Higgs inflation at the pole

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Overview

- Original Higgs inflation
- Higgs pole inflation
- (P)reheating
- Small quartic coupling and Sugra
- Summary

Higgs Inflation

No new evidence of physics BSM $\Longrightarrow$ **Inflaton = SM Higgs boson??**
Interesting possibility: if true, we could test the high energies of the early universe with our accessible EW data.

$$V = \lambda_H \left(H^\dagger H - \frac{v_H}{2} \right)^2$$

✖

$\lambda_H \longrightarrow \mathcal{O}\left(10^{-12}\right)$

Overproduction of density fluctuations

Unfortunately, the Higgs SM potential doesn't work to explain inflation

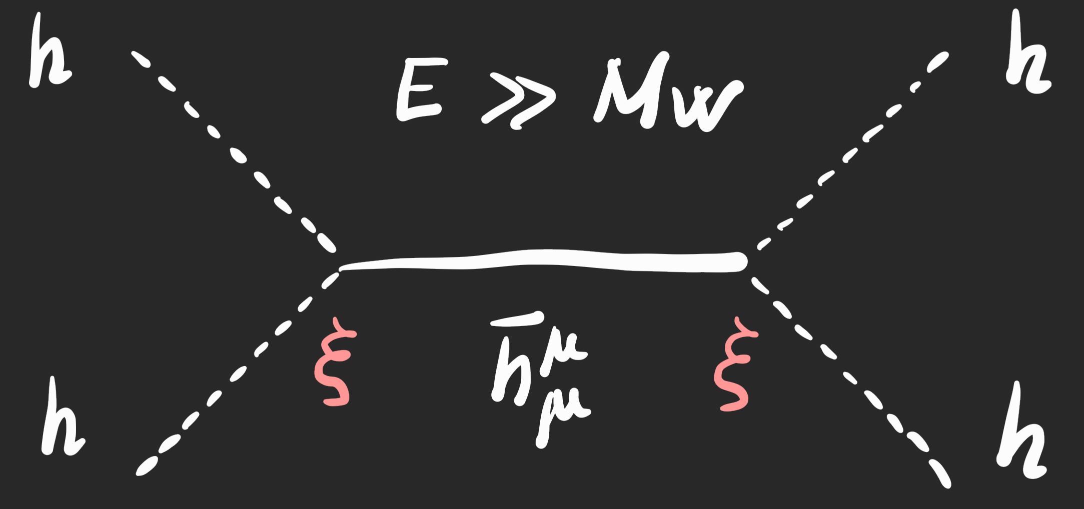
Higgs Inflation + non-minimal coupling

[Bezrukov, Shaposnikov]

