Tachyonic preheating in the mixed Higgs-R^2 model

Speaker: Minxi He

2020/08/19@RESCEU SUMMER SCHOOL

MH, R. Jinno, K. Kamada, A. A. Starobinsky, J. Yokoyama, arXiv: 2007.10369

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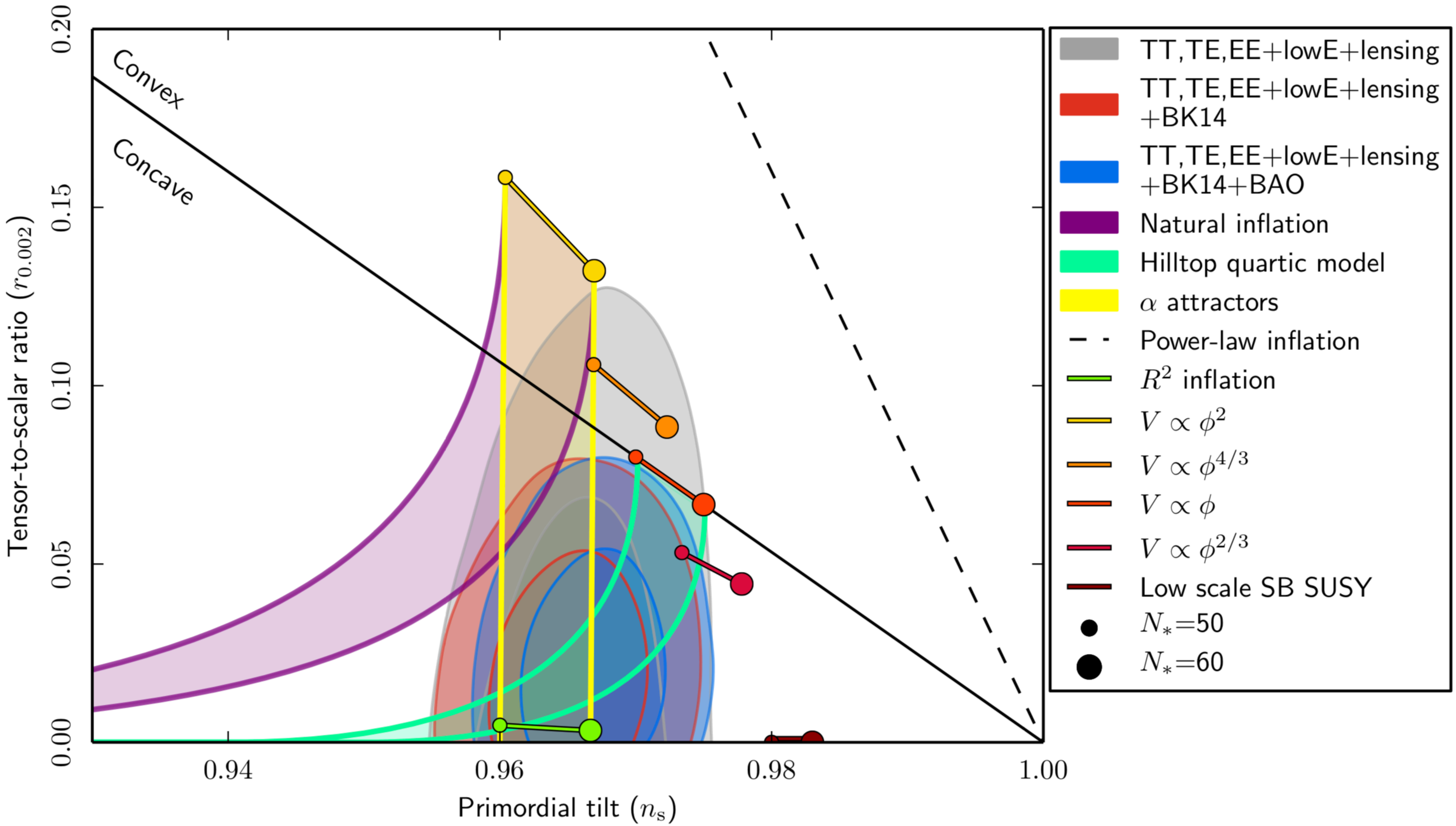


0.20
0.15
0.10
0.05
0.00
Tensor-to-scalar ratio ($r_{0.002}$)
0.94
0.96
0.98
1.00
Primordial tilt (n_s)
Convex
Concave
TT,TE,EE+lowE+lensing
TT,TE,EE+lowE+lensing +BK14
TT,TE,EE+lowE+lensing +BK14+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
R^2 inflation
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
Low scale SB SUSY
N_*=50
N_*=60

Planck 2018

Introduction

F. L. Bezrukov, M. E. Shaposhnikov, Phys.Lett.B659:703-706,2008

J.L. Cervantes-Cota and H. Dehnen, Nucl. Phys. B 442 (1995) 391

A.O. Barvinsky, A. Yu. Kamenshchik and A.A. Starobinsky, JCAP 11 (2008) 021

A. A. Starobinsky, Phys. Lett. B 91, 99 (1980)

- The Higgs inflation

$$S_J = \int d^4x\sqrt{-g_J}\left[\left(\frac{M_{\rm pl}^2}{2} + \xi|\mathcal{H}|^2\right)R_J - g_J^{\mu\nu}\partial_\mu\mathcal{H}\partial_\nu\mathcal{H}^\dagger - \lambda|\mathcal{H}|^4\right]$$

- The Starobinsky model

$$S_J = \int d^4x\sqrt{-g_J}\left[\frac{M_{\rm pl}^2}{2}R_J + \frac{M_{\rm pl}^2}{12M^2}R_J^2\right]$$

Well motivated

The Mixed Higgs-R^2 Model

Jordan frame

$$S_{\rm J} = \int d^4x\sqrt{-g_{\rm J}}\left[\left(\frac{M_{\rm pl}^2}{2} + \xi|\mathcal{H}|^2\right)R_{\rm J} + \frac{M_{\rm pl}^2}{12M^2}R_{\rm J}^2 - g_{\rm J}^{\mu\nu}\partial_\mu\mathcal{H}\partial_\nu\mathcal{H}^\dagger - \lambda|\mathcal{H}|^4\right]$$

Conformal coupling: $\xi = -1/6$
but we consider $\xi > 0$

Y-C. Wang, T. Wang, Phys. Rev. D96(12):123506, 2017
Y. Ema, Phys. Lett. B770:403-411, 2017
MH, A. A. Starobinsky, J. Yokoyama, JCAP, 1805(05):064, 2018
A. Gundhi, C. F. Steinwachs, Nucl. Phys. B 954 (2020) 114989
V.-M. Enckell, K. Enqvist, S. Rasanen, and L.-O. Wahlman, JCAP 01 (2020) 041

Introduction

Some important reasons to consider this model

- Higgs inflation is not UV-completed

  Burgess et al (2009), Bardon et al (2009)…

- Preheating in Higgs inflation is beyond the cutoff scale of the theory

  Ema, Jinno, Mukaida, Nakayama (2016)

- R^2 emerges in Higgs inflation from many points of view, such as renormalization group running, scattering amplitude and non-linear sigma model.

  Salvi et al (2015), Netto et al (2016), Calmet & Kuntz (2016), Liu et al (2018), Ghilencea (2018), Ema (2019), Ema et al (2020)

- R^2 may play an important role in the vacuum stability.

  Gorbunov, Tokareva, Phys. Lett. B 788 (2019) 37-41
  Ema, Mukaida, van de Vis (2020)

The Mixed Higgs-R^2 Model

Jordan frame

$$S_{\rm J} = \int d^4x\sqrt{-g_{\rm J}}\left[\left(\frac{M_{\rm pl}^2}{2} + \xi|\mathcal{H}|^2\right)R_{\rm J} + \frac{M_{\rm pl}^2}{12M^2}R_{\rm J}^2 - g_{\rm J}^{\mu\nu}\partial_\mu\mathcal{H}\partial_\nu\mathcal{H}^\dagger - \lambda|\mathcal{H}|^4\right]$$

Field redefinition

$$\sqrt{\frac{2}{3}}\frac{\varphi}{M_{\rm pl}} \equiv \ln\left(\frac{2}{M_{\rm pl}^2}\left|\frac{\partial\mathcal{L}_{\rm J}}{\partial R_{\rm J}}\right|\right)$$

