Instability of the electroweak vacuum in Starobinsky inflation

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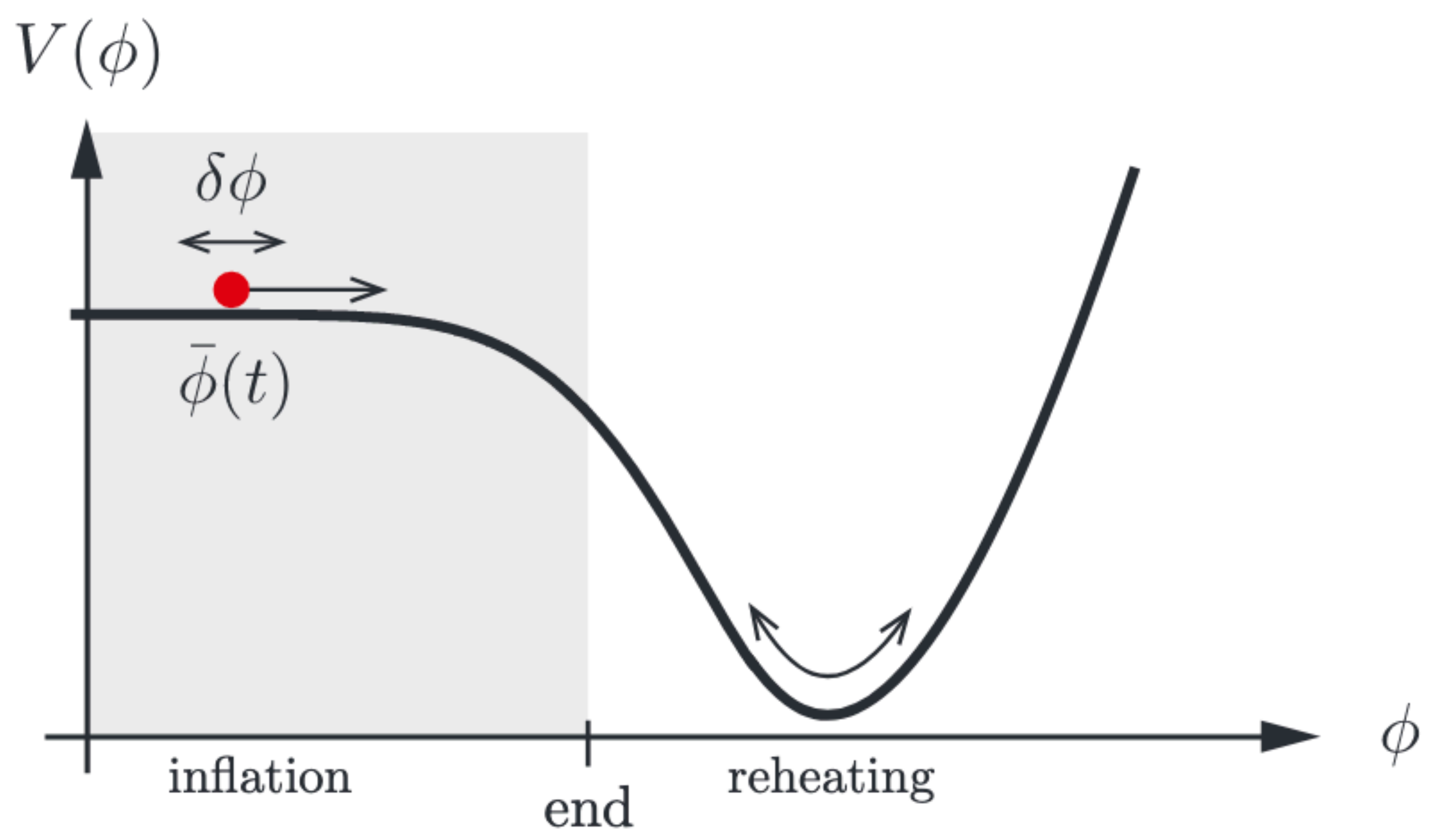
Based on arXiv: 2206.05926

Introduction

- Inflation explains homogeneity and flatness of the universe
- Inflation solves the horizon problem by shrinking comoving Hubble radius

$$\frac{d}{dt}(aH)^{-1} < 0$$

- In particular, the slow-roll inflation: inflaton(s) ϕ slowly rolls down $V(\phi)$



