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Hybrid inflation, dark energy and dark matter

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Abstract

It has been suggested that the dark energy density $\rho_v \sim 10^{-12}$ eV^4 in the universe is associated with a metastable (false) vacuum, while the true vacuum has a vanishing cosmological constant. By including supergravity corrections we show how this is naturally realized in realistic supersymmetric hybrid inflation models. With a fundamental supersymmetry breaking scale $\sim$ TeV, the LSP is not a suitable candidate for cold dark matter. We consider axion physics to overcome this and simultaneously provide a resolution of the MSSM μ problem.

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Recent studies of the cosmic microwave background radiation [1], Supernovae 1a [2] and large scale structure [3], taken collectively, present a fairly compelling case for a dark (vacuum) energy density $\rho_v \sim 10^{-12}$ eV^4. Indeed, ρ_v is estimated to provide almost 70% of the critical energy density, with matter (including baryons and possibly neutrinos) making up the remaining 30% or so. Understanding the origin of ρ_v poses one of the most fundamental theoretical challenges, namely how $\rho_v \sim 10^{-120} M_P^4$ happens to be so much smaller than M_P^4, where $M_P = 2.4 \times 10^{18}$ GeV denotes the reduced Planck mass. Another related problem is to understand how ρ_v and the matter density ρ_m which, in principle, can be expected to scale very differently with the universe expansion, are of comparable magnitudes today.

It is conceivable that ρ_v is associated with a false vacuum energy, with the true vacuum possessing a zero cosmological constant [4–6]. In this admittedly modest approach to the problem, one tries to identify the origin of ρ_v and also ensure that the false vacuum is sufficiently long lived. To this we wish to add in this Letter an important new ingredient, namely inflation. This would help us explain how the universe got stuck in the false vacuum in the first place.

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The model described below is organized within the framework of supersymmetric hybrid inflation [7] which is associated with the breaking of some gauge symmetry G to H_0, where H_0 could be the MSSM gauge group or something larger. A remarkable feature of these models is that the symmetry breaking scale of G is estimated from the quadrupole anisotropy, $\frac{\delta T}{T}$, to be of order 10^{16} GeV, the supersymmetric GUT scale, $M_{\rm GUT}$. A nice, and perhaps the simplest, example of G is the MSSM gauge symmetry supplemented by a gauged $U(1)_{B-L}$ symmetry [8]. To realize $(\rho_v)^{1/4} \sim 10^{-3}$ eV we assume, following [6], that the fundamental supersymmetry breaking scale in nature is $\sim$ TeV [9], so that the gravitino mass $m_{3/2} \sim \mathrm{TeV}^2/M_P$ more or less coincides with $(\rho_v)^{1/4}$. Furthermore, following [6], a new (acceleressence) sector containing a chiral superfield χ is introduced, which communicates with other sectors only via gravity. The χ sector will be arranged to yield a potential which has a false (metastable) minimum separated by ρ_v from the true minimum with zero cosmological constant.

We will see that during inflation driven from the visible sector, taking supergravity corrections into account, the scalar component of χ acquires a mass of order the Hubble constant H, causing it to be trapped in the false minimum at the origin. If the barrier separating the two minima is sufficiently high, the field stays stuck in the false vacuum even after inflation ends. Because the gravitino is ultralight, the MSSM sector does not provide a suitable cold dark matter (CDM) candidate. Potential CDM candidates include stable relics from the supersymmetry breaking sector [6], or a suitable pseudogoldstone boson [10], and finally axions that we shall shortly discuss.

The model consists of three components namely, the visible sector, a strongly coupled supersymmetry breaking hidden sector, and the acceleressence sector which we will refer to as G, T and χ sectors, respectively. The G sector, as we shall see, consists of the MSSM superfields and additional ones used to implement inflation and the axion mechanism. We do not need to specify the details of the supersymmetry breaking sector except to note that it contains a (possibly composite) chiral field T, whose auxiliary component has a vev $\langle F_T\rangle \sim \mathrm{TeV}^2$. The T sector communicates via gauge interactions with the visible sector, so that the supersymmetric partners of the known (SM) particles can acquire masses in the range of M_Z to TeV. The χ sector, following [6], allows us to relate the observed vacuum energy density to a false vacuum energy density. As stated before, this sector consists of a chiral superfield χ which communicates with the two sectors G and T only via gravity. With the superpotential

$$W_{\rm acc} = \frac{\sigma}{3}\chi^3, \tag{1}$$

and including soft supersymmetry breaking terms, the χ potential takes the form

$$V_{\rm acc} = \sigma^2|\chi|^4 - \left(A\chi^3 + \text{h.c.}\right) + m^2|\chi|^2 + V_1, \tag{2}$$

