Coleman-Weinberg Inflation
with
Quark Chiral Condensate
and
Dynamically Fine-tuned Initial Condition

Kengo Shimada

with S. Iso (KEK) and K. Kohri (KEK)

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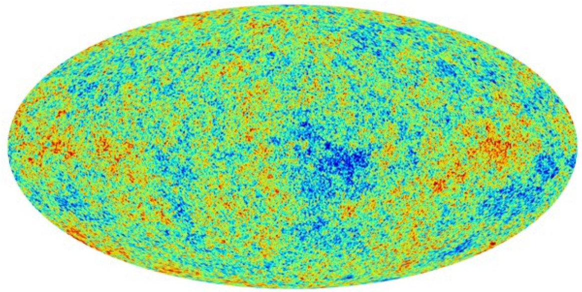
1. Introduction

- INFLATION (quasi-de Sitter period)

  Solution of
  - Horizon problem
  - Flatness problem
  - Monopole problem



(Almost) scale invariant fluctuation

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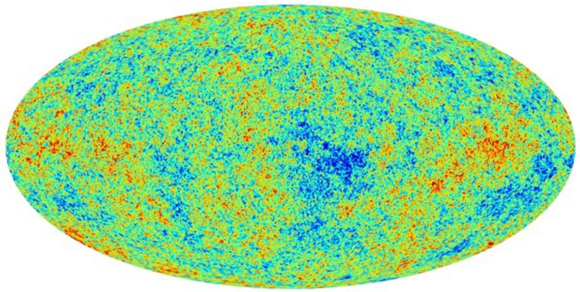


(Almost) scale invariant fluctuation

CMB power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln \frac{k}{k_*} + \cdots}$$

$$A_s \approx 2.2 \times 10^{-9}$$

$$r = \frac{A_t}{A_s} < 0.12 \qquad n_s - 1 \approx -0.04$$

$$\alpha_s = \frac{dn_s}{d\ln k}\ , \cdots$$

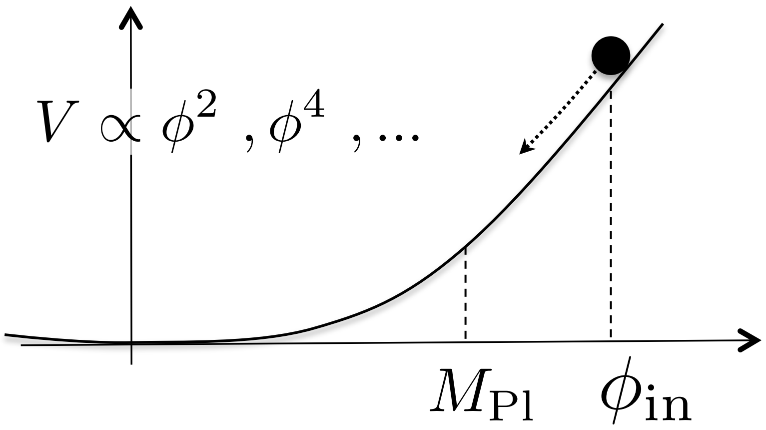
Particle physics model

$$V \qquad \partial_\phi V$$

$$\partial_\phi^2 V \qquad \partial_\phi^3 V \qquad \cdots$$

1. Introduction

Simplest model



Good — "Chaotic" initial condition

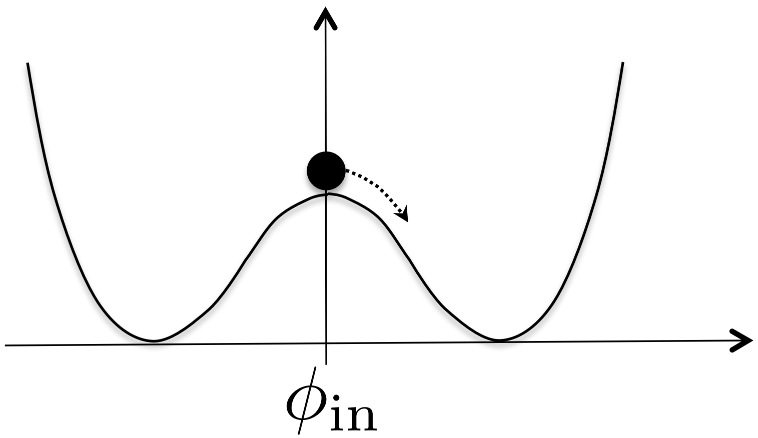
(No tuning of $\phi_{\rm in}$ is required.)

Bad — Validity of the effective potential?

Too large tensor-scalar ratio

(large field inf.) $r > 0.12$

"New" (hilltop) inflation



Good — Small tensor-scalar ratio

(small field inf.) $r \approx 0$

Bad — Fine-tuning of the initial condition $\phi_{\rm in}$ is necessary.

1. Introduction

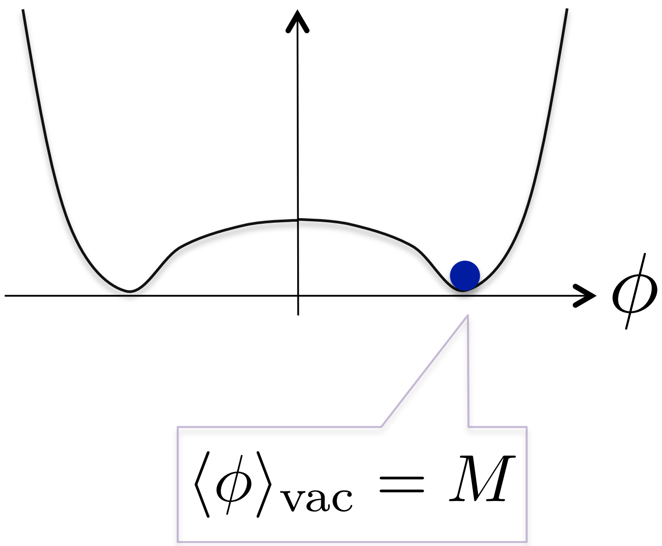
- Classical scale invariance (CSI)

$$V(h) = -\cancel{\frac{\mu^2}{2}}h^2 + \frac{\lambda}{4}h^4$$

As a solution of
gauge hierarchy problem

- Coleman-Weinberg (CW) mechanism ➡ radiative mass scale generation

$$V(\phi) = \frac{\lambda_\phi}{4}\phi^4\left(\ln\frac{\phi^2}{M^2} - \frac{1}{2}\right)$$



