Higgs Dynamics in the Early Universe

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March 26, 2015

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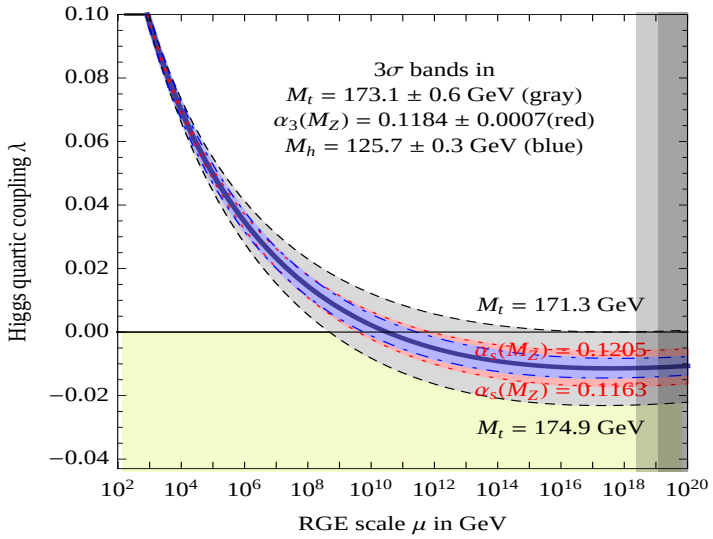
Standard Model Higgs

- SM Higgs detected at LHC $m_h \simeq 125\mathrm{GeV}$, accidental vacuum stability

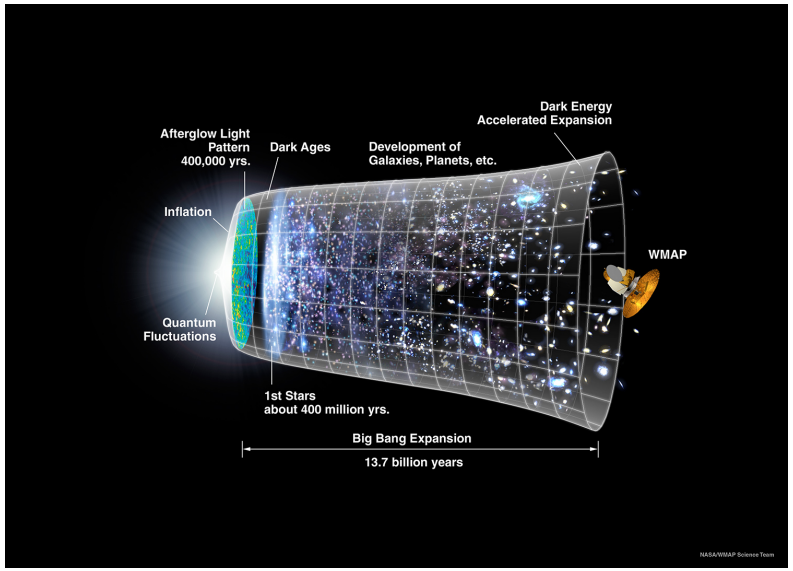


[Degrassi et.al. 2012]

- SM self-consistent up to $\mu_{\mathrm{crit}} \sim 10^9$ GeV but new physics needed: primordial perturbations, dark matter, baryogenesis ...
- Higgs potential at $\mu \gg \mu_{\mathrm{EW}}$ SM + corrections: cosmological ramifications?

Higgs imprints on the sky?

- The very early universe probes Higgs physics at $\mu \gg \mu_{\mathrm{LHC}}$
- Inflation particularly interesting, Higgs either the inflaton or a light spectator scalar



- Initial conditions for the hot big bang epoch related to Higgs potential in both cases

Case 1: Higgs as the inflation

- Implies significant deviation from the SM potential

$$V(h) = \frac{1}{4}\lambda_{\rm SM}(\mu)h^4 + V_{\rm BSM}(h) \sim V_{\rm BSM}(h)$$

- Pure SM potential too steep to inflate for $h \ll M_{\rm P}$

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

- Need new physics to flatten the potential

Higgs inflation

- A specific scenario with non-minimal (and non-perturbative) curvature coupling [Bezrukov, Shaposhnikov 07]

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

- Make a conformal transformation $\tilde{g}_{\mu\nu} = g_{\mu\nu}(1 + \xi h^2/M_P^2)$, Higgs potential flattened for $h\sqrt{\xi} \gg M_P$

