Cosmological aspects of the next-to-minimal supersymmetric standard model

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Collaborate with
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based on
K. Kadota, M. Kawasaki, KS, hep-ph/1503.06998.
A. Mazumdar, KS, M. Yamaguchi, work in progress.

Abstract

- Discuss cosmological aspects of the next-to-minimal supersymmetric standard model (NMSSM):

NMSSM =

Minimal Supersymmetric Standard Model (MSSM)

+

Additional gauge singlet superfield S

- Formation of domain walls in the context of primordial inflation

- Estimate the gravitational wave signatures from domain walls and their parameter dependence

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 $\sim M_{\rm SUSY}$

$\Rightarrow$ 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 Z3 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

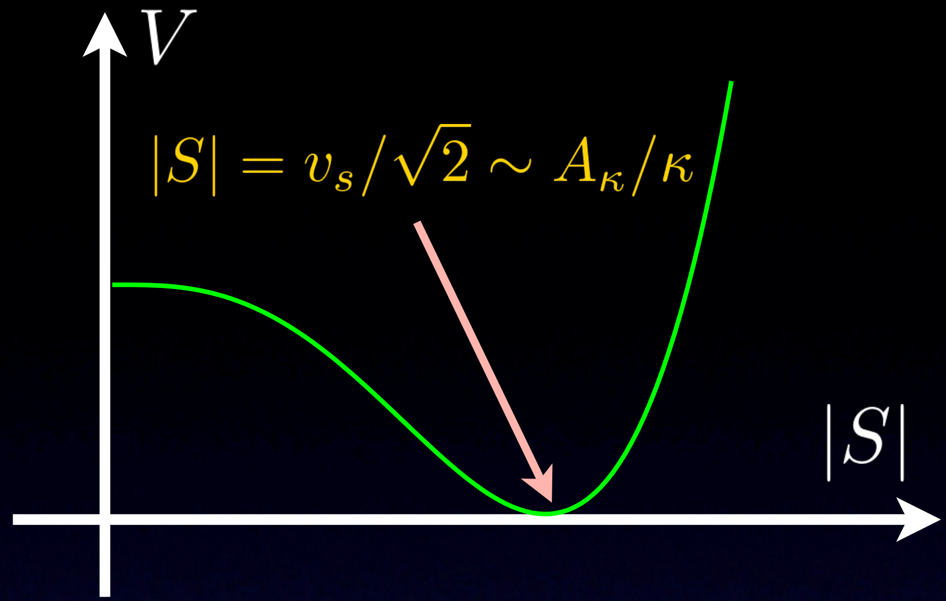
$$\Rightarrow \quad W_{\text{NMSSM}} = \lambda S H_u H_d + \frac{\kappa}{3}S^3 + \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D^c_j - \lambda^u_{ij} H_u Q_i U^c_j$$

Two parameters: (λ, κ)

