Some like it hot: R^2 term heals Higgs inflation, but does not cool it

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The talk is based on arxiv:1807.02392, arxiv:1904.04737

Standard Model Higgs inflation

A minimal model for the inflationary stage — no new fields added

Action for the Higgs boson in a unitary gauge ($\mathcal{H} = h/\sqrt{2}$)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_p^2 + \xi h^2}{2}R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda}{4}(h^2 - v^2)^2\right)$$

Einstein frame action

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_p^2}{2}R + \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda}{4}\frac{(h(\chi))^4}{(1+\xi h(\chi)^2/M_p^2)^2}\right)$$

$$\frac{d\chi}{dh} = \frac{\sqrt{1+\xi(1+6\xi)h^2/Mp^2}}{1+\xi h^2/M_p^2}$$

$$h > M_p/\sqrt{\xi}, \;\; V(\chi) \simeq \frac{\lambda M_p^4}{4\xi^2}\left(1 - e^{-2\chi/(\sqrt{6}M_p)}\right)^2$$

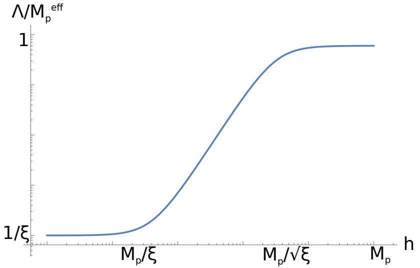
In order to produce CMB normalization one needs $\lambda/\xi^2 \simeq 4\times 10^{-10}$, $\xi \sim 10^4$.

Field-dependent cutoff scale

Until which scale is it a valid description?

In the small field domain ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}/M_p$) the minimal suppression scale of non-renormalizable operator

$$L_{int} = \frac{\xi h^2 \partial^2 h^\mu_\mu}{M_p} \rightarrow \Lambda = \frac{M_p}{\xi}$$



Why UV completion is reqiured?

- Connection between the inflationary parameters and low energy physics
- Description of the preheating and reheating process

Y.Ema, R. Jinno et al., arXiv:1609.05209
M. DeCross, D. Kaiser, A. Prabhu, arXiv:1610.08916

$$T_{reh} \sim 10^{-3} M_p \gtrsim \frac{M_p}{\xi}$$

Reheating can not be described in the Higgs inflation model!

UV completion with R^2-term

The Starobinsky inflation is safe from the low cutoff scale problem: $\Lambda \sim M_p$.

$$S_0 = \int d^4x\sqrt{-g}\left(-\frac{M_p^2 + \xi h^2}{2}R + \frac{\beta}{4}R^2 + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda}{4}(h^2 - v^2)^2\right)$$

How does it work?

- Introduce a Lagrange multiplier L and an auxiliary scalar $\mathcal{R}$,

$$S = \int d^4x\sqrt{-g}\left(L_h - \frac{M_p^2 + \xi h^2}{2}\mathcal{R} + \frac{\beta}{4}\mathcal{R}^2 - L\mathcal{R} + LR\right)$$

- Integrate out the field $\mathcal{R}$: the problematic ξ appears only in the potential

$$S = \int d^4x\sqrt{-g}\left(L_h + LR - \frac{1}{4\beta}(L + \frac{1}{2}\xi h^2 + \frac{1}{2}M_p^2)^2\right)$$

- L is a dynamical field connected to the scalar graviton (scalaron)

Einstein frame action

Hereafter we use $M_p = 1/\sqrt{6}$

$$S = \int d^4x\sqrt{-g}\left(-\frac{R}{12} + \frac{1}{2}e^{-2\phi}(\partial h)^2 + \frac{1}{2}(\partial\phi)^2 - \right.$$

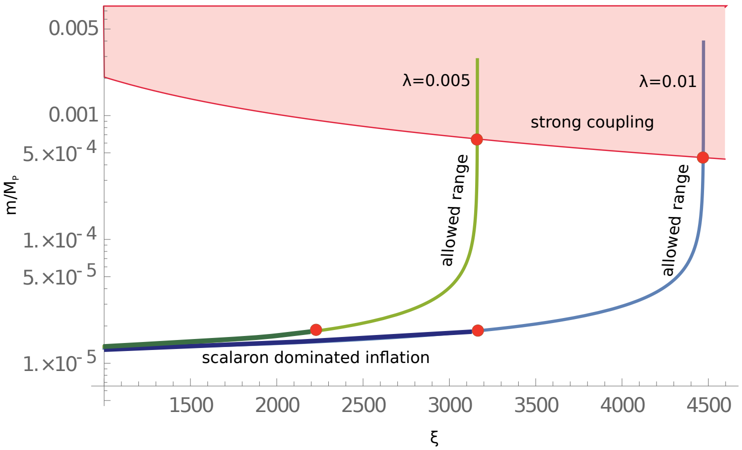
$$\left. -\frac{1}{4}e^{-4\phi}\left(\lambda h^4 + \frac{1}{36\beta}(e^{2\phi} - 1 - 6\xi h^2)^2\right)\right)$$