$$P_R(k) \equiv A_s(k/k_*)^{n_s-1}$$

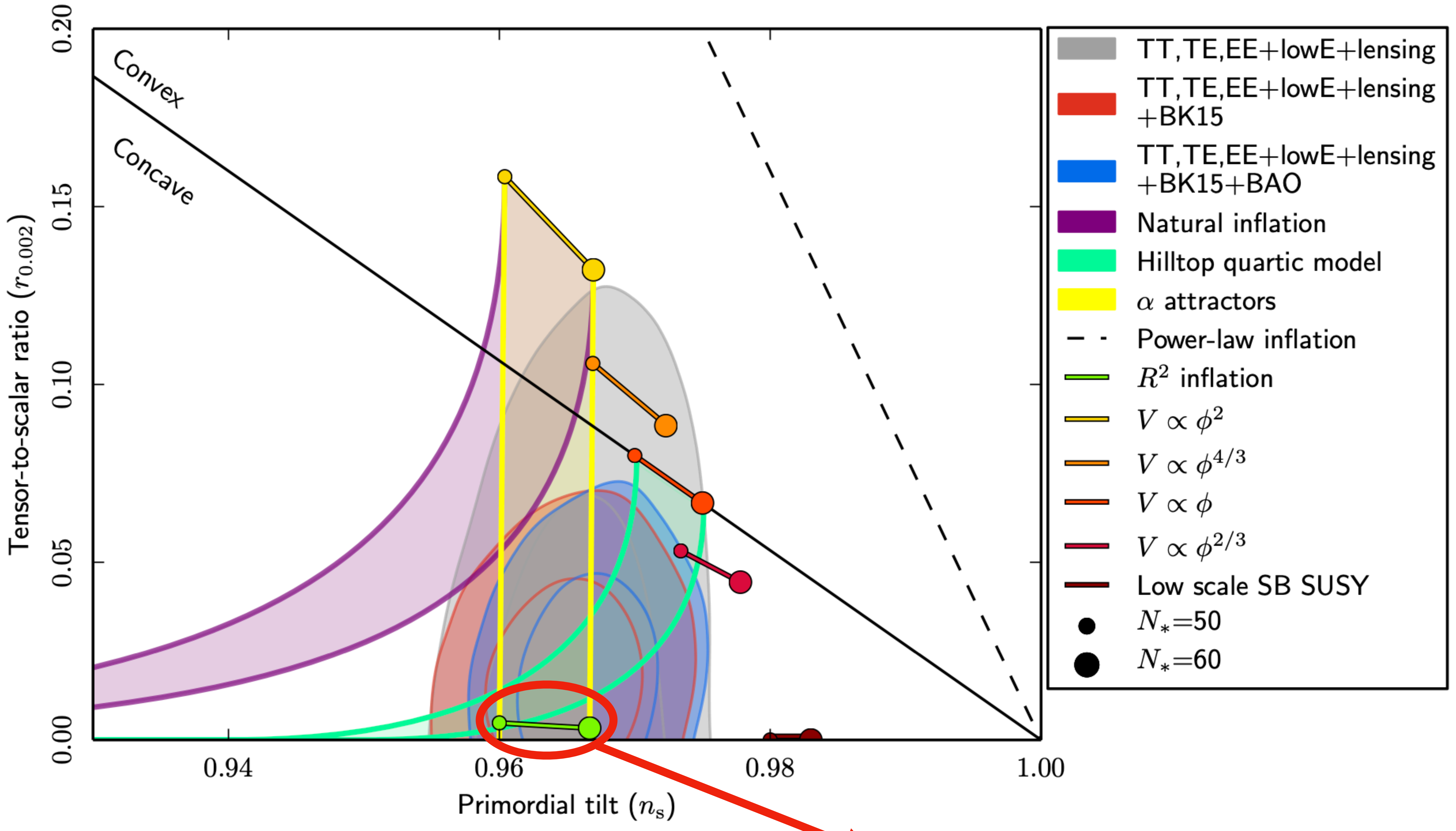
$$P_h(k) \equiv A_t(k/k_*)^{n_t}$$

$$r \equiv \frac{A_t}{A_s}$$

Introduction

- Motivation

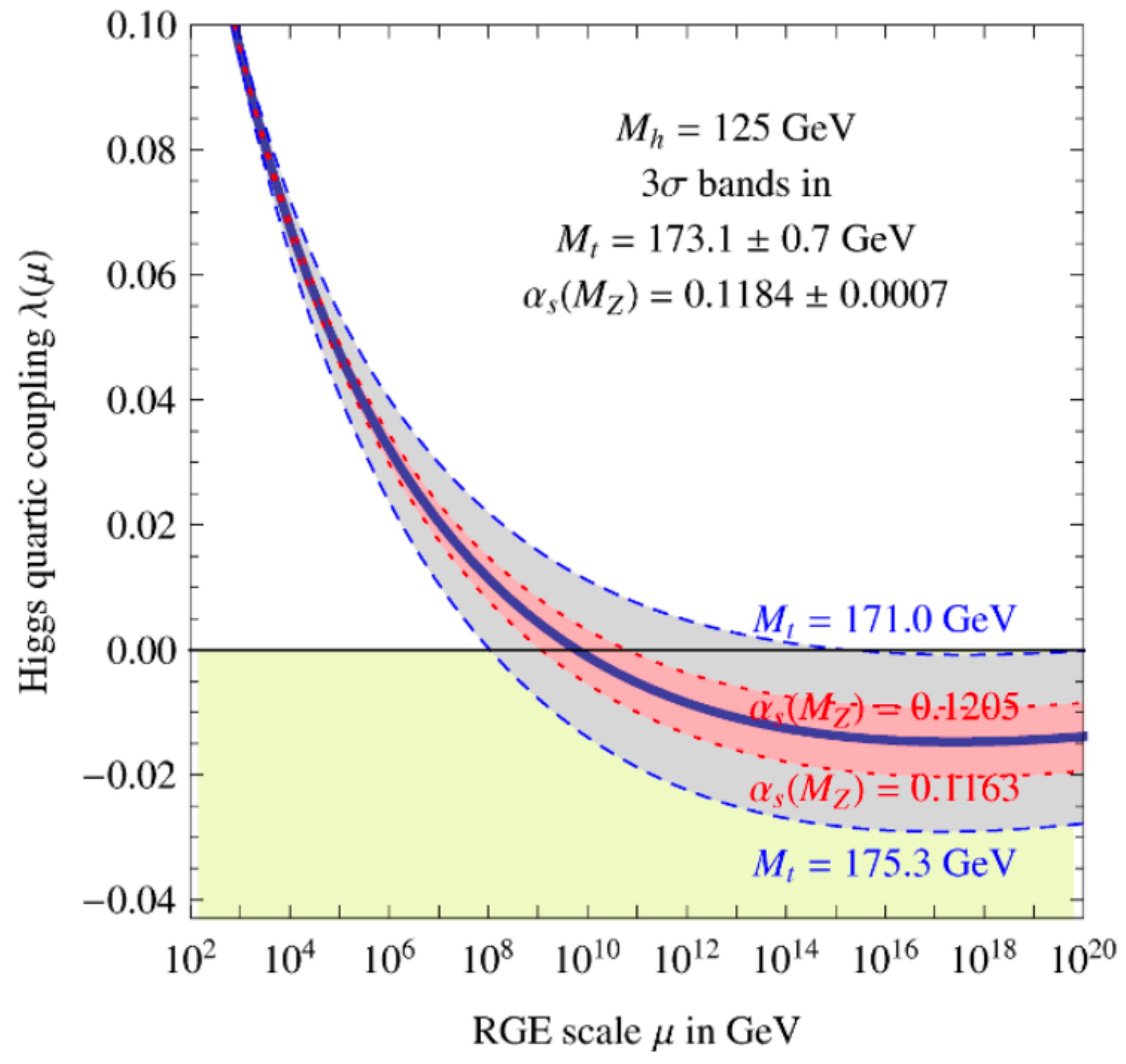
[Planck Collaboration, 1807.06211]