- Z3 is spontaneously broken when S, H_u, H_d acquire VEVs

⇒ Formation of domain walls

Potential for S

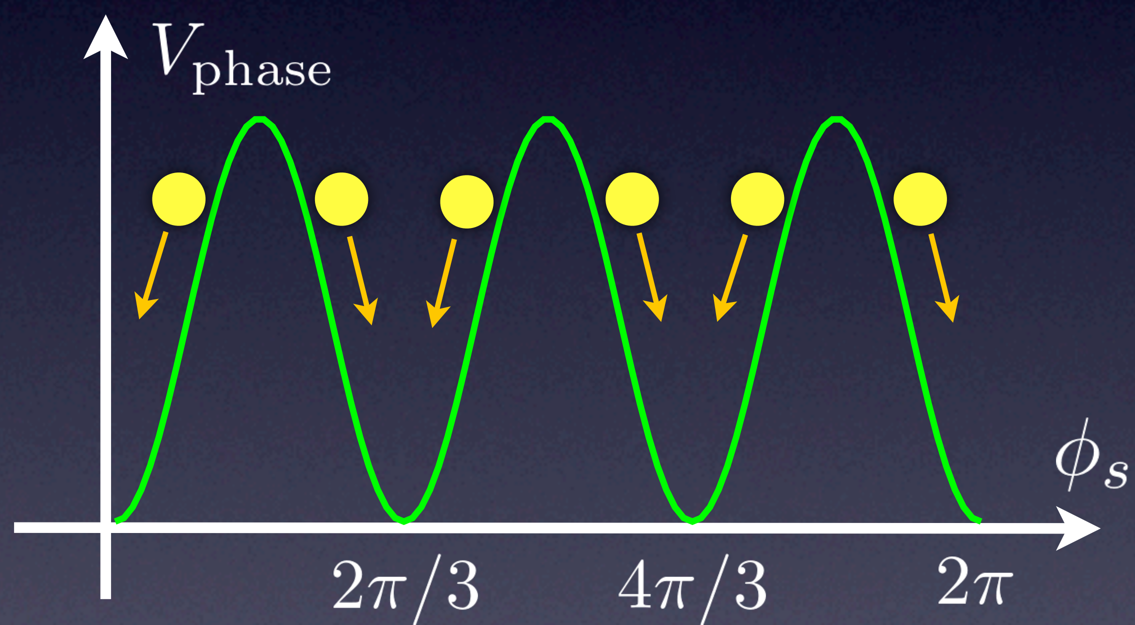


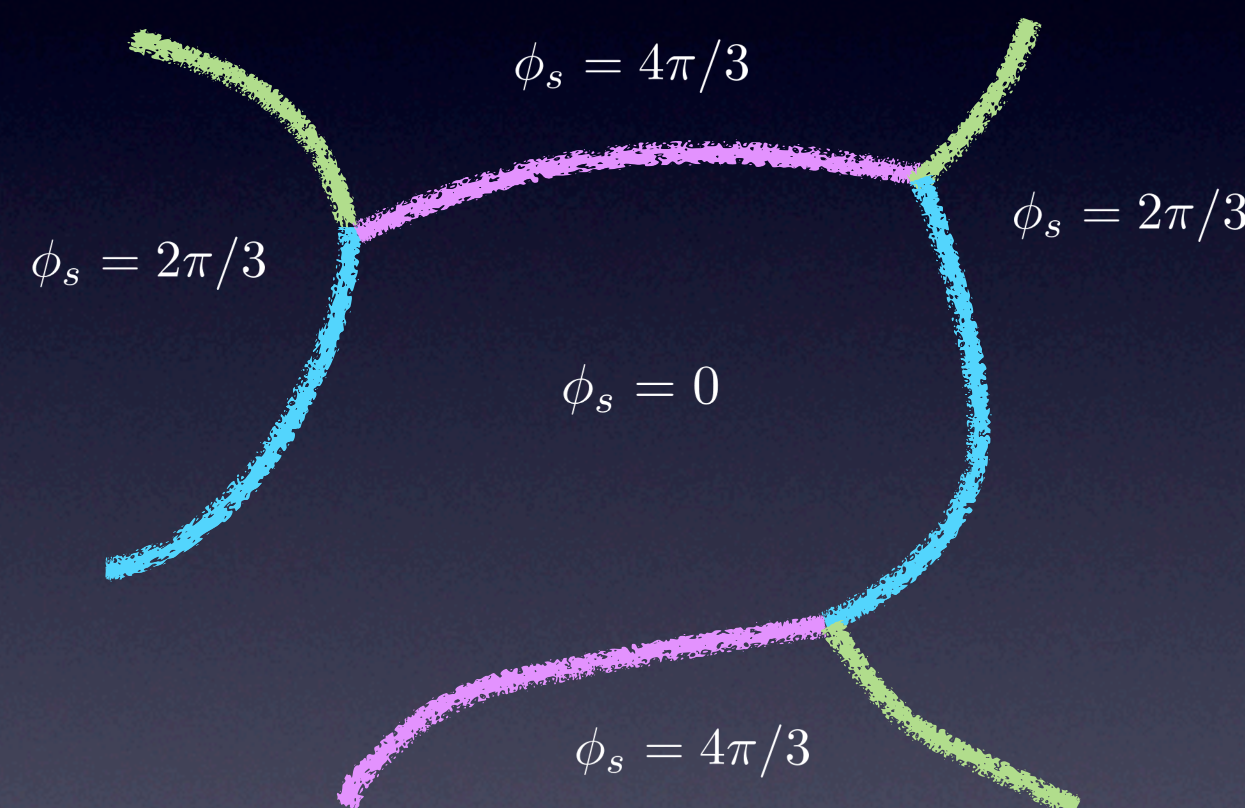
$$V \simeq m_S^2|S|^2 + \kappa^2|S|^4 + \underbrace{\left[\frac{1}{3}\kappa A_\kappa S^3 + \text{c.c.}\right]}_{V_{\text{phase}}}$$

