Metastable Electroweak Vacuum and Chaotic Inflation

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Based on 1602.00483; and 1605.04974
In collaboration with Ema, Nakayama; and Kawasaki, Yanagida
Introduction
Metastable EW Vacuum

**Near-criticality** of the Standard Model?

- $\lambda < 0$ at $\sim 10^{10} \text{GeV}$ for the center value of $M_t$.

**v.s. Cosmology; Stability against cosmological evolution**

- High scale inflation v.s. Metastable electroweak vacuum

- v.s. New Physics; modify the effective potential. [Many works...]

10^{10} \text{GeV}

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Large Hubble parameter during inflation: $H_{\text{inf}} \sim 10^{13-14}$ GeV.

- Smoking gun signature: large tensor to scalar ratio: $r \sim 0.1 \left( \frac{H_{\text{inf}}}{10^{14} \text{ GeV}} \right)^2$
- Simple, solve initial condition problem; but require a Planckian field excursion.

- $r > 0.1$ : disfavored; $r \sim \mathcal{O}(0.01)$ : now being constrained.
- $r \sim 10^{-3}$ : may be probed in the future (e.g. LiteBIRD, PIXIE).
Metastability v.s. Cosmology

 Thermal History of Universe

- Vacuum decay during inflation
- Vacuum decay during preheating?
- Vacuum decay (in finite temp.)
  - Long enough life time even at $T \sim 10^{18}\text{GeV}$ for the center value of the top quark mass.

Our Work!

![Diagram showing the thermal history of the universe with stages of inflation, preheating, and reheating.](Image)

- Preheating
  - $V(h)$
  - Inflaton oscillation dominated
- Reheating
  - $V(h)$
  - Radiation dominated

- Non-thermal equil.
- Thermal equil.

Hawking, Moss, PLB110(1982); Starobinsky, Yokoyama, PRD50(1994)

Espinosa, Giudice, Riotto, JCAP05(2008)002; Rose, Marzo, Urbano, 1507.06912
During Inflation
**Higgs-Inflaton Coupling**

**Light** fields, $m \ll H_{\text{inf}}$, acquire fluctuations during inflation.

- Stochastic fluctuation v.s. Potential force
  - To avoid the vacuum decay

  $$H_{\text{inf}} \lesssim 10^9 \text{ GeV} \left( \frac{h_{\text{max}}}{10^{10} \text{ GeV}} \right)$$

  - Observed patches $\sim \exp(3N)$ should not exhibit the vacuum decay.
  - One order of magnitude severer bound is obtained. [e.g. Espinosa+, JHEP09(2015)174]

**Heavy** fields fluctuations, $m \gg H_{\text{inf}}$, are suppressed.

- Quartic coupling
  $$-\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} c^2 \phi^2 h^2$$

- Curvature coupling
  $$-\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} \xi R h^2$$

  **Higgs-inflaton coupling** can save the EW vacuum!

  - during inflation
    $$m_{H; h}^2 = c^2 \phi_{\text{inf}}^2$$

  - Stabilized if
    $$\gtrsim H_{\text{inf}}^2$$

  $$m_{H; h}^2 = 12 \xi H_{\text{inf}}^2$$

[Hawking, Moss, PLB110(1982); Starobinsky, Yokoyama, PRD50(1994)]

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Outlook during Inflation

- High scale inflation v.s. Metastable EW vacuum

© Lower bound on the couplings from $m_{H;h} > 3H_{\text{inf}}/2$

- Quartic coupling
  $$c \gtrsim \frac{3H_{\text{inf}}}{2\phi_{\text{inf}}} \sim 3 \times 10^{-6} \left( \frac{m_\phi}{10^{13} \text{ GeV}} \right)$$

- Curvature coupling
  $$\xi \gtrsim \frac{3}{16} \sim 0.2$$

- Small Higgs-inflaton coupling can save the EW vacuum

  - Quartic coupling
    $$-\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} c^2 \phi^2 h^2$$

  - Curvature coupling
    $$-\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} \xi R h^2$$

  ![Diagram showing the instability and stability during inflation](image-url)

  - Unstable during inflation
  - Stable during inflation

  - $c \phi_{\text{inf}} \sim H_{\text{inf}}$
  - $\xi \sim 0.2$

[(e.g.) Espinosa, Giudice, Riotto, JCAP05(2008)002]

[(e.g.) Lebedev, Westphal, PLB719(2013)]
During Preheating

Based on 1602.00483.
In collaboration with Y.Ema and K.Nakayama.

