UNIVERSITY OF JYVÄSKYLÄ

Electroweak Vacuum Stability During and After Inflation

Mindaugas Karčiauskas

Enqvist, MK, Lebedev, Rusak, Zatta (2016) arXiv:1608.08848
Ema, MK, Lebedev, Zatta (2017) arXiv:1703.04681

LINUX

Higgs Mass and the Standard Model Consistency

1. SM is consistent up to $m_{\rm Pl}$: $111\ \mathrm{GeV} < M_h < 175\ \mathrm{GeV}$

   Higgs mass: $M_h = 125.09 \pm 0.24\ \mathrm{GeV}$ Aad et al. (2015)

2. No other states discovered

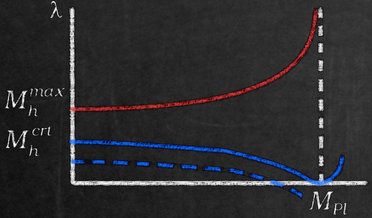
- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}$ GeV
  - $V_{\rm max}^{1/4} \sim 10^{9}$ GeV
- Lifetime $\gg$ age of the universe

Higgs Mass and the Standard Model Consistency

1. SM is consistent up to $m_{\rm Pl}$: $\quad 111\ {\rm GeV} < M_h < 175\ {\rm GeV}$

   Higgs mass: $\quad M_h = 125.09 \pm 0.24\ {\rm GeV}$ Aad et al. (2015)

2. No other states discovered



- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}$ GeV
  - $V_{\rm max}^{1/4} \sim 10^{9}$ GeV
- Lifetime $\gg$ age of the universe

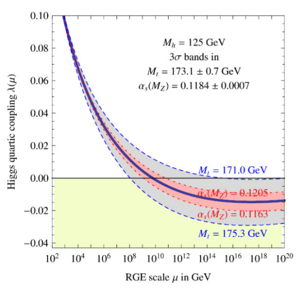
Higgs Mass and the Standard Model Consistency

1. SM is consistent up to $m_{\rm Pl}$: $111\ {\rm GeV} < M_h < 175\ {\rm GeV}$

Higgs mass: $M_h = 125.09 \pm 0.24\ {\rm GeV}$ Aad et al. (2015)

2. No other states discovered

Degrassi et al. (2012)



- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}$ GeV
  - $V_{\rm max}^{1/4} \sim 10^9$ GeV
- Lifetime $\gg$ age of the universe

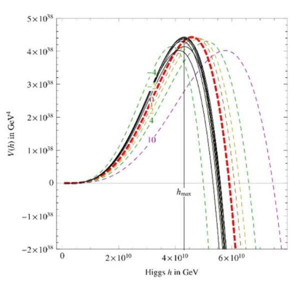
Higgs Mass and the Standard Model Consistency

1. SM is consistent up to $m_{\rm Pl}$: $111\ \mathrm{GeV} < M_h < 175\ \mathrm{GeV}$

Higgs mass: $M_h = 125.09 \pm 0.24\ \mathrm{GeV}$ Aad et al. (2015)

2. No other states discovered

Espinosa et al. (2015)



- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}\ \mathrm{GeV}$
  - $V_{\max}^{1/4} \sim 10^{9}\ \mathrm{GeV}$
- Lifetime $\gg$ age of the universe

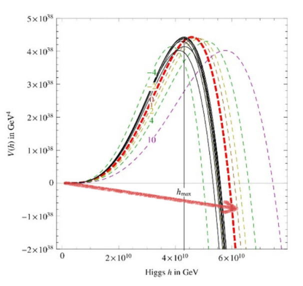
Higgs Mass and the Standard Model Consistency

1. SM is consistent up to $m_{\rm Pl}$: $111\ \mathrm{GeV} < M_h < 175\ \mathrm{GeV}$

Higgs mass: $M_h = 125.09 \pm 0.24\ \mathrm{GeV}$ Aad et al. (2015)

2. No other states discovered

Espinosa et al. (2015)



- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}$ GeV
  - $V_{\rm max}^{1/4} \sim 10^9$ GeV
- Lifetime $\gg$ age of the universe

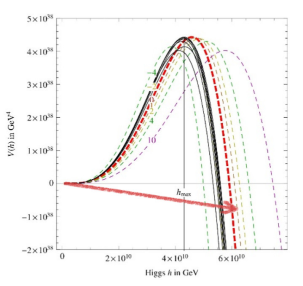
Higgs Mass and the Standard Model Consistency

1. SM is consistent up to m_{Pl}: $111\ \mathrm{GeV} < M_h < 175\ \mathrm{GeV}$

   Higgs mass: $M_h = 125.09 \pm 0.24\ \mathrm{GeV}$ Aad et al. (2015)

2. No other states discovered

Espinosa et al. (2015)



- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}\ \mathrm{GeV}$
  - $V_{\max}^{1/4} \sim 10^{9}\ \mathrm{GeV}$
- Lifetime $\gg$ age of the universe