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

- Need $\xi \sim 10^4$, not a generic effective theory but a very special setup [Burgess, Lee, Trott 10; Bezrukov, Magnin, Shaposhnikov, Sibiryakov 10]

Higgs inflation

- Non-renormalizable, match low/high energy regimes by hand
- Ambiguity in predictions but can get $N \sim 60$ e-folds and (typically)

$$\mathcal{P}_\zeta \simeq 2.4 \times 10^{-9}, \qquad n_s \simeq 0.97, \qquad r \simeq 0.003$$

- "Postdictions" after BICEP2: could arrange inflation at an inflection point and get $r \ll 0.1$ [Bezrukov, Shaposhnikov 14,15; Hamada, Kawai, Oda, Chan Park 14]
- BICEP2 = dust, predictions still depend on the matching procedure

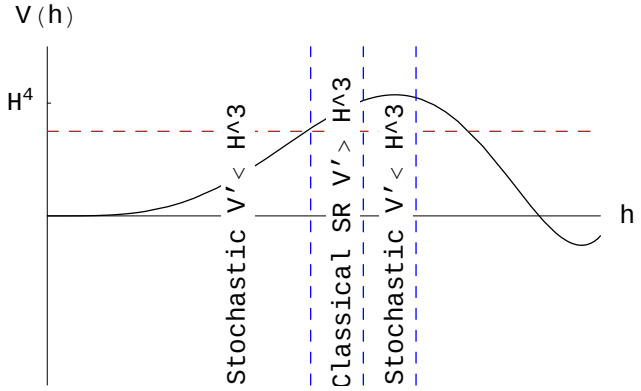
Case 2: Higgs as a spectator

- Realized generically if $V(h) \ll H^2 M_{\rm P}^2$, in particular if the potential is close to SM

$$V(h) = \frac{1}{4}\lambda_{\rm SM}(\mu)\,(1+\mathcal{O}(1))\,h^4$$

- Inflation needs to be driven by new physics beyond SM, e.g. a scalar singlet [Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal, Spethmann 13]
- Higgs dynamically irrelevant and light, fluctuates around the minimum with $\delta h \sim H/(2\pi)$

Spectator Higgs during inflation



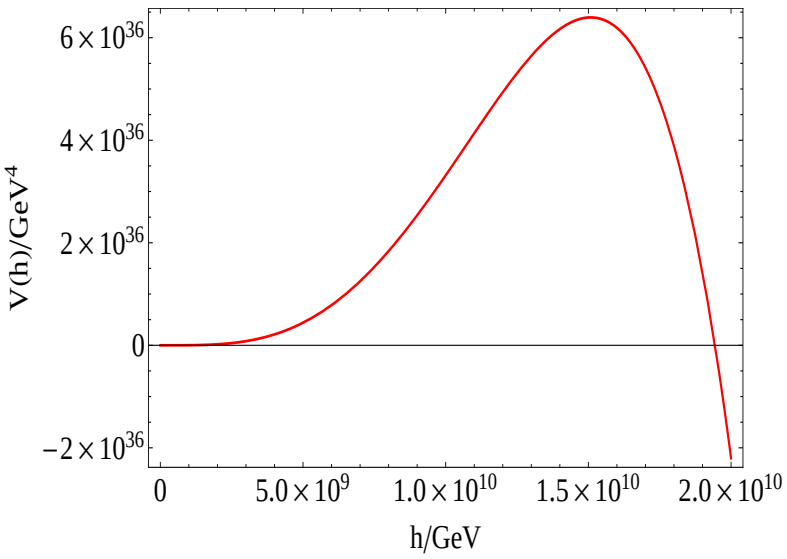
- Higgs relaxes to the asymptotic stochastic regime in $N = \mathcal{O}(100)$ e-folds

$$P(h) = C\exp\left(-\frac{8\pi^2 V(h)}{3H^4}\right), \qquad h_* \sim \sqrt{\langle h^2 \rangle} \sim 0.4\frac{H}{\lambda^{1/4}}$$

- Inflation generates a primordial Higgs condensate, non-vacuum initial conditions for hot big bang

Vacuum stability during inflation

- If $H \gtrsim V_{\rm max}^{1/4} \sim 10^9 {\rm GeV}$ fluctuate out of SM vacuum in one Hubble time?