1. Introduction

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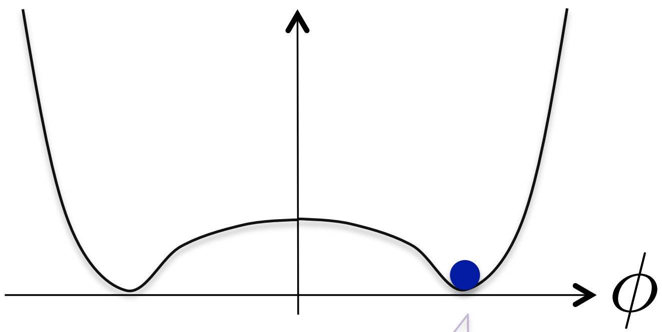
$$V(h) = -\cancel{\frac{\mu^2}{2}} h^2 + \frac{\lambda}{4} h^4$$

As a solution of gauge hierarchy problem

- Coleman-Weinberg (CW) mechanism ⇒ radiative mass scale generation

$$V(\phi) = \frac{\lambda_\phi}{4}\phi^4 \left(\ln \frac{\phi^2}{M^2} - \frac{1}{2} \right) + \frac{\lambda_{\text{mix}}}{4}\phi^2 h^2 + \frac{\lambda_h}{4} h^4$$



$$\langle \phi \rangle_{\text{vac}} = M$$

$\lambda_{\text{mix}} < 0$ EW symmetry breaking

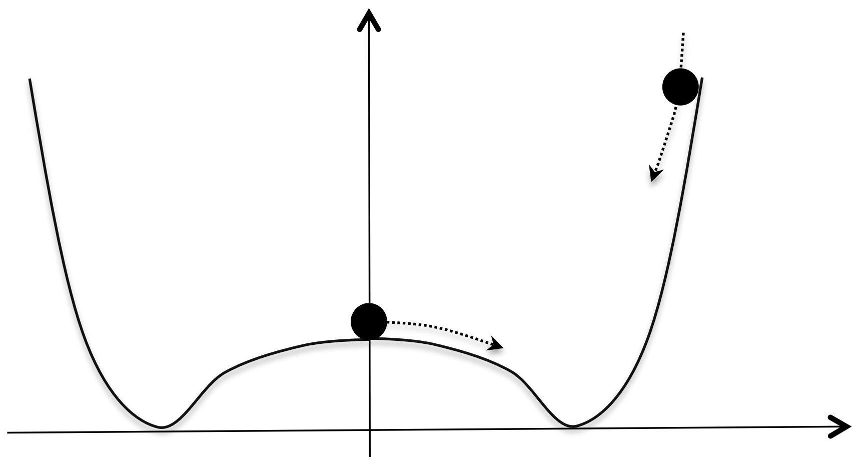
⇒

$$\langle h \rangle_{\text{vac}}^2 = |\lambda_{\text{mix}}| M^2 / (2\lambda_h)$$

$$m_h = \sqrt{|\lambda_{\text{mix}}|}\ M$$

1. Introduction

- Two possibilities of inflation (Chaotic or New inflation)



1. Introduction

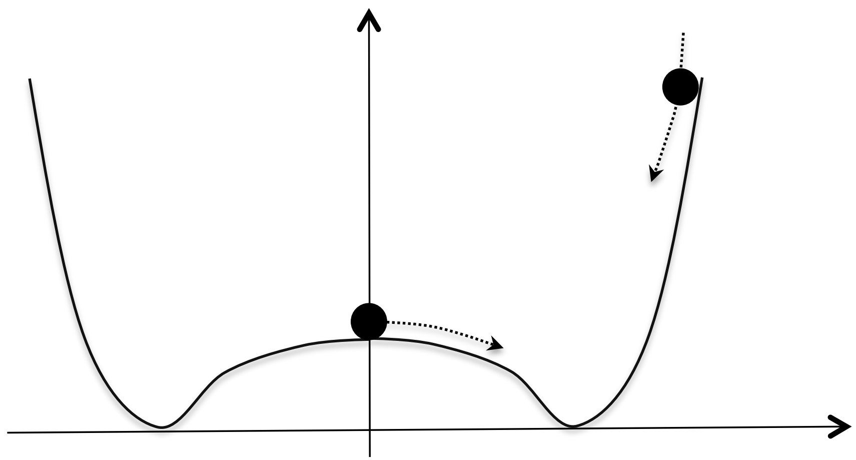
- Two possibilities of inflation (Chaotic or New inflation)

"Chaotic" initial condition (large field inf.)