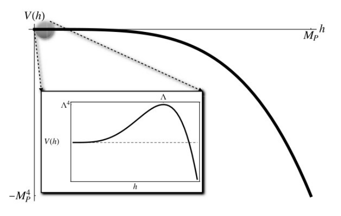
Higgs Mass and the Standard Model Consistency

1. SM is consistent up to $m_{\rm Pl}$: $111\,{\rm GeV} < M_h < 175\,{\rm GeV}$

Higgs mass: $M_h = 125.09 \pm 0.24\,{\rm GeV}$ Aad et al. (2015)

2. No other states discovered

Lebedev & Westphal (2013)



- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}\,{\rm GeV}$
  - $V_{\rm max}^{1/4} \sim 10^9\,{\rm GeV}$
- Lifetime $\gg$ age of the universe

- Questions:
  1. Why isn't Higgs in an energetically favourable state?
  2. How EW vacuum survived inflation?

Production of Infrared Modes

- Langevin equation

$$\frac{\mathrm{d}h}{\mathrm{d}N} \simeq -\frac{\lambda h^3}{3H^2} + \frac{H}{2\pi}\xi\left(N\right)$$

- Safe energy scale for inflation

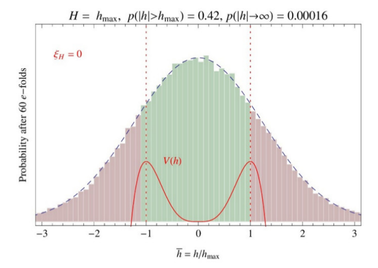
$$H < 10^9\ \mathrm{GeV} \quad \Leftrightarrow \quad V_{\mathrm{inf}}^{1/4} < 10^{13}\ \mathrm{GeV}$$

- If GW are detected ($r > 10^{-4}$)

$$H > 10^{12}\ \mathrm{GeV} \quad \Leftrightarrow \quad V_{\mathrm{inf}}^{1/4} > 10^{15}\ \mathrm{GeV}$$

Production of Infrared Modes

Espinosa et al. (2015)



- Langevin equation

$$\frac{\mathrm{d}h}{\mathrm{d}N} \simeq -\frac{\lambda h^3}{3H^2} + \frac{H}{2\pi}\xi(N)$$

- Safe energy scale for inflation

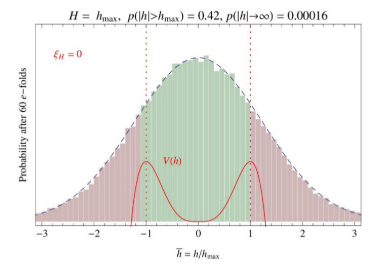
$$H < 10^9 \text{ GeV} \quad \Leftrightarrow \quad V_{\text{inf}}^{1/4} < 10^{13} \text{ GeV}$$

- If GW are detected ($r > 10^{-4}$)

$$H > 10^{12} \text{ GeV} \quad \Leftrightarrow \quad V_{\text{inf}}^{1/4} > 10^{15} \text{ GeV}$$

Production of Infrared Modes

Espinosa et al. (2015)



- Langevin equation

$$\frac{\mathrm{d}h}{\mathrm{d}N} \simeq -\frac{\lambda h^3}{3H^2} + \frac{H}{2\pi}\xi(N)$$

- Safe energy scale for inflation

$$H < 10^9\ \mathrm{GeV} \quad \Leftrightarrow \quad V_{\mathrm{inf}}^{1/4} < 10^{13}\ \mathrm{GeV}$$

- If GW are detected ($r > 10^{-4}$)

$$H > 10^{12}\ \mathrm{GeV} \quad \Leftrightarrow \quad V_{\mathrm{inf}}^{1/4} > 10^{15}\ \mathrm{GeV}$$

Stabilising EW Vacuum

- Non-SM interactions
  - The running of $\xi \Rightarrow$ Large non-minimal coupling
  - Reheating $\Rightarrow$ Higgs-inflaton interaction

Stabilising EW Vacuum

- Non-SM interactions
  - The running of $\xi \Rightarrow$ Large non-minimal coupling
  - Reheating $\Rightarrow$ Higgs-inflaton interaction

$$\mathcal{L} \supset \xi h^2 R$$

See the next talk by Marco.

