Massless Preheating and Electroweak Vacuum Metastability

Jeff Kost
[University of Sussex]

[arXiv:2105.06939]

collaborators on this work:
Chang Sub Shin [IBS-CTPU]
Takahiro Terada [IBS-CTPU]

2021 APS Divison of Particles and Fields Meeting

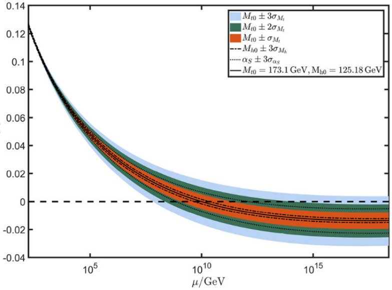
Monday, July 12th, 2021

Metastability of Electroweak Vacuum

- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs** ***negative*** at energy scales $\mu \gtrsim 10^{10}\,\mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

[arXiv:1809.06923]

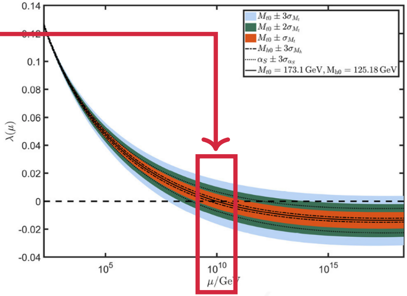


Metastability of Electroweak Vacuum

- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\ \mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

[arXiv:1809.06923]



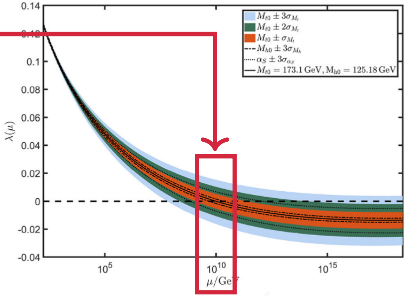
Metastability of Electroweak Vacuum

- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\,\mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

i.e., electroweak vacuum is **metastable**.

[arXiv:1809.06923]



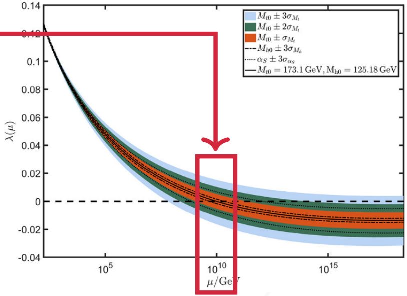
Metastability of Electroweak Vacuum

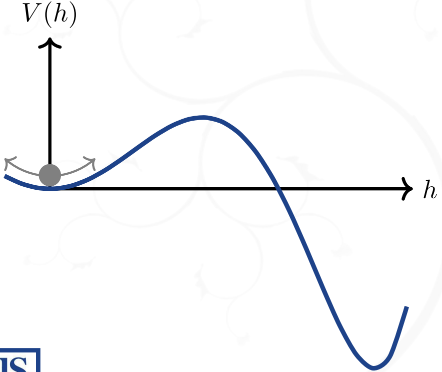
- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\,\mathrm{GeV}$

$$V(h) \;\supset\; \frac{1}{4}\lambda_h(\mu)h^4$$

i.e., electroweak vacuum is **metastable**.

[arXiv:1809.06923]





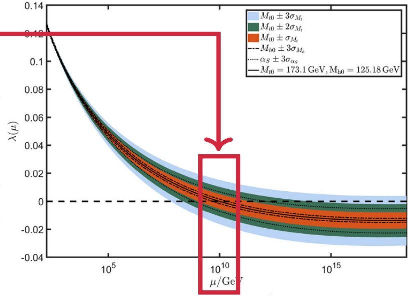
Metastability of Electroweak Vacuum

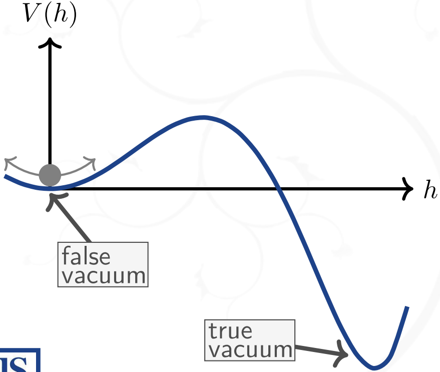
- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\ \mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

i.e., electroweak vacuum is **metastable**.

[arXiv:1809.06923]





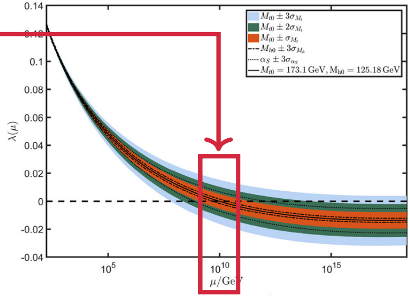
Metastability of Electroweak Vacuum

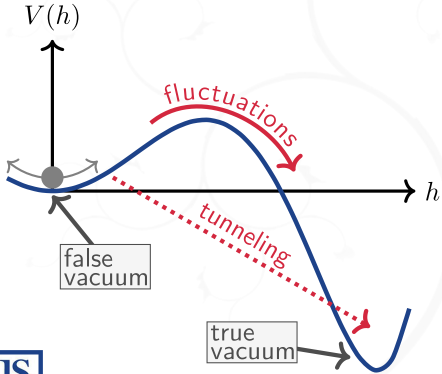
- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\ \mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

i.e., electroweak vacuum is **metastable**.

[arXiv:1809.06923]





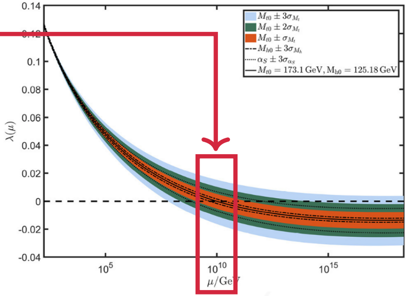
Metastability of Electroweak Vacuum

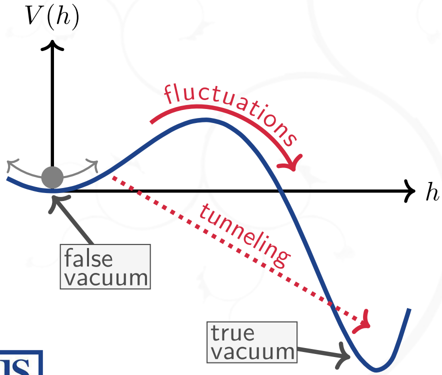
- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\ \mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

i.e., electroweak vacuum is **metastable**.