where σ, A can be made real and positive by proper phase rotations of the fields. Here, both A and m are of order 10^{-3} eV, and V_1 is adjusted to make the total energy density vanish at the absolute minimum which lies at $\chi = \frac{3A+\sqrt{9A^2-8\sigma^2m^2}}{4\sigma^2}$ for $9A^2 > 8\sigma^2m^2$. Note that $V_{\rm acc}$ also has a local (false) minimum at $\chi = 0$ which is separated from the true minimum by ρ_v. It is possible to make the lifetime of this metastable state (much) greater than the age of the universe. The dark energy conundrum could be explained if the field χ is trapped at the origin rather than in the true minimum. We will show that supersymmetric hybrid inflation provides a natural mechanism to drive the χ field to the false minimum thereby realizing the acceleressence scenario.

The G sector contains the superpotential responsible for the simplest model of hybrid inflation [7,11]

$$W_{\rm inf} = \kappa S\left[\phi\bar{\phi} - M^2\right], \tag{3}$$

where $\phi, \bar{\phi}$ denote a conjugate pair of non-G singlet superfields, S is a gauge singlet superfield and a $U(1)_R$ symmetry is imposed under which $S \to e^{i\alpha}S$, $\phi\bar{\phi} \to \phi\bar{\phi}$, and $W_{\rm inf} \to e^{i\alpha}W_{\rm inf}$. The parameters κ and M can be made real and positive by field redefinitions. In the unbroken supersymmetric limit, vanishing of the F- and D-terms imply that the supersymmetric vacuum corresponds to $\langle S\rangle = 0, |\langle\bar{\phi}\rangle| = |\langle\phi\rangle| \equiv M$. To realize inflation, S is displaced from its present day location to values that exceed M. The appearance of a vacuum energy density of order κ^2M^4 induces radiative corrections to the tree level potential, with the result that $\frac{\delta T}{T} \propto (\frac{M}{M_P})^2$ [7,11]. Thus, M is of order 10^{16} GeV, the supersymmetric GUT scale [7]. The scalar spectral index in this class of models is estimated to be $n_s = 0.99 \pm 0.01$ [7,11].

Let us now include supergravity corrections that link the inflaton and the χ sector. The supergravity corrections coming from supersymmetry breaking in the strongly-coupled sector are small during inflation and would only play a significant role near the end of inflation, by which time the χ field is trapped in the false minimum. Assuming minimal supergravity, the scalar potential corresponding to a superpotential W and Kähler potential K is given by [12]

$$V = \exp\left(\frac{K}{M_P^2}\right)\left[\left(W_i + \frac{K_i W}{M_P^2}\right)K^{-1}_{ij^*} \times \left(W^*_{j^*} + \frac{K_{j^*}W^*}{M_P^2}\right) - 3\frac{|W|^2}{M_P^2}\right], \tag{4}$$

where $K_i = \partial_i K$, $W_i = \partial_i W$, $K^{-1}_{ij^*}$ is the inverse of the Kähler metric and the indices i, j run through all chiral fields.

We can parametrize, without explicit details of the supersymmetry breaking sector, the supergravity mediated supersymmetry breaking effects on the visible and χ sector by explicitly including a constant term W_0 in the superpotential. The presence of W_0 ensures the cancellation of the cosmological constant, so that the vacuum energy at the global minimum is zero. The size of supersymmetry breaking in the T sector implies that $W_0 \simeq m_{3/2}M_P^2 \sim O(\text{TeV}^2)M_P$ and $\langle W_i K^{-1}_{ij^*} W^*_{j^*}\rangle \sim O(\text{TeV}^4)$ to leading order in $1/M_P$ (provided there are no Planckian vevs).

With the minimal Kähler potential $K_1 = SS^\dagger + \phi\phi^\dagger + \bar\phi\bar\phi^\dagger$ from the inflationary sector and $K_2 = \chi\chi^\dagger$ from the acceleressence sector, the scalar potential is given by (we employ the same notation for superfields and their corresponding scalar components)

$$V = \exp\left(\frac{K_1 + K_2}{M_P^2}\right)\left[\left|\kappa S\bar\phi + \phi^*\frac{W}{M_P^2}\right|^2 + \left|\kappa S\phi + \bar\phi^*\frac{W}{M_P^2}\right|^2 + \left|\kappa\left(\phi\bar\phi - M^2\right) + S^*\frac{W}{M_P^2}\right|^2 + \left|\sigma\chi^2 + \chi^*\frac{W}{M_P^2}\right|^2 + \cdots - 3\frac{|W|^2}{M_P^2}\right], \tag{5}$$