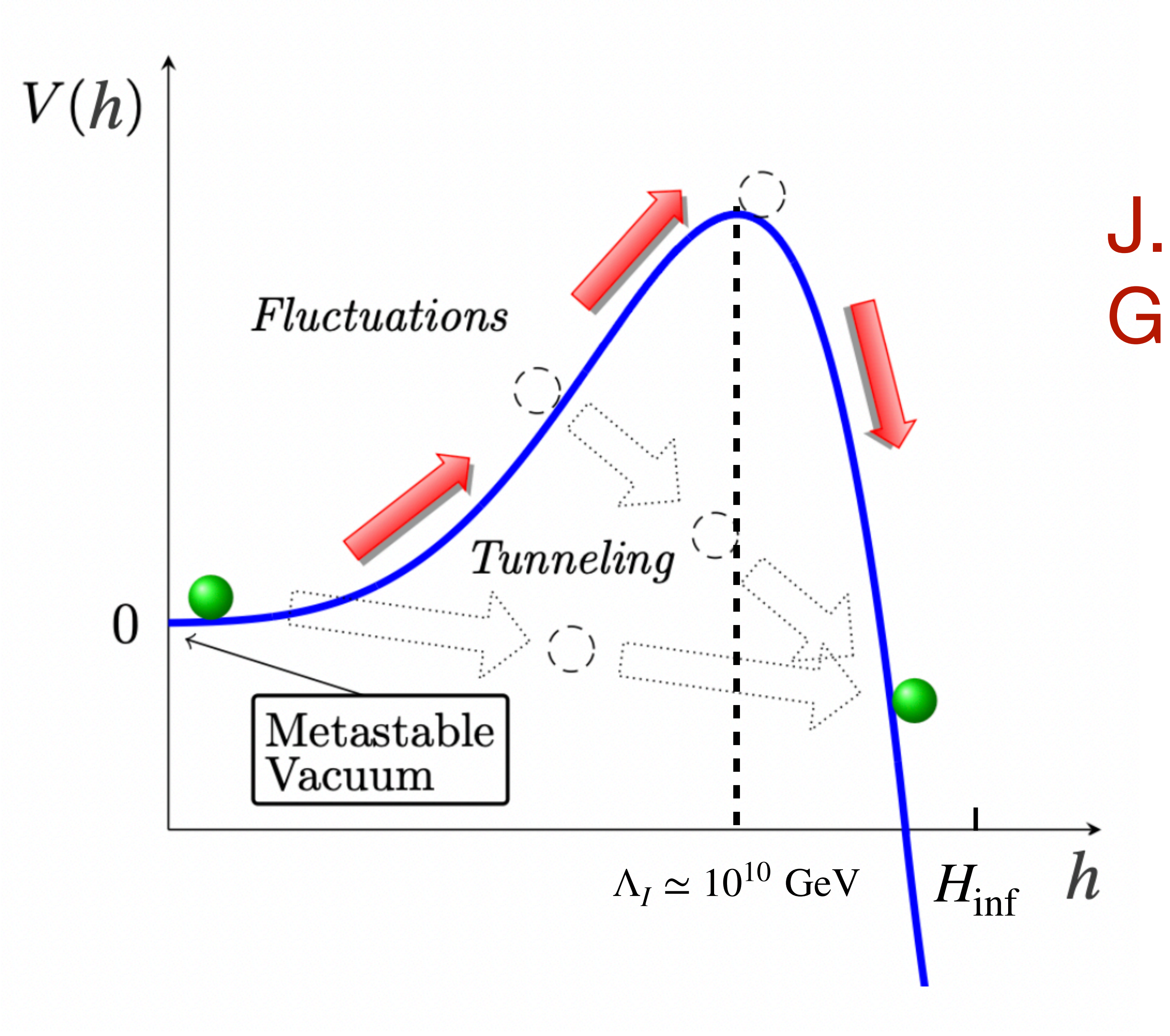


Starobinsky inflation model

Introduction

- Instability of the electroweak vacuum during inflation





J. Espinosa, et al. 0710.2484
G. Degrassi,et al. 1205.6497

During inflation: $\delta h \sim \dfrac{H_{\rm inf}}{2\pi}$

Introduction

- Non-minimal coupling $\frac{1}{2}\xi_h R h^2$

during inflation: $m_{\rm eff}^2 = 12\xi_h H_{\rm inf}^2$ → lower bound on ξ_h

after inflation: oscillating $m_{\rm eff}^2$ → upper bound on ξ_h

Y. Ema, et al. 1602.00483
K. Enqvist, et al. 1608.08848

- If $\xi_h \neq 1/6$, ϕh^2, $\phi^2 h^2$, $\dot{\phi}^2 h^2$ are induced by conformal transformation

N. Takeda, Y. Watanabe. 1305.0561
D. Gorbunov, A. Panin. 1009.2448

- More inflaton-Higgs couplings than the inflation models without the R^2 term

- We use lattice simulation to study the dynamics of Higgs field during preheating epoch to obtain the upper bounds on ξ_h.

- Introduction
- Starobinsky inflation
- Vacuum instability after inflation
- Summary

Starobinsky inflation

- Single-field inflation model A. Starobinsky. Phys.Lett.B 91 (1980)

$$S_J = \int d^4x \sqrt{-\tilde{g}} \left[-\frac{M_\mathrm{p}^2}{2} (\tilde{R} - \frac{\tilde{R}^2}{6\mu^2}) \right]$$

$\tilde{R}$: Ricci scalar in Jordan frame

μ: parameter with the dimension of mass

- Conformal transformation to Einstein frame

$$g_{\mu\nu} = \Omega^2 \tilde{g}_{\mu\nu}, \quad \Omega^2 \equiv \exp\left(\sqrt{\frac{2}{3}} \frac{\phi}{M_\mathrm{p}} \right)$$

Starobinsky inflation

- Equivalent scalar-tensor theory

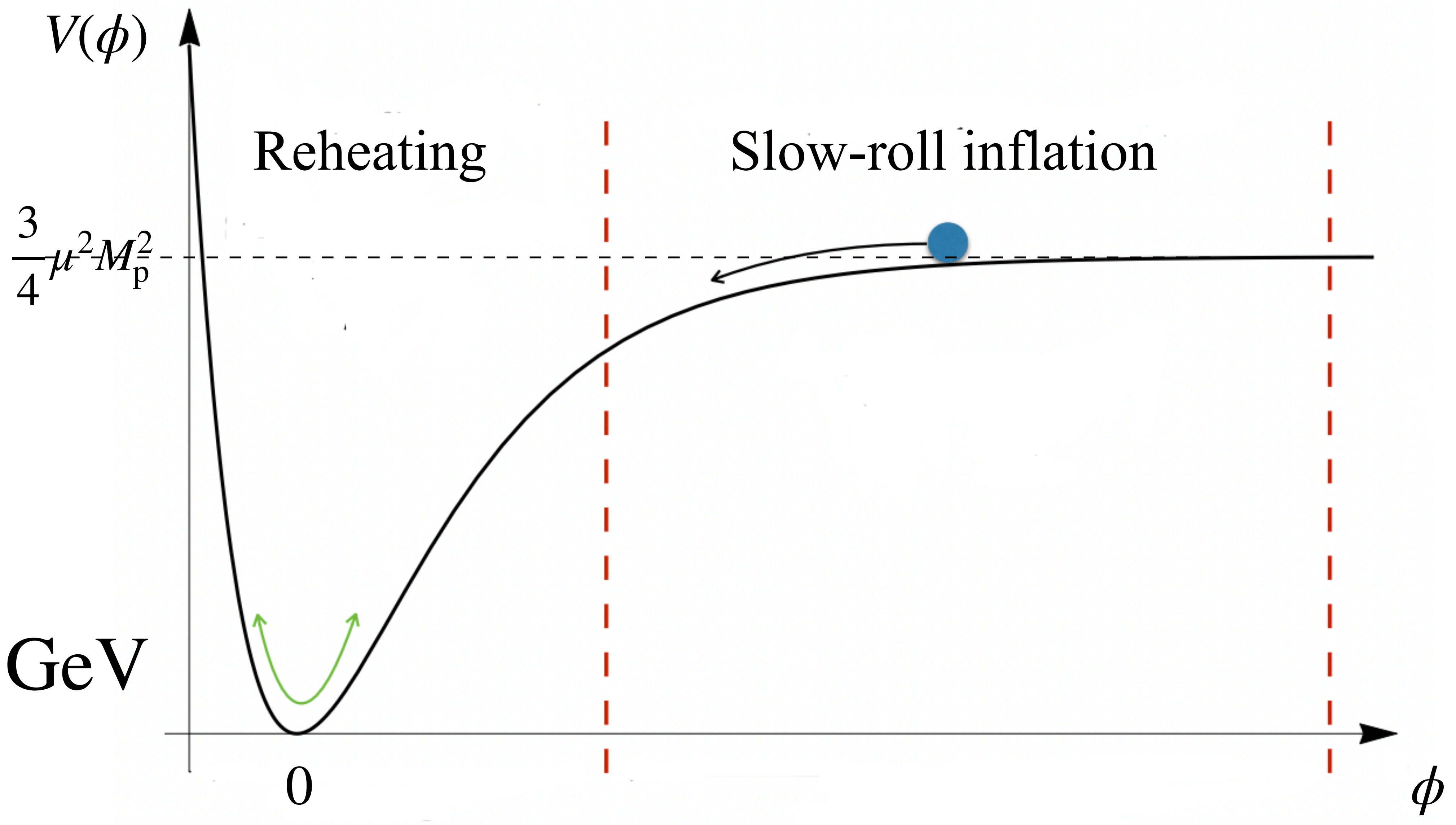
$$S_E = \int d^4x\sqrt{-g}\left[-\frac{M_p^2}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

- potential of the scalaron ϕ

$$V(\phi) = \frac{3}{4}\mu^2 M_p^2\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\phi}{M_p}\right)\right]^2$$

around $\phi = 0$:

$$V(\phi) \simeq \frac{1}{2}\mu^2\phi^2 + O(\phi^3)$$



μ is the mass of inflaton, $\mu \sim 10^{13}$ GeV, Hubble rate $H_{\rm inf} \simeq 10^{13}$ GeV

