次最小超対称標準模型に対する宇宙論的制限

Ken'ichi Saikawa
Tokyo Institute of Technology (Titech)

Collaborate with
Kenji Kadota (IBS), Masahiro Kawasaki (ICRR),
Anupam Mazumdar (Lancaster U), Masahide Yamaguchi (Titech),
and Jun'ichi Yokoyama (RESCEU)

based on
[1] K. Kadota, M. Kawasaki, KS, hep-ph/1503.06998. (accepted in JCAP)
[2] A. Mazumdar, KS, M. Yamaguchi, J. Yokoyama, work in progress.

Abstract

- Discuss cosmological aspects of the Z_3-invariant next-to-minimal supersymmetric standard model (NMSSM)
- Formation of domain walls in the context of primordial inflation Mazumdar, KS, Yamaguchi, Yokoyama, work in progress
  - Can it be avoided ?
  - Under what conditions ?
- Estimate the gravitational wave signatures from domain walls and their parameter dependence

Kadota, Kawasaki, KS, 1503.06998

1. NMSSM as a solution to the μ-problem

Renormalizable superpotential of the MSSM

$$W_{\rm MSSM} = \mu H_u H_d + \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D^c_j - \lambda^u_{ij} H_u Q_i U^c_j$$

μ-term

$i, j, k = 1, 2, 3$: family indices

- μ-problem: Why $\mu \sim M_{\rm SUSY}$ rather than $\mu \sim M_{\rm GUT}$ or $M_{\rm Pl}$?
- Introduce a gauge singlet S and replace the μ-term

$$\mu H_u H_d \rightarrow \lambda S H_u H_d$$

- Singlet acquires a VEV to induce an effective μ-term

$$\mu_{\rm eff} = \lambda \langle S \rangle = \frac{\lambda}{\sqrt{2}} v_s \qquad \langle S \rangle = \frac{1}{\sqrt{2}} v_s$$

- No dimensionful parameter except for soft SUSY breaking effects $\sim M_{\rm SUSY}$

→ naively expected that $\mu_{\rm eff} \sim \mathcal{O}(M_{\rm SUSY})$

- Need to forbid any dimensionful parameters like

$$\mu H_u H_d, \quad \mu'^2 S, \quad \text{and} \quad \mu'' S^2$$

- Impose a Z_3 symmetry

$$Z_3 : \ \Phi \to e^{2\pi i/3} \Phi$$

$\Phi = (L, E^c, Q, U^c, D^c, H_u, H_d, S)$: every chiral supermultiplets of the NMSSM

$$\Rightarrow \quad W_{\rm NMSSM} = \boxed{\lambda S H_u H_d + \frac{\kappa}{3} S^3} \quad \text{Two parameters: } (\lambda, \kappa)$$

$$+ \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D^c_j - \lambda^u_{ij} H_u Q_i U^c_j$$

- Z_3 is spontaneously broken when S, H_u, H_d acquire VEVs

⇒ Formation of domain walls

Decoupling limit

- $v_s \gg v_u, v_d$ is possible if $\lambda \ll 1$

  cf. $\mu = \frac{1}{\sqrt{2}}\lambda v_s \approx \mathcal{O}(M_{\rm SUSY})$ $\langle S \rangle = \frac{v_s}{\sqrt{2}},\ \langle H_u \rangle = \frac{v_u}{\sqrt{2}},\ \langle H_d \rangle = \frac{v_d}{\sqrt{2}}$

- In this limit, the potential can be approximated as

$$V \simeq \kappa^2 |S|^4 + m_S^2 |S|^2 + \left[\frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right]$$

$$\Rightarrow \quad v_s \simeq -\frac{\sqrt{2}A_\kappa}{4\kappa}\left(1 + \sqrt{1 - \frac{8m_S^2}{A_\kappa^2}}\right)$$

$A_\kappa,\ m_S \sim \mathcal{O}(M_{\rm SUSY})$: soft SUSY breaking parameters

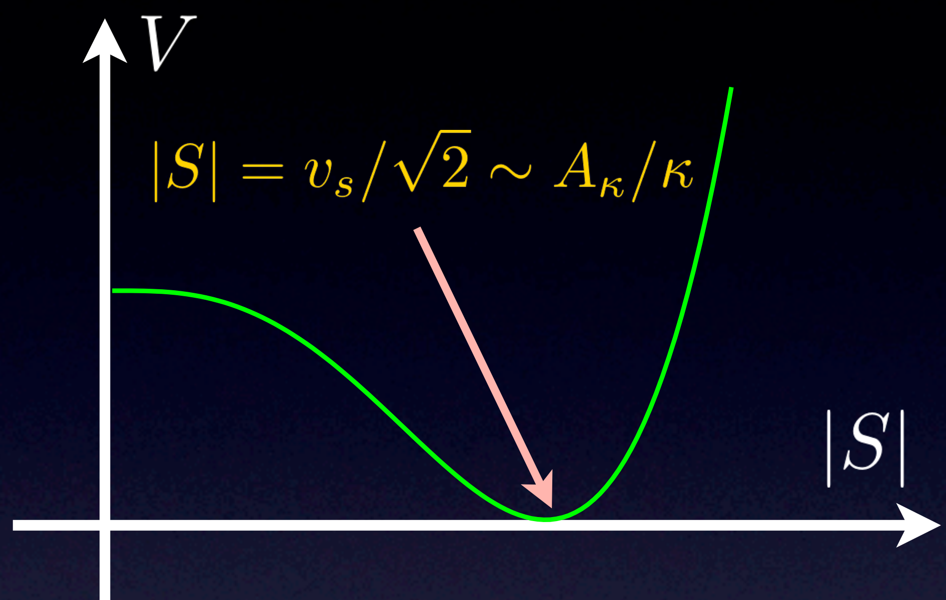
- λ and κ should be of the same order of magnitudes since $\mu \sim \lambda v_s \sim (\lambda/\kappa)A_\kappa \sim M_{\rm SUSY}$

- Decoupling limit is given by

$$\boxed{v_s \sim |A_\kappa/\kappa| \quad \text{for} \quad \lambda \sim \kappa \to 0}$$

