Chaotic inflation in Jordan frame supergravity

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based on

HML, arXiv: 1005.2735 [hep-ph]

Planck 2010, June 2, 2010, CERN

Outline

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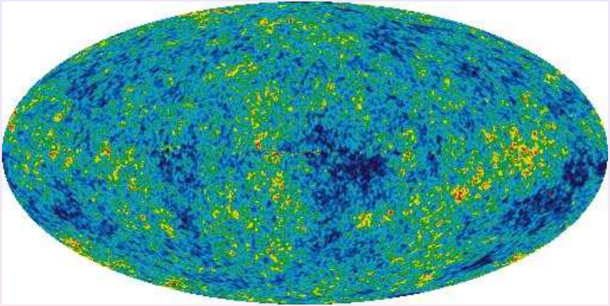
Cosmic Microwave Background



- Basic observed quantities

$$\delta_H = (1.91 \pm 0.17)\cdot 10^{-5}, \quad n_s = 0.960 \pm 0.013$$
$$\text{(COBE)} \qquad\qquad \text{(WMAP, BAO, SN)}$$

Cosmic inflation

- The inflationary period present in the early universe solves or explains flatness, isotropy, homogeneity, horizon and unwanted relic problems in the standard Big Bang cosmology.
- Quantum fluctuations during inflation provides a seed for the large-scale structure formation.
- The vast majority of inflationary models belong to the classical 'slow-roll' motion of a scalar field with $\epsilon \ll 1$ and $|\eta| \ll 1$, resulting in scale-invariant and gaussian spectrum from $n_s = 1 - 6\epsilon + 2\eta$.
- The number of e-foldings of inflation is required to be

$$N_{\rm efold} = 62 + \ln(10^{16}{\rm GeV}/V_{\rm end}^{1/4}) - \frac{1}{3}\ln(V_{\rm end}^{1/4}/\rho_{\rm reh}^{1/4}).$$

Standard Model Higgs inflation

[Bezrukov, Shaposhnikov (2007); De Simone et al (2008); Bezrukov et al (2008)]

- Higgs boson is believed to be present in the SM, triggering electroweak symmetry breaking and generating all the fermion masses.
- If Higgs boson is the inflaton, the required self-coupling ($\lambda \sim 10^{-13}$) would not be compatible with the experimental value, $0.11 < \lambda \lesssim 0.27$, from $114.4\mathrm{GeV} < m_h \lesssim 182\mathrm{GeV}$ (LEP direct bound + precision electroweak data at 95% CL).
- The Higgs inflation with non-minimal coupling may be a new interesting possibility. The non-minimal coupling to gravity is always present in a renormalized scalar theory with self interaction in curved spacetime.

- The Lagrangian proposed for the SM Higgs inflation is in Jordan frame

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}M_P^2\mathcal{R} + \xi|\mathcal{H}|^2\mathcal{R} - |D_\mu\mathcal{H}|^2 - \lambda\Big(|\mathcal{H}|^2 - \frac{v^2}{2}\Big)^2.$$

- After Weyl-scaling to Einstein frame, there appears a plateau in the Higgs potential at $h \gg M_P/\sqrt{\xi}$ (with $\mathcal{H} = \frac{1}{\sqrt{2}}h$):

$$V_E = \frac{\frac{1}{4}\lambda(h^2 - v^2)^2}{(1+\xi h^2/M_P^2)^2} \simeq \frac{M_P^4}{4\xi}\Big(1 - 2e^{-2\phi/(\sqrt{6}M_P)}\Big)$$

with ϕ being the canonically normalized Higgs.

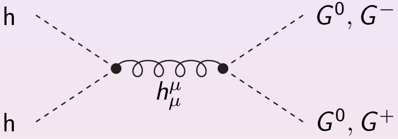
- For $N_{\rm efold} \simeq 60$, spectral index is $n_s \simeq 0.968$ while tensor-to-scalar ratio is $r \simeq 3\times 10^{-3}$, being consistent with observations.
- But, a large non-minimal coupling is required from the COBE normalization: $\xi \simeq 5\times 10^4\sqrt{\lambda}$.

