Quantum Regeneration of Dark Energy and Unification with the Inflaton Field

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Abstract.
Early Inflation and Dark Energy are two cosmological epochs where the universe accelerates and we present the possibility that these stages are due to the same particle the uniton field ϕ. After Inflation the field ϕ decays and reheats the universe. To obtain Dark Energy ϕ must be regenerated via a quantum process (back decay). This back decay happens at a late time, close to present time, and therefore our unification allows to unify Inflation with Dark Energy but also and explains the coincidence problem.

INTRODUCTION

Dark Energy "DE" and early Inflation [1] are the two known stages of positive acceleration of our universe. They are both separated by a long period of time where our universe was dominated by radiation first and later by matter so that structure was able to form. From a particle physics point of view the most appealing candidate for the DE is a scalar field [4]-[5] which interacts weakly with standard model "SM" particles. Here we will assume that DE and inflation are given in terms of the same scalar field and we will call this field the "uniton" ϕ, from inflaton-dark energy unification [6]. Inflation takes place when the scalar potential is flat enough and by choosing the right potential $V(\phi)$ we can easily achieve it, however, most of the time our universe was in a decelerating phase and this phase must be naturally explained by any inflation-dark energy unification. We reheat the universe and obtain a long period of deceleration by coupling the uniton to another scalar φ. After early inflation the uniton decays into φ, reheating the universe, while at low energies (close to present time) φ decays back and regenerates the uniton. The appearance of DE is then via a quantum process and not only through its classical evolution. The standard reheating process is enhanced in our class of models since the conditions for instant preheating [8] are easily met and we have an efficient decay. In the reheating epoch the uniton evolves through a region where the mass of φ vanishes but the potential $V(\phi)$ does not. To reheat the universe with the standard model "SM" particles we couple φ to the SM particles at high energies, where φ and SM particles are relativistic, via a $2 \leftrightarrow 2$ process. They achieve thermal equilibrium "TE" and remain in TE as long as φ and the SM particles remain relativistic. The quantum regeneration scenario for DE, presented here, has some interesting generic properties and can be observationally or experimentally tested. The explicit form of the uniton potential $V(\phi)$ is not important as long as if inflates the universe at an early and late epoch and the uniton field evolves a through region (e.g. $|\phi| \ll 1$) where the conditions for instant preheating are met. The field φ remains relativistic until present time and therefore we have more relativistic energy density given by

$$\Omega_\varphi = \frac{g_\varphi}{g_r}\Omega_r \tag{1}$$

with $g_\varphi = 1, g_r = g_\varphi + g_{SM}$ the relativistic degrees of freedom. This extra Ω_φ is favored by the cosmological data [9] and since the interaction between DE and φ remains at low energies it can also have phenomenological consequence in structure formation and the evolution of DE. In fact, an interacting DE has been proposed to explain a w smaller than -1 for DE [10]. In models where inflation and reheating takes place at a low energy, as in the model presented here with $E \leq E_I = O(100)\,TeV$, the temperature is large to produce all SM particles but low enough so that φ could be produced at LHC. Of course we should be careful not to contradict present day constrained from charged particles [11] or a long range force [12].

GENERAL FRAMEWORK

Our starting point is a flat FRW universe with the uniton ϕ, a second φ scalar field and the SM. We take the lagrangian $L = L_{SM} + \widetilde{L}$, where L_{SM} is the SM lagrangian,

$$\widetilde{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\phi) - B(\varphi) - V_{int}(\phi,\varphi,SM). \tag{2}$$

The uniton potential is $V(\phi)$ while V_{int} is the complete interaction potential. The potential $B(\varphi)$ may be required to stabilize φ, e.g. $B(\varphi) = \lambda\varphi^4$ for V_{int} in eq.(20). The requirement for V is that it satisfies the slow roll conditions $|V'/V| < 1, |V''/V| < 1$, where a prime denotes derivative w.r.t. to ϕ, at the inflation epoch and at present time for DE. We also take V such that ϕ evolves through regions where instant preheating is possible, e.g. $V(\phi = 0) \neq 0$. The interaction term V_{int} has two important consequences. On the classical level it couples the differential equations of ϕ and φ through derivatives of V_{int} while at a quantum level it allows for a particle decay.

We define the energy density and pressure for the field ϕ as

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V, \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V \tag{3}$$

and

$$\rho_\varphi = \frac{1}{2}\dot{\varphi}^2 + B + V_{int}, \quad p_\varphi = \frac{1}{2}\dot{\varphi}^2 - B - V_{int} \tag{4}$$

for φ. The total energy density and pressure are then given by $\rho = \rho_\phi + \rho_\varphi, p = p_\phi + p_\varphi$. The classical evolution of ϕ and φ is given by the equations of motion [14]

$$\ddot{\phi} + 3H\dot{\phi} + V' + V'_{int} = 0 \tag{5}$$

$$\ddot{\varphi} + 3H\dot{\varphi} + B_\varphi + V_{int,\varphi} = 0 \tag{6}$$

with $H^2 = \rho/3$ and $8\pi G \equiv 1$.

