Reheating Process in Mixed Higgs-R^2 Model

Speaker: Minxi He (IPNS, KEK)

2022/07/25@PASCOS, MPIK

MH, R. Jinno, K. Kamada, S. C. Park, A. A. Starobinsky, J. Yokoyama, Phys. Lett. B 791 (2019) 36-42, arXiv: 1812.10099
MH, R. Jinno, K. Kamada, A. A. Starobinsky, J. Yokoyama, JCAP 01 (2021) 066, arXiv: 2007.10369
MH, JCAP 05 (2021) 021, arXiv: 2010.11717

Contents

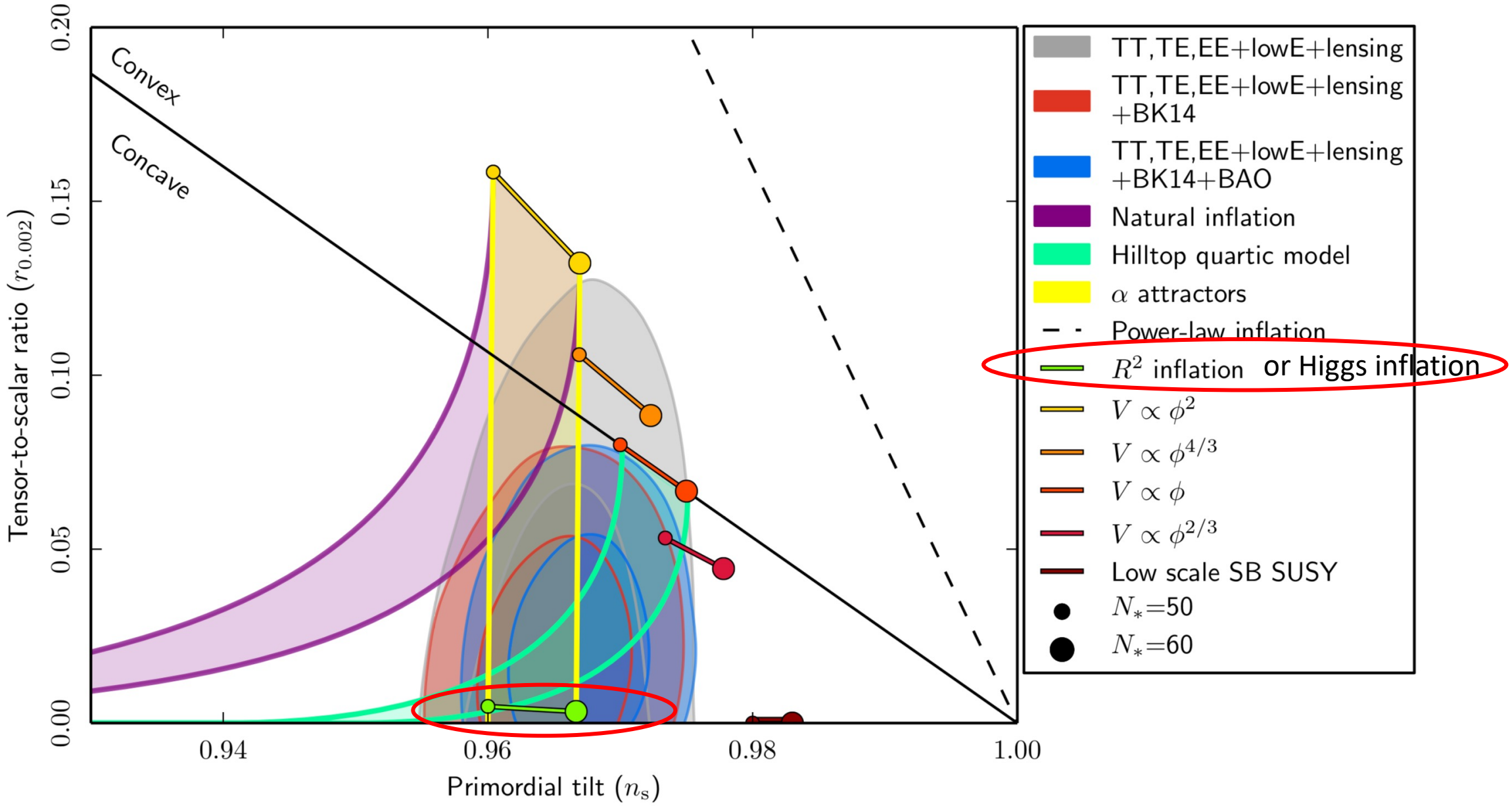
The Mixed Higgs-R^2 Inflation Model

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 $\xi > 0$

Wang and Wang, (2017)
Ema, (2017)
MH, Starobinsky, Yokoyama, (2018)
Gundhi and Steinwachs, (2020)
Enckell, Enqvist, Rasanen, Wahlman, (2020)


Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.94
0.96
0.98
1.00
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
or Higgs 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

The Mixed Higgs-R^2 Inflation Model

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

  Spiky effective mass of longitudinal mode of gauge boson

  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, (2019)
  Ema, Mukaida, van de Vis (2020)

The Mixed Higgs-R^2 Inflation 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