Outline

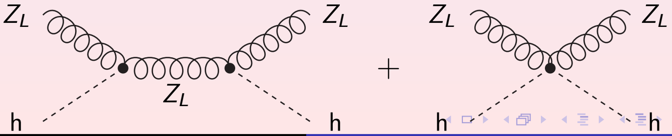
Unitarity bound on new physics

[Burgess, HML, Trott (2009,2010); Barbon, Espinosa (2009); Hertzberg (2010)]

- In Jordan frame, $\mathcal{L}_J = \frac{1}{\Lambda}(h^2 + (G^0)^2 + G^+G^-)\Box h^\mu_\mu$ with $\Lambda \equiv \frac{M_P}{\xi}$ leads to unitarity violation at $E \sim \Lambda$:



- In Einstein frame, $\mathcal{L}_E = -\frac{M_Z^2}{2v^2} Z_\mu Z^\mu (2avh + bh^2)$ with $a = 1 - \frac{3v^2}{\Lambda^2}, b = 1 - \frac{12v^2}{\Lambda^2}$ leads to unitarity violation at $E \sim \Lambda$:



Naturalness of Higgs inflation

[Burgess, HML, Trott (2009); Barbon, Espinosa (2009)]

- The effective theory of inflation as a derivative expansion breaks down unless the Hubble scale satisfies $H \ll \Lambda$. In Higgs inflation, the Hubble scale, $H \simeq \sqrt{\lambda}\Lambda$, is close to the unitarity bound.
- The effective Higgs potential below Λ is generically expanded as $V_J = \sum_n a_n \frac{h^{4+2n}}{\Lambda^{2n}}$ and the non-minimal coupling is expanded in a similar way as $f = \sum_n b_n \frac{h^{2+2n}}{\Lambda^{2n}}$. But the Higgs inflation takes place for a large Higgs vev, $h \gg \frac{M_P}{\sqrt{\xi}} \sim \sqrt{\xi}\Lambda$. Thus, one needs to arrange the higher order terms such that the plateau of the Higgs potential remains.
- Supersymmetry and discrete symmetries may help not to generate dangerous higher corrections by loops.

Outline

1. Inflation and SM Higgs
2. Unitarity bound and naturalness
3. Higgs inflation in supergravity

Jordan frame supergravity

[Einhorn, Jones (2009); Ferrara, Kallosh, Linde, Marrani, Van Proeyen (2010)]

- In SUSY, the scalar potential is given by the Kähler potential K and the superpotential W.
- The 4D supergravity action in Jordan frame is

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{6}\Omega\mathcal{R} - \Omega_{i\bar{j}} D_\mu \phi^i D^\mu \bar{\phi}^{\bar{j}} + \Omega b_\mu^2 - V_J$$

  where $\Omega = -3e^{-K/3}$, $b_\mu = -\frac{i}{2\Omega}(D_\mu\phi^i \partial_i\Omega - D_\mu\bar{\phi}^{\bar{i}}\partial_{\bar{i}}\Omega)$ and V_J is related to the standard Einstein-frame potential as $V_J = \frac{\Omega^2}{9} V_E$ with $V_E = e^K(K^{i\bar{j}}(D_i W)(D_{\bar{j}} W^\dagger) - 3|W|^2) + V_D$.
- For the canonical scalar kinetic terms, the frame function is

$$\Omega = -3 + \delta_{i\bar{j}}\phi^i\bar{\phi}^{\bar{j}} - \frac{3}{2}(F(\phi) + \mathrm{h.c.})$$

  Then, a non-minimal coupling can be introduced for an appropriate holomorphic function F.

Inflation in Jordan frame supergravity

- Consider an inflation model with two singlets S and X with the following frame function and superpotential:

$$\Omega = -3 + S^\dagger S + X^\dagger X - \frac{3}{2}(\chi S^2 + \mathrm{h.c.}),$$
$$W = \frac{1}{2}\lambda X S^2$$

where a global $U(1)$ with charges $q_X = -2$ and $q_S = +1$ is broken only by the non-minimal coupling.

- For $|X|, |S| \ll 1$ and $\chi |S|^2 \gg 1$, the Jordan-frame scalar potential is

$$V_J \simeq \frac{1}{4}|\lambda|^2 |S|^4 - \frac{|\lambda|^2}{6\chi}|X|^2 (S^2 + S^{\dagger 2}) + \mathcal{O}\Big(\frac{|\lambda|^2}{\chi^2}|X|^4\Big).$$

So, X becomes tachyonic along the direction of $\mathrm{Re}(S)$.