[arXiv:1809.06923]





- Timescale for vacuum decay today is much longer than age of the universe, **BUT** dynamics earlier in cosmological history would have *significantly* threatened **destabilization**.

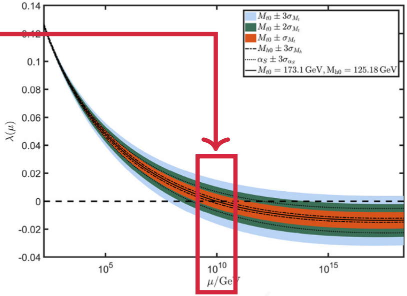
Metastability of Electroweak Vacuum

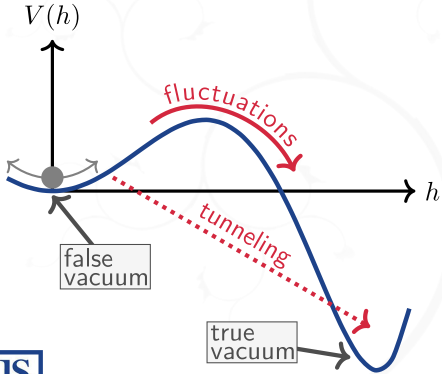
- Current measurements of SM parameters suggest the Higgs self-coupling $\lambda_h(\mu)$ **runs *negative*** at energy scales $\mu \gtrsim 10^{10}\,\mathrm{GeV}$

$$V(h) \supset \frac{1}{4}\lambda_h(\mu)h^4$$

i.e., electroweak vacuum is **metastable**.

[arXiv:1809.06923]





- Timescale for vacuum decay today is much longer than age of the universe, **BUT** dynamics earlier in cosmological history would have *significantly* threatened **destabilization**.

The fact that false vacuum has persisted may provide ***window*** into early-universe dynamics involving the Higgs field.

Threats to Metastability in the Early Universe

Threats to Metastability in the Early Universe

During inflation:

• Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

Threats to Metastability in the Early Universe

During inflation:

• Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

$\Rightarrow$ need interactions that ***stabilize*** Higgs during inflation

Threats to Metastability in the Early Universe

During inflation:

• Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

$\Rightarrow$ need interactions that ***stabilize*** Higgs during inflation

• Minimal such extensions involve scalar curvature R and/or inflaton ϕ:

$$\mathcal{L} \supset -\frac{1}{2}\xi_h h^2 R - \frac{1}{2} g^2 h^2 \phi^2$$

Threats to Metastability in the Early Universe

During inflation:

• Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

$\Rightarrow$ need interactions that ***stabilize*** Higgs during inflation

• Minimal such extensions involve scalar curvature R and/or inflaton ϕ:

$$\mathcal{L} \supset -\frac{1}{2}\xi_h h^2 R - \frac{1}{2} g^2 h^2 \phi^2$$

HOWEVER, after inflation:

• These interactions tend to ***destabilize*** the Higgs after inflation due to non-perturbative preheating dynamics, recreating our metastability problem

Threats to Metastability in the Early Universe

During inflation:

• Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

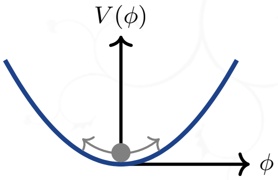
$\Rightarrow$ need interactions that ***stabilize*** Higgs during inflation

• Minimal such extensions involve scalar curvature R and/or inflaton ϕ:

$$\mathcal{L} \supset -\frac{1}{2}\xi_h h^2 R - \frac{1}{2} g^2 h^2 \phi^2$$

HOWEVER, after inflation:

• These interactions tend to ***destabilize*** the Higgs after inflation due to non-perturbative preheating dynamics, recreating our metastability problem



Specifically, ϕ gives Higgs fluctuations h_k time-dependent, oscillatory effective masses:

$$\omega_{h_k}^2 = \frac{k^2}{a^2} + g^2\phi^2 + \xi_h R$$

Threats to Metastability in the Early Universe

During inflation:

• Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

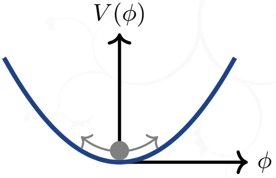
$\Rightarrow$ need interactions that ***stabilize*** Higgs during inflation

• Minimal such extensions involve scalar curvature R and/or inflaton ϕ:

$$\mathcal{L} \supset -\frac{1}{2}\xi_h h^2 R - \frac{1}{2} g^2 h^2 \phi^2$$

HOWEVER, after inflation:

• These interactions tend to ***destabilize*** the Higgs after inflation due to non-perturbative preheating dynamics, recreating our metastability problem



Specifically, ϕ gives Higgs fluctuations h_k time-dependent, oscillatory effective masses:

$$\omega_{h_k}^2 = \frac{k^2}{a^2} + \boxed{g^2\phi^2} + \boxed{\xi_h R}$$

parametric resonance

tachyonic instability

Threats to Metastability in the Early Universe

During inflation:

- Light scalar fields generically develop fluctuations proportional to Hubble scale H. For the Higgs, this could trigger decay of the vacuum.

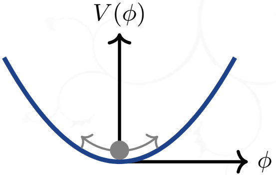
$\Rightarrow$ need interactions that ***stabilize*** Higgs during inflation

- Minimal such extensions involve scalar curvature R and/or inflaton ϕ:

$$\mathcal{L} \supset -\frac{1}{2}\xi_h h^2 R - \frac{1}{2} g^2 h^2 \phi^2$$

HOWEVER, after inflation:

- These interactions tend to ***destabilize*** the Higgs after inflation due to non-perturbative preheating dynamics, recreating our metastability problem



Specifically, ϕ gives Higgs fluctuations h_k time-dependent, oscillatory effective masses:

$$\omega_{h_k}^2 = \frac{k^2}{a^2} + \boxed{g^2\phi^2} + \boxed{\xi_h R}$$

parametric resonance

tachyonic instability

$\Rightarrow$ leads to **amplification** of fluctuations h_k

In most preheating scenarios, the growth of fluctuations *weakens* and eventually *terminates* as the universe expands.