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

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

In unitary gauge

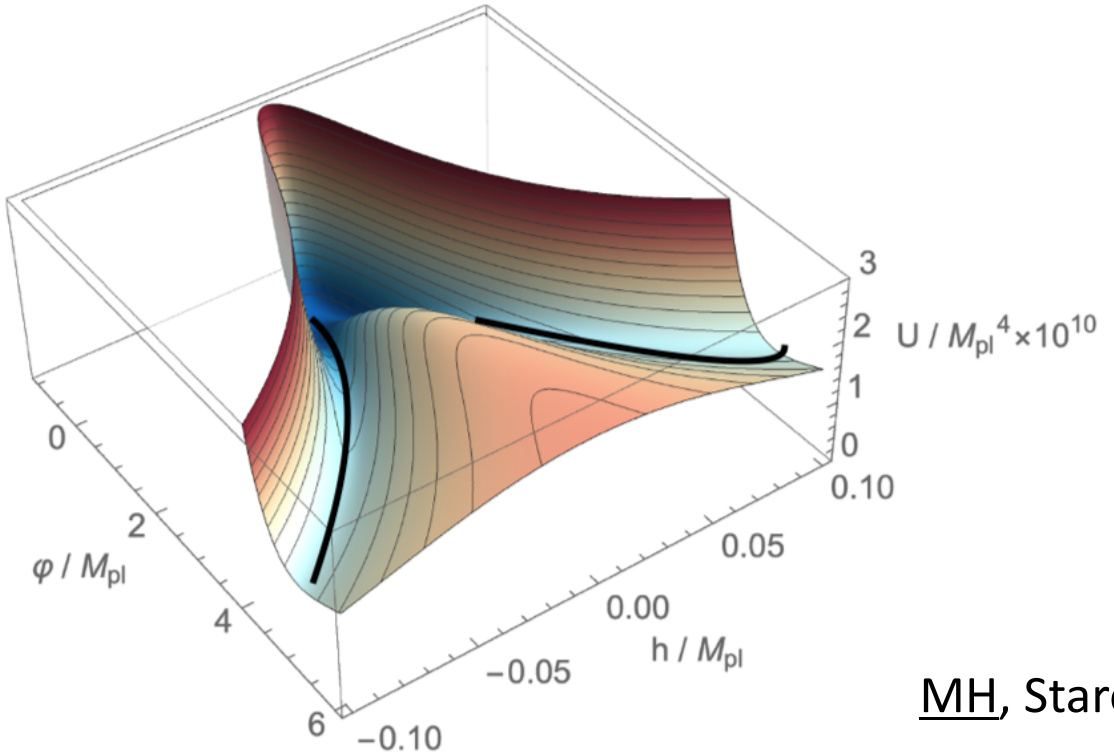
Inflation dynamics

- Inflation dynamics----effective R^2-inflation ($\xi \gg 1$)

Inherit the best-fit prediction

  - Same prediction on $n_s - r$ plane as Starobinsky model
  - Smooth connection between Starobinsky model and Higgs inflation

$$\tilde{M}^2 \equiv \frac{M^2}{1 + \dfrac{3\xi^2 M^2}{\lambda M_{\rm pl}^2}}$$

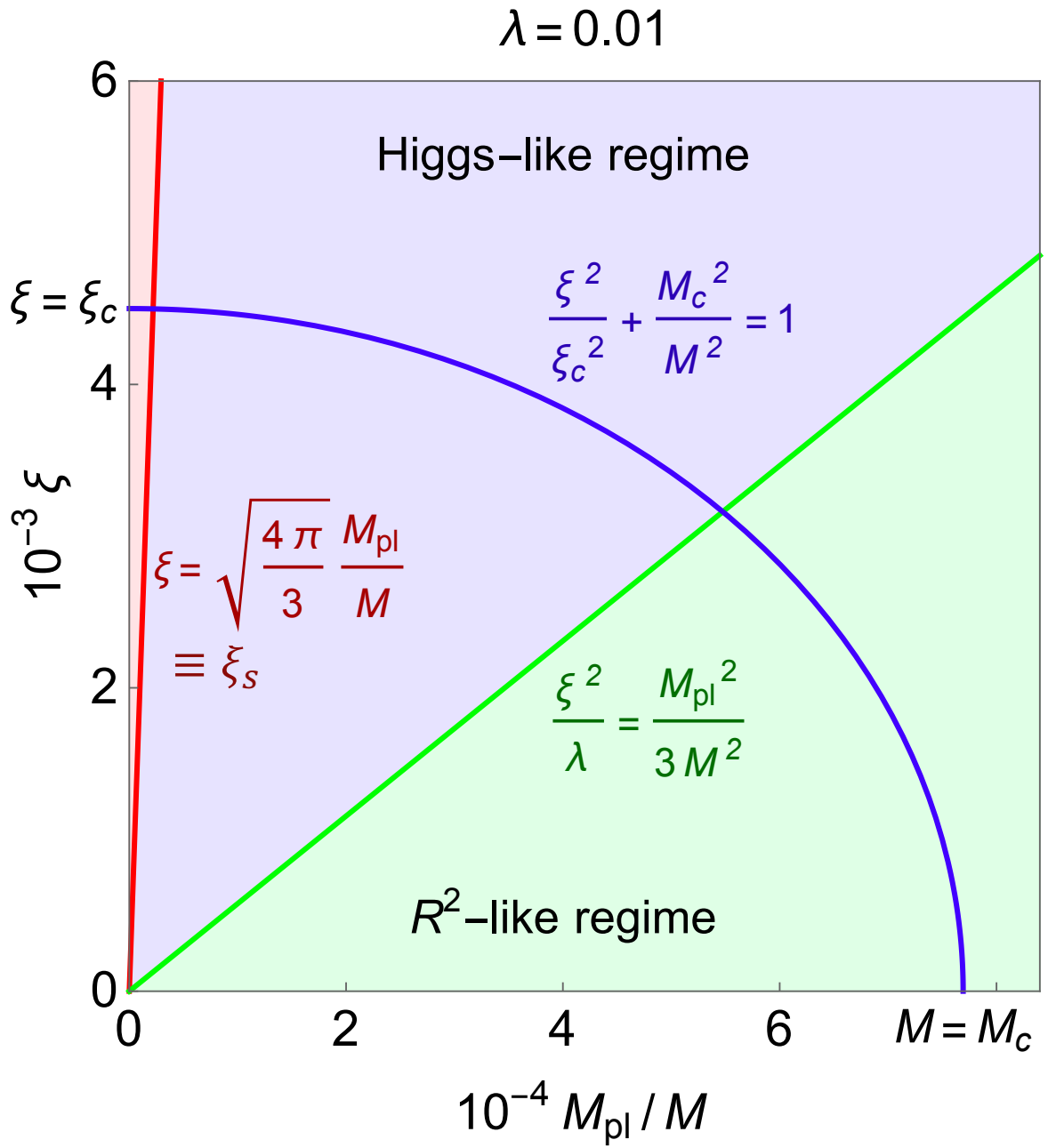


MH, Starobinsky, Yokoyama, (2018)

