Destabilization of the electroweak vacuum from preheating

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Key points

- High scale inflation is incompatible with the metastability of the electroweak vacuum due to inflationary amplification of Higgs fluctuations.
- A possible resolution is to stabilize the Higgs potential during inflation via Higgs-inflaton coupling.
- Such couplings lead to explosive production of Higgs fluctuations after inflation via parametric and tachyonic resonance.
- This may again cause destabilization significantly restricting the available parameter space for such models.

Introduction

Based on the measurements of the masses of the Higgs boson and the top quark, the electroweak vacuum we occupy today appears to be metastable, i.e., there exists a deeper minimum of the effective Higgs potential than the one we occupy but the expected tunneling rate is small in relation to the age of the universe. Nevertheless, the question remains why the universe ended up in an energetically disfavoured vacuum to begin with.

Since during inflation light fields acquire expectation values of the order of the Hubble parameter, the Higgs field would have been driven into the true vacuum during inflation if the inflationary scale exceeds the instability scale of the Higgs potential. A possible remedy is to couple the Higgs to the inflaton in order to stabilize the potential during inflation. We consider the effect of these couplings on the dynamics of the Higgs and vacuum stability after the end of inflation.

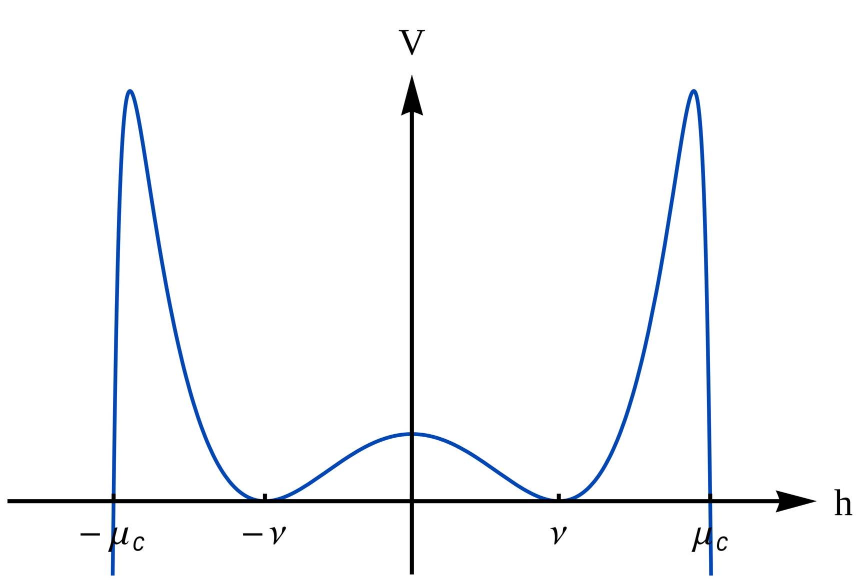

Figure 1: Sketch of effective Higgs potential.

Vacuum metastability

- The self-coupling of the Higgs field turns negative at the scale $\mu_c \sim 10^{10}$ GeV.