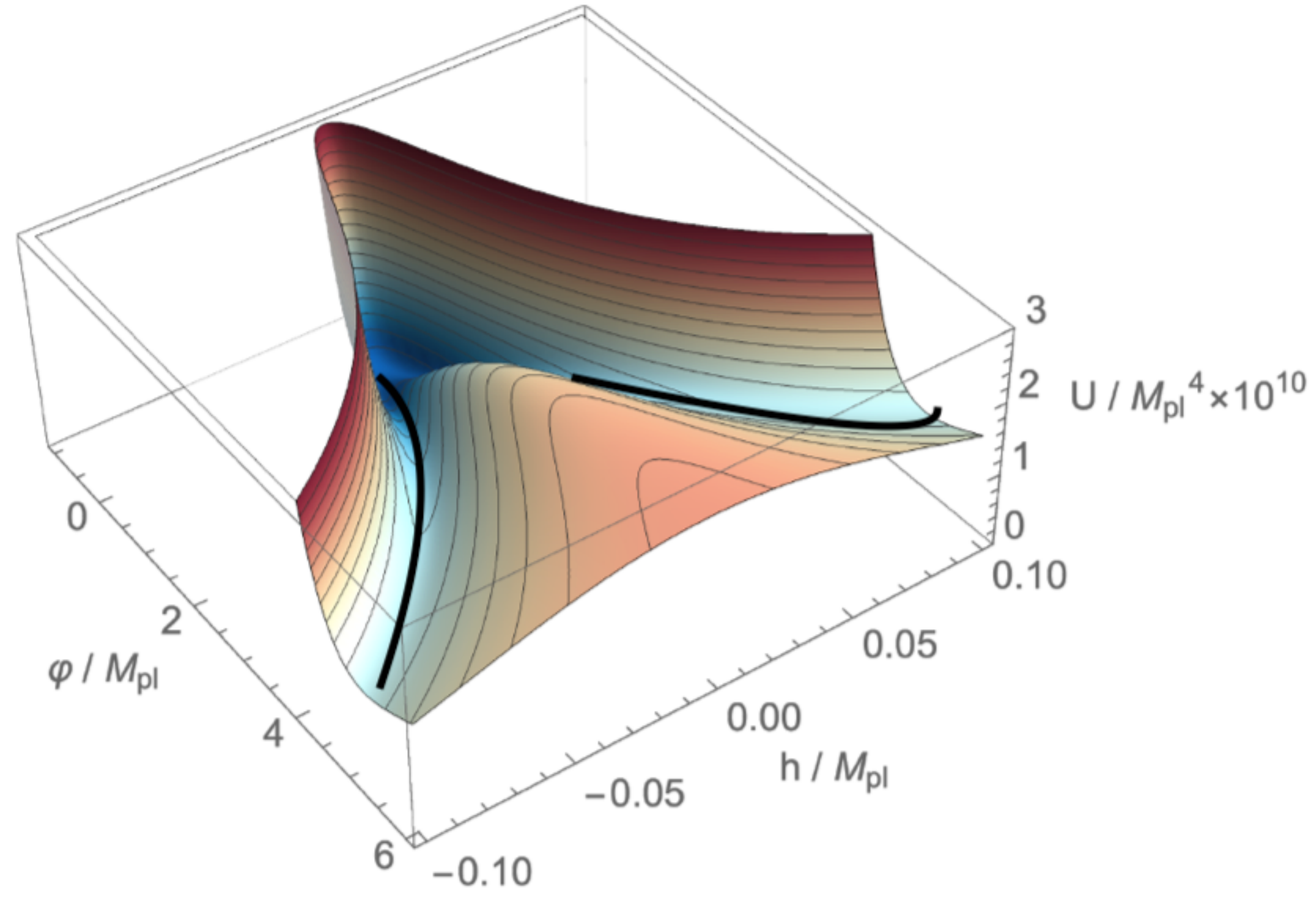
Conformal transformation

$$g_{{\rm E}\mu\nu}(x) = e^{\sqrt{\frac{2}{3}}\frac{\varphi(x)}{M_{\rm pl}}}g_{{\rm J}\,\mu\nu}(x) \equiv e^{\alpha\varphi(x)}g_{{\rm J}\,\mu\nu}(x)$$

Einstein frame

$$S_{\rm E} = \int d^4x\sqrt{-g_{\rm E}}\left[\frac{M_{\rm pl}^2}{2}R_{\rm E} - \frac{1}{2}g_{\rm E}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{1}{2}e^{-\alpha\varphi}g_{\rm E}^{\mu\nu}\partial_\mu h\partial_\nu h - U(\varphi,h)\right]$$

$$U(\varphi,h) = \frac{\lambda}{4}e^{-2\alpha\varphi}h^4 + \frac{3}{4}M_{\rm pl}^2M^2\left[1 - \left(1 + \frac{\xi}{M_{\rm pl}^2}h^2\right)e^{-\alpha\varphi}\right]^2 .$$



3
2
1
0
U / $M_{pl}^4 \times 10^{10}$
0
2
4
6
φ / M_{pl}
0.10
0.05
0.00
−0.05
−0.10
h / M_{pl}

The Mixed Higgs-R^2 Model

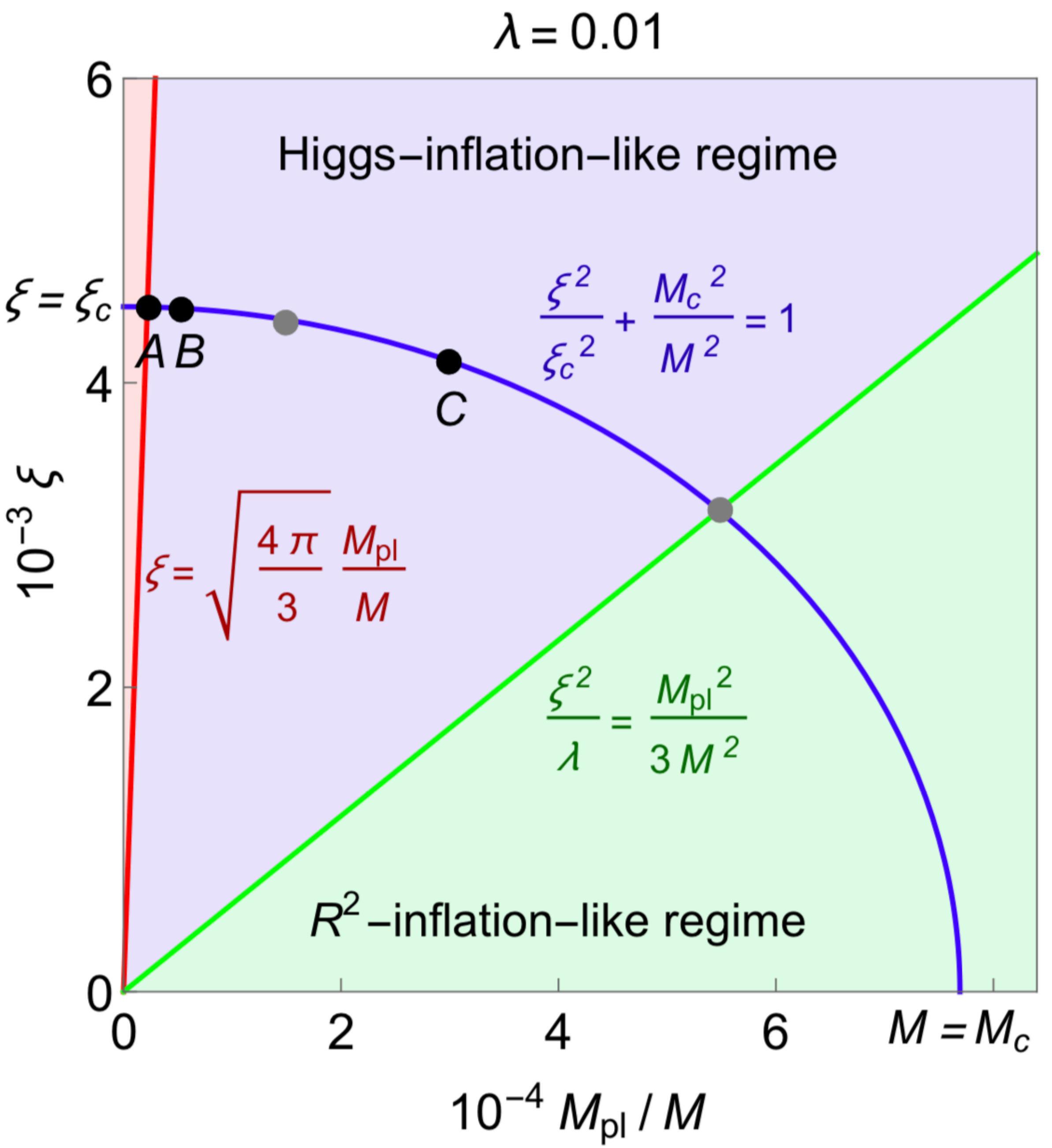
- Inflation dynamics----effective single field theory
  - Same prediction on $n_s - r$ plane as Starobinsky model
  - Smooth connection between Starobinsky model and Higgs inflation

- Cutoff scale is Planck scale----a candidate of UV-extension of the Higgs inflation