Vacuum instability after inflation

- The total action in Jordan frame

$$S_J = \int d^4x\sqrt{-\tilde{g}}\left[-\frac{M_{\rm p}^2}{2}\left(\tilde{R} - \frac{\tilde{R}^2}{6\mu^2}\right) + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu h \partial_\nu h + \frac{1}{2}\xi_h \tilde{R} h^2 - \frac{1}{4}\lambda(Q)h^4\right]$$

Ricci-scalar squared

Higgs non-minimal coupling

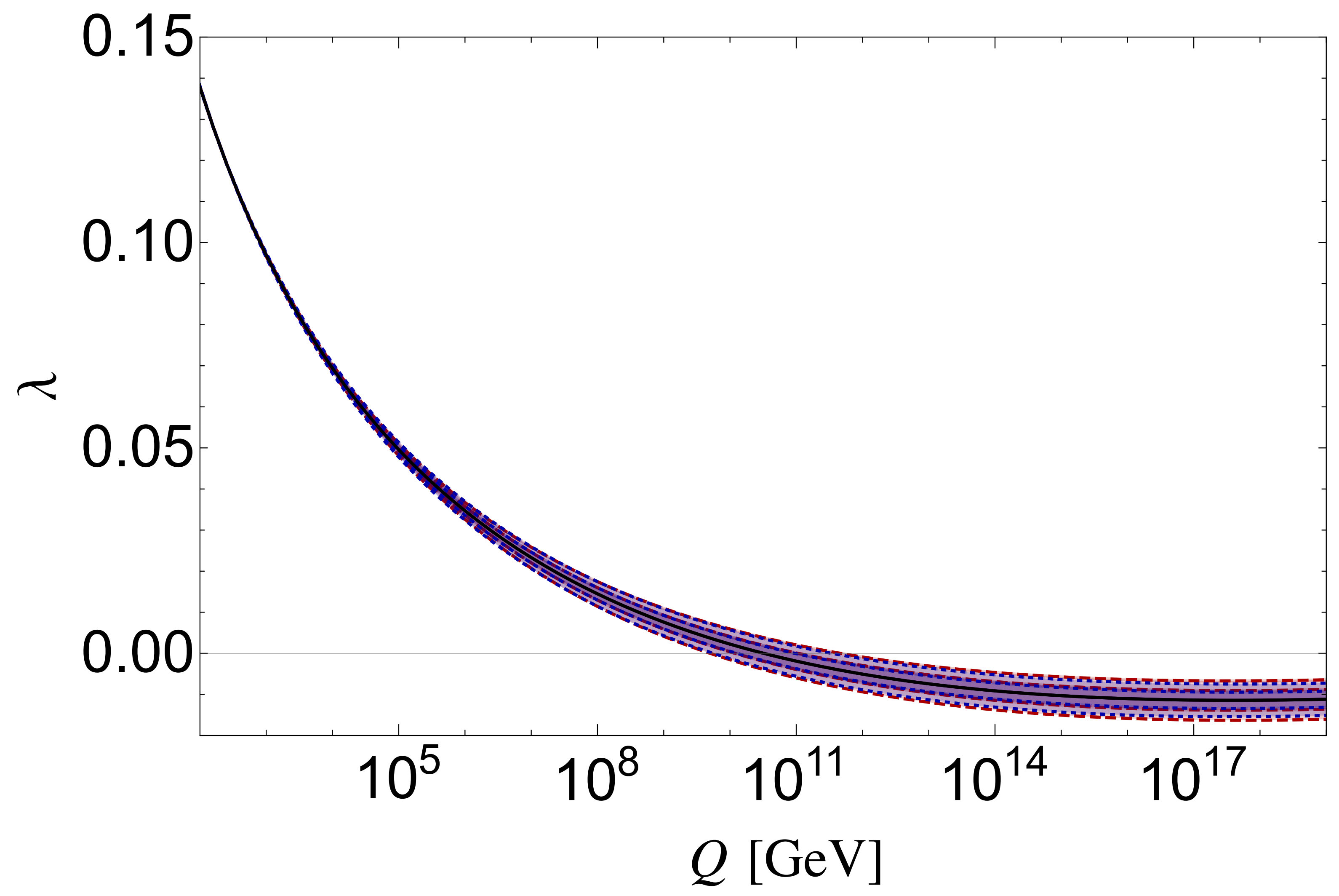
Higgs potential

- $\xi_h > 0$
- Q : renormalization scale

Vacuum instability after inflation

- Einstein-frame action of scalaron ϕ and canonical Higgs field $h_c \equiv e^{-\chi/2}h$

$$\tilde{V}(\phi, h_c) = \frac{3\mu^2 M_p^2}{4}(1-e^{-\chi})^2 + \frac{1}{2}m_{\rm eff}^2 h_c^2 + \frac{1}{4}\left(\lambda(Q) + \frac{3\mu^2}{M_p^2}\xi_h^2\right)h_c^4 \qquad \chi = \sqrt{\frac{2}{3}}\frac{\phi}{M_p}$$



and (in the homogeneous inflaton background)

$$m_{\rm eff}^2 \simeq -\xi_h R + \left(\xi_h - \frac{1}{6}\right)\left(\frac{\dot{\phi}^2}{M_p^2} + \sqrt{6}\frac{\partial_\phi V(\phi, h=0)}{M_p}\right)$$

During inflation: $m_{\rm eff}^2 \simeq 12\xi_h H_{\rm inf}^2$

During preheating: $m_{\rm eff}^2$ oscillates, efficient particle creation; ϕh^2, $\phi^2 h^2$, $\dot{\phi}^2 h^2$

Vacuum instability after inflation

- During preheating

  Simulate Higgs dynamics on lattice

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\partial_i^2\phi}{a^2} + \frac{1}{\sqrt{6}M_\mathrm{p}}e^{-\chi}\left[\dot{h}^2 - \frac{(\partial_i h)^2}{a^2}\right] + \frac{\partial V}{\partial\phi} = 0$$

$$\ddot{h} + 3H\dot{h} - \frac{\partial_i^2 h}{a^2} - \sqrt{\frac{2}{3}}\frac{1}{M_\mathrm{p}}\left[\dot{\phi}\dot{h} - \frac{(\partial_i\phi)(\partial_i h)}{a^2}\right] + e^{\chi}\frac{\partial V}{\partial h} = 0$$