where $W = W_{\rm inf} + W_{\rm acc} + W_{\rm MSSM} + W_0$, and the ellipsis represent contributions from the MSSM fields. With $|\bar\phi| = |\phi|$ along the D-flat direction of the scalar potential, the tadpole term $-2\kappa M^2 m_{3/2}S + \text{h.c.}$ induces a shift in the vevs [13]:

$$\langle S\rangle \simeq \frac{m_{3/2}}{\kappa}, \qquad \left|\langle\phi\rangle\right| = \left|\langle\bar\phi\rangle\right| \simeq M\left(1 - \frac{m_{3/2}^2}{2\kappa^2 M^2}\right). \tag{6}$$

The corresponding F-terms are

$$F_S \simeq -\frac{m_{3/2}^2}{\kappa}, \qquad F_\phi = F_{\bar\phi} \simeq m_{3/2}M. \tag{7}$$

The supergravity corrections play an important role during inflation. With $\phi = \bar\phi = 0$ and $|S| > M$, the scalar potential is given by

$$V \simeq \kappa^2 M^4\left[1 + \left|\frac{\chi}{M_P}\right|^2\right] - \left(\frac{\sigma\kappa M^2}{3M_P}\frac{S^*}{M_P}\chi^3 + \text{h.c.}\right) + \sigma^2|\chi|^4, \tag{8}$$

where only the dominant lower order terms are displayed, and the higher order terms in χ can be safely ignored for our discussion. Note that during inflation, the χ field acquires a positive mass squared larger than H^2 ($\sim \frac{\kappa^2 M^4}{3M_P^2}$). The coefficient of χ^3 term, $\frac{\sigma}{\sqrt{3}}\frac{S}{M_P}H$, is suppressed compared to H, and therefore χ rapidly settles at the origin during inflation.

With the end of inflation, the effective potential for χ is given by Eq. (2) which can be seen as follows. The soft mass squared term $m_0^2|\chi|^2 = am_{3/2}^2|\chi|^2$, where $a \sim O(1)$, arises from W_0 introduced to cancel the cosmological constant as discussed earlier, with $m_{3/2}^2 \sim O(\text{meV}^2)$. Terms of $O(m_{3/2})\chi^3$ do not follow in the same way because of a cancellation between contributions from $W_\chi K^{-1}_{\chi\chi^*}K_{\chi^*}\frac{W^*}{M_P^2}$ and $-3\frac{|W|^2}{M_P^2}$ terms. With the minimal Kähler potential, given that the inflationary sector contains the vevs $|\langle\phi\rangle| = \langle\bar\phi\rangle| \simeq M_{\rm GUT}$, we find the term $O(m_{3/2}(\frac{M_{\rm GUT}}{M_P})^2)\chi^3 + \text{h.c.}$ To realize a χ^3 term of the correct magnitude, we include the higher order Kähler term [6]

$$\int d^4\theta\,\frac{T + T^\dagger}{M_P}\chi^\dagger\chi, \tag{9}$$

from which the term $A\chi^3$ in Eq. (2) can be generated, where $A \sim \sigma\frac{F_T}{M_P} \sim \sigma 10^{-3}$ eV. As for the quartic term, it just comes from the usual F-term squared, i.e. $W_i K^{-1}_{ij^*} W^*_{j^*}$. Thus after inflation, the χ sector scalar potential takes the form

$$V_{\mathrm{acc}} = \sigma^2|\chi|^4 - \left[\left(A + O(m_{3/2})\left(\frac{M_{\mathrm{GUT}}}{M_P}\right)^2\right)\chi^3 + \mathrm{h.c.}\right] + m_0^2|\chi|^2 + V_1, \tag{10}$$

which is essentially equivalent to Eq. (2).

The next question we would like to address is that of dark matter. The superlight gravitino with mass $\sim 10^{-3}$ eV is not a suitable dark matter candidate which forces us to look for alternative CDM candidates. One plausible candidate would be the lightest field in the supersymmetry breaking hidden sector as one would expect it to have quantum numbers not shared by fields in the other sectors and hence, be stable [6]. Another plausible candidate could be a pseudogoldstone boson such as the majoron, associated with a spontaneously broken global $U(1)_{B-L}$ symmetry [10]. We will focus here on axion CDM introducing a PQ symmetry $U(1)_{PQ}$ [14], since the associated physics can also be exploited to resolve the MSSM μ problem [15,16]. Implementation of this mechanism turns out to be not entirely straightforward.