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

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

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

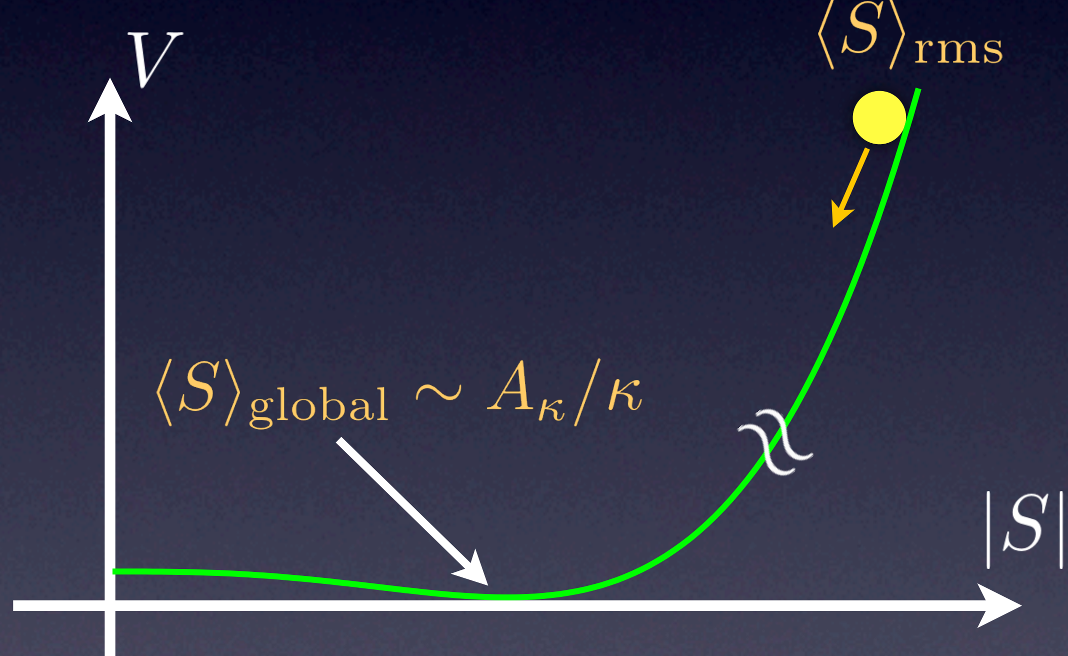
How ? and under what conditions ?

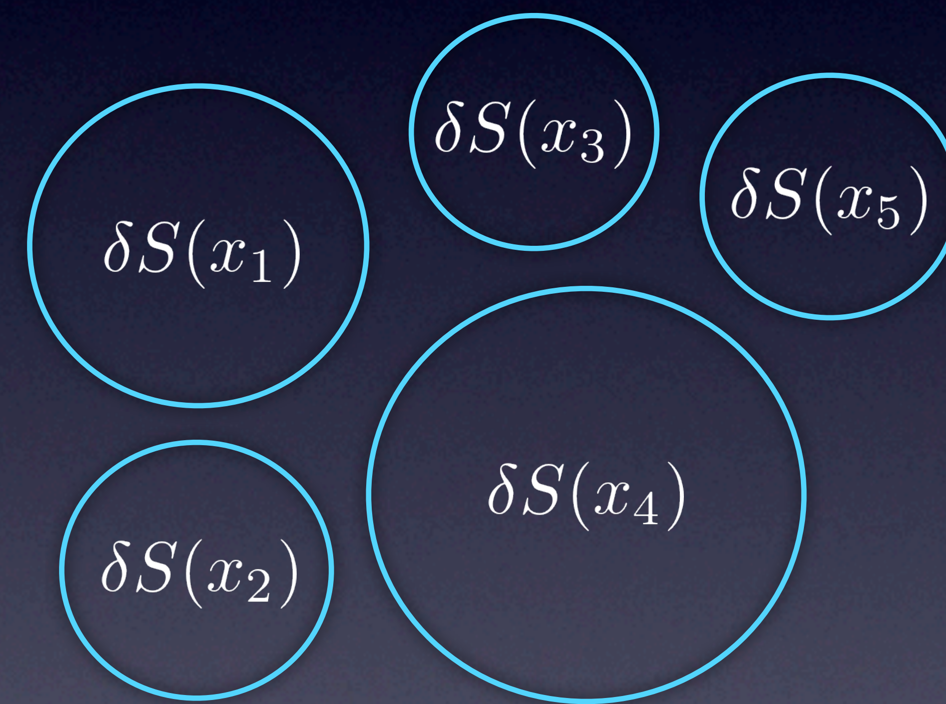
Let us carefully see the evolution of S after inflation

