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Can inflation induce supersymmetry breaking in a metastable vacuum?

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Abstract

We argue that fields responsible for inflation and supersymmetry breaking are connected by gravitational couplings. In view of the recent progress in studying supersymmetry breaking in a metastable vacuum, we have shown that in models of supersymmetric hybrid inflation, where R-symmetry plays an important role, the scale of supersymmetry breaking is generated dynamically at the end of inflation and turns out to be consistent with gravity mediation.

Dynamical supersymmetry breaking in a metastable vacuum introduced by Intriligator, Seiberg and Shih (ISS) [1] is receiving a lot of attention in the recent literature. The ISS model consists of (i) an asymptotically free SYM theory with an appropriate number of chiral multiplets (metaphorically called "quarks") which by duality is described by another IR free SYM theory at low energy; (ii) the addition of a quark mass term in the UV (electric) theory. This term is dual to a linear term in the superpotential of the IR (or magnetic) theory which has an R-symmetry and breaks supersymmetry. The non-perturbative dynamical part of this superpotential [2] restores supersymmetry but leaves a metastable vacuum where it is broken. There has been relevant progress in several directions such as R-symmetry breaking [3,4], mediation (basically gauge mediation) of the supersymmetry breaking to the MSSM sector [5], gauging of the flavour symmetries [6] and also mechanisms to generate the ISS scale ($\mu_{\rm ISS}$) [7].

In this Letter, we investigate whether R-symmetric gravitational couplings between the ISS sector and the sector generating supersymmetric hybrid inflation (SHI) [8], would determine the ISS scale. Indeed, we find this scale to be given by the inflation scale as fitted in SHI scenarios, $M_{\rm Inf}$, and the scale of the electric–magnetic phase transition of the dual gauge theories, Λ. Combining an ISS consistency condition with the fact that $\mu_{\rm ISS}$ is bounded by the EWSB phenomenology of the MSSM we get a relatively narrow allowed interval for Λ, hence for $\mu_{\rm ISS}$. It turns out to be consistent with gravity mediation and can be made suitable for gauge mediation by a simple change, although the concrete realization of the mediation mechanism is not quite addressed here. Notice that the gravitational coupling of the two sectors is determined by R-symmetry which is instrumental in both ISS and SHI mechanisms.

As far as the SHI phenomenology is concerned, without aiming at a careful study of its several aspects, the reheating temperature obtained either by inflaton decay into the quarks of the ISS sector or through a gravitational coupling between the inflaton and, e.g., right handed neutrinos, turns out to be phenomenologically adequate. The completion of the model by the explicit coupling to the MSSM as well as the crucial issue of R-symmetry breaking are postponed to future publications.

The set-up consists of three components namely, the inflationary sector (Inf), the supersymmetry breaking sector (here the ISS sector) and the MSSM sector. The Inf sector consists of superfields used to implement inflation. The scenario is organized within the framework of the well-known supersymmetric hybrid inflation model [8], with a superpotential given by[1]

[1] Since Eq. (1) has to be quadratic in χ, one can invoke a $Z_2 : \chi \to -\chi$, present in Eq. (1) or, as more frequently done in the literature, to introduce a $U(1)$ and a conjugate pair $\chi, \bar{\chi}$. In our case, the $U(1)$ breaking by the χ vev would yield a goldstone boson that would restore supersymmetry in ISS. Our choice here is the simplest one, an alternative being to gauge the $U(1)$.

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$$W_{\rm Inf} = kS\big(\chi^2 - M_{\rm Inf}^2\big), \tag{1}$$

where S, χ are chiral superfields. A $U(1)_R$ symmetry is present under which S has R-charge 2 as well as the superpotential and χ has no R-charge. The parameters k and $M_{\rm Inf}$ can be made real and positive by field redefinitions.[2] The interest of the SHI is inherent in its R-invariance. It has the advantage of avoiding the large supergravity corrections with canonical Kähler potential due to the linearity in the S superfield [8].

The ISS sector is described by a supersymmetric $SU(N_c)$ gauge symmetry with N_f flavors of quark, antiquark pairs in the electric theory. Here Λ is the strong-coupling scale of the theory, below which the theory can be described as the magnetic dual, $SU(N)$ gauge theory, where $N = N_f - N_c$ with N_f flavors of magnetic quarks, $q_i^c, \tilde{q}_c^i$ ($i = 1, \ldots, N_f$ and $c = 1, \ldots, N$) and a $N_f \times N_f$ gauge singlet superfield Φ_j^i (the meson field $\Phi = Q\tilde{Q}/\Lambda$). The magnetic theory is IR free if $N_c + 1 \leqslant N_f \leqslant \frac{3}{2}N_c$ and has the superpotential given by

