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Non-minimal quartic inflation in supersymmetric $SO(10)$

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ABSTRACT

We describe how quartic ($\lambda\phi^4$) inflation with non-minimal coupling to gravity is realized in realistic supersymmetric $SO(10)$ models. In a well-motivated example the $16 - \overline{16}$ Higgs multiplets, which break $SO(10)$ to $SU(5)$ and yield masses for the right-handed neutrinos, provide the inflaton field ϕ. Thus, leptogenesis is a natural outcome in this class of $SO(10)$ models. Moreover, the adjoint (45-plet) Higgs also acquires a GUT scale value during inflation so that the monopole problem is evaded. The scalar spectral index n_s is in good agreement with the observations and r, the tensor to scalar ratio, is predicted for realistic values of GUT parameters to be of order 10^{-3}–10^{-2}.

By incorporating a single right-handed neutrino per generation to cancel new anomalies from gauging the accidental global $U(1)_{B-L}$ symmetry of the Standard Model (SM), both $SU(4) \times SU(2)_L \times SU(2)_R$ [1] and $SO(10)$ [2] provide particularly compelling examples of unifying the strong and electroweak forces. A non-supersymmetric model of SO(10) inflation [3], based on an earlier $SU(5)$ model [4], was proposed a longtime ago. In this class of $SO(10)$ inflation models, driven by a gauge singlet field with minimal coupling to gravity and utilizing the Coleman–Weinberg potential [5], the scalar to tensor ratio r, a canonical measure of gravity waves generated during inflation, is estimated to be $\gtrsim 0.02$, for $n_s = 0.96$–0.97 [6]. Depending on the $SO(10)$ symmetry breaking pattern, an observable number density of intermediate mass magnetic monopoles may be present in our galaxy [7].

In this letter we propose to implement primordial inflation in realistic supersymmetric $SO(10)$ models [8]. We do this with a supergravity generalization of non-minimal $\lambda\phi^4$ inflation [9]. Recall that $\lambda\phi^4$ inflation with a minimal coupling to gravity predicts an r value close to 0.25–0.3, depending on the number of e-foldings ($N_0 = 60$–50). This prediction for r lies well outside the 2-σ range allowed by Planck [10] and WMAP 9 [11]. In contrast, $\lambda\phi^4$ inflation with a suitable non-minimal coupling to gravity is in good agreement with the data regarding the key parameters n_s and r. The quantity r, in particular, can be as low as 0.003 or so, for $n_s = 0.96$–0.97. The discussion closely follows a previous model [12] based on supersymmetric $SU(5)$.

In order to retain perturbative unification of the MSSM gauge couplings in supersymmetric $SO(10)$ we prefer to work with lower dimensional $SO(10)$ representations. We employ $16 - \overline{16}$ Higgs to break $SO(10)$ to $SU(5)$ while keeping supersymmetry unbroken. The $\overline{16}$ vacuum expectation value (VEV) also provides large masses ($\lesssim 10^{14}$ GeV), via higher dimensional operators, to the right-handed neutrinos. In addition, the adjoint 45-plet, in conjunction either with a 54-plet or using higher dimensional operators, is employed to complete the breaking of $SO(10)$ to the MSSM gauge symmetry. Finally, following [13], we can employ two Higgs 10-plets to implement electroweak symmetry breaking and accommodate the charged fermion masses and mixings as well as neutrino oscillation data. This summarizes the basic structure of a realistic supersymmetric $SO(10)$ model.