Stabilising EW Vacuum

- Non-SM interactions
  - The running of $\xi \Rightarrow$ Large non-minimal coupling
  - Reheating $\Rightarrow$ Higgs-inflaton interaction

$$V \supset \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{4}\sigma\phi h^3$$

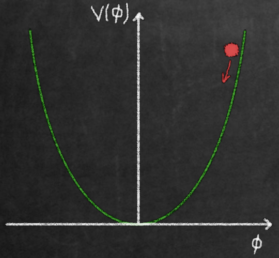
Stabilising EW Vacuum

- Non-SM interactions
  - The running of $\xi \Rightarrow$ Large non-minimal coupling
  - Reheating $\Rightarrow$ Higgs-inflaton interaction

$$V \supset \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{4}\sigma\phi h^3$$

Suppresses quantum fluctuations during inflation
Enhances parametric and tachyonic resonances after inflation

Higgs-Inflaton Coupling



- Higgs-inflaton coupling

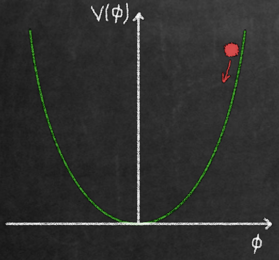
$$V(\phi, h) = \frac{1}{2} m^2 \phi^2 + \frac{1}{4} \lambda(h) h^4 + \frac{1}{4} \lambda_{h\phi} \phi^2 h^2 + \frac{1}{2} \sigma \phi h^2$$

- Constraints

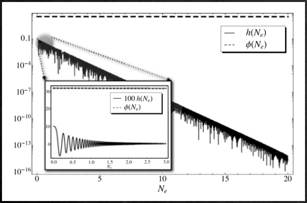
$$10^{-10} < \lambda_{h\phi} < 10^{-6}$$

- Perturbations

Higgs-Inflaton Coupling



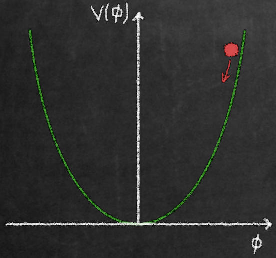
Lebedev & Westphal (2013)



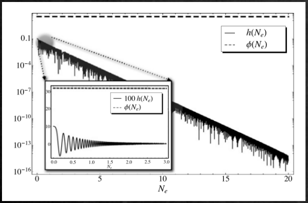
- Higgs-inflaton coupling

$$V\left(\phi, h\right) = \frac{1}{2} m^2 \phi^2 + \frac{1}{4} \lambda\left(h\right) h^4 + \frac{1}{4} \lambda_{h\phi} \phi^2 h^2$$

Higgs-Inflaton Coupling



Lebedev & Westphal (2013)



- Higgs-inflaton coupling

$$V(\phi, h) = \frac{1}{2} m^2 \phi^2 + \frac{1}{4} \lambda(h) h^4 + \frac{1}{4} \lambda_{h\phi} \phi^2 h^2$$

- Initial inflaton value

$$\phi \sim 10 m_{\rm Pl}$$

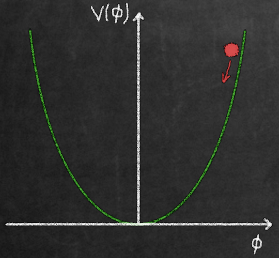
- Constraints

Heavy Higgs — Small rad. corr.

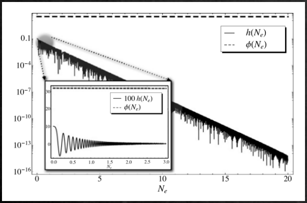
$$10^{-10} < \lambda_{h\phi} < 10^{-6}$$

- Perturbations

Higgs-Inflaton Coupling



Lebedev & Westphal (2013)



- Higgs-inflaton coupling

$$V(\phi, h) = \frac{1}{2} m^2 \phi^2 + \frac{1}{4} \lambda(h) h^4 + \frac{1}{4} \lambda_{h\phi} \phi^2 h^2$$

- Initial inflaton value

$$\phi \sim 10 m_{\mathrm{Pl}}$$

- Constraints

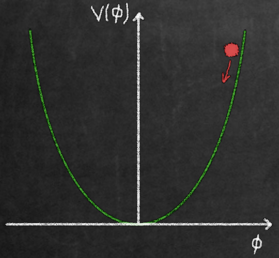
Heavy Higgs — Small rad. corr.

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

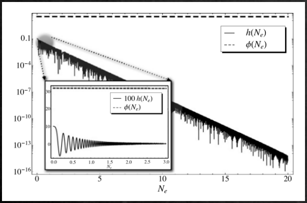
- Perturbations

$$\frac{\mathrm{d}h}{\mathrm{d}N} \simeq -\frac{\lambda h^3}{3H^2} + \frac{H}{2\pi} \xi(N)$$

Higgs-Inflaton Coupling



Lebedev & Westphal (2013)



- Higgs-inflaton coupling

$$V(\phi, h) = \frac{1}{2} m^2 \phi^2 + \frac{1}{4}\lambda(h)\, h^4 + \frac{1}{4}\lambda_{h\phi}\phi^2 h^2$$

- Initial inflaton value

$$\phi \sim 10 m_{\mathrm{Pl}}$$

- Constraints

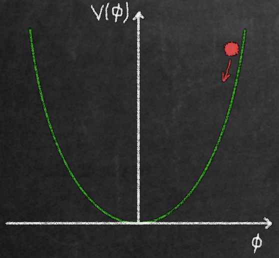
Heavy Higgs — Small rad. corr.