Potential for S

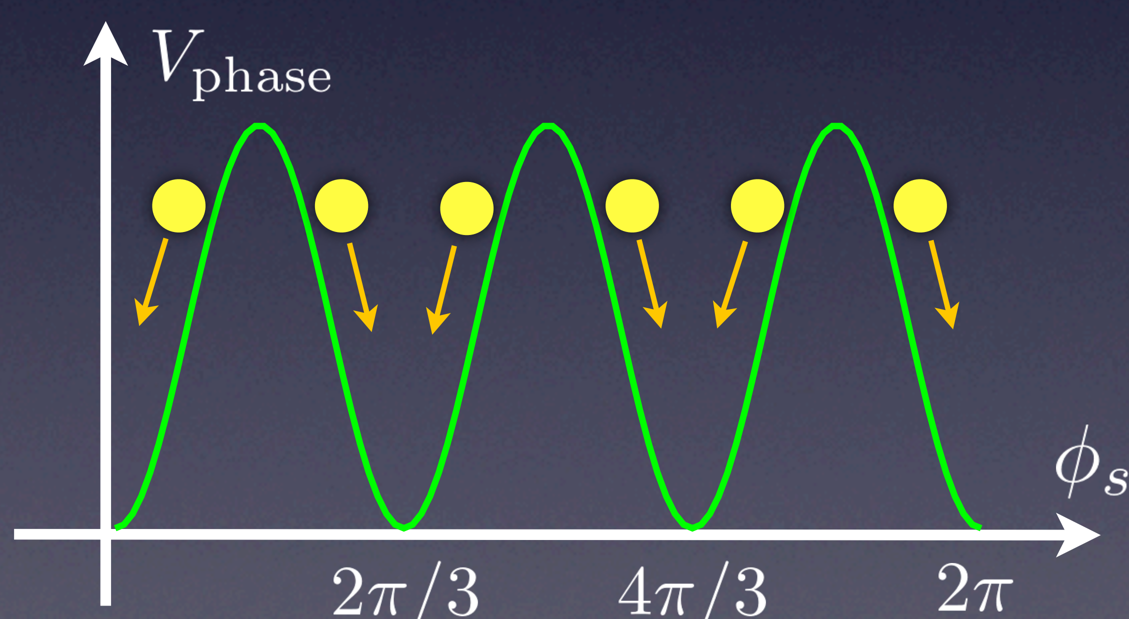
Radial direction $|S|$

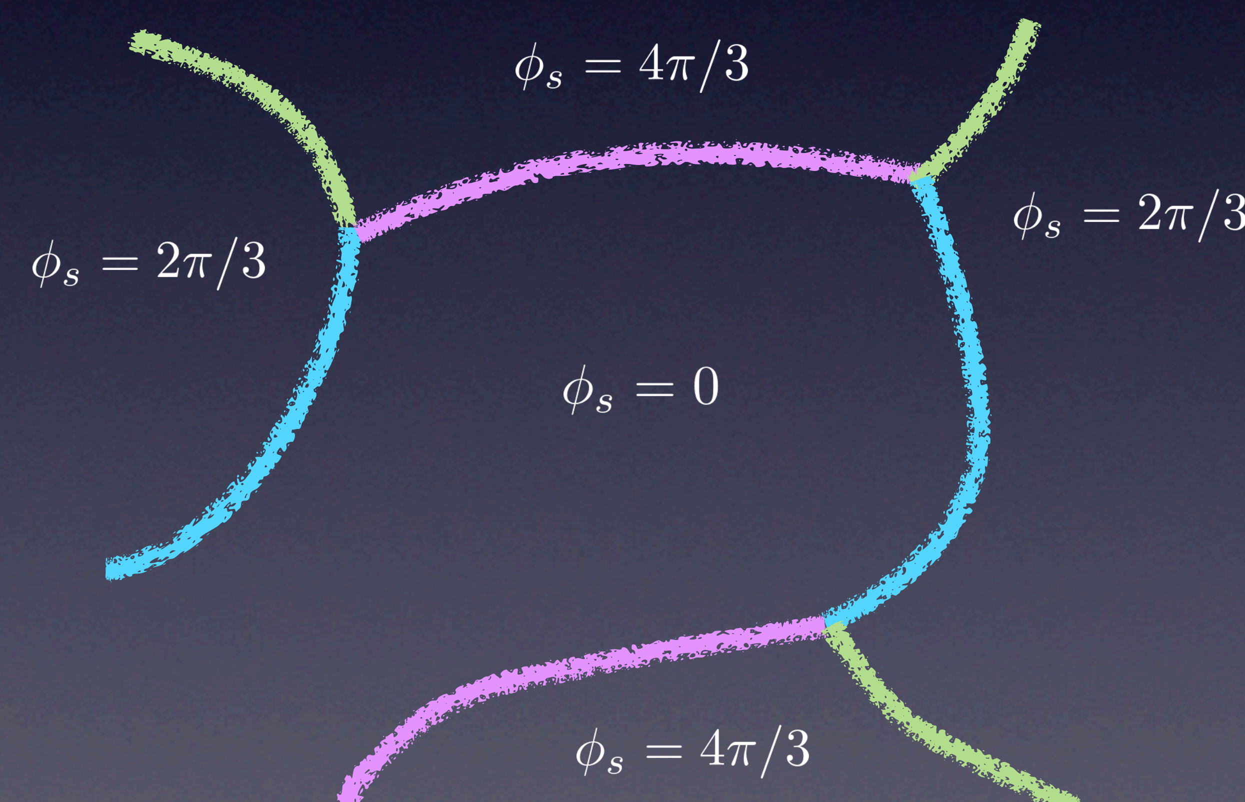


$$\langle S \rangle = v_s e^{i\phi_s}/\sqrt{2}$$

$$V \simeq m_S^2|S|^2 + \kappa^2|S|^4 + \underbrace{\left[\frac{1}{3}\kappa A_\kappa S^3 + \text{c.c.}\right]}_{V_{\text{phase}}}$$

Phase dependent terms



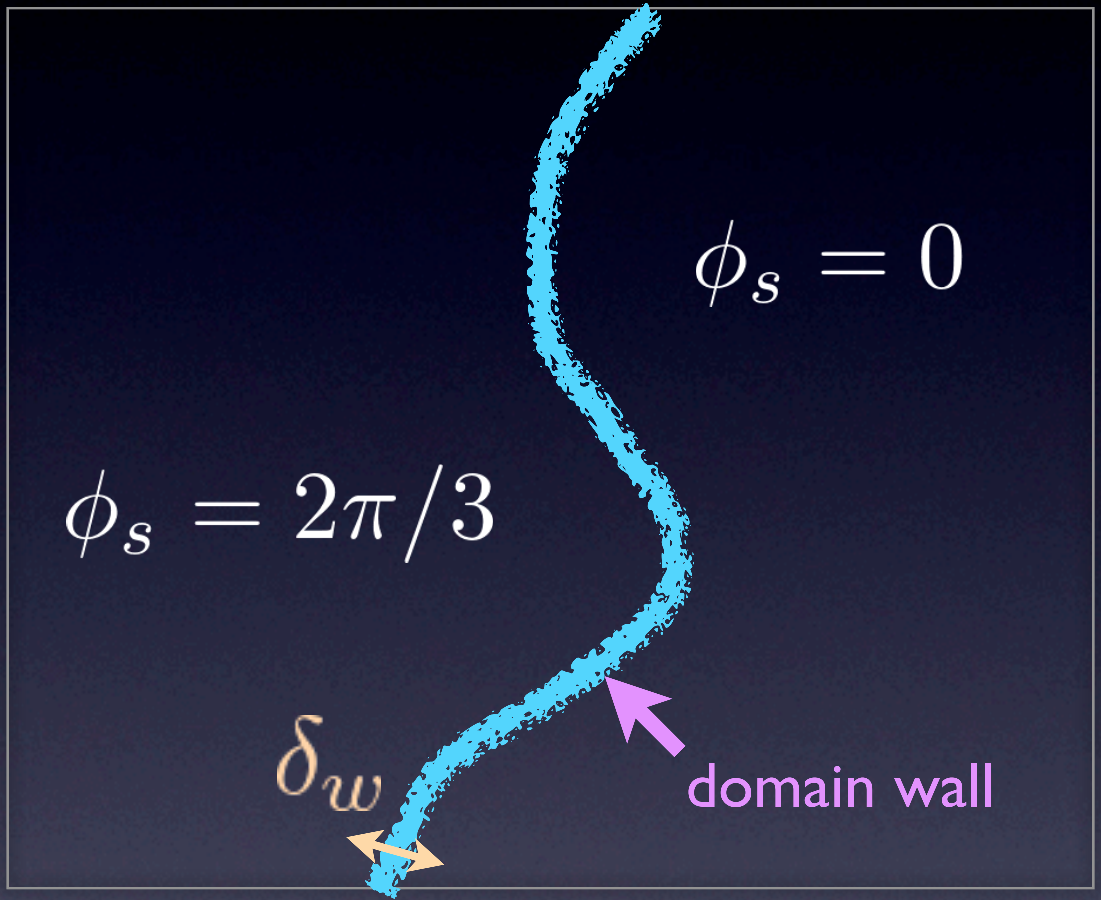


- Three degenerate minima related by $\phi_s \to \phi_s + 2\pi k/3, \; k = 0, 1, 2$
- Domain walls are formed at their boundaries

