Renormalized Vacuum Field Fluctuations and Inflationary Electroweak Vacuum Instability

Hiroki Matsui & Kaznori Kohri (Collaborator)

KEK Theory Center, IPNS, KEK, Tsukuba, Ibaraki 305-0801, Japan,
The Graduate University of Advanced Studies (Sokendai), Tsukuba, Ibaraki 305-0801, Japan


Abstract: In the inflationary Universe, the vacuum field fluctuations \((\delta \phi)\) enlarge in proportion to the Hubble scale \(H\). Therefore, the large inflationary vacuum fluctuations of the Higgs field \((\delta \phi)\) are potentially catastrophic to trigger the electroweak vacuum transition of the Universe. Thus, we revisit the electroweak vacuum instability from the perspective of the dynamical behavior of the global Higgs field \(\phi\) determined by the effective potential \(V_{\text{eff}}(\phi)\) on the de-Sitter spacetime and the renormalized vacuum fluctuations \((\delta \phi)\) via dimensional regularization and point-splitting regularization. In the simplest scenario, the electroweak vacuum stability is inevitably threatened by the dynamical behavior of the global Higgs field \(\phi\), or the formations of Anti-de Sitter (AdS) domains or bubbles.

1. Electroweak Vacuum Stability

The recent LHC experiments of the Higgs boson mass \(m_H = 125.09 \pm 0.21\text{ (stat) } \pm 0.18\text{ (syst)} \text{ GeV}\) and the top quark mass \(m_t = 172.44 \pm 0.13\text{ (stat) } \pm 0.47\text{ (syst)} \text{ GeV}\) suggest that the electroweak vacuum is unstable and finally cause a catastrophic vacuum decay through quantum tunneling.

Is the electroweak vacuum dead or alive?


Fortunately, the vacuum decay timescale is longer than the age of our Universe. However, the recent investigations reveal that the electroweak vacuum metastability is incompatible with the large-scale inflation.

The inflationary vacuum fluctuations \((\delta \phi)\)

\[
(\delta \phi)^2 \sim \frac{H^2 \Lambda}{3} \approx 10^{17} \text{ GeV}
\]

However, the above estimation as the Fokker-Planck equation or the Hawking-Moss instanton are rough. In this talk, we present the electroweak vacuum instability on the inflationary Universe from the rigid perspective of the quantum field theory (QFT) in curved spacetime.

2. Renormalized Vacuum Field Fluctuations and Effective Potential on de-Sitter Spacetime

The inflationary vacuum fluctuations of the Higgs field \((\delta \phi)\) destabilize the effective Higgs potential \(V_{\text{eff}}(\phi)\) as the backreactions or generate the Anti-de-Sitter (AdS) domains or bubbles. These unwanted phenomena trigger off a catastrophic vacuum transition to the Planck energy true vacuum and cause an immediate collapse of the Universe.

The inflationary vacuum fluctuations during Inflation

The relative large non-minimal Higgs-gravity coupling \(\xi_{\phi} \gtrsim 0.1\) can stabilize the effective Higgs potential \(V_{\text{eff}}(\phi)\) as the backreactions or generate the Anti-de-Sitter (AdS) domains or bubbles. These unwanted phenomena trigger off a catastrophic vacuum transition to the Planck energy true vacuum and cause an immediate collapse of the Universe.

3. Electroweak Vacuum Instability during Inflation

The one-loop standard model Higgs potential \(V_{\text{SM}}(\phi)\) destabilizes the effective Higgs potential \(V_{\text{eff}}(\phi)\) as the backreactions or generate the Anti-de-Sitter (AdS) domains or bubbles. These unwanted phenomena trigger off a catastrophic vacuum transition to the Planck energy true vacuum and cause an immediate collapse of the Universe.

4. Conclusion and Discussion

The relative large non-minimal Higgs-gravity coupling \(\xi_{\phi} \gtrsim 0.1\) can stabilize the effective Higgs potential and suppress formations of AdS domains or bubbles during inflation. However, after inflation, \(\xi_{\phi} R\) drops rapidly and sometimes becomes negative. Therefore, the effect of the stabilization via \(\xi_{\phi} R\) disappears and the Higgs effective potential becomes rather unstable. Furthermore, \(\xi_{\phi} R\) can generate the large Higgs field vacuum fluctuations via tachyonic resonance during subsequent preheating stage.

The two catastrophic scenarios during inflation

After all, if \(H > \Lambda\), the safety of our electroweak vacuum is inevitably threatened during inflation or after inflation. We can avoid this situation by assuming the inflationary stabilization via \(\Lambda_{\phi}\) or the high-order corrections from GUT or Planck-scale new physics etc. In any case, however, the electroweak vacuum instability from inflation gives tight constraints on the beyond the standard model.