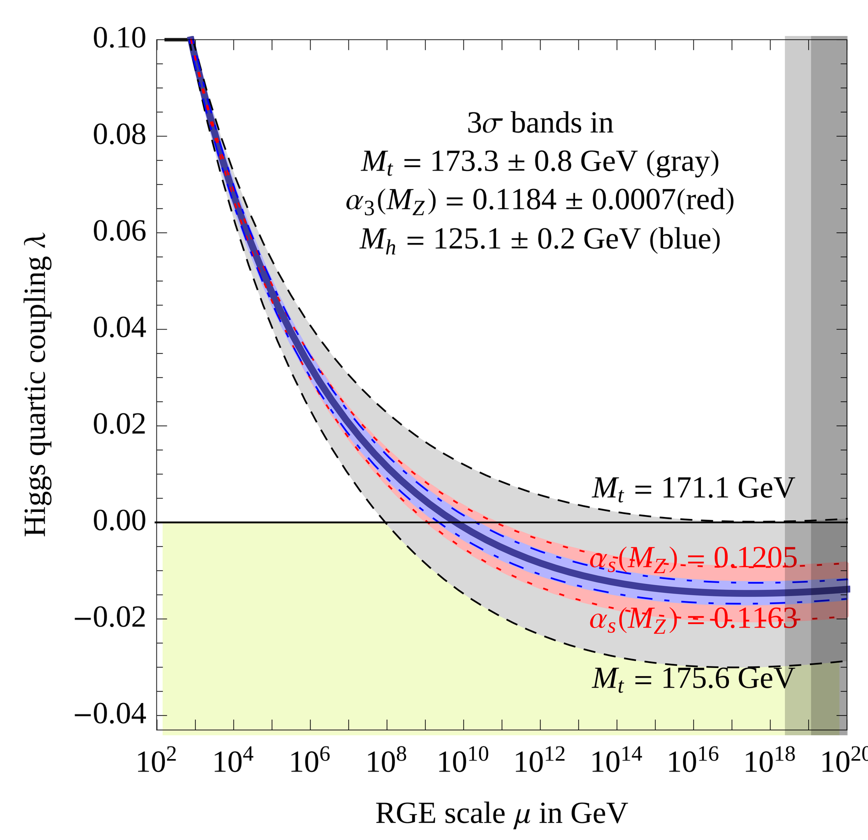

Figure 2: Running of the Higgs self-coupling [1]

- This implies the existence of a deeper vacuum state than ours at high energies. The behaviour of the effective potential

$$V_{\rm eff} = \frac{\lambda_h(h)}{4} h^4 \qquad (1)$$

is sketched in Figure 1.
- The lifetime of our vacuum far exceeds the age of the universe so no immediate worry.
- However, how did we get here?

Higgs during inflation

- During inflation, fluctuations in light fields ($m^2 \ll H_{\rm inf}^2$) are amplified.
- As a result, expect the field after inflation to have

$$\sqrt{\langle h^2 \rangle} \simeq 0.36 \lambda_h^{-1/4} H_{\rm inf}. \qquad (2)$$

- If $H_{\rm inf} > \mu_c$, the Higgs is driven into the true vacuum by inflationary dynamics.
- High scale inflation appears to be inconsistent with the universe occupying our electroweak vacuum.

Higgs-inflation coupling

- The potential can be stabilized by adding Higgs-inflaton couplings

$$-\Delta\mathcal{L} = \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{2}\sigma_{h\phi}\phi h^2. \qquad (3)$$

- New instability scale

$$\tilde{\mu}_c^2 \simeq 6 \times 10^{12} \frac{\lambda_{h\phi}}{|\lambda_h|} H_{\rm inf}^2. \qquad (4)$$

- However, must not spoil inflation.

Stability during inflation

Stability during inflation is ensured for

$$10^{-10} < \lambda_{h\phi} < 10^{-6}$$

$$\sigma_{h\phi} < \sqrt{2}\lambda_{h\phi} M_{\rm pl}$$

Higgs after inflation

- After inflation ends the infaton starts to oscillate.
- The oscillating effective Higgs mass induced by the inflaton results in resonant amplification of Higgs modes.
- The quartic coupling $\frac{1}{4}\lambda_{h\phi}\phi^2 h^2$ leads to parametric resonance (see [2])