Properties of domain walls

$$V \simeq \kappa^2 |S|^4 + m_S^2 |S|^2 + \left[\frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right]$$

$$S = \frac{1}{\sqrt{2}} v_s e^{i\phi_s} \quad v_s \sim \left|\frac{A_\kappa}{\kappa}\right|$$



- Width of the wall

$$\delta_w \sim \left|\frac{\partial^2 V}{\partial (v_s \phi_s)^2}\right|^{-1/2}$$
$$\sim |\kappa A_\kappa v_s|^{-1/2} \sim \mathcal{O}(M_{\rm SUSY}^{-1})$$

- Surface mass density

$$\sigma_{\rm wall} = \int dz \rho_{\rm wall}(z)$$
$$\sim \delta_w \times V \sim \mathcal{O}(\kappa v_s^3)$$

$\rho_{\rm wall}(z)$: energy density of the wall

z : coordinate perpendicular to the surface of the wall

Note that $\sigma_{\rm wall} \sim \mathcal{O}(\kappa v_s^3) \gg \mathcal{O}(M_{\rm SUSY}^3)$ for $\kappa \ll 1$

We expect that domain walls are formed if the singlet scalar S takes different phases from place to place.

How ? and under what conditions ?

Let us carefully see the evolution of S after inflation.

2. Conditions for (non-)formation of domain walls

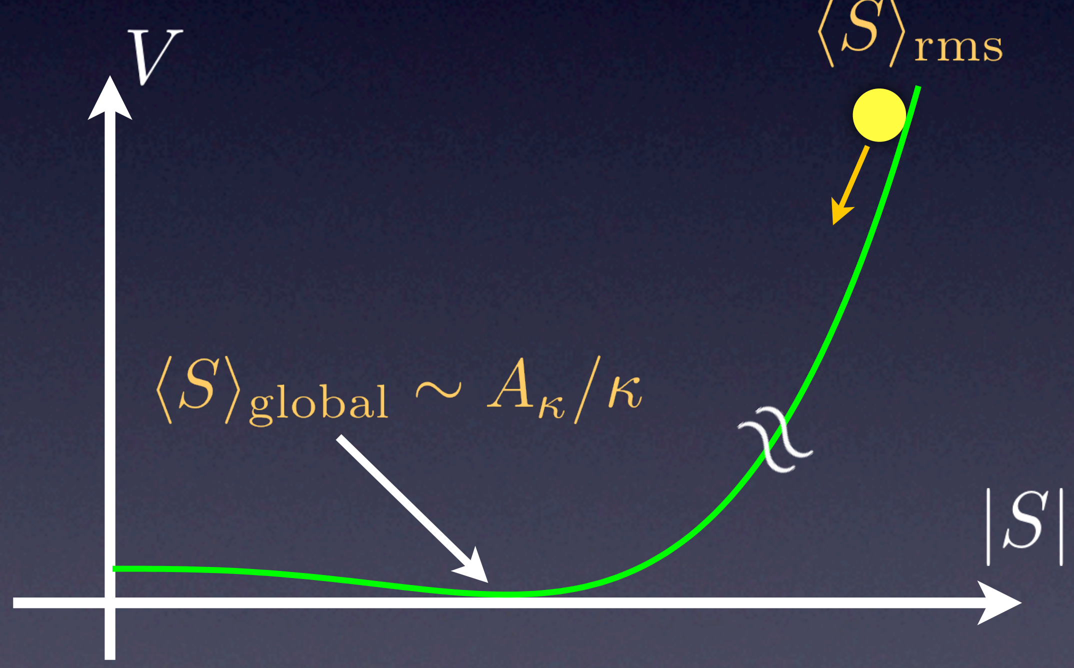
Mazumdar, KS, Yamaguchi, Yokoyama, work in progress

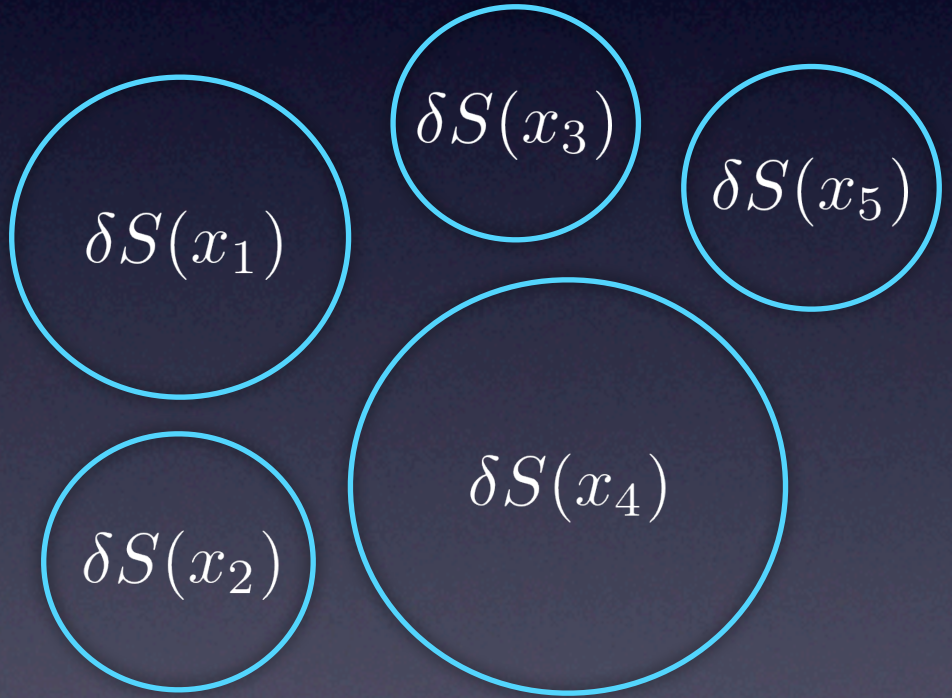
During inflation, S is effectively massless $m_S \ll H_{\rm inf}$

$H_{\rm inf}$: Hubble parameter during inflation

➡ S is easily displaced from the global minimum due to the quantum fluctuations $\delta S \sim \mathcal{O}(H_{\rm inf})$

$$\kappa^2 |S|^4 \simeq H_{\rm inf}^4 \quad \Rightarrow \quad \langle S \rangle_{\rm rms} \sim H_{\rm inf}/\sqrt{\kappa} \gg \langle S \rangle_{\rm global}$$





