Scenarios of Reheating and Inflaton Decay -

The Higgs as a Bridge between Inflation and Big Bang Nucleosynthesis

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Based on
D.Figueroa,T.Byrnes, "The Standard Model Higgs as the origin of the hot Big Bang", arXiv:1604.03905

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Setup

- After inflation reheating sets the stage for a hot Big Bang
- Before Big Bang Nucleosynthesis (BBN) the universe has to be dominated by Standard Model (SM) species
- The connection between inflaton and SM is still unclear
- The Higgs is a fitting candidate as the only scalar field in SM
- Three possibilities for the Higgs:
  1. The Higgs is the inflaton
  2. The Higgs is not the inflaton but it is coupled to it
  3. The Higgs is neither the inflaton nor is it coupled to it

Constraints on Coupling

- Think of scale-free quartic operator $g^2\phi^2|\mathcal{H}|^2$ with dimensionless coupling g (case 2)
- In order to still get inflation it is required that $g^2 \lesssim g^2_{max} \sim \mathcal{O}(10^{-3})$[1] for direct couplings or $g^2 \lesssim g^2_{max} \sim \mathcal{O}(10^{-7})$[2] for radiatively induced couplings
- Inflaton induced Higgs mass $m^2_{\mathcal{H}} = g^2\phi^2$ is sub-Hubble during inflation if $g^2 < g^2_{min} \sim \mathcal{O}(10^{-10}) \Rightarrow$ Higgs will be light degree of freedom during inflation
- Energy transfer via non-perturbative broad resonance would require $g^2 \gtrsim g^2_{np} \sim \mathcal{O}(10^{-8})$

[1] D. H. Lyth and A. Riotto, Phys. Rept. 314, 1 (1999), hep-ph/9807278
[2] C. Gross, O. Lebedev, and M. Zatta (2015), 1506.05106

Weak Coupling Limit

- Consider such a weak coupling ($g^2 \ll g_{min}^2$) that they are practically decoupled (case 3), called the *weak coupling limit*
- Extremely small couplings often considered unnatural but the constraints on g allow this choice
- From now on $m_p = \frac{1}{\sqrt{8\pi G}} \simeq 2.44 \cdot 10^{18}$GeV, $a(t)$ the scale factor, t the conformal time and subscript $*$ evaluation at end of inflation

Stability of SM

- In unitary gauge the Higgs can be written as a real degree of freedom $\mathcal{H} = h/\sqrt{2}$ with an effective potential $V = \lambda(h)h^4/4$
- Inflation can be characterized as de Sitter period with constant H_*
- V remains quartic if $H_* \gg M_{EW} \sim \mathcal{O}(10^2)$GeV
- The running of λ becomes negative above some critical energy scale μ_c in the range of $\sim 10^{11} - 10^{16}$GeV
- During inflation we get $H_* \leq H_*^{max} \simeq 9 \cdot 10^{13}$GeV[3]
- To retain stability of the SM we need $\lambda > 0$ and also choose $10^{-5} < \lambda \lesssim 10^{-2}$

[3] P. Ade et al. (Planck) (2015), 1502.02114

Coupling to Gravity

1. Higgs minimally coupled to gravity
   - The Higgs behaves as a light spectator field
   - Variance in equilibrium becomes $\langle h^2 \rangle \simeq \frac{\mathcal{O}(0.1)}{\sqrt{\lambda}} H_*^2$
2. Higgs non-minimally coupled to gravity
   - Coupling represented by $\xi |\phi|^2 R$
   - If $\xi \lesssim 0.1$ the Higgs is light and we recover case 1
   - With $\xi \gg 0.1$ the Higgs is heavy and not excited during inflation
   - A sudden drop of R at the end of inflation induces excitation with variance $\langle h^2 \rangle \simeq \frac{\mathcal{O}(0.1)}{\sqrt{\xi}} H_*^2$

- Higgs always in form of condensate with high vacuum expectation value (VEV), either during inflation or at the end of it