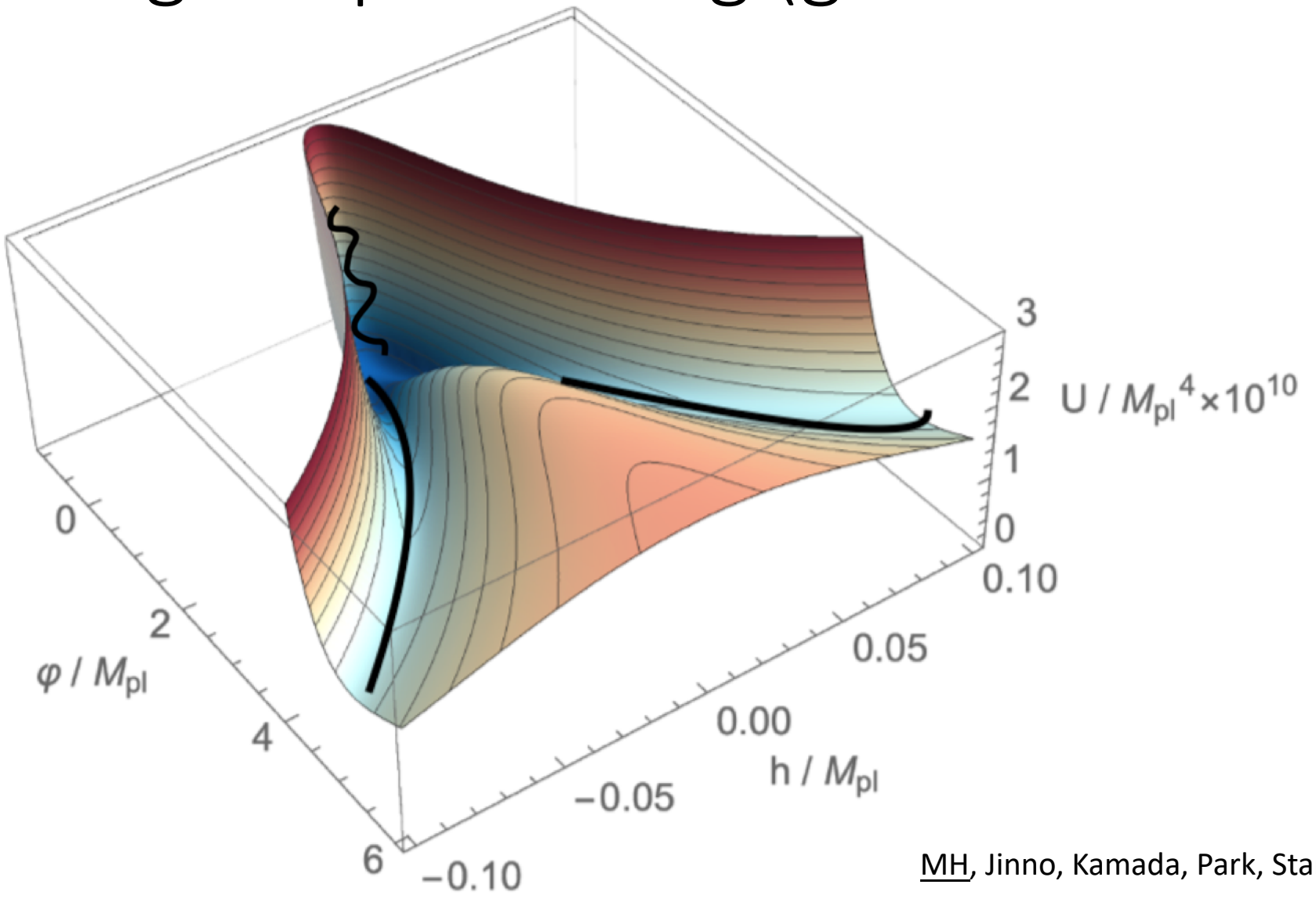
Parameter space

- R^2-like regime
- Higgs-like regime
- Strongly-coupled regime

$$\xi, M, or\ \theta = \cos^{-1}\frac{\xi}{\xi_c}$$

