# Higgs Dynamics During And After Inflation

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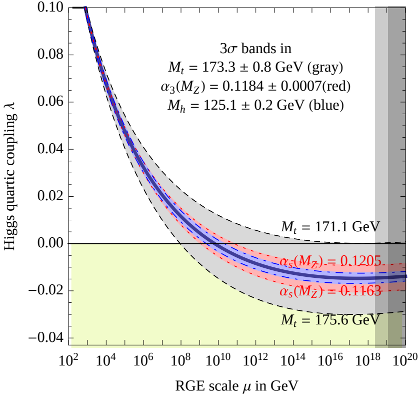
# Running of the Higgs self coupling

Buttazzo et al., 1307.3536

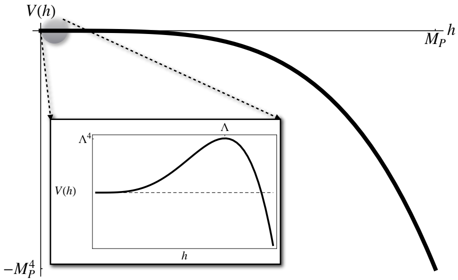



Main contribution at one loop

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\ln\mu} \propto \alpha m_H^4 - \beta m_t^4$$

$\lambda$ turns negative at $\sim 10^{10}\mathrm{GeV}$!

# The SM Higgs potential




Cosmological puzzles:

- What put the Higgs in the EW vacuum?
- Why it remained there during inflation?

# Possible solutions

Introduce the couplings

- $\frac{1}{2}\lambda_{h\phi}h^2\phi^2$
- $\frac{1}{2}\xi h^2 R$

Lebedev & Westphal, 1210.6987

Espinosa, Giudice, Riotto, 1210.6987

Can give a mass for the Higgs that makes it roll towards the origin

$$h \sim h(0)e^{-3Ht/2}$$

# Full potential for the Higgs

Both couplings are generated via loops:

- $\lambda_{h\phi}$ is implied by reheating

Gross, Lebedev, MZ, 1506.05106

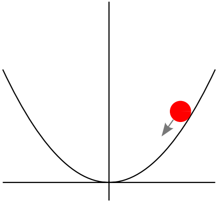

- $\xi$ is generated via graviton interaction

For $h \gg v$ the full Higgs potential takes the form

$$V = \lambda h^4 + \frac{1}{2}\xi R h^2 + \frac{1}{2}\lambda_{h\phi}\phi^2 h^2 + \sigma \phi h^2$$

# Preheating

After inflation the inflaton oscillates around its minimum



$$V(\phi) = \frac{1}{2}m^2\phi^2$$

$$\phi \simeq \Phi \cos mt \quad \text{with} \quad \Phi \sim \Phi_0\, a^{-3/2}$$

- Can lead to resonant production of Higgs particles

$\langle h^2 \rangle \propto$ Number of Higgs quanta

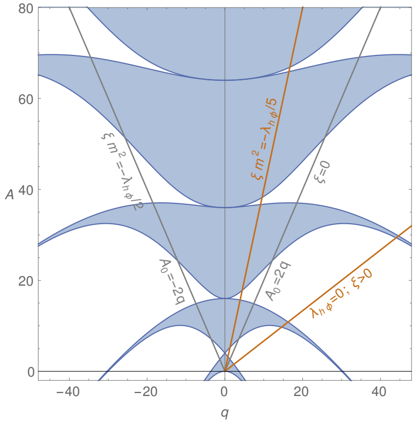
# Preheating with non-zero $\lambda_{h\phi}$ and $\xi$

Mathieu Equation: $$X_k'' + (A_k + 2q\cos 4z)\, X_k = 0 \qquad z = mt/2$$

with

$$A_k = \left(\frac{k}{ma}\right)^2 + 2\left(\lambda_{h\phi} + \xi m^2\right)\frac{\Phi^2}{m^2}$$

$$q = \left(\lambda_{h\phi} + 3\xi m^2\right)\frac{\Phi^2}{m^2}$$




## Strength of the resonance:

- Angle of the line
- Speed of the crossing

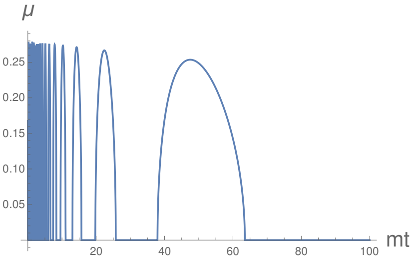
Ema, Karciauskas, Lebedev, MZ, 1703.04681

# Preheating with non-zero $\lambda_{h\phi}$ and $\xi$

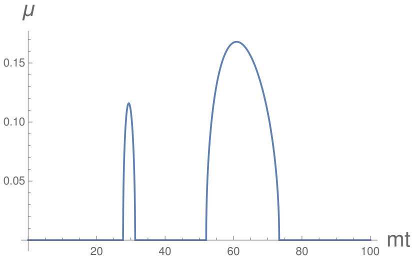
When the mode $k$ is in the white region its amplitude grows as

