Higgs Physics in the Early Universe

Sami Nurmi

University of Jyväskylä

March 23, 2016

University of Helsinki

Enckell, Enqvist, SN (1603.????)
Markkkanen, Nurmi (1512.07288)
Enqvist, Rusak, SN, Weir (1506.06895)
Herranen, Markkanen, SN, Rajantie (1407.3141, 1506.04065)
Enqvist, Meriniemi, SN (1306.4511; 1404.3699)
Enqvist Rusak SN, (1404.3631)

Three angles to inflation

Signatures of inflaton(s)

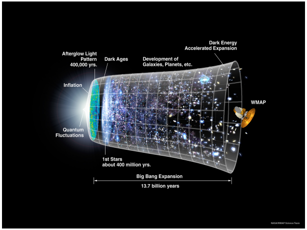
- CMB + LSS observations probe V, V', V'' only over $\Delta N \sim 3$, reconstruction of $\mathcal{L}$ not possible
- Much tighter constraints within specific models

Signatures of moduli (or spectators)

- Extensions of SM typically contain several scalars, may acquire fluctuations during inflation
- Constrained by the observational success of single field slow roll: no non-Gaussianity, no isocurvature...

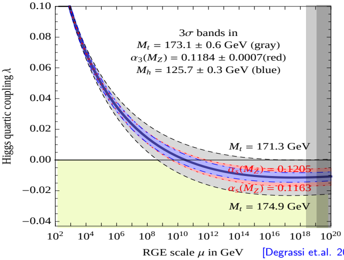
Theoretical consistency

- Light spectators fluctuate up to $\rho \sim H^4$, vacuum stability not automatic

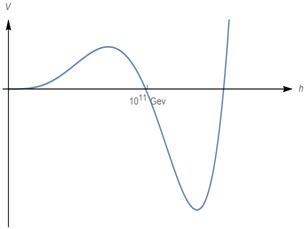


Ramifications of the Higgs field

- SM Higgs found at LHC, EW vacuum metastable but $t_{\rm decay} \gg 10^{11}$ years [1]
- Self-consistency does not require new physics below $\Lambda_{\rm inst.} \sim 10^{11}$ GeV



[Degrassi et.al. 2012]



What happens in the early universe assuming SM Higgs?

- Higgs generically a light spectator, primordial Higgs condensate formed: when does it decay, observational ramifications?
- Consistency, do we need new physics beyond SM to stabilise the vacuum?
- Higgs could also be the inflaton if $\mathcal{L} = \frac{1}{2}M_P^2 R + \frac{1}{2}\xi h^2 R$ (and no higher order terms!)

[1] [Espinosa, Giudice, Riotto 07]

Case I: Specator Higgs

- Assume the Higgs close to vacuum during inflation, energetically subdominant spectator field
- Effective potential feels curvature, a non-minimal coupling radiatively generated

$$\mathcal{L}_{\rm SM} \to \mathcal{L}_{\rm SM} + \xi R h^2$$

- Treating gravity as a fixed background get at one-loop

$$\frac{d\xi}{d\ln\mu} = \frac{1}{16\pi^2}(\xi - 1/6)(12\lambda + 6y_t^2 - \frac{3}{2}g'^2 - \frac{9}{2}g^2)$$

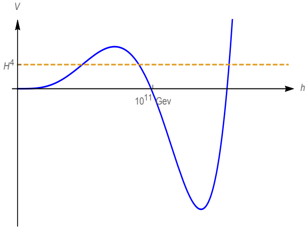
- The one-loop improved effective Higgs potential takes the form [2]

$$V \simeq \frac{1}{4}\lambda(\mu)h^4 + \frac{1}{2}\xi(\mu)Rh^2, \qquad \mu^2 = h^2 + R$$

- During inflation the curvature is large $R = 12H^2$, dominates the potential for $H \gtrsim 10^{11}$ GeV can be neglected for $H \ll 10^{11}$ GeV