Oscillation ➡ Non-perturbative particle production

➡ Dynamical fine-tuning of $\phi_{\rm in}$

Small field "new" inflation



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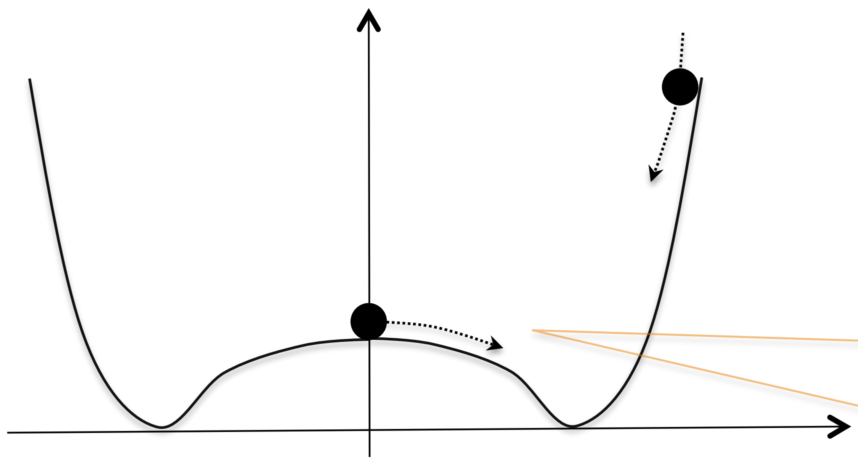

Another problem in new inflation

Solution:
quark chiral condensate

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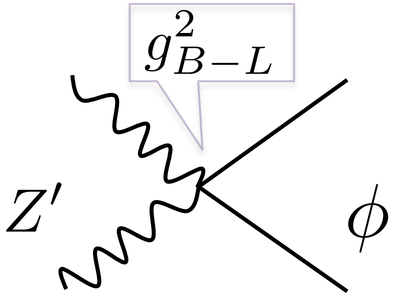
Model (CSI model with minimal gauged $B-L$) S.Iso, N.Okada, Y.Orikasa (2009)

Accidental global symmetry in the SM

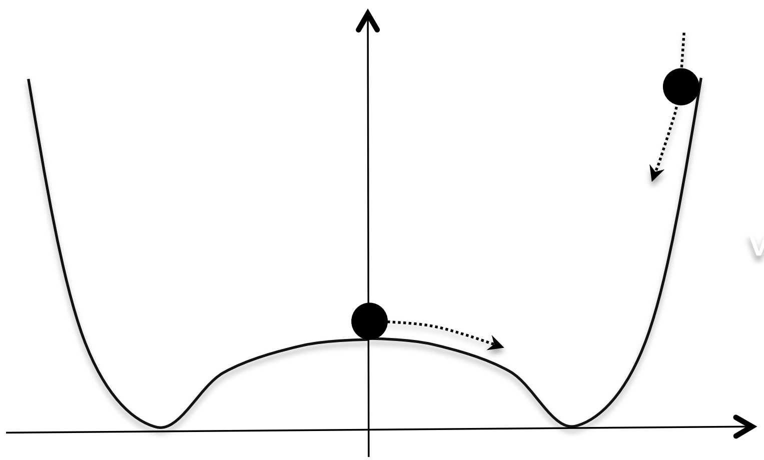


→ Z' (promoting to local symmetry)

→ ν_{R} (canceling the gauge anomaly)

- Seesaw
- Leptogenesis
- Dark matter

→ $B-L$ Higgs boson : ϕ



CW mechanism

ϕ -4 pt. self coupling

$$\lambda_\phi \sim g^4_{B-L}$$

$$M = \langle \phi \rangle_{\mathrm{vac}}$$
$$> 1 \sim 10\mathrm{TeV}$$

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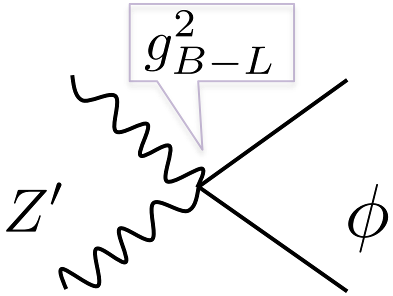
Accidental global symmetry in the SM



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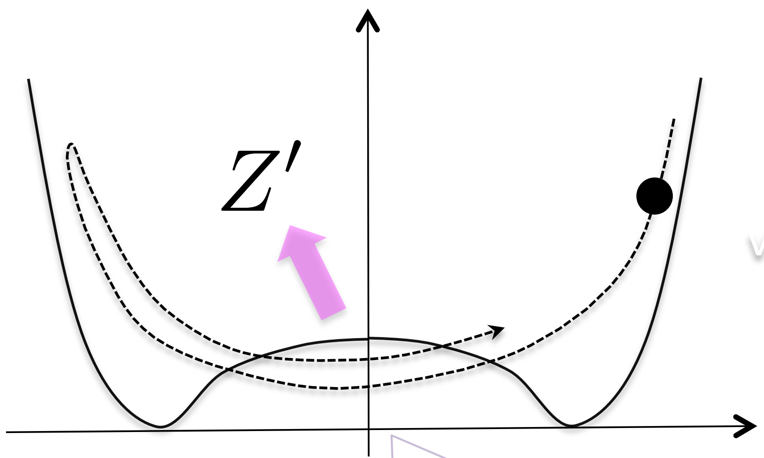


ϕ -4 pt. self coupling

$$\lambda_\phi \sim g^4_{B-L}$$

$$M = \langle \phi \rangle_{\mathrm{vac}}$$
$$> 1 \sim 10\mathrm{TeV}$$

$$\dot{m}_{Z'} = g_{B-L}\dot{\phi} > \omega^2_{Z'}$$

2. Preheating from chaotic initial condition

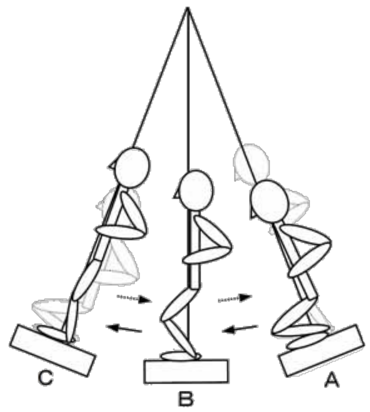
- Parametric resonance (non-perturbative particle production) Linde et al. (1997)

