Higgs Dynamics in the Early Universe

Sami Nurmi
University of Helsinki,

April 3, 2014

Novel Signatures of Inflation 2014
CP^3-Origins, Odense, Denmark

Kari Enqvist,Tuukka Meriniemi, SN (arxiv:1306.4511)
Kari Enqvist,Tuukka Meriniemi, SN (arxiv:1404.????)
Kari Enqvist,SN, Stanislav Rusak (arxiv:1404.????)

Standard Model Higgs

- 2012: SM Higgs (-like boson) detected at LHC

$$m_h \simeq 125 - 126\mathrm{GeV}$$

- Vacuum stability within SM up to very high energies

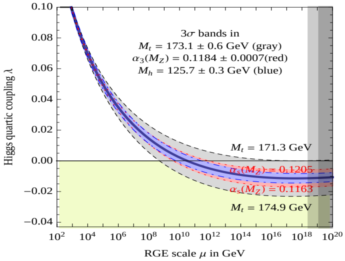


Figure: [Degrassi et.al. 2012]

- Consistent with no new physics below $\lambda(h_{\rm crit}) = 0$

Vacuum stability

- For large field values $h \gg \nu \simeq 246$ GeV

$$V(h) = \frac{\lambda(h)}{4} h^4$$

- At one loop

$$\beta_\lambda = \frac{\mathrm{d}\lambda}{\mathrm{d}\ln h} = 12\lambda^2 + 6y_t^2\lambda - 3y_t^4$$

- Beyond one loop also α_s enters in the running of $\lambda(h)$
- Instability scale $\lambda(h_{\mathrm{crit}}) = 0$ determined by m_h, m_t, α_s [Degrassi et. al. 2012]

$$\lambda(M_P) = -0.0144 + 0.0028\left(\frac{m_h}{GeV} - 125\right) \pm 0.0047_{\sigma_{m_t}} \pm 0.00018_{\sigma_{\alpha_s}} \pm 0.0028_{\sigma_{th}}$$

Standard Model Higgs + cosmology

- New physics required above the electroweak scale: baryogenesis, dark matter, primordial perturbations (+ dark energy)
- Concentrate on the primordial perturbations here
- Pure SM cannot be the inflaton

$$\epsilon = 8\frac{M_P^2}{h^2}\left(1 + \frac{\beta_\lambda}{4\lambda}\right) \gg 1$$

unless for a very delicate choice of parameters

$$\beta(h_f) \sim -4\lambda(h_f) \Rightarrow \epsilon \ll 1$$

false vacuum + de Sitter, no graceful exit within SM

Standard Model Higgs + cosmology

- To inflate we either have to add new fields beyond SM or modify the SM Higgs potential
- Higgs inflation [Bezrukov, Shaposhnikov 07]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{M_P^2}{2} R - \xi H^\dagger H R$$

make a conformal transformation

$$\tilde{g}_{\mu\nu} = g_{\mu\nu}(1 + \xi h^2 / M_P)$$

Higgs potential flattened for $h\sqrt{\xi} \gg M_P$

$$V(h) \simeq \frac{\lambda M_P^2}{4\xi^2}\left(1 - \frac{2M_P^2}{\xi h^2}\right)$$

Higgs inflation

- Putting in $m_h \simeq 125$ GeV mass one gets $N \sim 60$ e-folds with and $\mathcal{P}_\zeta = 2.4 \times 10^{-9}$ for a large coupling $\xi \sim 10^4$
- In addition, the model predicts

$$n_s \simeq 0.97, \qquad r = 0.003$$

  Not consistent with BICEP2 $r = 0.2$!
- Non-generic realizations still viable [Bezrukov, Shaposhnikov 14], inflate at an inflection point (or shallow false vacuum [Masina 14]) with very specific SM parameters

SM Higgs and inflation

- Assume inflation is driven by fields beyond the SM
- SM Higgs should then be a subdominant field during inflation
- Taking BICEP2 seriously

$$H_{\rm inf} \sim 10^{14}{\rm GeV} \ , \qquad \rho_{\rm inf}^{1/4} \sim 10^{16}{\rm GeV}$$

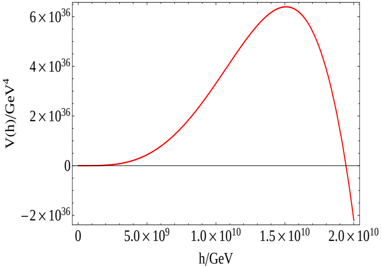
what are the ramifications on the SM Higgs during inflation?

[Enqvist, Meriniemi,SN]

- Conditions for stability, imprints of eventual Higgs fluctuations, initial conditions for the hot big bang epoch?

Conditions for consistency

- The Higgs should relax to $\nu = 246$ GeV by $T = \mathcal{O}(100)$ GeV, a non-trivial condition for $H_{\rm inf} \sim 10^{14}$ GeV



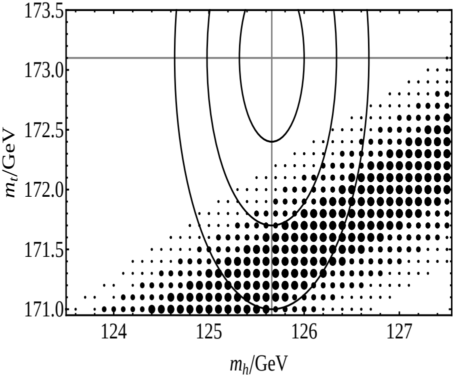
$V(h)$ for best fit parameters $M_t = 173.1\,\mathrm{GeV}$, $\alpha_S = 0.1184$ and $M_h = 125.5\,\mathrm{GeV}$.