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

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

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





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

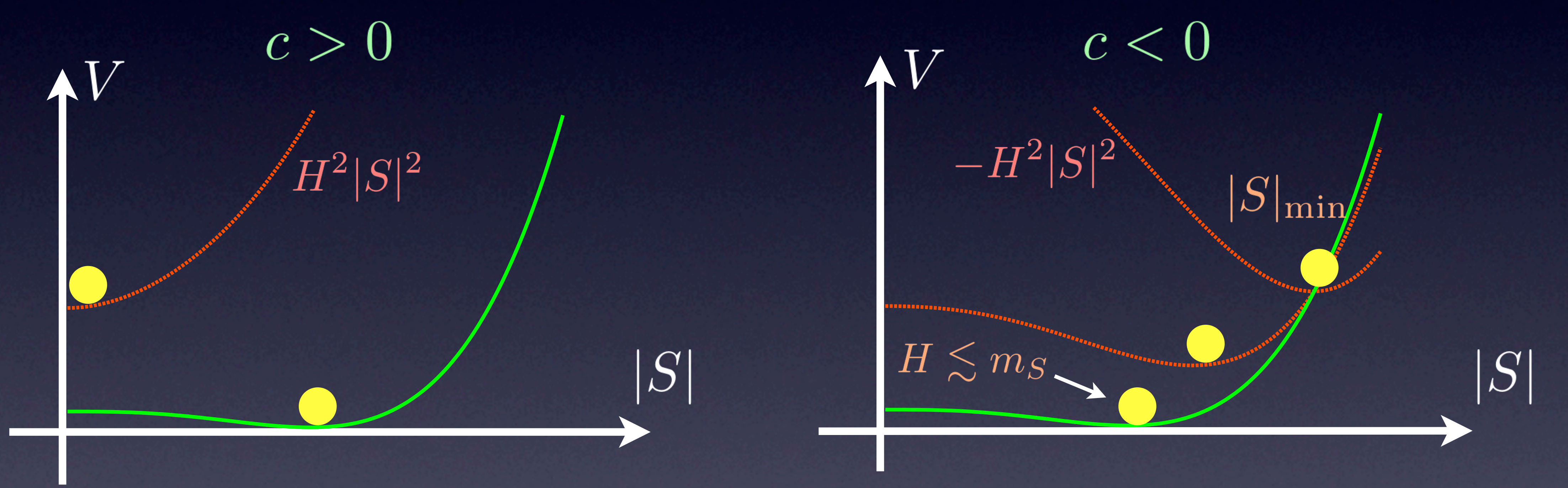
Tkachev, Khlebnikov, Kofman, Linde, Phys. Lett. B440, 262 (1998); Kasuya, Kawasaki, PRD61, 083510 (2000)

Supergravity effects

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

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

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



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

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

No oscillation → the defect formation can be avoided

Conditions to avoid the domain wall formation

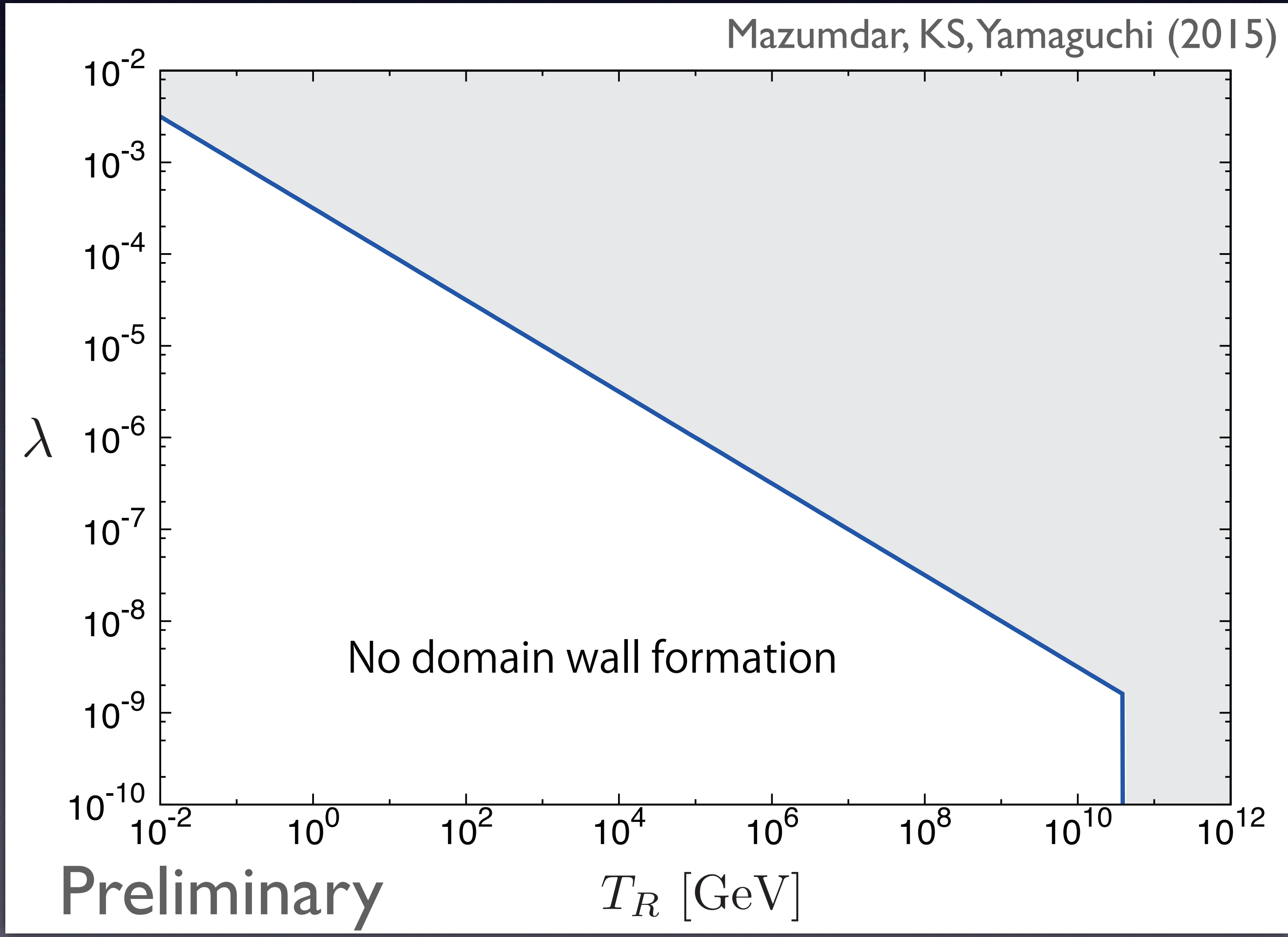
- Inflaton oscillation lasts for a sufficiently long time