Energy Transfer to SM

- After inflation the Higgs oscillates around the minimum of its potential, creating electroweak gauge bosons and charged fermions with every crossing[4]
- The Higgs is a small part of the total energy budget of the universe during inflation

$$r_* \equiv \frac{\langle V_* \rangle}{\rho_{Inf}} \sim \frac{\lambda h_{rms}^4/4}{3m_p^2 H_*^2} \sim \delta \cdot \mathcal{O}(10^{-12}) \left(\frac{H_*}{H_*^{max}} \right)^2 \ll 1 \quad (1)$$

$\delta = 1$ (case 1), or $\delta = \lambda/\xi$ (case 2)

- During the initial Higgs oscillations there is abrupt energy transfer into gauge bosons which eventually backreact into the Higgs condensate exciting higher modes

[4]K. Enqvist, T. Meriniemi, and S. Nurmi, JCAP 1310, 057 (2013), 1306.4511

Decay of the Higgs

- Energy transfer into SM ends at $t = t_{end}$, abelian simulations suggest[5]

$$t_{end} \simeq 58.9 \beta^{\frac{-(1+3\omega)}{3(1+\omega)}} q_{tot}^{0.4} H_*^{-1}, \quad q_{tot} \equiv \frac{g_Z^2 + 2g_W^2}{4\lambda} \quad , \qquad (2)$$

  $g_Z^2,\ g_W^2$ the $W^{\pm},\ Z$ gauge couplings, $\beta \equiv \sqrt{\lambda} h_* / H_*$ the intial Higgs frequency, ω the post-inflationary EoS
- With resonable parameters $\mathcal{O}(10^2) \lesssim H_* t_{end} \lesssim \mathcal{O}(10^4)$
- Creation of fermions via parametric non-perturbative effects and decay/scattering of gauge bosons into/with fermions is ignored in t_{end}

[5] D. G. Figueroa, J. Garcia-Bellido, and F. Torrenti, Phys.Rev. D92, 083511 (2015), 1504.04600

Evolution of SM Species

- Average energy density of the Higgs scales with $1/a^4$, SM decay products inherit this scaling: $\rho_{SM} = 3m_p^2 H_*^2 r_* / a^4$, with a_* set to 1
- Inflaton energy density after Inflation evolves as $\rho_{Inf} = 3m_p^2 H_*^2 / a^{3(\omega+1)}$ and thus

$$r(t) \equiv \frac{\rho_{SM}}{\rho_{Inf}} = r_* a^{3\omega-1} \sim \delta \cdot 10^{-12} \left(\frac{H_*}{H_*^{max}} \right)^2 a^{3\omega-1} \,, \quad (3)$$

ω being the averaged EoS

- Between end of inflation and BBN $-1/3 < \omega \leq 1$ is required
- Typically $0 \lesssim \omega \lesssim 1/3$ but no reason to exclude stiff case $1/3 < \omega \leq 1$

Post-Inflationary Equation of State

- During inflation slow roll $V \gg K$ is typical
- A drop to $V < K/2$ triggers end of inflation with $\omega = \frac{K-V}{K+V} > 1/3$ becoming stiff
- Simple realization of this Kination-Domination (KD) regime by a rapid transition from $V \gg K$ during inflation to $V \ll K$ after inflation
- $V = 0$ after inflation yields $\omega = 1$ and $V/K \ll 1 (V \neq 0)$gives $\omega \simeq 1 - \mathcal{O}(V/K)$
- Define $\delta\omega \equiv (\omega - 1/3)$

Consequences for r(t)

