Minimal Inflation

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Abstract

Using the universal X superfield that measures in the UV the violation of conformal invariance we build up a model of multifield inflation. The underlying dynamics is the one controlling the natural flow of this field in the IR to the Goldstino superfield once SUSY is broken. We show that flat directions satisfying the slow roll conditions exist only if R-symmetry is broken. Naturalness of our model leads to scales of SUSY breaking of the order of 10^{11-13} Gev, a nearly scale-invariant spectrum of the initial perturbations and negligible gravitational waves. We obtain that the inflaton field is lighter than the gravitino by an amount determined by the slow roll parameter η. The existence of slow-roll conditions is directly linked to the values of supersymmetry and R-symmetry breaking scales. We make cosmological predictions of our model and compare them to current data.

Key words: SUSY; cosmology; inflation

1. Introduction

In spite of the enormous success of inflationary cosmology [1, 2, 3, 4, 5, 6, 7, 8, 9] at describing the observed properties of the Universe, we are still missing a derivation from first principles where the inflaton field is identified with one, or several, fundamental fields in particle physics. This manifests itself the in the fact that we still do not count with a natural way of identifying the inflaton field and the properties of its potential required to satisfy experimental constraints [10, 11].

It was quickly realized after the inflationary scenario was proposed more than 30 years ago, that supersymmetry could provide a natural scenario with plenty of flat directions which could lead to inflation [18, 19, 20, 21, 22, 23]. When the theory couples to supergravity, there are a num-

ber of new problems that appear [24], and we will discuss some of them later on.

Current observational constraints from CMB temperature and polarization experiments and large-scale structure limit the amount the inflaton field has moved to approximately $< 2M_{pl}$[14], where M_{pl} is the reduced Planck mass. Therefore, inflationary models that search for the inflaton at very large energies, like for example chaotic inflation, are severely constrained already by current observations. With the current new generation of CMB experiments (Planck, EBEX, Spider, SPUDS etc...) it will be possible to further constraint how much the inflaton field has displaced during the inflationary period that gave rise to our current casual horizon. It is therefore useful to revisit again the problem of steep directions in SUGRA models to understand if a flat direction can be obtained at all.

In this paper we will suggest a natural embedding of inflationary dynamics in the effective low-energy Lagrangian

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describing supersymmetry breaking. Our approach will be quite independent of the microphysics underlying supersymmetry breaking, and will only rely on universal properties of this symmetry. Since we are not committing ourselves to any particular microscopic realization of supersymmetry breaking, some of our comments about reheating for instance will be rather sketchy. A more detailed and precise presentations of our ideas will appear elsewhere [25]. Like most inflationary theories containing supersymmetry, we present a simple model of multifield inflation (sometimes called hybrid) [26], identify naturally the inflaton field and its potential, and then fit a few observational data to estimate the few parameters of our model. We compute, in particular, the number of e-folding and the amplitude of density fluctuations at horizon crossing. It is surprising to find that the scale of supersymmetry breaking indicated by this analysis is between $10^{11} - 10^{14}$GeV. An interesting spin-off of our model is that the inflaton is lighter than the gravitino by an amount $\sqrt{\eta}$, where η is one of the slow roll parameters (see below).

We would like to stress that in this paper we are always assuming F-breaking of supersymmetry. In D-breaking scenarios our arguments do not apply, at least as presented here [1].

2. General framework

Supersymmetry is a natural framework to define inflationary scenarios for two main reasons. First of all, SUSY naturally leads to the existence of flat, or nearly flat directions (pseudomoduli), allowing for slow roll scenarios. Second, and more important, the order parameter of supersymmetry breaking is the vacuum energy density. Hence, naturally associated with its breaking, supersymmetry contains two main ingredients necessary in inflationary scenarios: vacuum energy and reasonably flat directions.

In a remarkable recent work, Komargodski and Seiberg [27] have presented a new formalism to understand supersymmetry breaking, its general properties, its non-linear realizations [28], and a systematic way to understand the low-energy couplings of goldstinos to other fields. Although many things were known before (see references in [27]) this work, the presentation is quite insightful, and it played a major part in the inspiration of this work.

The basic starting point in [27] is the Ferrara-Zumino multiplets of currents [29]. A vector superfield composed of the R-symmetry current, the supercurrent, and the energy momentum tensor. This vector superfield satisfies the general relation:

$$\bar{D}^{\dot{\alpha}} J_{\alpha,\dot{\alpha}} = D_\alpha X. \tag{1}$$

The chiral superfield X is essentially defined uniquely [2] in the ultraviolet. Following [27] the superfield X has the following properties:

- In the UV description of the theory, it appears in the right hand side of 1, where it represents a measure of the violation of conformal invariance.