Y. Ema, arXiv:1701.07665

Bounds on β:

- No strong coupling $\rightarrow$ $\xi^2/\beta \lesssim 1 < 4\pi$
- CMB normalization can be satisfied if $\beta + \xi^2/\lambda = 2 \times 10^9$

Bounds on the scalaron mass



R^2 term: a proper variables

Which field interacts with gauge bosons and fermions?

$$L_{kin} = \frac{1}{2}e^{-2\phi}(\partial h)^2 + \frac{1}{2}(\partial\phi)^2$$

It is a mixture of ϕ and h.
New variables: $h = e^{\Phi}\tanh H$, $\phi = e^{\Phi}/\cosh H \rightarrow$ Higgs is canonical

$$L_{kin} = \frac{1}{2}\cosh^2 H(\partial\chi)^2 + \frac{1}{2}(\partial H)^2$$

$$V = \frac{1}{4}\left(\lambda\sinh^4 H + \frac{1}{36\beta}(1 - e^{-2\Phi}\cosh^2 H - 6\xi\sinh^2 H)^2\right)$$

$$L_{gauge} = \frac{g^2h^2}{4}e^{-2\phi}W_\mu^+W_\mu^- = \frac{g^2}{4}\sinh^2 H\ W_\mu^+W_\mu^-$$

Unitarity breaking scale

Standard model:

$$m_W = \frac{1}{2} g h$$

R^2- Higgs:

$$m_W = \frac{g}{2} \sinh H$$

The growing part of amplitude

$$\mathcal{A} \sim \frac{g^2 p^2}{m_W^2} \left(\frac{4}{g^2} \left(\frac{d m_W(H)}{dH} \right)^2 - 1 \right) \sim \frac{p^2}{6 M_p^2}$$

$$\Lambda_U = \sqrt{6} M_p$$

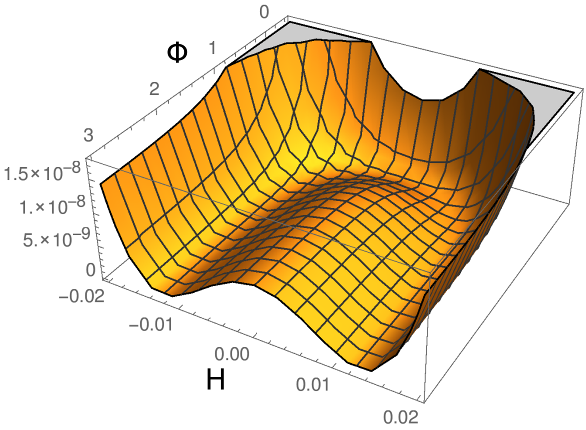
Higgs inflation:

$$\Lambda_U = \frac{M_p}{\xi}, \ H \sim v \quad \Lambda_U = \frac{M_p}{\sqrt{\xi}}, \ H \sim M_p$$

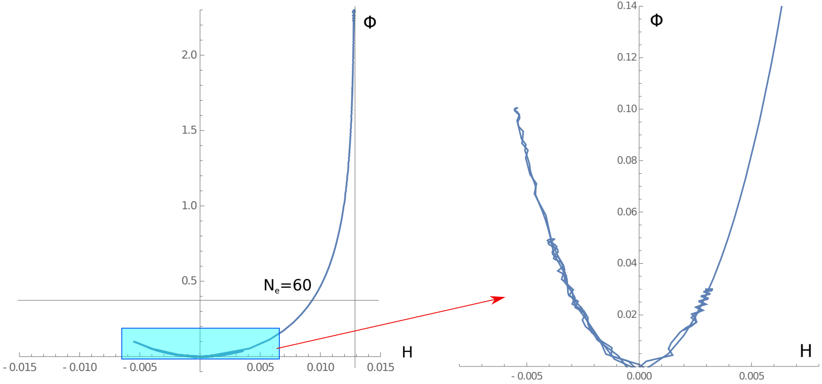
F. Bezrukov, A. Magnin, M. Shaposhnikov and S. Sibiryakov, arxiv:1008.5157

Potential: who drives inflation?

$$V = \frac{1}{4}\left(\lambda \sinh^4 H + \frac{1}{36\beta}(1 - e^{-2\chi}\cosh^2 H - 6\xi \sinh^2 H)^2\right)$$