$$T > T_R \quad \text{at} \quad H^2 \simeq m_S^2$$

T_R : reheating temperature

- Thermal fluctuations remain irrelevant

$$\delta S_{\rm th}/\langle S \rangle \sim T/\langle S \rangle < \mathcal{O}(1)$$



- Formation of domain walls is inevitable

  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.

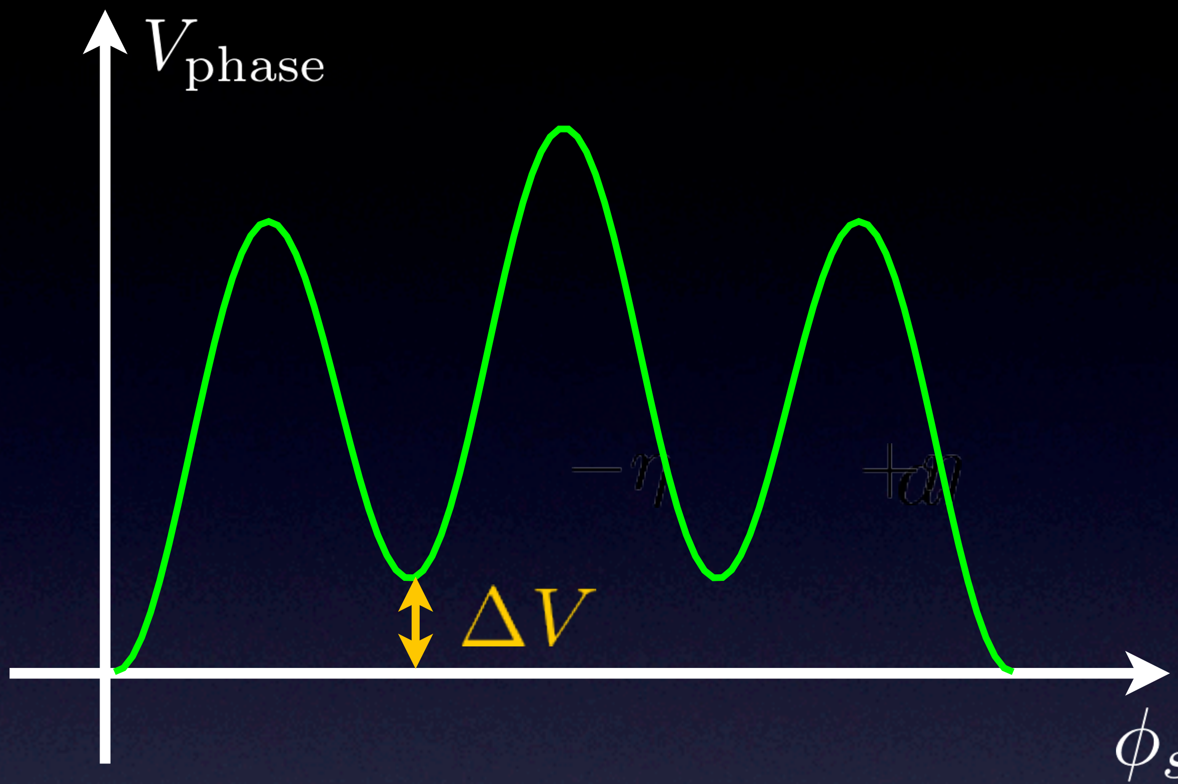
Collapse of domain walls

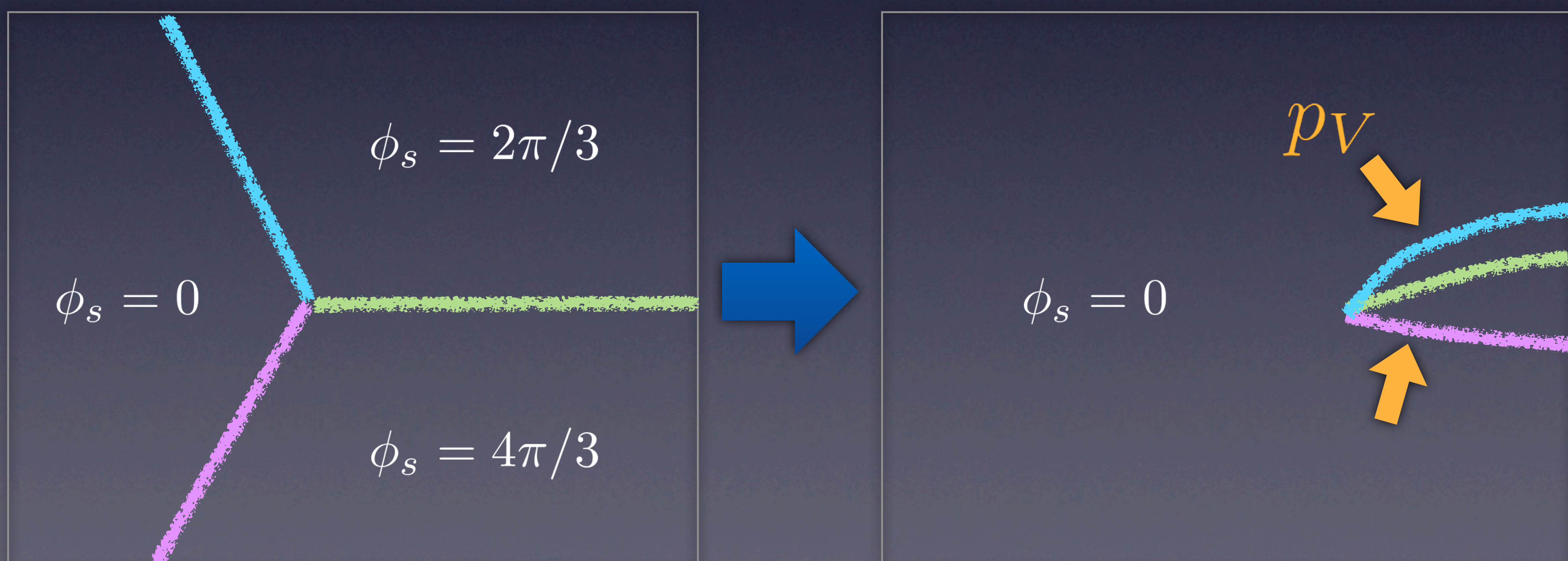
Approximate discrete symmetry (bias)

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 $p_V \sim \Delta V$ which determines the decay time $t_{\rm dec} \propto 1/\Delta V$