Y. Ema, Phys. Lett. B770:403-411, 2017
D. Gorbunov, A. Tokareva, Phys. Lett. B788 (2019) 37-41

Parameter space

- R^2-like regime
- Higgs-like regime
- Strong coupling regime



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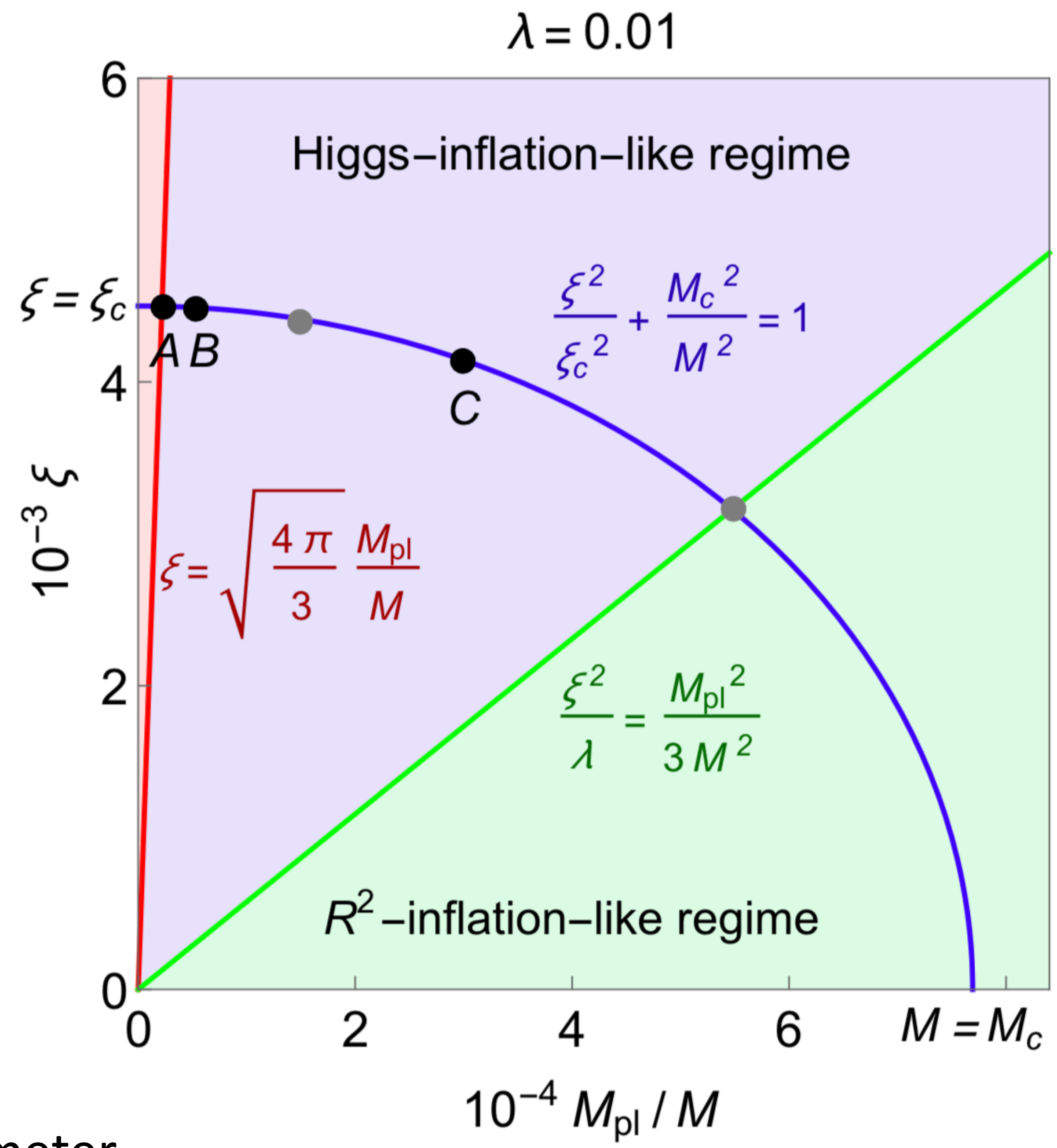

- Fixed λ
- Observation constraint

→ Only one free parameter

The Mixed Higgs-R^2 Model

- Inflation dynamics----effective single field theory
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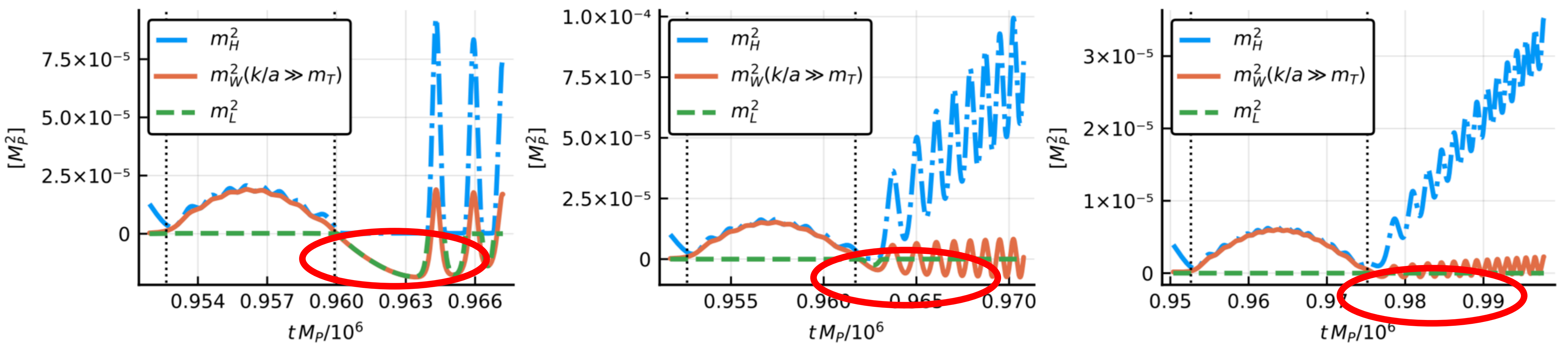
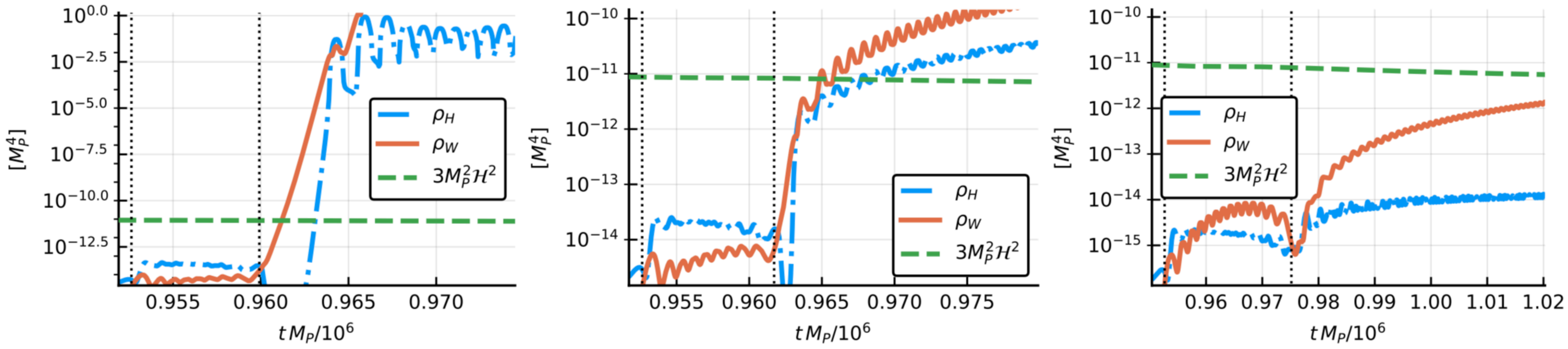
Y. Ema, Phys. Lett. B770:403-411, 2017
D. Gorbunov, A. Tokareva, Phys. Lett. B788 (2019) 37-41

- Spike preheating is well below cutoff scale of the theory and not so violent as the pure Higgs inflation

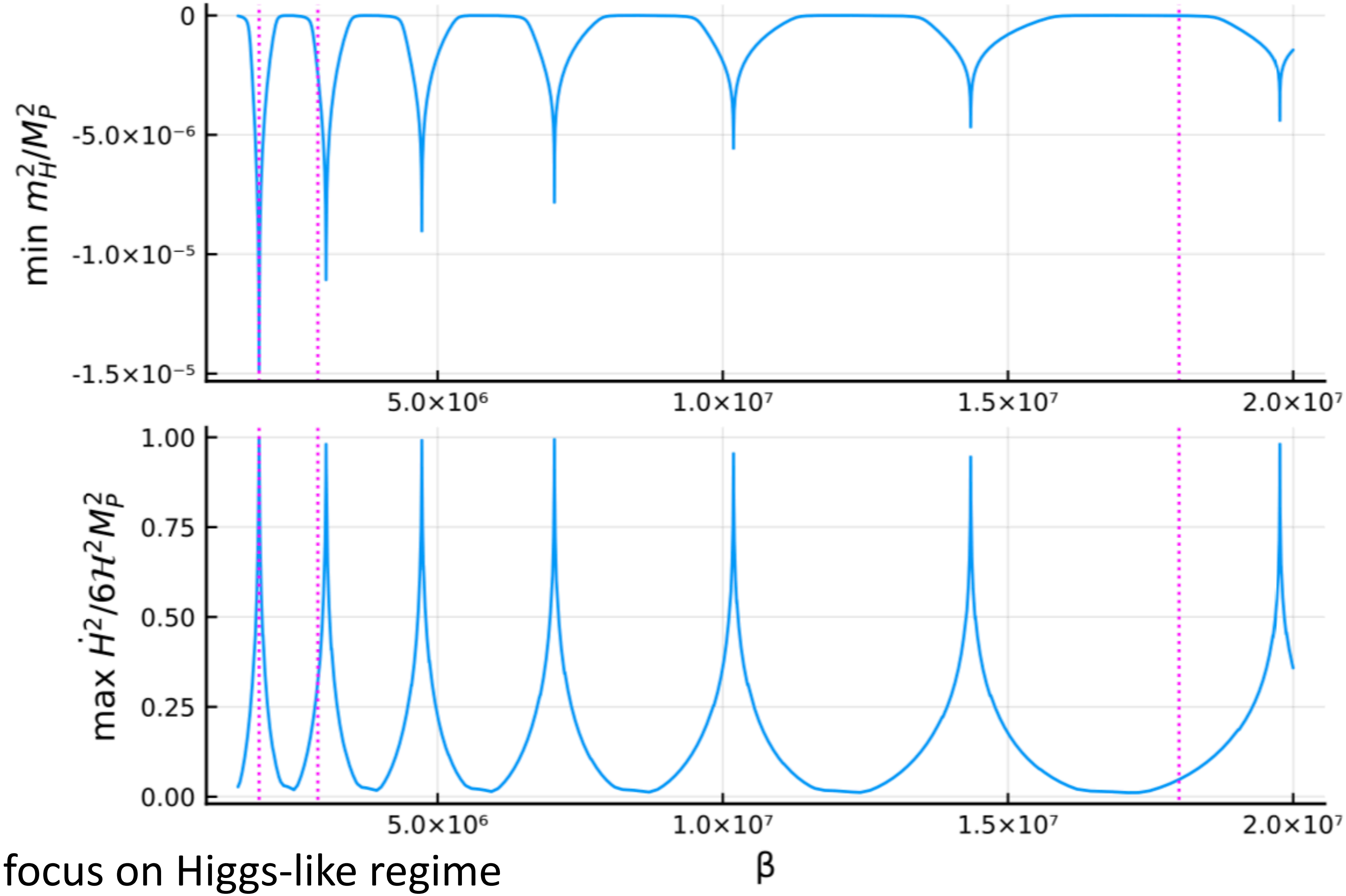
<u>MH</u>, R. Jinno, K. Kamada, S. C. Park, A. A. Starobinsky, J. Yokoyama, Phys.Lett. B791 (2019) 36-42