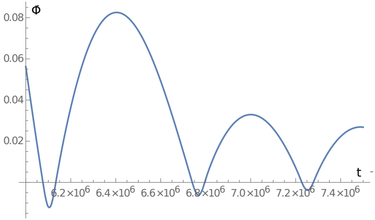
Tragectory

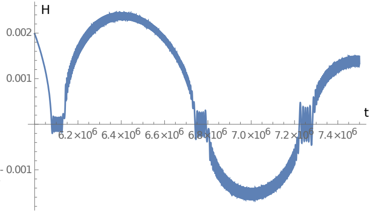

Φ
2.0
1.5
1.0
0.5
N_e=60
H
- 0.015
- 0.010
- 0.005
0.005
0.010
0.015
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Φ
H
- 0.005
0.000
0.005

Reheating: background dynamics

Oscillation timescales:

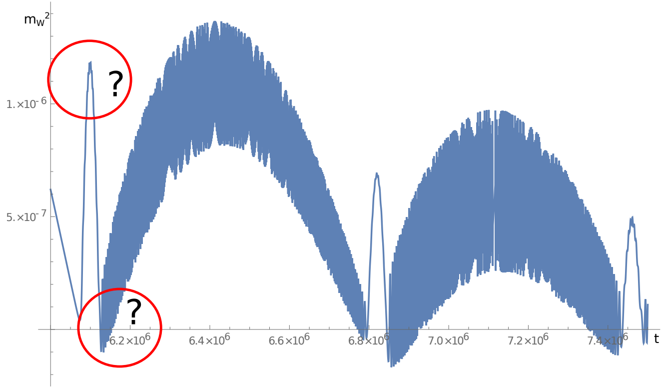
- Scalaron: $m^2 = 1/(18\beta)$
- Oscillations around the minimum: $M^2_{min} = \lambda\Phi/\xi$
- Fast oscillations in the valley: $M^2 = 2\Phi/(3\beta)$





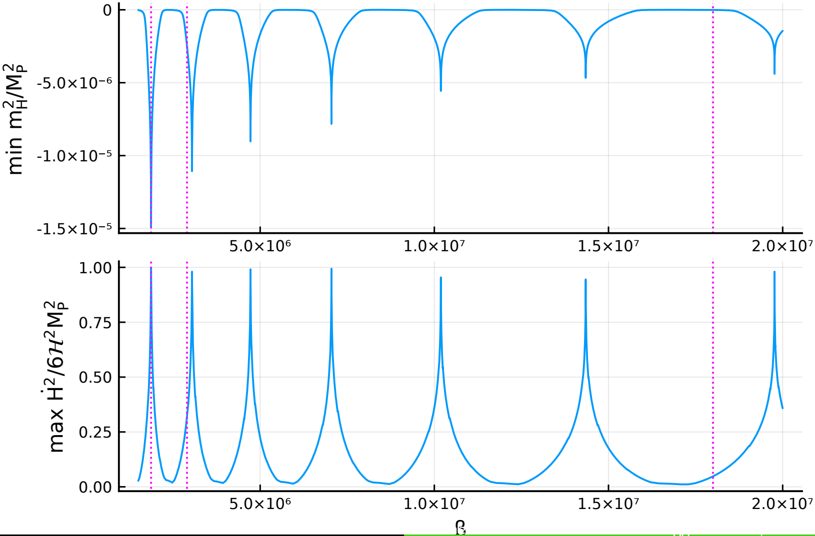
Which process is responsible for reheating?

Production of weak gauge bosons (longitudinal components)?



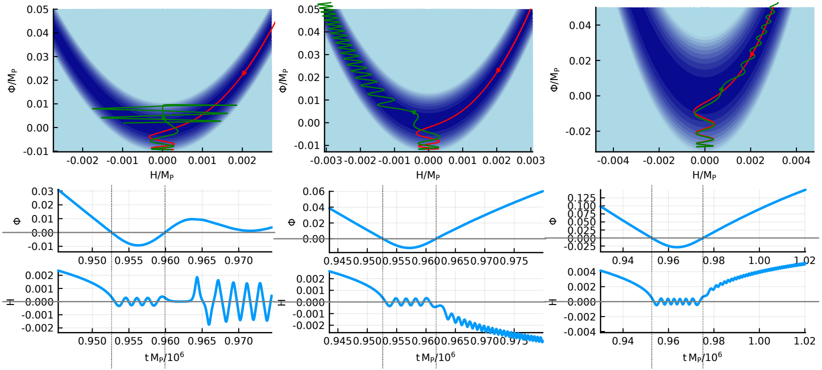
Minxi He, Ryusuke Jinno, Alexei A. Starobinsky et al., arXiv:1812.10099