After inflation, S oscillates around $S = 0$, reducing its amplitude

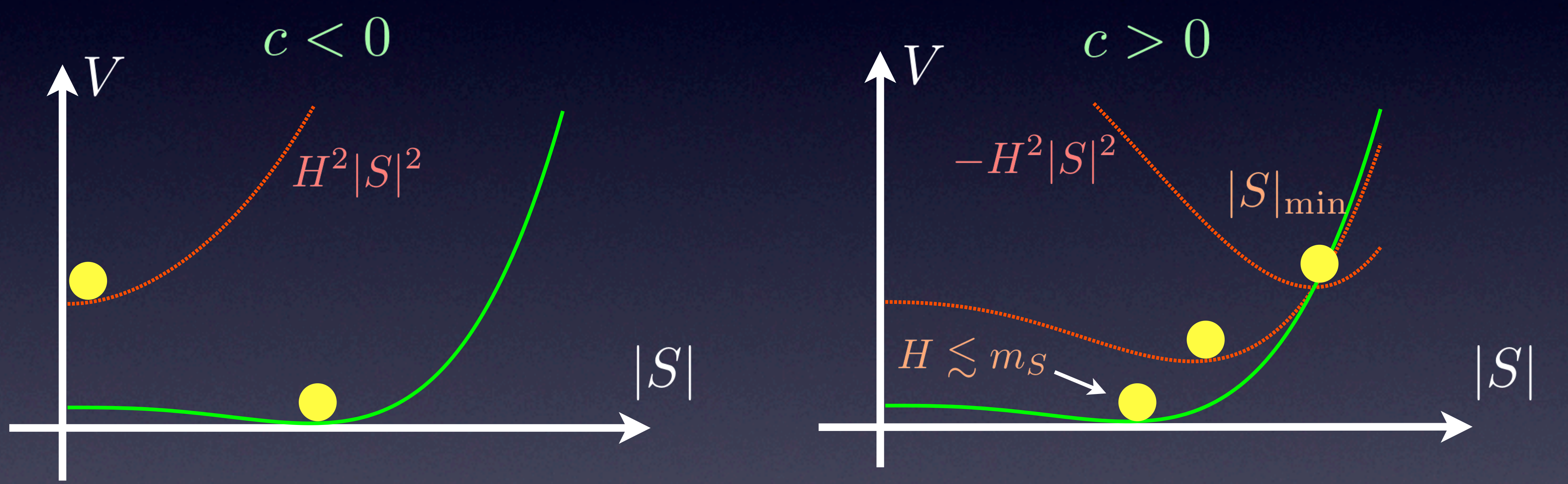
➡ Fluctuations δS are enhanced due to the parametric resonance, which results in the formation of defects

Supergravity effects

S acquires the effective mass of $\mathcal{O}(H)$

$$\mathcal{L} \supset \frac{|S|^2}{M_{\rm Pl}^2}\partial_\mu I^* \partial^\mu I,\ \frac{|S|^2}{M_{\rm Pl}^2} V(I) \quad \Rightarrow \quad \boxed{m_{S,{\rm eff}}^2 = -cH^2}$$

I : inflaton field $\quad c \sim \mathcal{O}(1)$: model-dependent parameter



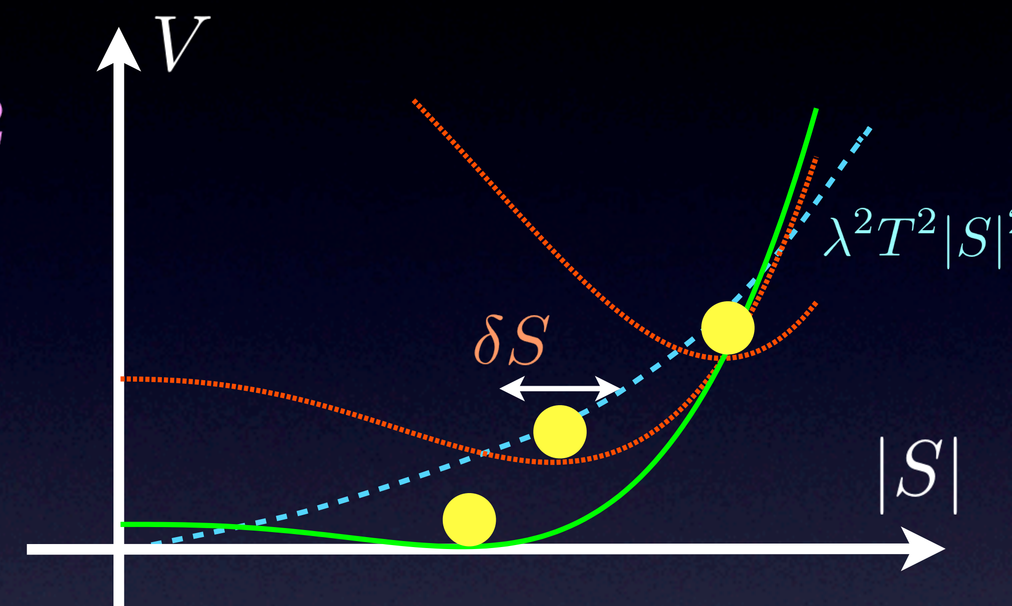
If $c > 0$, S tracks minimum of the effective potential after inflation

$$V(S) \simeq -cH^2|S|^2 + \kappa^2|S|^4 \quad \Rightarrow \quad \boxed{|S|_{\rm min} \simeq \frac{\sqrt{c}H(t)}{\sqrt{2}\kappa}}$$

No oscillation → the defect formation can be avoided

Finite temperature effects

- Following conditions must be satisfied until S reaches the global minimum ($cH^2 \gtrsim m_S^2$)
  - Correction term $\Delta V \propto \lambda^2 T^2 |S|^2$ in the effective potential should not alter the tracking behavior:



$$\lambda^2 T^2 \ll cH^2$$

  - Thermal fluctuations $\delta S(x) \sim T$ should remain small:

$$|S|_{\rm min} \gg \delta S(x) \sim T$$

- Above two requirements lead to the same condition (recall that $|S|_{\rm min} \propto \sqrt{c}H/\kappa$ and $\kappa \simeq \lambda$)

$$\lambda T \ll \sqrt{c}H \quad \text{for} \quad cH^2 \gtrsim m_S^2$$

Conditions to avoid the domain wall formation

1. Existence of the negative effective mass $-cH^2|S|^2$ during and after inflation

2. $A_\kappa^2/m_S^2 \gtrsim \mathcal{O}(10)$ must be satisfied to prevent the S field from rotating in the phase direction at late times (This is automatically satisfied if $v_s \neq 0$)