- The regime $h \ll h_{\rm max}$ should be stable against inflationary fluctuations $\delta h \sim H$

$$V(h_{\rm max}) > H_{\rm inf}^4 \sim 10^{56}\mathrm{GeV}^4$$

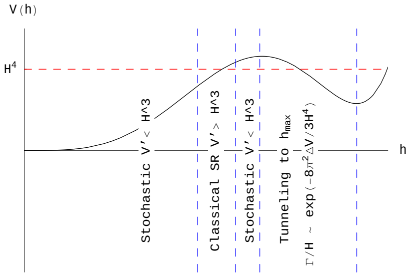
Conditions for consistency

- The stability $V(h_{\rm max}) > H_{\rm inf}^4$ implies a low top mass within SM



- Or the SM Higgs sector needs to be significantly modified below the inflationary scale

Higgs dynamics during inflation



- Higgs relaxes to the asymptotic stochastic regime in $N = \mathcal{O}(100)$ e-folds after the tunneling

$$P(h) = C\exp\left(-\frac{8\pi^2 V(h)}{3H^4}\right) \quad (1)$$

$$h_* \sim \sqrt{\langle h^2 \rangle} \sim 0.4\frac{H}{\lambda^{1/4}} \sim 10^{14}\mathrm{GeV}$$

Dynamics after the end of inflation

- Inflation $H_{\rm inf} \sim 10^{14}$ GeV + SM generates a Higgs condensate $h \sim 10^{14}$ GeV
- How does the hot bing bang epoch with this initial condition look like?
- In particular, when and how does the condensate decay?
- Implications on phase transitions, baryogenesis in SM extensions, generation of adiabatic perturbationsthrough Higgs fluctuations?

Decay of the Higgs condensate

- Consider first the Higgs decay at $T = 0$, this is the case if the Higgs decays before the inflaton(s)
- Efficient perturbative channels $h \to WW, ZZ, t\bar{t}$ kinematically blocked for $h \sim 10^{14}$ GeV

$$m_Z > m_W = \frac{gh}{2}, m_t = \frac{y_t h}{\sqrt{2}} \quad > \quad m_h = \frac{\lambda h^2}{2}$$

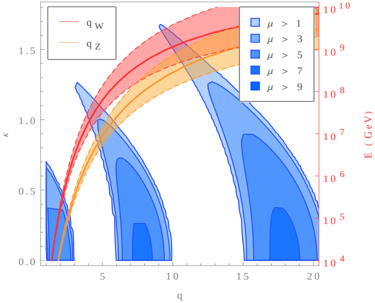
- Higgs decays non-perturbatively into weak gauge bosons

$$\ddot{A}_i^a - \nabla^2 A_i^a - \partial_i(\dot{A}_0^a - \partial_j A_j^a) + \frac{g^2\chi^2}{4}A_i^a \quad = \quad g\epsilon^{abc}\eta^{\mu\nu}\left[\partial_\mu(A_\nu^b A_i^c) + A_\mu^b\partial_\nu A_i^c - A_\mu^b\partial_i A_\nu^c\right]$$
$$+ g^2\eta^{\mu\nu}\left[A_\mu^a A_\nu^b A_i^b - (A_\mu^b A_\nu^b)A_i^a\right] + \frac{gg'\chi^2}{2}\delta^{a3}B_i \ ,$$

- Neglecting the non-Abelian terms one finds $t_{\rm dec} = \mathcal{O}(10^2)H_{\rm end}^{-1}$ [Enqvist, Meriniemi,SN]

Details of the resonance

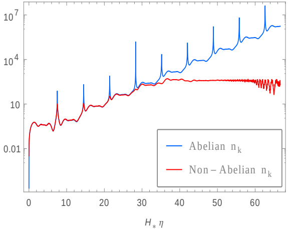
- The actual resonance dynamics quite complicated



- Here $q = 4g^2/\lambda$ for W and $q = 4(g^2 + g'^2)/\lambda$ for Z

Details of the resonance

- Non-Abelian terms significant during the final stages of the resonance [Enqvist,SN,Rusak (in progress)]



- Eventually need to do a lattice simulation [Enqvist,SN,Rusak,Weir (in progress)]
- In finite T the resonance shuts down and the Higgs condensate thermalizes through 2-loop processes [Enqvist,SN,Tenkanen,Tuominen (in progress)]

Conclusions

- Pure SM Higgs cannot be the inflaton, investigate its dynamics when inflation driven by field(s) beyond SM
- Higgs is a light spectator field during inflation, ends up in the false vacuum unless $V(h_{\rm max}) > H_{\rm inf}^4$
- Consistent with $H_{\rm inf} \sim 10^{14}$ GeV implied by BICEP2 only for low top mass values, otherwise need to modify the Higgs potential
- If $N_{\rm TOT} \gg 100$ a Higgs condensate $h \sim 10^{14}$ GeV generated from generic initial values in the beginning of inflation
- The condensate decays non-perturbatively into weak gauge bosons after the end of inflation
- Careful analysis of the resonance dynamics needed to find out the thermalization rate, implications on baryogenesis, Higgs induced perturbations (adiabatic or isocurvature) ...