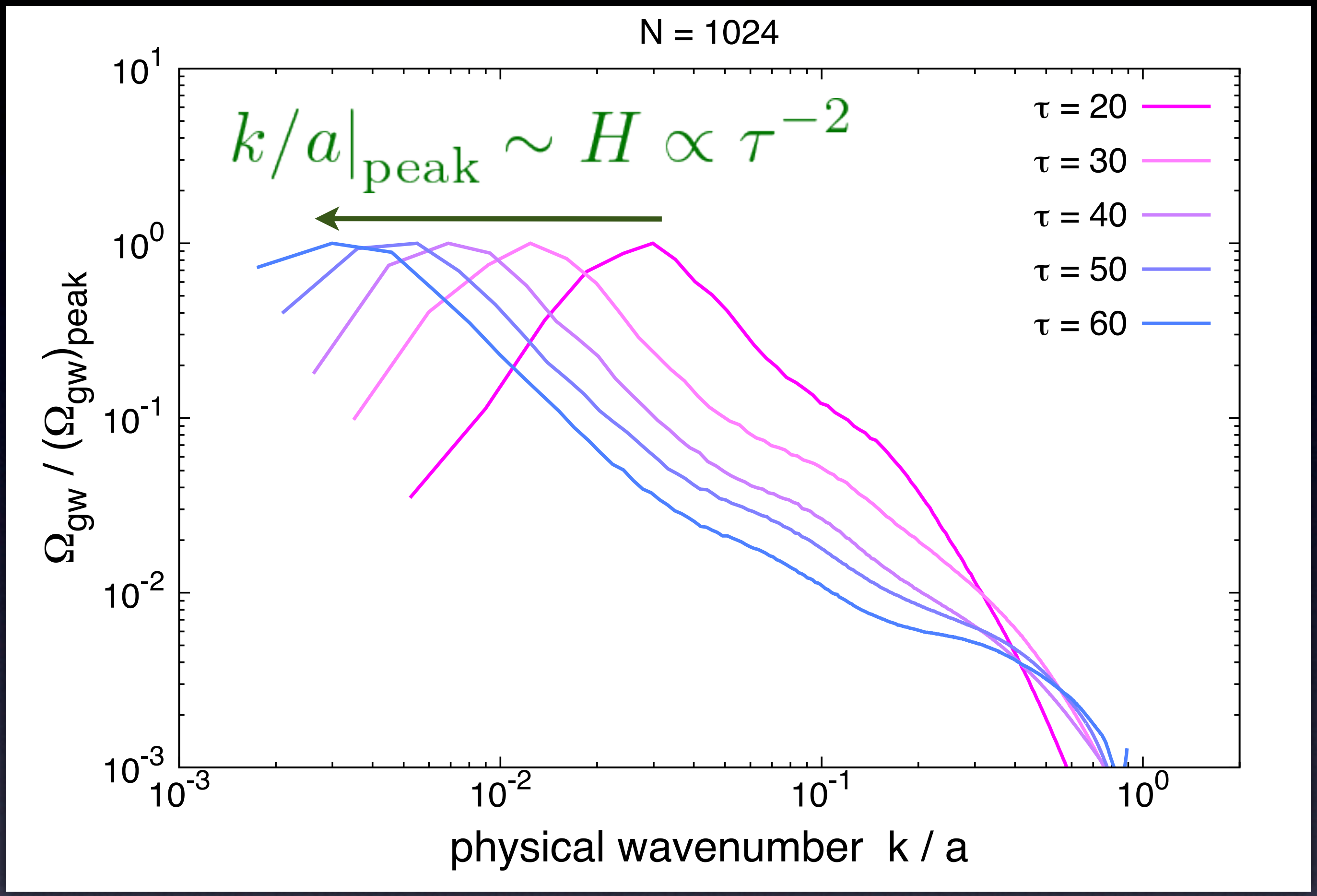


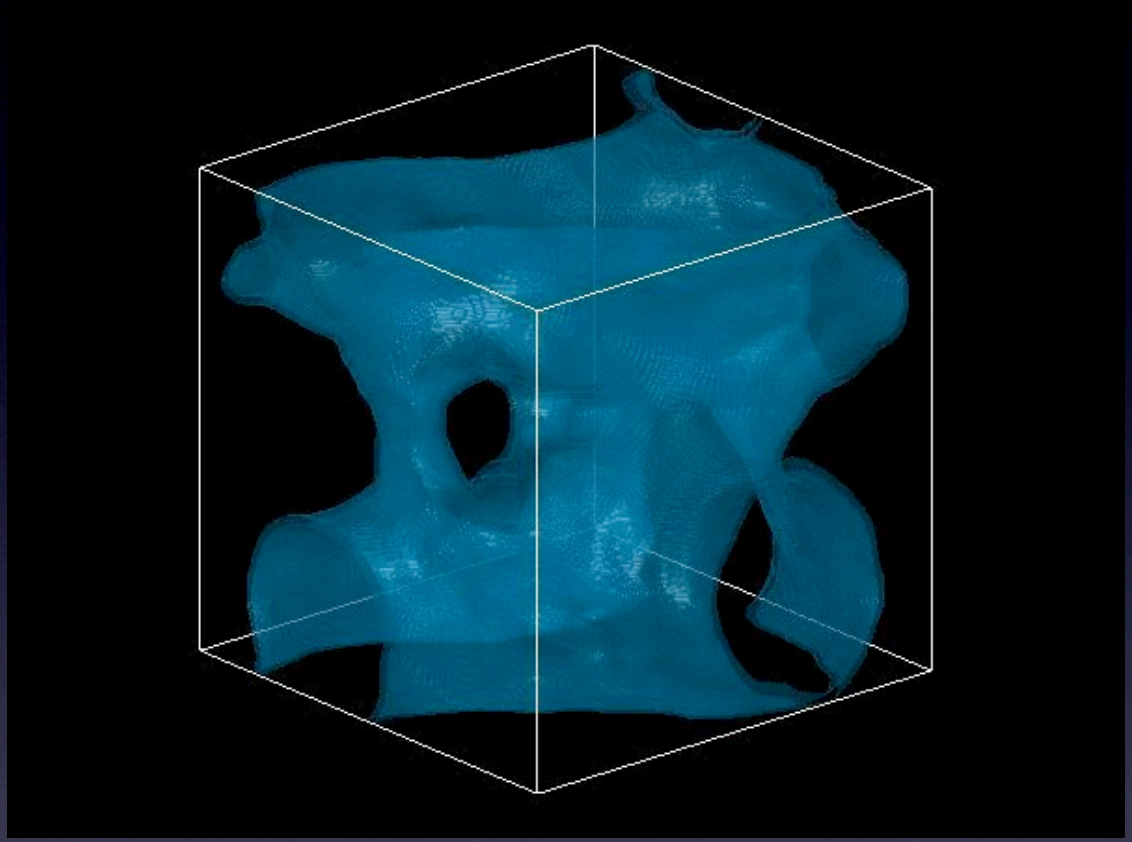


Gravitational waves from domain walls

Hiramatsu, Kawasaki, KS, JCAP02(2014)031

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





- Amplitude $$\Omega_{\rm gw}h^2(t_0) \simeq 1.7\times10^{-17}\left(\frac{\sigma_{\rm wall}}{1{\rm TeV}^3}\right)^2\left(\frac{t_{\rm dec}}{0.01{\rm sec}}\right)^2$$

