Electroweak vacuum metastability and low-scale inflation

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Based on **arXiv:1706.08920**

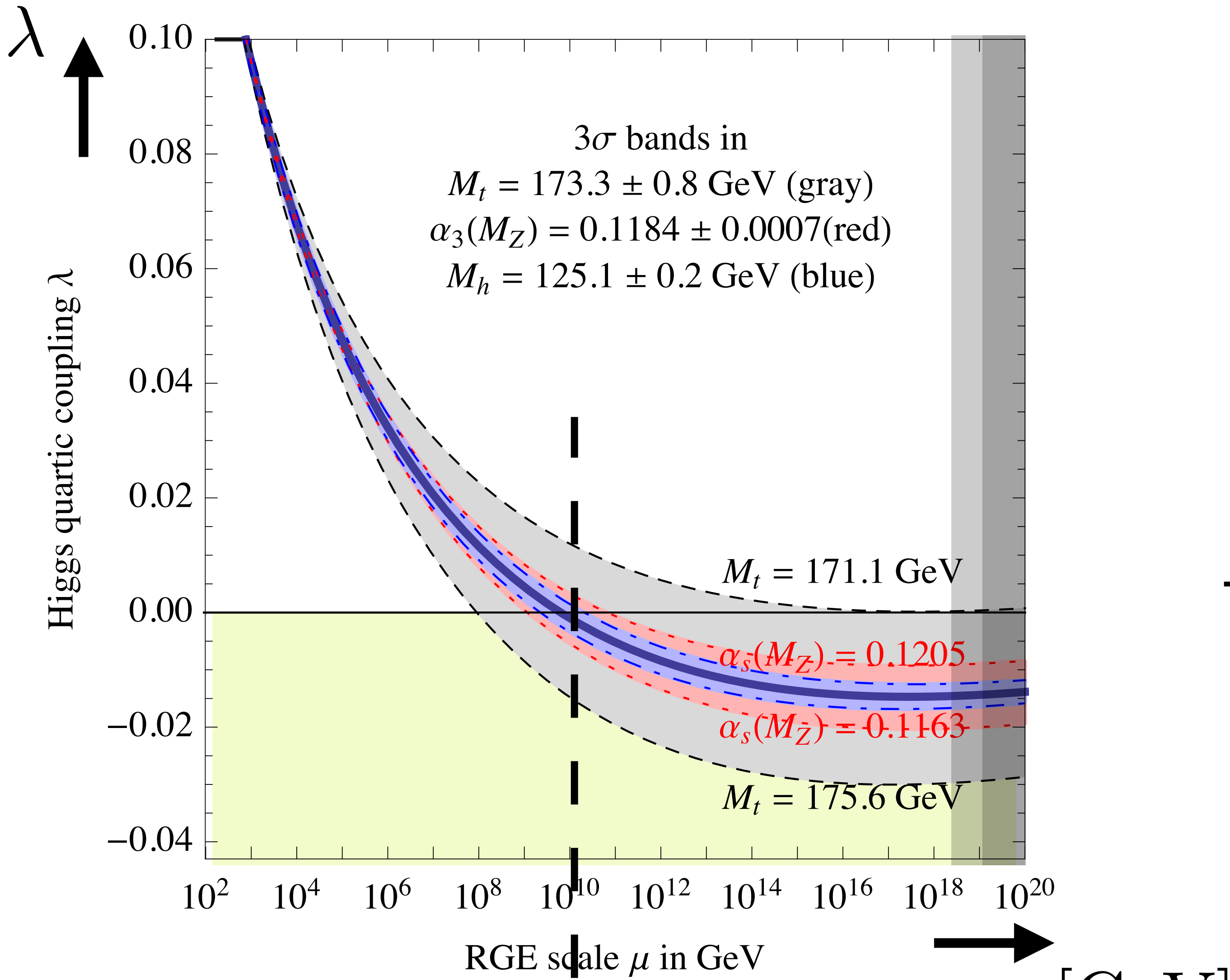
with K. Mukaida (Kavli IPMU → DESY) and K. Nakayama (Tokyo U.)