[2] [Herranen, Markkanen, SN, Rajantie 14]

Inflationary Higgs dynamics for $H < \Lambda_{\rm inst}$



- Vacuum stability not endangered, can choose $\xi \ll 1$ in

$$V \simeq \frac{1}{4}\lambda(\mu)h^4 + \frac{1}{2}\xi(\mu)Rh^2, \qquad \mu^2 = h^2 + R$$

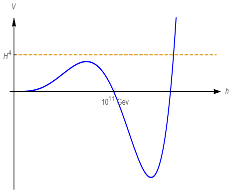
- SM Higgs is a light spectator $V'' \ll H^2$, $V \ll H^2 M_P^2$
- Stochastic motion driven by $\delta h \sim H/(2\pi)$

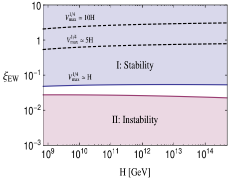
$$P(h) = C\exp\left(-\frac{8\pi^2 V(h)}{3H^4}\right), \qquad \langle h^2\rangle \sim \frac{H^2}{\lambda^{1/2}}$$

- Inflation generates an effective primordial Higgs condensate $h_* \sim \sqrt{\langle h^2\rangle} \sim H/\lambda^{1/4}$, non-equilibrium initial conditions the for the hot big bang[1]
- Could have interesting observational impacts: baryogenesis[2] CMB fluctuations[3], non-thermal DM production[4], phase transitions , ... constraints on viable Higgs couplings to physics beyond SM!
- Crucial to understand how the condensate decays, sets the time-scale for the non-equilibrium period!

[1] [Enqvist, Meriniemi, SN 13], [2] [Kusenko, Pearce, Yang 14], [3] [De Simone, Riotto 12], [4] [Enqvist, SN, Tenkanen, Tuominen 14]

Inflationary Higgs dynamics for $H > \Lambda_{\rm inst}$





- If $\xi \simeq 0$, Higgs would have fluctuated to the negative energy minimum [1], not consistent with what we observe today!
- Stability/instability determined by the curvature coupling

$$V \simeq \frac{1}{4}\lambda(\mu)h^4 + \frac{1}{2}\xi(\mu)Rh^2, \qquad \mu^2 = h^2 + R$$

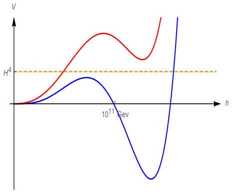
$$m_{\rm eff}^2 \to 12\xi H^2 \quad \text{for} \quad \lambda \to 0$$

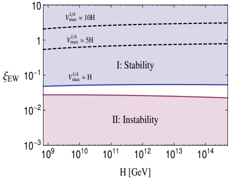
- One loop analysis: stability maintained within the SM if $\xi \gtrsim 0.01$ at $\mu = 100$ GeV, no new physics required [2]
- No condensate generated for $\xi > 1/6$, Higgs effectively massive
- Condensate may form for $0.01 \lesssim \xi < 1/6$ but a more careful analysis needed (in progress)

[1] [Kobakhidze, Spencer-Smith 13; Fairbairn, Hogan 14; Enqvist, Meriniemi, SM 14; etc.]

[2] [Herranen, Markkanen, SN, Rajantie 14; Espinosa, Giudice, Riotto 07], see also [Lebedev 12; Lebedev, Westphal 12; etc.]

Inflationary Higgs dynamics for $H > \Lambda_{\rm inst}$





- If $\xi \simeq 0$, Higgs would have fluctuated to the negative energy minimum [1], not consistent with what we observe today!
- Stability/instability determined by the curvature coupling

$$V \simeq \frac{1}{4}\lambda(\mu)h^4 + \frac{1}{2}\xi(\mu)Rh^2, \qquad \mu^2 = h^2 + R$$

$$m_{\rm eff}^2 \to 12\xi H^2 \quad \text{for} \quad \lambda \to 0$$

- One loop analysis: stability maintained within the SM if $\xi \gtrsim 0.01$ at $\mu = 100$ GeV, no new physics required [2]
- No condensate generated for $\xi > 1/6$, Higgs effectively massive
- Condensate may form for $0.01 \lesssim \xi < 1/6$ but a more careful analysis needed (in progress)

[1] [Kobakhidze, Spencer-Smith 13; Fairbairn, Hogan 14; Enqvist, Meriniemi, SM 14; etc.]