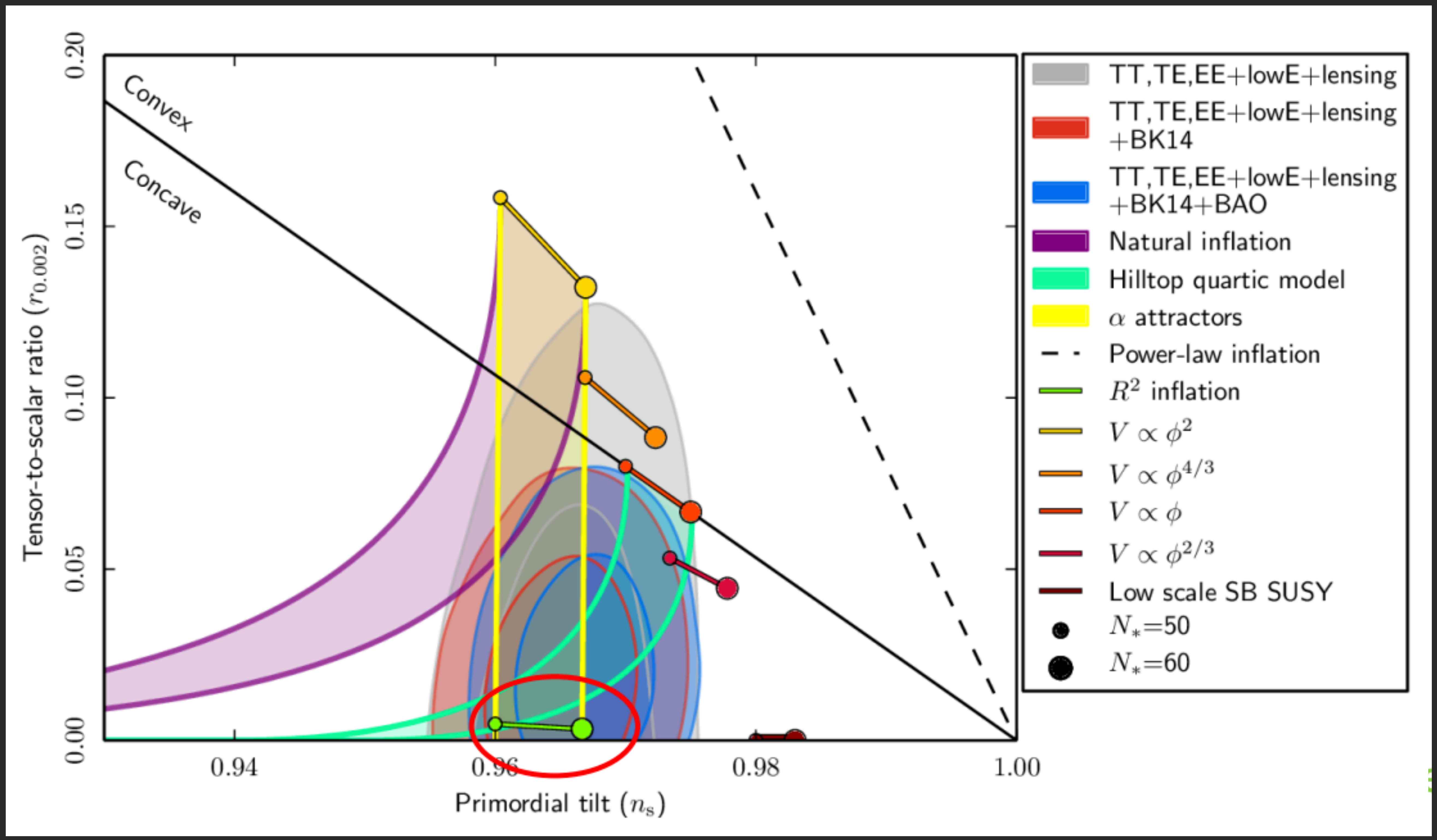
$$\mathscr{L} = \sqrt{-g_J}\left[-\frac{1}{2}\left(1+\xi h^2\right)R_J + \frac{1}{2}g_J^{\mu\nu}\partial_\mu h \partial_\nu h - \frac{\lambda}{4}h^4\right]$$

Non minimal coupling

$$\xi^2/\lambda \sim 10^{10} \implies \xi \sim 10^4$$



[Burgess, HML, Trott (2009,2010); Barbon, Espinosa (2009); Hertzberg (2010)]



$\Lambda_{\text{cutoff}} = M_P/\xi$ is a **low cutoff** scale

Higgs pole inflation

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

Conformal coupling to gravity

$$\Omega(H) = 1 - \frac{1}{3M_p^2} \left| H \right|^2 + \sum_{n=2}^{\infty} \frac{b_n}{\Lambda^{2n-4}} \left| H \right|^{2n}$$

General EFT

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

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From now on we take $b_n = 0$