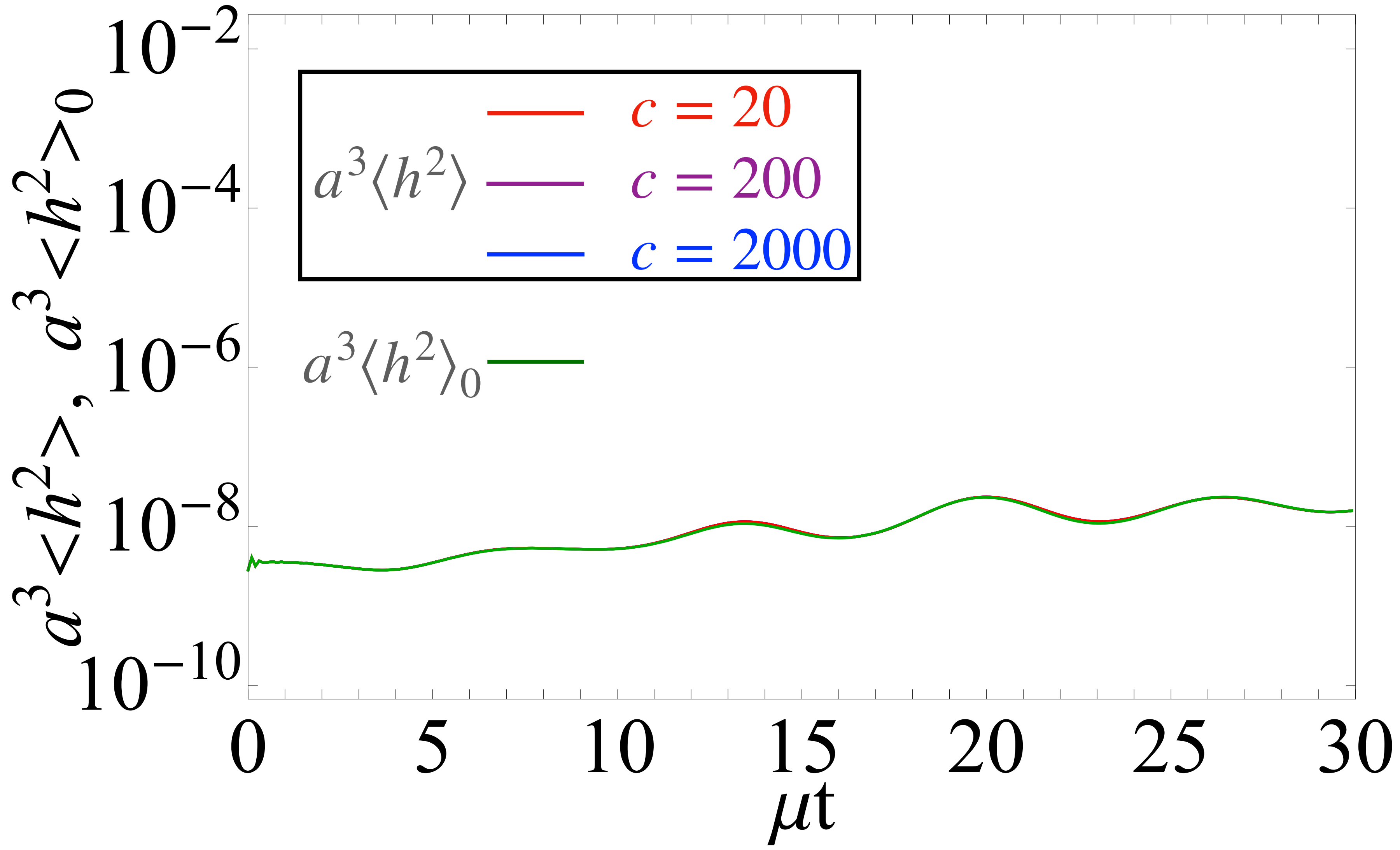
$$V(\phi, h) = \frac{3\mu^2 M_\mathrm{p}^2}{4}\left(1 - e^{-\chi} + \frac{\xi_h}{M_\mathrm{p}^2}e^{-\chi}h^2\right)^2 + \frac{\lambda\left(Q\right)}{4}e^{-2\chi}h^4$$

- $Q = \sqrt{\langle h^2 \rangle}$

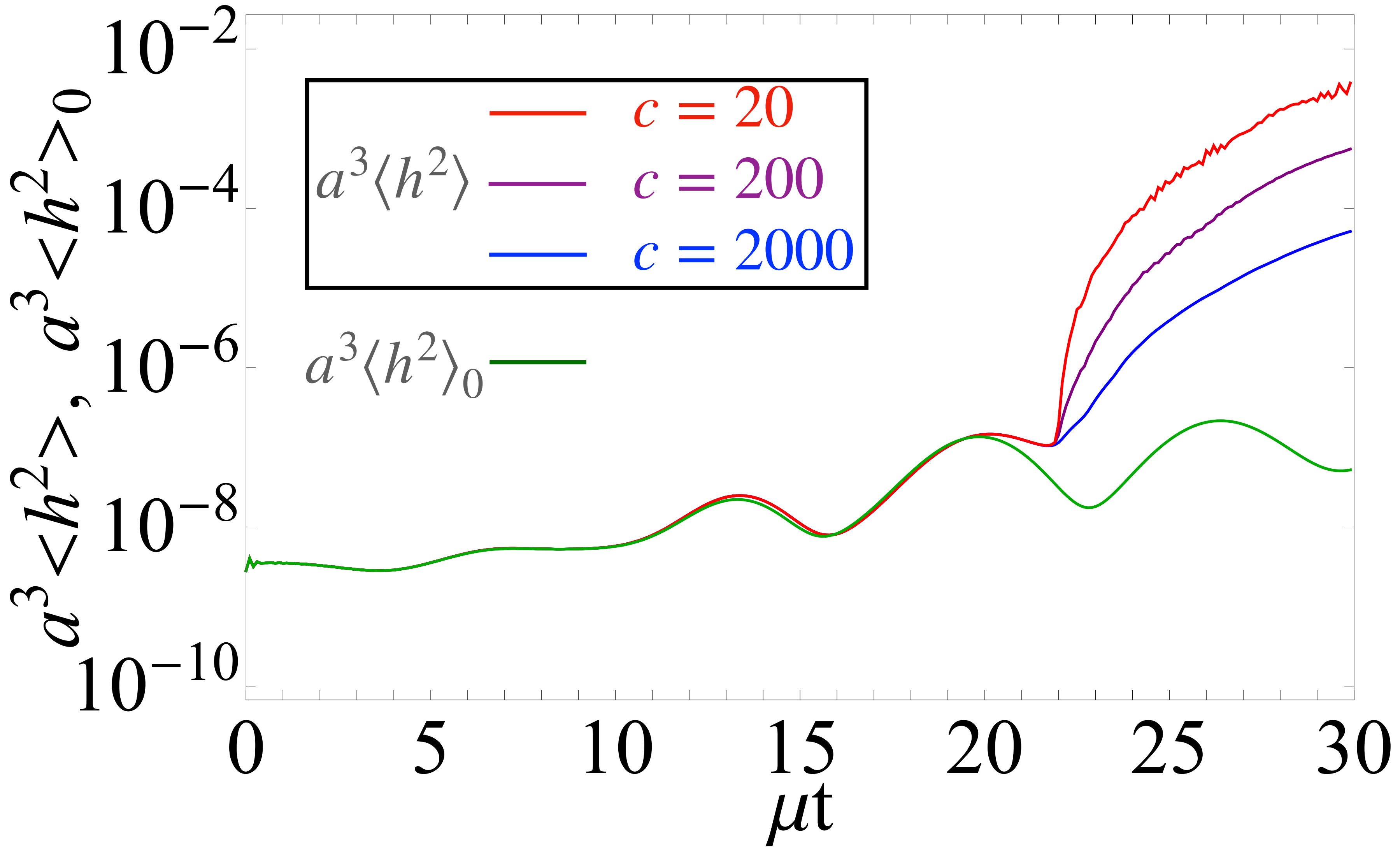
Vacuum instability after inflation

- Simulation results of $\langle h^2 \rangle$ and $\langle h^2 \rangle_0$ $(|\lambda| = 0)$