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

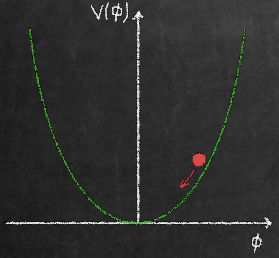
- Perturbations

$$\frac{\mathrm{d}h}{\mathrm{d}N} \simeq -\frac{\lambda h^3 + \frac{1}{2}\lambda_{h\phi}\phi^2 h}{3H^2} + \frac{H}{2\pi}\xi(N)$$

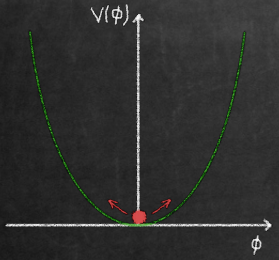
Parametric Resonance



Parametric Resonance

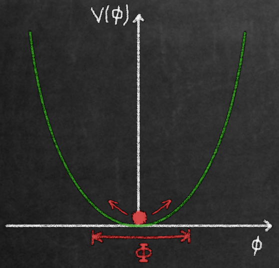


Parametric Resonance



$$\phi(t) = \Phi(t)\cos(mt)$$

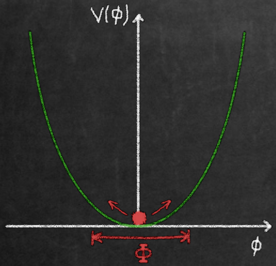
Parametric Resonance



$$\phi(t) = \Phi(t)\cos(mt)$$

$$\Phi(t) \propto t^{-1}$$

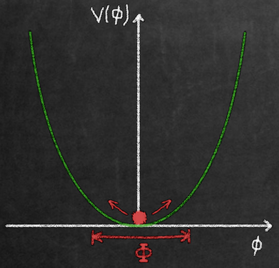
Parametric Resonance



- Spectator field

$$V\left(\phi,\chi\right)\supset\frac{g}{2}\phi^2\chi^2$$

Parametric Resonance



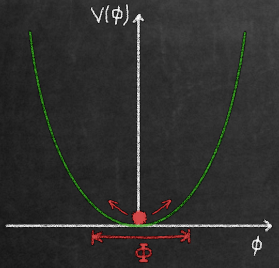
- Spectator field

$$V(\phi, \chi) \supset \frac{g}{2}\phi^2\chi^2$$

- “Mathieu” equation

$$\ddot{\chi}_k + \left[\frac{k^2}{a^2} + g\Phi^2(t)\cos^2(mt)\right]\chi_k = 0$$

Parametric Resonance



- Spectator field

$$V(\phi,\chi) \supset \frac{g}{2}\phi^2\chi^2$$

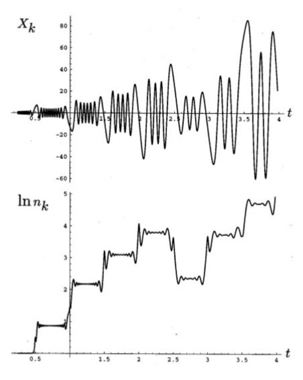
- "Mathieu" equation

$$\ddot{\chi}_k + \underbrace{\left[\frac{k^2}{a^2} + g\Phi^2(t)\cos^2(mt)\right]}_{\omega^2}\chi_k = 0$$

- Parametric resonance $\left|\frac{\omega'}{\omega^2}\right| \gg 1$

Parametric Resonance

Kofman et al. (1997)



- Spectator field

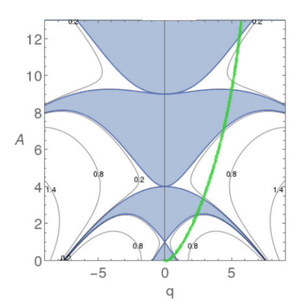
$$V(\phi, \chi) \supset \frac{g}{2}\phi^2\chi^2$$

- "Mathieu" equation

$$\ddot{\chi}_k + \underbrace{\left[\frac{k^2}{a^2} + g\Phi^2(t)\cos^2(mt)\right]}_{\omega^2}\chi_k = 0$$

- Parametric resonance $\left|\frac{\omega'}{\omega^2}\right| \gg 1$

Parametric Resonance



- Spectator field

$$V(\phi, \chi) \supset \frac{g}{2}\phi^2\chi^2$$

- "Mathieu" equation

$$\ddot{\chi}_k + \underbrace{\left[\frac{k^2}{a^2} + g\Phi^2(t)\cos^2(mt)\right]}_{\omega^2} \chi_k = 0$$

