Unified Matter Inflation in SUSY GUTs

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Abstract. In this presentation based on reference [1] we explore the novel possibility that the inflaton responsible for cosmological inflation is a gauge non-singlet matter field in supersymmetric (SUSY) Grand Unified Theories (GUTs). We consider hybrid-like inflation models in SUSY (more specifically tribrid inflation models [2]), where we show that the scalar components of gauge non-singlet superfields, together with fields in conjugate representations, may form a D-flat direction suitable for inflation.
We apply these ideas to SUSY models with an Abelian gauge group, a Pati-Salam gauge group and finally Grand Unified Theories based on $SO(10)$. Here, the scalar components of the matter superfields in the **16**s may combine with a single $\overline{\mathbf{16}}$ to form the inflaton. Thus in some sense this "unified particle" can act as the "mother of the universe", as it contains the inflaton responsible for inflation as well as all the matter present today.

1. Introduction

The inflationary paradigm remains extremely successful in solving the horizon and flatness problems of the standard Big Bang cosmology, and at the same time in explaining the origin of structure of the observable Universe and the absence of relic topological defects [3] (for a textbook review, see e.g. [4]).

A long standing question in inflation models is: Who is the inflaton? We are still far from answering this question. Indeed it is still unclear whether the inflaton, the (presumed) scalar field responsible for inflation, should originate from the observable (matter) sector or the hidden (e.g. moduli) sector of the theory. However the connection between inflation and particle physics is rather difficult to achieve in the observable sector due to the lack of understanding of physics beyond the Standard Model (SM) and in the hidden sector due to the lack of understanding of the string vacuum.

However over the past dozen years there has been a revolution in particle physics due to the experimental discovery of neutrino mass and mixing (for a review, see e.g. [5]), and this improves the prospects for finding the inflaton in the observable sector. Indeed, if the SM is extended to include the seesaw mechanism [6–11] and SUSY, the right-handed sneutrinos, the superpartners of the right-handed neutrinos, become excellent inflaton candidates.

Despite the unknown identity of the inflaton, conventional wisdom dictates that it must be a gauge singlet since otherwise radiative corrections would spoil the required flatness of the inflaton potential. For example in SUSY models scalar components of gauge non-singlet superfields have quartic terms in their potential, due to the D-terms, leading to violations of the slow-roll conditions which are inconsistent with recent observations by WMAP. In addition, gauge non-singlet inflatons would be subject to one-loop Coleman-Weinberg corrections from loops with gauge fields which could easily lead to large radiative corrections that induce an unacceptably large slope of the inflaton potential. Furthermore a charged inflaton is in general also subject to two-loop corrections to its mass which can easily be larger than the Hubble scale [12]. Such a contribution is in principle large enough to spoil inflation for any gauge non-singlet scalar field, leading to a sort of "gauge η-problem".

In this talk we shall argue that, contrary to conventional wisdom, the inflaton may in fact be a gauge *non*-singlet (GNS). For definiteness we shall confine ourselves here to examples of SUSY hybrid inflation and show that the scalar components of gauge non-singlet superfields, together with fields in conjugate representations, may form a D-flat direction suitable for inflation. Along this D-flat trajectory the usual F-term contributes the large vacuum energy. We apply these ideas first to a simple Abelian gauge group $G = U(1)$, then to a realistic SUSY Pati-Salam model, then to $SO(10)$ SUSY GUTs, where the scalar components of the matter superfields in the **16**s may combine with a single $\overline{\mathbf{16}}$ to form the inflaton, with the right-handed sneutrino direction providing a possible viable trajectory for inflation.

Indeed, assuming the sneutrino inflationary trajectory, we calculate the one-loop Coleman-Weinberg corrections and the two-loop corrections usually giving rise to the "gauge η-problem" and show that both corrections do not spoil inflation. In addition we show that the monopole problem [13] can be resolved. The usual η-problem arising from SUGRA [14] may be resolved using a Heisenberg symmetry [15] with stabilized modulus [16].

2. SUSY Hybrid Inflation with a GNS Inflaton

SUSY hybrid inflation is typically based on the superpotential [17]

$$W_0 = \kappa\, S\left(H\bar{H} - M^2\right) \tag{1}$$

where the superfield S is a singlet under some gauge group G, while the superfields H and $\bar{H}$ reside in conjugate representations (reps) of G. The F-term of S provides the vacuum energy to drive inflation, the scalar component of the singlet S is identified as the slowly rolling inflaton, and the scalar components of H and $\bar{H}$ are waterfall fields which take zero values during inflation but are switched on when the inflaton reaches some critical value, ending inflation and breaking the gauge group G at their global minimum $\langle H\rangle = \langle \bar{H}\rangle = M$. Typically G is identified as a GUT group and H, $\bar{H}$ are the Higgs which break that group..