$M_t = 172$ GeV, $\alpha_s = 0.1179$



$\xi_h = 1.4$



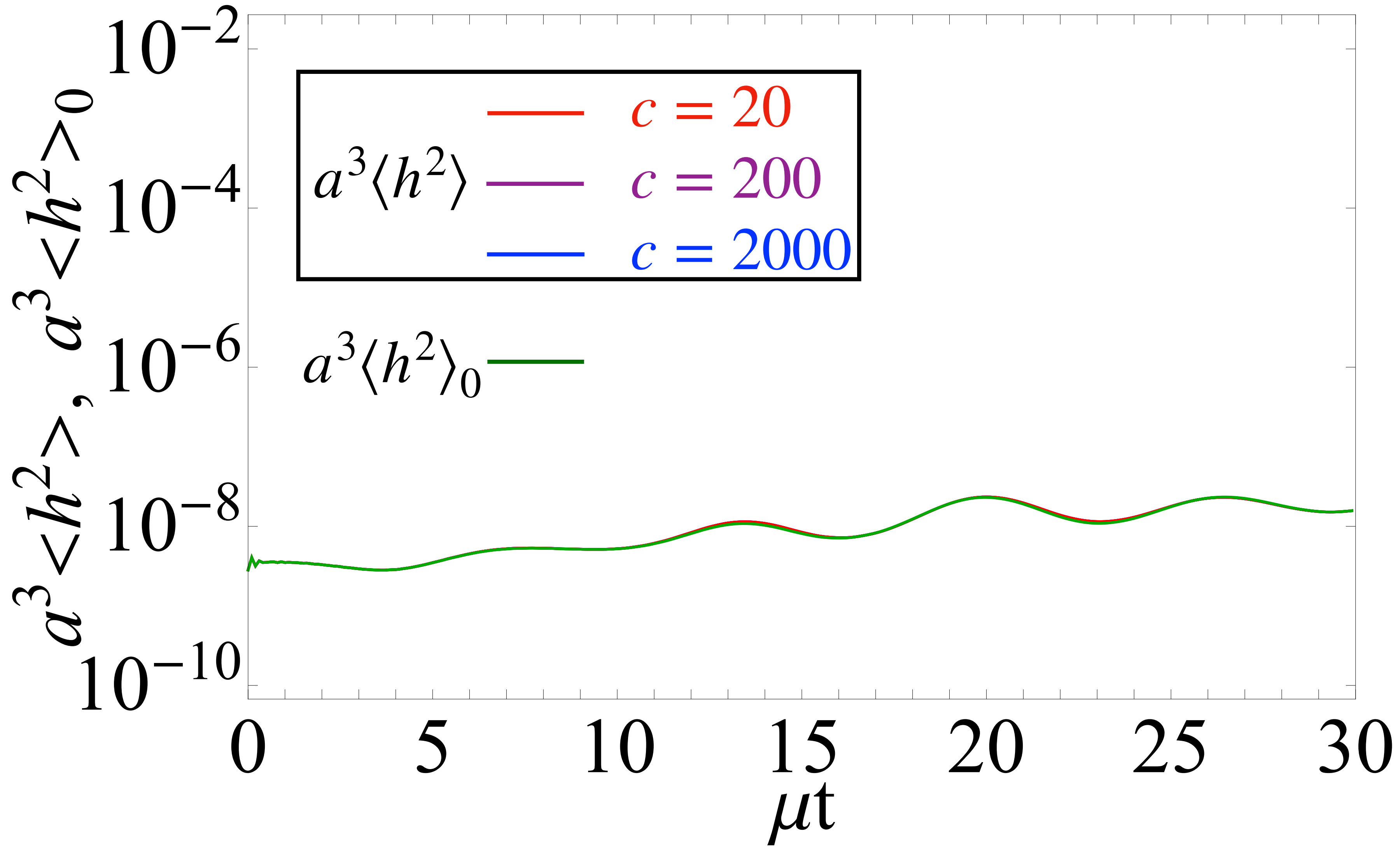
$\xi_h = 1.8$

$dt = 10^3/\mu, N = 128, L = 20/\mu$

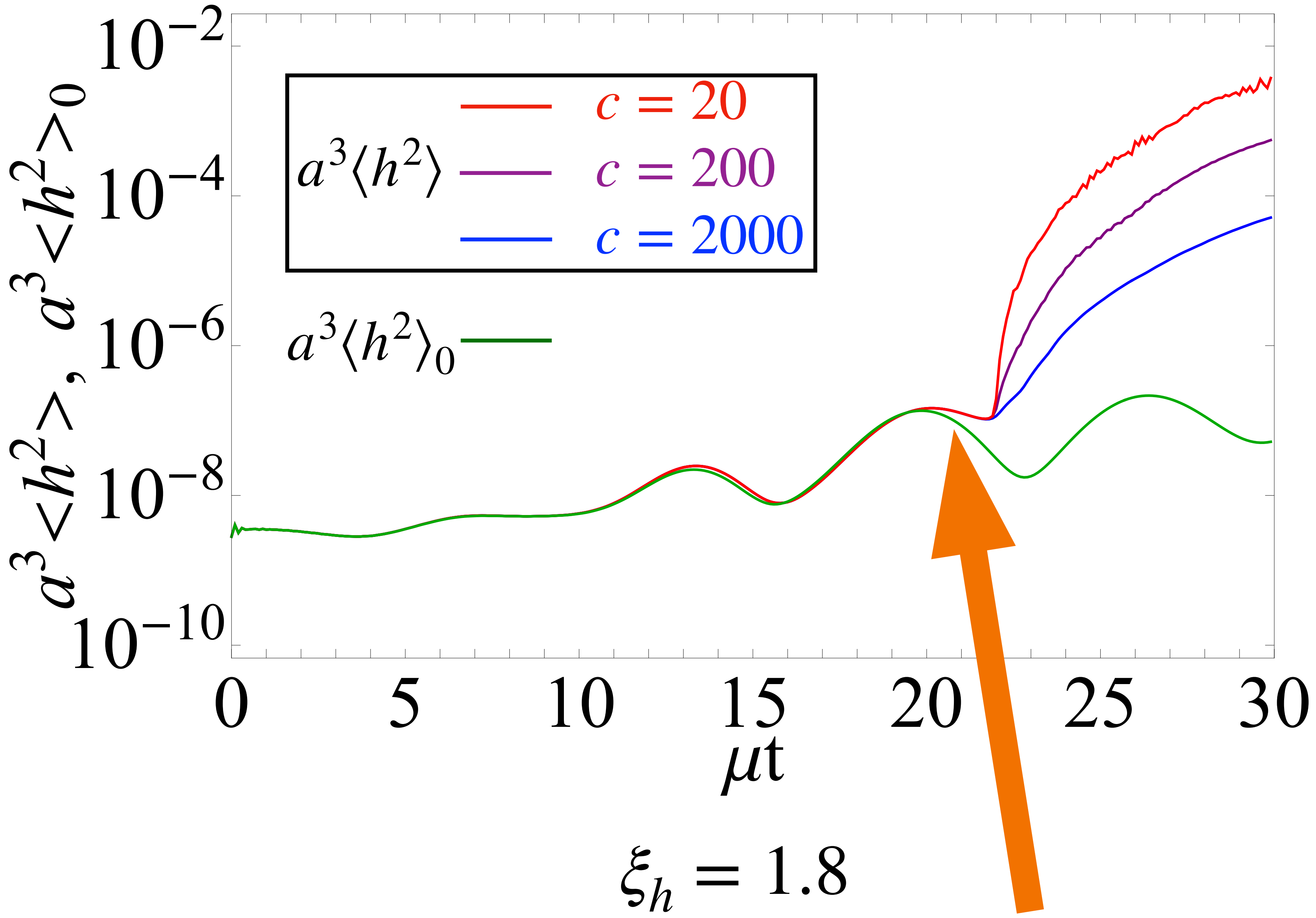
Vacuum instability after inflation

- Simulation results of $\langle h^2 \rangle$ and $\langle h^2 \rangle_0$ ($|\lambda| = 0$)