In most preheating scenarios, the growth of fluctuations *weakens* and eventually *terminates* as the universe expands.

$\Rightarrow$ models usually viable for some range of couplings

In most preheating scenarios, the growth of fluctuations *weakens* and eventually *terminates* as the universe expands.

$\Rightarrow$ models usually viable for some range of couplings

important exception: models which exhibit **scale invariance**, since dynamical properties are *independent* of expansion.

i.e., models of "massless preheating"

In most preheating scenarios, the growth of fluctuations *weakens* and eventually *terminates* as the universe expands.

$\Rightarrow$ models usually viable for some range of couplings

important exception: models which exhibit **scale invariance**, since dynamical properties are *independent* of expansion.

i.e., models of "massless preheating"

Under minimal assumptions, this corresponds to (Jordan-frame) potential

$$V_{\mathrm{J}}(\phi, h) \;=\; \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{2} g^2 h^2 \phi^2 + \frac{1}{4}\lambda_h h^4$$

In most preheating scenarios, the growth of fluctuations *weakens* and eventually *terminates* as the universe expands.

$\Rightarrow$ models usually viable for some range of couplings

important exception: models which exhibit **scale invariance**, since dynamical properties are *independent* of expansion.

i.e., models of "massless preheating"

Under minimal assumptions, this corresponds to (Jordan-frame) potential

$$V_{\rm J}(\phi, h) = \boxed{\frac{1}{4}\lambda_\phi \phi^4} + \frac{1}{2} g^2 h^2 \phi^2 + \frac{1}{4}\lambda_h h^4$$

$\Rightarrow$ background inflaton evolution:

$$\frac{d^2\varphi}{d\eta^2} + \lambda_\phi \varphi^3 = 0$$

for conformal time η and $\varphi \equiv a\phi$

$$\varphi(x) = \overline{\varphi}\,\mathrm{cn}\left(x - x_0, \frac{1}{\sqrt{2}}\right),$$

with rescaled time $x \equiv \sqrt{\lambda_\phi}\overline{\varphi}\eta$.

In most preheating scenarios, the growth of fluctuations *weakens* and eventually *terminates* as the universe expands.

$\Rightarrow$ models usually viable for some range of couplings

important exception: models which exhibit **scale invariance**, since dynamical properties are *independent* of expansion.

i.e., models of "massless preheating"

Under minimal assumptions, this corresponds to (Jordan-frame) potential

$$V_{\rm J}(\phi, h) = \boxed{\frac{1}{4}\lambda_\phi \phi^4} + \frac{1}{2} g^2 h^2 \phi^2 + \frac{1}{4}\lambda_h h^4$$

$\Rightarrow$ background inflaton evolution:

$$\frac{d^2\varphi}{d\eta^2} + \lambda_\phi \varphi^3 = 0$$

for conformal time η and $\varphi \equiv a\phi$

$$\varphi(x) = \overline{\varphi}\,\mathrm{cn}\left(x - x_0, \frac{1}{\sqrt{2}}\right),$$

with rescaled time $x \equiv \sqrt{\lambda_\phi}\overline{\varphi}\eta$.

Similarly, Higgs fluctuations grow *steadily* and ***uninterrupted***—appears catastrophic for EW metastability.

on closer inspection,
is there a **regime of viability** for massless preheating?

Comments On Inflationary Regime

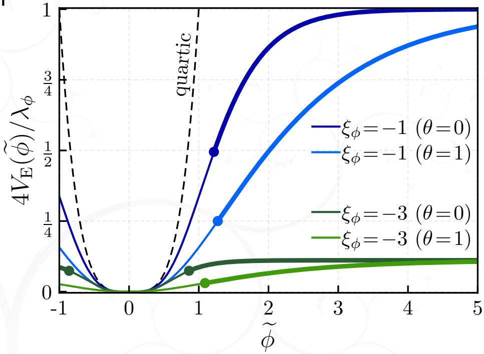
- Our preheating study is relatively independent of the inflationary model.

Comments On Inflationary Regime

- Our preheating study is relatively independent of the inflationary model.

- Nevertheless, a viable inflationary regime is realized by allowing a **non-minimal coupling** for the inflaton

$$\mathcal{L} \supset -\tfrac{1}{2}\xi_\phi \phi^2 R.$$



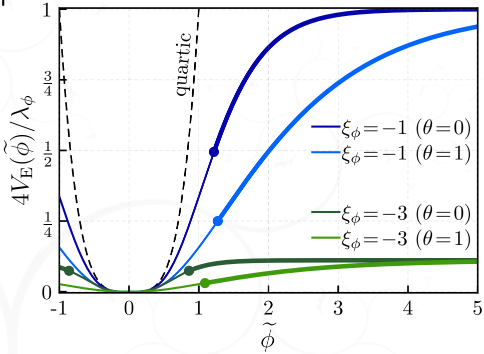
Comments On Inflationary Regime

- Our preheating study is relatively independent of the inflationary model.

- Nevertheless, a viable inflationary regime is realized by allowing a **non-minimal coupling** for the inflaton

$$\mathcal{L} \supset -\tfrac{1}{2}\xi_\phi \phi^2 R.$$

- For generality, we also consider both the metric $(\theta = 1)$ and Palatini formulations $(\theta = 0)$ of gravity.



Comments On Inflationary Regime

- Our preheating study is relatively independent of the inflationary model.

