Fate of the Primordial Higgs Condensate

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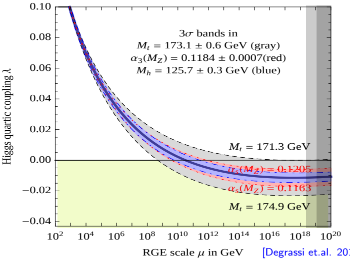
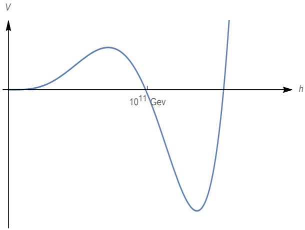
Enqvist, Rusak, SN, Weir (1506.06895)
Herranen, Markkanen, SN, Rajantie (1407.3141, 1506.04065)
Enqvist, Meriniemi, SN (1306.4511; 1404.3699)
Enqvist Rusak SN, (1404.3631)

Standard Model Higgs

- SM Higgs found at LHC $m_h = 125.7 \pm 0.4$ GeV $V(h) = \frac{\lambda}{4}(h^2 - \nu^2)^2$
- EW vacuum metastable but $t_{\rm decay} \gg 10^{10}$ 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?

- Consistency, do we need new physics to stabilise the vacuum? [Talk by Tommi Markkanen]
- Higgs generically a light spectator field and gets displaced from vacuum during inflation, observational ramifications?
- In particular, how does the primordial Higgs condensate decay?

[1] [Espinosa, Giudice, Riotto 07]

Higgs potential during inflation

- Assume the Higgs energetically subdominant and consider radiative corrections in a fixed gravitational background, a non-minimal coupling necessarily generated

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

- Can choose $\xi(\mu_0) = 0$ at some scale μ_0 but cannot do so over a range of scales

$$\frac{d\xi}{d\ln\mu} \sim \frac{1}{16\pi^2}(\xi - 1/6)(\lambda + y_t^2 - g^2)$$

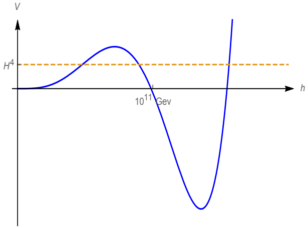
- The one-loop improved effective Higgs potential takes the form [2]

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

- During inflation the curvature is large $R = 12H^2$, dominates the potential for $H \gtrsim \Lambda_{\rm inst}$ can be neglected for $H \lesssim \Lambda_{\rm inst}$

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

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



- Solutions relaxing towards the SM vacuum rapidly enter the regime

$$V'' = 3\lambda h^2 \ll H^2, \qquad V(h) \ll 3H^2 M_P^2$$

- Stochastic motion driven by $\delta h \sim H/(2\pi)$

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

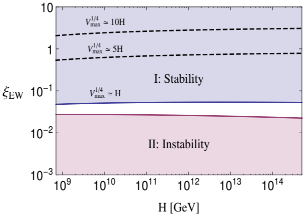
- Higgs is a light spectator, inflation needs to be driven by physics beyond SM (Different from Higgs inflation which assumes a specific UV fixed point & initial conditions)

- 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]

If the inflationary scale is higher

- As $\lambda \rightarrow 0$ the curvature coupling starts to dominate the Higgs potential, stability/instability determined by the induced mass $m^2_{\rm eff} \sim 12\xi H^2$
- SM vacuum sufficiently stable during inflation if $\xi(\mu_{\rm EW}) \gtrsim 0.01$, no new physics needed[1]



- Higgs effectively massive for $\xi > 1/6$, no fluctuations generated during inflation. Instead particle production at reheating through $V_{\rm int} = \xi R(t) h^2$, vacuum stability bounds ξ from above[2].

[1] [Herranen, Markkanen, SN, Rajantie 14, Espinosa, Giudice, Riotto 07], [2] [Herranen, Markkanen, SN, Rajantie 15]

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 either in $T = 0$ (inflaton not yet decayed into SM) or finite T background, start by considering the first case
- 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]