$$-\mathcal{L}_{int} = \frac{\lambda}{4}\phi^4 + \frac{g^2}{2}\phi^2\chi^2$$

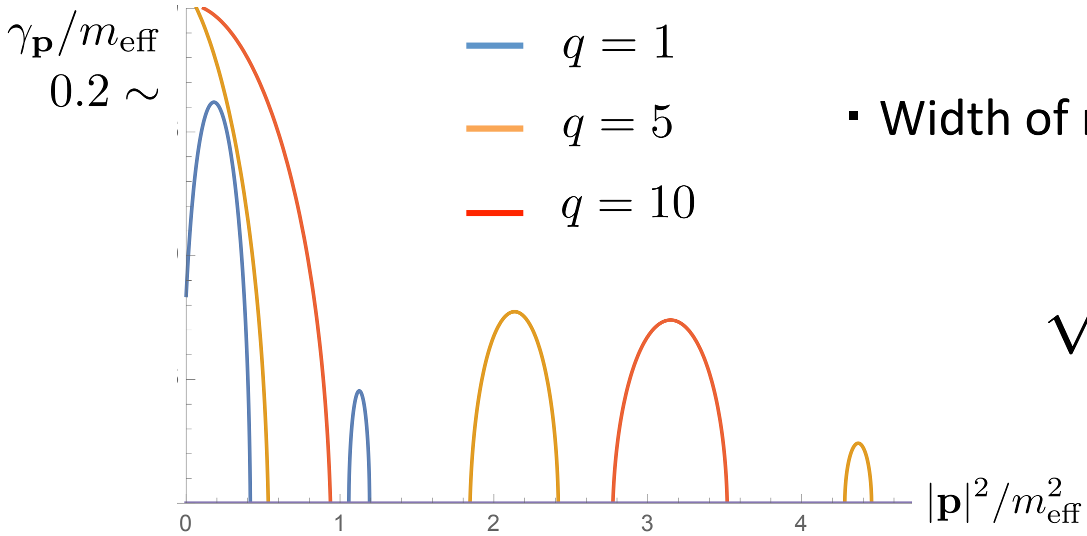
$$\chi = Z'$$
$$g = g_{B-L}$$

$$\phi(t) \approx \Phi \times \cos(m_{\text{eff}} t)$$
$$m_{\text{eff}} = 0.847\sqrt{\lambda}\Phi$$

$$m_\chi(t) = g\phi(t)$$
$$\approx g\Phi\cos(m_{\text{eff}} t)$$



Exponential growth $n_{\chi,\mathbf{p}} \propto e^{\gamma_{\mathbf{p}} t}$ for $\mathbf{p}$ in resonance bands



- Width of resonance bands

Strength of external force

$$\sqrt{q} = \frac{g\Phi}{m_{\text{eff}}} \gg 1$$

2. Preheating from chaotic initial condition

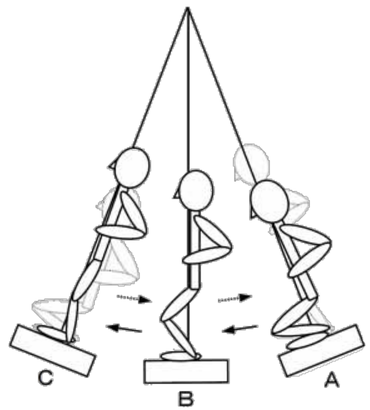
・Parametric resonance (non-perturbative particle production) Linde et al. (1997)

$$-\mathcal{L}_{int} = \frac{\lambda}{4}\phi^4 + \frac{g^2}{2}\phi^2\chi^2$$

$$\boxed{\begin{aligned} \chi &= Z' \\ g &= g_{B-L} \end{aligned}}$$

$$\boxed{\begin{aligned} \phi(t) &\approx \Phi \times \cos(m_{\rm eff} t) \\ m_{\rm eff} &= 0.847\sqrt{\lambda}\Phi \end{aligned}}$$

$$m_\chi(t) = g\phi(t) \approx g\Phi\cos(m_{\rm eff} t)$$



Exponential growth $n_{\chi,\mathbf{p}} \propto e^{\gamma_{\mathbf{p}} t}$ for $\mathbf{p}$ in resonance bands

・Violation of adiabaticity (particle picture)

$$\kappa_{\mathbf{p}}^2 = \left.\frac{\omega_{\chi\mathbf{p}}^2}{|\dot{m}_\chi|}\right|_{\phi=0} < 1$$