- Nevertheless, a viable inflationary regime is realized by allowing a **non-minimal coupling** for the inflaton

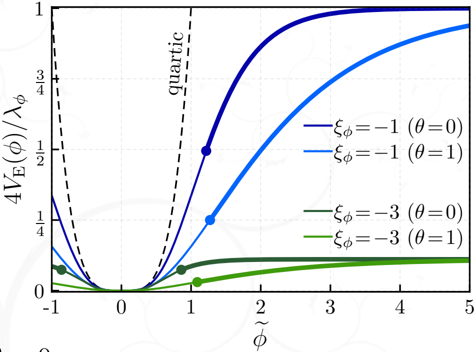
$$\mathcal{L} \supset -\tfrac{1}{2}\xi_\phi \phi^2 R.$$

- For generality, we also consider both the metric $(\theta = 1)$ and Palatini formulations $(\theta = 0)$ of gravity.

- Overall, we have the (Einstein-frame) potential in the inflationary regime

$$V_{\mathrm{E}}(\widetilde{\phi}) = \frac{\lambda_\phi}{4\xi_\phi^2} \begin{cases} \tanh^4\left(\sqrt{-\xi_\phi}\widetilde{\phi}\right) & \text{for } \theta = 0 \\ \left(1 - e^{-\sqrt{\frac{2}{3}}\widetilde{\phi}}\right)^2 & \text{for } \theta = 1 \end{cases}$$

where $\widetilde{\phi}$ is the canonical inflaton field.



Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

$$\omega^2_{\mathcal{H}_k} = k^2 + g^2\varphi^2\left(1 + \xi_\phi \frac{\varphi^2}{a^2}\right) + \xi a^2 R$$

Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\omega^2_{\mathcal{H}_k} = k^2 + g^2\varphi^2\Big(1 + \overbrace{\xi_\phi \frac{\varphi^2}{a^2}}^{\text{falls as } 1/a^2}\Big) + \underbrace{\xi a^2 R}_{\text{falls as } 1/a^2}$$

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\omega_{\mathcal{H}_k}^2 = k^2 + \underbrace{g^2\varphi^2}_{\text{no dissipation}}\Big(1 + \xi_\phi \overbrace{\frac{\varphi^2}{a^2}}^{\text{falls as } 1/a^2}\Big) + \underbrace{\xi a^2 R}_{\text{falls as } 1/a^2}$$

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

$$\omega^2_{\mathcal{H}_k} = k^2 + \underbrace{g^2\varphi^2}_{\text{no dissipation}}\Big(1 + \xi_\phi \overbrace{\frac{\varphi^2}{a^2}}^{\text{falls as } 1/a^2}\Big) + \underbrace{\xi a^2 R}_{\text{falls as } 1/a^2}$$

$\Rightarrow$ In general, Higgs has **two dynamical phases** of evolution:

Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\omega_{\mathcal{H}_k}^2 = k^2 + \underbrace{g^2\varphi^2}_{\text{no dissipation}}\Big(1 + \overbrace{\xi_\phi \frac{\varphi^2}{a^2}}^{\text{falls as } 1/a^2}\Big) + \underbrace{\xi a^2 R}_{\text{falls as } 1/a^2}$$

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

$\Rightarrow$ In general, Higgs has **two dynamical phases** of evolution:

(1) **tachyonic production** driven by curvature interactions
[relatively short lived since terms dissipate as $1/a^2$]

$$n_h \simeq \frac{1}{8}\left(\sqrt{\lambda_\phi}\overline{\varphi}\right)^3 \left(\frac{3^{9/4}\sqrt{\xi}}{2\pi x^2}\right)^{3/2}\left(\frac{x}{x_0}\right)^{4\sqrt{\frac{2\xi}{3\sqrt{3}}}}$$

for $x \lesssim \sqrt{6\xi}$
(and $\xi > 0$)

Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\omega^2_{\mathcal{H}_k} = k^2 + \underbrace{g^2\varphi^2}_{\text{no dissipation}}\Big(1 + \overbrace{\xi_\phi \frac{\varphi^2}{a^2}}^{\text{falls as } 1/a^2}\Big) + \underbrace{\xi a^2 R}_{\text{falls as } 1/a^2}$$

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

$\Rightarrow$ In general, Higgs has **two dynamical phases** of evolution:

1. **tachyonic production** driven by curvature interactions
   [relatively short lived since terms dissipate as $1/a^2$]

$$n_h \simeq \frac{1}{8}\left(\sqrt{\lambda_\phi}\overline{\varphi}\right)^3 \left(\frac{3^{9/4}\sqrt{\xi}}{2\pi x^2}\right)^{3/2}\left(\frac{x}{x_0}\right)^{4\sqrt{\frac{2\xi}{3\sqrt{3}}}} \quad \text{for } x \lesssim \sqrt{6\xi} \text{ (and } \xi > 0)$$

2. **parametric resonance** driven by quartic interaction
   [*terms do not dissipate* due to scale invariance $\Rightarrow$ unimpeded Higgs production]

$$n_h \simeq \frac{1}{2}\left(\frac{\sqrt{\lambda_\phi}\overline{\varphi}}{2\pi}\right)^3\left(\frac{g^2}{2\lambda_\phi}\right)^{3/4}\frac{e^{2\mu_{\max}x}}{\sqrt{\mu_{\max}x}}$$

Production of Higgs Particles

- The effective masses of Higgs fluctuations (in Einstein frame) are

$$\xi \equiv \xi_h + \xi_\phi - 6\theta\xi_h\xi_\phi - \frac{1}{6}$$

$$\omega^2_{\mathcal{H}_k} = k^2 + \underbrace{g^2\varphi^2}_{\text{no dissipation}}\Big(1 + \overbrace{\xi_\phi \frac{\varphi^2}{a^2}}^{\text{falls as } 1/a^2}\Big) + \underbrace{\xi a^2 R}_{\text{falls as } 1/a^2}$$

$\Rightarrow$ In general, Higgs has **two dynamical phases** of evolution:

1. **tachyonic production** driven by curvature interactions
[relatively short lived since terms dissipate as $1/a^2$]

$$n_h \simeq \frac{1}{8}\left(\sqrt{\lambda_\phi}\overline{\varphi}\right)^3 \left(\frac{3^{9/4}\sqrt{\xi}}{2\pi x^2}\right)^{3/2} \left(\frac{x}{x_0}\right)^{4\sqrt{\frac{2\xi}{3\sqrt{3}}}}$$

for $x \lesssim \sqrt{6\xi}$
(and $\xi > 0$)