The axion mechanism is easily implemented in models in which the gravitino mass, $m_{3/2} \sim$ TeV. With the introduction of two G-singlet superfields $N, \bar{N}$ carrying appropriate PQ and R charges, the superpotential terms $N^2\bar{N}^2/M_P$ and $N^2H_uH_d/M_P$ can provide (H_u, H_d denote the MSSM Higgs superfields) a vev for the scalar components of $N, \bar{N}$ of magnitude $(m_{3/2}M_P)^{1/2}$, after taking the supersymmetry breaking terms (proportional to $m_{3/2}$) into account. This vev has the right order of magnitude ($\sim 10^{11}$ GeV) for axion dark matter, assuming that $m_{3/2} \sim \mathrm{TeV} \sim m_N$ (m_N is the soft mass for N). The second field $\bar{N}$ is needed to ensure the invariance of the superpotential, under $U(1)_{PQ}$. Its vev breaks $U(1)_R$ and ensures that the R-axion is phenomenologically harmless.

With $m_{3/2} \sim 10^{-3}$ eV in our present case, the above scenario cannot be realized in the simple way outlined above. Furthermore, superpotential terms such as $N^2\bar{N}^2/M_P$ give rise to F-term contributions $\gg \mathrm{TeV}^2$, which can be disastrous for the χ sector, through non-minimal Kähler terms such as $\int d^4\theta\, N^\dagger N\chi^\dagger\chi/M_P^2$. We will attempt to implement the axion mechanism with a single G-singlet superfield N, by retaining only

Table 1
R and axion (PQ) charge assignments for various superfields. We have used the convention under which $[W]_R = 1$. Additionally, the fields Q, L, E^c, U^c and D^c are odd under a Z_2 matter parity to eliminate rapid proton decay

Field	S	ϕ	$\bar{\phi}$	$H_{u,d}$	Q	U^c	D^c	L	E^c	N	χ
R	1	0	0	1/2	1/2	0	0	1/2	0	0	1/3
PQ	0	0	0	1	−1	0	0	−1	0	−1	0

the superpotential term

$$W_{PQ} = \lambda\frac{N^2H_uH_d}{M_P}, \tag{11}$$

and letting m_N, the coefficient of the mass term associated with the real component of N, also called the saxion, be a free parameter to be determined from the consistency requirements. Namely, that the μ problem is resolved with a N vev of order 10^{11} GeV in order to generate axion dark matter [15], and that there are no cosmological problems associated with the N field. How m_N acquires the desired mass scale requires a more complete analysis of supersymmetry breaking which is beyond the scope of this Letter. The cosmological evolution of the saxion field turns out to be somewhat non-trivial. The R and PQ charges of the various superfields are listed in Table 1.

The potential responsible for breaking the axion symmetry is taken to be

$$V_{PQ} \simeq -m_N^2|N|^2 + \lambda^2\left(\frac{M_W}{M_P}\right)^2|N|^4 + V_2, \tag{12}$$

where a negative mass squared term for the N field may, for instance, be induced via radiative corrections [16]. The second term follows from the superpotential in Eq. (11) after electroweak symmetry breaking. A constant term V_2 has been included to set V_{PQ} to zero at the true minimum. Requiring $f_a = |\langle N\rangle| \sim 10^{11}$ GeV [17] yields[1] $m_N \sim \lambda \times 10^{-5}\ \mathrm{GeV} \sim 10^{-7}$ GeV, with $\lambda \sim 10^{-2}$ so that the μ term ~ 100 GeV. The saxion mass then is also of

[1] This can be achieved, for instance, by arranging a cancellation between the contribution from the Higgs-mediated supersymmetry breaking via the Higgs soft terms (as required by electroweak symmetry breaking) and the contribution from an effective contact interaction of N with the hidden sector arising from integrating out a messenger field of mass $\sim 10^{10}$ GeV. We thank the referee for raising this point.

this magnitude. Since we have a very light and consequently a long lived (essentially stable) scalar we should ensure that no cosmological difficulties arise as a consequence. Note that in Eq. (12) we could introduce an additional quartic term $\gamma|N|^4$, with $\gamma \sim 10^{-38}$. This latter coupling, whose origin like that of m_N we will not discuss here, will be useful in cosmology. The values for m_N and γ proposed here suggest the presence of heavy fields that link the N superfields with the supersymmetry breaking sector.

