A simple UV completion for Higgs and Higgs-dilaton inflation.

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May, 31

Standard Model Higgs inflation

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

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

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

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

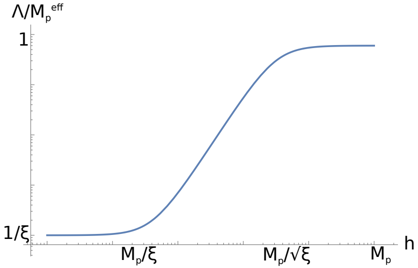
In order to produce CMB normalization one needs $\lambda/\xi^2 \simeq 4 \times 10^{-10}$, $\xi \sim 10^4$.

Field-dependent cutoff scale

Until which scale it is 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

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



Why UV completion is needed?

- No way to make the cutoff scale higher than the Planck mass is expected $\Rightarrow$ having $\Lambda \sim M_p$ is already a good improvement
- 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

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

UV completion with R^2-term

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

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 appear only in the potential

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

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

Einstein frame action

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

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

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

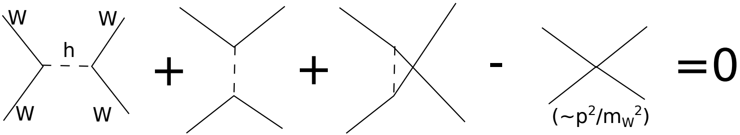
Y. Ema, arXiv:1701.07665

Bounds on β:

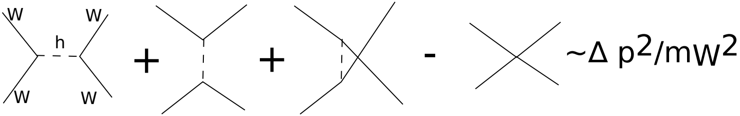
- No strong coupling $\rightarrow$ $\xi^2/\beta \lesssim 1 < 4\pi$
- CMB normalization can be satisfied if $\lambda < \xi^2/\beta$

Unitarity in the gauge sector

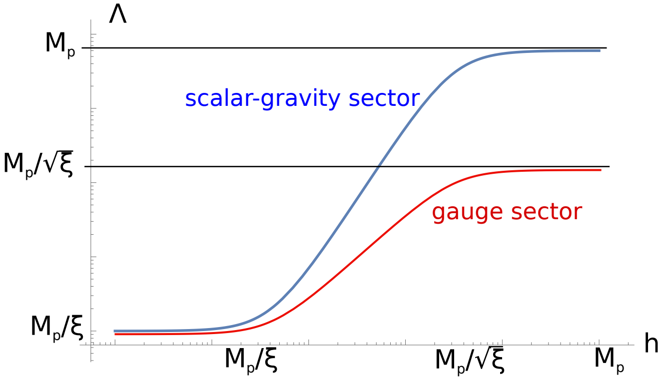
Scattering of the gauge bosons (longitudinal modes)
In the Standard model the growing part of the amplitude is cancelled



If the Higgs interactions are modified there is no cancellation anymore



Gauge bosons unitarity cutoff in Higgs inflation



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: $h = e^\chi \tanh H, \ \phi = e^\chi / \cosh H \rightarrow$ Higgs is canonical

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

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

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

Unitarity breaking scale

Standard model:

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

R^2- Higgs:

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

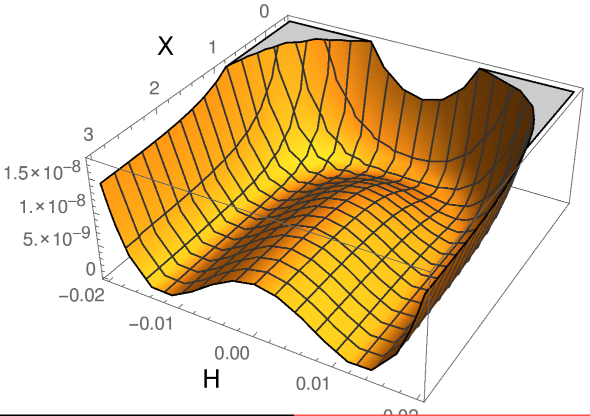
The growing part of amplitude

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

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

Potential: who drives inflation?