$$X_k \propto e^{\mu \, \Delta m t}$$

$A_0 = 2q$



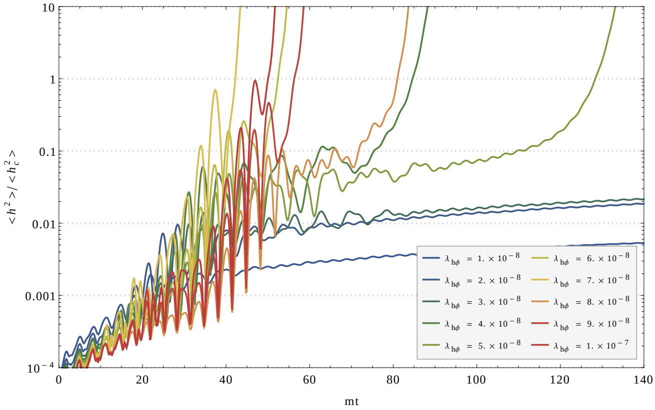

$A_0 = 3q$




Ema, Karciauskas, Lebedev, MZ, 1703.04681

# Evolution of $\langle h^2 \rangle$

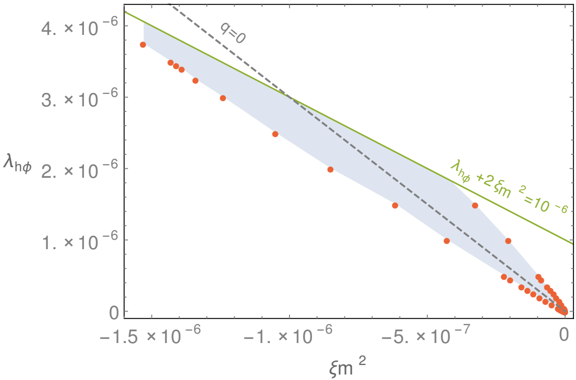
$$\langle h^2 \rangle \simeq \int \frac{d^3k}{(2\pi a)^3} |X_k|^2 \longrightarrow \text{induces a negative mass term } 3\lambda \langle h^2 \rangle$$




Enqvist, Karciauskas, Lebedev, Rusak, MZ, 1608.08848

# Lattice results

Stable region obtained via classical lattice simulations




Ema, Karciauskas, Lebedev, MZ, 1703.04681

# Adding the trilinear coupling $\sigma$

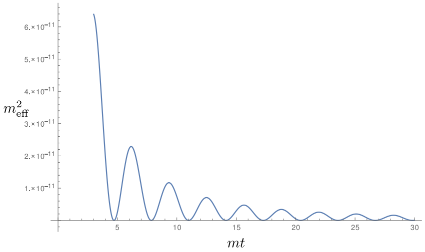
Eigenmodes evolve according to the Whittaker-Hill equation

$$X_k'' + (A_k + 2p\cos 2z + 2q\cos 4z)\, X_k = 0$$

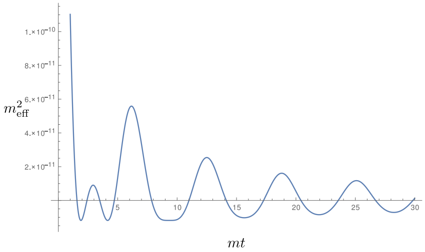
where $p = 2\,\sigma\,\Phi/m^2$

- Two different frequencies
- Higgs tachyonic during part of the oscillation

Without $\sigma h^2\phi$




With $\sigma h^2\phi$



# Conclusions

The couplings $\xi$ and $\lambda_{h\phi}$ can affect dramatically the Higgs dynamics

In particular they:

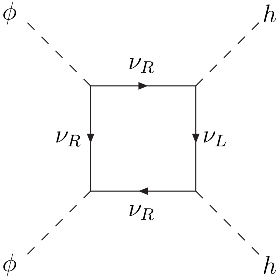
- can explain how the universe ended up in the EW vacuum
- are generated by quantum effects
- can destabilize the vacuum during preheating

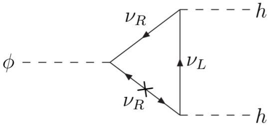
# Thank you

# Example: right-handed neutrino

$$-\Delta\mathcal{L} = \lambda_\nu \phi \nu_R \nu_R + y_\nu h \bar{\nu}_L \nu_R + M \nu_R \nu_R + \text{h.c.}$$

At one-loop



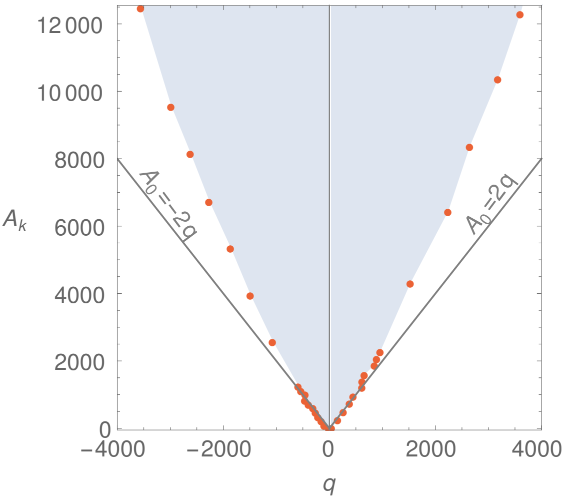




Need to add the counterterms

$$-\Delta\mathcal{L} \supset \lambda_{h\phi} h^2 \phi^2 + \sigma_{h\phi} h^2 \phi$$

# Lattice results

Parameter space for stability up to the end of preheating:




Ema, Karciauskas, Lebedev, MZ, 1703.04681