

$$\sigma > \kappa^{-\frac{1}{3}} (500\,\mathrm{GeV})^3 \left(\frac{T_d}{10\,\mathrm{MeV}} \right)^3 \left(\frac{H_i}{1\,\mathrm{TeV}} \right)^{-\frac{1}{3}} .$$

(iii)

$$\sigma < T_d^2 M_G \sim (100\,\mathrm{TeV})^3 \left(\frac{T_d}{10\,\mathrm{MeV}} \right)^2 .$$

3. Conclusion

- We have shown that the entropy production due to the decay of domain-walls with $\sigma = (1 \sim 100\,\mathrm{TeV})^3$ can dilute the dangerous moduli.

- The AD baryogenesis is compatible with our model.
- The overclosure limit on the axion decay constant can be greatly relaxed.

Appendix Model

Let us consider the following superpotential,

$$W = \sqrt{\lambda} \sum_i^N \sum_j^N Z_{ij} \Phi_i \Phi_j + \frac{2\epsilon}{\sqrt{\lambda}} \sum_i Z_{ii} \Phi_i^2,$$

where Φ_i and Z_{ij} are the fundamental and bi-fundamental representation of S_N group.

The relevant scalar potential is

$$\begin{aligned} V(\Phi) \quad &\simeq \quad V_0 - m_0^2 \textstyle\sum_i |\Phi_i|^2 - m_{3/2}^2 \sum_i (\Phi_i^2 + \Phi_i^{*2}) \\ &\qquad + \lambda (\textstyle\sum_i |\Phi_i|^2)^2 + 4\epsilon \sum_i |\Phi_i|^4, \end{aligned}$$

Since the minima are along the real axes, let us rewrite the potential in terms of $\phi_i \equiv \mathrm{Re}\Phi_i$:

$$V(\phi) \simeq V_0 - \frac{m_0^2}{2}\sum_i \phi_i^2 + \frac{\lambda}{4}(\sum_i \phi_i^2)^2 + \epsilon \sum_i \phi_i^4,$$

This actually agrees with the O(N) model.
There are 2^N minima given by

$$\phi_{\min} = (\pm v_2, \ldots, \pm v_2) \qquad v_2 \equiv m_0/\sqrt{\lambda N}$$

The tension is

$$\sigma_1 \sim m_{3/2} v_2^2 \sim (1\,\mathrm{TeV})^3 \, (\lambda N)^{-1} \left(\frac{m_{3/2}}{1\,\mathrm{TeV}}\right)\left(\frac{m_0}{1\,\mathrm{TeV}}\right)^2.$$

The decay occurs through the following interaction:

$$W = c' \langle W \rangle \sum_i \Phi_i^3 / M_G^3$$

$$\Rightarrow \quad V_A = c\, m_{3/2}^2 \sum_i \Phi_i^3 / M_G + \mathrm{h.c.}$$

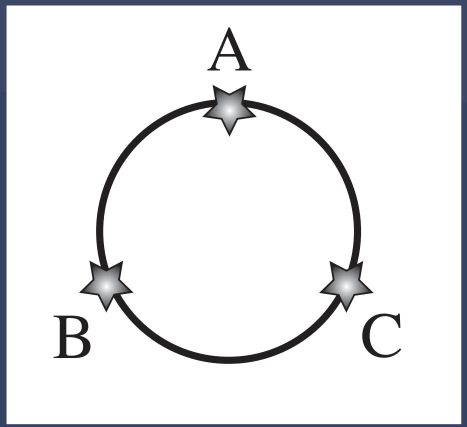
The decay temperature is given by

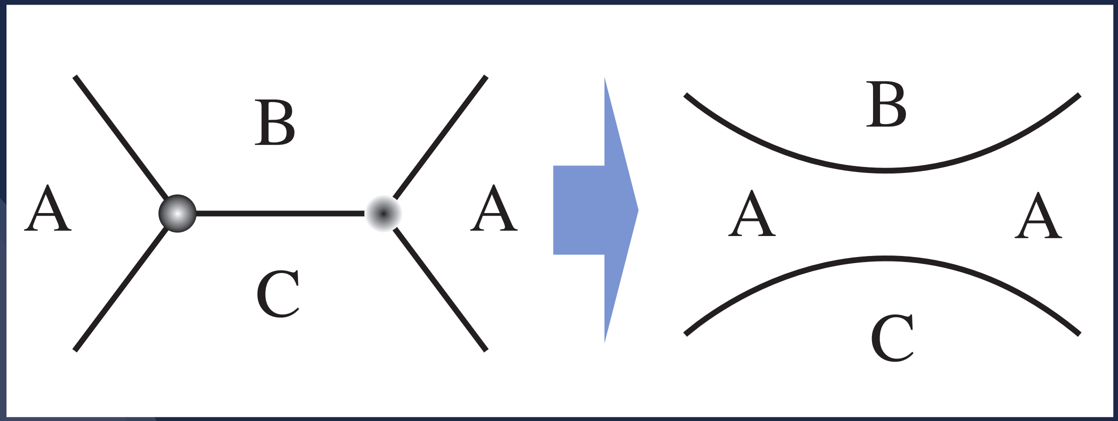
$$\frac{T_d}{100\mathrm{MeV}} \sim (\lambda N)^{-\frac{3}{8}} \left(\frac{c}{0.1}\right)^{\frac{1}{4}} \left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)^{\frac{1}{2}} \left(\frac{m_0}{1\mathrm{TeV}}\right)^{\frac{3}{4}} .$$

○ Z_2-type
○ U(1)-type

The domain-wall network obeys the scaling law.

(Garagounis and Hindmarsh, `03) (Ryden, Press and Spergel, `90)





For more complicated vacuum structure, annihilation processes become less effective, leading to the frustrated domain walls.