3. Thermal effects must remain irrelevant

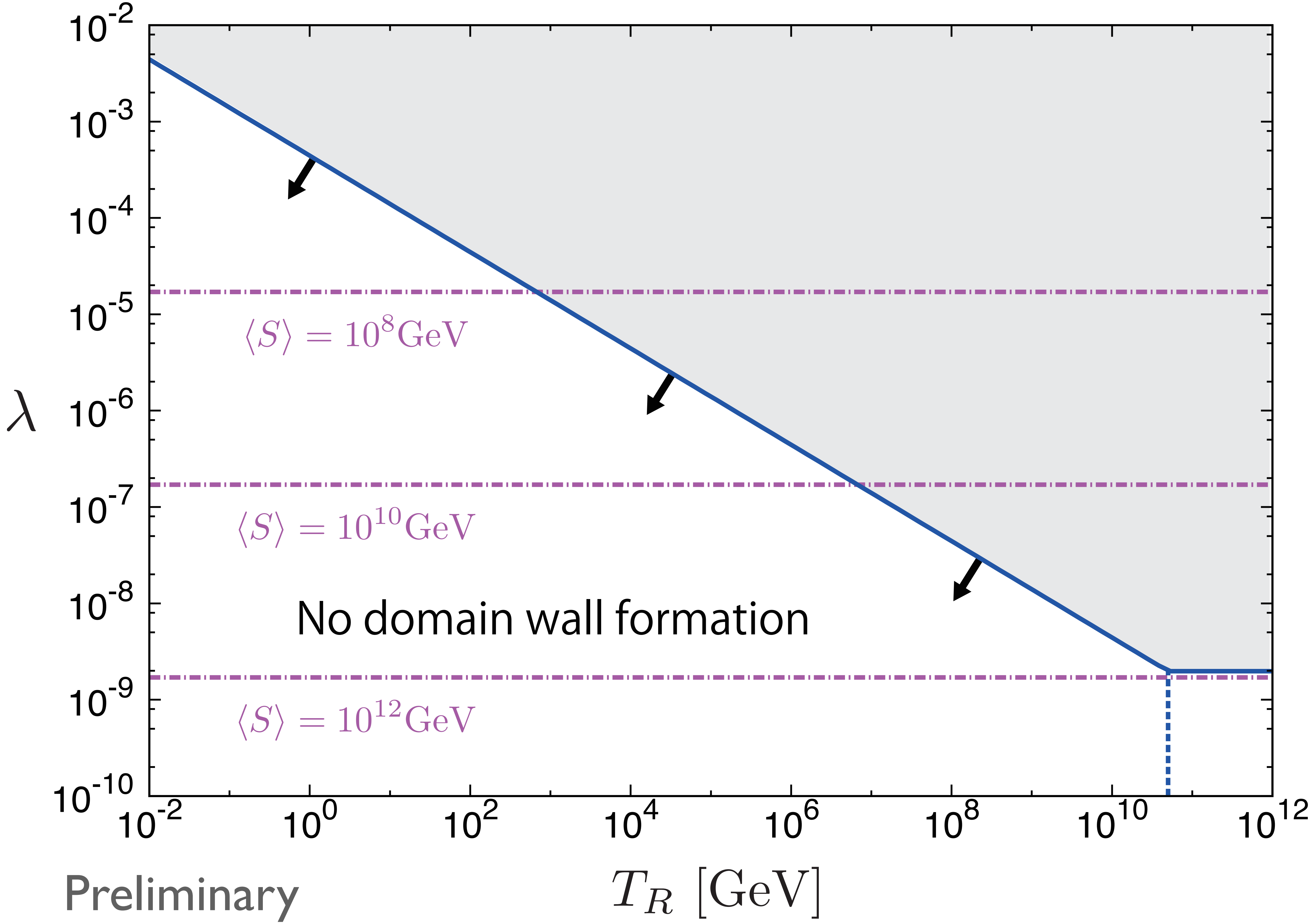
$$\lambda T \ll \sqrt{c}H \quad \text{for} \quad cH^2 \gtrsim m_S^2$$

➡ puts a constraint on the couplings (λ, κ) and reheating temperature T_R

4. Initial field value should be uniquely determined during inflation

$$\kappa^2|S|^4 \sim c^2 H_{\rm inf}^4/\kappa^2 > \mathcal{O}(H_{\rm inf}^4) \quad \Rightarrow \quad c > \kappa$$

Mazumdar, KS, Yamaguchi, Yokoyama (2015)



Preliminary

- Formation of domain walls is likely to occur if T_R and/or couplings (λ, κ) are sufficiently large.
- What occurs if they are formed ?
  - If they are absolutely stable, they come to overclose the universe. (conflict with standard cosmology)

    Zel'dovich, Kobzarev, Okun, JETP 40, 1 (1975)
  - They must collapse at some early time.
  - If they lived for sufficiently long time, they can be a source of the gravitational wave background.

3. Gravitational waves from domain walls

Kadota, Kawasaki, KS, 1503.06998

Collapse of domain walls

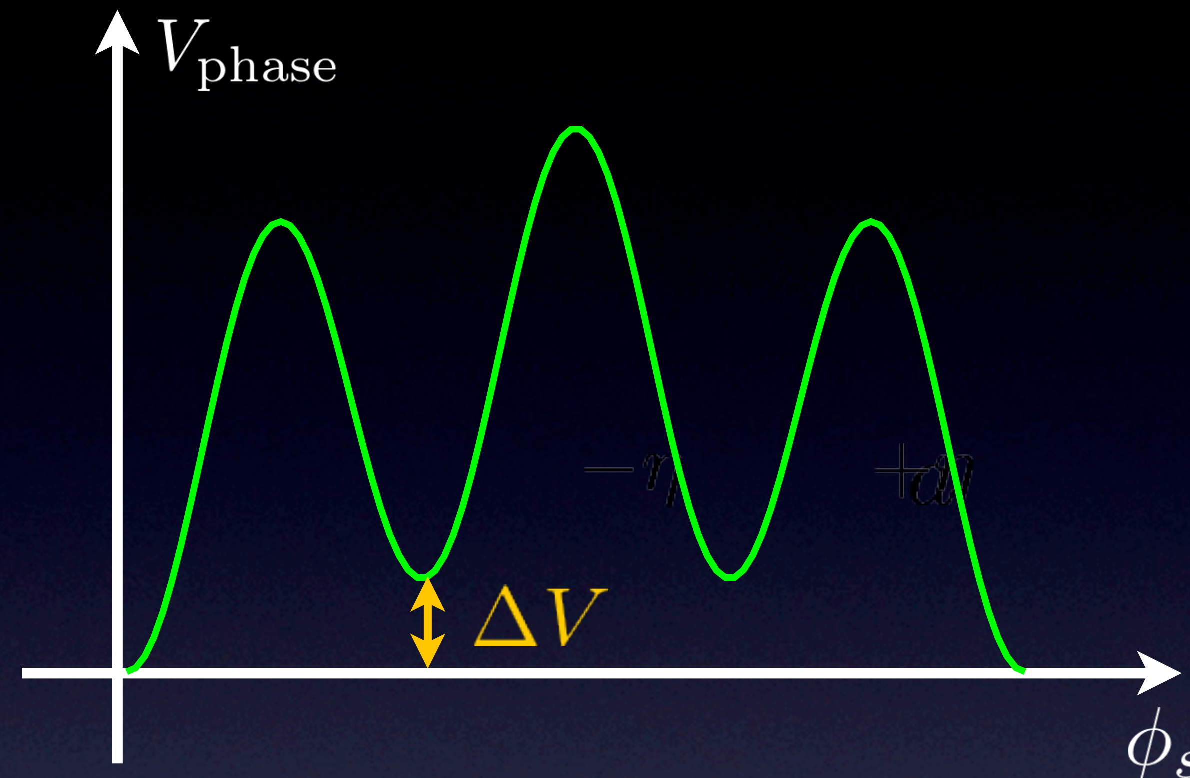
Approximate discrete symmetry (bias)