UNITON POTENTIAL V(ϕ)

The choice of V is not essential in this class of models as long as it is flat at a high energy and late time to give an accelerating universe and that the evolution of the field ϕ go through values where $V \neq 0$ with $m_\varphi = 0$ so that $|\dot{m}_\varphi/m_\varphi^2| \gg 1$. However, to be more specific we present as an example the potential [6]

$$V(\phi) = \frac{V_I}{2}\left(1 - \frac{2}{\pi}\arctan[k\phi]\right) \tag{7}$$

with V_I, k constant parameters. The potential in eq.(7) can be motivated by the interaction $AB \to C \to A'B'$, with the exchange of a scalar particle with propagator $1/(E_c^2 - p_c^2 - m_c^2)$. The Yukawa potential $V_Y \propto e^{-mr}/r$ is obtained as the fourier transformation for $E_c \simeq 0$ while our potential corresponds to zero momentum with $p_c = 0$ and $E_c = m_A - m_B$. Integrating the propagator with imaginary energy $E_c = i\widetilde{E}_c$ we get a potential $V_s \propto \int_{-\infty}^{\infty} dE_c/(E_c^2 - m_c^2) = -i\pi/m_c$ and an euclidian action $S_E = -iS \propto -iV_s \propto -\pi/m_c$. This S_E gives an exponentially suppressed transition rate connecting a maximum (e.g. at V_I) to a minimum (e.g. $V = 0$), i.e. a sphaleron configuration. If we take the integration limits as $E_{max} = m_A - m_B = \phi$ we have $V \propto \int_{-\phi}^{\phi} d\widetilde{E}_c/(\widetilde{E}_c^2 + m_c^2) = 2\arctan[\phi/m_c])/m_c$ corresponding to V in eq.(7). We could identify the energy scale V_I as the ultraviolet cutoff scale above which susy (or another symmetry) gives a vanishing V.

We constrain the values of V_I, k in eq.(7) by demanding that during inflation $c\delta\rho/\rho = V^{3/2}/V' = 5.2 \times 10^{-4}, c = \sqrt{75\pi^2}$ and at present time the DE density $V(\phi_o = 1) \simeq V_o = (2 \times 10^{-3} eV)^4$. The potential in eq.(7) has $V' = -V_I k/[\pi(1 + k^2\phi^2)]$, $m_{\phi 0}^2 = V'' = 2V_I k^3\phi/[\pi(1 + k^2\phi^2)^2]$ and the limits $V(-\infty) = V_I, V(0) = V_I/2$ and $V(\infty) = 0$. If we take $k \gg 1$ (as will be needed later on) then the potential V satisfies the slow roll conditions and accelerates the universe for $\phi < -k^{-1/3}$ and for $\phi \geq 1$. During the last 60 e-folds of inflation we have $k^{-1/3} \leq -\phi \ll 1$ and the potential can be approximated by $V \simeq V_I$, $V' \simeq -V_I/k\phi^2 \simeq -V_I k^{-1/3}$ and $V^{3/2}/V' \simeq V_I^{1/2} k^{1/3}$ while for $\phi \simeq 1$ we have $V(\phi_o \simeq 1) = V_o \simeq V_I/k$. We then obtain the values $k \simeq 10^{66} \gg 1$ and $V_I \simeq 10^{-53} \ll 1$. The dimension of V_I is $[V_I] = [E^4]$ so we obtain an inflationary epoch $E_I = V_I^{1/4} \simeq 100 TeV$ while $[k] = [1/E]$ and $1/k = O(E_I(V_I/m_{pl}^4)) = O(E_I^5)$.

Decay

In a non expanding universe the number density $n = N/\text{Vol}$, where N is the total number of particles and Vol the volume, evolves as $n(t) = n_i e^{-\Gamma(t-ti)}$ where Γ is the transition (constant) rate. The differential transition rate is given by [13]

$$d\Gamma = \text{Vol}(2\pi)^4 |M_{ab}|^2 \delta^4(PI - PF)\Pi_a \frac{1}{2E_a \text{Vol}} \Pi_b \frac{d^3 p_b}{2E_b(2\pi)^3} \tag{8}$$

where $PI(PF)$ is the initial (final) momentum, Vol is the volume (normalized to one particle per volume) and $M_{ab} \equiv \langle b|M|a\rangle$ is the transition amplitude. The conservation of energy-momentum requires that initial and final energies are equal, $E_i = E_f$ and $p_i = p_f$. In a process of a identical initial particles with energy E_a and mass m_a and a final state consisting of b particles with the same energy E_b and mass m_b so that $E_i = aE_a = bE_b = E_f$ differential transition rate is

$$\Gamma = c_{ab}|M_{ab}|^2 n_a^{a-1} p_b^{b-1} E_a^{b-a-3} \tag{9}$$

$c_{ab} = (a/b)^{b-2} 2^{(1-a-b)} (2\pi)^{3-2b}/a$. In the limit where the decaying particle is non-relativistic with $E_a \simeq m_a \gg m_b, p_b \simeq E_b$ then eq.(9) becomes

$$\Gamma = c_{ab}|M_{ab}|^2 n_a^{a-1} E_a^{2b-a-4} = c_{ab}|M_{ab}|^2 n_a^{a-1} m_a^{2b-a-4} \tag{10}$$