$$W_{\rm ISS} = h\,{\rm Tr}\, q\Phi\tilde{q} - h\mu_{\rm ISS}^2\,{\rm Tr}\,\Phi, \tag{2}$$

along with the dynamical superpotential

$$W_{\rm dyn} = N\left(h^{N_f}\frac{\det\Phi}{\Lambda^{N_f-3N}}\right)^{\frac{1}{N}}, \tag{3}$$

where $h = O(1)$ and $\mu_{\rm ISS} \ll \Lambda$ are constants. Eq. (2) has an R-symmetry with $R_\Phi = 2$ ($R_Q = R_{\tilde{Q}} = 1$ upto a baryon number) and $R_{q,\tilde{q}} = 0$. Our aim is to generate the scale of supersymmetry breaking $\mu_{\rm ISS}$ (from inflation). Note that by duality the second term in Eq. (2) corresponds to a mass term $\mu_{\rm ISS}^2 Q\tilde{Q}/\Lambda$ in the electric theory.

We have assumed that the two sectors Inf and ISS can communicate with each other only through gravity. This gravitational couplings must have R-charge 2 as both $W_{\rm ISS}$ and $W_{\rm Inf}$ have. Therefore all these couplings have to be linear in $Q\tilde{Q}$. The lowest dimensional operator is then given by

$$W_{\rm int} = \frac{g}{M_P}\chi^2\,{\rm Tr}\,Q\tilde{Q}, \tag{4}$$

where $M_P = 2.4 \times 10^{18}$ GeV is the reduced Planck scale and g is a coupling constant. Once χ acquires a vev after inflation, this term will automatically generate the electric quark's mass hence its dual, the $\mu_{\rm ISS}$ term of the ISS.

Now consider the scalar potential obtained from Eqs. (1), (2),

$$V = k^2\big|\chi^2 - M_{\rm Inf}^2\big|^2 + 4|\chi|^2\big(k^2|S|^2 + g^2|Q\tilde{Q}|^2/M_P^2\big). \tag{5}$$

To realize inflation, S is displaced from its present day location to values that exceed $M_{\rm Inf}$. The field χ is then attracted to the origin by a large mass term and the potential is completely flat along S. The appearance of a vacuum energy density of order $k^2 M_{\rm Inf}^4$ is responsible for inflation. The supersymmetry breaking by this vacuum energy can be exploited to generate a slope along the inflationary valley ($\chi = 0, |S| > S_c$). The existence of the mass splitting in χ supermultiplet leads to the one loop correction [8]

$$\Delta V = \frac{k^4 M_{\rm Inf}^4}{8\pi^2}\left[\ln\frac{2k^2S^2}{\mu_r^2} + O\big(M_{\rm Inf}^4/S^4\big)\right], \tag{6}$$

which can be calculated from the Coleman–Weinberg formula. Here μ_r is a renormalization scale. One can then calculate the ϵ ($= \frac{M_P^2}{2}(\frac{V'}{V})^2$) and η ($= M_P^2\frac{V''}{V}$) parameters of inflation. The inflation ends when $S_c \simeq M_{\rm Inf}$ so that the mass term of χ becomes negative. The spectral index in this class of models is estimated to be $n_s \gtrsim 0.98$, which is only consistent with the current WMAP measurement of spectral index in the 2σ range [10,11]. The scenario can be well improved by adding a non-canonical Kähler term as $k_{ss}|S|^4/M_P^2$ in the Kähler potential [12]. It is shown in [13] (see Fig. 3 therein), that with $k_{ss} = 0.01$, the spectral index fit in with the preferred 1σ range from recent WMAP data, $n_s \simeq 0.95^{+0.015}_{-0.019}$, where the coupling $3 \times 10^{-3} \lesssim k \lesssim 6 \times 10^{-2}$. At the end of inflation, the Inf system rolls towards the minimum at V_1, $S = 0$, $|\langle\chi\rangle| = M_{\rm Inf}$. Now we can realize the impact of the term $W_{\rm int}$. Once the χ field starts acquiring a vev, this term would generate a dynamical mass term for quarks, $m_Q = g\langle\chi\rangle^2/M_P \ll \Lambda$. So at this point the ISS sector can be described by the IR magnetic phase

$$W_{\rm ISS} = \Phi_{ij}q_i\tilde{q}_j - m_Q\Lambda\,{\rm Tr}\,\Phi + W_{\rm dyn}, \tag{7}$$

which consists of metastable supersymmetry breaking vacua at $\langle q\rangle = \langle\tilde{q}^T\rangle = \mu_{\rm ISS} = \sqrt{m_Q\Lambda}$, $\Phi = 0$.