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

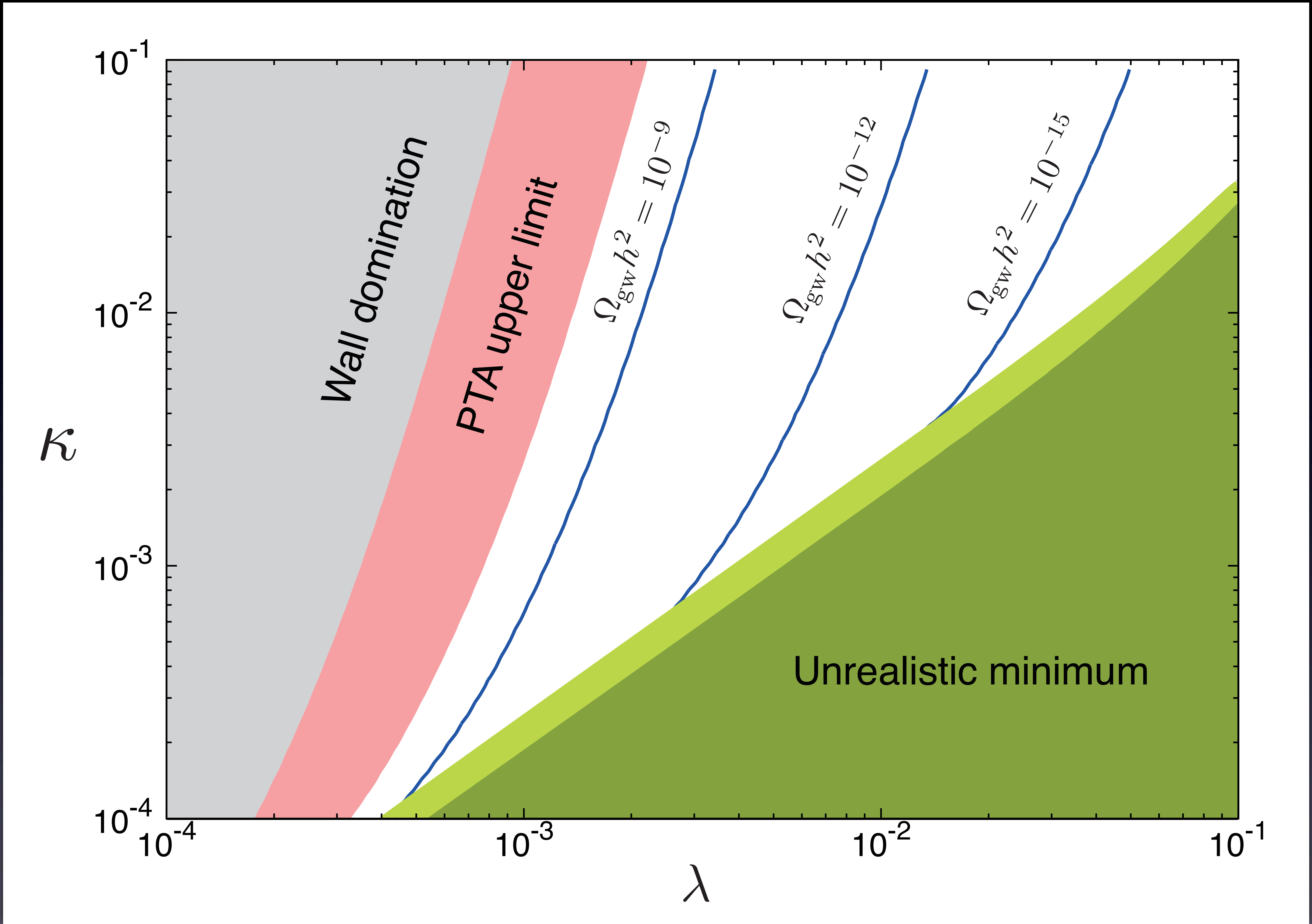
- Peak frequency $$f_{\rm peak}(t_0) = \frac{a(t_{\rm dec})}{a(t_0)}H(t_{\rm dec}) \simeq 10^{-9}{\rm Hz}\left(\frac{0.01{\rm sec}}{t_{\rm dec}}\right)^{1/2}$$

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

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

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

Kadota, Kawasaki, KS, 1503.06998



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

Conclusions

- Domain wall formation in the NMSSM can be avoided if
  - There exists a negative Hubble mass for the singlet scalar
  - Reheating temperature is sufficiently low
- If domain walls are formed, they can produce gravitational waves (typically probed by pulsar timing observations)
- Prospects
  - Investigating particle production from domain walls: Connection with dark matter physics (?) Kadota, KS, work in progress
  - Collider experiments will probe large (λ, κ) region

Several observational windows would be combined to yield a clue to understand the early history of the universe