[2] [Herranen, Markkanen, SN, Rajantie 14; Espinosa, Giudice, Riotto 07], see also [Lebedev 12; Lebedev, Westphal 12; etc.]

Higgs dynamics after inflation: stability

- During reheating $R = 12H^2$ (inflation) evolves to $R = 0$ (rad. dom.), e.g. single field inflation

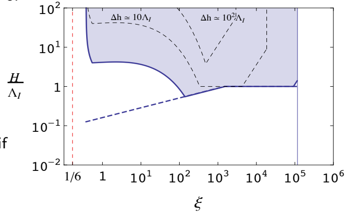
$$R = M_P^{-2}\left(4V(\phi) - \dot{\phi}^2\right)$$

- Induces an oscillatory mass term for the Higgs

$$f''(\eta) + \left(k^2 + \left(\xi - \frac{1}{6}\right) a^2 R\right) f(\eta) = 0\ , \qquad f(\eta) \equiv h(\eta)a(\eta)$$

- Tachyonic instability when $R < 0$, exponential production of Higgs particles [1]

$$\langle h^2 \rangle \propto \frac{H^2}{\sqrt{\xi}} \exp\left(\frac{2\sqrt{\xi}\,\phi_0}{M_P}\right)$$



- May trigger a transition to the negative energy minimum if

$$\sqrt{\langle h^2 \rangle} \gtrsim \Lambda_{\rm inst.}$$

- Constrains ξ from above!

- Could also constrain inflaton-Higgs couplings [2], novel probe of reheating physics

[1] [Herranen, Markkanen, SN, Rajantie 15]

[2] [Gross, Lebedev, Zatta 15, Ema, Mukaida, Nakayama 16; Kohri, Matsui 16]

Decay of the primordial Higgs condensate

- SM Higgs rather generically displaced from vacuum after the end of inflation

$$h_* \sim \begin{cases} \frac{H}{\lambda^{1/4}} & , H \lesssim 10^{11}\, GeV \\ \frac{H}{\xi} & , H \gg 10^{11}\, GeV, |\xi| < 1/6 \quad (?) \end{cases}$$

- Decay very fast in finite T background, more complicated if $T = 0$ (inflaton not yet decayed into SM)
- Efficient perturbative channels $h \to WW, ZZ, t\bar{t}$ kinematically blocked

$$m_W = \frac{gh}{2}, m_t = \frac{y_t h}{\sqrt{2}} > m_h = \sqrt{3\lambda} h$$

- Higgs decays non-perturbatively into weak gauge bosons[3]

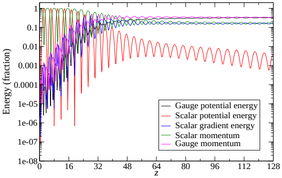
$$\begin{aligned} \ddot{A}_i^a - \nabla^2 A_i^a - \partial_i(\dot{A}_0^a - \partial_j A_j^a) + \frac{g^2 h^2}{4} A_i^a &= g\epsilon^{abc}\eta^{\mu\nu}\left[\partial_\mu(A_\nu^b A_i^c) + A_\mu^b \partial_\nu A_i^c - A_\mu^b \partial_i A_\nu^c\right] \\ &+ g^2\eta^{\mu\nu}\left[A_\mu^a A_\nu^b A_i^b -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

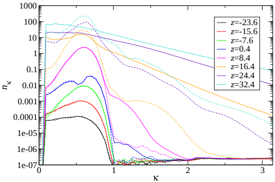
- Need a lattice simulation to study the highly non-linear dynamics