Recall that a non-minimal $\lambda\phi^4$ inflation scenario is defined by the following action in the Jordan frame:

$$\mathcal{S}_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(1+\xi\varphi^2)\mathcal{R} + \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{\lambda}{16}\varphi^4\right], \tag{1}$$

where we have set to unity the reduced Planck mass, $M_P = 2.44 \times 10^{18}$ GeV. In the limit $\xi \to 0_+$ the non-minimal gravitational coupling term $\xi\varphi^2 R$ vanishes and we approach minimal $\lambda\varphi^4$ chaotic inflation. In the Einstein frame with a canonical gravity sector, we can describe the action with a new inflaton field (σ) which has a canonical kinetic term. The relation between σ and φ is given by

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$$\left(\frac{d\sigma}{d\varphi}\right)^2 = \frac{1+\xi(6\xi+1)\varphi^2}{\left(1+\xi\varphi^2\right)^2}\,. \tag{2}$$

The action in the Einstein frame is then given by

$$S_E = \int d^4x\sqrt{-g_E}\left[-\frac{1}{2}\mathcal{R}_E + \frac{1}{2}(\partial\sigma)^2 - V_E(\sigma(\varphi))\right], \tag{3}$$

with

$$V_E = \frac{\lambda}{16}\frac{\varphi^4}{(1+\xi\varphi^2)^2}. \tag{4}$$

The slow-roll parameters in terms of the original scalar field (φ) are expressed as

$$\begin{aligned}
\epsilon(\varphi) &= \frac{1}{2}\left(\frac{V_E'}{V_E\sigma'}\right)^2,\\
\eta(\varphi) &= \frac{V_E''}{V_E\,(\sigma')^2} - \frac{V_E'\sigma''}{V_E\,(\sigma')^3},\\
\zeta(\varphi) &= \left(\frac{V_E'}{V_E\sigma'}\right)\left(\frac{V_E'''}{V_E\,(\sigma')^3} - 3\frac{V_E''\sigma''}{V_E\,(\sigma')^4} + 3\frac{V_E'\,(\sigma'')^2}{V_E\,(\sigma')^5}\right.\\
&\qquad \left. - \frac{V_E'\,\sigma'''}{V_E\,(\sigma')^4}\right),
\end{aligned} \tag{5}$$

where a prime denotes a derivative with respect to φ. The amplitude of the curvature perturbation $\Delta_{\mathcal{R}}$ is given by

$$\Delta_{\mathcal{R}}^2 = \left.\frac{V_E}{24\pi^2\epsilon}\right|_{k_0}, \tag{6}$$

with $\Delta_{\mathcal{R}}^2 = 2.195\times10^{-9}$ from the Planck measurement [10] with the pivot scale chosen at $k_0 = 0.002\ \mathrm{Mpc}^{-1}$. The number of e-folds is given by

$$N_0 = \frac{1}{\sqrt{2}}\int_{\varphi_e}^{\varphi_0}\frac{d\varphi}{\sqrt{\epsilon(\varphi)}}\left(\frac{d\sigma}{d\varphi}\right), \tag{7}$$

where φ_0 is the inflaton value at horizon exit of the scale corresponding to k_0, and φ_e is the inflaton value at the end of inflation, which is defined by $\max[\epsilon(\varphi_e), |\eta(\varphi_e)|] = 1$. The value of N_0 depends logarithmically on the energy scale during inflation as well as on the reheating temperature, and is typically taken to be $N_0 = 50$–60.

The slow-roll approximation is valid as long as the conditions $\epsilon \ll 1$, $|\eta| \ll 1$ and $\zeta \ll 1$ hold. In this case, the scalar spectral index n_s, the tensor-to-scalar ratio r, and the running of the spectral index $\alpha = \frac{dn_s}{d\ln k}$, are given by

$$n_s = 1-6\epsilon+2\eta,\ \ r = 16\epsilon,\ \ \alpha = 16\epsilon\eta - 24\epsilon^2 - 2\zeta. \tag{8}$$

Here the inflationary predictions are evaluated at $\varphi = \varphi_0$. With the constraint $\Delta_{\mathcal{R}}^2 = 2.215\times10^{-9}$, once N_0 is fixed, the inflationary predictions as well as the quartic coupling λ are determined as a function of ξ. In Table 1 we list the numerical results for selected values of ξ. The inflationary predictions are consistent with the Planck results ($n_s = 0.9655\pm0.0062$, $r \lesssim 0.07$ and $\alpha = 0.0057\pm0.0071$ at 68% C.L.) for $\xi \gtrsim 0.01$. As ξ increases, the inflationary predictions approach $n_s \simeq 0.968$, $r \simeq 0.00296$ and $\alpha \simeq -5.23\times10^{-4}$, while the quartic coupling is monotonically increasing.