- After stabilizing the angular mode of S, the Lagrangian density in Einstein frame is

$$\begin{aligned}\mathcal{L}_E &\simeq -\frac{1}{2}(\partial_\mu\varphi)^2 - e^{-2\varphi/(\sqrt{6}M_P)}|\partial_\mu X|^2 \\ &\quad -\frac{|\lambda|^2 M_P^4}{4\chi^2}\left[1 - 2e^{-2\varphi/(\sqrt{6}M_P)} - \frac{2}{3}e^{-2\varphi/(\sqrt{6}M_P)}\frac{|X|^2}{M_P^2}\right].\end{aligned}$$

- The X singlet has a tachyonic effective mass of order the Hubble scale as $m_X^2 \simeq -2H^2$, spoiling the slow-roll inflation along the S singlet. This problem is generic for the canonical scalar kinetic terms in Jordan frame.

[Ferrara, Kallosh, Linde, Marrani, Van Proeyen (2010)]

Higher order corrections

- An introduction of $\Delta\Omega = -\frac{\gamma}{M_P^2}(X^\dagger X)^2$ in the frame function cures the tachyonic mass problem without changing the inflaton potential:

$$m_X^2 \simeq (12\gamma e^{2\varphi/(\sqrt{6}M_P)} - 2)H^2 > 0$$

  for $e^{-2\varphi/(\sqrt{6}M_P)} \sim 0.02$ and $\gamma > 0.003$.
- COBE normalization gives a constraint, $\frac{\chi}{|\lambda|} \simeq 5 \times 10^4$.
- Derivative expansion is valid for $H \simeq \frac{|\lambda| M_P}{\chi} \ll \Lambda \simeq \frac{M_P}{\chi}$, i.e. $|\lambda| \ll 1$.
- But, higher order corrections for S in the frame function must be suppressed at cutoff scale and be not generated by heavy thresholds. For instance, for $\Delta\Omega = \frac{c}{\Lambda^2}(S^\dagger S)^2$, we need $|c| \ll 1$ for the non-minimal coupling to be dominant.

- Take two heavy chiral superfields $\Phi_{1,2}$ with $U(1)$ charges $q_1 = +1$ and $q_2 = -1$, and $Z_2 : \Phi_{1,2} \to -\Phi_{1,2}$ and $S, X \to S, X$. Then, the additional superpotential is $W' = \frac{1}{2}\kappa X \Phi_1^2 + M\Phi_1\Phi_2$ and the frame function is canonical. The one-loop effective frame function is then

$$\Delta\Omega = -\frac{1}{32\pi^2}\left[2M^2 \ln\left(\frac{M^2}{\mu^2}\right) + \left\{\ln\left(\frac{M^2}{\mu^2}\right) + 2\right\}|\kappa X|^2 + \frac{|\kappa X|^4}{6M^2}\right].$$

- In this case, we get $\gamma = \frac{|\kappa|^4}{192\pi^2}\frac{M_P^2}{M^2}$. So, for $M \sim \frac{M_P}{\xi}$, the tachyon-free condition ($\gamma > 0.003$) gives rise to $|\kappa| > \frac{0.97}{\sqrt{\chi}}$.

Implication on the Higgs inflation in NMSSM

- The NMSSM extension of the Higgs inflation is described by

$$\Omega = -3 + H_u^\dagger H_u + H_d^\dagger H_d + X^\dagger X + \frac{3}{2}(\chi H_u H_d + \mathrm{h.c.}),$$
$$W = \frac{1}{2}\lambda X H_u H_d + \frac{1}{3}\rho X^3.$$

[Einhorn, Jones (2009); Ferrara et al (2010)]

- Our analysis for the toy model with two singlets is directly applied to the Higgs inflation in NMSSM with D-flat condition, curing the tachyonic mass problem of the X singlet.
- The effective μ term is $\mu = \frac{3}{2}\chi m_{3/2} + \frac{1}{2}\lambda\langle X\rangle$. Thus, since the μ term is of order the soft mass, $m_{3/2} \ll m_{\rm soft}$, for a large non-minimal coupling.

Conclusion

- Supersymmetric extensions of the Higgs inflation may help address the naturalness issues in the SM Higgs inflation.
- However, the generic higher order terms in the frame function would be dangerous for the slow-roll inflation.
- An introduction of higher order terms is necessary for curing the tachyonic mass problem in supersymmetric Higgs inflation. On the other hand, one must suppress the accompanying dangerous higher order term for the inflaton.
- From a simple toy model for heavy physics, we showed that the tachyonic mass problem can be resolved without spoiling the slow-roll conditions by a Z_2 symmetry.
- In the NMSSM Higgs inflation, a large non-minimal coupling generates the μ term larger than gravitino mass, so gravitino can be LSP and a dark matter candidate.