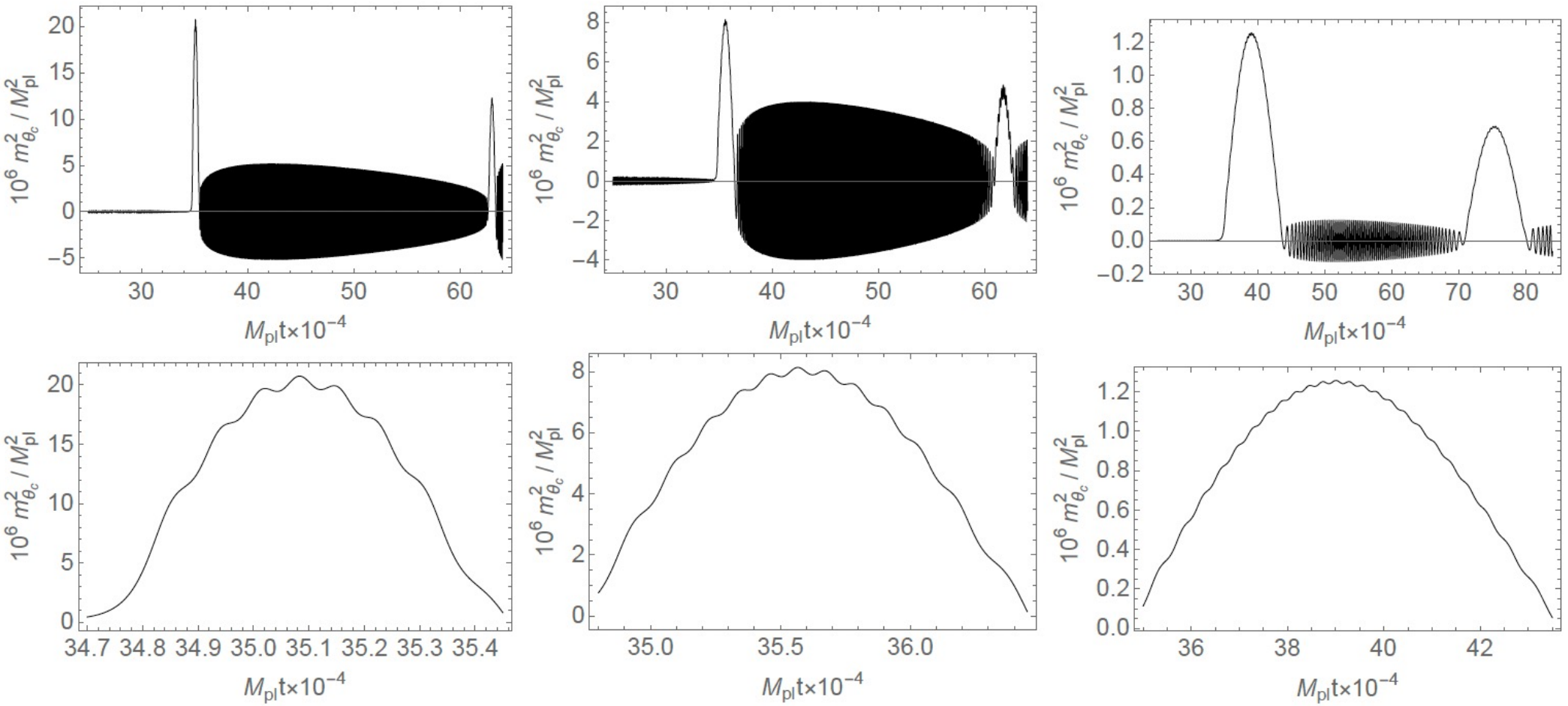


First stage of preheating (generic for all parameters)

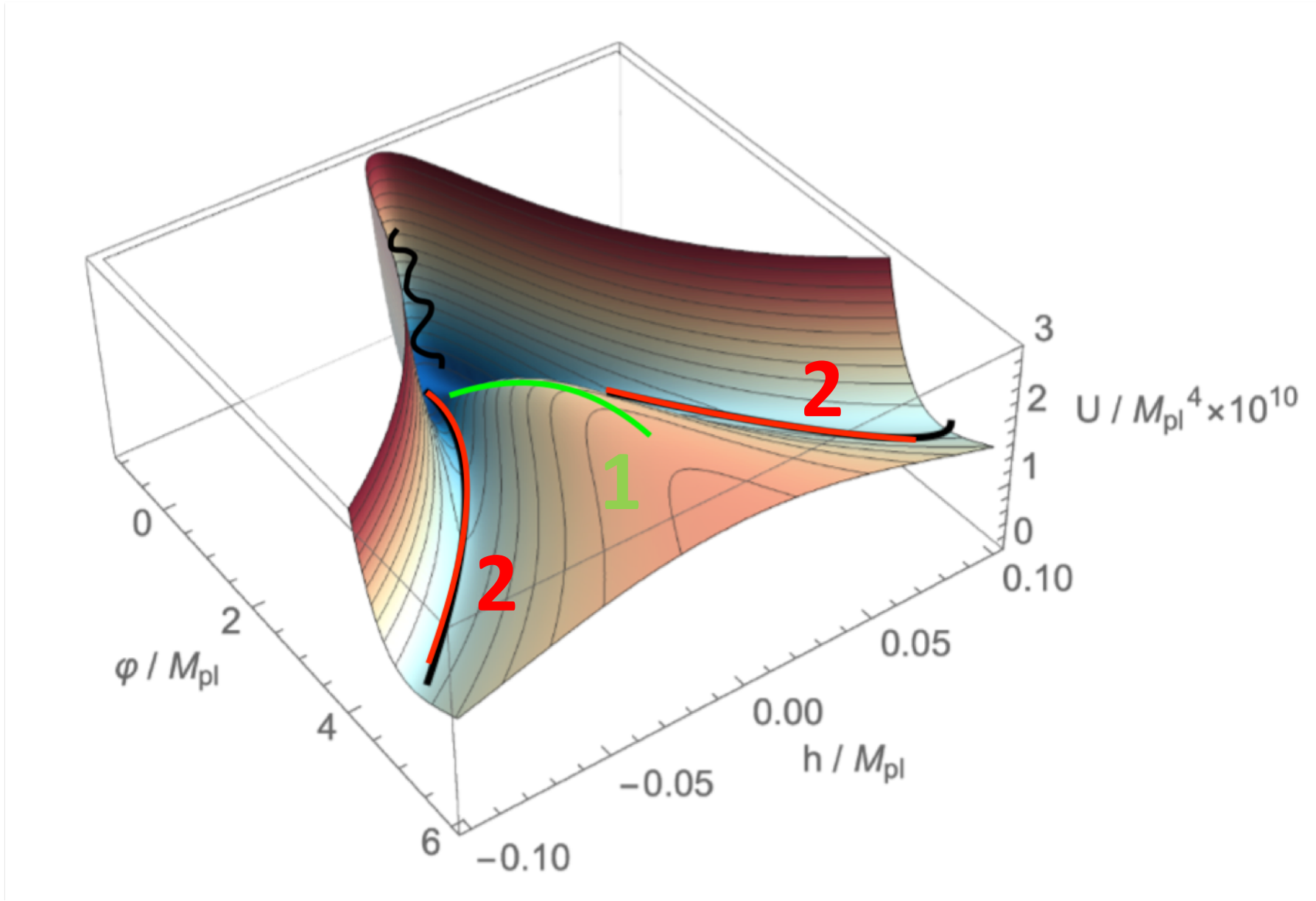


MH, Jinno, Kamada, Park, Starobinsky, Yokoyama, (2019)