3 [Bezrukov, Shaposhnikov 08, Garcia-Bellido, Figueroa, Rubio 08, Enqvist, Meriniemi,SN 13, Figueroa, Garcia-Bellido, Torrenti 15]

Results of the lattice computation

- Resonance produces gauge fields modes sharply peaked at $k \sim q^{1/4}$, non-Abelian interactions efficiently broaden the distribution
- The gauge field particles scatter off the Higgs rapidly destroying remnants of the condensate, in sharp contrast to the Abelian case where distributions remain peaked and scatterings are inefficient [1]



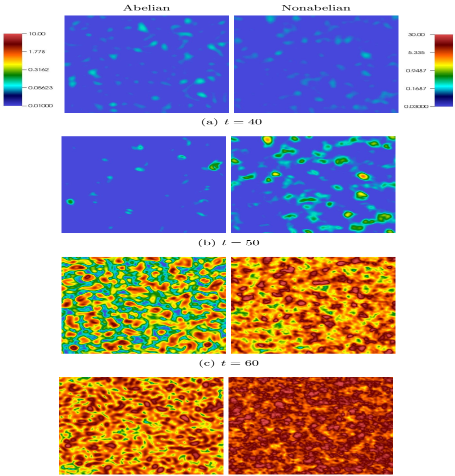


- Complete decay of the primordial condensate within $N \lesssim \mathcal{O}(10)$ oscillation cycles, sets the framework for investigating eventual observational imprints (thermalisation scale still unclear, analogous to heavy ion collisions)
- Similar condensates generated for other light scalars (e.g. SM + singlet), may have significant impacts on non-thermal DM generation [2]

[1] [Enqvist,SN,Rusak,Weir 15]

[2] [Enqvist, SN, Tenkanen, Tuominen 14; SN, Tenkanen, Tuominen 15; Kainulainen, SN, Tenkanen, Tuominen, Vaskonen 16; etc.]

Abelian vs. non-Abelian



(a) $t = 40$

(b) $t = 50$

(c) $t = 60$

(d) $t = 70$

1

Case II: Higgs as the inflation

- SM Higgs could be the inflaton [1] if it is far from vacuum and $\xi \ll 1$

$$\mathcal{L} = \frac{M_P^2}{2} R + \frac{\xi}{2} h^2 R + \mathcal{L}_{\rm SM}$$

- Go to Einstein frame by $g_{\mu\nu} \to (1 + \xi h^2/M_P^2) g_{\mu\nu}$ and $h \to \chi(h)$

$$V(\chi) = \frac{1}{4}\lambda(\mu) \begin{cases} \chi^4 & , \ \chi \ll M_P/\xi \\ \frac{M_P^4}{\xi^2} \left(1 - {\rm e}^{-\sqrt{\frac{2}{3}} \frac{\chi}{M_P}}\right)^2 & , \ \chi \gg M_P/\xi \end{cases}$$

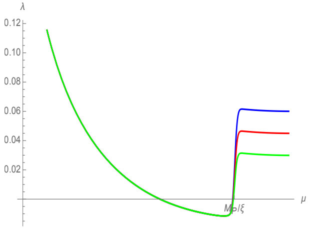
- Requires suppression of higher order operators, not a generic effective theory but self-consistent: all energies below the unitarity cutoff [2]

[1] [Bezrukov, Shaposhnikov 07]

[2] [Barbon, Espinosa 09; Burgess, Lee, Trott 10; Bezrukov, Magnin, Shaposhnikov 10]

Matching the low and high energy regimes

- Radiative corrections to SM couplings perturbatively calculable for $\chi \simeq 0$ & $\mu < M_P/\xi$ and for $\chi \gtrsim M_P/\xi$ & $M_P/\xi < \mu < M_P/\sqrt{\xi}$
- Matching of the two regimes depends on unknown non-renormalisable physics [4]