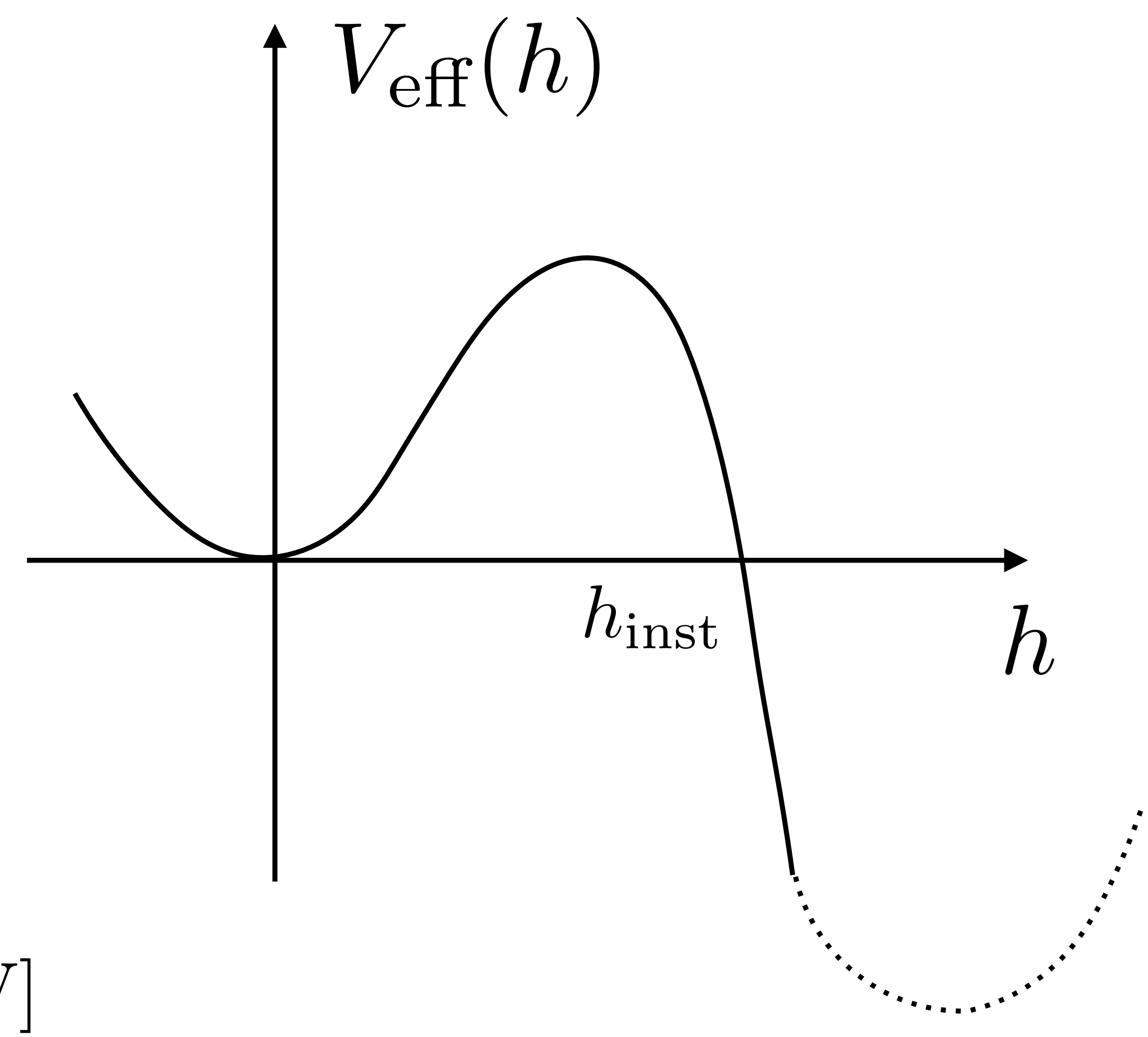
Introduction

Metastability

[Buttazzo+ 13]

Electroweak (EW) vacuum may be metastable??





$h_{\rm inst} \sim 10^{10}$ GeV

λ becomes negative $\sim 10^{10}$ GeV for the center value of $M_{\rm top}$.

Cosmology must be compatible with it.

Metastability vs inflation

- Energy scale during inflation: $H_{\rm inf}$ (Hubble parameter)
  - Metastability can be problematic for $H_{\rm inf} \gtrsim h_{\rm inst}$.

[Espinosa+07; Lebedev+12; Kobakhidze+13; ...]

This is why most people mainly concern high-scale inflation models.

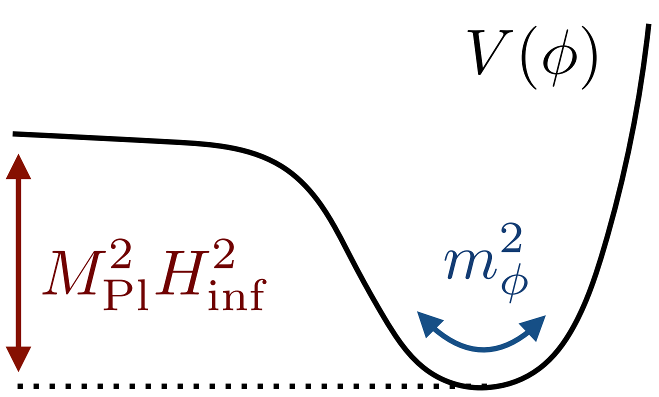
- But, energy scale after inflation: m_ϕ (inflaton mass)
  - Metastability can be problematic for $m_\phi \gtrsim h_{\rm inst}$.

[Herranen+15; YE+16; Kohri+16; Enqvist+16; ...]

- Typically $m_\phi \gg H_{\rm inf}$ for low-scale inflation. [YE, Mukaida, Nakayama 17]

Metastability has interesting implications

even for low-scale inflation with $h_{\rm inst} \gg H_{\rm inf}$.



Outline

1. Introduction

2. Resonant particle production

3. Numerical results

4. Summary

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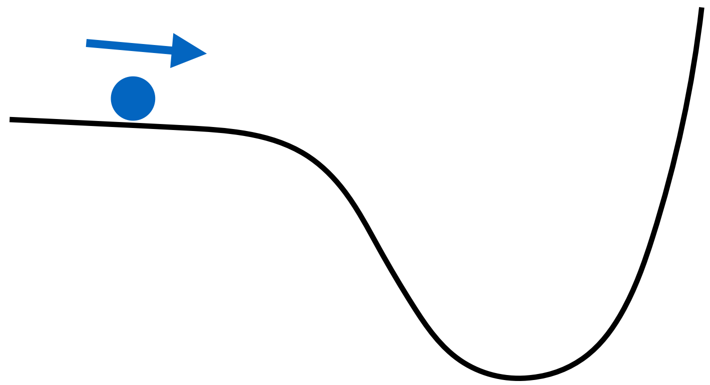
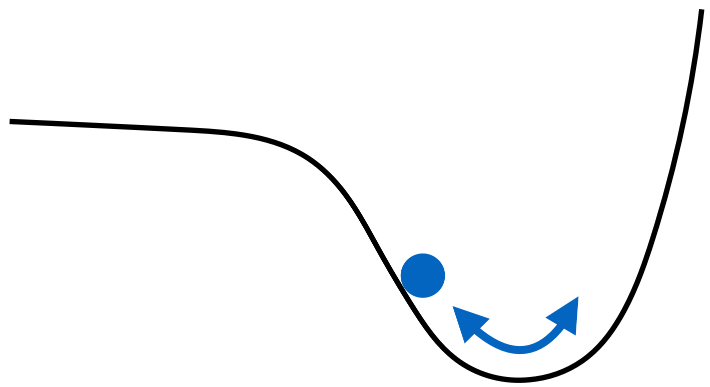
Dynamics of inflaton