Insufficient preheating by spikes

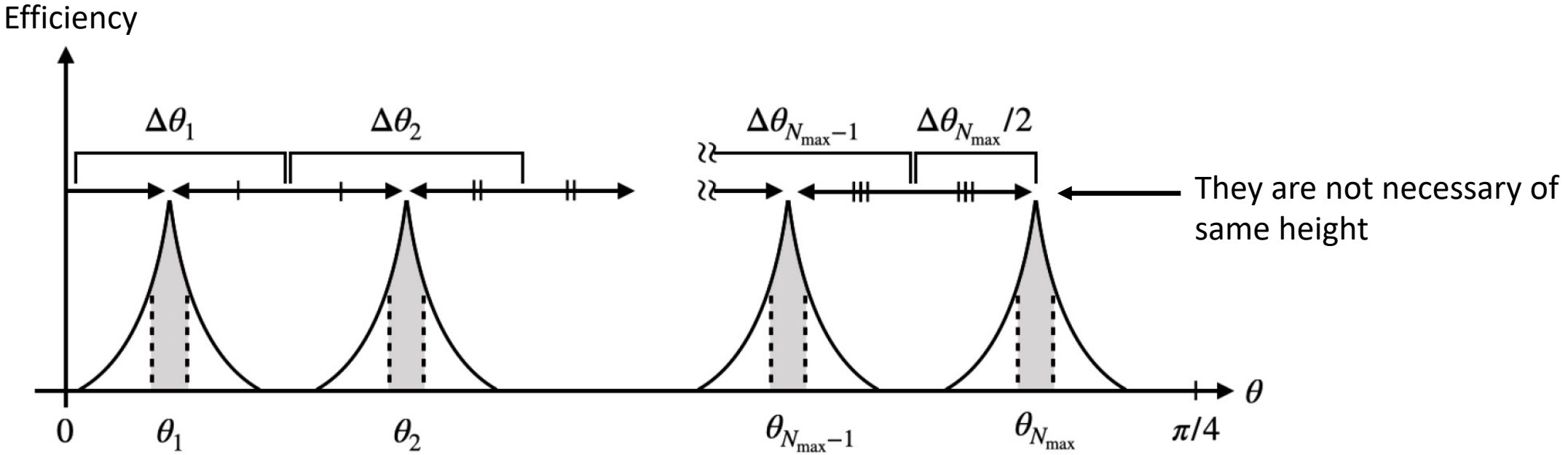


MH, Jinno, Kamada, Park, Starobinsky, Yokoyama, (2019)


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

Tachyonic preheating

- Condition for occurrence: finding out all the parameters that could induce locally maximal tachyonic instability (in the first scalaron oscillation) and their distribution in the parameter space



MH, Jinno, Kamada, Starobinsky, Yokoyama, arXiv: 2007.10369

Tachyonic preheating

- Condition for occurrence: finding out all the parameters that could induce locally maximal tachyonic instability (in the first scalaron oscillation) and their distribution in the parameter space

- Degree of fine-tuning
  - Maximal efficiency for each critical points (analytical)

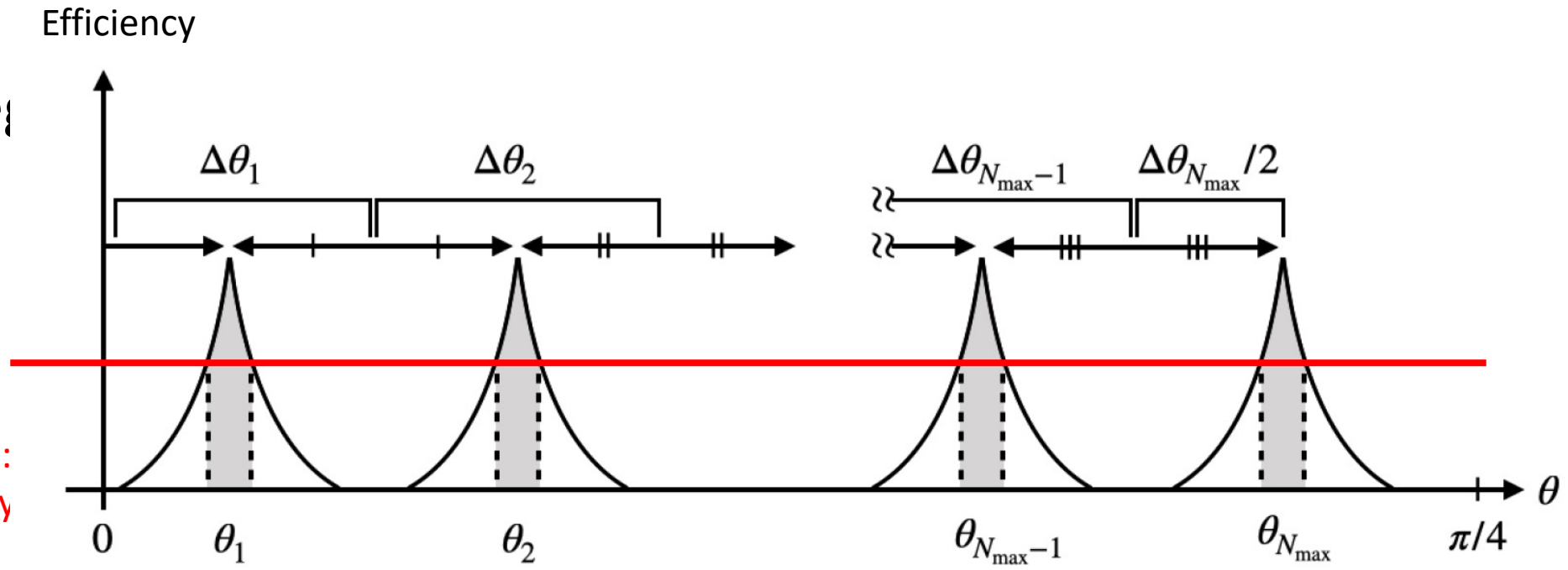
  - How much deviation from the critical points is allowed for the tachyonic effect to still be significant?