Effective mass of Higgs perturbation and longitudinal mode of the weak gauge bosons

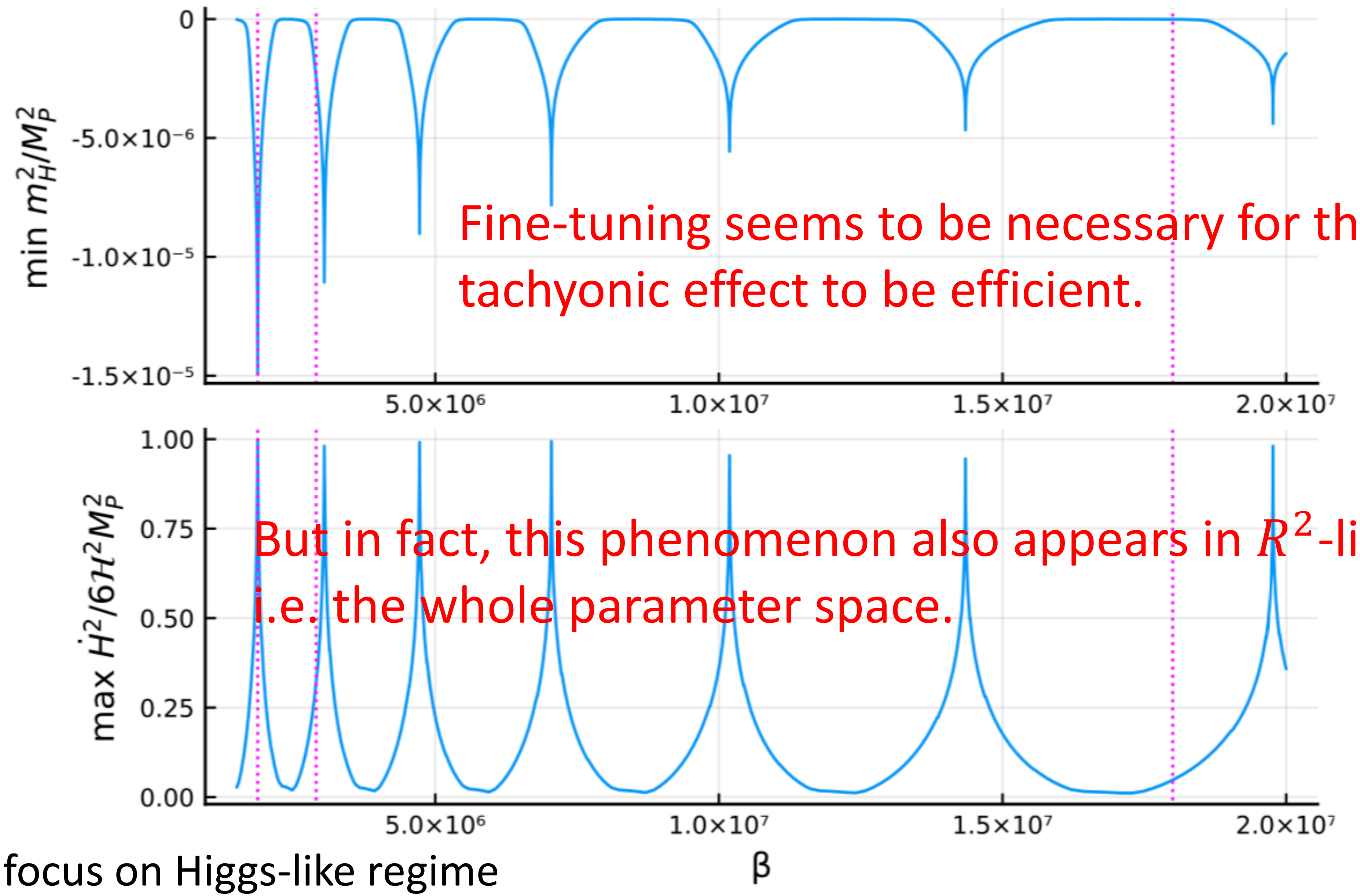


F. Bezrukov, D. Gorbunov, C. Shepherd, A. Tokareva, Phys. Lett. B 795, 657 (2019)



Only focus on Higgs-like regime

F. Bezrukov, D. Gorbunov, C. Shepherd, A. Tokareva, Phys. Lett. B 795, 657 (2019)



Fine-tuning seems to be necessary for the tachyonic effect to be efficient.

But in fact, this phenomenon also appears in R^2-like regime, i.e. the whole parameter space.

Only focus on Higgs-like regime

F. Bezrukov, D. Gorbunov, C. Shepherd, A. Tokareva, Phys. Lett. B 795, 657 (2019)

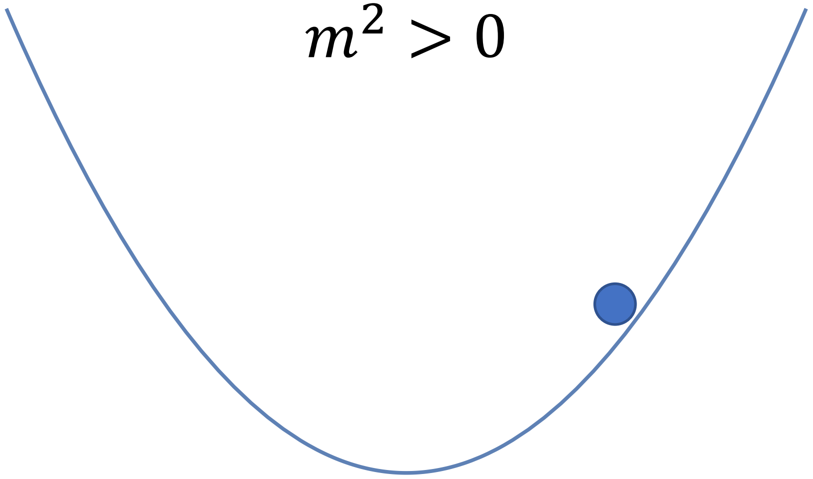
Tachyonic preheating

- What is "tachyonic" ?