1. Slow-roll during inflation.



= accelerated expansion

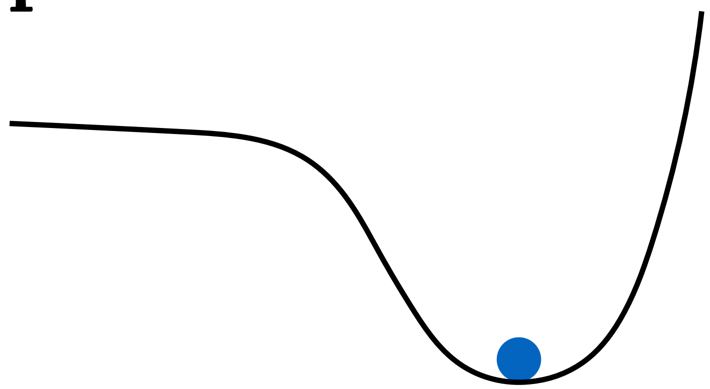
2. Oscillate after inflation.



if exponential particle production

preheating epoch

3. Finally decay, and reheating completes.



= beginning of hot big bang

Dynamics of inflaton

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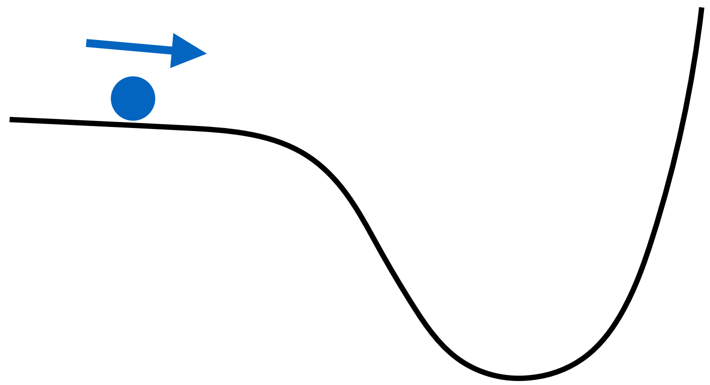

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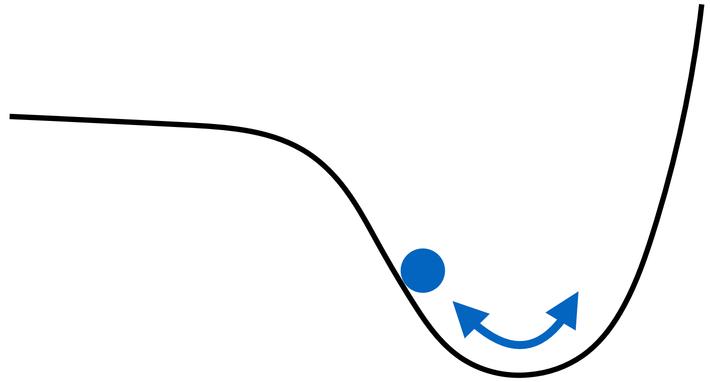

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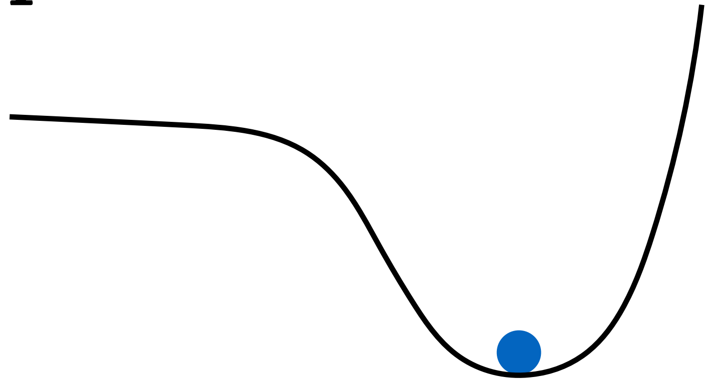
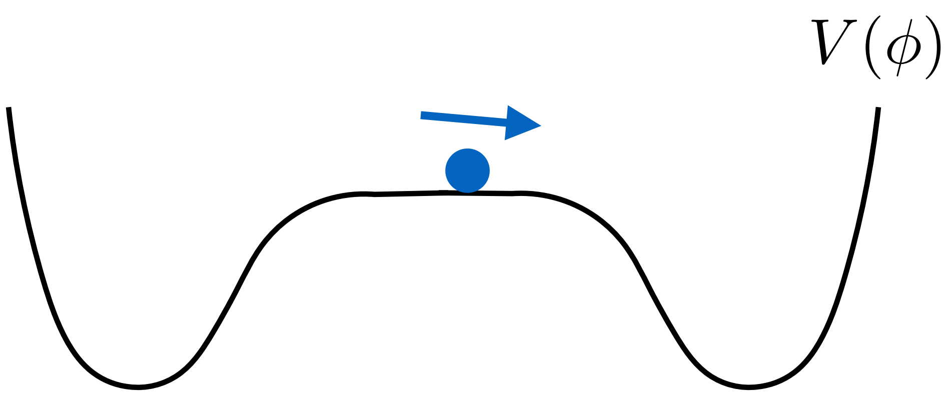


Set up

- Take the hill-top inflation model as an example. [Boubekeur, Lyth 05]

$$V(\phi) = \Lambda^4 \left[1 - \left(\frac{\phi}{v_\phi} \right)^6 \right]^2 .$$



$$H_{\rm inf} \simeq 10^7\,{\rm GeV}, \quad m_\phi \simeq 2 \times 10^{11}\,{\rm GeV} \quad {\rm for} \quad v_\phi / M_{\rm pl} = 10^{-3}.$$

- Coupling between inflaton and Higgs at around the minimum:

$$\mathcal{L}_{\rm int} = \frac{\lambda_h}{4} h^4 + \frac{\sigma_{h\phi}}{2} \varphi h^2 + \frac{\lambda_{h\phi}}{2} \varphi^2 h^2,$$

where $\varphi \equiv v_\phi - \phi$ is the inflaton at around the minimum.