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

Conformal transformation

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

$$g_{J,\mu\nu} = g_{E,\mu\nu}/\Omega$$

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

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

Higgs-pole

Cancels in the unitarity gauge $H^T = (0,h)^T/\sqrt{2}$

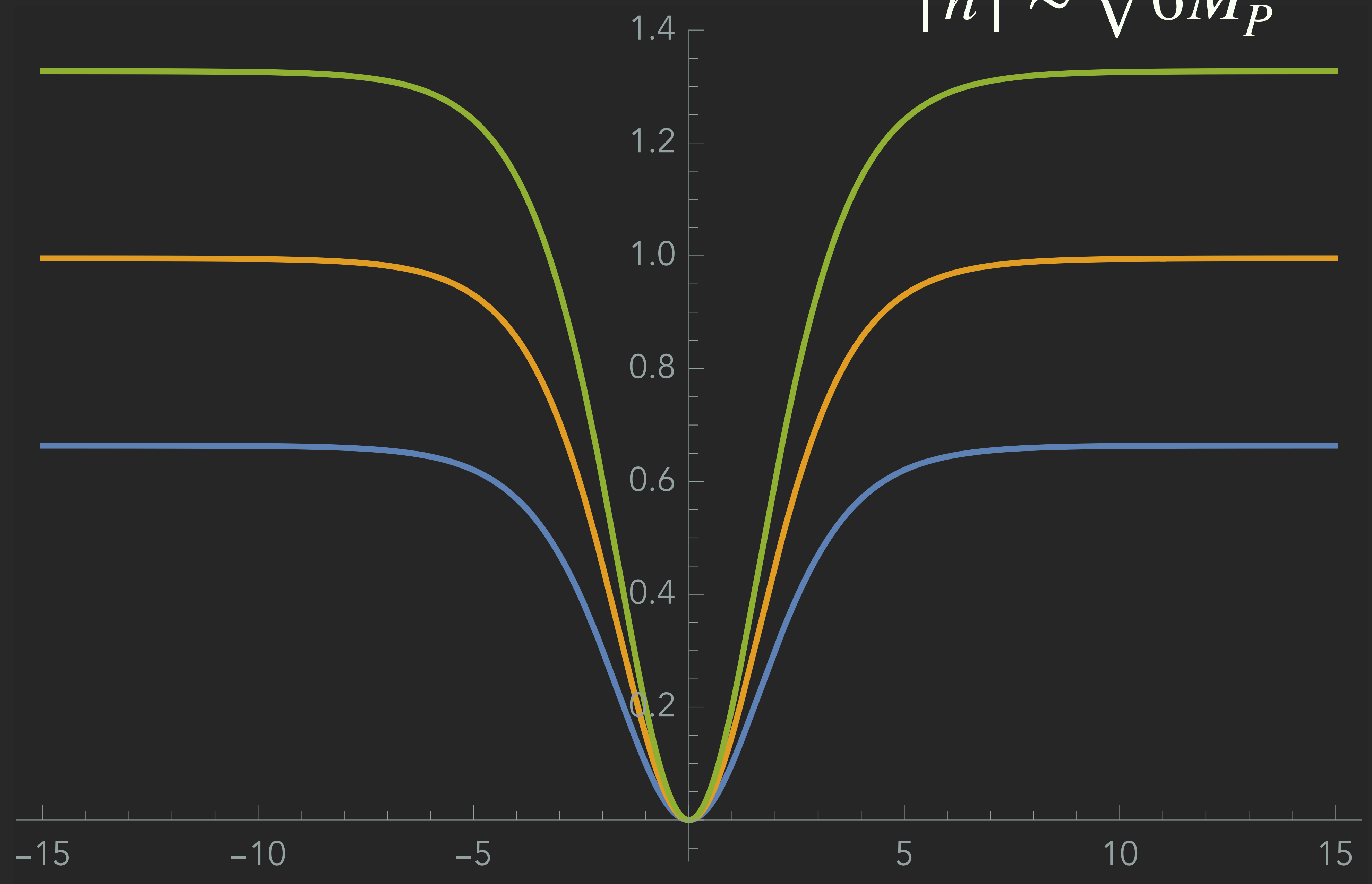
$$V_E(H) = \frac{V_J(H)}{\left(1 - \frac{1}{3M_P^2}|H|^2\right)^2}$$

Inflation

Working example

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

α **- attractor**



In terms of the canonical field $h = \sqrt{6}M_P \tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)$

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

Inflation happens: for a vanishing Jordan frame potential $\Longleftrightarrow$ at the pole of the kinetic Einstein frame

Inflationary predictions

$$V_E(\phi) = V_I\left[\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^{2m}$$

Predictions insensitive to m

$$n_s = 1 - \frac{4N+3}{2\left(N^2 - \frac{9}{16m^2}\right)} \qquad r = \frac{12}{N^2 - \frac{9}{16m^2}}$$

For $N = 60$ we get $n_s = 0.966$ and $r = 0.0033$

The CMB normalization constrains the EFT

$$3^m c_m \left(\frac{\Lambda}{M_P}\right)^{4-2m} = (3.1 \times 10^{-8})\, r = 1.0 \times 10^{-10}$$

For m=2, $\lambda_H = 1.1 \times 10^{-11}$

EWSB and quartic coupling

$$V_E(H) = V_0 + \mu_H^2 |H|^2 + \lambda_H |H|^4 + \sum_{m=3}^{\infty} c_m \Lambda^{4-2m} |H|^{2m}$$