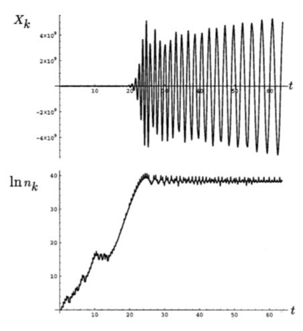
- Parametric resonance $\left|\frac{\omega'}{\omega^2}\right| \gg 1$

$$A(t) \equiv \frac{k^2}{a^2} + q(t)$$

$$q(t) \equiv \frac{1}{2} g\Phi^2(t)$$

Parametric Resonance

Kofman et al. (1997)



- Spectator field

$$V(\phi, \chi) \supset \frac{g}{2}\phi^2\chi^2$$

- "Mathieu" equation

$$\ddot{\chi}_k + \underbrace{\left[\frac{k^2}{a^2} + g\Phi^2(t)\cos^2(mt)\right]}_{\omega^2}\chi_k = 0$$

- Parametric resonance $\left|\frac{\omega'}{\omega^2}\right| \gg 1$

$$A(t) \equiv \frac{k^2}{a^2} + q(t)$$

$$q(t) \equiv \frac{1}{2}g\Phi^2(t)$$

EW Vacuum Stability: Parametric Resonance

- Mirror symmetry

$$\phi \leftrightarrow -\phi \quad \Rightarrow \quad V \supset \frac{1}{4}\lambda_{h\phi}\phi^2 h^2$$

- Higgs EoM: $\ddot{h}_k + \omega_k^2 h_k \simeq 0$

$$\omega_k^2 = \left(\frac{k}{a}\right)^2 + \frac{1}{2}\lambda_{h\phi}\Phi(t)^2\cos^2(mt) + 3\frac{\lambda(h)}{a^{3/2}}\langle h^2\rangle$$

- Numerical results

$$\lambda = 0.01 \cdot \text{sign}\left(h_{\text{crt}}^{\text{SM}} - \sqrt{\langle h^2\rangle}\right) \quad \Rightarrow \quad \lambda = -0.01$$

EW Vacuum Stability: Parametric Resonance

- Mirror symmetry

$$\phi \leftrightarrow -\phi \quad \Rightarrow \quad V \supset \frac{1}{4}\lambda_{h\phi}\phi^2 h^2$$

- Higgs EoM: $\ddot{h}_k + \omega_k^2 h_k \simeq 0$

$$\omega_k^2 = \left(\frac{k}{a}\right)^2 + \frac{1}{2}\lambda_{h\phi}\Phi(t)^2\cos^2(mt) + 3\frac{\lambda(h)}{a^{3/2}}\langle h^2\rangle$$

- Numerical results

$$\lambda = 0.01 \cdot \mathrm{sign}\left(h_{\mathrm{crt}}^{\mathrm{SM}} - \sqrt{\langle h^2\rangle}\right) \quad \Rightarrow \quad \lambda = -0.01$$

EW Vacuum Stability: Parametric Resonance

- Mirror symmetry

$$\phi \leftrightarrow -\phi \quad \Rightarrow \quad V \supset \frac{1}{4}\lambda_{h\phi}\phi^2 h^2$$

- Higgs EoM: $\ddot{h}_k + \omega_k^2 h_k \simeq 0$

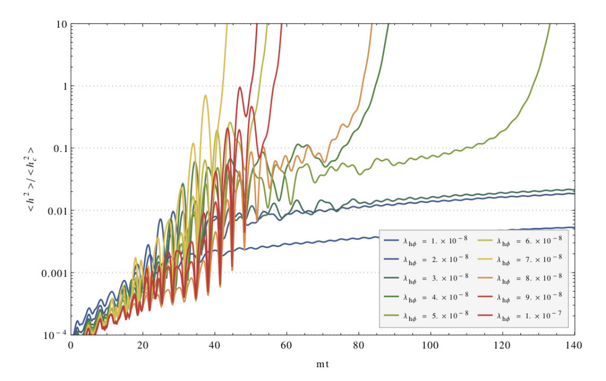
$$\omega_k^2 = \left(\frac{k}{a}\right)^2 + \frac{1}{2}\lambda_{h\phi}\Phi(t)^2\cos^2(mt) + 3\frac{\lambda(h)}{a^{3/2}}\langle h^2\rangle$$

- Numerical results

$$\lambda = 0.01 \cdot \mathrm{sign}\left(h_{\mathrm{crt}}^{\mathrm{SM}} - \sqrt{\langle h^2\rangle}\right) \quad \Rightarrow \quad \lambda = -0.01$$

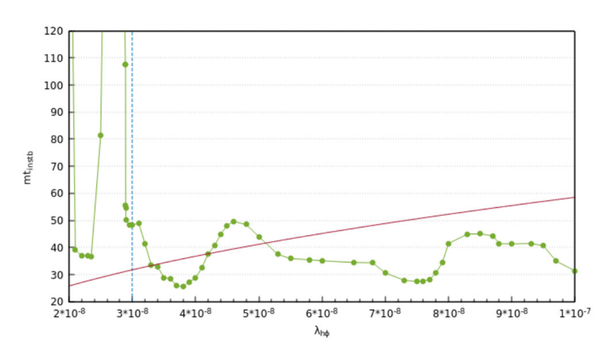
EW Vacuum Stability:
Parametric Resonance