$$\ddot{x} + m^2 x = 0$$

Harmonic oscillator

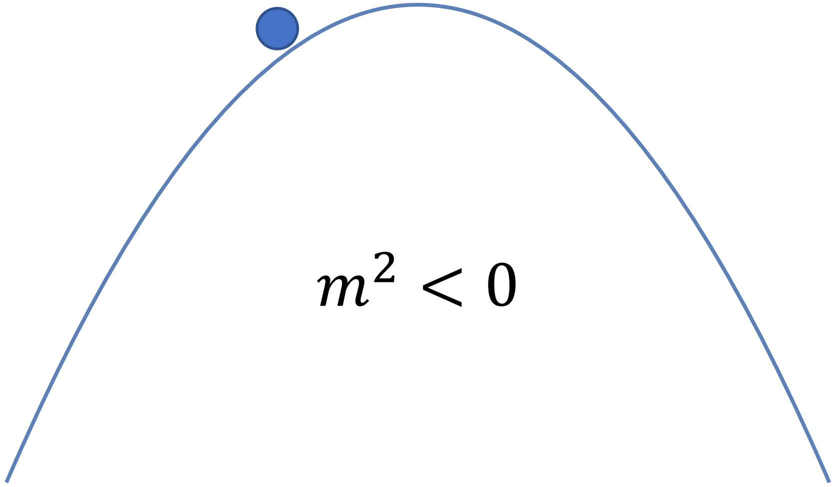
$$m^2 > 0$$



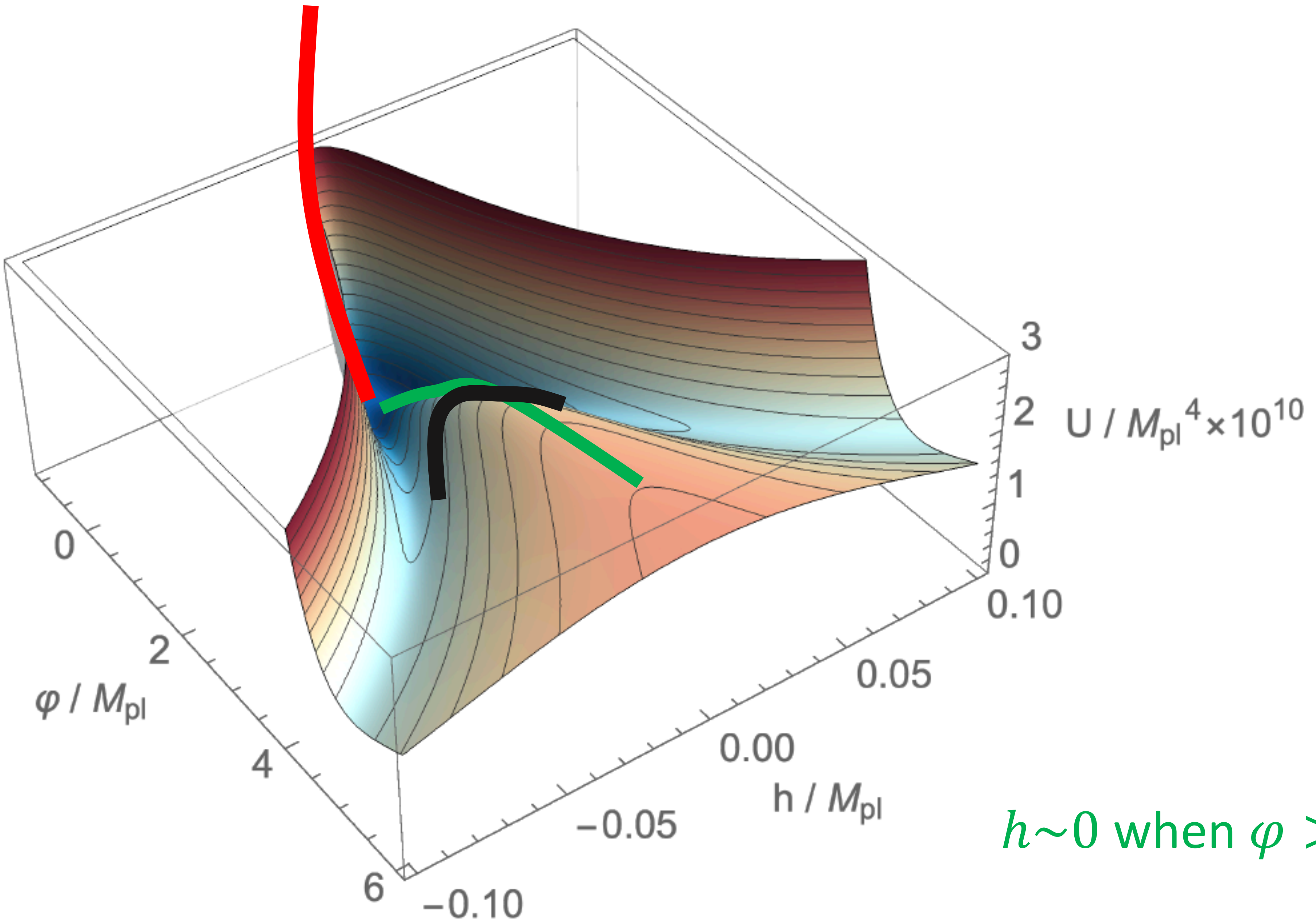
$$x = A \sin(mt + \theta)$$

Tachyonic instability

$$m^2 < 0$$



$$x = Ae^{+|m|t} + Be^{-|m|t}$$



$h \sim 0$ when $\varphi > 0$

Tachyonic preheating

- Condition for occurrence: finding out all the parameters that could induce tachyonic instability

- Degree of fine-tuning

  - Maximal efficiency → whether it is efficient enough to take away significant amount of energy from the inflaton.

  - How much deviation from the maximal efficiency is allowed to still be significant?

Tachyonic preheating

- Condition for occurrence: finding out all the parameters that could induce tachyonic instability

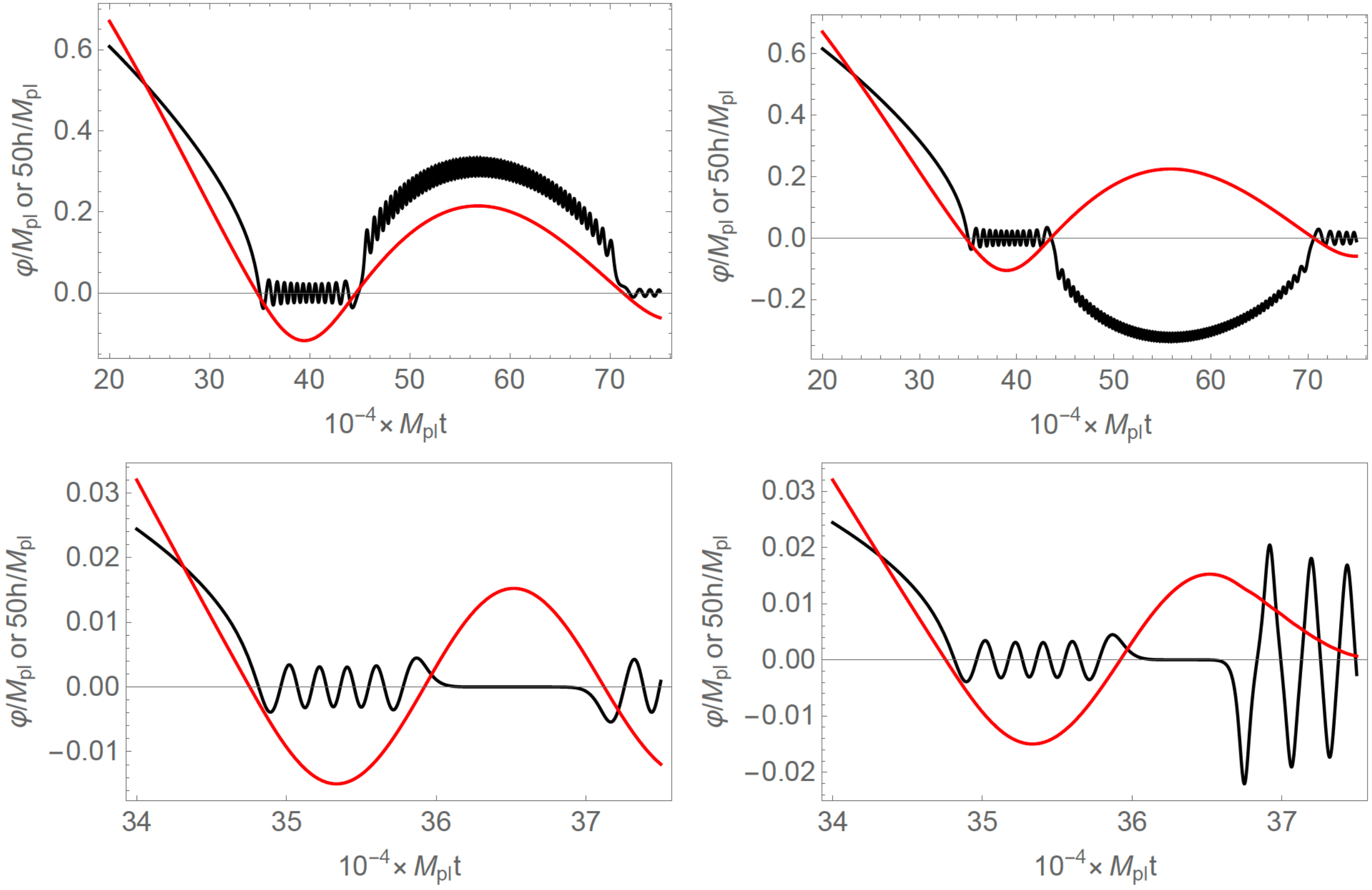
- Degree of fine-tuning

  Criterion: without taking into account any backreaction, the tachyonic instability can take away half of the inflaton energy.

  - Maximal efficiency → whether it is efficient enough to take away significant amount of energy from the inflaton.

  - How much deviation from the maximal efficiency is allowed to still be significant?