Consider the following simple extension of the superpotential in Eq. (1),

$$W = W_0 + \frac{\zeta}{\Lambda}\left(\phi\,\bar{\phi}\right)\left(H\bar{H}\right) \tag{2}$$

where we have included an additional pair of GNS superfields ϕ and $\bar{\phi}$ in conjugate reps of G which couple to the Higgs superfields via a non-renormalizable coupling controlled by a dimensionless coupling constant ζ and a scale Λ. At first glance, we might expect the presence of the effective operator in Eq. (2), that we have added to the superpotential W_0 in Eq. (1), to not perturb the usual SUSY hybrid inflation scenario described above. However its presence allows the new possibility that inflation is realized via slowly rolling scalar fields contained in the superfields ϕ and $\bar{\phi}$ with the singlet field S staying fixed at zero during (and after) inflation. In a SUGRA framework, non-canonical terms for S in the Kähler potential can readily provide a large mass for S such that it quickly settles at $S = 0$. On the other hand, large SUGRA mass contributions can be avoided for ϕ and $\bar{\phi}$ using a Heisenberg symmetry [16].

While the singlet S field is held at a zero value by SUGRA corrections, the scalar components of ϕ, $\bar{\phi}$, having no such SUGRA corrections, are free to take non-zero values during the inflationary epoch. The non-zero ϕ, $\bar{\phi}$ field values provide positive mass squared contributions to all components of the waterfall fields H and $\bar{H}$ during inflation, thus stabilizing them at zero by the F-term potential from the second term in Eq. (2). As in standard SUSY hybrid inflation, the F-term of S, arising from W_0 in Eq. (1), yields a large vacuum energy density $V_0 = \kappa^2 M^4$ which drives inflation and breaks SUSY. Since ϕ, $\bar{\phi}$ are the only fields which are allowed to take non-zero values during inflation, they may be identified as inflaton(s) provided that their potential is sufficiently flat. Since both ϕ and $\bar{\phi}$ carry gauge charges under G, their vacuum expectation values (VEVs) break G already during inflation, thus, although ϕ and $\bar{\phi}$ are GNS fields under the original gauge group G, they are clearly gauge singlets under the surviving subgroup of $G' \subset G$ respected by inflation. This trivial observation will help to protect the ϕ and $\bar{\phi}$ masses against large radiative corrections. Another key feature is that the quartic term in the ϕ and $\bar{\phi}$ potential arising from D-term gauge interactions may be avoided in a D-flat valley in which the conjugate fields ϕ and $\bar{\phi}$ take equal VEVs.

3. Explicit Example with $G = U(1)$

Let us now explicitly calculate the full global SUSY potential for the model in Eq. (2), assuming an Abelian gauge group $G = U(1)$. For $G = U(1)$ and equal charge for ϕ and H we obtain a D-term contribution (setting a possible Fayet-Iliopoulos term to zero)

$$V_D = \frac{g^2}{2} \left(|\phi|^2 - |\bar{\phi}|^2 + |H|^2 - |\bar{H}|^2 \right)^2 , \tag{3}$$

which on the inflationary trajectory $\langle H \rangle = \langle \bar{H}^* \rangle = 0$ obviously has a D-flat direction $\langle \phi \rangle = \langle \bar{\phi}^* \rangle$. Under the assumption that the D-term potential Eq. (3) has already stabilized the fields in the D-flat valley, the remaining potential is generated from the F-term part which can be calculated with the equations of motion $F^{*i} = -\partial W / \partial \phi_i$. Plugging in the D-flatness condition $\langle \phi \rangle = \langle \bar{\phi}^* \rangle$ and setting $S = 0$, the F-term potential reduces to

$$V_F = \left| \kappa^2 \left(M^2 - H\bar{H} \right) \right|^2 + 2 \frac{|\zeta|^2}{\Lambda^2} |\phi|^2 |H|^2 |\bar{H}|^2 + \frac{|\zeta|^2}{\Lambda^2} |\phi|^4 |H|^2 + \frac{|\zeta|^2}{\Lambda^2} |\phi|^4 |\bar{H}|^2 , \tag{4}$$

which is of the typical hybrid-form, cf. Fig. 1.