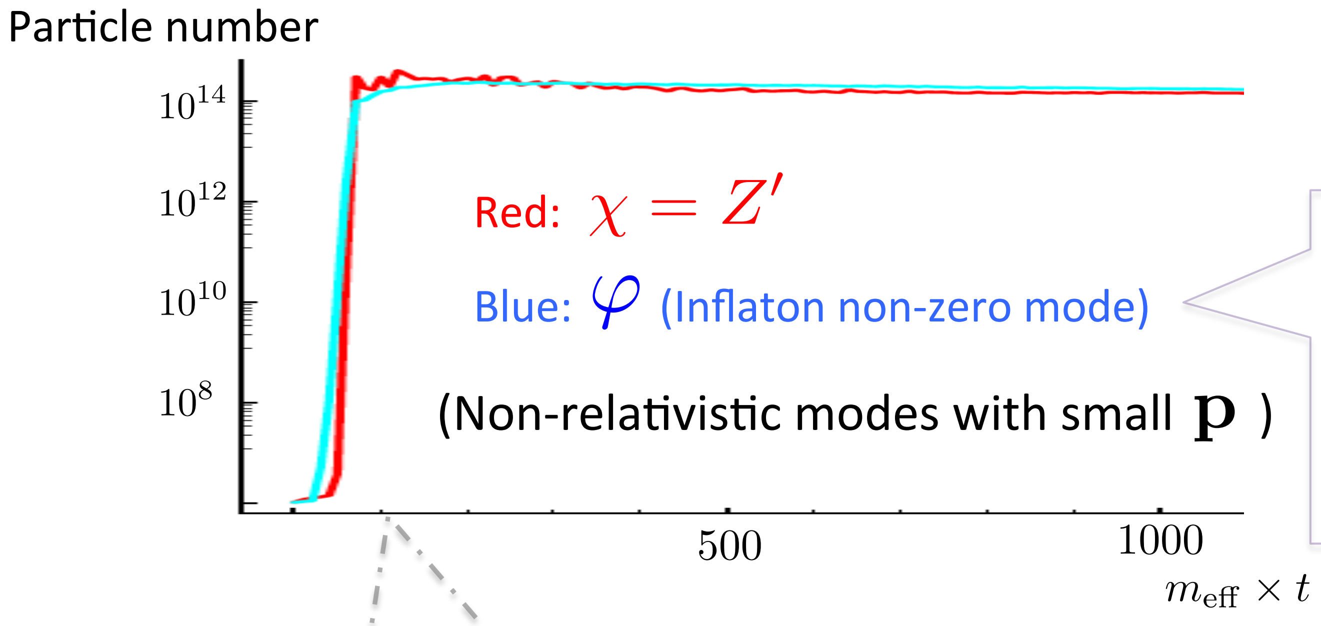
・Width of resonance bands

Strength of external force

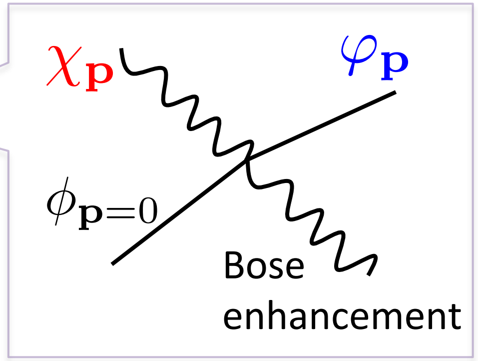
$$\sqrt{q} = \frac{g\Phi}{m_{\rm eff}} \gg 1$$

2. Preheating from chaotic initial condition

- Parametric resonance (non-perturbative particle production)



G. Felder
L. Kofman (1997)



Exponential growth

is terminated by
the back-reaction
from the produced $\chi = Z'$ and φ .

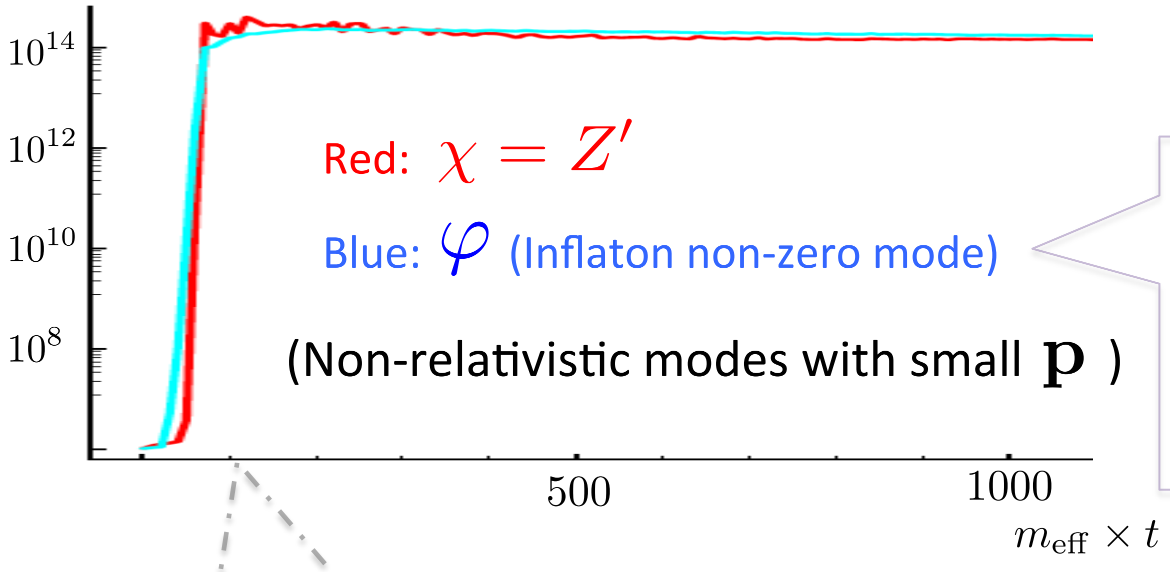
$$q \cancel{>} 1 \qquad \kappa^2 \cancel{<} 1$$

2. Preheating from chaotic initial condition

- Parametric resonance (non-perturbative particle production)

Particle number

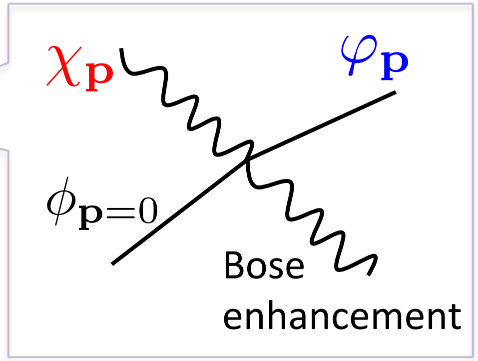
G. Felder
L. Kofman (1997)



Red: $\chi = Z'$

Blue: φ (Inflaton non-zero mode)

(Non-relativistic modes with small $\mathbf{p}$)



Exponential growth

is terminated by
the back-reaction
from the produced $\chi = Z'$ and φ .

