Higgs inflation at the pole

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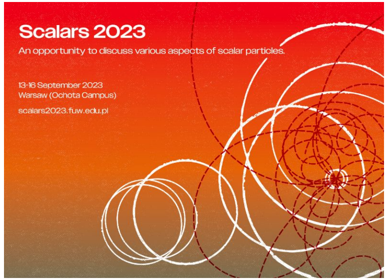
Based on *Higgs Inflation at the Pole*, SC, Hyun Min Lee and Adriana Menkara, **2306.07767**



Original Higgs-Inflation framework

Higgs-Inflation is interesting because you can (in principle) *connect physics at high-energy inflationary scale to low-energy Higgs physics* constrained at LHC. The original model is simple :

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R$$

Bezrukov and Shaposhnikov, **0710.3755**

➡ Need a *large non-minimal coupling to gravity ξ ~ 10^4* to accommodate inflation with CMB constraints

While the cutoff scale of the *EFT is "large"* $\Lambda \sim \frac{M_{\rm Pl}}{\sqrt{\xi}}$ *during inflation,* unitarity can still be violated during preheating through resonant collective effects , for such large ξ

Burgess, Lee, Trott, **0902.4465, 1002.2730**, Barbon, Espinosa, **0903.0355**, Hertzberg, **1002.2995**, Bezrukov, Magnin, Shaposhnikov,Sibiryakov, **1008.5157**

Ema, Jinno,Mukaida, Nakayama, **1609.05209**, Hamada, Kawana, Scherlis, **2007.04701**, Lebedev, Mambrini, Yoon, **2305.05682**

The model

We consider an alternative to the original *Higgs-inflation scenario, without large non-minimal couplings*

➡ Higgs field with a *conformal coupling to gravity* in the Jordan frame :

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2} M_P^2 \Omega(H) R(g_J) + |D_\mu H|^2 - V_J(H)$$

conformal non-minimal coupling to gravity

$$\Omega(H) = 1 - \boxed{\frac{1}{3M_P^2}} |H|^2$$

with

$$V_J(H) = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \boxed{\sum_{n=3}^{\infty} \frac{c_n}{\Lambda^{2n-4}} |H|^{2n}}$$

consider first a generic Higgs EFT

The model

- In Jordan frame

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}M_P^2\,\Omega(H)R(g_J) + |D_\mu H|^2 - V_J(H)$$

Performing the Weyl transformation from the Jordan frame to the Einstein frame

- In Einstein frame

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_P^2 R(g_E) + \frac{|D_\mu H|^2}{\boxed{\left(1-\frac{1}{3M_P^2}|H|^2\right)^2}} - \frac{\Omega^{-2}(H)}{3M_P^2}\left(|H|^2|D_\mu H|^2 - \frac{1}{4}\partial_\mu|H|^2\partial^\mu|H|^2\right) - V_E(H)$$

pole of Higgs kinetic term

with $V_E(H) = \frac{V_J(H)}{\boxed{\left(1-\frac{1}{3M_P^2}|H|^2\right)^2}}$

The model

- In Jordan frame

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pole of Higgs kinetic term

with $V_E(H) = \dfrac{V_J(H)}{\boxed{\left(1-\frac{1}{3M_P^2}|H|^2\right)^2}}$

in unitary gauge

The model

Our model is then the following one :

$$\boxed{V_J(H) = c_m \Lambda^{4-2m} |H|^{2m} \left(1 - \frac{1}{3M_P^2}|H|^2\right)^2}$$

a specific EFT potential in the Jordan frame

Similar construction than *T-alpha attractor* models (also embedded in supergravity) Kallosh, Linde, **1306.5220**

$$\boxed{V_E(H) = 3^m c_m \Lambda^{4-2m} M_P^{2m} \left[\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^{2m}}$$

ϕ is the canonical field in Einstein frame

$$h = \sqrt{6} M_P \tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)$$

It corresponds to a very simple EFT in the Einstein frame $V_E(H) = c_m \Lambda^{4-2m} |H|^{\boxed{2m}}$

parameter "m" determines the shape of Higgs-inflaton potential

The model

$$V_J(H) = c_m \Lambda^{4-2m} |H|^{2m} \left(1 - \frac{1}{3M_P^2}|H|^2\right)^2$$

$$V_E(H) = 3^m c_m \Lambda^{4-2m} M_P^{2m} \left[\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^{2m}$$