Related works:
[Herranen et al., PRL115(2015)241301; Kohri, Mastui]
Non perturbative Higgs production

• Inflaton oscillation → Higgs mass oscillation → Higgs production

- Quartic coupling: $c^2 \Phi^2 h^2/2$
  \[ m_{H,h}(t) \approx \frac{c^2 \Phi^2(t)}{2} \left[ \cos(2m_\phi t) + 1 \right] \]
  
  "Ordinary" resonance: $q(t) \sim c^2 \Phi^2(t)/m_\phi^2$
  
  [Kofman, Linde, Starobinsky]

- Curvature coupling: $\xi R h^2/2$
  \[ m_{H,h}(t) \approx \frac{\xi m_\phi^2 \Phi^2(t)}{2M_{pl}^2} \left[ 3 \cos(2m_\phi t) + 1 \right] \]
  
  "Tachyonic" resonance: $q(t) \sim \xi \Phi^2(t)/M_{pl}^2$
  
  [Bassett, Liberati]

Non-adiabatic change of the effective mass → Large Higgs fluctuations

\[ \left| \frac{\dot{\omega}_{k,h}}{\omega_{k,h}^2} \right| > 1 \quad \text{Condition for explosive Higgs Production} \]

\[ q(t) > 1 \]
Resonance is Inevitable

- **Higgs production via Parametric Resonance:** $-\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2}c^2\phi^2h^2$

  - Parametric resonance is almost *inevitable*!
    - Required coupling
      $$c\Phi_{\text{ini}} \gtrsim H_{\text{inf}}$$
    - Condition for resonance
      $$q(t_{\text{ini}}) > 1 \rightarrow c\Phi_{\text{ini}} \gtrsim m_\phi$$

- **Higgs production via Tachyonic Resonance:** $-\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2}\xi Rh^2$

  - Tachyonic resonance is almost *inevitable*!
    - Required coupling
      $$\xi \gtrsim 0.2$$
    - Condition for resonance
      $$q(t_{\text{ini}}) > 1 \rightarrow \xi \gtrsim \frac{M_{\text{pl}}^2}{\Phi_{\text{ini}}^2}$$
Vacuum decay via Resonance

- Vacuum decay during resonance: $1 < q(t) \propto \Phi^2(t)$

  - Tachyonic effective mass < Inflaton induced mass.

  \[ |\delta m^2_{\text{self}; h}| \equiv 3|\lambda| \langle h^2 \rangle \propto |\lambda| p_*^2 \left\{ e^{2\mu_{\text{qtc}} m_\phi t} \mu \sqrt{\xi \frac{\Phi^2(t)}{M_{\text{pl}}}} \right\} \]

  - Upper bounds on Higgs-inflaton coupling.

\[ m^2_{H; h} = \begin{cases} \frac{c^2 \Phi^2(t)}{2} \left[ \cos(2m_\phi t) + 1 \right] \\ \frac{\xi m_\phi^2 \Phi^2(t)}{2 M_{\text{pl}}^2} \left[ 3 \cos(2m_\phi t) + 1 \right] \end{cases} \]

Unstable during inflation

Unstable during preheating

\[ - \mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} c^2 \phi^2 h^2 \]

\[ - \mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} \xi \dot{h}^2 \]

Unstable during inflation

Stable?

Unstable during preheating

\[ c \Phi_{\text{ini}} \]

\[ \xi \]

\[ c \lesssim 10^{-4} \times \left[ \frac{0.1}{\mu_{\text{qtc}}} \right] \left[ \frac{m_\phi}{10^{13} \text{GeV}} \right] \]; \quad \xi \lesssim 10 \times \left[ \frac{1}{\mu_{\text{crv}}} \right]^2 \left[ \frac{\sqrt{2} M_{\text{pl}}}{\Phi_{\text{ini}}} \right]^2 \]
Vacuum decay via Parametric Resonance:  
\[ \mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2}c^2\phi^2h^2 \]

- Stable: \( c = 1 \times 10^{-4} \)
- Unstable: \( c = 2 \times 10^{-4} \)

To check \( c \lesssim 10^{-4} \times \left[ \frac{0.1}{\mu_{\text{qtc}}} \right] \left[ \frac{m_\phi}{10^{13} \text{GeV}} \right] \), we performed a classical lattice simulation.
Numerical Simulation

- Vacuum decay via Tachyonic Resonance:
  \[ -\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} \xi R h^2 \]

- To check \( \xi \lesssim 10 \times \left[ \frac{1}{\mu_{\text{crv}}} \right]^2 \left[ \frac{\sqrt{2} M_{\text{pl}}}{\Phi_{\text{ini}}} \right]^2 \), we performed a classical lattice simulation.

- Stable: \( \xi = 10 \)
  - Numerical Simulation

- Unstable: \( \xi = 20 \)
  - Resonance is over:
    \[ p^* < m_\phi \]

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Summary
Summary

- Higgs-inflaton coupling may **destabilize it at the preheating**.