* $m_h^2 \simeq 0$ at the minimum $\varphi = 0$ to realize the EW scale.

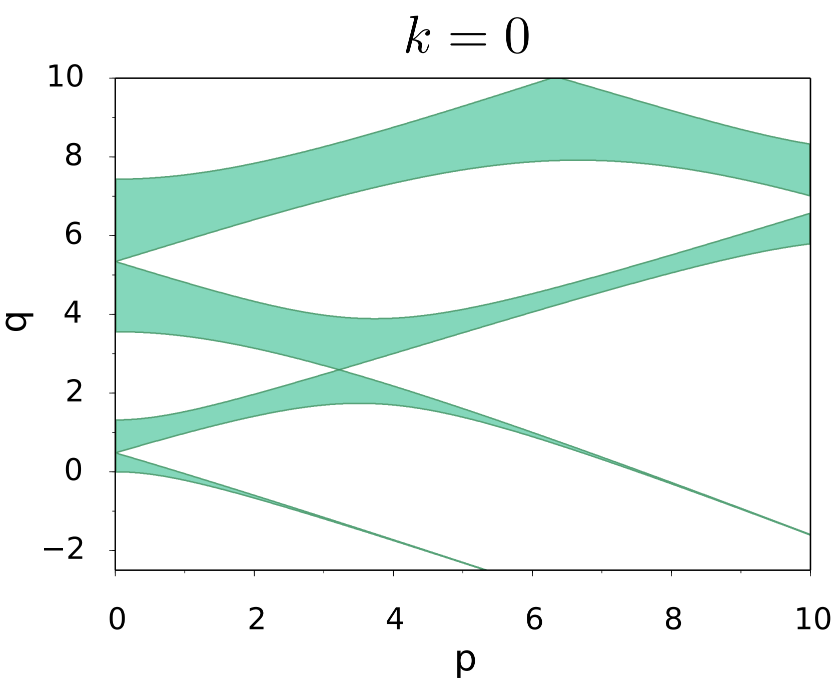
Particle production

- Higgs production: qualitatively described by Whittaker-Hill equation.

$$\frac{d^2 h_k}{dz^2} + \left[A_k + 2p\cos 2z + 2q\cos 4z\right] h_k = 0,$$

$$A_k = \frac{4k^2}{m_\phi^2} + 2q,\ \ p = \frac{2\sigma_{h\phi}\varphi_{\rm ini}}{m_\phi^2},\ \ q = \frac{\lambda_{h\phi}\varphi_{\rm ini}^2}{m_\phi^2},\ \ z = \frac{m_\phi t}{2}.$$

Unshaded region = resonant particle production.



- Inflaton particle: also resonantly produced due to **anharmonic** potential.

It breaks the inflaton condensation = the end of the preheating.

Main idea: Higgs production causes tachyonic mass to Higgs

$$m_{\rm tac}^2 \simeq -3|\lambda_h|\langle h^2\rangle$$

from the negative quartic coupling → causes the EW vacuum decay.

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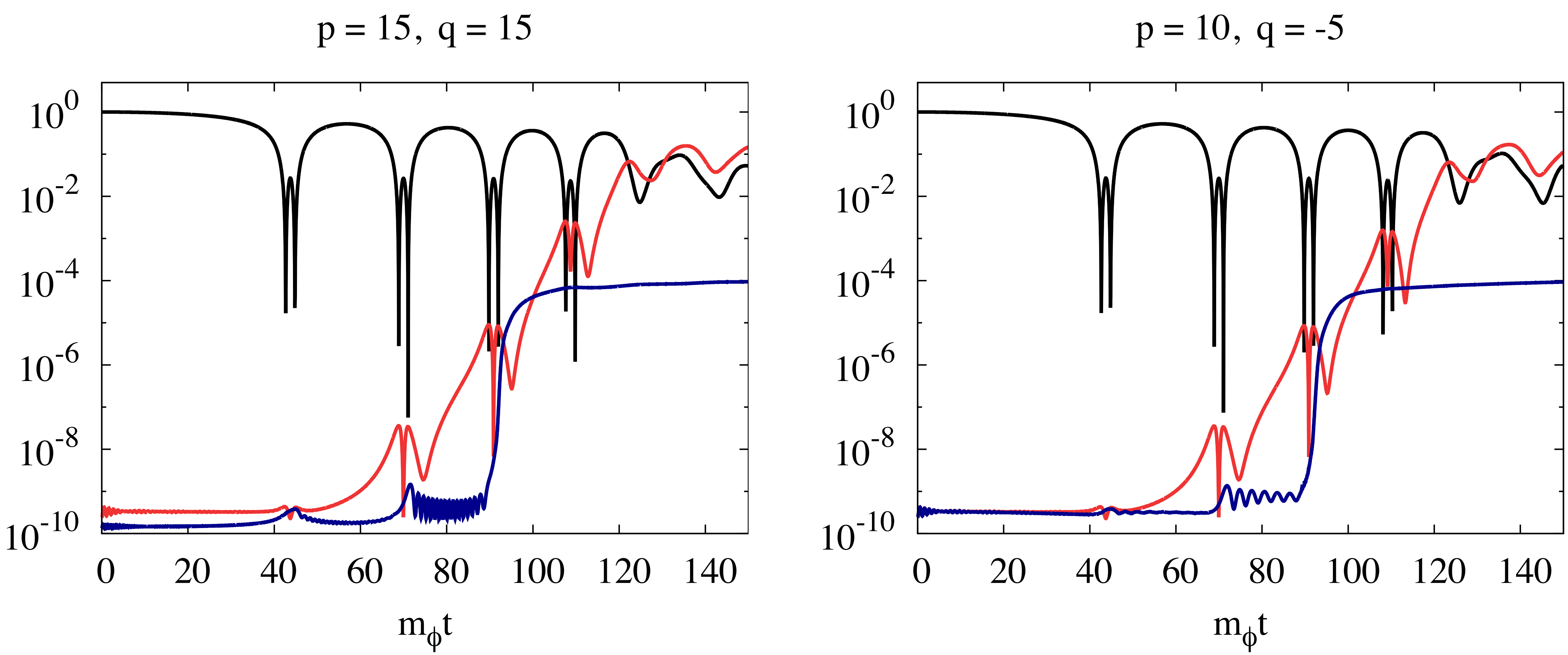
Lattice simulation