Chaotic behaviour of the background: resonant points of the scalaron mass



Reheating: two field dynamics

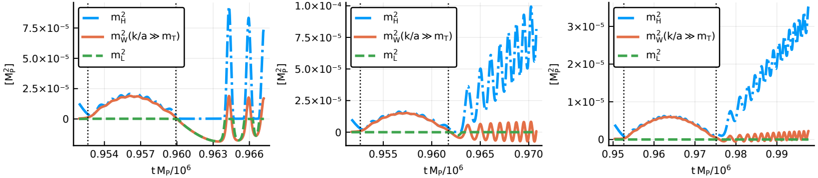
Oscillations after inflation



Reheating: tachionic modes

The inflaton background can produce:

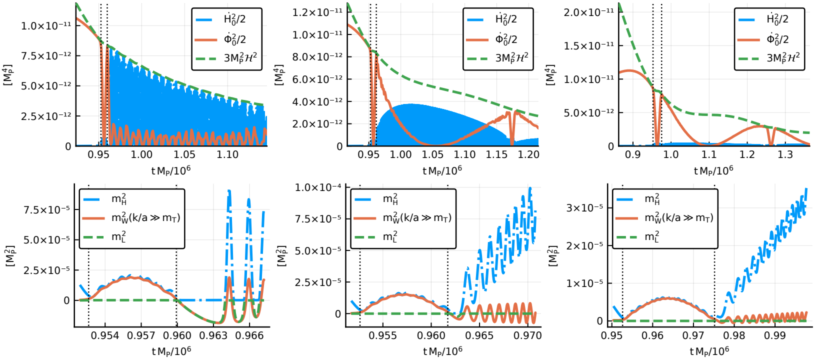
- 'Higgs' modes, $m_H^2 = V_{HH}$
- weak gauge bosons, $m^2 = V_H / \tanh H - 4V$



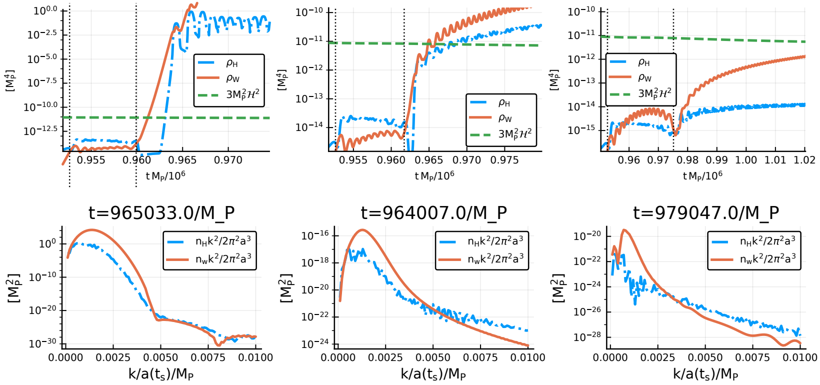
Decay of the modes:

- $\Gamma_W = 0.8\alpha_W \langle m_W \rangle \sim m$
- $\Gamma_H = 0.1 y_b^2 \langle m_H \rangle \ll m$

Energy balance



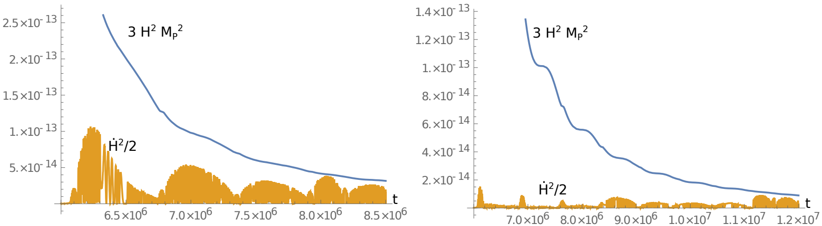
Reheating: production of radial Higgs modes and longitudinal gauge bosons



Results for the reheating temperature

What if we are not in the 'resonant' point?

- Back reaction has to be included.
- However, after small number of crossings we anyway fall into the region where a lot of energy is stored in the Higgs field.



Instant reheating, $T_{reh} \simeq 10^{15}$ GeV Predictions:

$$N_e = 59 \quad n_s = 0.97 \quad r = 0.0034$$

Conclusions

- Higgs inflation can be UV completed up to the Planck scale
- The completion can be achieved by means of introducing only one extra term in the lagrangian (R^2-term)
- At the beginning, inflation is driven by the R^2 degree of freedom, then the trajectory turns to a Higgs direction
- R^2 term can also improve the stability of Higgs potential for a certain range of top quark masses
- In this model, the reheating is instant. It lasts much less than the Hubble time.
- For several special values of the scalaron mass the reheating comes after the first zero crossing of the scalaron. For other points, the back reaction is important.

Thanks for your attention!