- Need new physics on Higgs sector if $H \gtrsim 10^9$ GeV? [Kobakhidze, Spencer-Smith 13; Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal Spethmann 14; Kehagias, Riotto 14]

Vacuum stability during inflation

- Non-minimal coupling $\xi(\mu)R^2h^2$ necessarily generated through radiative corrections
- During inflation $R = 12H^2$, dominates for $H \gtrsim 10^9$ GeV when $\lambda_{\rm flat} \sim 0$? [Herranen, Markkanen, Nurmi, Rajantie 14; Espinosa, Giudice, Riotto 08]
- Need to compute one-loop corrections in curved space, R contributions can be resummed [Parker,Toms 85]

$$\Gamma^{(1)} = -\frac{i}{2}\mathrm{Tr}\ln G^{-1} \sim -\int d^4a\sqrt{-g}M^4\ln\left(M^2/\mu^2\right)$$

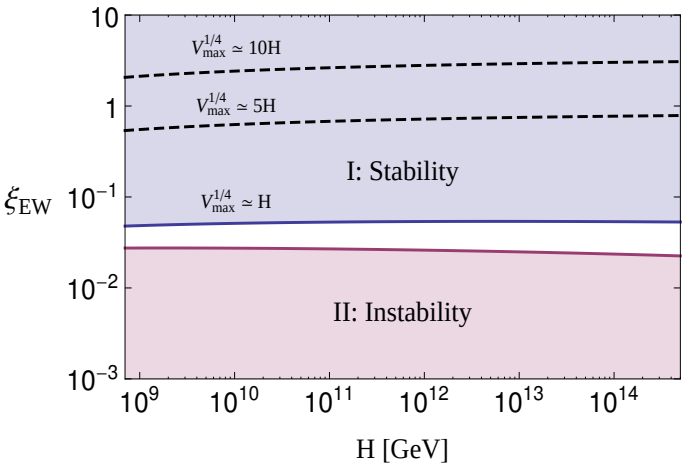
$$M^2 = m^2 + \left(\xi - \frac{1}{6}\right)R$$

Vacuum stability during inflation

- One-loop effective potential for SM [Herranen, Markkanen, Nurmi, Rajantie 14]

$$V_{\rm eff} = -\frac{1}{2}m^2(t)\phi^2(t)+\frac{1}{2}\xi(t)R\phi^2(t)+\frac{1}{4}\lambda(t)\phi^4(t)\sum\frac{n_i}{64\pi^2}(M_i^2(\phi)+\theta_i R)^2\left[\ln\frac{|(M_i^2(\phi)+\theta_i R)^2|}{\mu^2(t)}-c_i\right]$$

- Curvature effects crucial for the stability



- No new physics required to explain the stability!

Dynamics after the end of inflation

- Out of equilibrium initial conditions after the end of inflation $h \sim H/\lambda^{1/4}$
- When and how does the condensate decay?
- Observable ramifications in SM extensions: dark matter generation, lepto/baryogenesis [Kusenko, Pearce, Yang 14], generation of adiabatic perturbations through Higgs fluctuations [De Simone, Riotto 12]

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 $h \sim 10^6$ GeV

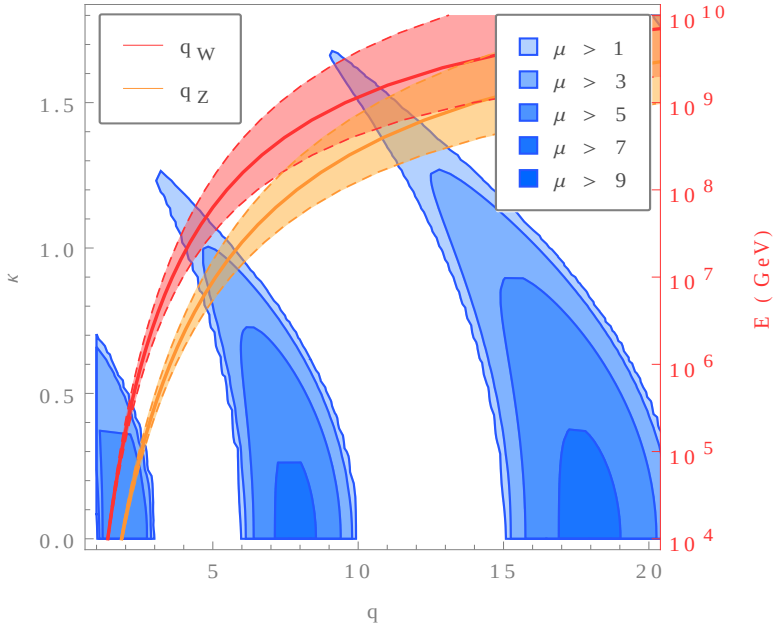
$$m_Z > m_W = \frac{gh}{2}, m_t = \frac{y_t h}{\sqrt{2}} \quad > \quad m_h = \frac{\lambda h^2}{2}$$