Next we discuss how this scenario is implemented in a realistic supersymmetric $SO(10)$ model. The relevant superpotential terms for inflation are given by

Table 1
Inflationary predictions for various ξ values in $\lambda\phi^4$ inflation with non-minimal gravitational coupling.

$N_0 = 60$						
ξ	φ_0	φ_e	n_s	r	$-\alpha(10^{-4})$	λ
0	22.2	3.46	0.951	0.260	−7.93	5.59×10^{-13}
0.001	22.2	3.43	0.957	0.174	−7.650	8.36×10^{-13}
0.01	21.7	3.18	0.965	0.0451	−6.12	3.45×10^{-12}
0.1	17.8	2.15	0.967	0.00784	−5.39	4.34×10^{-11}
1	8.52	1.00	0.968	0.00346	−5.25	1.85×10^{-9}
10	2.89	0.337	0.968	0.00301	−5.24	1.60×10^{-7}
100	0.920	0.107	0.968	0.00297	−5.23	1.58×10^{-5}
252	0.580	0.0677	0.968	0.00297	−5.23	1.0×10^{-4}
1000	0.291	0.0340	0.968	0.00296	−5.23	1.58×10^{-3}
10000	0.0921	0.0107	0.968	0.00296	−5.23	0.158

$$\mathcal{W} \supset \frac{1}{2}m_A A^2 + \bar{z}(m-yA)z - \frac{1}{2}m_A\left(\frac{m}{y}\right)^2, \tag{9}$$

where $z, \bar{z}$ denote the $16-\overline{16}$ fields, A represents the 45-plet, and the last term has been included so that $\langle\mathcal{W}\rangle = 0$ at the desired supersymmetric minimum with $SO(10)$ broken to the SM gauge group. To implement non-minimal $\lambda\phi^4$ inflation an appropriate Kähler potential, following [14], is given by

$$\Phi = 1-\frac{1}{3}\left(|\bar{z}|^2+|z|^2+|A|^2\right)+\frac{1}{3}\gamma(\bar{z}z+h.c.)+\frac{1}{6}\gamma_A(A^2+h.c.), \tag{10}$$

where the parameter coefficients γ and γ_A are assumed to be real and positive constants.

The inflaton trajectory is parametrized by the D-flat direction

$$\bar{z} = z = \frac{1}{2}\varphi,\ \ A = \frac{a}{\sqrt{2}}, \tag{11}$$

where the field VEVs φ and a break $SO(10)\to SU(5)$ and $SO(10)\to SU(3)\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$, respectively. Thus, the initial theory reduces to a model with two real scalars φ and a, and the Jordan frame action is given by

$$\begin{aligned}
\mathcal{S} = \int d^4x\sqrt{-g}\Big[&-\frac{1}{2}\Phi\mathcal{R} + \frac{1}{2}g^{\mu\nu}(\partial_\mu\varphi)(\partial_\nu\varphi)\\
&+\frac{1}{2}g^{\mu\nu}(\partial_\mu a)(\partial_\nu a) - V_J\Big].
\end{aligned} \tag{12}$$