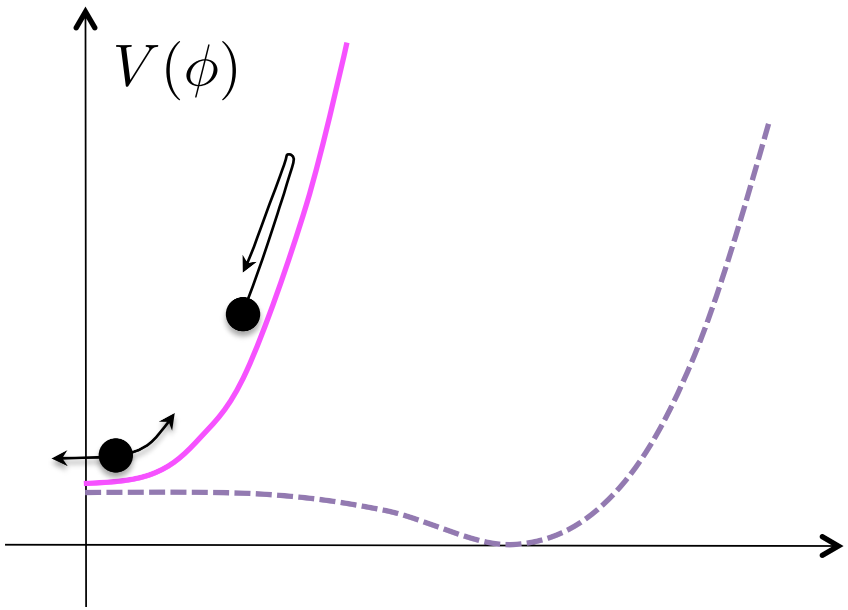
"Equilibrium" state

composed of low momentum modes

with amplitudes

$$q \cancel{>} 1 \qquad \kappa^2 \cancel{<} 1 \qquad \Longleftrightarrow \qquad \Phi \sim \sqrt{\langle \varphi^2 \rangle} \sim \sqrt{\langle \chi^2 \rangle} \propto a^{-1}$$

2. Preheating from chaotic initial condition



$$m_{\text{eff}} \sim g_{B-L}\Phi$$

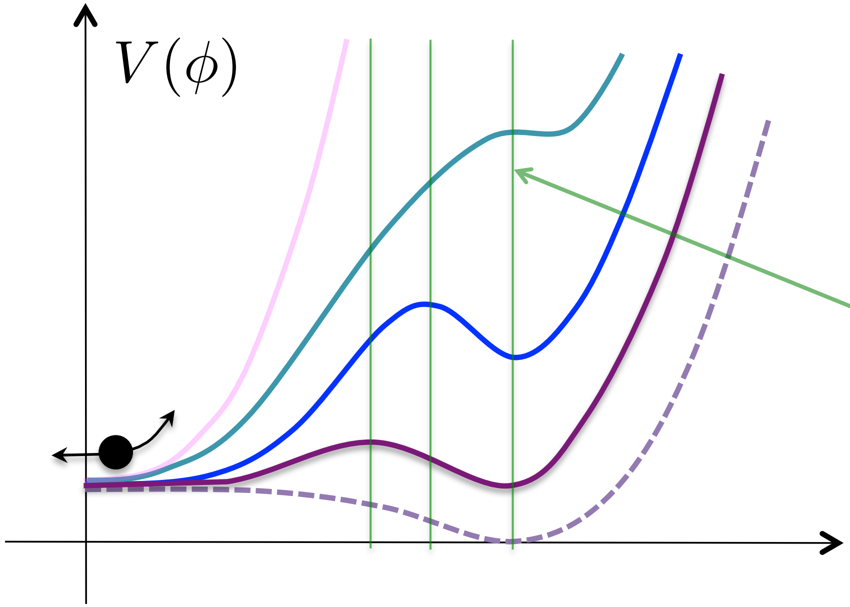
Oscillating around $\phi \approx 0$
along (**non-thermal**) **effective potential**

$$\langle Z'^2 \rangle \sim \Phi^2$$

$$\Rightarrow V_{\text{eff}} = g_{B-L}^2 \langle Z'^2 \rangle \phi^2/2 \sim (g_{B-L}\Phi)^2 \phi^2/2$$

When / Where does the oscillation stop ?

2. Preheating from chaotic initial condition

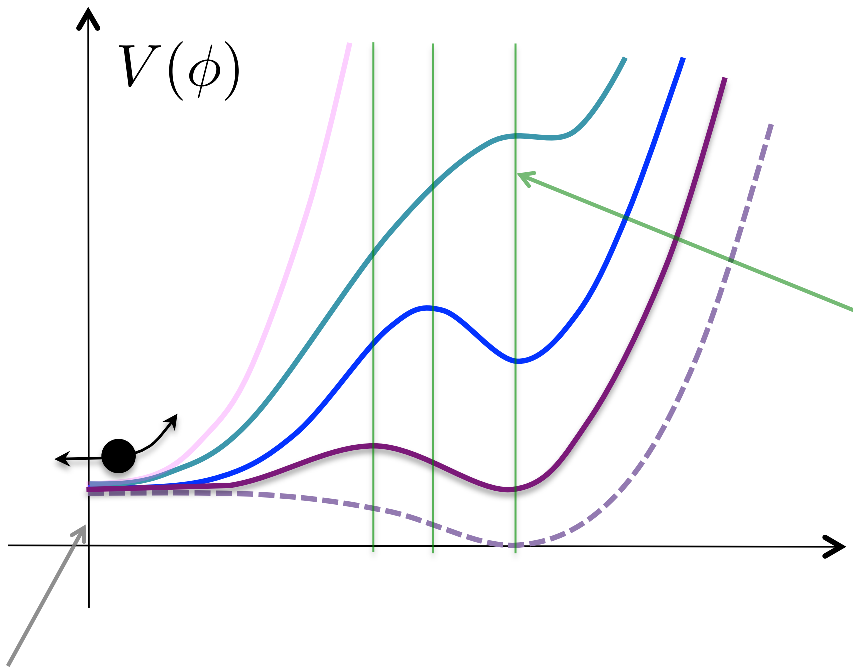


$$m_{\rm eff} \sim g_{B-L}\Phi$$

Position of potential wall $\dfrac{\Phi}{g_{B-L}} \gg \Phi$

Trapped around $\phi \approx 0$
by **(non-thermal) effective potential**

2. Preheating from chaotic initial condition



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Position of potential wall $\dfrac{\Phi}{g_{B-L}} \gg \Phi$