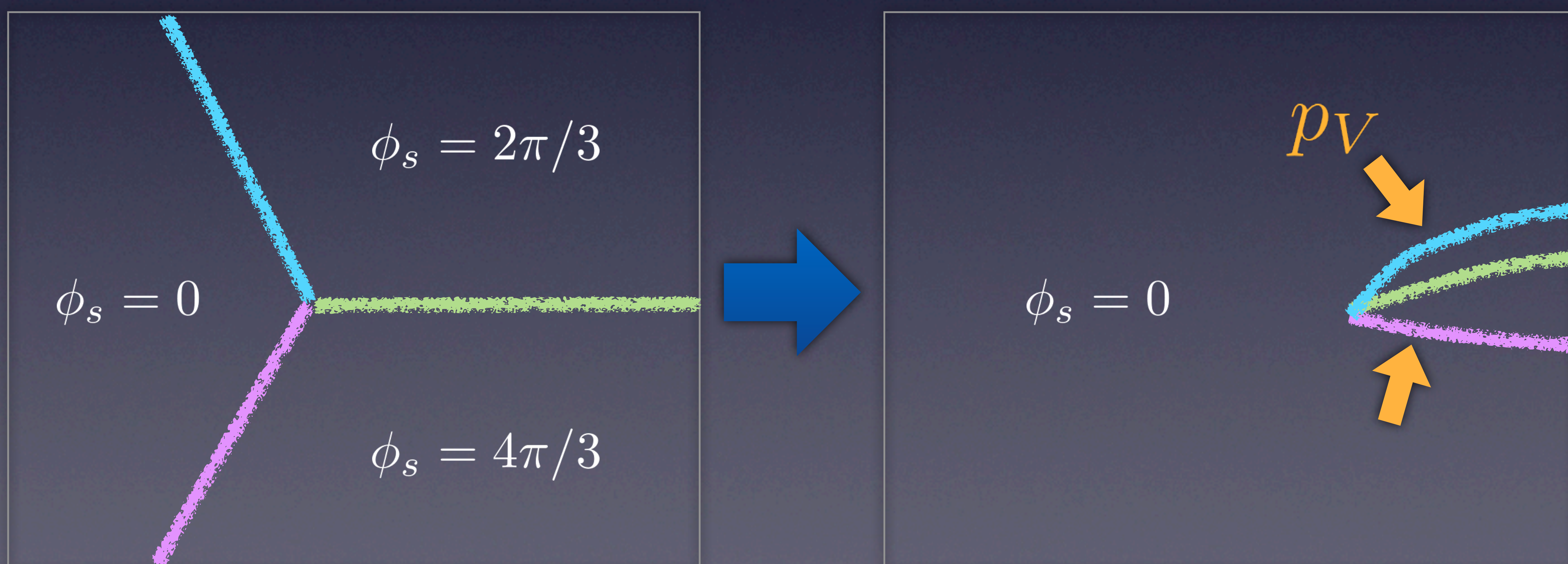
Vilenkin, PRD23, 852 (1981)

$\Delta V \sim \Lambda^4 \qquad \Lambda \ll v_s$

→ Degenerate vacua are lifted

→ Domain walls are annihilated due to the pressure $p_V \sim \Delta V$





Annihilation occurs when

$$p_V \sim p_T$$

Decay time

$$t_{\rm dec} \sim R|_{p_V = p_T} \sim \frac{\sigma_{\rm wall}}{\Lambda^4}$$

$$\sim 7{\rm sec} \left(\frac{\sigma_{\rm wall}}{1{\rm TeV}^3}\right) \left(\frac{0.1{\rm MeV}}{\Lambda}\right)^4$$

$p_T \sim \sigma_{\rm wall}/R$: tension

R : curvature radius of walls

$\sigma_{\rm wall}$: surface mass density of walls

- Decay products of domain walls may dissociate light element created during Big Bang Nucleosynthesis (BBN)

  → Require that $t_{\rm dec} \lesssim 0.01{\rm sec}$

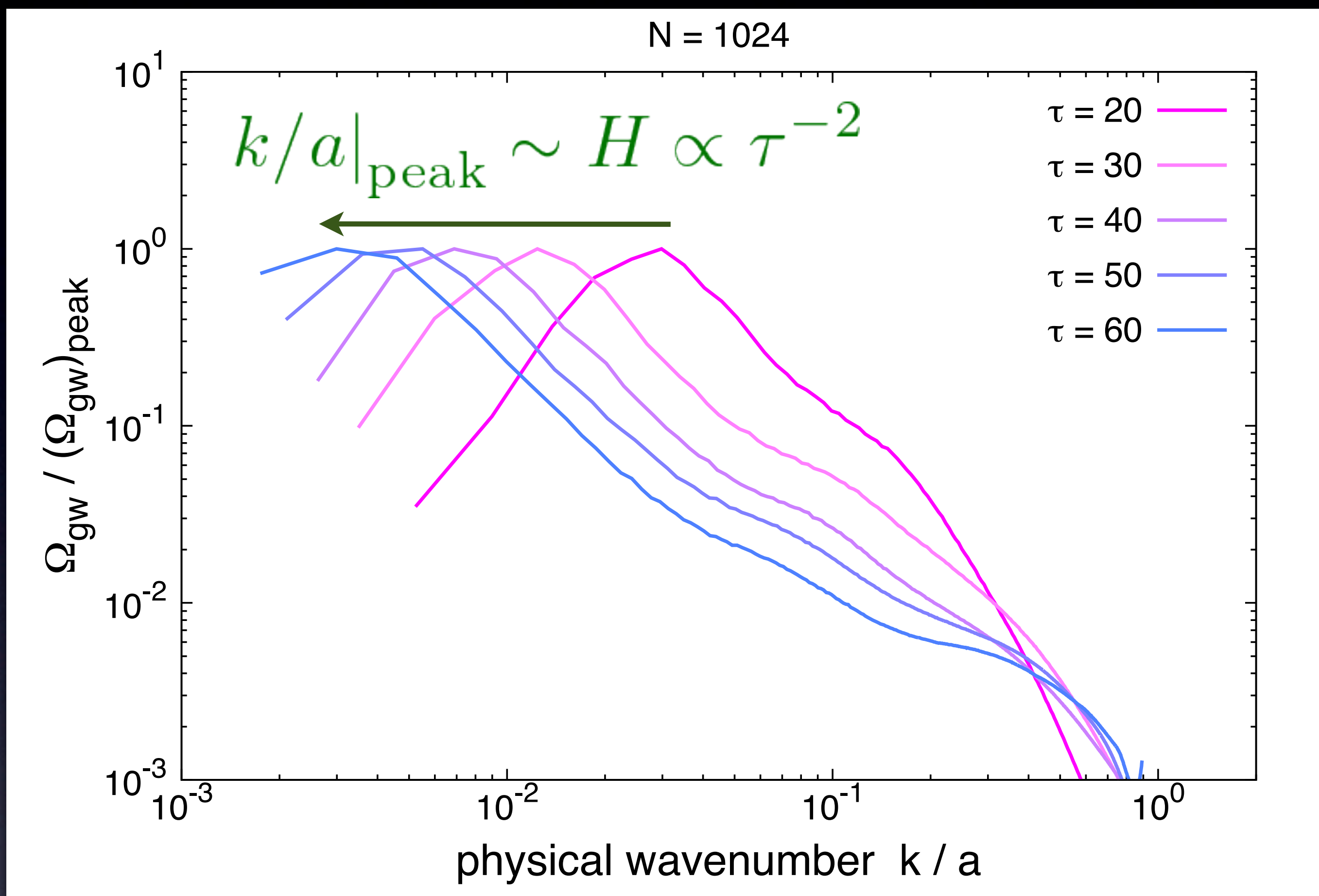
- Domain walls exist at early epoch and decay before the epoch of BBN

