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Dark energy and the false vacuum

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Abstract

In this paper, I will present highlights of a recent model of dark energy and dark matter in which the present universe is 'trapped' in a *false vacuum* described by the potential of an axion-like scalar field (the acceleron) which is related to a new strong interaction gauge sector, $SU(2)_Z$, characterized by a scale $\Lambda_Z \sim 3 \times 10^{-3}$ eV. This false vacuum model mimicks the ΛCDM scenario. In addition, there are several additional implications such as a new mechanism for leptogenesis coming from the decay of a 'messenger' scalar field, as well as a new model of 'low-scale' inflation whose inflaton is the 'radial' partner of the acceleron.

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1. Dark energy and the false vacuum

It is by now customary to present the 'energy budget' to illustrate the relative importance of the various components which comprise the present universe. With $\Omega_X = \rho_X/\rho_c$, one has $\Omega_{\text{baryons}} \sim 4\%$ for baryons (visible and dark), $\Omega_{DM} \sim 23\%$ for non-baryonic dark matter, and $\Omega_{DE} \sim 73\%$ for the mysterious dark energy which is responsible for the present acceleration of the universe. In terms of energy density, the latter (dominant) fraction is usually expressed as $\rho_V \approx (3 \times 10^{-3}\,\text{eV})^4$. Tremendous efforts have been and will be made to probe the nature of this dark energy. The latest constraint given in terms of the equation of state of the dark energy $p = w\rho$ gives a value [1] for w, $w \approx -1$, which is quite consistent with the ΛCDM scenario with $w = -1$. Hopefully, the important question concerning the nature of the dark energy will be resolved by future projects which could in principle go to high redshifts and determine whether or not the equation of state is varying with z.

If the present universe appears to be one which is dominated by a cosmological constant Λ, we are faced with a very uncomfortable question: Why is it so *small*, i.e. why is $\rho_V \sim 10^{-123} M_{pl}^4$? This is the 'new' cosmological constant problem as compared with the 'old' cosmological constant problem which is one in which one searches for a reason why it should be exactly equal to zero. If indeed there is such a *reason* then the present value of the cosmological constant (or something that mimicks it) should be considered to be just a 'transient' phenomenon with the universe being stuck in some kind of false vacuum which will eventually decay into the *true vacuum* with a *vanishing* cosmological constant. In this case, the problem boils down to the search for a *dynamical* model in which the false vacuum energy density is $\sim(3 \times 10^{-3}\,\text{eV})^4$. Furthermore, such a *reason* would *prevent* the existence of any *remnant* of vacuum energies associated with various spontaneous symmetry breakdowns (SSB) (electroweak, QCD, and possibly others). For example, it would prevent a partial cancellation of the electroweak vacuum energy down to the present value since that would constitute a fundamental cosmological constant in contradiction with that premise. The true electroweak vacuum would then have $\Lambda = 0$. And similarly for other (*completed*) phase transitions. Anything that mimicks a non-zero cosmological constant would be associated with a false vacuum. What could then be this sought-after deep reason for the cosmological constant to vanish in a true vacuum? Needless to say, this is a fundamental and very difficult question and there are many interesting approaches for tackling it. It is beyond the scope of this paper to discuss all of them. One recent interesting proposal [2] dealt with the consequences of the existence of a fundamental cosmological constant. It was argued in [2] that, within the framework of general relativity, catastrophic gravitational instabilities which are developed during the DeSitter Epoch (for a fundamental Λ) would reverse the arrow of time disagreeing with observations and leading the author to conclude that either one forbids a fundamental cosmological constant or one modifies general relativity during the epoch dominated by that constant. We will adopt the former point of view, namely a vanishing cosmological constant for the true vacuum.

In what follows, I will describe a model [3, 4][1] based on the assumption that the true vacuum has a vanishing cosmological constant and that we are presently trapped in a false vacuum with an energy density $\rho_V \approx (3 \times 10^{-3}\,\text{eV})^4$. I will argue that the value $\sim 10^{-3}$ eV represents a *new dynamical scale* associated with a new gauge group[2] $SU(2)_Z$ which grows strong at that scale. In this model, the present acceleration of the universe is driven by an axion-like particle denoted by a_Z whose potential is induced by $SU(2)_Z$ instanton effects and which exhibits two minima: the false vacuum in which $a_Z \neq 0$ and $\rho_V \approx (3 \times 10^{-3}\,\text{eV})^4$, and the true vacuum in which $a_Z = 0$ and $\rho_V = 0$. One of the important features of this model is that it can be *testable* in future collider (such as the LHC) experiments. This is because the model contains a scalar field—the so-called messenger field—with a mass less than 1 TeV and which carries both $SU(2)_Z$ and electroweak quantum numbers. This and other consequences will be discussed below.

First I will briefly describe the model with its particle content as well as its results. Next I will describe in a little more detail what these results mean.