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

MH, Jinno, Kamada, Starobinsky, Yokoyama, arXiv: 2007.10369

Tachyonic preheating

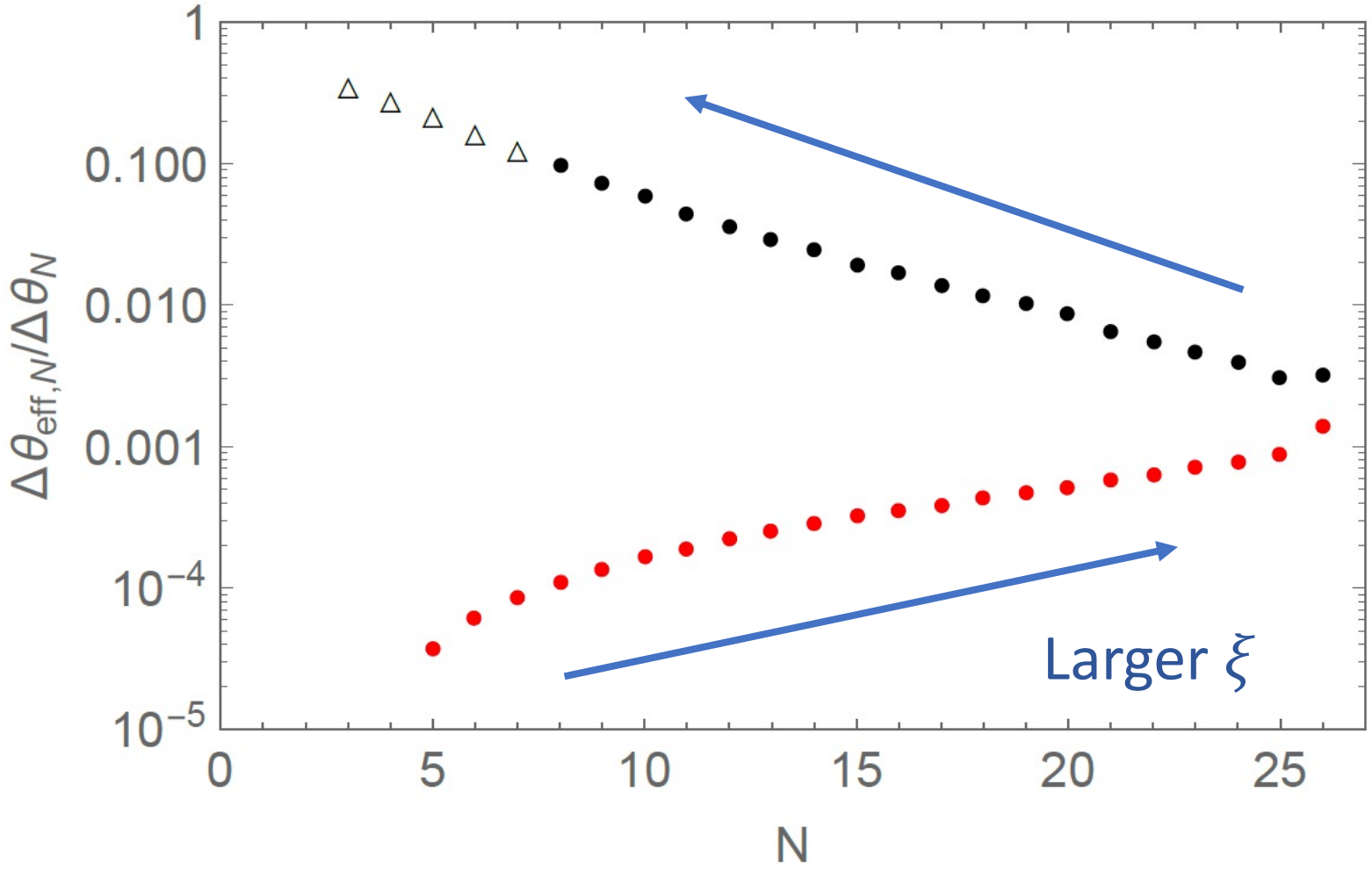
- Condition for occurrence: finding out all the parameters that could induce locally maximal tachyonic instability (in the first scalaron oscillation) and their distribution in the parameter space