Therefore we find that the evolution of the ISS system is eventually connected with the dynamics of the χ field. During inflation, $Q, \tilde{Q}$ acquire positive mass square terms $O(H^2)$ ($H^2 = k^2M_{\rm Inf}^4/3M_P^2$) from supergravity corrections and thereby they settle at the origin.[3] Since the relevant inflation scale and Λ are not very far away, it is equally interesting to consider the scheme in the magnetic phase. Analogously, one expects Φ to get a mass $O(H)$ during inflation, under the assumption of regular enough Kähler potential and to become small enough.[4] So a nice feature of the model is that either way, we end up at the origin. Note that at this time there is no other mass term for Q, $\tilde{Q}$ (or linear term in Φ) from $W_{\rm int}$ as $\chi = 0$. Once the inflation ends, the Inf system falls toward the minimum at V_1 and performs damped oscillation about it. On the other hand, when χ starts to become non-zero after inflation the term $\mu_{\rm ISS}$ is generated. Taking into account the non-perturbative term, $W_{\rm dyn}$, it develops the supersymmetric minimum in the ISS sector at

$$\langle q\rangle = \langle\tilde{q}^T\rangle = 0; \qquad \langle\Phi\rangle = \mu_{\rm ISS}(\chi)\left(\epsilon^{\frac{N_f-3N}{N_c}}\right)^{-1}\mathbb{I}_{N_f}, \tag{8}$$

[2] Alternatively this sector can also be interpreted as strongly coupled supersymmetric gauge theories with quantum moduli spaces [9].

[3] Here we are approximating the UV Kähler potential for Q, $\tilde{Q}$, with characteristic scale M_P, by its canonical form since the relevant UV scale is $M_{\rm Inf} \ll M_P$.

[4] In this phase, the metric has an unknown dependence on the scale Λ and we assume the moduli space to be smooth enough around origin. Then the Kähler potential is regular there and is given by $K = \alpha\,{\rm Tr}\,\Phi^\dagger\Phi + \beta\,{\rm Tr}\,q^\dagger q + \cdots$, with α and β positive, for $\Phi \ll \Lambda$. Another positive contribution to $V(\Phi)$ comes from $W_{\rm dyn}$ but, for $\Phi < \Lambda$, it is at most comparable with the contributions from Φ dependent terms in the Kähler potential.

where

$$\epsilon = \frac{\mu_{\rm ISS}(\chi)}{\Lambda} \ll 1. \tag{9}$$

The other minimum for ISS is at $\Phi = 0$ and $q = \tilde{q} = \mu_{\rm ISS}$ and becomes a local minimum which breaks supersymmetry due to the rank conditions. Here we see that Φ is situated at the origin from the beginning and now there is a possibility that it could end up in the supersymmetric minimum. But this is not the case in this scenario. The authors in [1] have estimated the tunneling rate from the supersymmetry breaking to the supersymmetry preserving vacuum and the action of the bounce solution is of the form

$$S_{\rm bounce} = \frac{2\pi^2}{3}\frac{N^3}{N_f^2}\left(\frac{\langle\Phi\rangle}{\mu_{\rm ISS}}\right)^4 \simeq \frac{1}{\epsilon^{4(N_f-3N)/(N_f-N)}} \gg 1, \quad \text{for } \epsilon \ll 1, \tag{10}$$

since $\chi \lesssim M_{\rm ISS}$. Therefore once the Φ field is pushed to the origin during inflation, it will stay there and that becomes the metastable supersymmetry breaking minimum. In other words, our scenario provides a natural explanation why [14] the ISS system should be in the metastable minimum, not in the supersymmetric minimum.

An inflationary scenario would be complete by a successful reheating process [15]. The superpotential $W_{\rm Inf}$ leads to the common inflaton-system mass as $m_S = m_\chi = 2kM_{\rm Inf}$. So that when χ is performing oscillations around the minima V_1, χ could decay into ISS quarks/squarks with

$$\Gamma \simeq \frac{g^2 k}{4\pi}\frac{M_{\rm Inf}^3}{M_P^2}, \tag{11}$$

and reheat temperature $O(10^{9\text{–}10}$ GeV) which is consistent with the gravitino problem [16]. This is not of great interest from the point of view of creating MSSM particles after inflation. Thus we can think off adding some other couplings in $W_{\rm Inf}$, e.g.: (i) Sh_1h_2 where $h_{1,2}$ are MSSM higgses carrying zero R-charge [17]; (ii) $\chi^2 h_1h_2/M_P$, where $h_{1,2}$ have $R = 1$ each; or (iii) $f_{ij}\chi^2 N_iN_j/M_P$, where N_i are neutrino superfields and i, j are generation indices. But, (i) will not work in this scenario as it restores supersymmetry[5] while (ii) is also not good as it yields a large μ-term. Instead, (iii) works fine with a reheat temperature $O(10^{9\text{–}10}$ GeV). First of all it provides mass for the right handed neutrinos $f_{ij}M_{\rm Inf}^2/M_P = O(10^{10}$ GeV) (at least one has to be less than $m_\chi/2$ for χ to decay) which is not only in the right ballpark to explain the light neutrino mass through the see-saw mechanism but also opens up the possibility to have non-thermal leptogenesis [18].