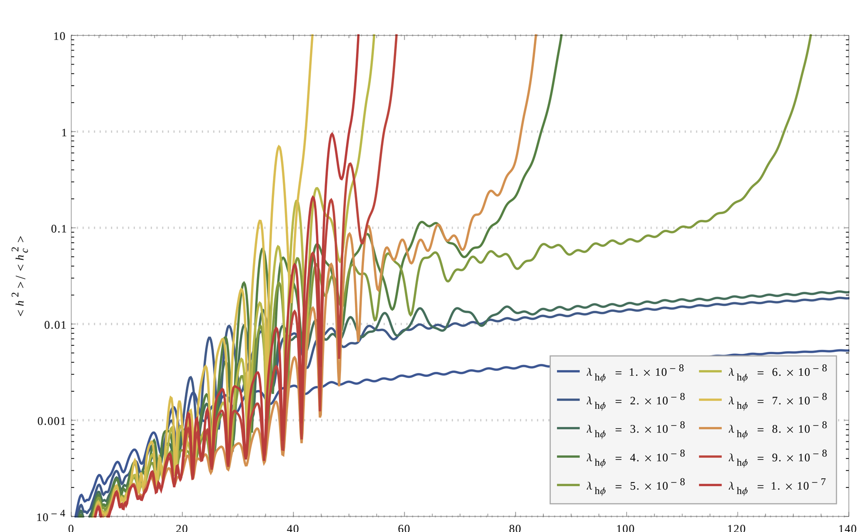

Figure 3: Amplification of Higgs quanta due to parametric resonance.

- The trilinear coupling $\frac{1}{2}\sigma_{h\phi}\phi h^2$ leads to tachyonic resonance (see [3])

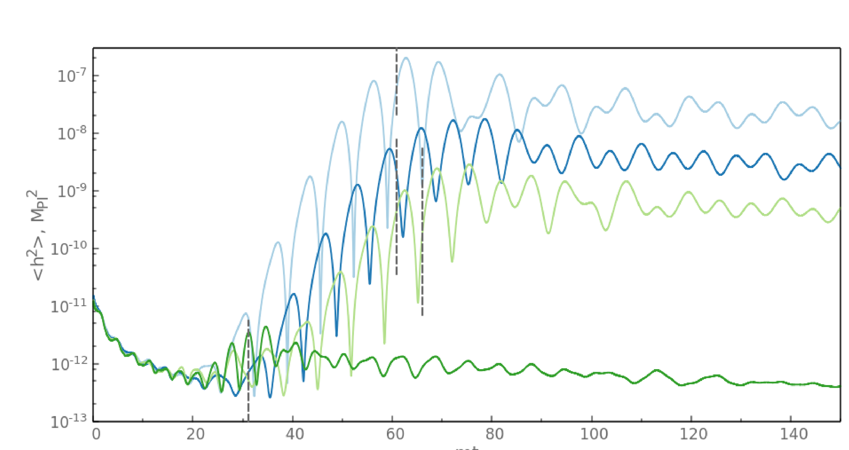

Figure 4: Amplification of Higgs quanta due to tachyonic resonance.

- The amplitude of the inflaton oscillations decays due to the expansion of the universe: $\Phi \propto a^{-3/2}$.
- The resonance stops when $\Phi \sim \lambda_{h\phi} m_{\rm inf}$ and $\sim m_{\rm inf}^2/\sigma_{h\phi}$ for parametric and tachyonic respectively.
- If $\langle h^2 \rangle \sim \tilde{\mu}_c^2$ before the resonance terminates the Higgs is driven into the true vacuum.

Stability after inflation

Stability after inflation is ensured for

$$\lambda_{h\phi} < 3 \times 10^{-8}$$

$$|\sigma_{h\phi}| < 10^9 \text{ GeV}$$

Conclusions

High scale inflation pushes the Higgs field into the true vacuum making it inconsistent with the fact that we now occupy a metastable false vacuum. These can be reconciled if the Higgs potential is stabilized during inflation by introducing a Higgs-inflaton coupling. However, once inflation ends, this coupling results in explosive amplification of Higgs quanta due to parametric (for quartic couplings) or tachyonic (for trilinear couplings) resonance. Thus the dynamics during preheating significantly restricts the available parameter space for such models.

Additional Information

- After the resonance $\tilde{\mu}_c^2$ decreases faster than $\langle h^2 \rangle$ so destabilization may still happen at very late times. However, in such cases need to know details of reheating.
- Instead of coupling the Higgs to the inflaton one can introduce a non-minimal coupling to gravity

$$-\Delta\mathcal{L} = \frac{1}{2}\xi R h^2. \qquad (5)$$

In this case the phenomenology is very similar: during preheating the Ricci curvature contributes an oscillating effective mass leading to tachyonic resonance putting new constraints on the allowed range of non-minimal coupling ξ (see [4])

References

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