- We performed classical lattice simulation with

$$d = 2+1,\ N = 2048,\ L = 1500 m_\phi^{-1}\ , dt = 5\times 10^{-3} m_\phi^{-1}.$$

- EW vacuum indeed decays during the preheating epoch!!

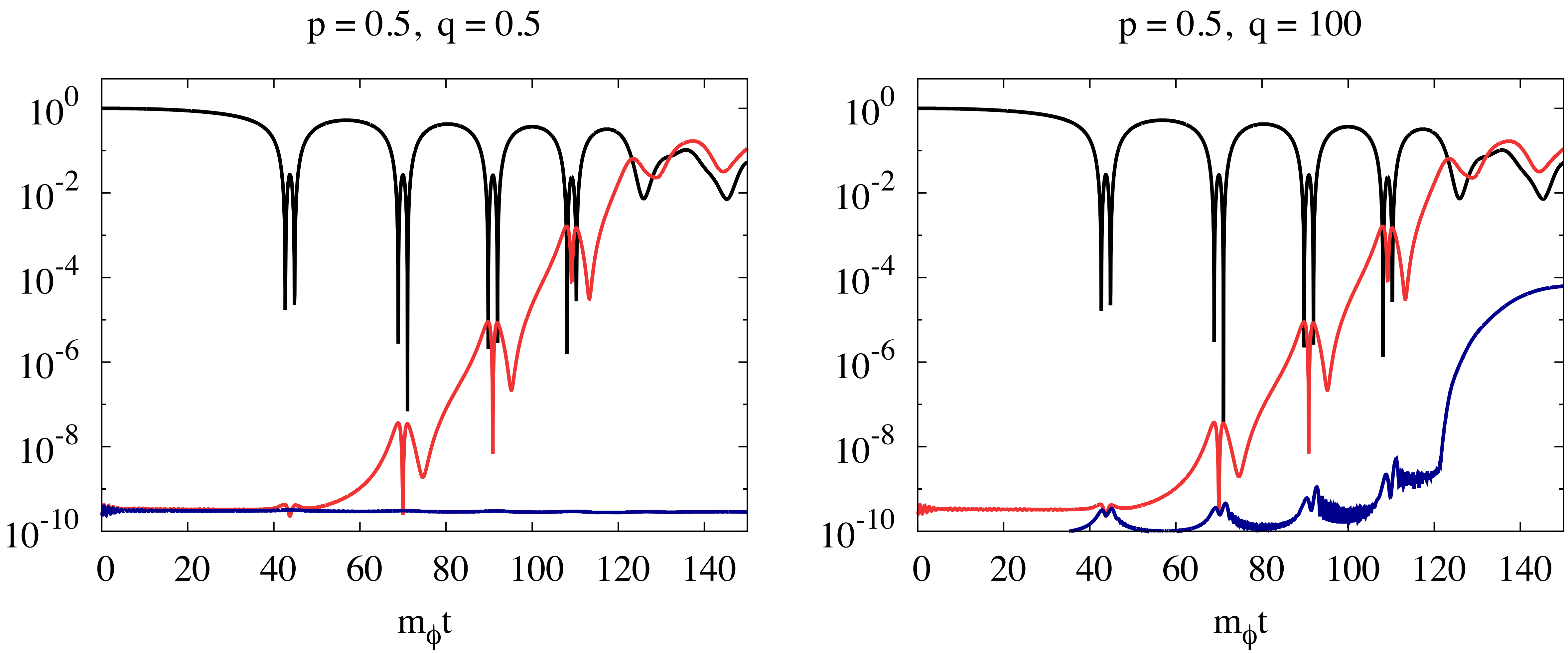


$$v_\phi / M_{\rm Pl} = 10^{-2},\quad \text{black} : \langle\varphi\rangle^2,\ \text{red} : \langle\varphi^2\rangle - \langle\varphi\rangle^2,\ \text{blue} : \langle h^2\rangle$$

Lattice simulation

- In order for the EW vacuum to survive the preheating epoch,

$$|p| \lesssim \mathcal{O}(1) \quad \text{and} \quad |q| \lesssim \mathcal{O}(10)$$ are required.