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

$$V_E(\phi) = V_0 + 3\mu_H^2 M_P^2 \tanh^2\left(\frac{\phi}{\sqrt{6}M_P}\right) + 9\lambda_H M_P^4 \tanh^4\left(\frac{\phi}{\sqrt{6}M_P}\right) + \sum_{m=3}^{\infty} 3^m c_m \Lambda^{4-2m} M_P^{2m} \tanh^{2m}\left(\frac{\phi}{\sqrt{6}M_P}\right)$$

CMB $\frac{3\mu_H^2}{M_P^2} + 9\lambda_H + \sum_{m=3}^{\infty} 3^m c_m \left(\frac{\Lambda}{M_P}\right)^{4-2m} = 1.0 \times 10^{-10}$

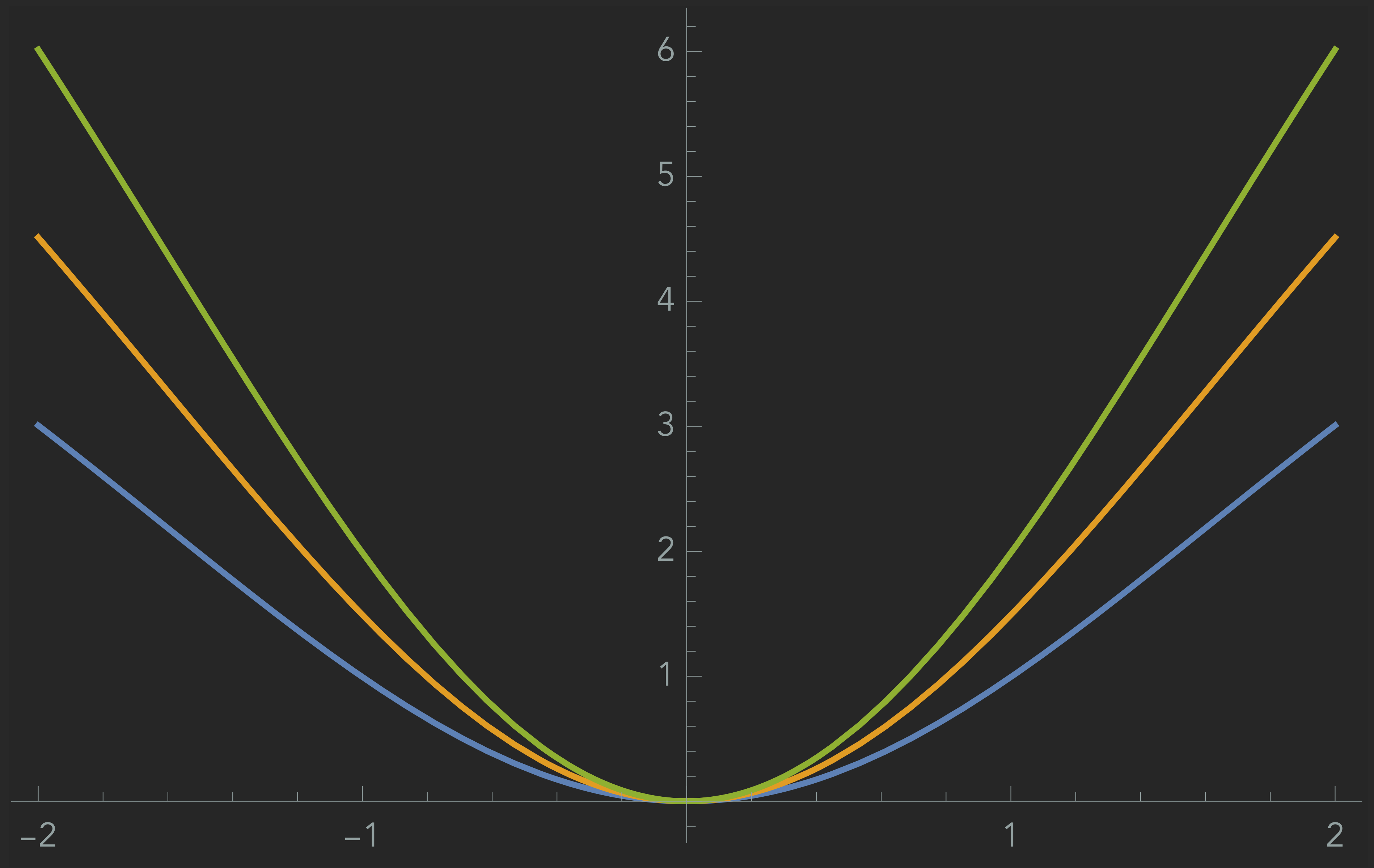
For consistent EWSB

$$9\lambda_H M_P^4 \gtrsim 3|\mu_H^2| M_P^2 \implies \lambda_H > 1.1 \times 10^{-15}$$