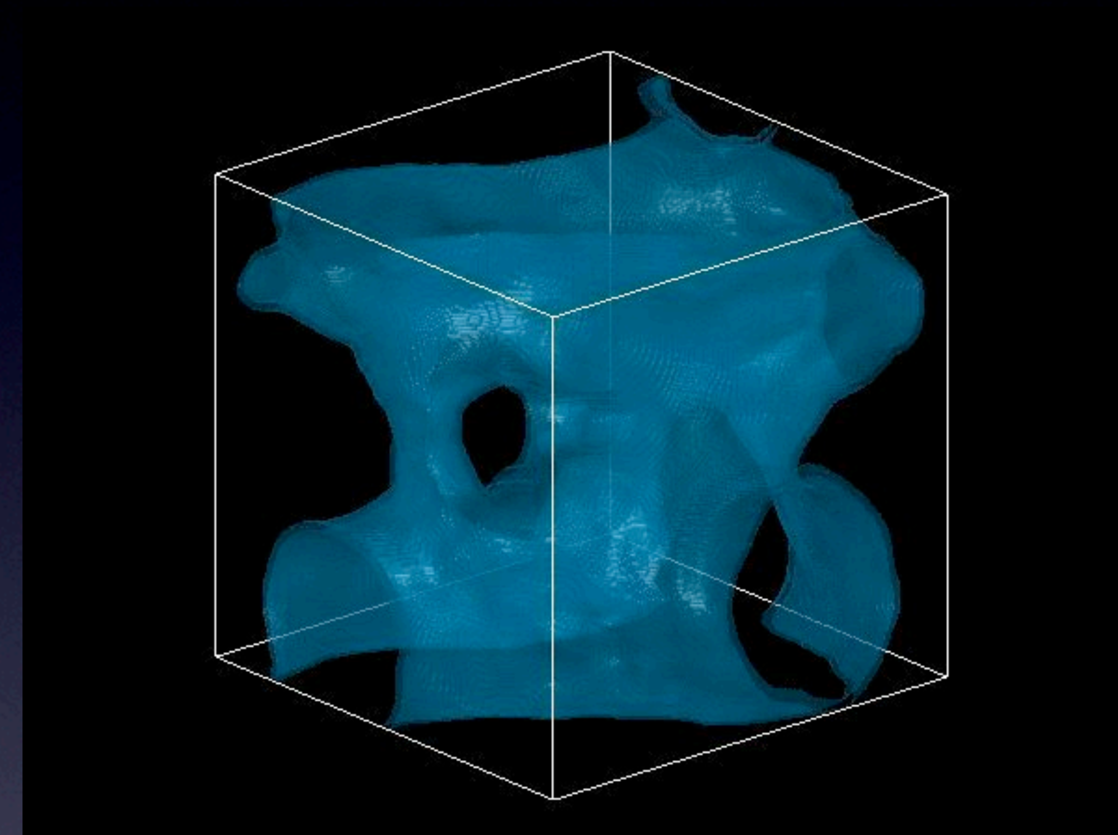
  → Gravitational waves are expected to be produced

Gravitational waves from domain walls

Hiramatsu, Kawasaki, KS, JCAP02(2014)031

- Simulation of scalar fields in 3D lattice with 512^3 and 1024^3





- Amplitude $\Omega_{\mathrm{gw}} h^2(t_0) \simeq 1.7 \times 10^{-17} \left(\frac{\sigma_{\mathrm{wall}}}{1\mathrm{TeV}^3}\right)^2 \left(\frac{t_{\mathrm{dec}}}{0.01\mathrm{sec}}\right)^2$

$$\Omega_{\mathrm{gw}} = \frac{1}{\rho_c(t)} \frac{d\rho_{\mathrm{gw}}}{d\ln k}$$

- Peak frequency $f_{\mathrm{peak}}(t_0) = \frac{a(t_{\mathrm{dec}})}{a(t_0)} H(t_{\mathrm{dec}}) \simeq 10^{-9}\mathrm{Hz} \left(\frac{0.01\mathrm{sec}}{t_{\mathrm{dec}}}\right)^{1/2}$

$$\rho_c(t) = \frac{3H^2}{8\pi G}$$

- Decay before BBN: $t_{\mathrm{dec}} \lesssim 0.01\mathrm{sec} \ \rightarrow \ f \gtrsim 10^{-9}\mathrm{Hz}$

cf. pulsar timing $\Omega_{\mathrm{gw}} h^2 \sim 10^{-8}$ at $f \sim 10^{-9} - 10^{-8}\mathrm{Hz}$

Cosmological constraints

- Gravitational waves

$$\Omega_{\rm gw}h^2 < \mathcal{O}(10^{-8})$$ from pulsar timing observations

$$\sigma_{\rm wall} \sim \kappa v_s^3 \qquad \mu = \lambda v_s/\sqrt{2} \approx \mathcal{O}(100\mathrm{GeV})$$

$$\Rightarrow \Omega_{\rm gw}h^2 \propto \sigma_{\rm wall}^2 t_{\rm dec}^2 \propto \kappa^2 v_s^6 t_{\rm dec}^2 \propto \kappa^2 \lambda^{-6} \mu^6 t_{\rm dec}^2$$

- Avoiding unrealistic minima of the potential
  - There might be some unrealistic minima on which

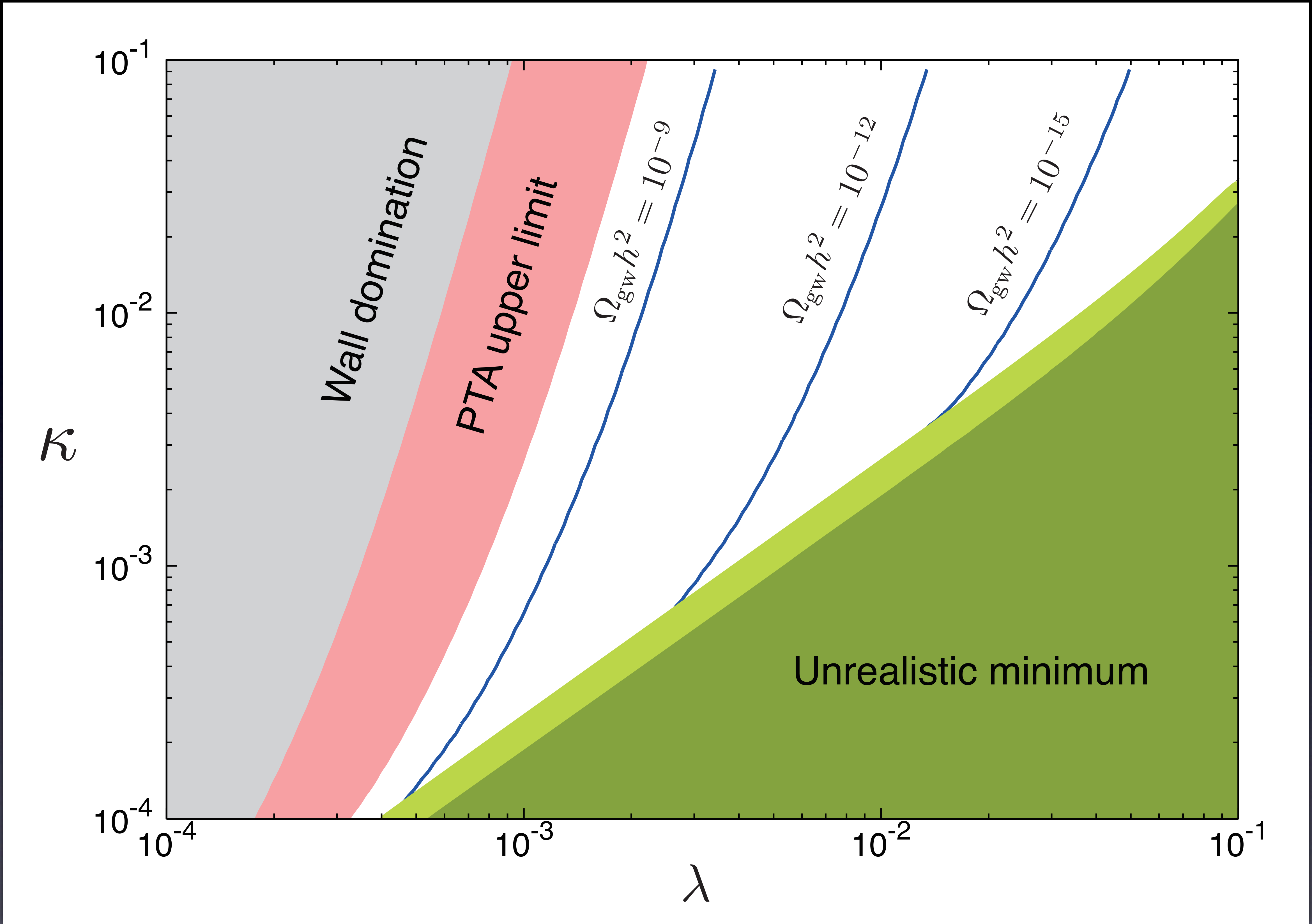
$$\langle H_u\rangle, \langle H_d\rangle \neq \left(\text{correct electroweak value}\right) \quad \text{and} \quad \langle S\rangle \neq \left(\text{correct value for } \mu\text{-term}\right)$$