- Higgs decays non-perturbatively into weak gauge bosons
  [Bezrukov, Shaposhnikov 08, Garcia-Bellido, Figueroa, Rubio 08, Enqvist, Meriniemi,Nurmi 13]

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

Details of the resonance

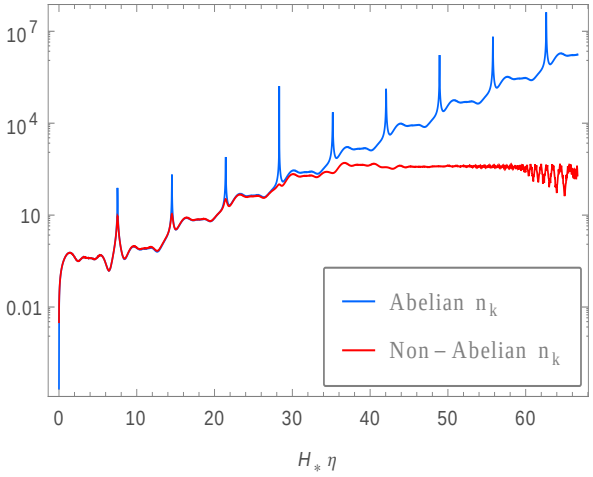
- The actual resonance dynamics quite complicated



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

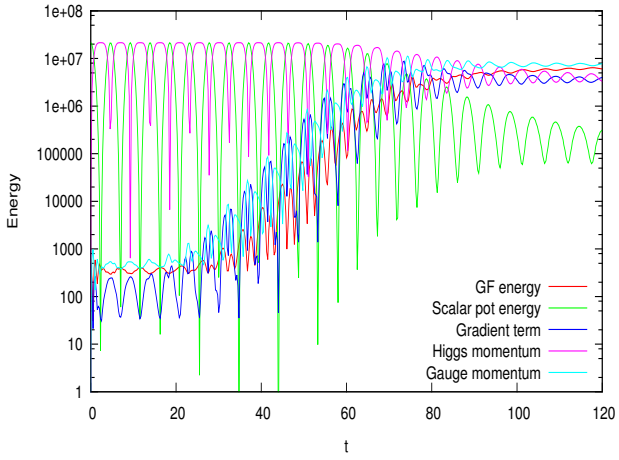
Details of the resonance

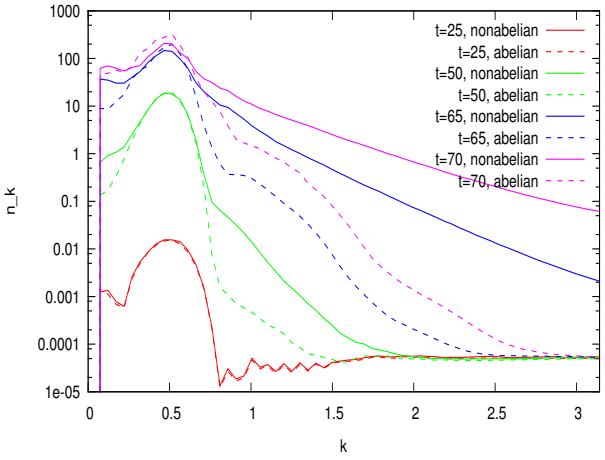
- Non-Abelian terms kick in when the number densities grow large [Enqvist,SN,Rusak 14], crucial to determine the duration and efficiency of the decay