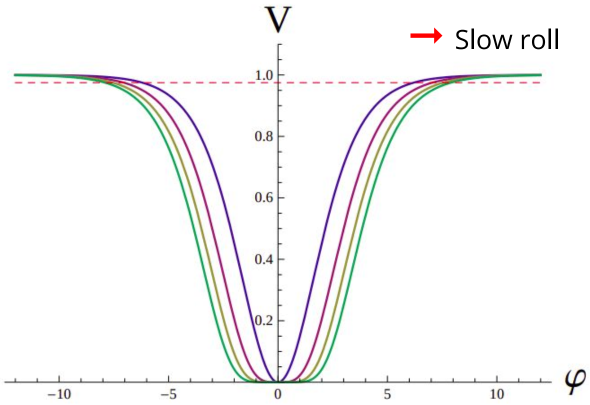


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

From Universality Class in Conformal Inflation, Kallosh and Linde, **1306.5220**

Higgs-Inflation takes place when h ~ MP ⇔ ϕ ≫MP, *at the pole*

Inflation is realized if :

1) Jordan frame *potential almost vanishes during inflation* ⇔ kinetic term diverges in Einstein

2) *Effective Planck mass* (i.e conformal coupling to gravity) is *close to vanish simultaneously* in the Jordan frame.

Slow-roll and CMB constraints

Same slow-roll as alpha-attractor models ; *depends slightly on the parameter m* which gives the shape of the potential after slow-roll

$$\begin{aligned} n_s &= 1 - 6\epsilon_* + 2\eta_* \\ &= 1 - \frac{4N+3}{2\left(N^2 - \frac{9}{16m^2}\right)}. \end{aligned}$$

$$r = 16\epsilon_* = \frac{12}{N^2 - \frac{9}{16m^2}}.$$

Constraints on the EFT from CMB $\boxed{3^m c_m \left(\frac{\Lambda}{M_P}\right)^{4-2m} = (3.1 \times 10^{-8})\, r}$

In the case *m = 2* (i.e quartic potential shape around the minimum)
➡ *quartic Higgs coupling* at inflationary scale has to be $\lambda_H = 1.1 \times 10^{-11}$

Slow-roll and CMB constraints

For *successful EWSB we need negative Higgs quadratic coupling $\mu_{H,}$* and *large enough quartic coupling λ_{H}, at low energy*. We include systematically these terms :

$$V_J(H) = \left(V_0 + \mu_H^2|H|^2 + \lambda_H|H|^4 + \sum_{m=3}^{\infty} c_m \Lambda^{4-2m}|H|^{2m}\right)\left(1 - \frac{1}{3M_P^2}|H|^2\right)^2$$

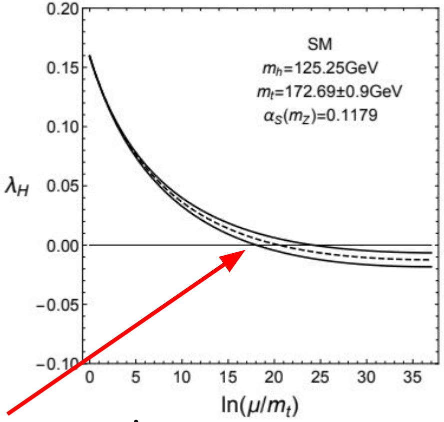
We can also have higher power terms that dominate the dynamics during and after inflation, for reheating :

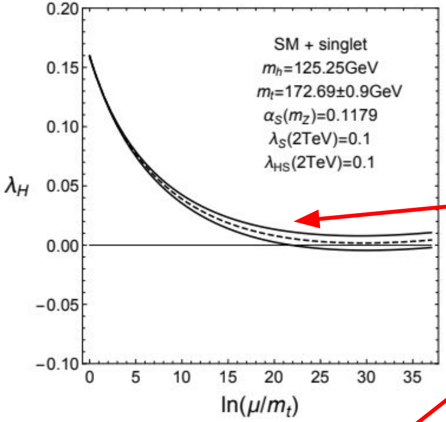
$$3^m c_m \left(\frac{\Lambda}{M_P}\right)^{4-2m} \gtrsim 9\lambda_H, \frac{3|\mu_H^2|}{M_P^2}, \frac{V_0}{M_P^4}$$

$$\boxed{\begin{aligned} \lambda_H &\gtrsim \frac{|\mu_H^2|}{3M_P^2} = 1.1 \times 10^{-15} \\ \lambda_H &\lesssim 1.1 \times 10^{-11} \end{aligned}}$$