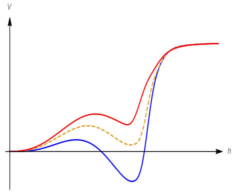
- Phenomenological approach: parametrise the ignorance by introducing a priori free jumps $\delta\lambda$ and δy_t at $\mu \sim M_P/\xi$
- Investigate how inflationary observables depend on $\delta\lambda$ and δy_t

4 [Bezrukov, Shaposhnikov 14; Bezrukov, Rubio, Shaposhnikov 14]

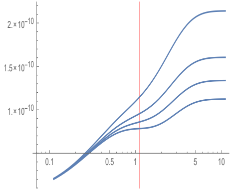
Constraints on the matching

- For m_t, m_h close to SM best fit $\lambda(\mu)$ runs negative below M_P/ξ, in general $\delta\lambda$ cannot be chosen zero

- Negative energy energy minimum between electroweak vacuum and inflationary plateau, must be lifted by thermal corrections at reheating



- Should get the observed amplitude of primordial perturbations: the inflationary scale H depends on $\delta\lambda$ and δy_t, may also affect the form of the potential

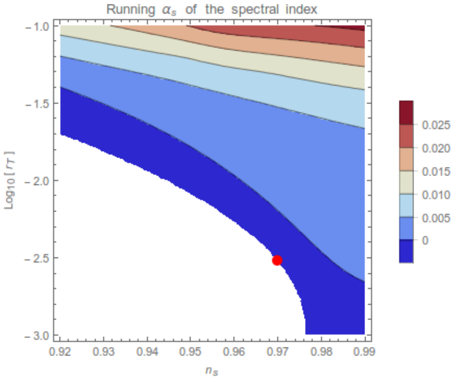


- Impose these constraints and scan over [5] $m_h, m_t, \xi, \delta\lambda, \delta y_t$

5 [Enckell, Enqvist, SN (in progress)]

Observational signatures

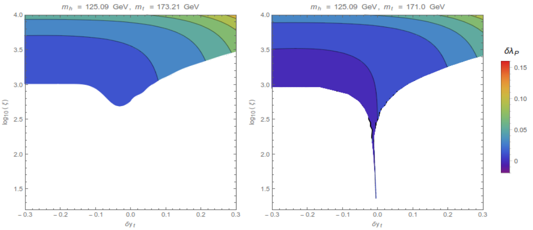
- Consistency relation between the spectral index n_s, its running α_s and the tensor to scalar ratio r_T, the scenario is falsifiable



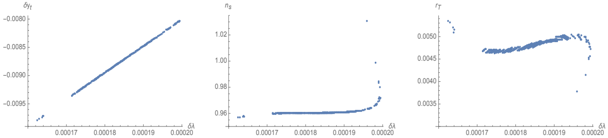
- For $m_t \gtrsim 171.8$ GeV the signatures always given by the red dot, $\mathcal{P} \simeq 2.14 \times 10^{-9}$ possible only for $\delta\lambda$ and δy_t which generate no wiggles in the inflationary potential
- In all other points $m_t \lesssim 171.8$ GeV, observed amplitude obtained also when there wiggles and predictions depend on $\delta\lambda$ and δy_t

Dependence on the matching

- For each choice of SM parameters m_h, m_t the viable values of $\delta\lambda$, δy_t, ξ tightly constrained, also $\xi \lesssim 100$ possible



- For $m_t \lesssim 171.8$ GeV, predictions not fixed by m_t, m_h, ξ



Conclusions

- The SM Higgs plays a key role in the very early universe
- Vacuum stability against Higgs fluctuations implies non-trivial constraints on physics during inflation and reheating, novel probe of high energy physics
- The Higgs generically a light spectator, inflation forms a primordial Higgs condensate: non-equilibrium initial conditions after inflation, observational imprints?
- The Higgs could also be the inflaton, theoretical foundation incomplete and predictions not uniquely determined by SM parameters, still falsifiable