- The model in [3, 4] (see footnote 1) is based on an *unbroken* vector-like gauge group $SU(2)_Z$. This group contains fermions, $\psi_i^{(Z)}$ with $i = 1, 2$, which transform as a *triplets* under $SU(2)_Z$ and as *singlets* under the SM, as well as 'messenger' scalar fields, $\tilde{\varphi}_{1,2}^{(Z)}$, which carry both quantum numbers: a *triplet* under $SU(2)_Z$ and a *doublet* under $SU(2)_L$. In addition, there is a complex singlet (under both sectors) scalar field

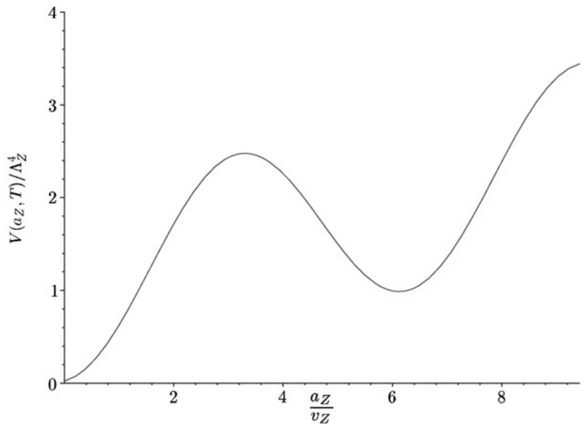
[1] This paper contains a more extensive list of references.

[2] I would like to thank Haim Goldberg for recently bringing my attention to his earlier paper [5], which considered a somewhat similar project, with a supersymmetric $SU(2)$ gauge group endowed with four massless fermions in a fundamental representation. In our model, $SU(2)_Z$ is non-supersymmetric and the particle content is entirely different from Goldberg's paper (two fermions in the adjoint representation which acquire a mass by coupling to a singlet scalar ϕ_Z, and two (one with electroweak scale mass and one with GUT scale mass) scalars which carry both $SU(2)_Z$ and electroweak quantum numbers, and hence the name 'messenger fields'). Also, the false vacuum here is different in origin, coming from an $SU(2)_Z$ instanton-induced potential for an axion-like scalar a_Z.

$\phi_Z = (\sigma_Z + v_Z)\exp(ia_Z/v_Z)$ which couples only to $\psi_i^{(Z)}$ because of a global $U(1)_A^{(Z)}$ symmetry.

- $\langle\phi_Z\rangle = v_Z$ spontaneously breaks the $U(1)_A^{(Z)}$ symmetry with a_Z becoming a pseudo-Nambu-Goldstone boson (PNGB) because of the explicit breaking due to $SU(2)_Z$ instanton effects. Note that a_Z is very similar to the Peccei-Quinn axion [6] in QCD except that we are dealing with another gauge group at another scale. It is a_Z which plays the role of the *acceleron* in our model [4] (see footnote 1). And it is also σ_Z that plays the role of the *inflaton* in a 'low-scale' inflationary scenario [7].
- The potential $V(a_Z)$ which plays a crucial role in the dark energy aspect of the model is induced by $SU(2)_Z$ instanton effects which become more relevant as the gauge coupling grows larger. In order for the $SU(2)_Z$ coupling $\alpha_Z = g_Z^2/4\pi \sim 1$ at $\Lambda_Z \approx 3 \times 10^{-3}$ eV, it was found that a number of constraints had to be satisfied (all of which have further implications): (1) the initial coupling at high energies has a value of the order of the SM couplings at comparable energies; (2) the masses of the $SU(2)_Z$ fermions $\psi_i^{(Z)}$ are in the range of 100–200 GeV and that of the lightest of the messenger field $\tilde{\varphi}_1^{(Z)}$ being in the range 300–1000 GeV. One may ask at this point why α_Z would be of the order of the SM couplings at high energies. It turns out that $SU(2)_Z$ can be 'grand unified' with the SM into the gauge group E_6 [8] which however breaks down quite differently from the usual approach: $E_6 \to SU(2)_Z \otimes SU(6) \to SU(2)_Z \otimes SU(3)_c \otimes SU(3)_L \otimes U(1) \to SU(2)_Z \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(2)_Z \otimes SU(3)_c \otimes U(1)_{em}$.
- With the value of the $SU(2)_Z$ gauge coupling at a temperature of $O(200$ GeV) (the favoured mass range for the fermions $\psi_i^{(Z)}$) being of the order of the electroweak coupling, its annihilation cross section was found to be typically of the order of a weak cross section and thus providing ideal (WIMP) cold dark matter candidates in the form of $\psi_i^{(Z)}$ [4] (see footnote 1).
- The lighter of the two messenger fields, $\tilde{\varphi}_1^{(Z)}$, which carries both $SU(2)_Z$ and electroweak quantum numbers, can couple only to $\psi_i^{(Z)}$ and a SM lepton. Its decay in the early universe can generate a SM lepton number asymmetry which transmogifies into a baryon number asymmetry through electroweak sphaleron processes [9].