- We have obtained **upper bounds** on Higgs-inflaton couplings.
  - Bounds could be severer if you look at all the observable patches $\sim e^{3N}$.
  - Towards precise bounds $\rightarrow$ Full inclusion of EW gauges on the lattice.

- Depend on reheating/thermalization in $\square$.

\[ L_{\text{int}}(\phi, h) = \frac{1}{2} \xi R h^2 \]
\[ L_{\text{int}}(\phi, h) = \frac{1}{2} c^2 \phi^2 h^2 \]

It is not easy to reheat the universe “adiabatically”.

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What we have discussed

- **Curvature coupling + Chaotic inflation**
  - **Curvature coupling**: stabilize the EW vacuum during inflation
  - **Chaotic inflation**: solve initial condition + provide the density fluctuations observed by Planck

- **Resonance is almost inevitable.**
  \[ q \sim \frac{\xi \phi_{\text{ini}}^2}{M_{\text{pl}}^2} \gtrsim 1 \]

\( V(\phi) \)

\( \sim M_{\text{pl}} \)
Simple Scenario

Description

- **Simple scenario consistent with the metastability**

  - **Curvature coupling + Chaotic inflation + New inflation**
    - **Curvature coupling**: stabilize the EW vacuum during inflation
    - **Chaotic inflation**: solve initial condition + provide the density fluctuations observed by Planck
    - **New inflation**: avoid the resonance + provide the dominant component of DM as PBHs

- **Resonance does not take place.**
  
  \[ q \sim \frac{\xi \langle \varphi \rangle^2}{M_{pl}^2} \ll 1 \]

- **Higgs is stabilized at its origin during the new inflation.**
  
  \[ N \sim \left( \frac{v^2}{8g\epsilon^2M_{pl}^2} \right)^{1/3} \sim O(10) \text{ for } \epsilon \sim \frac{v^2}{M_{pl}^2} \]
Simple Scenario

- Simple scenario consistent with the metastability

  - Curvature coupling + Chaotic inflation + New inflation
    - Curvature coupling: stabilize the EW vacuum during inflation
    - Chaotic inflation: solve initial condition + provide the density fluctuations observed by Planck
    - New inflation: avoid the resonance + provide the dominant component of DM as PBHs

\[ \mathcal{P}_\zeta(k) \sim \left( \frac{1}{2\sqrt{3}\pi} \epsilon M_{\text{pl}}^2 \right)^2 \]

\[ k \sim 10^{11} \text{Mpc}^{-1} \left( \frac{M_{\text{PBH}}}{10^{24} \text{g}} \right)^{-1/2} \]

\[ \Omega_{\text{PBH,tot}} = \Omega_c \]
Higgs-inflaton coupling may **destabilize it at the preheating**.

We have obtained **upper bounds** on Higgs-inflaton couplings.

- Bounds could be severer if you look at all the observable patches ∼ $e^{3N}$.
- Towards precise bounds → Full inclusion of EW gauges.

**Depend on reheating/thermalization in □**.

- $\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} c^2 \phi^2 h^2$
- $\mathcal{L}_{\text{int}}(\phi, h) = \frac{1}{2} \xi R h^2$

 It is not easy to reheat the universe “adiabatically”.

- See however [1605.04974](https://arxiv.org/abs/1605.04974) (and also [1605.07342](https://arxiv.org/abs/1605.07342)).
Back up
Simple Scenario

Simple scenario consistent with the metastability

- **Curvature coupling + Chaotic inflation + New inflation**
  - **Curvature coupling**: stabilize the EW vacuum during inflation
  - **Chaotic inflation**: solve initial condition + provide the density fluctuations observed by Planck
  - **New inflation**: avoid the resonance + provide the dominant component of DM as PBHs

\[ V(\phi) = \left( v^2 - g \frac{\phi^4}{M_{pl}^2} \right)^2 - \kappa v^4 \frac{\phi^2}{2M_{pl}^2} - \epsilon v^4 \frac{\phi}{M_{pl}} \]

\[ v \sim 10^{16} \text{ GeV} \]

\[ N \sim \left( \frac{v^2}{8g \epsilon^2 M_{pl}^2} \right)^{1/3} \sim \mathcal{O}(10) \quad \text{for} \quad \epsilon \sim \frac{v^2}{M_{pl}^2} \]

- Resonance does not take place.

\[ q \sim \frac{\xi \langle \phi \rangle^2}{M_{pl}^2} \ll 1 \]