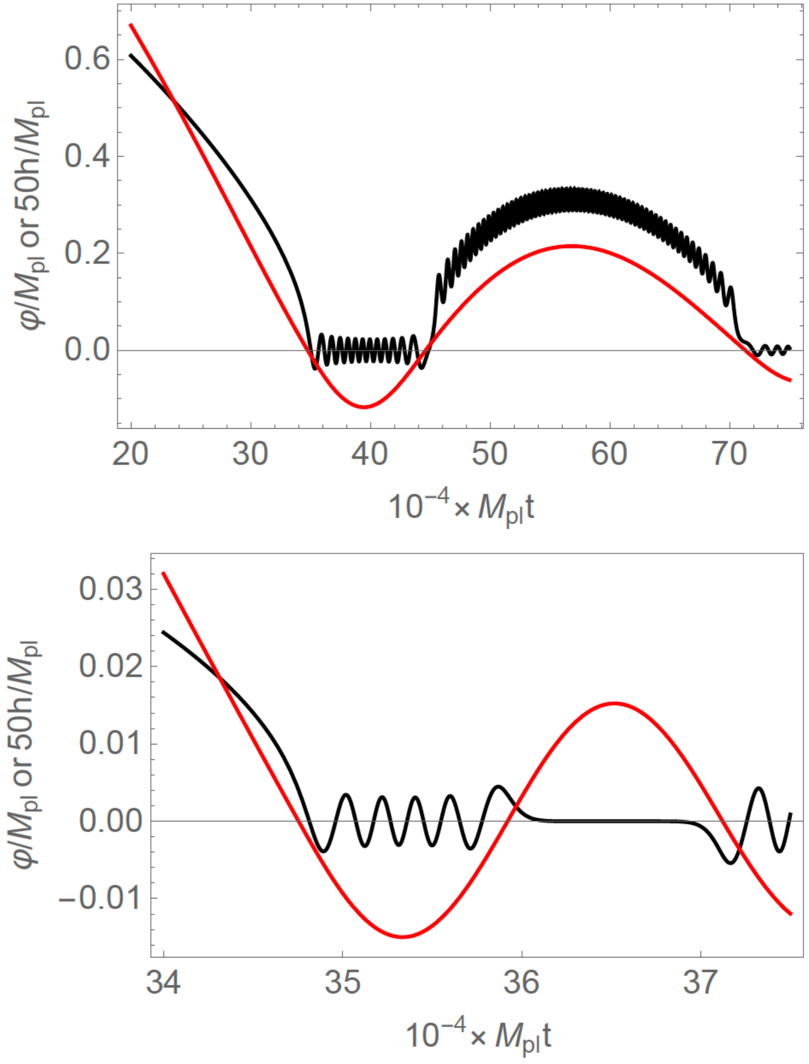
Condition for occurrence



Red: scalaron
Black: Higgs

The phase of Higgs field during $\varphi < 0$

Condition for occurrence



Red: scalaron
Black: Higgs

The phase of Higgs field during $\varphi < 0$

↓

The ratio between the frequencies of Higgs and scalaron

Condition for occurrence

- Mass ratio $\frac{m_h}{m_\varphi} = N\pi + \Delta\phi$ where N is N_+ and $\Delta\phi$ is small.

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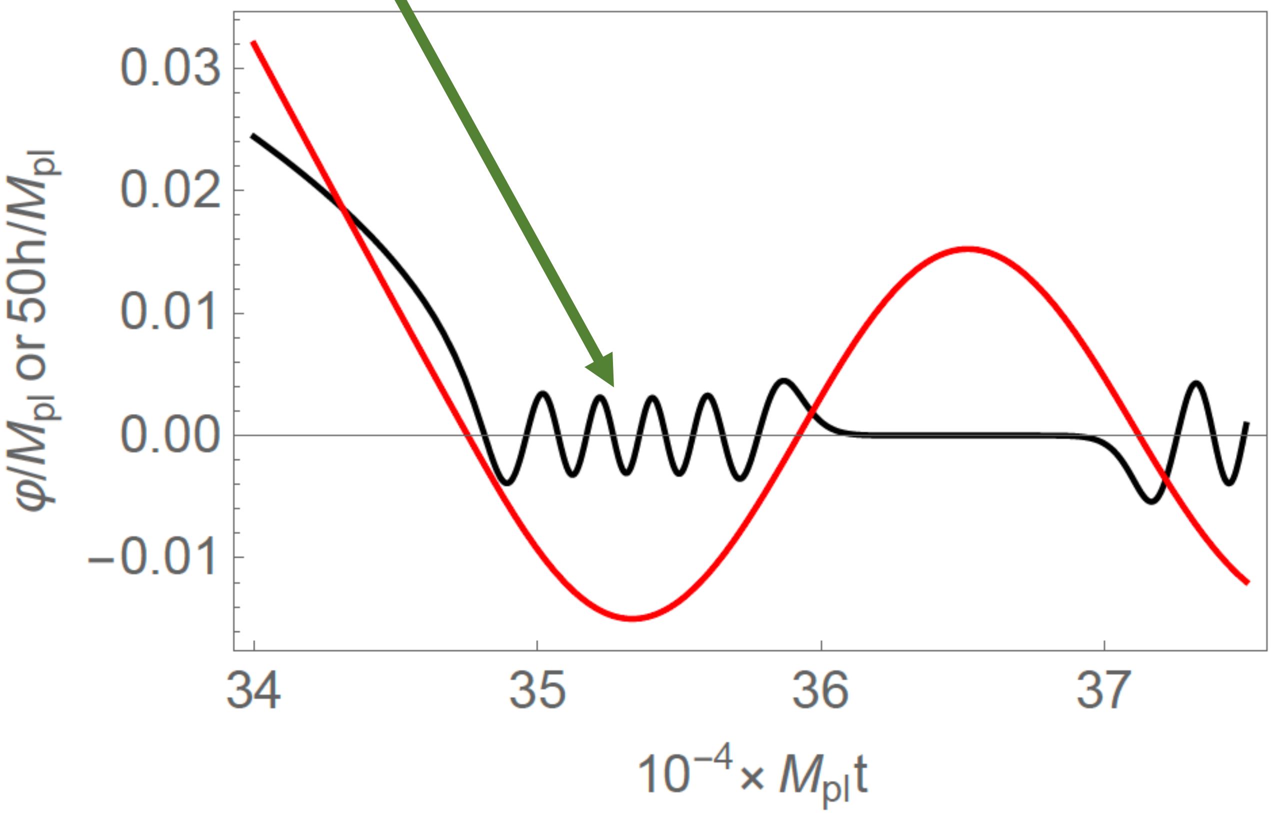
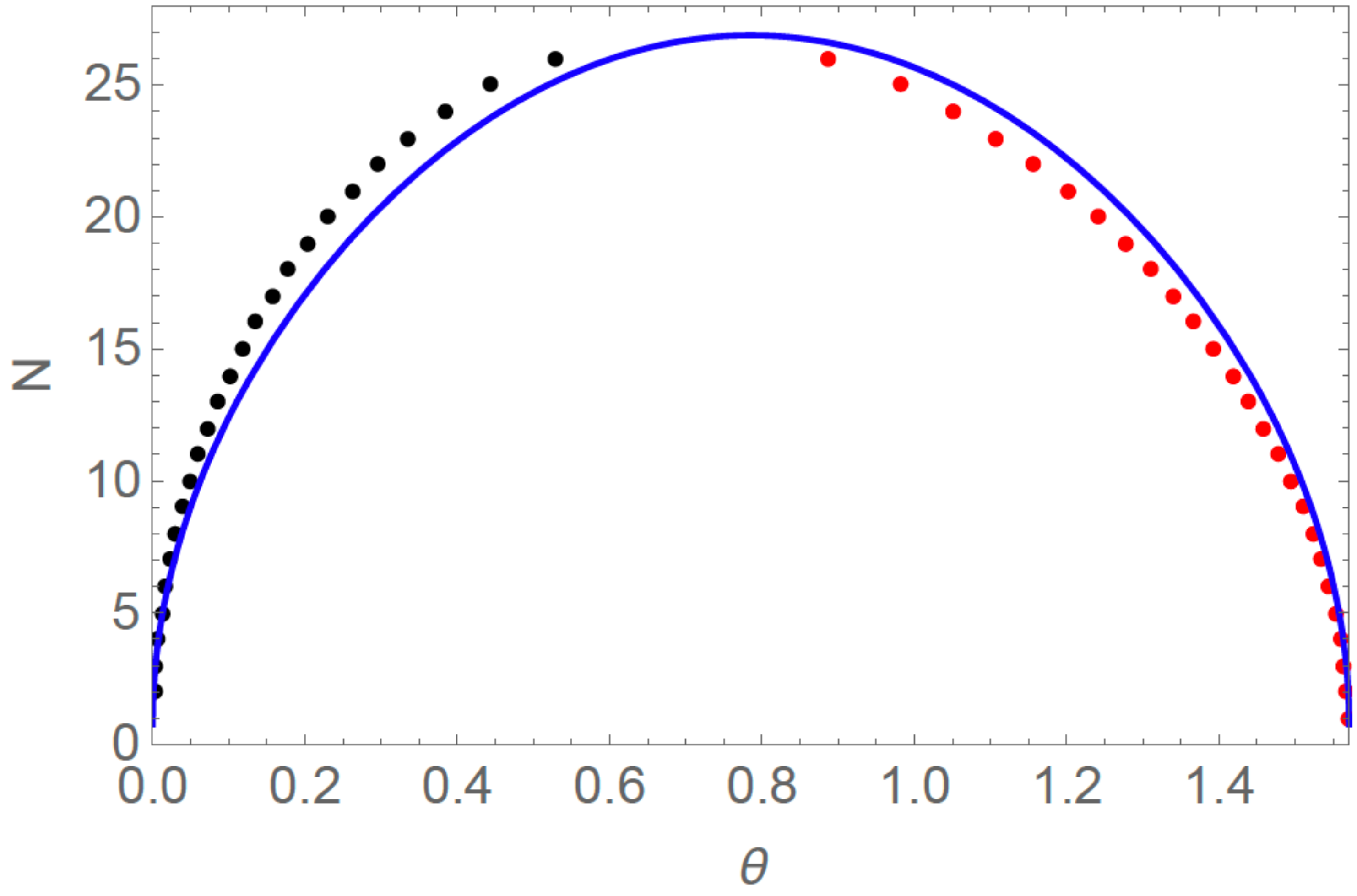


Condition for occurrence

- Mass ratio $\dfrac{m_h}{m_\varphi} = N\pi + \Delta\phi$ where N is N_+ and $\Delta\phi$ is small.
- Higgs-like regime $\dfrac{M_N}{M_{N+1}} \approx \dfrac{(N+1)^2}{N^2}$ M is convenient to describe Higgs-like regime
- R^2-like regime $\dfrac{\xi_N}{\xi_{N+1}} \approx \dfrac{N^2}{(N+1)^2}$ ξ is convenient to describe R^2-like regime

Once we find out one such parameter, we can know all others.