- 1. $\delta\omega < 0$ ($\omega \leq 1/3$): $r(t)$ either remains small or decreases even further
  2. $0 < \delta\omega \leq 2/3$ (stiff): r(t) grows exponentially
- For stiff EoS there is always a time t_{SM} with $r(t \geq t_{SM}) \geq 1$
- We choose $r(t_{SM}) = 1 = r_* a_{SM}^{3\delta\omega}$ with $a_{SM} \equiv a(t_{SM}) = r_*^{-1/3\delta\omega}$, with $a(t) \propto (H_* t)^{2/(2+3\delta\omega)}$ one finds

$$H_* t_{SM} \simeq r_*^{-\frac{(2+3\delta\omega)}{6\delta\omega}} \sim \left(\frac{10^{12}}{\delta}\right)^{\frac{(2+3\delta\omega)}{6\delta\omega}} \left(\frac{H_*}{H_*^{max}}\right)^{-\frac{(2+3\delta\omega)}{3\delta\omega}} \quad , \quad (4)$$

as estimate for t_{SM}

Possible Reheating Temperature

- One could calculate a temperatur T_{SM} at t_{SM} using $\rho_{SM} \equiv \frac{\pi^2}{30} g_{SM} T_{SM}^4 = 3 m_p^2 H_*^2 r_* / a_{SM}^4$

$$T_{SM} \simeq \frac{3}{g_{SM}^{1}/4} \cdot 10^{13} 10^{-\frac{4}{\delta\omega}} \delta^{\frac{4+3\delta\omega}{12\delta\omega}} \left(\frac{H_*}{H_*^{max}} \right)^{\frac{(2+3\delta\omega)}{3\delta\omega}} \text{GeV} \quad (5)$$

- This temperature can be identified with the reheating temperature but only if certain criteria are met

Cosmological Pertubations

- A sufficiently long KD regime allows the Higgs to generate the total SM energy density
- At $t = t_{SM}$ the Higgs field perturbations are converted into adiabatic perturbations
- Minimal coupling with gravity gives perturbations as $\delta h \sim H_*$, resulting in the power spectrum

$$\frac{\delta h^2}{\langle h^2 \rangle} \sim \sqrt{\lambda} \qquad (6)$$

- Unless λ is very small the resulting perturbations are far larger than the observed amplitude of 10^{-9}

Cosmological Perturbations

- Non minimal coupling to gravity gives a heavy Higgs during inflation, meaning that the perturbations are suppressed exponentially
- This does not give a completely smooth universe
- Perturbations of the inflaton are conserved even after $t > t_{SM}$
- Non minimal coupling to gravity is thus observationally viable, given that the inflaton produces the observed spectrum

Ensuring SM Dominance before BBN

- For viable reheating SM dominance has to establish before the BBN, $T_{SM} > T_{BBN} \simeq$ MeV
- With T_{SM}, $H_* = H_*^{max}$ and $\delta \sim \mathcal{O}(10^{-2})$ $\left(\delta \sim \mathcal{O}(10^{-4})\right)$ one receives $\omega \gtrsim 0.63$ $(\omega \gtrsim 0.69)$
- Shows that $\omega \simeq 1$ is not a strong constraint and will be taken as reference
- First temperature calculation did not account for a tachyonic Higgs field during KD after inflation with $m_h^2 = -6\xi H_*^2$
- Tachyonic behavior leads to exponential growth of Higgs amplitude $h \propto \exp\{\sqrt{6\xi} \int (\dot{a}/a) dt\}$

Stabilization after Tachyonic Phase

- Growth of h actually shuts off tachyonic instability on a shorter time scale than Hubble time, when $\lambda\langle h^2\rangle \gtrsim 6\xi H_*^2$
- The Higgs amplitude must not grow beyond a certain maximum amplitude h_{vac} in order to not fall into its true vacuum, $h \leq h_{vac}$
- Corresponding maximum Hubble rate is $H_*^{vac} = \sqrt{\frac{\lambda}{6\xi}} h_{vac}$
- At tachyonic stabilization we have

$$\langle h^2\rangle \sim \frac{6\xi}{\lambda} H_*^2 = h_{vac}^2 \left(\frac{H_*}{H_*^{vac}}\right)^2 , \tag{7}$$

$$r \equiv \frac{\langle V\rangle}{3m_p^2 H_*^2} \sim \mathcal{O}(10^{-8}) \cdot \frac{\xi^2}{\lambda} \left(\frac{H_*}{H_*^{vac}}\right)^2 \tag{8}$$