- Higgs is stabilized at its origin during the new inflation.
Simple Scenario

- Simple scenario consistent with the metastability
  - **Curvature coupling + Chaotic inflation + New inflation**
    - Curvature coupling: stabilize the EW vacuum during inflation
    - Chaotic inflation: solve initial condition + provide the density fluctuations observed by Planck
    - New inflation: avoid the resonance + provide the dominant component of DM as PBHs

\[ V(\varphi) = \left( v^2 - g \frac{\varphi^4}{M_{pl}^2} \right)^2 - \kappa v^4 \frac{\varphi^2}{2M_{pl}^2} - \varepsilon v^4 \frac{\varphi}{M_{pl}} \]

\[ v \sim 10^{16} \text{ GeV} \]

- Resonance does not take place.
  \[ q \sim \frac{\xi \langle \varphi \rangle^2}{M_{pl}^2} \ll 1 \]

- Higgs is stabilized at its origin during the new inflation.
  \[ N \sim \left( \frac{v^2}{8g \epsilon^2 M_{pl}^2} \right)^{1/3} \sim \theta(10) \text{ for } \epsilon \sim \frac{v^2}{M_{pl}^2} \]
Simple Scenario

- Simple scenario consistent with the metastability

  - Curvature coupling + Chaotic inflation + New inflation
    - Curvature coupling: stabilize the EW vacuum during inflation
    - Chaotic inflation: solve initial condition + provide the density fluctuations observed by Planck
    - New inflation: avoid the resonance + provide the dominant component of DM as PBHs

\[ P_\zeta(k) \sim \left( \frac{1}{2\sqrt{3}\pi} \epsilon M_{pl}^2 \right)^2 \]

\[ k \sim 10^{11} \text{Mpc}^{-1} \left( \frac{M_{PBH}}{10^{24} \text{g}} \right)^{-1/2} \]

\[ \Omega_{PBH,\text{tot}} = \Omega_c \]

\[ \frac{\Omega_{PBH}}{\Omega_c} \]

Kepler
Hawking
Femtolensing
MACHO/EROS
FIRAS
WMAP3
NS in GCs
Star Formation
\[ \Omega_{PBH}/\Omega_c \]
**Electroweak gauges**

- **EW gauge production from Higgs**
  - $g^2A^2h^2$ might stabilize the Higgs.
  - To mimic it, we have introduced another scalar $\chi$ via $g^2\chi^2h^2$.

- $\chi$-production is suppressed due to $g(<h^2>)^{1/2} \rightarrow$ Higgs dynamics is not altered.

- Same for the curvature coupling.
Electroweak gauges

- **EW gauge production from Higgs**
  
  - $g^2 A^2 h^2$ might stabilize the Higgs.
  
  - To mimic it, we have introduced another scalar $\chi$ via $g^2 \chi^2 h^2$.

\[ a^3 \langle \phi^2 \rangle - a^3 \langle h^2 \rangle \]

- $\chi$-production is suppressed due to $g(\langle h^2 \rangle)^{1/2} \rightarrow \text{Higgs dynamics is not altered.}$

- Same for the curvature coupling.
Inflaton decays into other SMs

■ **Caution**: relevant time scales are quite short, and thus instantaneous thermalization assumption is questionable…

- Quartic coupling
  \[ m_\phi t \lesssim \theta(10) \times \left( \frac{c}{10^{-4}} \right) \left( \frac{10^{13} \text{ GeV}}{m_\phi} \right) \]

- Curvature coupling
  \[ m_\phi t \lesssim 10 \times \left( \frac{\xi}{10} \right)^{\frac{1}{2}} \]

1. **Perturbative** inflaton decay: \( T_R < 10^{10} \text{ GeV} \).

- Thermal mass is always smaller: \[ p_\phi(t) > m_\phi \geq g T_{\text{max}} \approx 10^{13} \text{ GeV} \times g \left( \frac{T_R}{10^{10} \text{ GeV}} \right)^{\frac{1}{2}} \left( \frac{H_{\text{inf}}}{10^{14} \text{ GeV}} \right)^{\frac{1}{4}} \]
  
  * Here we naively assume instantaneous thermalization, but \( T_{\text{max}} \) may be much lower.

   [Harigaya, KM, JHEP05(2014)006; KM, Yamada, JCAP02(2016)003; (cf.) Ellis+, JCAP03(2016)008]

2. **Non-perturbative** inflaton decay: \( T_R > 10^{10} \text{ GeV} \).

- Parametric resonance of other SM particles (\( \chi \)) becomes relevant.
- Large \( \chi \) fluctuations with long wave length modes are produced.
- They might “kick” the Higgs towards True Vacuum(?)

\[ \Phi_{\text{ini}} \]

Normalized by the initial inflaton amplitude \( \Phi_{\text{ini}} \)

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