Here, the Kähler potential is expressed as

$$\Phi = 1+\xi\varphi^2+\xi_A a^2, \tag{13}$$

where $\xi = (\gamma-1)/6$ and $\xi_A = (\gamma_A-1)/6$. The scalar potential V_J in the Jordan frame is calculated as [15]

$$V_J = -\left(3\mathcal{W}\ \ \frac{\partial\mathcal{W}}{\partial\bar{z}}\ \ \frac{\partial\mathcal{W}}{\partial z}\ \ \frac{\partial\mathcal{W}}{\partial A}\right)\mathcal{M}^{-1}\left(3\mathcal{W}\ \ \frac{\partial\mathcal{W}}{\partial\bar{z}}\ \ \frac{\partial\mathcal{W}}{\partial z}\ \ \frac{\partial\mathcal{W}}{\partial A}\right)^\dagger, \tag{14}$$

where $\mathcal{M}^{-1}$ is the inverse of the matrix

$$\mathcal{M} = 3\begin{pmatrix}
\Phi & \frac{\partial\Phi}{\partial\bar{z}} & \frac{\partial\Phi}{\partial z} & \frac{\partial\Phi}{\partial A}\\
\frac{\partial\Phi}{\partial\bar{z}^\dagger} & \frac{\partial^2\Phi}{\partial\bar{z}^\dagger\partial\bar{z}} & \frac{\partial^2\Phi}{\partial\bar{z}^\dagger\partial z} & \frac{\partial^2\Phi}{\partial\bar{z}^\dagger\partial A}\\
\frac{\partial\Phi}{\partial z^\dagger} & \frac{\partial^2\Phi}{\partial z^\dagger\partial\bar{z}} & \frac{\partial^2\Phi}{\partial z^\dagger\partial z} & \frac{\partial^2\Phi}{\partial z^\dagger\partial A}\\
\frac{\partial\Phi}{\partial A^\dagger} & \frac{\partial^2\Phi}{\partial A^\dagger\partial\bar{z}} & \frac{\partial^2\Phi}{\partial A^\dagger\partial z} & \frac{\partial^2\Phi}{\partial A^\dagger\partial A}
\end{pmatrix}. \tag{15}$$

To compute the potential (14) we write $\mathcal{W}$ in terms of φ and a

$$\mathcal{W} = \frac{1}{4}m_A\left(a^2-2\left(\frac{m}{y}\right)^2\right)+\frac{1}{4}\varphi^2\left(m-\frac{y}{\sqrt{2}}a\right).$$

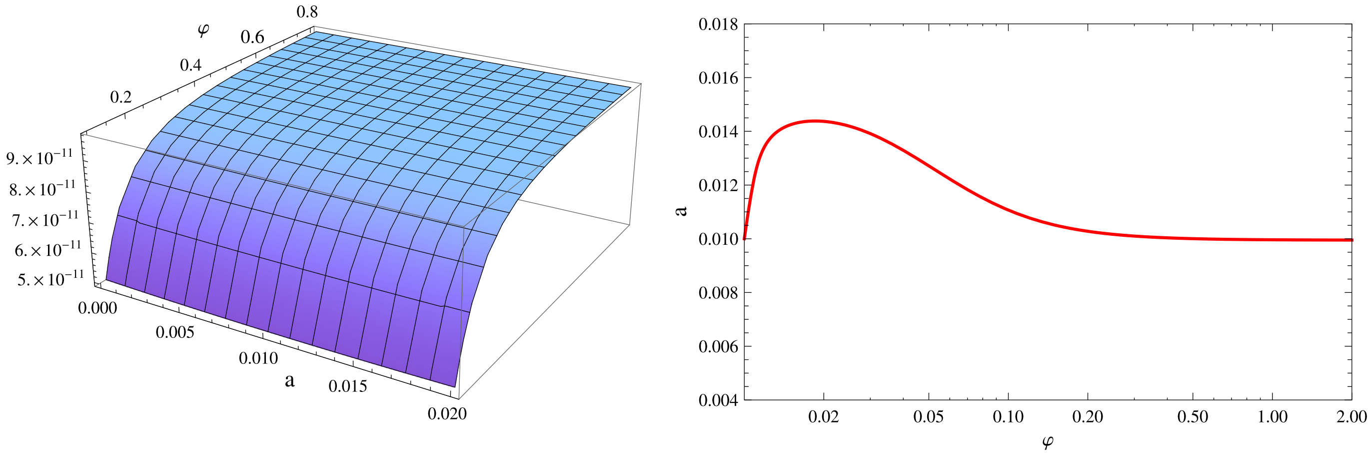

Fig. 1. The scalar potential V_E in the Einstein frame (left) and the inflaton trajectory (right). Here, we have fixed the parameters as $\xi = 252$, $\xi_A = -68$, $m = \frac{y}{\sqrt{2}} M_G$ and $m_A = \frac{y}{2\sqrt{2}} M_G$ with $y = 0.01$ and $M_G = 0.01$ (typical GUT scale).