- The expectation value of its θ^2 component is the order parameter of supersymmetry breaking. In this work we are only considering F-breaking of supersymmetry. We denote by f the expectation value of the F-component of X. It will sometimes be useful to write $f = \mu^2$, where μ is the microscopic scale of supersymmetry breaking.

- When supersymmetry is spontaneously broken, we can follow the flow of X to the infrared (IR). In the IR this field satisfies a non-linear constraint and becomes

[2]The ambiguities in the supercurrent multiplet and X are related to improvement terms in the various currents.

the "goldstino" superfield [3].

$$X_{NL}^2 = 0, \qquad (2)$$

$$X_{NL} = \frac{G^2}{2F} + \sqrt{2}\,\theta\,G + \theta^2\,F. \qquad (3)$$

The scalar component x of X becomes a goldstino bilinear. Its fermionic component is the goldstino fermion G, and F is the auxiliary field that gets the vacuum expectation value. A major part in the analysis in [27] is based on this novel nonlinear constraint satisfied by the superfield X in the IR. As shown there, the correct normalization of the goldstino superfield to derive all relevant low-energy theorems of broken supersymmetry is $X_{NL} = \frac{3}{8f}X$.

- Finally, X generalizes the usual spurion couplings appearing in the description of low-energy supersymmetric lagrangians. If m_{soft} describes the soft supersymmetry breaking masses at low energies, the standard spurion in the lagrangian is replaced by $\frac{m_{soft}}{f}X_{NL}$. This allows one to write the leading low-energy couplings of the goldtino to other matter fields.

Since we are going to consider goldstino couplings, we will work with a field whose expectation values are well below the Planck scale.

Our proposal is to identify in the UV the inflaton field with the scalar component of the superfield X. Since X is defined uniquely (up to the ambiguity mentioned in footnote one) in the UV, this provides a well defined prescription. Furthermore, we will identify the inflationary period precisely with the flow of X from the UV to the IR i.e. $X \rightarrow X_{NL}$. Note that by making this assumption we do not need to think of the inflaton as any extra fundamental field. In fact, independently of how SUSY is broken, and

what is the underlying fundamental theory we can always identify the $X-$superfield as well as its scalar component x. More importantly, by making this assumption we are identifying the vacuum energy driven inflation with the actual SUSY breaking order parameter.

In the supergravity context, once we have the Kähler potential $K(X,\bar{X})$ and the superpotential $W(X)$, the full scalar potential is given by [30]:

$$V = e^{\frac{K}{M^2}}(K_{X,\bar{X}}^{-1}DW\bar{D}W - \frac{3}{M^2}|W|^2) \qquad (4)$$

with

$$DW = \partial_X W + \frac{1}{M^2}\partial_X K\,W. \qquad (5)$$

M is the high energy scale below which we can write the effective action describing the dynamics of the X-superfield. It could be the Planck scale, or a GUT scale depending on the microscopic theory. We will work well below the scale M, and for simplicity take $M = M_{pl}$ In equation (4) we can see one of the basic problems in supergravity inflation [24]. As we will see later on, to satisfy the slow roll conditions, a necessary condition is that the η-parameter, defined by:

$$\eta = M_{pl}^2 \frac{V''}{V}, \qquad (6)$$

be much smaller than one. If we choose a Kähler potential $K(X,\bar{X})$ with R-symmetry, for instance the canonical one $K(X,\bar{X}) = X\bar{X} + \ldots$, where the $\ldots$ represents a function of $X\bar{X}$, it is easy to see that from the exponent of (4) we always get a contribution to η equal to 1: $\eta = 1 + \ldots$, no matter which component of X is taken as the inflaton field. This of course violates the slow roll conditions. Since we are considering a situation with supersymmetry breaking and gravity (early universe), we cannot exclude supergravity from the picture, and this leads to the η-problem in these theories.

The simplest way out of this problem without unreasonable fine tuning, is to have explicit R-symmetry breaking

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[3] A modified version of the nonlinear constraint (2) appears when one considers spontaneous R-symmetry breaking. In that case, the goldstino and the corresponding axion will be part of the same multiplet.

in the Kähler potential [4]. If we have explicit R-breaking, the expansion of V for small fields takes the form:

$$X = M(\alpha + i\beta) \tag{7}$$

$$V = f^2(1 + A_1(\alpha^2 + \beta^2) + B_1(\alpha^2 - \beta^2) + \ldots) \tag{8}$$

f is the supersymmetry breaking parameter representing the expectation value of an F-term, and hence with square mass dimensions. We assume that V is locally stable at least during inflation. Hence $A_1 \pm B_1 > 0$. We express the potential in terms of the dimensionless fields α, β. Their masses can be read off from (8):

$$m_\alpha^2 = \frac{2 f^2}{M^2}(A_1 + B_1), \qquad m_\beta^2 = \frac{2 f^2}{M^2}(A_1 - B_1). \tag{9}$$

The numbers A_1, B_1 are taken to be $O(1)$.