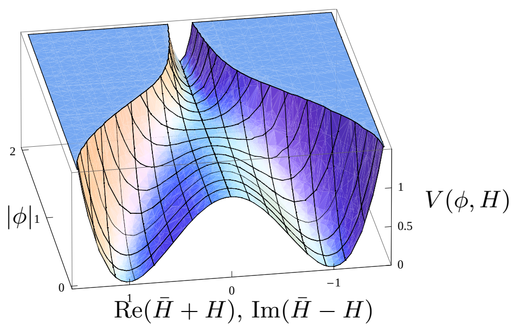

Figure 1: Plot of the F-term hybrid inflation potential in the D-flat valleys $\phi = \bar{\phi}^*$, $H = \bar{H}^*$.

Indeed, in the inflationary valley $S = H = \bar{H} = 0$ it has a flat inflaton direction $|\phi|$ and a tachyonic waterfall direction below some critical value $|\phi_c|$.

The tree-level flat direction is only lifted radiatively due to inflaton-dependent, SUSY breaking waterfall masses. Diagonalizing the mass matrices in the $(H, \bar{H})$-basis, the eigenvalues calculated from Eqs. (2) and (4) are 1 Dirac fermion with the squared mass $m_F^2 = |\zeta|^2 |\phi|^4 / \Lambda^2$ and 2 complex scalars with squared masses $m_S^2 = |\zeta|^2 |\phi|^4 / \Lambda^2 \pm |\kappa|^2 M^2$. Plugging these values into the formula for the one-loop Coleman-Weinberg potential and integrating back the equation of motion of the inflaton field to the point 60 e-folds before the end of inflation we obtain the following predictions for the model at hand

$$n_s \simeq 0.98 \quad , \quad r \lesssim 0.01 \quad , \quad M \simeq 7 \cdot 10^{15}\,\text{GeV} . \tag{5}$$

4. Sneutrino Inflation in SUSY Pati-Salam

In this section we discuss a fully realistic example of SUSY hybrid inflation with a GNS inflaton where G is identified with the SUSY Pati-Salam gauge group. Following the general ideas presented in the previous section, in the model under construction inflation will proceed along a trajectory in field space where the D-term contribution vanishes and the F-term contribution dominates the vacuum energy. In addition to that we want to associate the inflaton field to the "matter sector" of the theory so that the model is closely related to low energy particle physics.

Typically if there are only matter fields in the (CP conjugated) right-handed Pati-Salam reps R_i^c this would lead to large D-term contributions incompatible with inflation. Therefore, in addition to the matter fields R_i^c we also introduce another field $\bar{R}^c$ in the conjugate rep of the gauge group. For simplicity, we will discuss here the case where $i = 1, \ldots, 4$ and where there is only one $\bar{R}^c$. The introduction of $\bar{R}^c$ is also necessary in order to keep all the waterfall directions stabilized during inflation. After inflation, one linear combination of the fields R_i^c will pair up with $\bar{R}^c$ and become heavy, while three other combinations remain light and contain the three generations of SM fields. In addition, the superfields containing the right-handed neutrinos of the seesaw mechanism will obtain their large masses after inflation.

More specifically, the (minimalist) field content of our model reads

$$\begin{aligned} R_i^c &= (\bar{\mathbf{4}}, \mathbf{1}, \bar{\mathbf{2}}) = \begin{pmatrix} u_i^c & u_i^c & u_i^c & \nu_i^c \\ d_i^c & d_i^c & d_i^c & e_i^c \end{pmatrix}, \; \bar{R}^c = (\mathbf{4}, \mathbf{1}, \mathbf{2}) = \begin{pmatrix} \bar{u}^c & \bar{u}^c & \bar{u}^c & \bar{\nu}^c \\ \bar{d}^c & \bar{d}^c & \bar{d}^c & \bar{e}^c \end{pmatrix} \\ H^c &= (\bar{\mathbf{4}}, \mathbf{1}, \bar{\mathbf{2}}) = \begin{pmatrix} u_H^c & u_H^c & u_H^c & \nu_H^c \\ d_H^c & d_H^c & d_H^c & e_H^c \end{pmatrix}, \; \bar{H}^c = (\mathbf{4}, \mathbf{1}, \mathbf{2}) = \begin{pmatrix} \bar{u}_H^c & \bar{u}_H^c & \bar{u}_H^c & \bar{\nu}_H^c \\ \bar{d}_H^c & \bar{d}_H^c & \bar{d}_H^c & \bar{e}_H^c \end{pmatrix} \end{aligned} \tag{6}$$