Condition for occurrence



$N_{max} = 26$

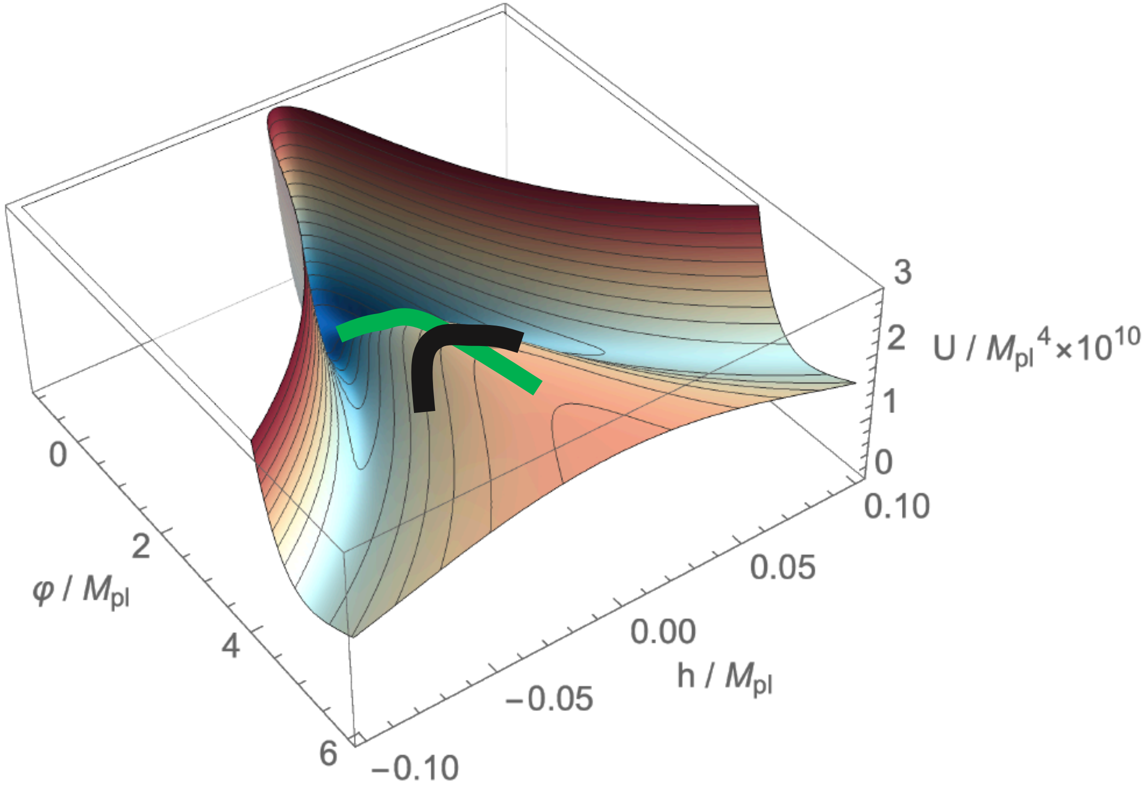
Maximal Efficiency

- Simplified Equation of motion for the Higgs inhomogeneity when $\varphi > 0$ and $h \sim 0$

$$\ddot{\tilde{\delta h}}_k + \omega_{h,k}^2 \tilde{\delta h}_k \approx 0$$

$$\omega_{h,k}^2 \equiv k_p^2 + m_h^2 = k_p^2 + \frac{\partial^2 U}{\partial h^2}$$

$$m_h^2 = -3\alpha\xi M^2 \varphi(t)$$



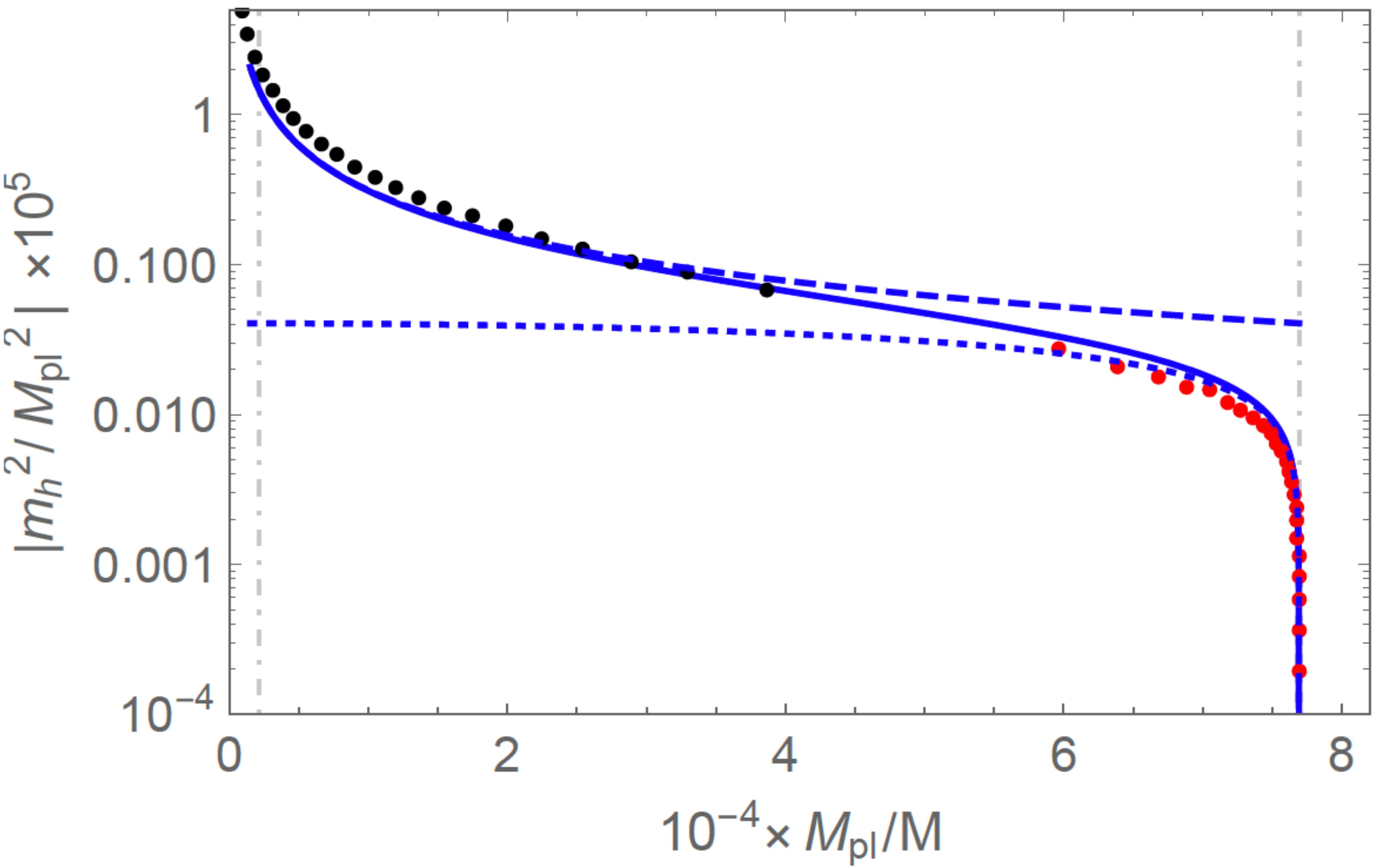
Maximal Efficiency

- Maximal efficiency → roughly speaking, maximal $|m_h|\Delta t$
- Δt : frequency of scalaron oscillation (similar to the spike width)
- $|m_h|$: $m_h^2 = -3\alpha\xi M^2 \underline{\varphi(t)}$

Maximal Efficiency

- Maximal efficiency → roughly speaking, maximal $|m_h|\Delta t$
- Δt : frequency of scalaron oscillation (similar to the spike width)
- $|m_h|$: $m_h^2 = -3\alpha\xi M^2\varphi(t)$

$$m_{h,\max}^2 = \left|\frac{\partial^2 U}{\partial h^2}\right|_{\varphi=\varphi_2,h=0} = 3C_2C_1\xi_N^i M_N^i M_c = 3C_2C_1\xi_c M_c^2 \cot\theta_N^i$$



$|m_h{}^2/M_{pl}{}^2| \times 10^5$
1
0.100
0.010
0.001
10^{-4}
0
2
4
6
8
$10^{-4} \times M_{pl}/M$