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



Recovering Higgs inflation

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

Valley:

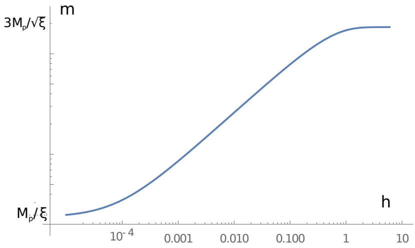
$$1 - e^{-2\chi}\cosh^2 H - 6\xi \sinh^2 H = 0$$

After integrating out heavy field and canonical normalization

$$V = \frac{1}{4}\frac{\lambda}{36\xi^2}(1 - e^{-2\bar{\chi}})^2, \quad \chi \gtrsim M_p$$

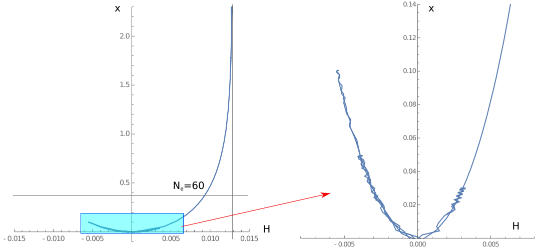
Validity of the single-field approximation

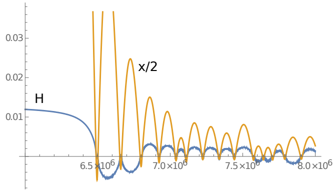
Effective mass of the orthogonal perturbation



$$m(0,0) = \frac{M_p}{\sqrt{3\beta}}, \quad \beta \sim \xi^2 \ \rightarrow m \sim \Lambda_c = \frac{M_p}{\xi}$$

Tragectory

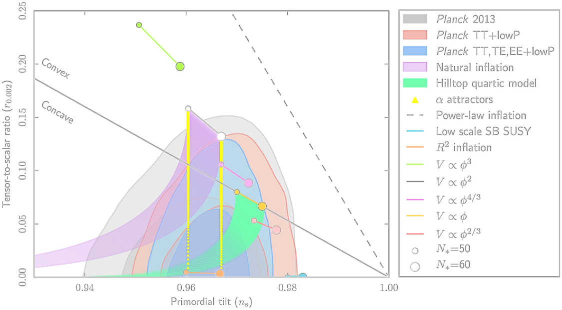

x
2.0
1.5
1.0
0.5
N_e=60
H
- 0.015
- 0.010
- 0.005
0.005
0.010
0.015
0.14
0.12
0.10
0.08
0.06
0.04
0.02
x
H
- 0.005
0.000
0.005


0.03
0.02
0.01
H
x/2
6.5×10^6
7.0×10^6
7.5×10^6
8.0×10^6

Predictions

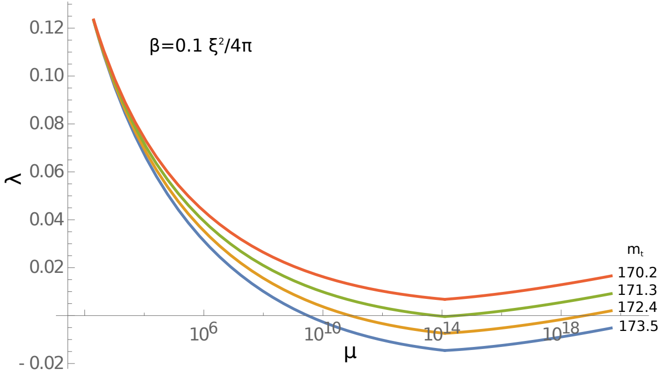
$$n_s = 1 - \frac{2}{N} = 0.966, \quad r = \frac{12}{N^2} = 0.0033$$

M. He, A. A. Starobinsky, J. Yokoyama, 1804.00409



Improving the stability of the Higgs potential

$$\delta\beta_\lambda = \frac{1}{16\pi^2}\frac{2\xi^2(1+6\xi)^2}{9\beta^2}$$



A scale invariant extension of the Standard model

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}[(\partial_\mu X)^2 - \xi X^2 R - \xi' h^2 R + (\partial_\mu h)^2] - \frac{\lambda}{4}(h^2 - \alpha^2 X^2)\right.$$

- Planck mass and Higgs vev are provided by the dilatov vev $\langle X \rangle$
- Scale invariance is broken spontaneousely
- This symmetry can be preserved at the quantum level if the renormalization scale is given by the dilaton vev
- The model can describe inflation with $\xi' \sim 10^3$, $\xi \lesssim 10^{-3}$