$M_t = 172$ GeV, $\alpha_s = 0.1179$



$\xi_h = 1.4$

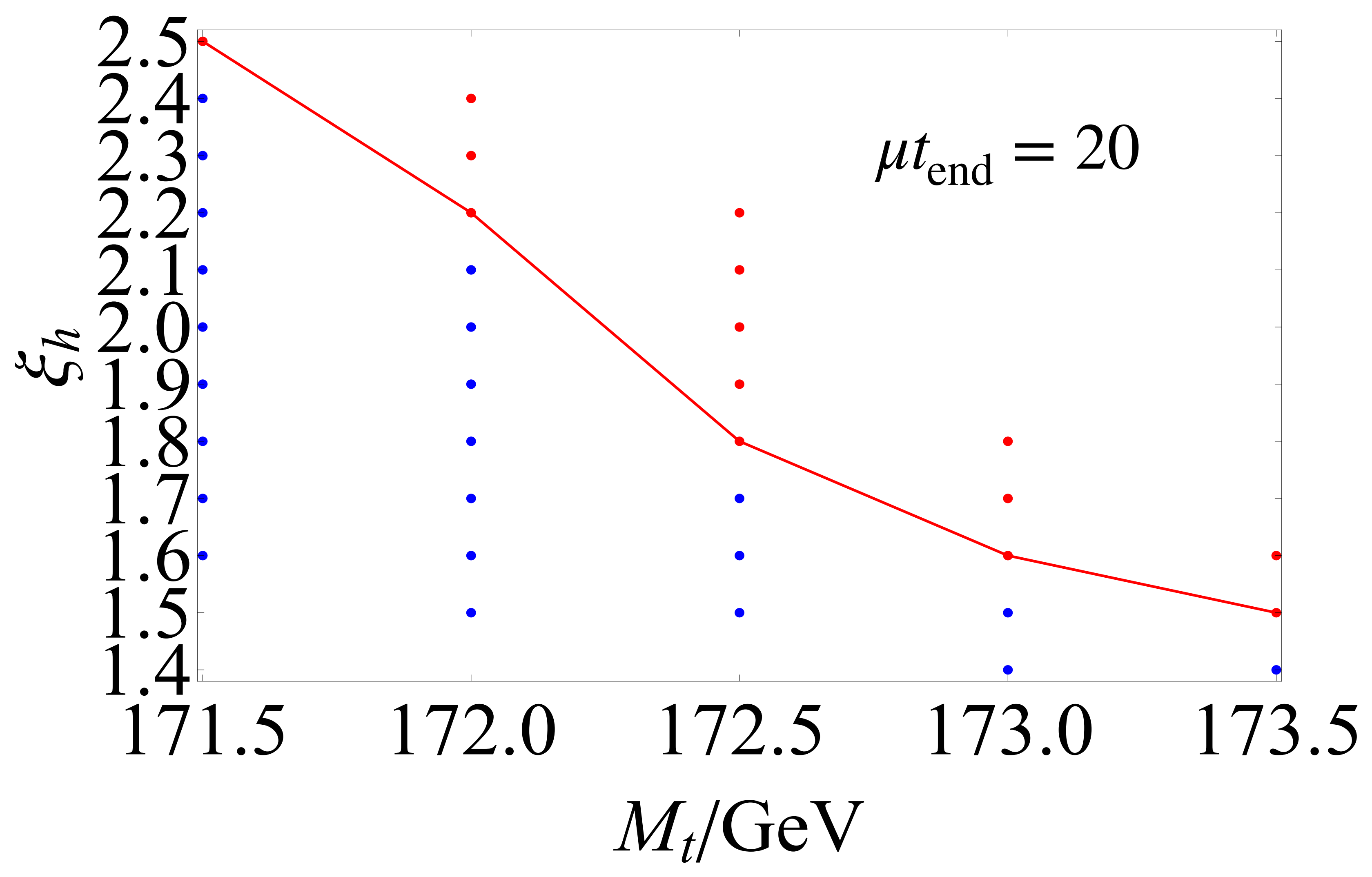


$\xi_h = 1.8$

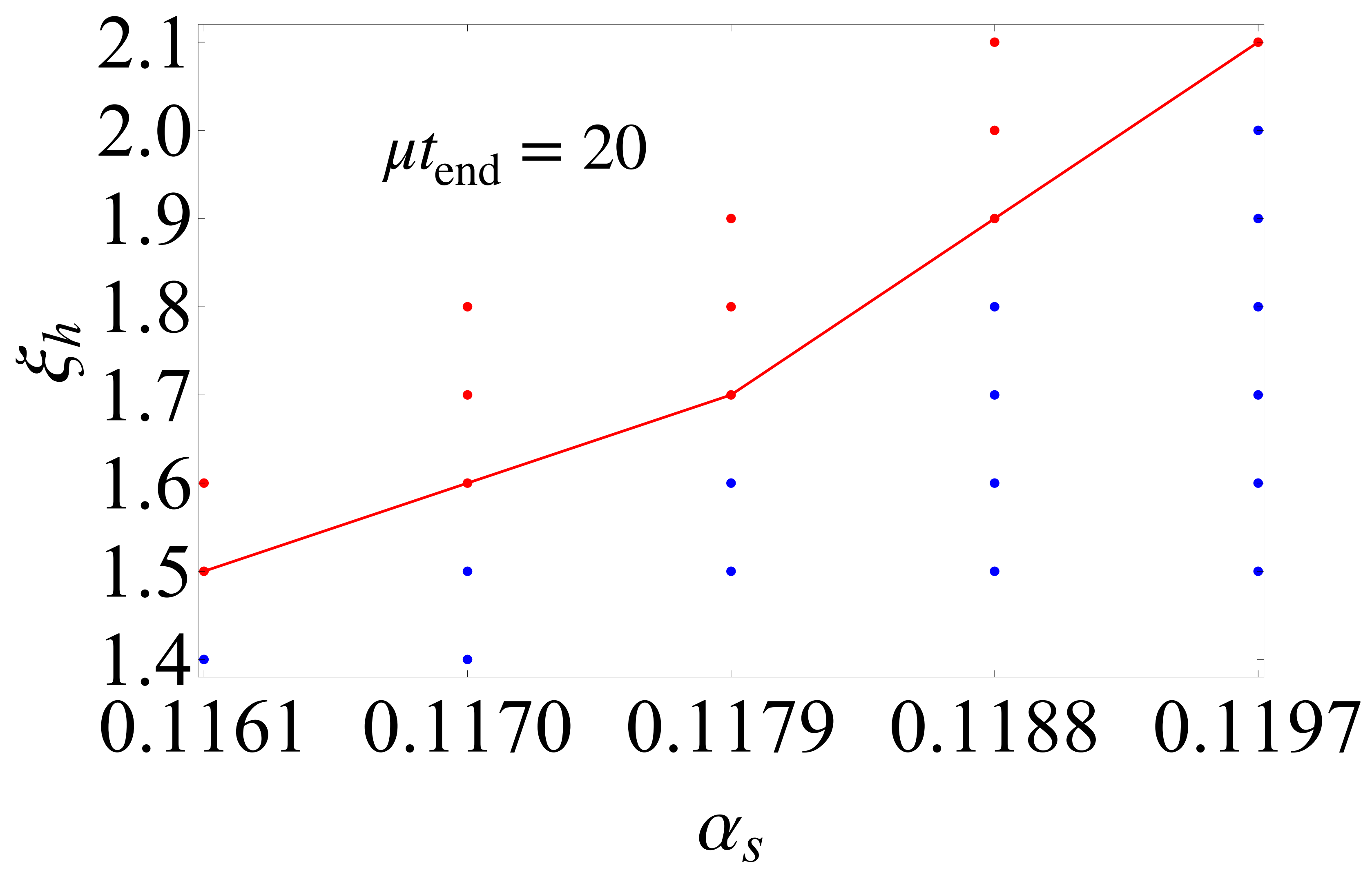
EW vacuum decays

$dt = 10^3/\mu, N = 128, L = 20/\mu$

Vacuum instability after inflation



$\alpha_s = 0.1179$



$M_t = 172.76$ GeV

- $\xi_h \ < \ 1.6 - 1.7$ for central values of M_t and α_s

- Smaller upper bounds on ξ_h than the previous study with: $m_{\rm eff}^2 \simeq \xi_h R$