Basically, the $SU(2)_Z$ instanton-induced potential $V(a_Z)$ has two degenerate vacua due to the remaining $Z(2)$ symmetry (two 'flavours' of $\psi_i^{(Z)}$), and is expressed as $V(a_Z, T) = \Lambda_Z^4\left[1 - \kappa(T)\cos\frac{a_Z}{v_Z}\right]$, where $\kappa(T) = 1$ at $T = 0$. This is lifted by a soft-breaking term $\kappa(T)\Lambda_Z^4\frac{a_Z}{2\pi v_Z}$ which is linked to $SU(2)_Z$ fermion condensates [10]. This is shown in the following figure for $V(a_Z, T)\big/\Lambda_Z^4$ as a function of a_Z/v_Z and for $T \ll \Lambda_Z$.



From the above figure, one notices that the metastable (false) vacuum is at $a_Z = 2\pi v_Z$ while the true vacuum is at $a_Z = 0$. For $T \gg \Lambda_Z$, $V(a_Z, T)$ is relatively flat because $SU(2)_Z$ isntanton effects are negligible there. One also expects a_Z to hover around $O(v_Z)$. It is assumed that, as $T < \Lambda_Z$, the universe got trapped in the false vacuum with an energy density $\rho_V = \Lambda_Z^4 \approx (3 \times 10^{-3}\,\text{eV})^4$.

It is interesting to estimate the various ages of the universe in this scenario (1) age of the universe when the $SU(2)_Z$ coupling grows strong ($\alpha_Z = 1$) at $T_Z \sim 3 \times 10^{-3}$ eV ~ 35 K corresponding to the background radiation temperature $T \approx 70$ K: $z \approx 25$, $t_z \approx 125 \pm 14$ Myr; (2) age of the universe when the deceleration 'stopped' and the acceleration 'started' ($\ddot{a} = 0$): $z_a \sim 0.67$, $t_a \approx 7.2 \pm 0.8$ Gyr; (3) age of the universe when $\rho_M \sim \rho_V$: $z_{eq} \approx 0.33$, $t_{eq} = 9.5 \pm 1.1$ Gyr.

Note that the equation of state is

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{a_Z}^2 - V(a_Z)}{\frac{1}{2}\dot{a_Z}^2 + V(a_Z)} < 0 \qquad \text{for} \quad \frac{1}{2}\dot{a_Z}^2 \ll V(a_Z).$$

With the present universe being trapped in a false vacuum, $\frac{1}{2}\dot{a}_Z^2 \sim 0$ leading to $w \approx -1$. Our model effectively mimics the ΛCDM scenario.

How long will it take for the false vacuum $a_Z = 2\pi v_Z$ to make a transition to the true vacuum $a_Z = 0$? A rough estimate using the thin wall approximation gives a bound on the Euclidean action $S_E \geqslant 5 \times 10^5 \left(\frac{v_Z}{\Lambda_Z}\right)^4 \geqslant 10^{89}$ for $v_Z \sim 10^9$ GeV (as deduced from the low-scale inflation model [7]). With the bubble nucleation rate $\Gamma = A \exp\{-S_E\}$ ($A \sim O(1)$) and the transition time $\tau = \frac{3H}{4\pi\Gamma} \geqslant (10^{-106}\,\text{s}) \exp(10^{89})$, one can see that indeed it would take a *very long* time for this to occur. As anticipated by many people, the universe will enter an inflationary stage and, in this scenario, the 'late' inflation will last an 'astronomical' time. Although it is entirely academic, it is interesting to note that the 'reheating', after this late inflation stops, occurs through the decay of a_Z into two $SU(2)_Z$ 'gluons' which, in turns, produce the messenger field $\tilde{\varphi}_1^{(Z)}$ and eventually SM leptons followed by SM quarks. (A somewhat analogous reheating mechanism for the low-scale (early) inflation [7] was also proposed.)