where $H^c, \bar{H}^c$ are the waterfall Higgs superfields breaking PS to the SM after inflation and in addition we introduce two further gauge singlet fields, namely S and X. The introduction of the spurion X, which aquires a VEV before the inflationary epoch, is due to two additional symmetries, namely a R-symmetry and a discrete $\mathbb{Z}_{10}$ symmetry, which allow us to restrict the allowed terms in the superpotential, which reads as follows

$$\begin{aligned} W =& \kappa\, S \left(\frac{\langle X \rangle}{\Lambda} H^c \bar{H}^c - M^2 \right) \\ &+ \frac{\lambda_{ij}}{\Lambda} (R_i^c \bar{H}^c)(R_j^c \bar{H}^c) + \frac{\gamma}{\Lambda} (\bar{R}^c H^c)(\bar{R}^c H^c) + \frac{\zeta_i}{\Lambda} (R_i^c \bar{R}^c)(H^c \bar{H}^c) + \frac{\xi_i}{\Lambda} (R_i^c \bar{H}^c)(\bar{R}^c H^c)\,. \end{aligned} \tag{7}$$

Here, two multiplets enclosed in brackets are contracted with their respective $SU(4)_C$ and $SU(2)_R$ indices.

We would like to remark at this point that the symmetries and charge assignments we have chosen are not unique and should mainly illustrate that it is possible to obtain the desired form of the superpotential by symmetry.

It turns out that the model has several tree-level flat directions in $R_i^c, \bar{R}^c$ field space and in principle inflation can proceed along any of them. However, let us now focus on the inflationary dynamics when the inflaton fields acquire VEVs along the sneutrino direction. As an explicit example we consider the simplest case where only one of the $R^c = R_1^c \neq 0$ as well as $\bar{R}^c \neq 0$ are slow-rolling, while all the others remain at zero $R_{i \neq 1}^c = 0$.

Computing the D-term potential in the case at hand, we find that it has a flat direction for $|\nu^c| = |\bar{\nu}^c|$. From now on, we assume that inflation occurs in this D-flat valley. Therefore the scalar potential during inflation has to be calculated with the D-flatness condition $|\nu^c| = |\bar{\nu}^c|$ imposed.

Looking at the resulting scalar potential we find that due to large F-term contributions to their masses from the VEVs of the inflaton fields, the waterfall fields are fixed at zero during inflation (S, as always, is fixed at 0 during and after inflation by SUGRA corrections). However, as the inflaton fields slowly roll to smaller values, the masses of the waterfall fields decrease and finally one direction in field space becomes tachyonic. The $H^c, \bar{H}^c$ fields now quickly roll to their true minima and inflation ends by the "waterfall".

One can calculate the critical values at which the system gets destabilized by setting the dynamical masses to zero. We find

$$|\tilde{\nu}^c_{\text{crit}}| = \sqrt{\frac{2\,|\kappa|\,M}{|\zeta|}}\,, \tag{8}$$

for the $\text{Re}(u^c_H + \bar{u}^c_H)$, $\text{Im}(\bar{u}^c_H - u^c_H)$, ... directions and the real, positive solutions

$$|\tilde{\nu}^c_{\text{crit}}| = \sqrt{\frac{2\,|\kappa|\,M}{|\zeta+\xi+2\gamma|}}\,, \qquad |\tilde{\nu}^c_{\text{crit}}| = \sqrt{\frac{2\,|\kappa|\,M}{|\zeta+\xi-2\gamma|}}\,, \tag{9}$$

for the $\text{Re}(\bar{\nu}^c_H - \nu^c_H)$- and $\text{Im}(\bar{\nu}^c_H - \nu^c_H)$-directions.

For generic non-zero values of γ (and for example small ξ), either the $\text{Re}(\bar{\nu}^c_H - \nu^c_H)$- or the $\text{Im}(\bar{\nu}^c_H - \nu^c_H)$-direction will become tachyonic for larger values of the inflaton VEV than the $\text{Re}(u^c_H + \bar{u}^c_H)$, ... directions. Consequently, it destabilizes first and the waterfall will happen in this direction in field space, breaking G_{PS} down to the Standard Model. Furthermore, since the waterfall happens in a preferred direction, the production of monopoles is avoided.