- After the rapid growth of the Higgs amplitude the coupling to gravity becomes irrelevant, since $\xi R \sim -6\xi H_*^2/a^6$

Fixing the Reheating Temperature

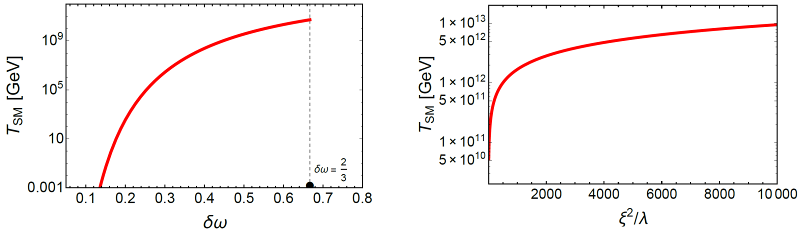
- To calculate the reheating temperature T_{RH} we now use Eqation (8) instead of (5)

$$T_{SM} \simeq \frac{3}{g_{SM}^{1/4}} \cdot 10^{14} 10^{\frac{-8}{3\delta\omega}} \left(\frac{H_*}{H_*^{max}} \right)^{\frac{2+3\delta\omega}{3\delta\omega}} \text{ GeV} \quad (9)$$

$$\sim 3 \cdot 10^{10} \left(\frac{\xi^2}{\lambda} \right)^{3/4} \left(\frac{H_*}{H_*^{max}} \right)^2 \text{ GeV (for } \omega = 1) \quad (10)$$

- With $T_{SM} > T_{BBN} \sim$ MeV one finds that $H_* \geq H_*^{min} \equiv (\xi^2/\lambda)^{-3/8} \cdot 10^7$ GeV
- Large inflationary energy scales are needed

Fixing the Reheating Temperature



Left: Behavior of T_{SM} for fixed values $\xi^2/\lambda = 10$ and $H_*/H_*^{max} = 1$.
Right: Behavior of T_{SM} for fixed values $\delta\omega = 2/3$ and $H_*/H_*^{max} = 1$.
Taken from D.Figueroa,T.Byrnes, "The Standard Model Higgs as the origin of the hot Big Bang", arXiv:1604.03905.

Respecting Radiation Domination

- Important to note that the SM dominance has to be some time before BBN to ensure expansion rate close to radiation domination RD
- We use $T_{SM} = pT_{BBN}$, $p > 1$ to get the Hubble rate at BBN $H(T_{BBN}) = H_{BNN}^{RD}(1 + 1/p^2)^{1/2}$
- Relative difference given by $\left(H(T_{BBN}/H_{BBN}^{RD} - 1\right) \cdot 100 \simeq \frac{1}{2p^2}\%$, so $p \geq 10$ is enough to respect an ideal radiation domination case

Ensuring Thermal Equilibrium before SM dominance

- Thermalization time can be estimated by $t_{Eq} \sim 1/(\alpha^2 T_{Eq})$ with $\alpha = g^2/(4\pi)$
- Define $t_{Eq} \equiv \gamma t_{end}$, then we use $\rho_{Eq} = (g_{Eq}\pi^2/30)T_{Eq}^4 = 3m_p^2 H_*^2 r_{vac}/a_{Eq}^4$, $T_{Eq} \sim 1/(\alpha^2 \gamma t_{end})$ and $a_{Eq} \simeq (2\gamma H_* t_{end})^{1/2}$ to find $\gamma \sim \mathcal{O}(10^3)/\xi$
- $t_{Eq} \ll t_{SM}$ is hence true
- For $t \geq t_{SM}$ the expansion becomes driven by a thermal relativistic plasma of SM species and thus T_{SM} can be identified with a reheating temperature
- For example with $\omega \simeq 1$, $H_* = 0.1 H_*^{vac} = 0.01 H_*^{max}$ and $\lambda = 0.005$ the temperature is $T_{SM} \simeq 10^9 \xi^{3/2}$ GeV