Hartree approximation: $h^4 \to \langle h^2 \rangle \, h^2$



EW Vacuum Stability:
Parametric Resonance

Lattice:



EW Vacuum Stability: Combined Resonance

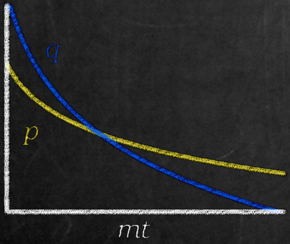
$$V(\phi, h) = \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda(h)\,h^4 + \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{2}\sigma\phi h^2$$

$$\omega_k^2 = \frac{1}{2}m^2\left[\left(\frac{k}{ma}\right)^2 + p(t)\cos(mt) + 2q(t)\cos^2(mt) + 3\frac{\lambda_h(h)}{a^{3/2}}\frac{\langle h^2\rangle}{m^2}\right]$$

EW Vacuum Stability: Combined Resonance

$$V(\phi, h) = \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda(h)\,h^4 + \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{2}\sigma\phi h^2$$

$$\omega_k^2 = \frac{1}{2}m^2\left[\left(\frac{k}{ma}\right)^2 + p(t)\cos(mt) + 2q(t)\cos^2(mt) + 3\frac{\lambda_h(h)}{a^{3/2}}\frac{\langle h^2\rangle}{m^2}\right]$$



- Amplitudes

$$q \equiv \frac{\lambda_{h\phi}\Phi^2}{2m^2} \qquad p \equiv 2\frac{\sigma_{h\phi}\Phi}{m^2}$$

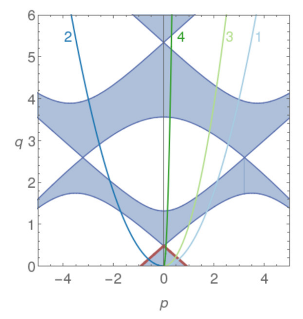
- Trilinear interaction grows

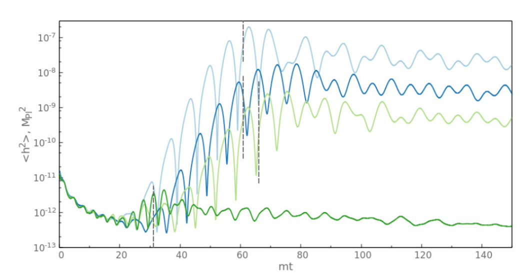
$$\frac{p}{q} \propto t$$

EW Vacuum Stability:
Combined Resonance

$$V(\phi, h) = \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda(h)\,h^4 + \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{2}\sigma\phi h^2$$

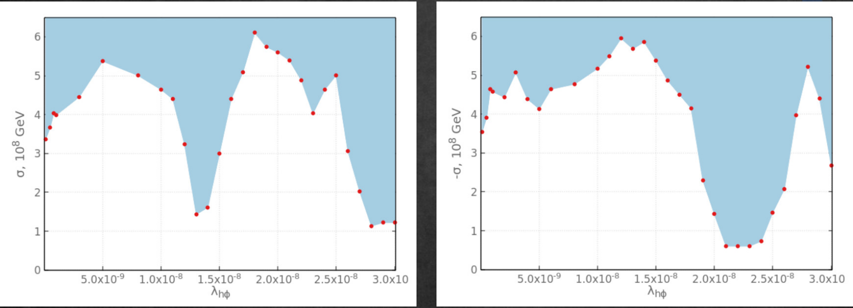
$$\omega_k^2 = \frac{1}{2}m^2\left[\left(\frac{k}{ma}\right)^2 + p(t)\cos(mt) + 2q(t)\cos^2(mt) + 3\frac{\lambda_h(h)}{a^{3/2}}\frac{\langle h^2\rangle}{m^2}\right]$$





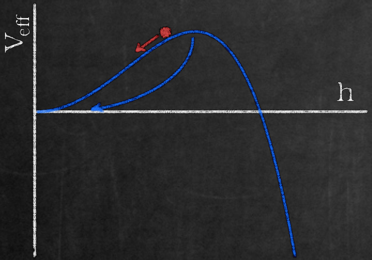
EW Vacuum Stability: Combined Resonance

Lattice easy:

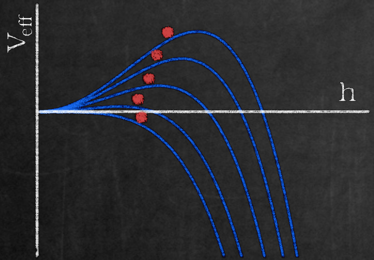


$$|\sigma| < 10^8 \text{ GeV}$$

Post-Resonance: A Possible Scenario



Post-Resonance: A Possible Scenario



- Ema et al. (2016):
  - Destabilised for allowed $\lambda_{h\phi}$
  - Stabilised by thermal bath (?)