One could be more explicit, and choose some supersymmetry breaking superpotential, like $W = fX$, and Kähler potential explicitly breaking R-symmetry, like: $K = X\bar{X} + (c/M^2)(X^3\bar{X} + X\bar{X}^3) + \ldots$ as in [27] leading to an effective action description of X for scales well below M. At this stage, we prefer not to consider explicit examples of UV-completions of the theory.

We consider the beginning of inflation well below M, hence the initial conditions are such that $\alpha, \beta << 1$. In fact, since β is the lighter field, we take this one to be the inflaton, and consider that initially $\alpha, \beta \sim \sqrt{f}/M$. For us the inflationary period goes from this scale until the value of the field is close to the typical soft breaking scale of the problem m_{soft}, where the field $X \to X_{NL}$ (2), at this scale X_{NL} behaves like a spurion [27] and as shown in Ref. [27], the leading couplings to low-energy supersymmetric matter can be computed as spurion couplings, for instance [5], if Q, V represent respectively low energy chiral and vector

superfields, we can have the couplings:

$$\mathcal{L} = -\int d^4\theta \left|\frac{X_{NL}}{f}\right|^2 m^2 Q e^V \bar{Q} \tag{10}$$

$$+ \int d^2\theta \frac{X_{NL}}{f}\left(\frac{1}{2}B_{ij}Q^i Q^j + \ldots + h.c.\right)$$

plus gauge couplings.

Once we reach the end of inflation, the field X becomes nonlinear, its scalar component is a goldstino bilinear and the period of reheating begins. The details of reheating depend very much on the microscopic model. At this stage one should provide details of the "waterfall" that turns the huge amount of energy f^2 into low energy particles. Part of this energy will be depleted and converted into low energy particles through the soft couplings in (10), and hence we can in principle compute a lower bound on the reheating temperature. Before making some comments on the reheating period, we analyze the cosmological consequences of a potential as simple as (8), as well as the assumptions we have made earlier about the inflaton and its range as inflation takes place.

3. The Inflaton Potential and Slow Roll Conditions

To study the conditions under which our potential provides inflation consistent with the latest cosmological constraints, we examine the slow-roll parameters, defined as [13]:

$$\epsilon = \frac{M_{pl}^2}{2}\left(\frac{V'}{V}\right)^2, \tag{11}$$

$$\eta = M_{pl}^2 \frac{V''}{V}, \tag{12}$$

where M_{pl} is the reduced Planck mass and ' denotes derivative with respect to the inflaton field. The observables are then expressed in terms of the above slow roll parameters as:

$$n_S = 1 - 6\epsilon + 2\eta, \tag{13}$$

$$r = 16\epsilon \tag{14}$$

$$n_t = -2\epsilon, \qquad (15)$$

$$\Delta_R^2 = \frac{V M_{pl}^4}{24\pi^2 \epsilon}. \qquad (16)$$

n_S is the slope of the scalar primordial power spectrum, n_t is the corresponding tensor one, r is the scalar to tensor ratio and Δ_R^2 is the amplitude of the initial perturbations. All these numbers are constrained by current cosmological observations [10, 11, 12]. We will use their constraints to explore the naturalness of our inflationary trajectories. Inflation takes place when the slow-roll parameters are much smaller than 1.

We will use the amplitude of initial perturbations and the number of efoldings to fit some of the paramenters of the toy model in the previous section. Recall that the potential in the range of interest is:

$$V = f^2(1 + A_1(\alpha^2 + \beta^2) + B_1(\alpha^2 - \beta^2) + \ldots), \quad (17)$$

which appears in figure 1. We can compute ϵ, η while rolling in the β direction:

$$\epsilon = 2((A_1 - B_1)\beta)^2 + \ldots \qquad (18)$$

$$\eta = 2(A_1 - B_1) + \ldots, \qquad (19)$$

since $\beta << 1$, ϵ is naturally small. We can make η small by a slight fine tuning of the difference $A_1 - B_1$. We will write η later as a ratio of the inflaton and gravitino masses. Once the slow roll conditions are satisfied, we can compute the number of efoldings (see for instance [16, 17]):

$$N = \frac{1}{M}\left|\int \frac{dx}{\sqrt{2\epsilon}}\right| = \left|\int_{\beta_i}^{\beta_f} \frac{d\beta}{2\sqrt{\epsilon}}\right| \qquad (20)$$