Now we want to evaluate the possible constraints over the mass scales $\mu_{\rm ISS}$, Λ. They are:
(a) metastability condition: $\mu_{\rm ISS} \ll \Lambda$ to preserve the ISS vacuum,
(b) supersymmetry mediation condition: $m_{\rm susy}M_P \simeq F_{\rm sugra} \geqslant F_{\rm ISS} = \mu_{\rm ISS}^2$,

where $m_{\rm susy} = O(\text{TeV})$ is the order of magnitude of the soft masses in the effective MSSM Lagrangian and (b) means that the mediation scale has to be less than the Planck mass. The conditions (a) and (b) respectively translate into:

$$\Lambda \gg \frac{g}{k}\frac{\sqrt{V_{\rm Inf}}}{M_P}, \quad \text{and} \quad \Lambda \leqslant \frac{k}{g}\frac{M_P^2}{\sqrt{V_{\rm Inf}}}m_{\rm susy}. \tag{12}$$

From the recent analysis done in [13] (see Fig. 4 therein), we get $V_{\rm Inf}^{1/4} = \sqrt{k}M_{\rm Inf}$ lies between 2.0×10^{13} and 10^{15} GeV which corresponds to the spectral index n_s in the 1σ range of WMAP3 data (with the same $k_{ss} = 0.01$ as we have considered earlier). Therefore the conditions in Eq. (12) can be simultaneously satisfied in the lower range for $V_{\rm Inf} = O(10^{13\text{–}14}\ \text{GeV})^4$. Without detailed study of the parameter space of the two independent couplings k and g, we see that with $k = O(10^{-2})$ and $g = O(10^{-1}\text{–}10^{-2})$ these conditions meet leading to $\mu_{\rm ISS} = O(10^{12}$ GeV) and $\Lambda = O(10^{14}$ GeV).

With this order of magnitude for the supersymmetry breaking scale, supergravity mediation could be sufficient to give mass to scalars. But this presupposes a cosmological constant suppression mechanism is at work so to cancel the $V = O(\mu_{\rm ISS}^4)$ contribution from (2) and (3)—which in any instance has to be made consistent with data on the cosmological constant.[6] However, it can be adapted to yield lower values of $\mu_{\rm ISS}$, possibly consistent with, e.g., gaugino mediation, by modifying the dependence of (1) on χ so that $\mu_{\rm ISS}$ would be reduced by powers of $M_{\rm Inf}/M_P$; for instance, a term χ^4 which could also improve the fit to the cosmological parameters. Of course a supersymmetry breaking mediation mechanism should be concocted.[7]

Gaugino mass generation remains a problem since it is closely related to R-symmetry breaking while $\Phi = 0$ at the metastable vacuum. The non-perturbative term, $W_{\rm dyn}$ explicitly breaks R-symmetry and produces the supersymmetry preserving (and R-symmetry breaking) vacuum. The Coleman–Weinberg correction may shift Φ from origin which breaks R-symmetry,[8] still all the fields have $R = 0, 2$, and gaugino cannot get mass [3], the direct coupling of Φ to the gauginos is forbidden by R-symmetry. An approach towards solving this R-symmetry problem is discussed in [4]. In this Letter we do not address the possibility of embedding our scenario into that kind of model to get a better phenomenologically viable model and we keep it for future work.

In conclusion we have given a simple model to naturally provide the scale of supersymmetry breaking from inflation in the context of ISS model. Quarks become massive after inflation

[5] Since R-symmetry cannot forbid a term like $\mathrm{Tr}\, Q\tilde{Q}h_1h_2/M_P$ thereby spoiling the existence of metastable vacua in ISS sector.

[6] It is well known that gravity mediation assumes this cancellation which relates the auxiliary field that break supersymmetry and the gravitino mass. Instead, here, the superpotential vanishes at $\Phi = 0$ so that the model should be further elaborated.

[7] Work in progress in collaboration with Philippe Brax.

[8] Once R-symmetry is broken spontaneously, it leads to the R-axion problem. As we are in the framework of supergravity, it is possible to make R-axions sufficiently heavy [19] due the explicit breaking of R-symmetry via the constant term present in the superpotential in order to get a realistic cosmological constant.

and the system ends up in the metastable supersymmetry breaking vacuum. We also realize that the scale of supersymmetry breaking (which is related with the scale of inflation) falls in a range where gravity mediation of the supersymmetry breaking into MSSM sector is possible.

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