Then we have

$$\frac{\partial \mathcal{W}}{\partial \bar{z}} = \frac{\partial \mathcal{W}}{\partial z} = \frac{1}{2}\varphi\left(m - \frac{y}{\sqrt{2}}a\right),$$
$$\frac{\partial \mathcal{W}}{\partial A} = \frac{m_A}{\sqrt{2}}a - \frac{y}{4}\varphi^2,$$

and

$$\mathcal{M} = 3\begin{pmatrix} \Phi & \xi\varphi & \xi\varphi & \sqrt{2}\xi_A a \\ \xi\varphi & -1/3 & 0 & 0 \\ \xi\varphi & 0 & -1/3 & 0 \\ \sqrt{2}\xi_A a & 0 & 0 & -1/3 \end{pmatrix}. \tag{16}$$

The potential minimum where $SO(10)$ is broken to the SM gauge group lies at

$$\phi = 2\frac{\sqrt{m\, m_A}}{y}, \quad a = \sqrt{2}\,\frac{m}{y}. \tag{17}$$

The dynamics of inflation is encoded in the scalar potential $V_E = V_J/\Phi^2$ in the Einstein frame. In Fig. 1 we show a 3-dimensional plot of V_E (left panel) and the inflaton trajectory (right panel). Here, we have fixed the parameters as $\xi = 252$, $\xi_A = -68$, $m = \frac{y}{\sqrt{2}} M_G$ and $m_A = \frac{y}{2\sqrt{2}} M_G$ with, $y = 0.01$ and $M_G = 0.01$ a typical value for the GUT scale. The right panel indicates that for $\varphi \gtrsim 0.1$ the inflaton trajectory is well approximated as a straight line such that the φ field is identified with the inflaton. Note that along this trajectory for $\varphi \gtrsim 0.1$, a stays nearly constant close to its value at the potential minimum, $a = M_G$ (see Eq. (17)). In this case, the scalar potential along the trajectory is greatly simplified as

$$\begin{aligned} V_E &\simeq \frac{y^2}{16}\left(\frac{\varphi^2 - M_G^2}{1 + \xi\varphi^2 + \xi_A M_G^2}\right)^2 \\ &\quad \times \frac{1 + \xi(6\xi+1)\varphi^2 + \xi_A M_G^2}{1 + \xi(6\xi+1)\varphi^2 + \xi_A(6\xi_A+1)M_G^2} \\ &\simeq \frac{y^2}{16}\frac{\varphi^4}{(1+\xi\varphi^2)^2}. \end{aligned} \tag{18}$$

Here we have used $\xi > \xi_A$ and $\varphi^2 \gg M_G^2$ for $\varphi \gtrsim 0.1$. This potential is exactly the same as Eq. (4) with the identification $\lambda = y^2$. Since the inflaton value at the end of inflation is found to be $\varphi_e = 0.677$ for $\xi = 252$ (see Table 1), the displacement of a during inflation is small and hence our inflation scenario in the context of supergravity is well approximated by $\lambda\phi^4$ inflation with non-minimal gravitational coupling. Table 1 shows the inflationary predictions as $n_s \simeq 0.968$, $r \simeq 0.00297$ and $\alpha \simeq -5.23 \times 10^{-4}$, which are consistent with the Planck results. Along the inflaton trajectory $SO(10)$ is broken to the SM, and hence the primordial monopoles are inflated away.