Details of the resonance

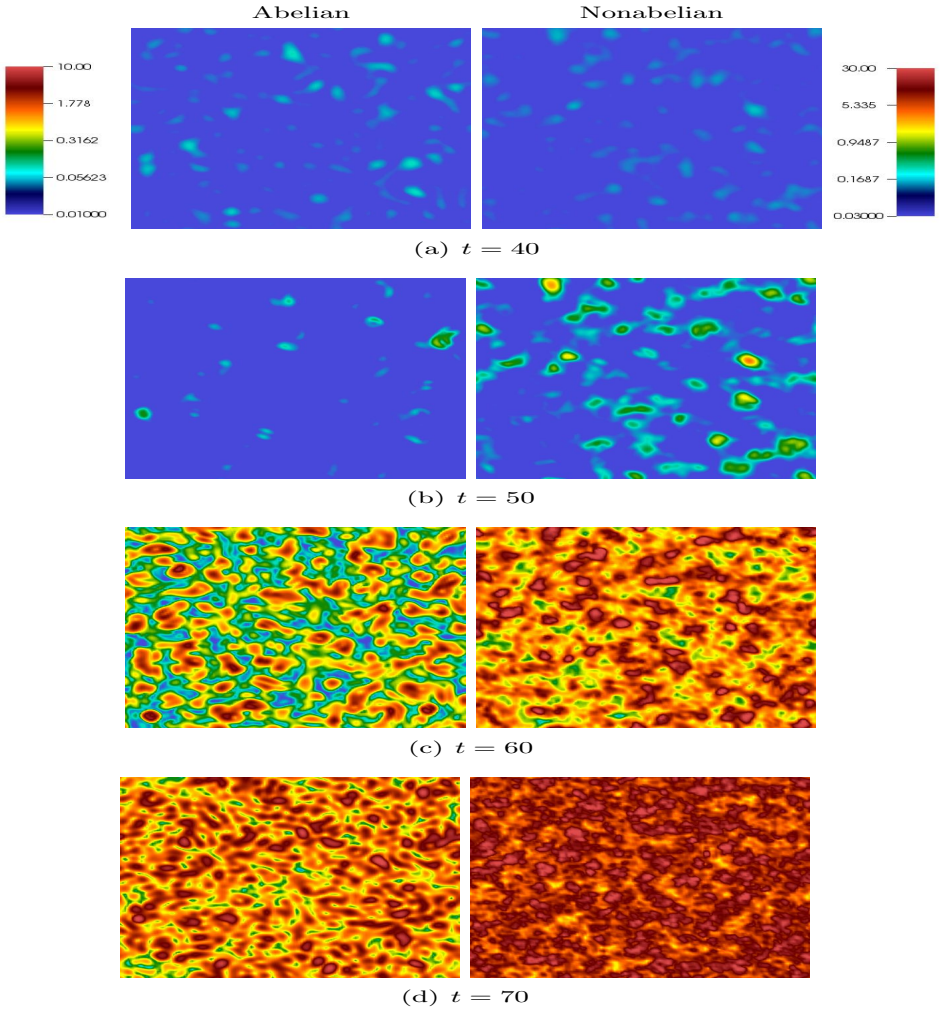
- The system needs to be investigated on lattice [Enqvist,SN,Rusak,Weir (in progress)]





- Non-Abelian interactions responsible for a rapid decay of the Higgs condensate ($N \lesssim \mathcal{O}(100)$ oscillation cycles)

Abelian vs. non-Abelian



(a) $t = 40$

(b) $t = 50$

(c) $t = 60$

(d) $t = 70$

Higgs decay in finite T

- Assume a thermal bath generated by the inflaton decay, Higgs resonance blocked

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

- Thermalization through 2-loop processes [Enqvist,Nurmi,Tenkanen,Tuominen 14]

$$\Gamma \sim 10^{-3} T \sim H \Longrightarrow t \sim 10^2 r^{1/2} H_{\rm reh}^{-1}$$

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

$$V = \frac{1}{4}\lambda_h h^4 + \lambda_{sh} s^2 h^2 + \lambda s^4$$

impacts for phase transitions [Cline, Kainulainen 12], Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal Spethmann 14 and out of equiliubrium DM generation [Nurmi, Tenkanen, Tuominen (in progress)]

Conclusions

- SM like Higgs generically a light spectator during inflation
- Inflation generates a Higgs condensate, non-vacuum initial conditions for the hot big bang
- Several possible observational ramifications: out of equilibrium DM, lepto/baryogenesis, phase transitions, Higgs induced primordial perturbations...
- Need to understand the dynamics and decay of the Higgs condensate in detail, highly non-trivial but an integral part of the early universe physics
- Just first few steps taken: interesting possibilities to find novel ways to probe and constrain physics beyond SM