Higgs-dilaton inflation

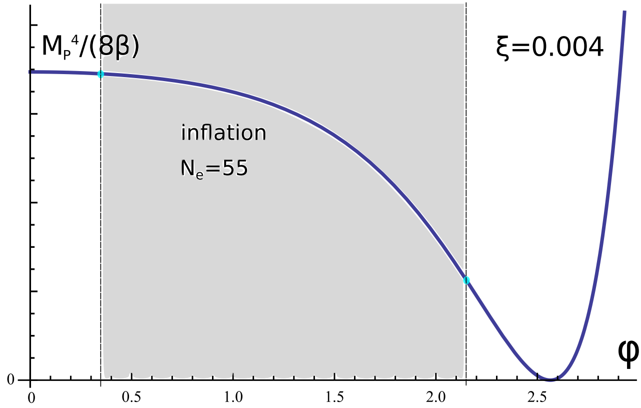
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}[(\partial_\mu X)^2 - \xi X^2 R - \xi' h^2 R + (\partial_\mu h)^2] - \frac{\lambda}{4}(h^2 - \alpha^2 X^2)\right.$$

In the Einstein frame ($\xi \ll \xi'$, inflation)

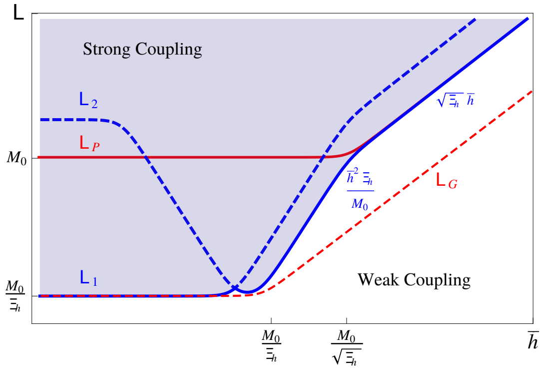
$$S = \int d^4x\sqrt{-g}\left(-\frac{M_p}{2}R + \frac{1}{2}\cosh^2\left(\frac{\phi}{\sqrt{6}M_p}\right)(\partial_\mu r)^2 + \frac{1}{2}(\partial_\mu \phi^2)\right) - V$$

$$V \simeq \frac{\lambda M_P^4}{\xi'^2}\left(1 - 6\xi\sinh^2\left(\frac{\phi}{\sqrt{6}M_p}\right)\right)^2$$

Picture of potential



Cutoff scales



F. Bezrukov, G. Karananas, et. al, arXiv:1212.4148

UV completion with R^2 term

R^2 term can provide a minimal UV completion up to Planck scale

$$S = \int d^4x\sqrt{-g}\,\left[\frac{1}{2}[\beta R^2 + (\partial_\mu X)^2 - \xi X^2 R - \xi' h^2 R + (\partial_\mu h)^2] - \frac{\lambda}{4}h^4\right]$$

In the Einstein frame

$$L = \frac{1}{2}\left((\partial H)^2 + \cosh^2 H(\partial\phi^2) + \cosh^2 H\cosh^2\phi(\partial\rho)^2\right) -$$

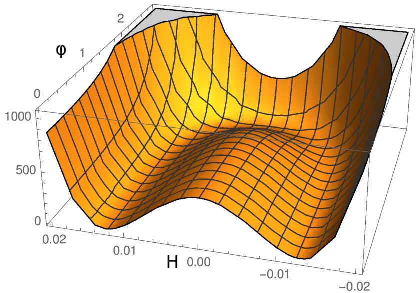
$$-\frac{1}{4}\left(\lambda\sinh^4 H + \frac{1}{36\beta}(1 - 6\xi\sinh^2\phi\cosh^2 H - 6\xi'\sinh^2 H)^2\right)$$

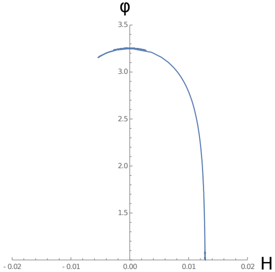
Here H is Higgs, ϕ is scalaron, ρ is dilaton (Goldstone boson)

$$L_{gauge} = \frac{g^2}{4}\sinh^2 H\;W^+_\mu W^-_\mu$$

The cutoff scale is again $\sqrt{6}M_p$

Potential and trajectories





$$n_s = 1 - 8\xi \coth\left(4\xi N\right) \sim 1 - \frac{1}{2N}, \quad \xi \lesssim 0.004$$

Conclusions

- Both Higgs and Higgs-dilaton 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

Thanks for your attention!