2. Implications of the dark energy model

(I) The first implication of this scenario is the existence of possible candidates for WIMP-like cold dark matter in the form of $\psi_i^{(Z)}$. Note that $\psi_{1,2}^{(Z)} = (3, 1)$ under $SU(2)_Z \otimes SM$ and have a mass $\sim$ O(100–200 GeV). The condition for $\psi^{(Z)}$ to be CDM candidates is

$$\Omega_{\psi^{(Z)}} = \frac{m_{\psi^{(Z)}} n_{\psi^{(Z)}}}{\rho_c} \approx \left(\frac{3 \times 10^{-27}\,\text{cm}^3\,\text{s}^{-1}}{\langle \sigma_{A,\psi^{(Z)}} v \rangle}\right),$$

with the annihilation cross section $\langle \sigma_{A,\psi^{(Z)}} \rangle$ being typically of the order of a weak cross section, i.e. $\langle \sigma_{A,\psi^{(Z)}} \rangle \sim 10^{-36}\,\text{cm}^2 \sim \frac{3 \times 10^{-9}}{\text{GeV}^2}$ in order for $\Omega_{\psi^{(Z)}} \sim O(1)$. This is the so-called WIMP. It was noticed in [3] and [4] (see footnote 1) that $\psi^{(Z)}$ with a mass ∼O (100–200 GeV) would do just that since one expects $\langle \sigma_{A,\psi^{(Z)}} \rangle \sim \frac{\alpha_Z(T)^2}{m_{\psi^{(Z)}}^2}$ and $\alpha_Z(T)^2 \sim 6 \times 10^{-4}$ over a large range of energy down to ∼100 GeV.

How do we detect those CDM candidates? The most obvious way would be an indirect method: $\tilde{\varphi}_1^{(Z)} \to \bar{\psi}_{1,2}^{(Z)} + l$, where l stands for a SM lepton. A pair of $\tilde{\varphi}_1^{(Z)}$ could be produced at the LHC through electroweak gauge boson fusion processes. The decays would have unusual geometries (e.g. the SM leptons need not be back-to-back) and $\psi^{(Z)}$ would 'appear' as missing energies.

(II) The second implication concerns a new mechanism for Leptogenesis via the decay of a 'messenger' scalar field $\tilde{\varphi}_1^{(Z)} = (3, 1, 2, Y/2 = -1/2)$ under $SU(2)_Z \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. As discussed in [9], the asymmetry between $\tilde{\varphi}_1^{(Z)} \rightarrow \bar{\psi}_{1,2}^{(Z)} + l$ and $\tilde{\varphi}_1^{(Z),*} \rightarrow \psi_{1,2}^{(Z)} + \bar{l}$ could provide a *net SM lepton number*. This becomes a net baryon number through EW sphaleron processes. It is by now a familiar phenomenon that the asymmetry comes from the interference between tree-level and one-loop contributions to the decays. Also, for the asymmetry $\neq 0$, we need *two* messenger fields: $\tilde{\varphi}_{1,2}^{(Z)}$, with $m_{\tilde{\varphi}_2^{(Z)}} \gg m_{\tilde{\varphi}_1^{(Z)}}$. The asymmetry which is defined as $\epsilon^{\tilde{\varphi}_1} = (\Gamma_{\tilde{\varphi}_1 l} - \Gamma_{\tilde{\varphi}_1^* \bar{l}})/(\Gamma_{\tilde{\varphi}_1 l} + \Gamma_{\tilde{\varphi}_1^* \bar{l}})$ is roughly -10^{-7}. This estimate comes from the SM lepton number asymmetry (n_{LSM}) per unit entropy (s): $n_{\mathrm{LSM}}/s \sim 2 \times 10^{-3} \epsilon_l^{\tilde{\varphi}_1}$, which, in turns, is related to the baryon number per unit entropy $n_B/s \sim -0.35 n_{\mathrm{LSM}}/s \sim -10^{-3} \epsilon_l^{\tilde{\varphi}_1} \sim 10^{-10}$, where the coefficient$-0.35$ is for the SM with three families and one Higgs doublet. In [8], it is shown that this puts an *upper* bound on the mass of the messenger field: $m_{\tilde{\varphi}_1} \leqslant 1$ TeV. This makes a search for this 'progenitor of SM lepton number', $\tilde{\varphi}_1$, fairly feasible at the LHC if its mass is low enough.

(III) The third implication comes from the interesting possibility that σ_Z ($\phi_Z = (\sigma_Z + v_Z)\exp(\mathrm{i}a_Z/v_Z)$) can play the role of the inflaton in a 'low-scale' inflationary scenario [7]. It was proposed that a Coleman–Weinberg potential for σ_Z is consistent with recent WMAP3 data on the spectral index n_s for $v_Z \sim 10^9$ GeV. The inflaton mass $m_{\sigma_Z} \simeq 450$ GeV is low enough so that it might be indirectly 'observed' at colliders such as the LHC through its coupling with $\psi_{1,2}^{(Z)}$ which, in turns, couple to $\tilde{\varphi}_1^{(Z)}$.

(IV) The fourth implication is the possibility of unifying $SU(2)_Z$ with the SM into E_6 as mentioned above [8]. This unification requires the existence of heavy mirror fermions which could be searched for at future colliders. An estimate for the proton lifetime gives, however, a mean value about an order of magnitude larger than the present lower bound ($\sim 2 \times 10^{32}$ years) which makes it inaccessible experimentally for quite some time.

Acknowledgments

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