From (19) we get:

$$N = \frac{1}{\sqrt{2}|A_1 - B_1|}\left|\log\frac{\beta_f}{\beta_i}\right|. \qquad (21)$$

In most models of supersymmetry breaking, the gravitino mass is given by:

$$m_{3/2} = \frac{f}{M}, \qquad (22)$$

hence, we can rewrite the parameters and masses in (9) as:

$$|A_1 - B_1| = \frac{1}{2}\frac{m_\beta^2}{m_{3/2}^2}, \qquad |A_1 + B_1| = \frac{1}{2}\frac{m_\alpha^2}{m_{3/2}^2}, \quad (23)$$

thus:

$$N = \sqrt{2}\left(\frac{m_{3/2}}{m_\beta}\right)^2\left|\log\frac{\beta_f}{\beta_i}\right| \qquad (24)$$

The number of efoldings is considered normally to be between $50 - 100$. Finally we will use the amplitude of initial perturbations to get one extra condition in the parameters of our potential. Using [11] (16) can be written as:

$$\left(\frac{V}{\epsilon}\right)^{1/4} = \frac{f^{1/2}}{2^{1/4}\left(|A_1 - B_1|\beta\right)^{1/2}} = .027M, \qquad (25)$$

where β is taken at N-efoldings before the end of inflation. Summarizing, the two cosmological constraints we get on the parameters of our potential can be written as:

$$N = \sqrt{2}\left(\frac{m_{3/2}}{m_\beta}\right)^2\left|\log\frac{\beta_f}{\beta_i}\right|, \qquad (26)$$

$$2^{1/4}\frac{m_{3/2}}{m_\beta}\left(\frac{\sqrt{f}}{M}\right)^{1/2} = 0.027, \qquad (27)$$

and the η parameter can be written as:

$$\eta = \left(\frac{m_\beta}{m_{3/2}}\right)^2. \qquad (28)$$

We take β_i above the supersymmetry breaking scale $\sqrt{f}/M = \mu/M$, and β_f close to m_{soft}/M, therefore we can easily get values for N between $50 - 100$ for moderate values of η, which is expressed here as the square of the ratio of the inflaton to the gravitino mass. It is interesting to notice that from (27), we can write the supersymmetry breaking scale μ in terms of the η-parameter:

$$\frac{\mu}{M} \approx 5.2 \ 10^{-4} \ \eta. \qquad (29)$$

Hence for a value of $\eta \sim .1$ we can get $\mu \sim 10^{13}$ GeV. Lower values of the supersymmetry breaking scale can be obtained by reducing η. However, since the inflaton mass is

$$m_\beta = m_{3/2}\sqrt{\eta}, \qquad (30)$$

we may end up with an inflaton whose mass is substantially lighter than the gravitino. For these values of η, μ, we have that $\beta_i \sim 10^{13}/M$, $\beta_f \sim 10^3/M$, and the number of efoldings is ~ 110.

We conclude then that with moderate values of η between $.1 - .01$ we can get supersymmetry breaking scales between $10^{11} - 10^{13}$ without major fine tunings. We easily get enough efoldings, and furthermore, the inflaton is lighter than the gravitino by an amount given by $\sqrt{\eta}$.

For the above range of parameters we can compare the predicted value of n_S in our model with observational constraints. This is shown in the right panel of Fig. 1. The yellow region is the current cosmological constraints from WMAP5 [11] and the other colored areas are the predictions for our model with minimal fine tuning for an stable (unstable) X potential, i.e. the field is concave (convex) respectively. The constraints will improve greatly when the Planck satellite releases its results next year, and therefore our model can be tested much more accurately.

Reheating can proceed in many ways, since we have not provided a detailed microscopic model. Once in the nonlinear regime, the X_{NL} field (whose scalar component is made of a goldstino bilinear) could efficiently convert the f^2-energy density into radiation. We can calculate the amount of entropy and particle density by using the Boltzman equation and assuming that the pair of Goldstinos will have an out-of-equilibrium decay[16]. Using that

$$T_{RH} = 10^{-10} \left(\sqrt{f}/GeV \right)^{3/2} GeV \qquad (31)$$

we obtain a range $10^7 < T_{RH} < 10^9$. This produces a particle abundance of $n_\chi \sim 10^{70-90}$ which are standard values. We can also compute the amount of entropy generated by the out-of-equilibrium decay as

$$S_f/S_i = 10^7 (\sqrt{f}/GeV)^{-1/2} \qquad (32)$$

which yields values in the range 10 to 1, and assures that there is no entropy overproduction. We could also compute the depletion of this energy through the soft couplings (10) yielding very similar values as above. In both cases, we can get sufficient reheating with temperatures between $\sqrt{f}$ and a fraction of $m_{3/2}$. The true value depends very much on the details of the microscopic model. However, there

seems to be no obstruction to reheating the universe to and acceptable value of temperature, particle abundances and entropy. We are currently working in a more detailed theory incorporating our scenario [25].