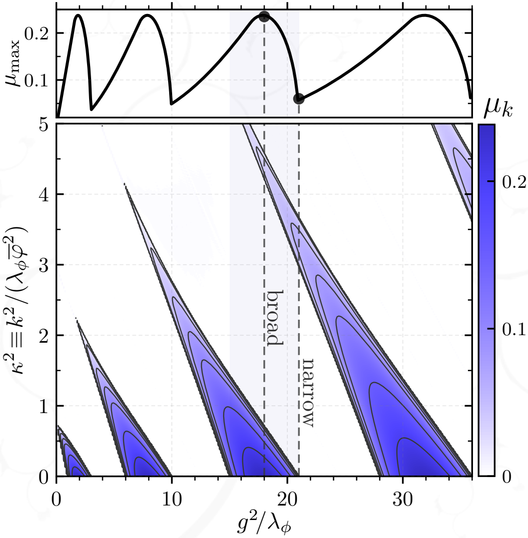
2. **parametric resonance** driven by quartic interaction
[*terms do not dissipate* due to scale invariance $\Rightarrow$ unimpeded Higgs production]

$$n_h \simeq \frac{1}{2}\left(\frac{\sqrt{\lambda_\phi}\overline{\varphi}}{2\pi}\right)^3 \left(\frac{g^2}{2\lambda_\phi}\right)^{3/4} \frac{e^{2\mu_{\max} x}}{\sqrt{\mu_{\max} x}}$$

growth rate $\mu_{\max}$ has non-trivial dependence on coupling g^2/λ_ϕ

Higgs modes grow as $n_{h_k} \propto e^{2\mu_k x}$

[for parametric resonance]

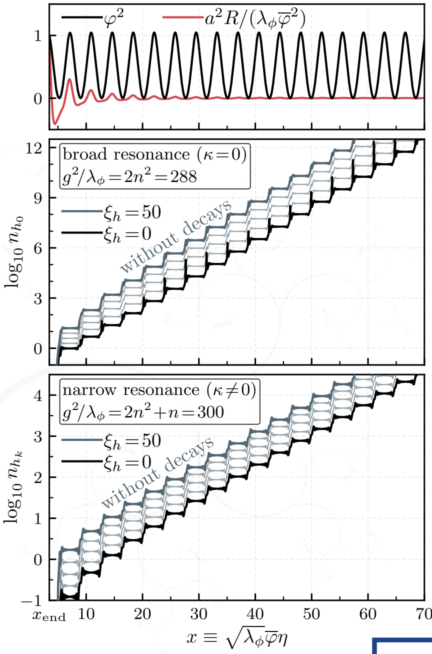


Two important effects neglected thus far:

1. **perturbative decays** of produced Higgs particles
2. **backreaction** of particle production on the system

① Perturbative Higgs Decays

- A crucial effect we have ignored thus far is that the Higgs undergoes **perturbative decays** to SM particles.



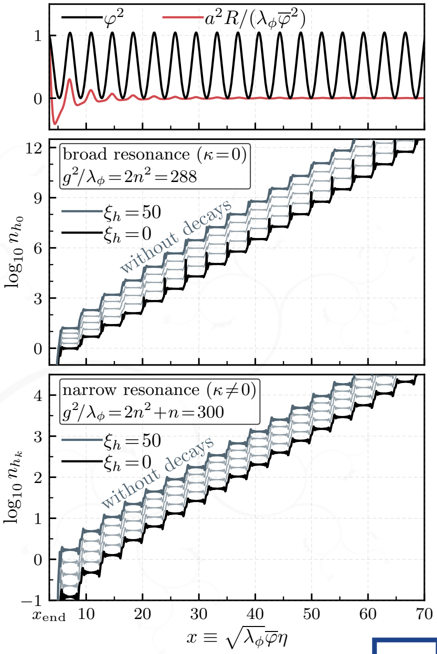
① Perturbative Higgs Decays

- A crucial effect we have ignored thus far is that the Higgs undergoes **perturbative decays** to SM particles.

- The dominant decay channel is into top quarks with the (rest-frame) decay rate

$$\Gamma_h = \frac{3y_t^2 m_h}{16\pi}$$

and effective mass $m_h \equiv \sqrt{g^2\phi^2 + \xi R}$.



① Perturbative Higgs Decays

- A crucial effect we have ignored thus far is that the Higgs undergoes **perturbative decays** to SM particles.

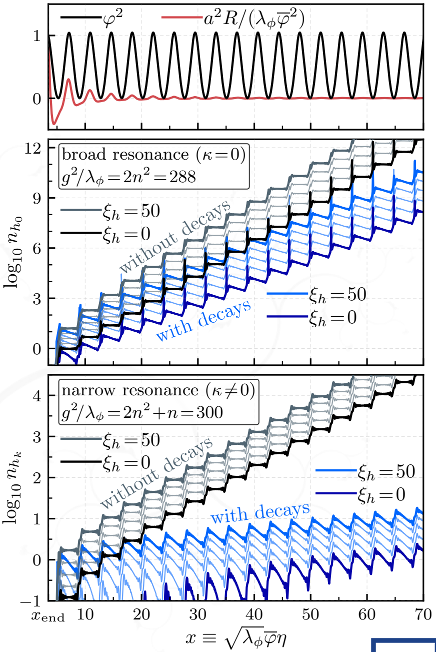
- The dominant decay channel is into top quarks with the (rest-frame) decay rate

$$\Gamma_h = \frac{3y_t^2 m_h}{16\pi}$$

and effective mass $m_h \equiv \sqrt{g^2\phi^2 + \xi R}$.

- As $\xi R \to 0$, the effect on the Higgs phase-space density n_{h_k} is to dissipate it as

$$\log n_{h_k} \propto -\int dx \frac{a\Gamma_h}{\sqrt{\lambda_\phi}\overline{\varphi}} \approx -0.036 y_t^2 \sqrt{\frac{g^2}{\lambda_\phi}}\, x$$



① Perturbative Higgs Decays

- A crucial effect we have ignored thus far is that the Higgs undergoes **perturbative decays** to SM particles.