Conclusions

- SM is a consistent theory up to $m_{\rm Pl}$
- But:
  1. Why EW vacuum?
  2. Stability during inflation?
- Reheating $\Rightarrow$ Higgs-Inflaton coupling

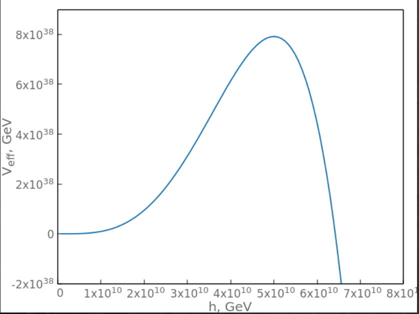
$$V \supset \frac{1}{4}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{4}\sigma\phi h^3$$

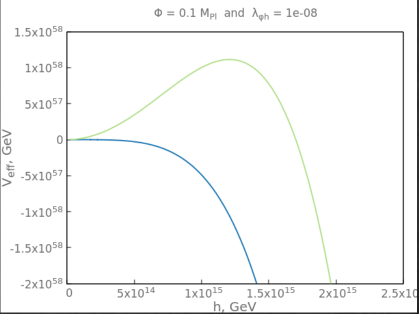
- EW vacuum is stable during preheating if

$$\begin{aligned} 10^{-10} < \quad \lambda_{h\phi} &< 3\times 10^{-8} \\ |\sigma| &< 10^{8}\ \mathrm{GeV} \end{aligned}$$

- After preheating EW vacuum is stabilised by thermal corrections (?)

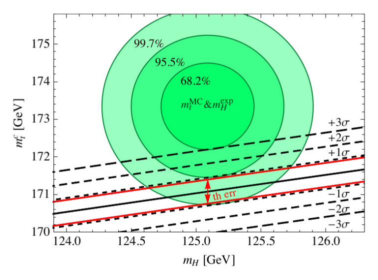
Inflaton Stabilised Potential





Metastability Bound

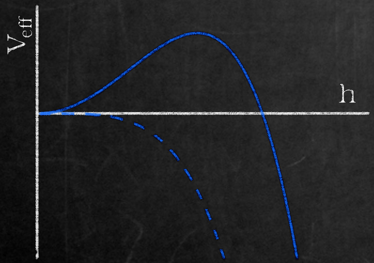
Iacobellis & Masina (2016)



EW Vacuum Stability:
Parametric Resonance

$$\omega_k^2 = m^2 \left[\left(\frac{k}{am} \right)^2 + q(t) \cos^2(mt) + 3 \frac{\lambda_h(h)}{a^{3/2}} \frac{\langle h^2 \rangle}{m^2} \right]$$

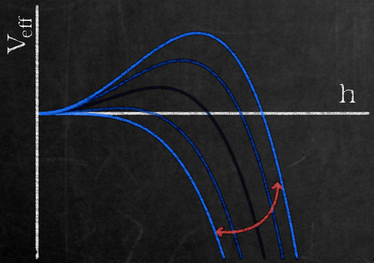
$$h \equiv \sqrt{\langle h^2 \rangle} \qquad q(t) \equiv \frac{\lambda_{h\phi} \Phi(t)^2}{2m^2}$$



EW Vacuum Stability: Parametric Resonance

$$\omega_k^2 = m^2 \left[\left(\frac{k}{am} \right)^2 + q(t) \cos^2(mt) + 3 \frac{\lambda_h(h)}{a^{3/2}} \frac{\langle h^2 \rangle}{m^2} \right]$$

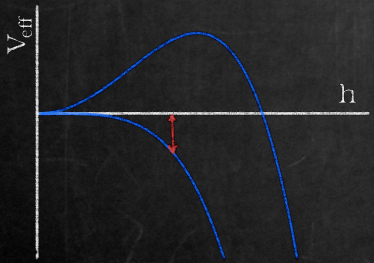
$$h \equiv \sqrt{\langle h^2 \rangle} \qquad q(t) \equiv \frac{\lambda_{h\phi} \Phi(t)^2}{2m^2}$$



EW Vacuum Stability:
Parametric Resonance

$$\omega_k^2 = m^2 \left[\left(\frac{k}{am} \right)^2 + q(t) \cos^2(mt) + 3 \frac{\lambda_h(h)}{a^{3/2}} \frac{\langle h^2 \rangle}{m^2} \right]$$

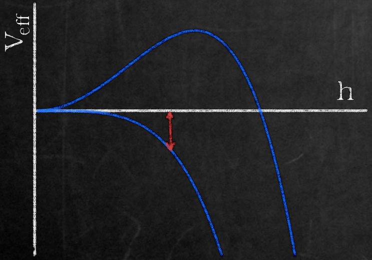
$$h \equiv \sqrt{\langle h^2 \rangle} \qquad q(t) \equiv \frac{\lambda_{h\phi} \Phi(t)^2}{2m^2}$$