  $\xi_h \lesssim 10$ in chaotic inflation

Y.Ema et al. 1602.00483

Summary

- We used lattice simulation to study Higgs dynamics during preheating epoch in the Starobinsky inflation

- Electroweak vacuum stability during inflation and preheating constraints $0.1 \lesssim \xi_h \lesssim 1.6$ for the central values of M_t and α_s

- Smaller upper bound on ξ_h than inflation models without the R^2 term

Backups

Einstein-frame actions

- Einstein-frame action of scalaron ϕ and Higgs field h

$$S_E = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm p}^2}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}e^{-\chi}g^{\mu\nu}\partial_\mu h\partial_\nu h - V(\phi, h)\right]$$

$$V(\phi, h) = \frac{3\mu^2 M_{\rm p}^2}{4}\left(1 - e^{-\chi} + \frac{\xi_h}{M_{\rm p}^2}e^{-\chi}h^2\right)^2 + \frac{\lambda(Q)}{4}e^{-2\chi}h^4$$

$$\chi = \sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm p}}$$

Einstein-frame actions

- Einstein-frame action of scalaron ϕ and canonical Higgs field h_c

$$S_E = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm p}^2}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}g^{\mu\nu}\partial_\mu h_c\partial_\nu h_c - \tilde{V}(\phi, h_c)\right]$$

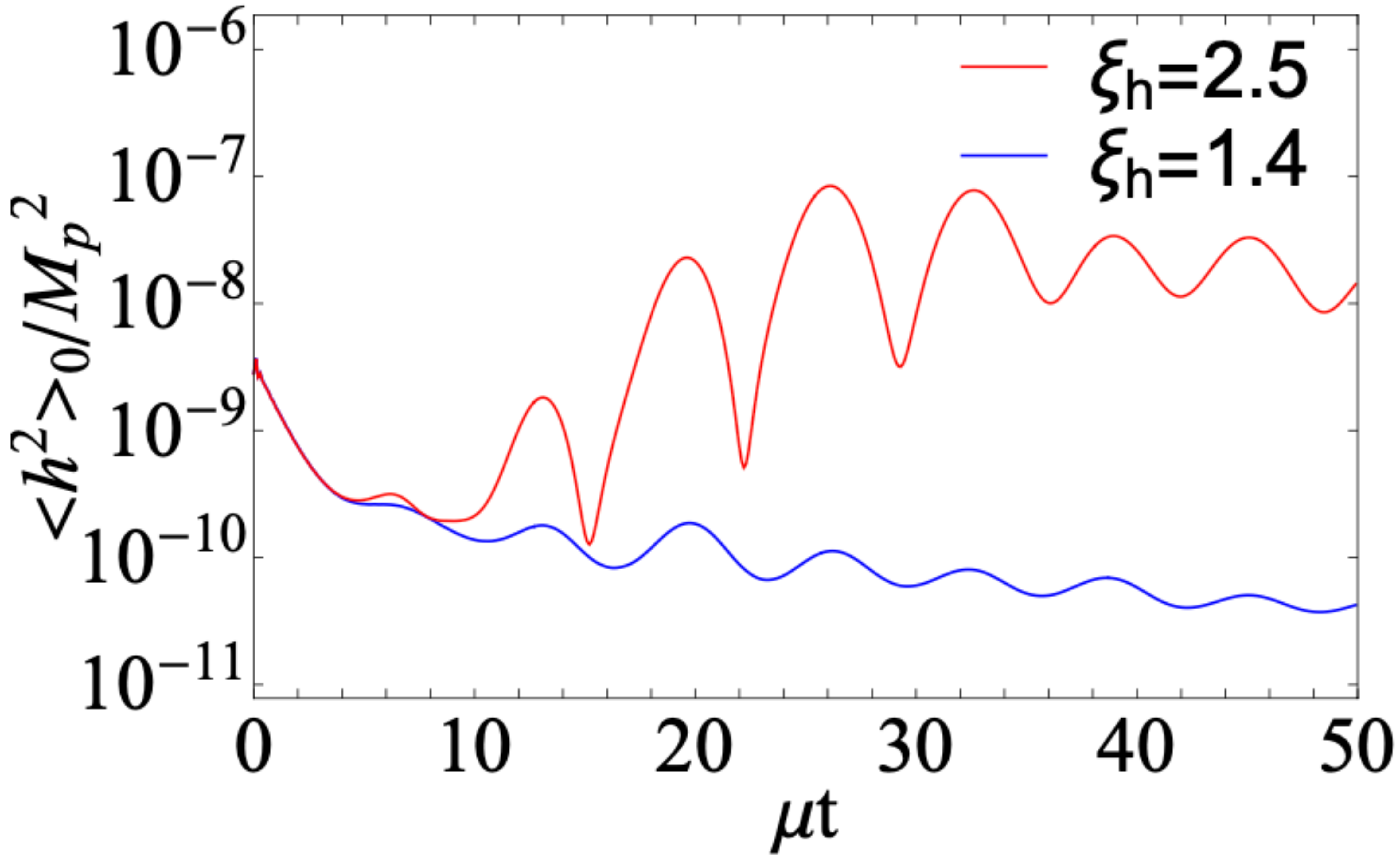
$$\tilde{V}(\phi, h_c) = \frac{3\mu^2 M_{\rm p}^2}{4}(1 - e^{-\chi})^2 + \frac{1}{2}m_{\rm eff}^2 h_c^2 + \frac{1}{4}\left(\lambda + \frac{3\mu^2}{M_{\rm p}^2}\xi_h^2\right)h_c^4$$

$$\chi = \sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm p}}$$

Vacuum stability

- Duration of resonances

Higgs variance evolution with $|\lambda| = 0$



$\langle h^2 \rangle_0$ drops before $\mu t \simeq 30$

$$q \equiv \sqrt{\frac{2}{3}}\frac{\bar{\phi}}{M_\mathrm{p}}(6\xi_h - 1)$$

Vacuum stability

- Thermalization due to two-to-two scattering

$$\Gamma_{\rm scatt} \sim \eta\mu^3\sigma \sim \frac{g^4}{4\pi}\eta\mu \quad < \quad H \sim O(0.1)\mu$$

η: occupation number

Thermalization effect is negligible before $\mu t \simeq 30$

- Take the time of the resonances: $t_{\rm end} = 20\ \mu^{-1}$ and $25\ \mu^{-1}$

- Criterion for the instability of electroweak vacuum

$$\left.\frac{\langle h^2\rangle - \langle h^2\rangle_0}{\langle h^2\rangle_0}\right|_{t=t_{\rm end}} > 2$$