Maximal Efficiency

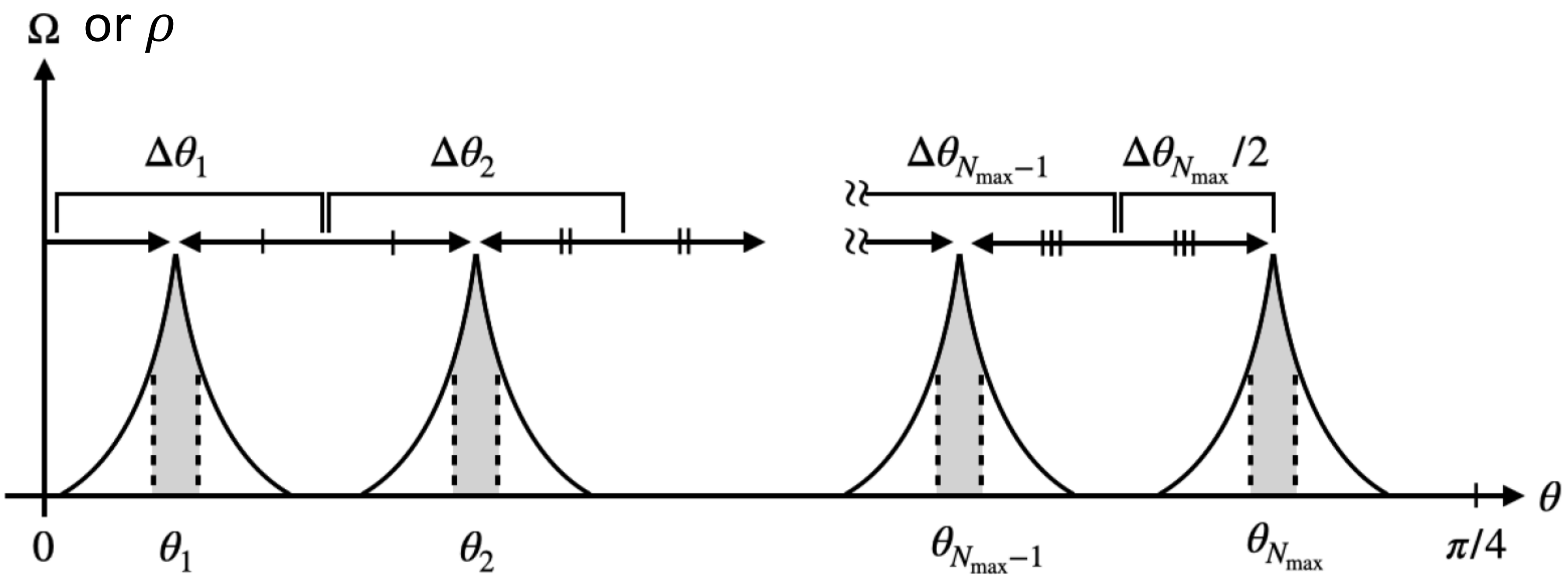
- Number density $$n_k = \left|\tilde{\beta}_k\right|^2 = \left|e^{\Omega_k} - e^{-\Omega_k}/4\right|^2 \approx e^{2\Omega_k}$$

$$\Omega_k \equiv \int_{t_{\mathrm{enter},0}}^{t_{\mathrm{exit},0}} |\omega_{h,k}(t')| dt'$$ → Basically $|m_h|\Delta t$

- Energy density $$\rho_{\delta h}(\xi) = \int \frac{d^3k}{(2\pi)^3} \omega_{h,k} n_k$$

Non-maximal Efficiency

- However, the efficiency of the tachyonic preheating with deviation from the maximal case is difficult to be described by analytical calculation.



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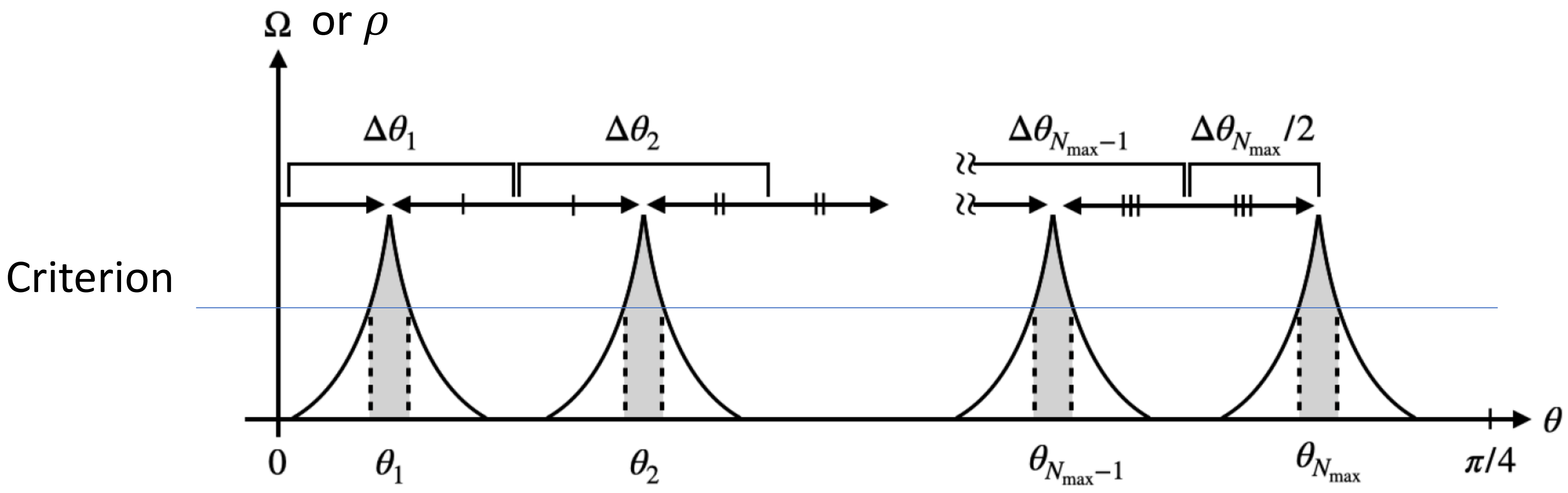
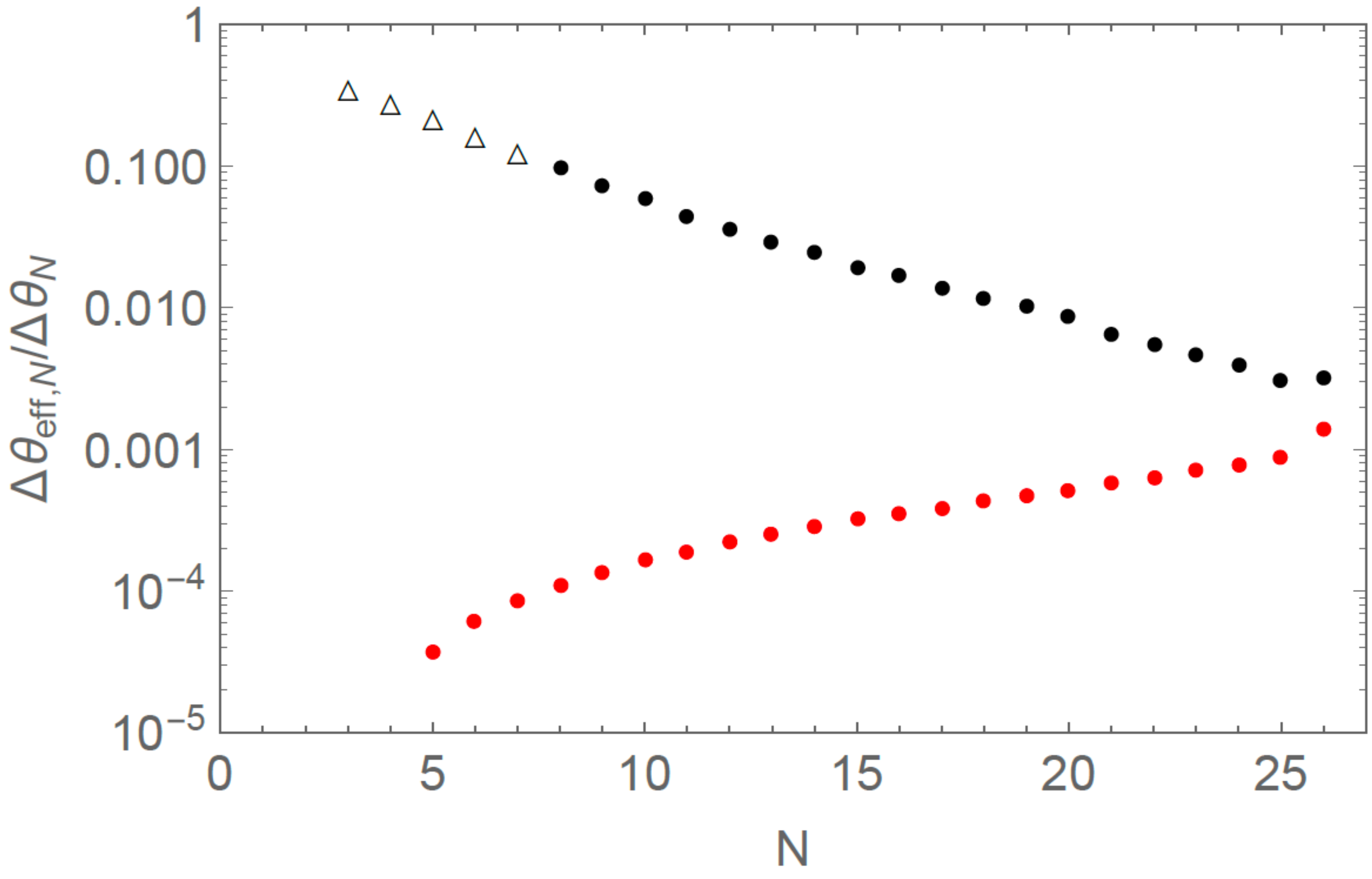


Degree of fine-tuning



Results from another paper

- Consider R^2-like regime

- Lattice simulation: backreaction

- Tachyonic effect appears very often (for subsequent scalaron oscillations) and is efficient

Fedor Bezrukov and Chris Shepherd, arXiv: 2007.10978

Conclusion and future work

- We find out the condition for the occurrence of the tachyonic preheating in the mixed Higgs-R^2 model
- We analytically calculate the maximal efficiency the tachyonic instability can achieve.
- We numerically find out the necessary degree of fine-tuning to realize sufficiently strong tachyonic preheating.
- Backreaction is not considered and we should further study the tachyonic phenomenon and compare the results with the other group.

Thank you for your attention!

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