Also, since the gauge symmetry is already broken by the inflaton VEVs during inflation, the inflaton direction basically decouples from the gauge interactions. Therefore the potentially dangerous one- and two-loop corrections to the inflaton potential are under control and pose no threat to the realization of slow-roll inflation.

After calculating the full mass spectrum on the inflationary trajectory and plugging it into the formula for the one-loop Coleman-Weinberg potential, one can again derive the inflationary predictions, which are very similar to those for the case $G = U(1)$ presented in the last section.

5. $SO(10)$ SUSY GUTs

In order to embed our model of the previous section into a $SO(10)$ framework we first have to make it explicitly left-right-symmetric by adding left-charged matter-supermultiplets as well as left-charged Higgs-supermultiplets to the theory.

At this stage the model contains two copies of the inflaton sector discussed in the previous section, one charged under $SU(2)_R$ and one charged under $SU(2)_L$, as well as additional couplings between the two sectors. In the absence of a discrete left-right symmetry we would expect the couplings in the left and right sector to be not exactly equal. With two potential sectors for inflation, inflation may happen in both of them with the respective sneutrinos playing the role of the inflaton. Thus we might have an "inflaton race" between the two sectors. Once the waterfall happens in one of the two sectors (with different couplings in each sector we do not expect this to happen simultaneously), inflation ends since the vacuum energy given by the F_S-term vanishes. At the same time the masses of the matter fields get fixed by the VEVs of the waterfall fields and the couplings between the left and the right sector.

In terms of the PS framework considered in the preceding section, each of the left- and right-charged leptoquark superfields as well as the Higgs superfields are unified into **16** reps and their conjugate counterparts into $\overline{\mathbf{16}}$ reps as

$$\begin{aligned} \mathbf{16} &= (\mathbf{4},\mathbf{2},\mathbf{1}) \oplus (\bar{\mathbf{4}},\mathbf{1},\bar{\mathbf{2}})\,, \\ \overline{\mathbf{16}} &= (\bar{\mathbf{4}},\bar{\mathbf{2}},\mathbf{1}) \oplus (\mathbf{4},\mathbf{1},\mathbf{2})\,. \end{aligned} \tag{10}$$

Choosing again proper symmetries to forbid unwanted operators, we arrive at the following superpotential relevant for inflation

$$W_{\text{inf}} = \kappa\, S \left(H\bar{H} - M^2\right) + \frac{\lambda_{ij}}{\Lambda}\, F_i F_j \bar{H}\bar{H} + \frac{\gamma}{\Lambda}\, \bar{F}\bar{F} H H + \frac{\zeta_i}{\Lambda}\, F_i \bar{F} H \bar{H} + \dots\ , \tag{11}$$

where F_i and $\bar{F}$ now contain the inflaton as well as the SM matter fields.

We assume that $SO(10)$ is broken to G_{PS} before inflation and then inflation, as well as the waterfall after inflation are realized as discussed in the previous section.

Again, we would like to emphasize at this point that the minimalist field content and the choice of symmetries mainly serves the purpose of giving a proof of existence that GNS inflation can be realized in $SO(10)$ GUTs. In a fully realistic model, which e.g. may also contain a full flavor sector, different symmetries may have to be chosen and the field content may have to be extended.

6. Conclusions

We have forged a connection between inflation and particle physics by identifying the inflaton with a unified matter particle in a SUSY GUT. When this is done the inflaton carries a gauge charge. This can lead to dangerous contributions to the inflaton potential from the D-terms and quantum corrections at the one- and two-loop level that are potentially big enough to violate the slow-roll conditions and render (hybrid) inflation impossible.

We have first presented our general setup - which relies on a "tribrid-like" superpotential together with a Heisenberg symmetry with stabilized modulus in the Kähler potential to solve the SUGRA η-problem - in the simplest case of an inflaton charged under $U(1)$.

We have then extended our model to the Pati-Salam gauge group, where we have explicitly calculated the inflaton potential up to one-loop order and also estimated the two-loop corrections for the case of inflation along the D-flat right-handed sneutrino trajectory. We have shown that all corrections are under control and that furthermore no topological defects are produced in the waterfall phase ending inflation.

Finally, we have sketched how the model can be embedded into a $SO(10)$ GUT, where now the inflaton resides in the 16-dim spinor representation of $SO(10)$, thus unifying the inflaton and the SM matter fields in one particle.

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