- The dominant decay channel is into top quarks with the (rest-frame) decay rate

$$\Gamma_h = \frac{3y_t^2 m_h}{16\pi}$$

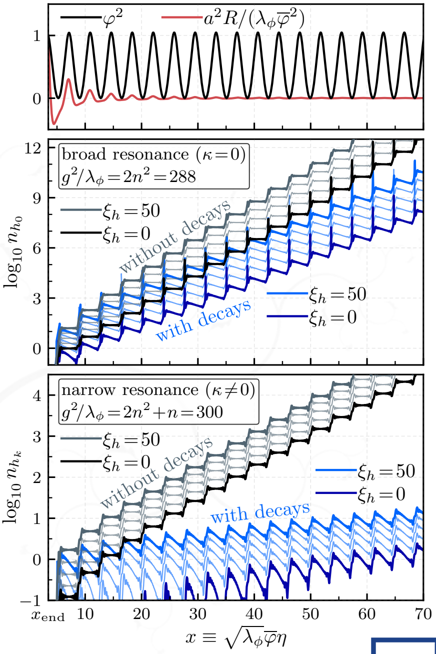
and effective mass $m_h \equiv \sqrt{g^2\phi^2 + \xi R}$.

- As $\xi R \to 0$, the effect on the Higgs phase-space density n_{h_k} is to dissipate it as

$$\log n_{h_k} \propto -\int dx \frac{a\Gamma_h}{\sqrt{\lambda_\phi}\overline{\varphi}} \approx -0.036 y_t^2 \sqrt{\frac{g^2}{\lambda_\phi}} x$$

The decay exponent depends linearly on time, *same* as growth exponents $2\mu_k x$.
$\Rightarrow$ decays could *entirely* ***suppress*** **production** of Higgs particles.

does *not* occur in massive preheating



② Backreaction

- Although fluctuations grow unimpeded, eventually their energy density will be comprable to inflaton background

variance of fluctuations

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 + \underbrace{\left(3\lambda_\phi \langle \phi^2 \rangle + g^2 \langle h^2 \rangle\right)}_{\text{backreaction on inflaton}} \phi \;=\; 0$$

② Backreaction

• Although fluctuations grow unimpeded, eventually their energy density will be comprable to inflaton background

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 + \underbrace{\left(3\lambda_\phi \langle \phi^2 \rangle + g^2 \overbrace{\langle h^2 \rangle}^{\text{variance of fluctuations}}\right)}_{\text{backreaction on inflaton}} \phi \;=\; 0$$

$\Rightarrow$ backreaction ***terminates*** (linear stage of) **preheating**, ending the dangerous particle production processes

② Backreaction

• Although fluctuations grow unimpeded, eventually their energy density will be comprable to inflaton background

variance of fluctuations

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 + \underbrace{\left(3\lambda_\phi \langle \phi^2 \rangle + g^2 \langle h^2 \rangle\right)}_{\text{backreaction on inflaton}} \phi \;=\; 0$$

$\Rightarrow$ backreaction ***terminates*** (linear stage of) **preheating**, ending the dangerous particle production processes

Ultimately due to $\langle \phi^2 \rangle$, ending linear stage at $x_{\rm NL} \approx 405$ (with $\lambda_\phi = 10^{-10}$).

② Backreaction

- Although fluctuations grow unimpeded, eventually their energy density will be comprable to inflaton background

variance of fluctuations

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 + \underbrace{\left(3\lambda_\phi \langle \phi^2 \rangle + g^2 \langle h^2 \rangle\right)}_{\text{backreaction on inflaton}} \phi \;=\; 0$$

⇒ backreaction ***terminates*** (linear stage of) **preheating**, ending the dangerous particle production processes

Ultimately due to $\langle \phi^2 \rangle$, ending linear stage at $x_{\mathrm{NL}} \approx 405$ (with $\lambda_\phi = 10^{-10}$).

- Also modifies the effective masses of the Higgs fluctuations

$$\omega_{h_k}^2 \;=\; \frac{k^2}{a^2} + g^2\phi^2 + \xi_h R + g^2 \langle \phi^2 \rangle + 3\lambda_h \langle h^2 \rangle$$

② Backreaction

- Although fluctuations grow unimpeded, eventually their energy density will be comprable to inflaton background

variance of fluctuations

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 + \underbrace{\left(3\lambda_\phi \langle \phi^2 \rangle + g^2 \langle h^2 \rangle\right)}_{\text{backreaction on inflaton}} \phi \;=\; 0$$

$\Rightarrow$ backreaction ***terminates*** (linear stage of) **preheating**, ending the dangerous particle production processes

Ultimately due to $\langle \phi^2 \rangle$, ending linear stage at $x_{\mathrm{NL}} \approx 405$ (with $\lambda_\phi = 10^{-10}$).

- Also modifies the effective masses of the Higgs fluctuations

$$\omega_{h_k}^2 \;=\; \frac{k^2}{a^2} + g^2\phi^2 + \xi_h R + g^2 \langle \phi^2 \rangle + \underbrace{3\lambda_h \langle h^2 \rangle}_{\text{source of destabilization}}$$

② Backreaction

- Although fluctuations grow unimpeded, eventually their energy density will be comprable to inflaton background

variance of fluctuations

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 + \underbrace{\left(3\lambda_\phi \langle \phi^2 \rangle + g^2 \langle h^2 \rangle\right)}_{\text{backreaction on inflaton}} \phi \ = \ 0$$

⇒ backreaction ***terminates*** (linear stage of) **preheating**, ending the dangerous particle production processes

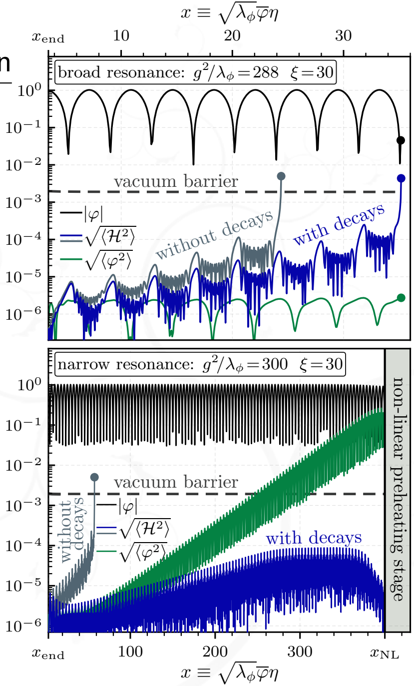
Ultimately due to $\langle \phi^2 \rangle$, ending linear stage at $x_{\mathrm{NL}} \approx 405$ (with $\lambda_\phi = 10^{-10}$).