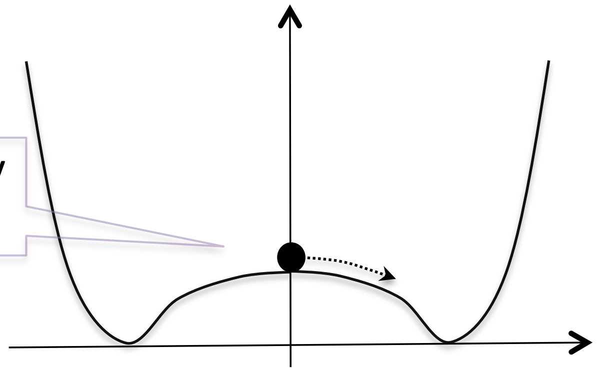
Trapped around $\phi \approx 0$
by (**non-thermal) effective potential**

$$V_0 \sim \lambda M^4 \sim g_{B-L}^4 M^4$$ ➡ De Sitter expansion with $H \sim \sqrt{V_0}/M_{\text{Pl}}$

- Oscillation stops when $H \sim m_{\text{eff}}$

↳ $$\frac{\Phi}{M} \sim g_{B-L}\frac{M}{M_{\text{Pl}}}$$ ➡ Initial condition of new inflation

3. New (small-field) inflation with chiral condensate



Dynamically fine-tuned

De Sitter expansion dilutes Z'

➡ Slow-roll inflation

CMB power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln \frac{k}{k_*} + \cdots}$$

$$r = \frac{A_t}{A_s} \approx 0$$

$$A_s \approx 2.2 \times 10^{-9}$$

$$\updownarrow$$

$$\lambda_\phi \sim g_{B-L}^4 \sim 10^{-14}$$

$n_s < 0.94$ Too small

Solution

Linear term $-C\phi$ ➡ $n_s \approx 0.96$

from chiral condensate $\langle \overline{q} q \rangle \sim \Lambda_{\mathrm{QCD}}^3$

3. New (small-field) inflation with chiral condensate

S. Iso, K. Kohri, KS (2014)

$\langle \overline{q} q \rangle$ can condense??

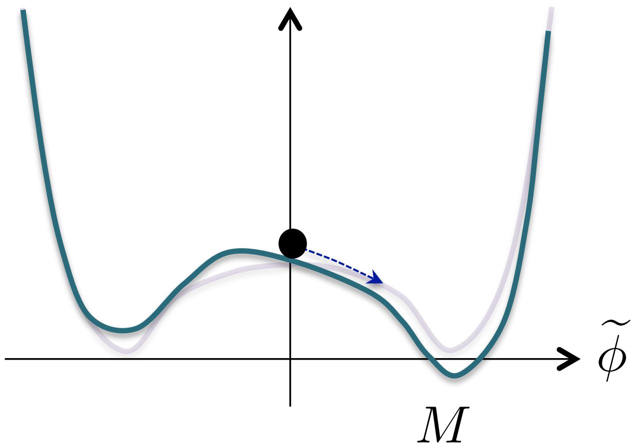
$$H \sim \frac{10^{-7} M^2}{M_{\rm Pl}} < \Lambda_{\rm QCD}$$

$$M < 10^{12} {\rm GeV}$$

$$-y_q \langle \overline{q} q \rangle h + \frac{\lambda_{\rm mix}}{4} h^2 \phi^2$$

Potential valley along

Inflaton $\widetilde{\phi}$ $\quad h^2 = \frac{|\lambda_{\rm mix}|}{2\lambda_h} \phi^2$



$$V_{\rm linear} = -\frac{246{\rm GeV}}{M} y_q \langle \overline{q} q \rangle \times \widetilde{\phi}$$

$$M \sim 10^9 {\rm GeV}$$

Observed n_s

4. Summary

- Colman-Weinberg inflation (as a cosmological aspect of CSI model)

Chaotic initial condition followed by preheating

⟹ CW new inflation with dynamically tuned initial condition

In the minimal gauged $B-L$ model,

- Linear term from $\langle \overline{q} q \rangle$ accounts for the observed n_s

with $\lambda_\phi \sim g_{B-L}^4 \sim 10^{-14}\,,\;\; M = \langle \phi \rangle_{\rm vac} \sim 10^9 {\rm GeV}$