Ensuring Higgs Dominance over Inflaton Decay Products

- Both inflaton and Higgs undergo a non-adiabatic change in their mass during the rapid transition from inflation to KD
- If a small fraction of the inflaton condensate decays into radiation the decay products might dominate over the Higgs forever
- In the limit of a fast transition one receives

$$\frac{\rho_{Inf}^{decay}}{3m_p^2 H_*^2} \sim \frac{m_\phi^4}{3m_p^2 H_*^2} \sim \mathcal{O}(10^{-9}) \cdot \eta_\phi^2 \left(\frac{H_*}{H_*^{max}}\right)^2 , \qquad (11)$$

  m_ϕ effective inflaton mass before transition,
  $\eta_\phi \equiv m_\phi^2/(3H_*^2) < 1$ a slow roll parameter
- Comparing this to the Higgs energy fraction after tachyonic stabilization we see that for $\xi \geq 1$ the Higgs dominates by a factor of $\sim \xi^2/(\lambda \eta_\phi^2) \gg 1$

Summary

- The Higgs coupling to the inflaton field is considered to be extremely small
- The Higgs is universally excited during or shortly after inflation
- With a non-minimal coupling to gravity ($\xi \gtrsim 1$)the Higgs is a curvaton candidate and the origin of the hot thermal plasma required for a hot Big Bang
- Major requirement to the inflaton field is that the background energy density is dominated by the kinetic part after inflation

Possible Observable Consequences and Outlook

- The KD regime after inflation could boost the gravitational waves expected from inflation to high frequencies
- Possible gravitational waves from the Higgs decay products themselves with peak amplitude $h^2\Omega_{GW}^{(o)} \sim 10^{-16}$ at $f_p \sim 10^{11} Hz$
- Introduction of a proper inflation-to-KD transition
- To study the production of dark matter and baryogenesis

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Coupling constraints calculated via[6]

$$-\Delta\mathcal{L} = \frac{\lambda_\nu}{2}\phi\nu_R\nu_R + y_\nu \bar{l}_L H^* \nu_R + \frac{M}{2}\nu_R\nu_R + h.c. \,, \tag{12}$$

$$-\Delta\mathcal{L} = y_Q \overline{q}_L H^* Q_R + \lambda_Q \phi \overline{Q}_L t_R + \mathcal{M}\overline{Q}_L Q_R + h.c. \,, \tag{13}$$

$$-\Delta\mathcal{L} = \frac{\lambda_{\phi s}}{4}\phi^2 s^2 + \frac{\sigma_{\phi s}}{2}\phi s^2 + \frac{\lambda_{hs}}{4}h^2 s^2 + \frac{\lambda_s}{4}s^4 + \frac{m_s^2}{2}s^2 \tag{14}$$

- (12) Via right-handed neutrinos
- (13) Via non-renormizable operators
- (14) Via dark matter production

[6] C. Gross, O. Lebedev, and M. Zatta (2015), 1506.05106.

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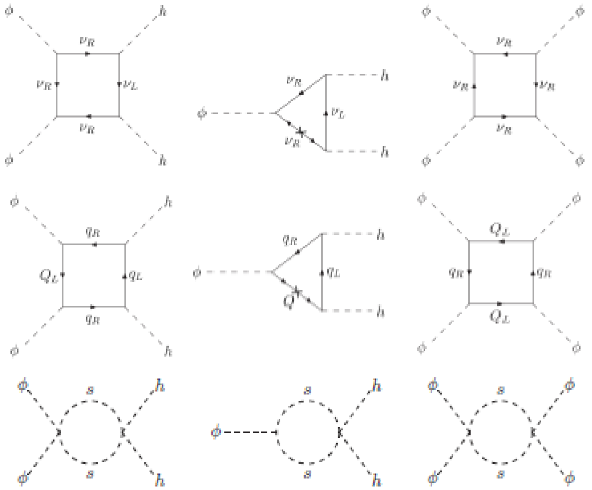

From top to bottom: via right-handed neutrinos, via non-renormizable operators, via dark matter production