Reheating

After inflation, the inflation condensate oscillates around the minima

$$V_E(\phi) \simeq \alpha_m \phi^{2m} \qquad |H| \ll \sqrt{6} M_P$$



General equation of state

$$\rho_\phi = \left\langle \frac{1}{2}\dot{\phi}^2 \right\rangle + \langle V_E(\phi) \rangle = (m+1)\langle V_E(\phi) \rangle$$

$$p_\phi = \left\langle \frac{1}{2}\dot{\phi}^2 \right\rangle - \langle V_E(\phi) \rangle = (m-1)\langle V_E(\phi) \rangle$$

$$\langle w_\phi \rangle = \frac{p_\phi}{\rho_\phi} = \frac{m-1}{m+1}$$

For $m \neq 1, \omega_\phi \neq 0$

The particular dynamics depends on the value of m

Reheating

$$\Gamma_\phi = \sum_f \Gamma_{\phi\to f\bar{f}} + \sum_{V=W,Z} \Gamma_{\phi\phi\to VV}$$

SM fermions **SM gauge bosons**

Fermions can be produced at initial stages $\phi_0 \sim M_P$

$$\langle\Gamma_{\phi\to f\bar{f}}\rangle = \frac{y_f^2\omega^3}{8\pi m_\phi^2}(m+1)(2m-1)\Sigma_m^f\left\langle\left(1-\frac{4m_f^2}{\omega^2 n^2}\right)^{3/2}\right\rangle$$

Gauge bosons can be produced at later times, for m>2

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

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

m	T_reh (GeV)
1	5.1×10^{13}
2	2.6×10^{9}
3	260
4	9.4×10^{5}
5	2.1×10^{7}

Reheating temperature for fermionic decays

***Parametric resonance is important for gauge boson production**

Preheating

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

The effective masses depend on the factor m in the potential

$$\frac{m^2 m_\varphi^2(t)}{\omega^2} = \frac{1}{\pi}\, m(2m-1)\left(\frac{\Gamma\left(\frac{1}{2m}\right)}{\Gamma\left(\frac{1}{2}+\frac{1}{2m}\right)}\right)^2 \mathscr{P}^{2m-2}(t)$$

$$\frac{m^2 m_W^2(t)}{\omega^2} = \frac{g^2}{8\pi\alpha_m}\left(\frac{\Gamma\left(\frac{1}{2m}\right)}{\Gamma\left(\frac{1}{2}+\frac{1}{2m}\right)}\right)^2 \phi_0^{4-2m}(t)\mathscr{P}^2(t)$$