- Also modifies the effective masses of the Higgs fluctuations

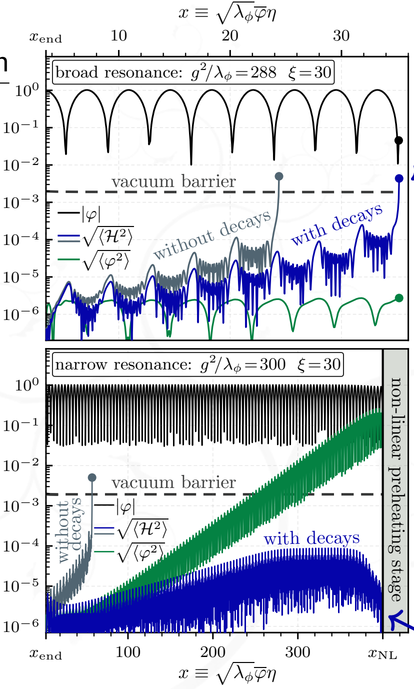
$$\omega_{h_k}^2 \ = \ \frac{k^2}{a^2} + g^2\phi^2 + \xi_h R + g^2 \langle \phi^2 \rangle + \underbrace{3\lambda_h \langle h^2 \rangle}_{\text{source of destabilization}}$$

⇒ tachyonic contriubtion $(3\lambda_h \langle h^2 \rangle < 0)$ can destabilize Higgs prior to x_{NL}.

evolution of Higgs/inflaton fluctuations



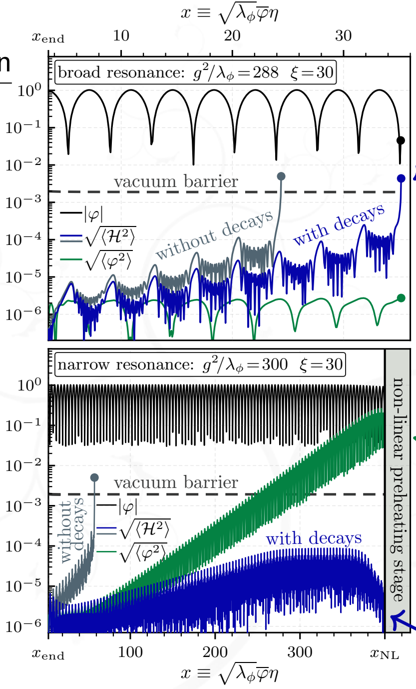
evolution of Higgs/inflaton fluctuations



perturbative decays extend lifetime

perturbative decays ensure viability

evolution of Higgs/inflaton fluctuations



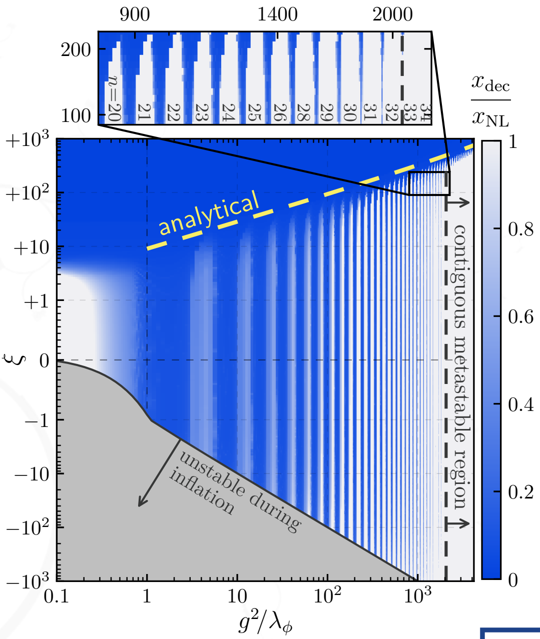
perturbative decays extend lifetime

inflaton fluctuations terminate linear stage of preheating

perturbative decays ensure viability

Summary of Results

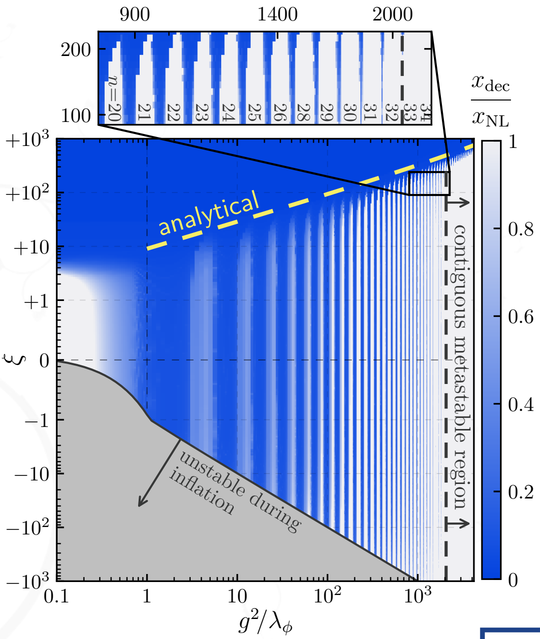
Calculate vacuum decay time $x_{\rm dec}$ numerically over parameter space of $\{g^2/\lambda_\phi, \xi\}$ Higgs couplings.



Summary of Results

Calculate vacuum decay time x_{dec} numerically over parameter space of $\{g^2/\lambda_\phi, \xi\}$ Higgs couplings.