  - For the height of the potential $V_{\rm min}$, we should confirm that

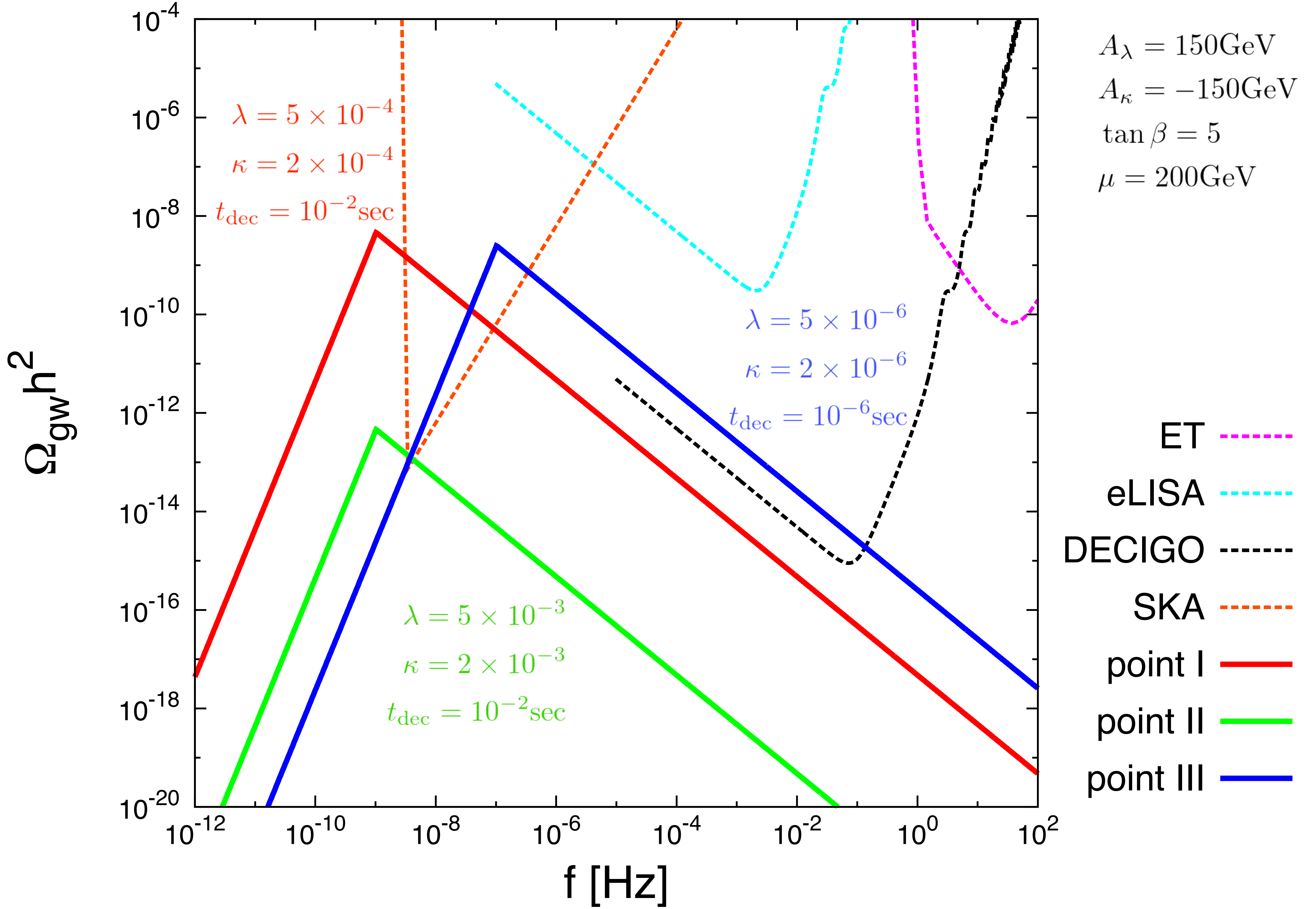
$$V_{\rm min,true} < V_{\rm min,unrealistic}$$

$t_{\rm dec} = 0.01{\rm sec}$

Kadota, Kawasaki, KS, 1503.06998



$$\Omega_{\rm gw}h^2 \propto \kappa^2 v_s^6 t_{\rm dec}^2 \propto \kappa^2 \lambda^{-6} \mu^6 t_{\rm dec}^2 \quad \text{for} \quad \lambda, \kappa \ll 1$$


$\Omega_{gw}h^2$
f [Hz]
$A_\lambda = 150\text{GeV}$
$A_\kappa = -150\text{GeV}$
$\tan\beta = 5$
$\mu = 200\text{GeV}$
$\lambda = 5 \times 10^{-4}$
$\kappa = 2 \times 10^{-4}$
$t_{\rm dec} = 10^{-2}\text{sec}$
$\lambda = 5 \times 10^{-6}$
$\kappa = 2 \times 10^{-6}$
$t_{\rm dec} = 10^{-6}\text{sec}$
$\lambda = 5 \times 10^{-3}$
$\kappa = 2 \times 10^{-3}$
$t_{\rm dec} = 10^{-2}\text{sec}$
ET
eLISA
DECIGO
SKA
point I
point II
point III

4. Conclusions

- Domain wall formation in the NMSSM can be avoided if
  - There exists a negative Hubble mass for the singlet scalar
  - Reheating temperature T_R is sufficiently low and/or Higgs-singlet couplings (λ, κ) are sufficiently small
- If domain walls are formed, they can produce gravitational waves
  → typically probed by pulsar timing observations
- Collider experiments will probe large (λ, κ) region:

Cosmology has a complementary role to probe the model