➡ Need a sizable quartic coupling for Higgs physics at low energy, *but a small (and positive) quartic coupling during inflation*

Higgs quartic coupling running

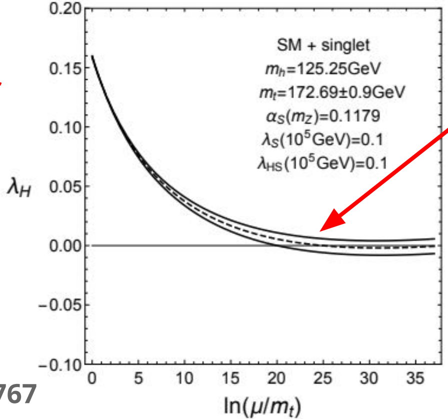




An *additional singlet scalar S,* can help to *achieve naturally small positive value of Higgs quartic coupling at inflationary scale*

Higgs quartic coupling *can run to negative values at inflationary* scale *in the SM*

$$V_E(S,H) = m_S^2|S|^2 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2$$



Higgs quartic coupling is also sensitive to masses in SM and subject to uncertainties at inflationary scale.

SC, Lee, Menkara, **2306.07767**

Supergravity embedding

Consider a modulus chiral multiplet T and a pair of Higgs chiral multiplets, Hu and Hd, which are conformally coupled to gravity in the Jordan frame

Ω, the conformal factor

$$K = -3M_P^2 \ln\boxed{\left(T + \bar{T} - \frac{1}{3M_P^2}|H_u|^2 - \frac{1}{3M_P^2}|H_d|^2\right)} \equiv -3M_P^2 \ln(\hat{\Omega}),$$

$$W = 2^{2k}\sqrt{\lambda_k}\, M_P^{3-2k} \boxed{\left(\frac{1}{k}(H_u H_d)^k - \frac{2}{3(k+1)M_P^2}(H_u H_d)^{k+1}\right)}$$

Wess-Zumino like superpotential

Need small coefficients of the superpotential for successful Higgs pole inflation, but immune to renormalization

➡ See *Universality Class in Conformal Inflation*, Kallosh and Linde, **1306.5220**, also derived in the context of no-scale supergravity in *Building Models of Inflation in No-Scale Supergravity*, Ellis et al, **2009.01709**, and Garcia et al, **2004.08404**

Supergravity embedding

Recover the same scalar part of the potential in Jordan frame

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}M_P^2\,\hat{\Omega}\,R + |D_\mu H_u|^2 + |D_\mu H_d|^2 - V_J + 3\hat{\Omega} b_\mu^2$$

where the Jordan frame potential V_J contains F and D terms :

$$\begin{aligned}\hat{V}_F &= \left|\frac{\partial W}{\partial H_u}\right|^2 + \left|\frac{\partial W}{\partial H_d}\right|^2 \\ &= 2^{4k}\lambda_k M_P^{6-4k}(|H_u|^2 + |H_d|^2)|H_u H_d|^{2(k-1)}\left|1 - \frac{2}{3M_P^2}H_u H_d\right|^2, \\ \hat{V}_D &= \frac{1}{8}g'^2(|H_u|^2 - |H_d|^2)^2 + \frac{1}{8}g^2\left((H_u)^\dagger\vec{\tau}H_u + (H_d)^\dagger\vec{\tau}H_d\right)^2.\end{aligned}$$

Running Higgs quartic couplings remain sizable because they are determined by the SM gauge couplings.

In D-flat direction, the effective Higgs quartic coupling is dynamically relaxed to zero:

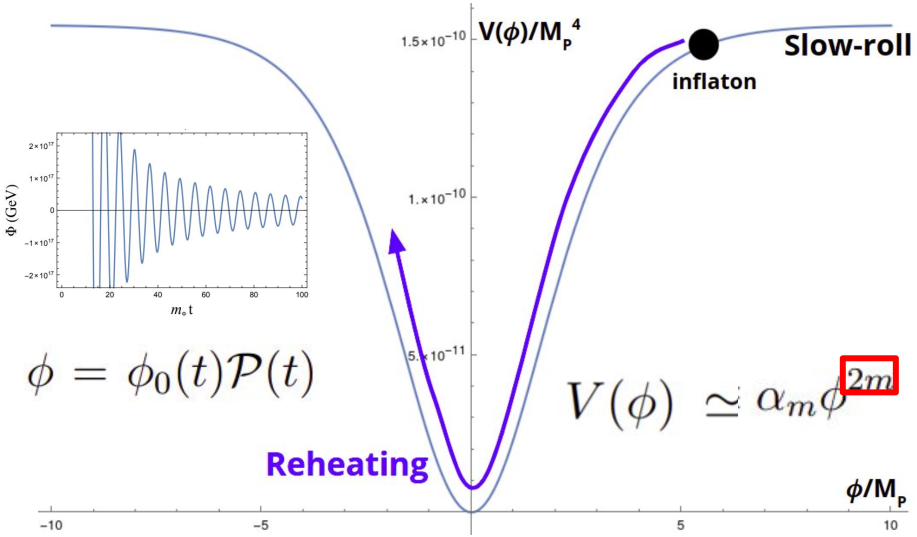
$$\boxed{V_J = 8\lambda_k M_P^{6-4k} h^{4k-2}\left(1 - \frac{1}{6M_P^2}h^2\right)^2}$$