EW Vacuum Stability: Parametric Resonance

$$\omega_k^2 = m^2 \left[\left(\frac{k}{am} \right)^2 + q(t) \cos^2(mt) + 3 \frac{\lambda_h(h)}{a^{3/2}} \frac{\langle h^2 \rangle}{m^2} \right]$$

$$h \equiv \sqrt{\langle h^2 \rangle} \qquad q(t) \equiv \frac{\lambda_{h\phi} \Phi(t)^2}{2m^2}$$



- Tachyonic region $\qquad h \propto e^{m_h^{\rm eff} \Delta t}$

$$\left(m_h^{\rm eff} \right)^2 = 3 |\lambda_h| \langle h^2 \rangle$$

$$\Delta t = \sqrt{\frac{6 |\lambda_h| \langle h^2 \rangle}{\lambda_{h\phi} \Phi^2 m^2}}$$

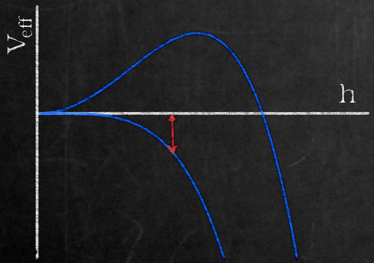
- Instability scale

$$m_h^{\rm eff} \Delta t < 1 \quad \Rightarrow \quad \lambda_{h\phi} < 3 \times 10^{-8}$$

EW Vacuum Stability: Parametric Resonance

$$\omega_k^2 = m^2 \left[\left(\frac{k}{am} \right)^2 + q(t) \cos^2(mt) + 3 \frac{\lambda_h(h)}{a^{3/2}} \frac{\langle h^2 \rangle}{m^2} \right]$$

$$h \equiv \sqrt{\langle h^2 \rangle} \qquad q(t) \equiv \frac{\lambda_{h\phi} \Phi(t)^2}{2m^2}$$



- Tachyonic region $\quad h \propto \mathrm{e}^{m_h^{\mathrm{eff}} \Delta t}$

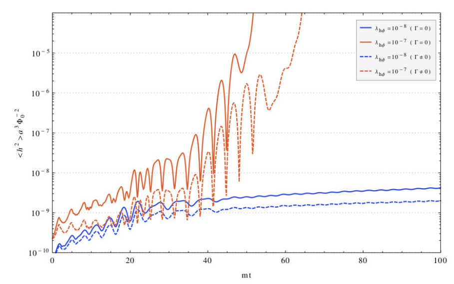
$$\left(m_h^{\mathrm{eff}}\right)^2 = 3 |\lambda_h| \langle h^2 \rangle$$

$$\Delta t = \sqrt{\frac{6 |\lambda_h| \langle h^2 \rangle}{\lambda_{h\phi} \Phi^2 m^2}}$$

- Instability scale

$$m_h^{\mathrm{eff}} \Delta t < 1 \quad \Rightarrow \quad \lambda_{h\phi} < 3 \times 10^{-8}$$

Perturbative Decay



- Perturbative decay

$$\Gamma\left(h \to t\bar{t}\right) = \frac{3y_t^2\, m_h^{\mathrm{eff}}}{16\pi}$$

where

$$y_t\left(m_h^{\mathrm{eff}}\right) \sim \frac{1}{2} \text{ and } m_h^{\mathrm{eff}} \simeq \sqrt{\frac{1}{2}\lambda_{h\phi}}\,|\phi|$$

- The reduction

$$\frac{\langle h^2 \rangle}{\langle h_\Gamma^2 \rangle} \sim \text{few}$$

A Model Example

$$-\Delta\mathcal{L} = \frac{1}{2}\lambda_\nu \phi \nu_R \nu_R + y_\nu \bar{l}_L \cdot H^* \nu_R + \frac{1}{2} M \nu_R \nu_R + \text{h.c.}$$

- We take

$$\lambda_{h\phi}\left(m_{\text{Pl}}\right) = 0 \qquad \text{and} \qquad \sigma\left(m_{\text{Pl}}\right) = 0$$

- At leading order

$$\lambda_{h\phi} \simeq \frac{\left|\lambda_\nu y_\nu\right|^2}{2\pi^2} \ln \frac{m_{\text{Pl}}}{\mu}$$

$$\sigma \simeq -\frac{M \left|y_\nu\right|^2 \text{Re}\lambda_\nu}{2\pi^2} \ln \frac{m_{\text{Pl}}}{\mu}$$

- The bound

$$\lambda_{h\phi} < 3 \times 10^{-8} \qquad \Rightarrow \qquad y_\nu < 0.2$$

$$|\sigma| < 10^8 \text{ GeV} \qquad\qquad M < 4 \times 10^{12} \text{ GeV}$$