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

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

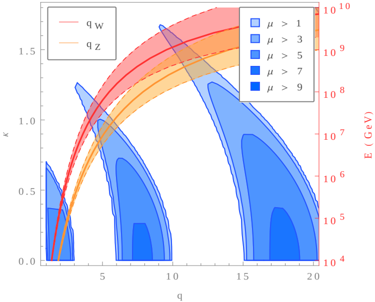
Details of the resonance

- Gauge fields start from vacuum, non-Abelian interactions initially negligible[4]

$$\ddot{A}_i^a + \left(\frac{k^2}{a^2} + \frac{g^2 h^2}{4} \right) A_i^a = 0$$

- Just the usual Mathieu equation with instability bands and exponentially growing solutions

$$n_k \sim e^{m\mu t}, \quad \text{for} \quad k \lesssim q^{1/4}$$

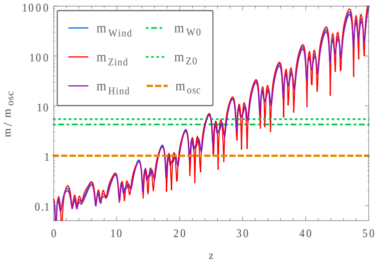


Here $q = 4g^2/\lambda$ for W and $q = 4(g^2 + g'^2)/\lambda$ for Z

4 [Enqvist, Meriniemi,SN 13, Figueroa, Garcia-Bellido, Torrenti 15]

Non-Abelian terms

- The resonance shuts off when the amplified gauge fields start back-reacting the Higgs dynamics $g^2\langle A^2\rangle \sim \lambda h^2$
- The condensate not yet decayed, dynamics after the backreaction crucial in determining the total duration of the decay process
- Non-Abelian terms no longer negligible[5] $g^2\langle A^2\rangle \sim gh^2$



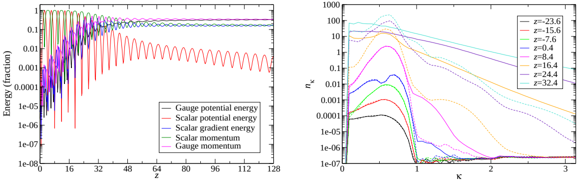
- The system needs to be investigated on lattice

5 [Enqvist, Meriniemi,SN 13]

Results of the lattice computation[a]

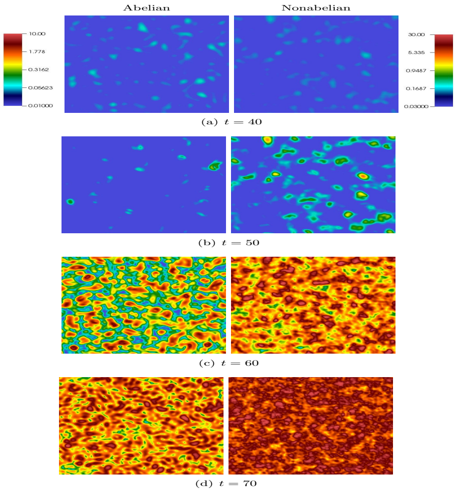
[a] [Enqvist,SN,Rusak,Weir 15]

- 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



- Complete decay of the primordial condensate within $N \lesssim \mathcal{O}(10)$ oscillation cycles, sets the framework for investigating eventual observational imprints

Abelian vs. non-Abelian



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Higgs decay in finite T

- If the inflaton has already reheated the SM sector the resonant channels blocked by thermal masses

$$\omega_k^2 = \frac{k^2}{a^2} + g^2 h^2(t) + c_i T^2$$

- Thermalization through 2-loop processes $\Gamma \sim 10^{-3} T$, still very fast [Enqvist,SN,Tenkanen,Tuominen 14]

$$\Gamma \sim H \Longrightarrow t \sim 10^2 r^{1/2} H_{\rm reh}^{-1}$$

- Similar condensates generated for other light fields, can thermalize much later e.g. SM + singlet

$$V = \lambda_h h^4 + \lambda_{sh} s^2 h^2 + \lambda s^4$$

impacts for phase transitions [Cline, Kainulainen 12, Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal Spethmann 14, ...] and out of equiliubrium DM generation [SN, Tenkanen, Tuominen 15]

Conclusions

- SM Higgs generically is a light spectator field during inflation, at least assuming $H \lesssim 10^{11}$ GeV
- Inflation generates a primordial Higgs condensate, transient non-equilibrium epoch at the onset of hot big bang
- The condensate decays non-perturbatively into weak gauge, the process starts at $m_h \sim H$ (corresponding to $t_{\rm osc} \sim \lambda^{1/4} H_{\rm inf}^{-1}$) and the decay is completed after $N = \mathcal{O}(10)$ oscillation cycles
- If the Higgs potential remains close to SM this epoch was there & observational imprints possible, an important window for probing BSM couplings