- De
  -
  -

Criterion: instability

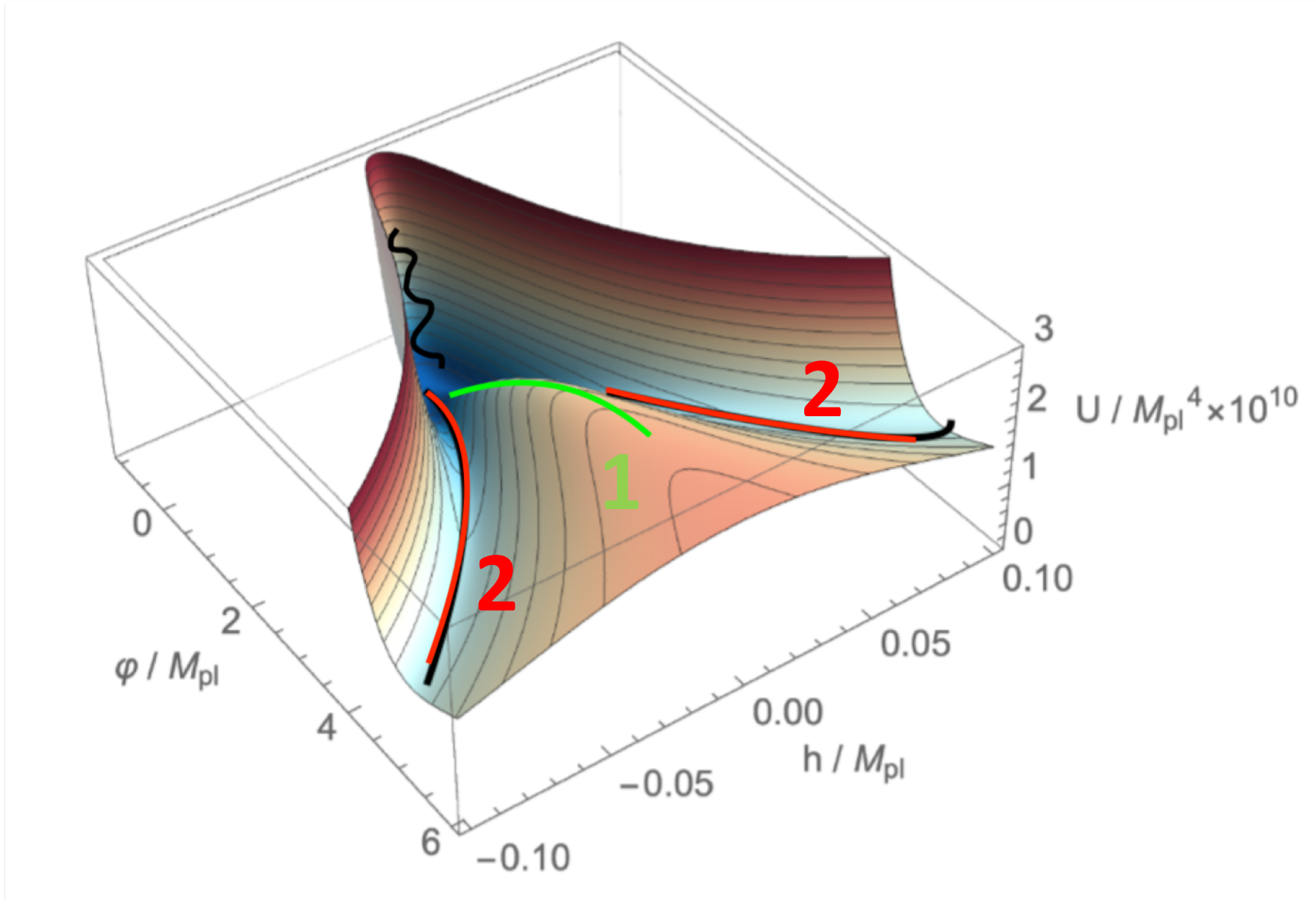
Degree of fine-tuning



What about other cases?

- Tachyonic instability is not significant

- Tachyonic instability is absent


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

Perturbative reheating

- Perturbative decay of background fields
  - Determine reheating temperature
- Perturbative decay of produced particles
  - Reduce the rescattering effect between produced particles and background

MH, arXiv: 2010.11717

Perturbative reheating

- Decay rate of scalaron to Higgs

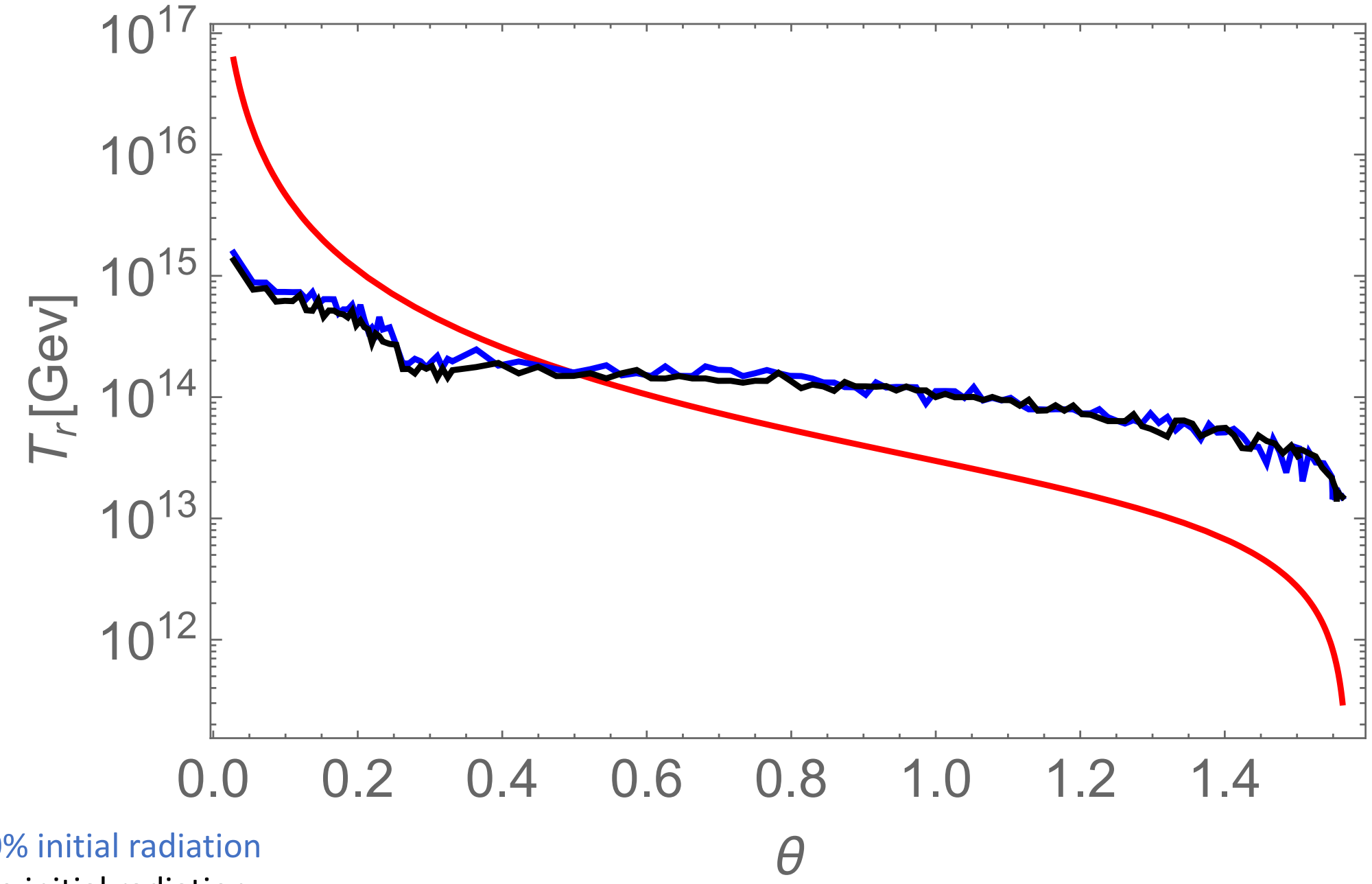
$$\Gamma_{\varphi\to\delta\tilde{h}\delta\tilde{h}} = \begin{cases} \dfrac{3}{16\pi}\dfrac{M^3}{M_{\rm pl}^2}\left(\dfrac{1}{6}+\xi\right)^2\left(1-12\xi\alpha|\varphi|\right)^{1/2}\ , & \varphi<0\ , \\ \dfrac{3}{16\pi}\dfrac{\tilde{M}^3}{M_{\rm pl}^2}\left(\dfrac{1}{6}-2\xi\dfrac{M^2}{\tilde{M}^2}\right)^2\left(1-24\xi\dfrac{M^2}{\tilde{M}^2}\alpha\varphi\right)^{1/2}\ , & \varphi>0\ , \end{cases}$$