4. Conclusions

In this short note we have studied the possibility of having supersymmetry breaking as the driving force of inflation. We have used the unique chiral superfield X which represents the breaking of conformal invariance in the UV, and whose fermionic component becomes the goldstino at low energies. Its auxiliary field is the F-term which gets the vacuum expectation value breaking supersymmetry.

It is crucial in our analysis to have explicit R-symmetry breaking along with supersymmetry breaking. This allows us to avoid the η problem in supergravity and to take the supersymmetric limit. The simplest model we obtain describes the components of X well below the Planck scale. It is written in terms of three parameters: the supersymmetry breaking parameter f and the masses of the real and imaginary components of the field x (the scalar component of X). In our analysis the imaginary part of x plays the role of the inflaton, and its mass was shown to be smaller than the gravitino mass by an amount given by $\sqrt{\eta}$. This imaginary component represents a pseudo-goldstone boson, or rather, a pseudomoduli. In supersymmetric theories such fields abound, and any of them could be used to construct some form of hybrid inflation. In our case, however, we want to use the minimal choice that is naturally provided by the universal superfield X that must exist in any supersymmetric theory.

Since we have not presented any detailed model, the cosmological consequences are a bit rudimentary, especially concerning reheating at the end of inflation. However, the comparison of the simplest model with present data, yields very interesting values for the supersymmetry breaking scale, and the ratio of the inflaton and gravitino masses.
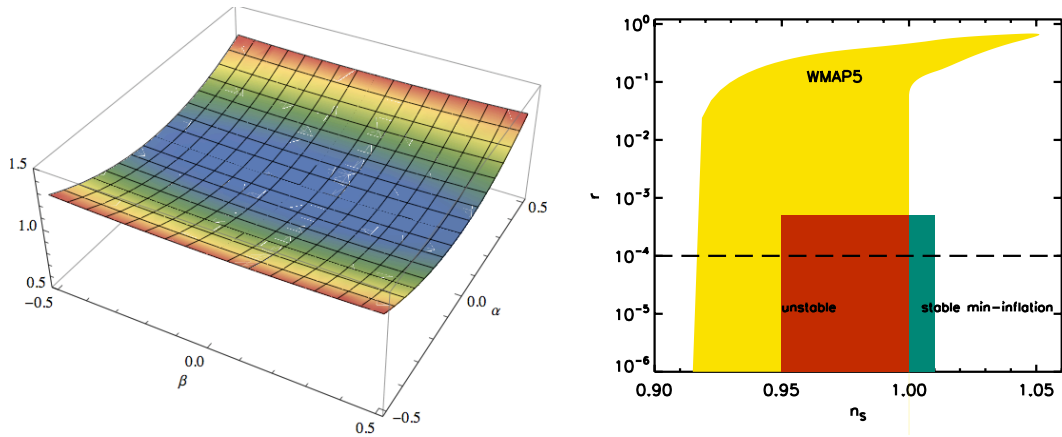
Figure 1: Left panel: The potential as a function of (α) and (β) components of the field X. Note the nearly flat direction (β) that we use for our inflationary trajectories. Graceful exit and particle creation occurs in the non-linear part of the X field. Right panel: WMAP5 cosmological constraints (yellow region) in the $r - n_S$ plane. For no-fine-tuned minimal inflation models the green and red area show our predictions for both cases of a stable (concave) potential and unstable (convex) potential. The Planck satellite will be able to provide significantly tigther constraints on r and especially n_S (at the $< 0.5\%$ level) thus further constraining our model. The dashed line is the limit in r that can be achieved with an ideal CMB polarization experiment [14]

These are bonuses which come directly from the observations of the initial density perturbations from WMAP data [11]. The fact that the inflaton is lighter than the gravitino may have interesting low-energy phenomenological implications. Furthermore in this simple model it is easy to obtain sufficient number of efoldings with moderate values of the η parameter.

To explore our proposal in more detail, it is important to construct an explicit model, even if not very realistic, in order to understand in more detail the end of inflation, the reheating mechanisms, and also the fine structure of the inflaton potential. We hope to report on this in the near future [25].

Acknowledgements

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