Gauge boson masses depend on the amplitude of the inflaton oscillation

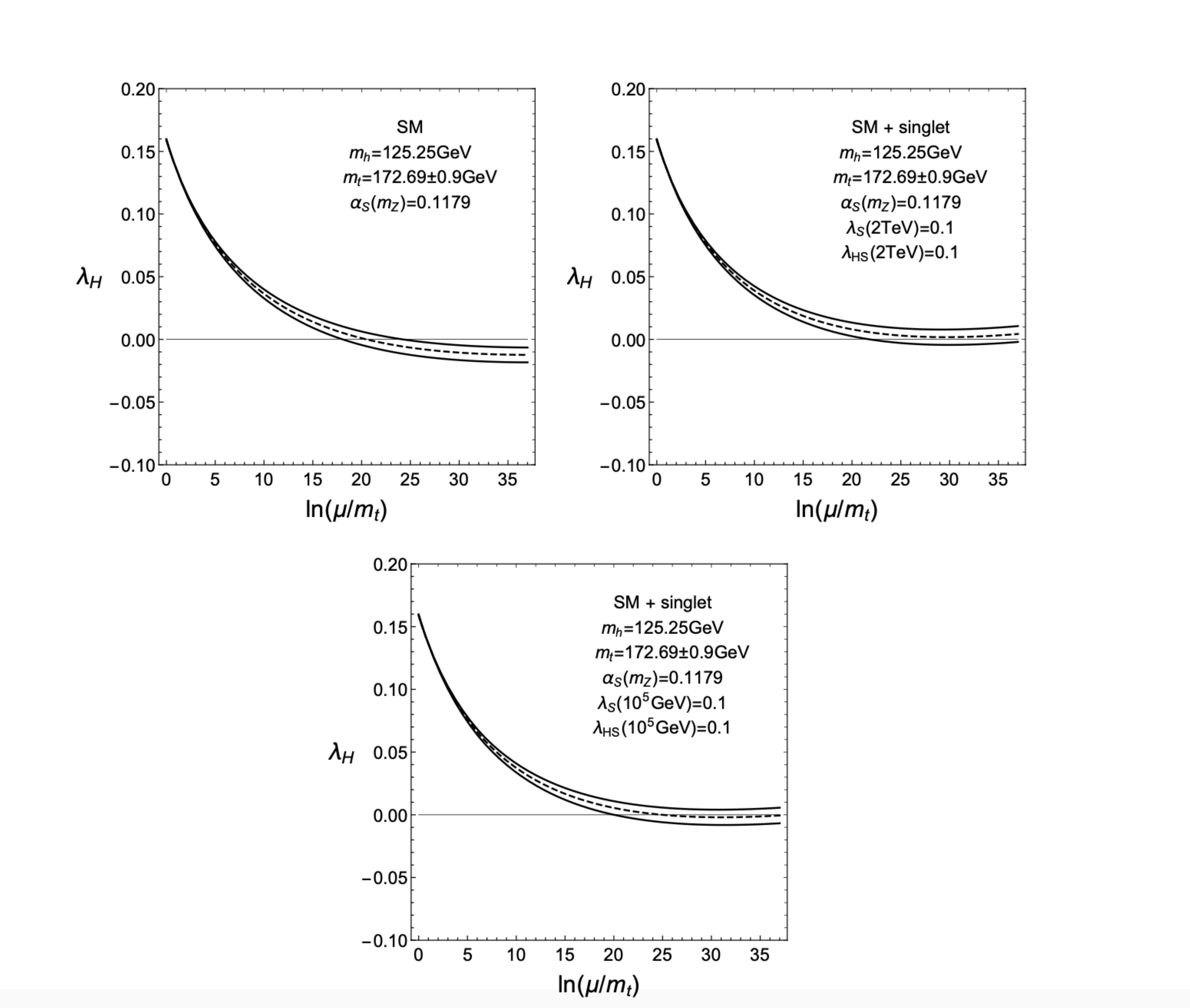
Future work

g^2/α_m **is large due to the CMB normalization** $\alpha_m \lesssim 10^{-10}$ $\Longrightarrow$ **Larger reheating temperatures? (Original Higgs inflation like)**

Back to the quartic coupling

The running Higgs quartic coupling is sensitive to:

- **the Higgs mass**
- **the top quark mass**
- **the strong coupling**



❌ **It turns negative around** $\mu \sim 10^{10}\,\mathrm{GeV}$

We need to keep the quartic coupling small and positive during inflation

✅ **Add a singlet scalar(decoupled during inflation)**

✅ **Relax the Higgs quartic** $\Longrightarrow$**sugra D-flat direction**

Supergravity embedding

Kähler

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

Conformally coupled

Superpotential

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

Fixed by Higgs-pole condition
Robust to loop corrections

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

Sugra Higgs pole inflation

Vacuum stability ensured by the SM gauge couplings

$$\hat{V}_D = \frac{1}{8} g'^2 (|H_u|^2 - |H_d|^2)^2 + \frac{1}{8} g^2 \Big((H_u)^\dagger \vec{\tau} H_u + (H_d)^\dagger \vec{\tau} H_d \Big)^2$$

Higgs fields along the D-flat direction $H_u = (0, h\sin\beta)/\sqrt{2}$ $H_u = (h\cos\beta, 0)/\sqrt{2}$ $T + \bar{T} = 1$

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2} M_P^2 \left(T + \bar{T} - \frac{1}{6M_P^2} h^2 \right) R + \frac{1}{2} (\partial_\mu h)^2 - V_J$$

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

Quartic couplings relaxed dynamically to zero:
no need of maintaining individual couplings to be small

Summary

- We proposed a new realization of Higgs inflation that relies on conformality.
- The quartic Higgs coupling needs to remain tiny during inflation.
- There’s a possibility to achieve Higgs-pole inflation with small quartic in supergravity.

Future works:

- Detailed preheating dynamics
- Other (non-susy) possibilities for dynamical relaxation of the Higgs quartic.