In contrast to the χ field that remains trapped at the origin both during and after inflation, the saxion field must reach its minimum to implement proper breaking of the $U(1)$ axion symmetry. In principle, it could stay at the origin during inflation. However, axion models are often plagued by the domain wall problem [18] and we prefer to circumvent this by letting N roll away from the origin during inflation. This can be accomplished by introducing suitable non-minimal Kähler potential terms. Consider, for instance, the Kähler potential

$$K_1 + \kappa_1 \frac{NN^\dagger SS^\dagger}{M_P^2}, \tag{13}$$

so that, during inflation, the relevant potential involving the N field is given by

$$\begin{aligned} V_{PQ,\inf} \simeq & -\left(3\beta H^2 + m_N^2\right)|N|^2 \\ & + \left[\frac{3}{2}\left(1 + 2\beta + 2\beta^2\right)\frac{H^2}{M_P^2} + \gamma\right]|N|^4 \\ & + 3\beta^2 \frac{H^2}{M_P^2}|N|^2|S|^2 + \cdots, \end{aligned} \tag{14}$$

where $\beta = (\kappa_1 - 1) > 0$. For $\beta \lesssim 10^{-1}$, the field N is rapidly driven to $\sqrt{\beta} M_P$. Note that the induced mass-squared term for S is suppressed relative to H^2 by a factor of β^3, so that the inflationary scenario described earlier remains intact. As the Hubble induced mass drops below m_N after reheat, which happens at a temperature of order 10^5 GeV, the N field moves, because of the quartic term $\gamma|N|^4$, to a new minimum at around 10^{13} GeV. A further drop in temperature to 10^2 GeV leads to the appearance of electroweak vevs, in which case the potential in Eq. (12) effectively takes over, and the N field reaches its true minimum value of around 10^{11} GeV. This creates a cosmological problem since the energy stored in the N field ($\sim \lambda^2 \times 10^{12}$ GeV^4) is comparable to the radiation energy density ($\sim 10^8$ GeV^4) and, with N having a lifetime that far exceeds the age of the universe, N would become the dominant component in the universe.

One mechanism for overcoming this is to invoke an epoch of thermal inflation [19]. We will not provide any details here since a similar problem was encountered in [20] where the decay of a heavy particle was employed to dilute sufficiently the saxion energy density. Of course, the release of entropy also dilutes any pre-existing baryon asymmetry and a mechanism should be found to resolve this problem [21]. Finally, let us note that in the presence of axions, the gravitino is replaced by the axino, with mass $\sim 10^{-7}$ eV (for $\lambda \sim 10^{-2}$), as the LSP. Its contribution to the energy density of the universe, like the gravitino, is negligible. Cold dark matter comes from axions and possibly also the saxion.

Some remarks about the R-axion are in order here. The $U(1)_R$ symmetry is explicitly broken by the constant superpotential term W_0. With a superpotential $W_0 + W_1$, where $W_1 = W_{\rm acc} + W_{\rm inf} + W_{PQ} + W_{\rm MSSM} + W_{\rm hidden}$, the R-axion mass is estimated to be [22]

$$m_a^2 = \frac{8}{f_R^2} \frac{W_0 |\langle W_{1i} K_{ij^*}^{-1} K_{j^*} - 3W_1\rangle|}{M_P^2}, \tag{15}$$

where the R-axion decay constant $f_R \sim r_i r_j v_i v_j^* \times \langle K_{ij^*}\rangle$, and r_i and v_i are the R charges and vevs of the fields, respectively. With the large R-singlet vev of $|\langle\phi\rangle| = |\langle\bar\phi\rangle| \simeq M$ and hidden sector fields (generically labeled T) with vevs $\langle T\rangle \sim \sqrt{\langle F_T\rangle} \lesssim O(\text{TeV})$, we expect that

$$f_R \sim O(\text{TeV}), \tag{16}$$

$$\left|\langle W_{1i} K_{ij^*}^{-1} K_{j^*} - 3W_1\rangle\right| \sim \langle W_{1i}\phi\rangle \sim m_{3/2} M^2. \tag{17}$$

Substituting Eqs. (16) and (17) in Eq. (15), we obtain an R-axion mass of ~ 10 GeV which is consistent with the astrophysical constraints.

In conclusion, we have explored a scenario in which supersymmetric hybrid inflation could play an essential role in understanding the origin of dark energy. This idea presumably can be extended to other successful models of inflation. Even though the true vacuum has a zero cosmological constant (how this comes about is beyond the scope of this Letter), supergravity corrections during inflation can trap acceleressence field at the origin, which happens to be a local (false) minimum. The energy density scale separating the true vacuum from the false one is arranged to be of order $\mathrm{TeV}^2/M_P \sim 10^{-3}$ eV. Because of the low ($\sim$ TeV) fundamental supersymmetry breaking scale, the MSSM LSP is not a plausible cold dark matter candidate. There are three potential CDM candidates including axions. It turns out that in addition to the axions, the saxion may also be a significant component of cold dark matter.

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