<u>SOME OBSERVATIONS</u>:

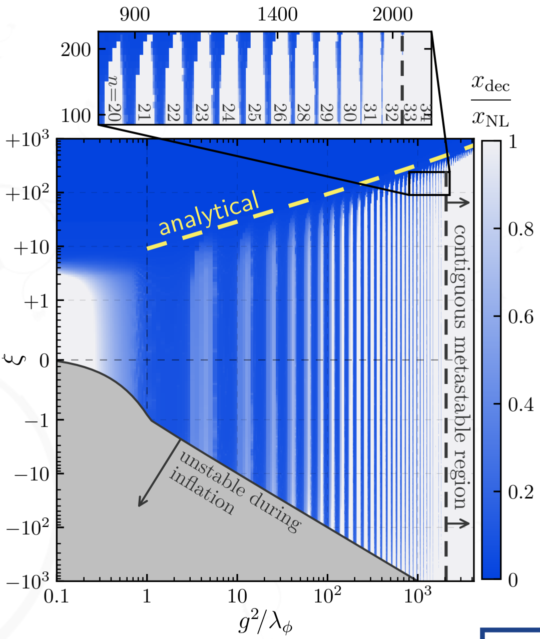


Summary of Results

Calculate vacuum decay time $x_{\rm dec}$ numerically over parameter space of $\{g^2/\lambda_\phi, \xi\}$ Higgs couplings.

SOME OBSERVATIONS:

- large number of disjoint metastable regions distributed throughout parameter space

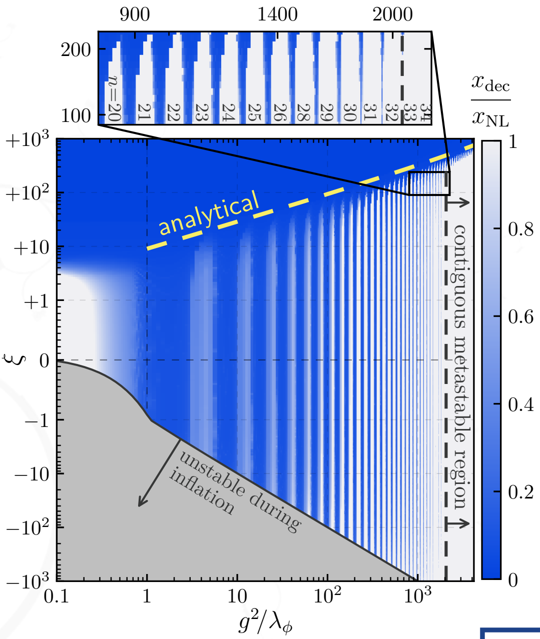


Summary of Results

Calculate vacuum decay time $x_{\rm dec}$ numerically over parameter space of $\{g^2/\lambda_\phi, \xi\}$ Higgs couplings.

SOME OBSERVATIONS:

- large number of disjoint metastable regions distributed throughout parameter space
- due to perturbative decays, a contiguous metastable region emerges at $g^2/\lambda_\phi \gtrsim 2\times 10^3$

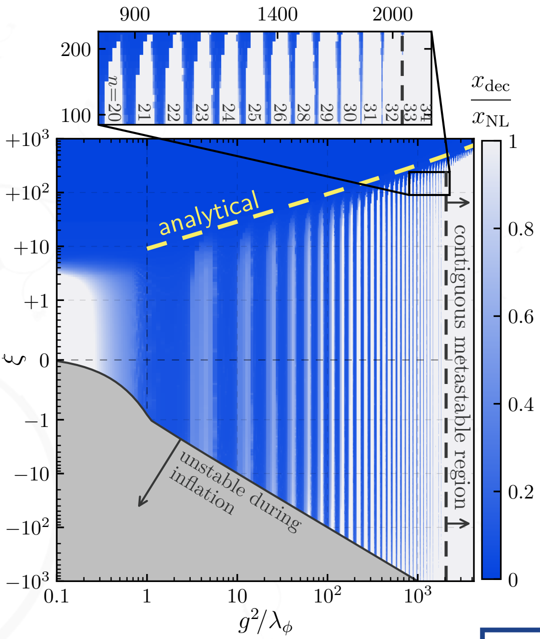


Summary of Results

Calculate vacuum decay time $x_{\rm dec}$ numerically over parameter space of $\{g^2/\lambda_\phi, \xi\}$ Higgs couplings.

SOME OBSERVATIONS:

- large number of disjoint metastable regions distributed throughout parameter space
- due to perturbative decays, a contiguous metastable region emerges at $g^2/\lambda_\phi \gtrsim 2\times 10^3$
- curvature coupling imposes envelope over metastable regions at $\xi \lesssim g^2/\lambda_\phi$—*i.e.*, large ξ viable as long as g^2/λ_ϕ is similarly large.



TAKE-HOME MESSAGE:

• Although models that lead to massless preheating appear catastrophic for electroweak vacuum metastability, fully accounting for backreaction and perturbative decays reveals a large number of disjoint (meta)stable regions.

• In contrast to other (massive) preheating scenarios, the Higgs-inflaton coupling is ultimately bounded *from below* to ensure viability.

TAKE-HOME MESSAGE:

• Although models that lead to massless preheating appear catastrophic for electroweak vacuum metastability, fully accounting for backreaction and perturbative decays reveals a large number of disjoint (meta)stable regions.

• In contrast to other (massive) preheating scenarios, the Higgs-inflaton coupling is ultimately bounded *from below* to ensure viability.

FUTURE WORK/DIRECTIONS:

• Inclusion of terms in inflaton potential, *e.g.*, small mass terms, that break scale invariance—new phases of evolution would be considered.

• The effect of spectator fields on the dynamics and non-linear onset x_{NL}.

• Extensions to multi-inflaton models with significant angular velocity

• Further extension of gravity formulation, *e.g.*, to Einstein-Cartan gravity.

TAKE-HOME MESSAGE:

• Although models that lead to massless preheating appear catastrophic for electroweak vacuum metastability, fully accounting for backreaction and perturbative decays reveals a large number of disjoint (meta)stable regions.

• In contrast to other (massive) preheating scenarios, the Higgs-inflaton coupling is ultimately bounded *from below* to ensure viability.

FUTURE WORK/DIRECTIONS:

• Inclusion of terms in inflaton potential, *e.g.*, small mass terms, that break scale invariance—new phases of evolution would be considered.

• The effect of spectator fields on the dynamics and non-linear onset x_{NL}.

• Extensions to multi-inflaton models with significant angular velocity

• Further extension of gravity formulation, *e.g.*, to Einstein-Cartan gravity.

THANK YOU FOR YOUR ATTENTION!