- Decay rate of Higgs (e.g. to top quarks)

$$\Gamma_{h\to\tilde{t}\bar{\tilde{t}}} = \begin{cases} \dfrac{3y_t^2}{16\pi}\left(3\xi\alpha|\varphi|\right)^{1/2}M\ , & \varphi<0\ , \\ \dfrac{3y_t^2}{16\pi}\left(6\xi\alpha\varphi\right)^{1/2}M\left(1-\dfrac{y_t^2}{\lambda}\dfrac{\tilde{M}^2}{M^2}\right)^{3/2}\ , & \varphi>0\ , \end{cases}$$

Reheating temperature

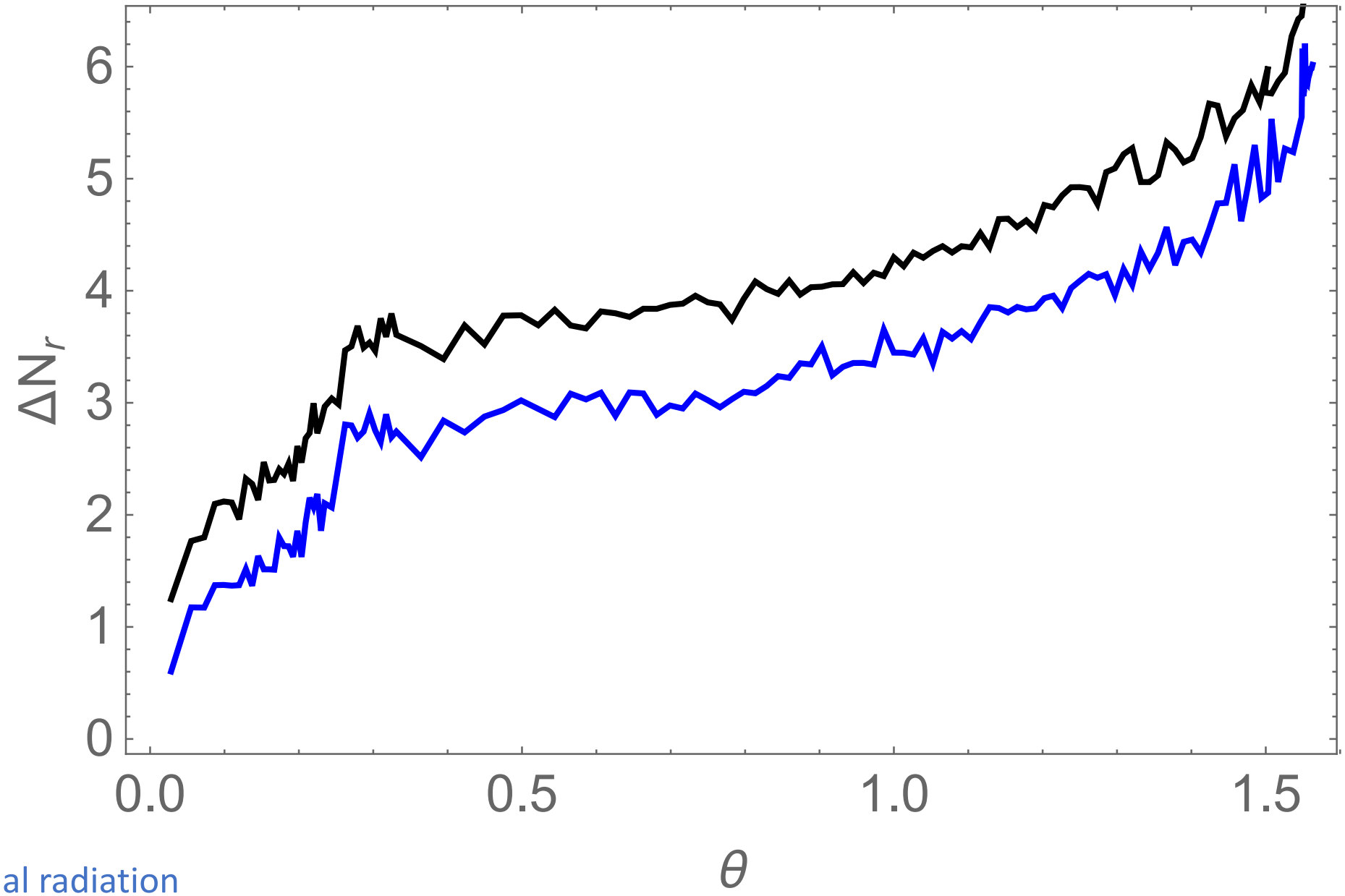
- In the presence of (insufficient) tachyonic preheating
  - Take into account it phenomenologically as initial radiation, consisting initially 90% of the total energy
- In the absence of tachyonic preheating
  - No initial radiation



Blue: 90% initial radiation

Black: no initial radiation

Red: calculated by scalaron decay rate, assuming both channels always open



Blue: 90% initial radiation

Black: no initial radiation

Summary

- Mixed Higgs-R^2 Inflation is healthy up to Planck scale and gives observationally favored predictions
- First stage of preheating is not problematic but not efficient enough
- Tachyonic preheating is possible to occur
  - Condition for occurrence
  - Degree of fine-tuning
- Perturbative reheating (tachyonic preheating is insufficient or absent)
  - Perturbative decay can affect the tachyonic preheating stage
  - Reheating temperature is independent of the preheating stage

Thank you for your attention!