same potential as the Higgs pole inflation

About (P)reheating

$|H| \ll \sqrt{6} M_P$ away from the pole, $V_E(\phi) \simeq \frac{c_m}{2^m} \Lambda^{4-2m} \phi^{2m} \equiv \alpha_m \phi^{\boxed{2m}}$

Reheating occurs while Higgs oscillates around the minimum of the potential, with generic equation of state



Oscillations depend on the *shape of the potential near the minimum*, i.e the *average equation of state of the Higgs condensate*

$$w = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\langle\dot{\phi}^2\rangle - \langle V(\phi)\rangle}{\frac{1}{2}\langle\dot{\phi}^2\rangle + \langle V(\phi)\rangle} = \boxed{\frac{m-1}{m+1}}$$

About (P)reheating

Higgs-inflaton have couplings to SM fermions and bosons, with potentially large effective masses during oscillations of the Higgs after inflation

$$\begin{aligned}\langle \Gamma_{\phi\to f\bar{f}}\rangle &= \frac{y_f^2\phi_0^2\omega^3}{8\pi(1+w_\phi)\rho_\phi}\sum_{n=-\infty}^{\infty} n^3|\mathcal{P}_n|^2\langle\beta_n^3\rangle \\ &= \frac{y_f^2\omega^3}{8\pi m_\phi^2}(m+1)(2m-1)\Sigma_m^f\left\langle\left(1-\frac{\boxed{4m_f^2}}{\omega^2 n^2}\right)^{3/2}\right\rangle\end{aligned}$$

we have to consider effective mass mf ~ y.ϕ(t) during oscillations (similarly for gauge bosons)

Perturbative decays to SM fermions dominate for m = 1 and m = 2 over scatterings towards gauge bosons and lead to high reheating temperature even from perturbative channels

SC, Lee, Menkara, **2306.07767**

m	$T_{\rm RH}$ [GeV]
1	5.1×10^{13}
2	2.6×10^{9}

reheating temperature achieved through perturbative decays towards fermions, for equation of state m = 1, m = 2.

For higher m, scattering towards gauge bosons can dominate Garcia, Kaneta, Mambrini, Olive, **2012.10756**

About (P)reheating

During preheating fragmentation of Higgs condensate into perturbations modifies the equation of state of the Higgs fluid Garcia, Pierre, **2306.08038**

$$\ddot{\varphi}_k + 3H\dot{\varphi}_k + \left(\frac{k^2}{a^2} + m_\varphi^2(t) + 6\xi_H\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2}\right)\right)\varphi_k = 0$$

Excitations of gauge bosons and perturbations of Higgs can be sourced from time dependent effective mass, that can trigger tachyonic instabilities

$$\frac{m^2 m_\varphi^2(t)}{\omega^2} = \mathcal{P}^{2m-2}(t) \qquad \frac{m^2 m_W^2(t)}{\omega^2} = \frac{g^2}{8\pi\alpha_m}\boxed{\phi_0^{4-2m}}(t)\mathcal{P}^2(t) \quad \text{where} \quad \frac{c_m}{2^m}\Lambda^{4-2m} \equiv \alpha_m$$

The effective mass of gauge bosons depends on the amplitude of the inflaton oscillations

Preheating could lead to higher reheating temperature than the perturbative reheating (*in progress !*)

In progress

➡ Extension of the model to dynamically relax Higgs quartic coupling to small values during inflation, in a non-supergravity construction

➡ Numerical analysis of the preheating in the general potential after inflation, taking into account resonances, backreactions, rescattering using Lattice simulations

➡ Taking into account fragmentation of the background condensate during its oscillations

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Thank you!