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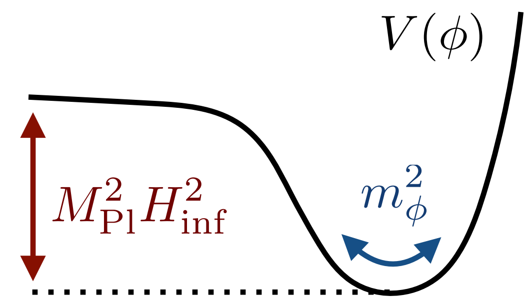
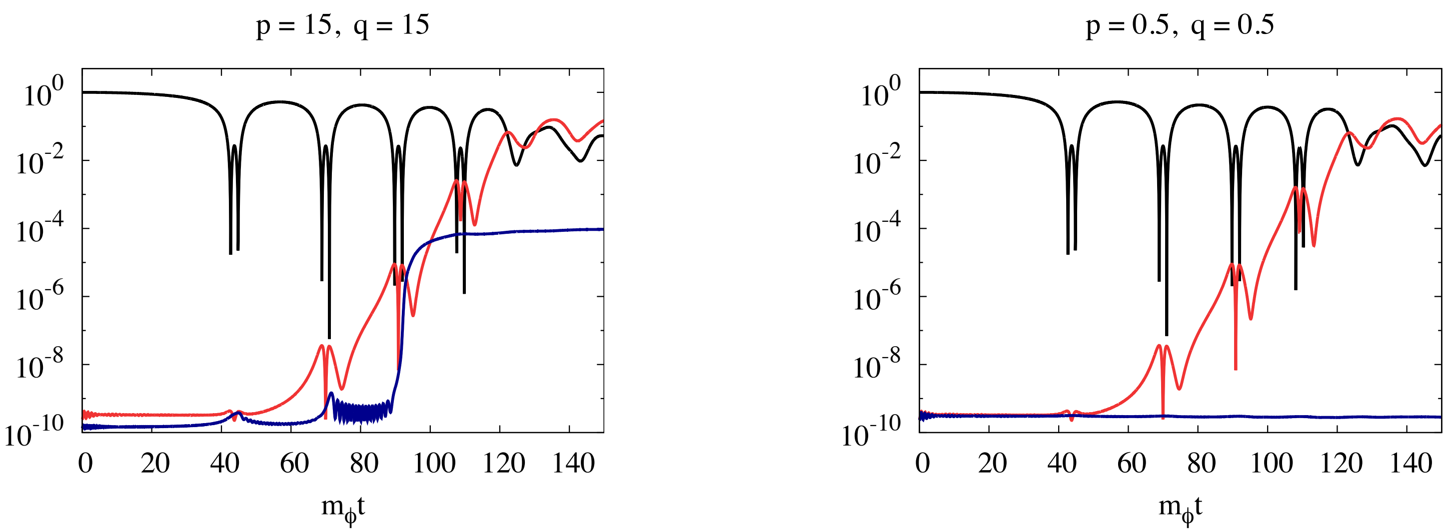
Summary

- EW vacuum metastability has interesting implications even for low-scale inflation with $h_{\rm inst} \gg H_{\rm inf}$.



- The couplings should satisfy $|p| \lesssim \mathcal{O}(1)$ and $|q| \lesssim \mathcal{O}(10)$ to avoid the EW vacuum decay during preheating.



- EW vacuum stability **after** preheating is also non-trivial.

Back up

Metastability

[Buttazzo+ 13]

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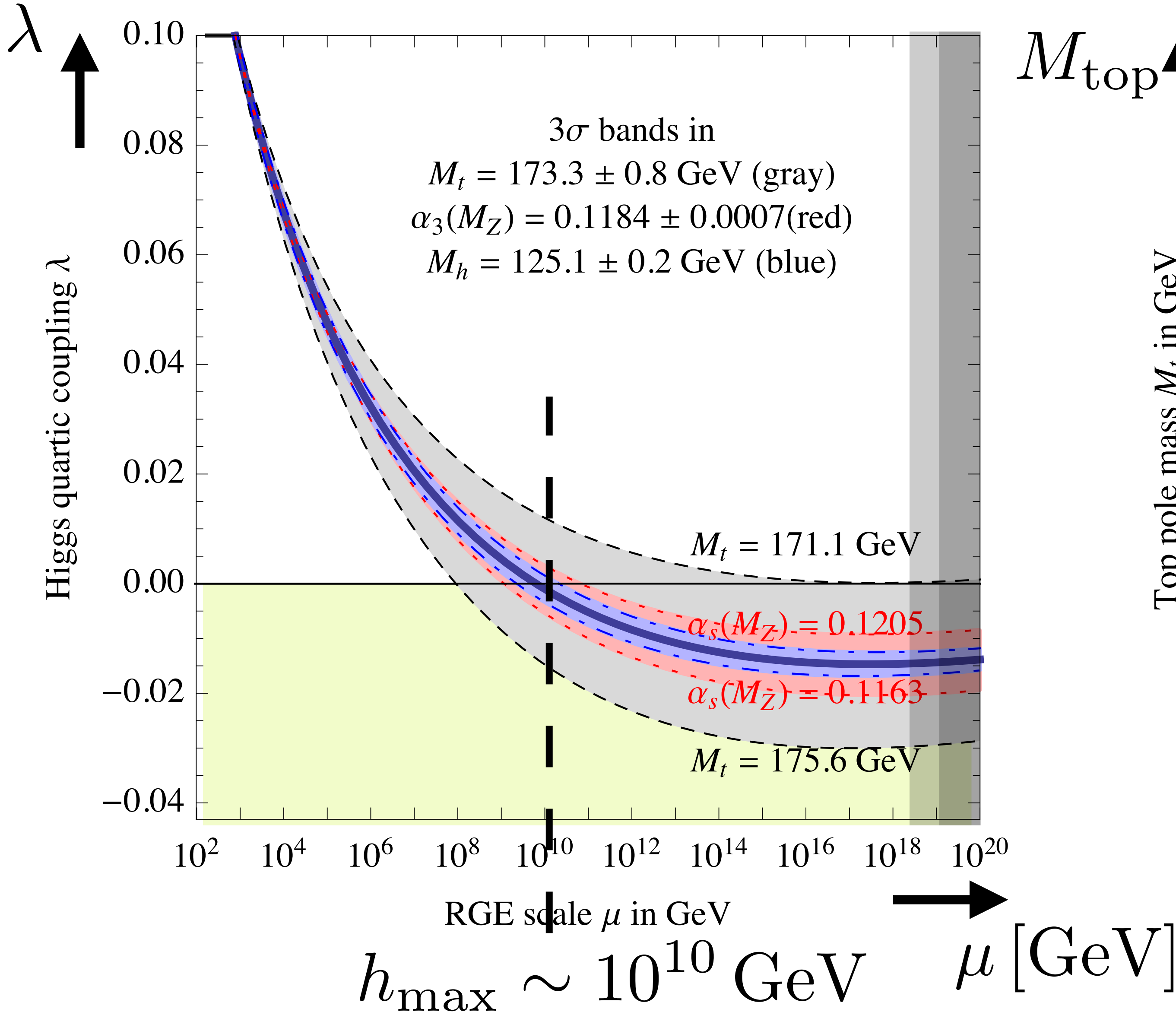