In our analysis, we have set $y = 0.01$. We find that the shape of the inflaton trajectory shown in the right panel of Fig. 1 is almost unchanged for a variety of choices of the model parameters, y, ξ and ξ_A.[1] In order to identify φ with the inflaton, the condition $\varphi_e \gtrsim 0.1$ is crucial. According to the results listed in Table 1, this means $\xi \lesssim 100$, or equivalently $\lambda = y^2 \lesssim 10^{-4}$. Following the $SO(10)$ symmetry breaking to the SM, the components $10 + \overline{10}$ of $SU(5)$ from $16, \overline{16}$ and 45 fields, have masses of $\mathcal{O}(yM_G) \lesssim 10^{14}$ GeV. There is some mass splitting of the same order within these multiplets but gauge coupling unification is essentially preserved. With the intermediate scale yM_G of order 10^{11}–10^{14} GeV, the tensor to scalar ratio r varies between 0.01 to 0.003 which should be testable in the foreseeable future.

The VEV of the $\overline{16}$ Higgs field not only breaks the $SO(10)$ symmetry but also generates Majorana masses for the right-handed neutrinos through higher dimensional operators of the form,

$$\mathcal{W} \supset \frac{c_i}{M_P}\mathbf{16}_i\mathbf{16}_i\bar{z}\bar{z}, \tag{19}$$

where $\mathbf{16}_i$ $(i = 1, 2, 3)$ denotes the matter field, and the coefficient c_i is taken to be flavor-diagonal. Associated with the $SO(10)$ symmetry breaking, the right-handed neutrinos acquire masses $M_i = c_i M_G^2/M_P = c_i m_\varphi \simeq c_i \times 10^{14}$ GeV, where $m_\varphi = yM_G = M_G^2/M_P$ is the inflaton mass.

Another important role of the higher dimensional operators is that after inflation the inflaton φ decays into right-handed neutrinos to reheat the Universe. We estimate the reheating temperature as

$$T_{RH} \simeq \sqrt{\Gamma_\varphi M_P} \simeq \frac{1}{\sqrt{16\pi}}M_3 = \frac{|c_3|}{\sqrt{16\pi}}m_\varphi, \tag{20}$$

where M_3 is the heaviest right-handed neutrino mass, compatible with kinematics, and

[1] We find that ξ_A must be negative in order to bound the scalar potential from below in the a-direction.

$$\Gamma_\varphi \simeq \frac{1}{16\pi}\left(\frac{M_3}{M_G}\right)^2 m_\varphi \tag{21}$$

is the total decay width of the inflaton (assuming $c_3 < 1/2$). Since $T_{RH} < M_3$, we expect that the reheating occurs after scatterings among the produced heavy neutrinos and their decays, and hence the actual reheating temperature is lower than the value estimated above. In order to avoid the cosmological gravitino problem [16], we consider the upper bound on the reheating temperature of $T_{RH} < 10^6 - 10^9$ GeV with the gravitino mass in the range of 100 GeV $\lesssim m_{\tilde{G}} \lesssim$ 10 TeV [17], and take c_3 small enough to satisfy this upper bound. Depending on the value of reheating temperature and the right-handed neutrino mass spectrum we can consider either thermal [18] or non-thermal [3] leptogenesis scenarios.

In summary, we have shown that $\lambda\phi^4$ inflation with non-minimal coupling to gravity can be realized in the framework of realistic supersymmetric $SO(10)$ models. An attractive feature is the utilization as inflaton of a field already present for particle physics reasons. In the example provided inflation is driven by the field that breaks $SO(10)$ to $SU(5)$ and provides masses to the right-handed neutrinos. Depending on additional details, thermal or non-thermal leptogenesis is a natural outcome. The field associated with monopole production is non-zero during inflation and so these topological defects are inflated away. With a scalar spectral index in the vicinity of 0.96–0.97 the tensor to scalar ratio r is estimated to be of order 10^{-3}–10^{-2}. Significantly larger values of r require appreciably smaller values of the quartic coupling.

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