Backup slides

The model

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_P^2 R(g_E) + \frac{|D_\mu H|^2}{\boxed{\left(1 - \frac{1}{3M_P^2}|H|^2\right)^2}}$$

$$-\frac{\Omega^{-2}(H)}{3M_P^2}\left(|H|^2|D_\mu H|^2 - \frac{1}{4}\partial_\mu|H|^2\partial^\mu|H|^2\right) - V_E(H)$$

with $$V_E(H) = \frac{V_J(H)}{\boxed{\left(1 - \frac{1}{3M_P^2}|H|^2\right)^2}}.$$

The *canonical field* is then the following one

$$h = \sqrt{6}M_P \tanh\left(\frac{\phi}{\sqrt{6}M_P}\right) \longrightarrow \frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_P^2 R + \frac{1}{2}(\partial_\mu\phi)^2 - V_E(\phi).$$

$$\boxed{V_E(\phi) = \cosh^4\left(\frac{\phi}{\sqrt{6}M_P}\right)V_J\left(\sqrt{3}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right)}$$

Inflation is possible depending on the shape of the Jordan frame potential for Higgs field

About (P)reheating

m	T_{RH} [GeV]
1	5.1×10^{13}
2	2.6×10^{9}
3	260
4	9.4×10^{5}
5	2.1×10^{7}
6	1.1×10^{8}
7	2.8×10^{8}
8	4.9×10^{8}
9	8.4×10^{8}
10	1.2×10^{9}

Table 2: Reheating temperature T_{RH}, determined from the decays of the Higgs inflaton into the SM fermions, including the kinematic suppression for the effective fermion masses. We chose some values of the equation of state parameter m during reheating.

About (P)reheating

But certainly more importantly, couplings to gauge bosons W, Z,

$$\langle \Gamma_{\phi\phi\to WW} \rangle = \frac{g^4 \phi_0^2 \omega}{16\pi m_\phi^2} (m+1)(2m-1)\Phi_W,$$

$$\langle \Gamma_{\phi\phi\to ZZ} \rangle = \frac{(g^2+g'^2)^2 \phi_0^2 \omega}{32\pi m_\phi^2} (m+1)(2m-1)\Phi_Z,$$

$$\Phi_V \equiv \Sigma_m^V \left\langle \frac{\beta_n^V (3 + 3(\beta_n^V)^4 - 2(\beta_n^V)^2)}{(1-(\beta_n^V)^2)^2} \right\rangle, \quad V = W, Z$$

Generalized Higgs pole expansions

Generalize the non-minimal coupling function and the Higgs potential (an expansion around the pole)

$$\Omega(H) = \left(1-\frac{1}{3M_P^2}|H|^2\right)\sum_{n=0}^{\infty}\tilde{b}_n\left(1-\frac{1}{3M_P^2}|H|^2\right)^n,$$

$$V_J(H) = \Lambda^{4-2m}|H|^{2m}\left(1-\frac{1}{3M_P^2}|H|^2\right)^2\sum_{n=0}^{\infty}\tilde{c}_n\left(1-\frac{1}{3M_P^2}|H|^2\right)^n$$

$$V_E(\phi) \simeq 3^m c_m \Lambda^{4-2m} M_P^{2m}\left(1-\left(4m-\frac{\hat{c}_1}{4c_m}\right)e^{-2\phi/(\sqrt{6}M_P)}+\cdots\right).$$

If $\hat{c}_1 \lesssim c_m$, the next order terms in the pole expansion are subdominants

1-loop RGEs

$$V_E(S,H) = m_S^2|S|^2 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2$$

$$\begin{aligned}
(4\pi)^2\frac{d\lambda_H}{d\ln\mu} &= \left(12y_t^2 - 3g'^2 - 9g^2\right)\lambda_H - 6y_t^2 + \frac{3}{8}\left[2g^4 + (g'^2+g^2)^2\right] + 24\lambda_H^2 + 4\lambda_{HS}^2, \\
(4\pi)^2\frac{d\lambda_{HS}}{d\ln\mu} &= \frac{1}{2}\left(12y_t^2 - 3g'^2 - 9g^2\right)\lambda_{HS} + 4\lambda_{HS}(3\lambda_H + 2\lambda_S) + 8\lambda_{HS}^2, \\
(4\pi)^2\frac{d\lambda_S}{d\ln\mu} &= 20\lambda_S^2 + 8\lambda_{HS}^2
\end{aligned} \tag{67}$$