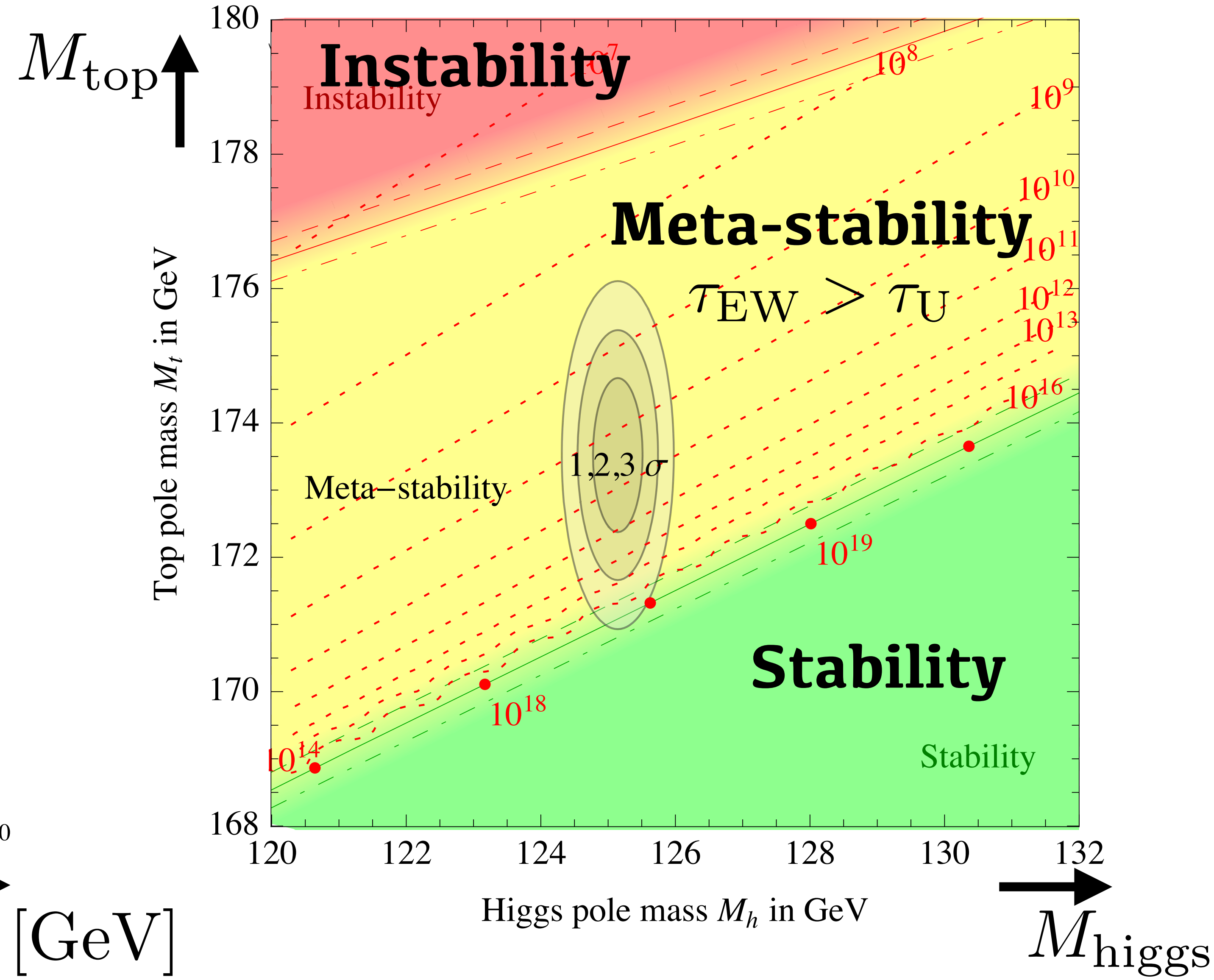

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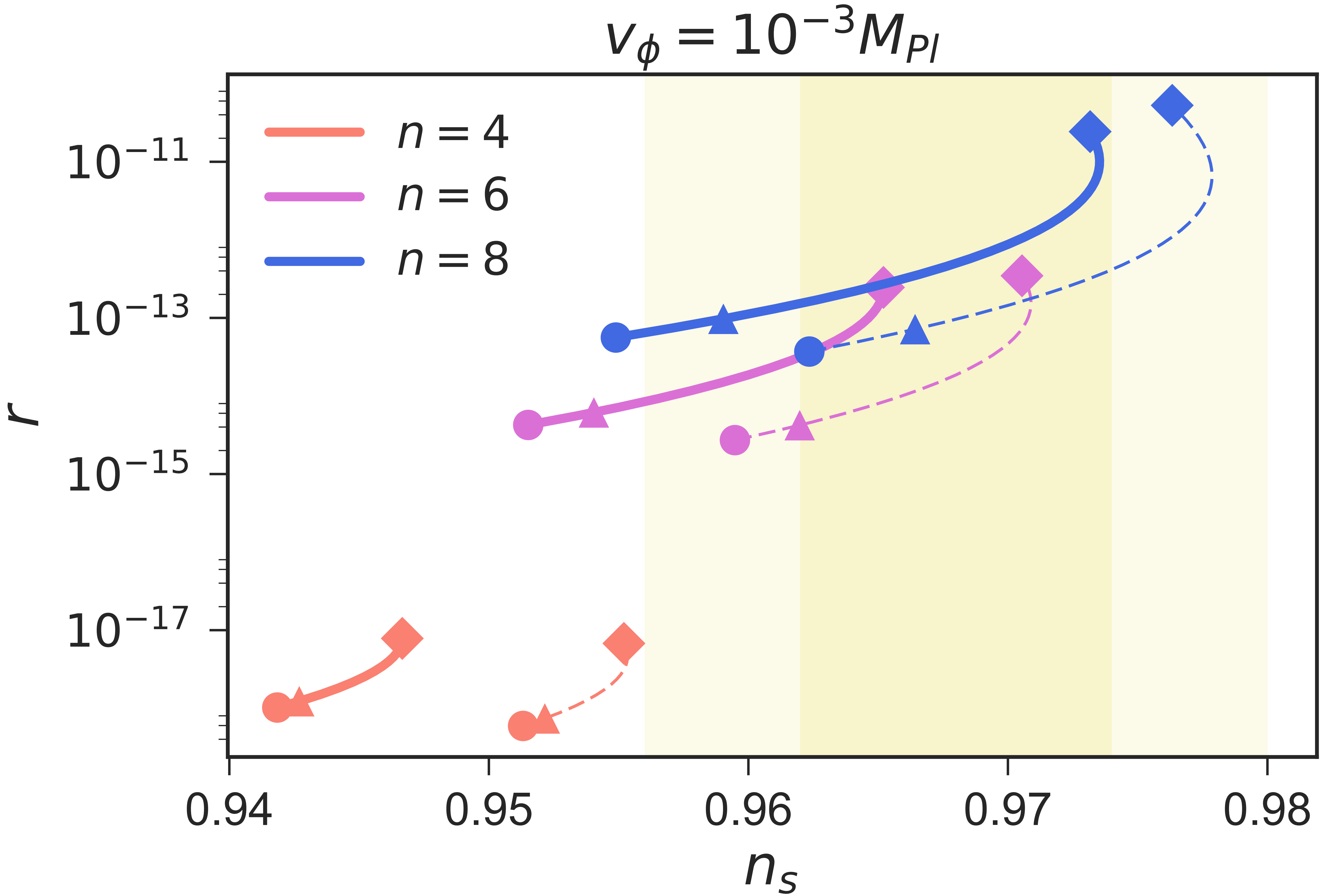
➡ **Cosmology must be compatible with it.**

Inflationary prediction



Classical lattice simulation

Classical lattice simulation: [Khlebnikov, Tkachev 96]

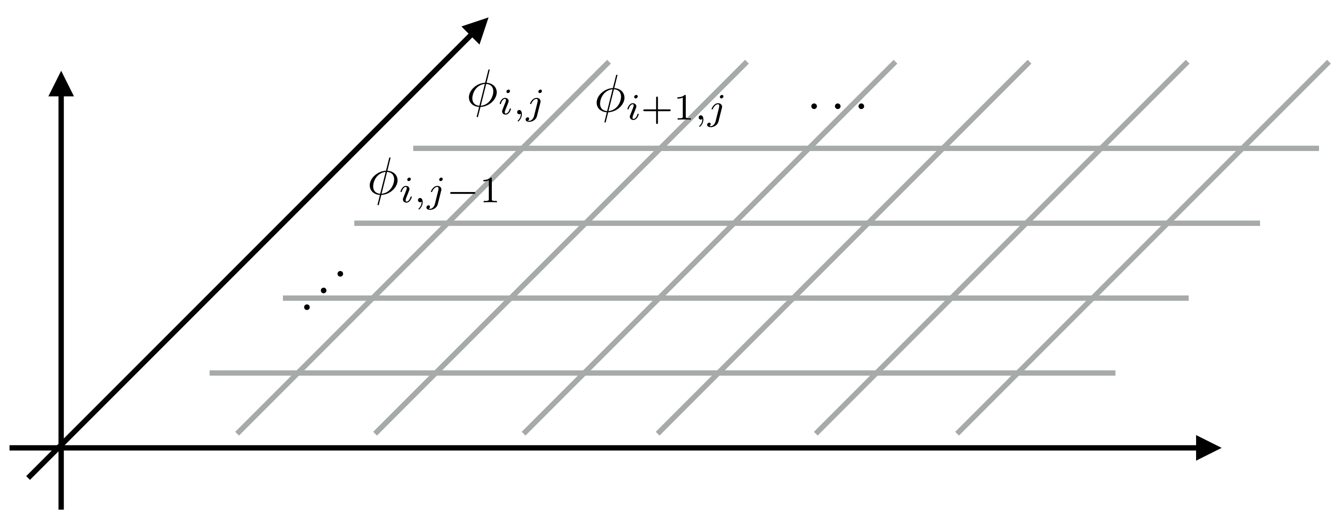
(1) Divide space coordinates into meshes.

(2) Introduce gaussian fluctuations (quantum fluctuation).

(3) Solve the discretized classical equations of motion.

* Classical approximation is valid in the large occupation number limit.

[Polarski, Starobinsky 96]



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