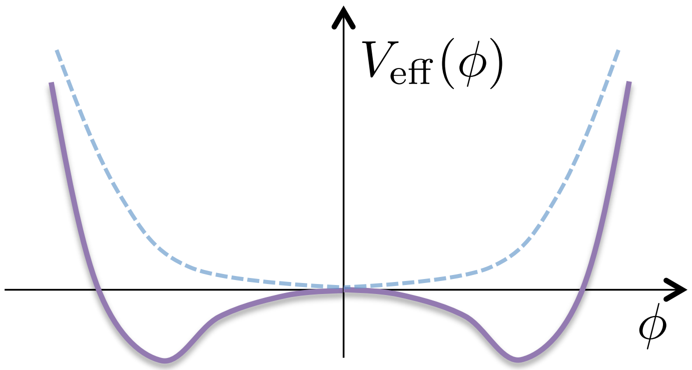
Collaboration with P. Serpico

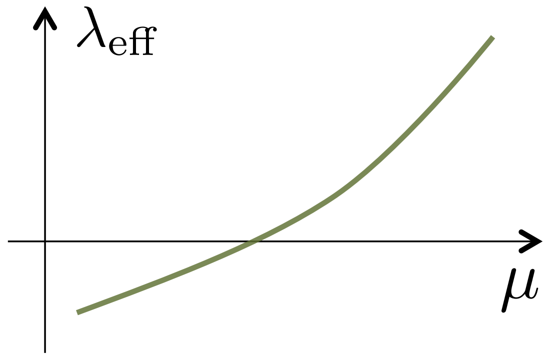
Sterile neutrino DM production during preheating process

⟹ Implications for leptogenesis and collider physics

Thank you

- CW potential





$\phi = M$

$$V_{\text{eff}}(\phi) = \frac{\lambda_{\text{eff}}}{4}\phi^4 = \frac{\boxed{\lambda_{(\mu)}}}{4}\phi^4 + \frac{\boxed{\beta_{(\mu)}}}{8}\phi^4 \ln\left(\frac{\phi^2}{\mu^2}\right) + \cdots$$

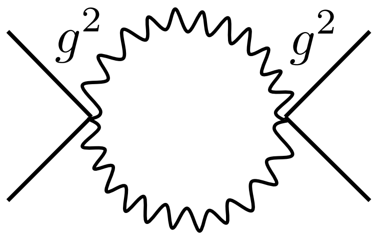
$$\Rightarrow \frac{\beta_{(M)}}{8}\phi^4\left[\ln\left(\frac{\phi^2}{M^2}\right) - \frac{1}{2}\right] + V_0$$

Characterized by **two** parameters

$\Rightarrow$ $M \quad \beta_{(M)}$

$$V_0 = \frac{\beta_{(M)} M^4}{16}$$

$$\lambda_\phi \equiv \frac{11}{6}\beta_{(M)}$$: Physical coupling @ $\phi = M$

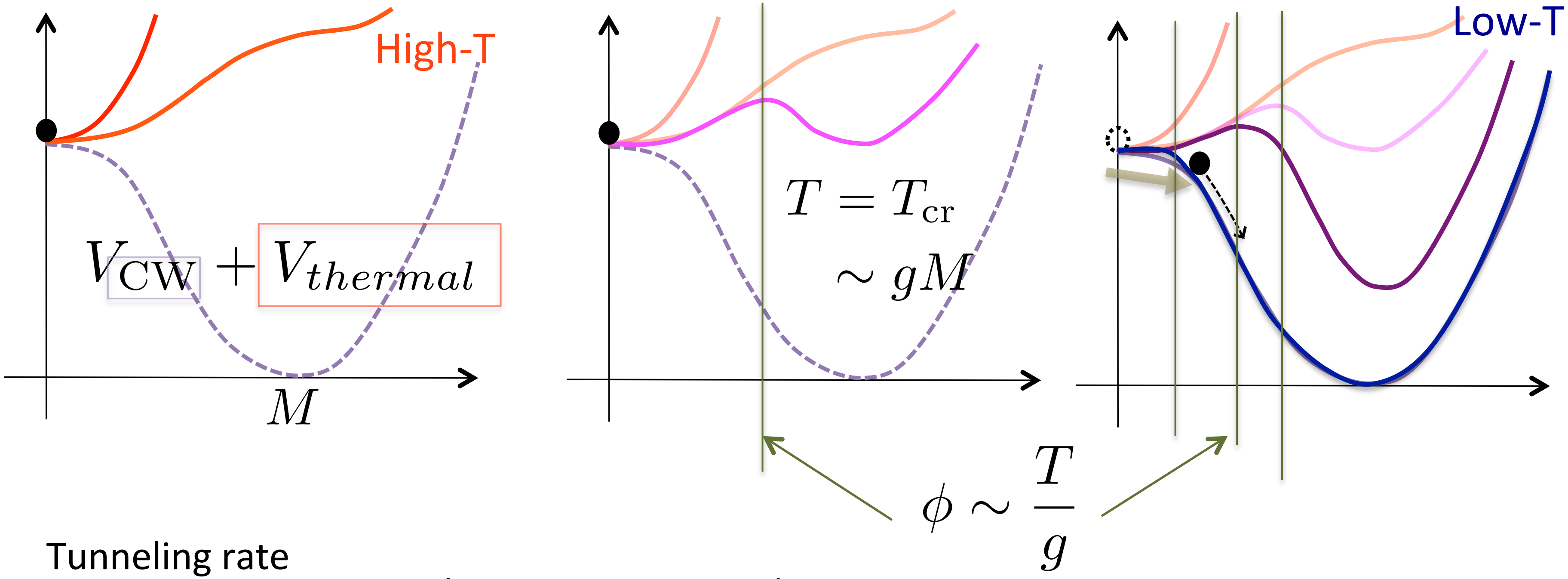


$$\lambda_\phi \sim g^4$$

PHASE TRANSITION IN CW POTENTIAL

with pre-existing thermal bath

(Original NEW INFLATION scenario by Linde (1982))



Tunneling rate

$$R \sim T \exp\left(\frac{-\mathcal{O}(10)}{g^3 \ln(T_{\rm cr}/T)}\right)$$

$$\frac{T|_{\rm tunnel}}{g} \to 0$$

For $g \ll 1$

Tunneling process becomes negligible

$R/H \sim 1$ → 1st order phase transition

e.g. GUT new inflation

→ Slow-roll inflation