On the other hand if all particles involved are relativistic and in TE then eq.(9) with $n_a = c_n T^3, c_n = g_a \zeta(3)/\pi^2$ and $E_a = T$ is

$$\Gamma = \tilde{c}_{ab}|M_{ab}|^2 E_a^{2(b+a)-7}, \tag{11}$$

$\tilde{c}_{ab} = c_{ab} c_n^{a-1}$. In quantum field theory it is common to take the interaction between two scalar fields as power laws with $V_{int} = g\phi^m \varphi^n/2$ with $m > 0, n > 0$ and $n + m \leq 4$. However, the potential for DE is in general a non renormalizable potential and has a more complicated expression such as an exponential $e^{-\alpha\phi}$ or an inverse power $1/\phi^\alpha$. Therefore, we will consider a generic interaction potential $V_{int}(\phi, \varphi)$. The quantum states in field theory are perturbations around the minimum of the potential, however, since a scalar field that is cosmologically evolving has not reached its lowest energy state, we must expand ϕ around its classical average $\phi_0(t)$ at any given time, $\phi(t) = \phi_0(t) + \delta\phi(t)$, and it is the fluctuation $\delta\phi$ that gives the quantum state. An expansion around a stable point of the potential V, as in a quadratic potential, the creation of particles are not energetically favored. However when the perturbations are unstable the creation of particles is energetically favored. Let us assume an interaction term $V_{int} = gh(\phi)\varphi^n$ with h not necessarily a positive power law function of ϕ. If we expand h in a Taylor series around $\phi_0(t)$ the interaction term V_{int} gives an effective coupling

$$V_{int} \simeq gh_0\varphi^n + gh_0' \,\delta\phi\, \varphi^n + \frac{1}{2} gh_0'' \,\delta\phi^2\, \varphi^n + ... \tag{12}$$

between a quantum fields $\delta\phi$ with $1 \leq a$ and b quantum fields $\delta\varphi$ with $1 \leq b \leq n$, after expanding $\varphi = \varphi_0 + \delta\varphi$. Since ϕ is dynamically evolving, the expansion point ϕ_0 and all the couplings $h_0, h_0', ...$ are functions of time. Considering a polynomial interaction we can determine the process of an initial state of a-particles going into a final state of b-particles. The transition amplitude is

$$M_{ab} = \frac{1}{a!b!} \frac{d^a}{d\phi^a} \frac{d^b V_{int}}{d\varphi^b} \tag{13}$$

and the total transition rate is then given by $\Gamma = \Sigma_{a,b}\Gamma_{ab}$ where a takes the value from $1 \leq a \leq a_{max}$ and $1 \leq b \leq b_{max}$. Clearly the total transition rate Γ will be dominated by the largest Γ_{ab}. If we take a polynomial potential

$$V_{int}(\phi, \varphi) = g\phi^m \varphi^n \tag{14}$$

with arbitrary values of m,n and use eq.(13) we have

$$M_{ab} = \frac{m!n!}{a!(m-a)!b!(n-b)!}\, g\phi^{m-a}\varphi^{n-b} \tag{15}$$

and eq.(9) becomes

$$\Gamma_{ab} = \Gamma_{12}\Gamma_i^{a-1}\Gamma_f^{b-2} \tag{16}$$

$$\Gamma_0 \equiv \frac{c_0 g^2 \phi^{2(m-1)}\varphi^{2(n-2)}}{m_\phi}, \quad \Gamma_i \equiv \frac{n_\phi}{\phi^2 m_\phi}, \quad \Gamma_f \equiv \frac{m_\phi^2}{\varphi^2} \tag{17}$$

and $c_0 = (\frac{m!n!}{a!(m-a)!b!(n-b)!})^2 c_{ab}$. The quantity Γ_{12} corresponds to the decay with $a = 1, b = 2$, Γ_i gives the contribution from a larger number ($a > 1$) of initial decaying particles ϕ while Γ_f corresponds to a larger number ($b > 2$) of final product particles φ. We clearly see that if $\Gamma_i = n_\phi/\phi^2 m_\phi > 1$ then a large value of "a" gives a bigger Γ_{ab} or if $\Gamma_f = m_\phi^2/\varphi^2 > 1$ when "b" takes its maximum value $b = n$.

In the decay of ϕ two different and complementary scenarios take place. On the one hand we have $\Gamma/H \gg 1$ giving an exponentially suppressed ρ_ϕ after the decay. On the other hand, the conditions for a non adiabatic process and instant preheating are met, i.e. we have $\dot{m}_\varphi/m_\varphi^2 > 1$, since the potential $V(\phi) \neq 0$ while ϕ roles down its potential around the value $\phi = 0$ and the mass of φ, $m_\varphi^2 = 6g\phi\varphi$, vanishes. Taking into account these facts we expect an efficient decay of ϕ into φ. Furthermore, since φ is coupled to the SM it will decay into SM particles and the resulting energy density ρ_ϕ will essentially vanish giving rise to a relativistic $\rho_R = \rho_{SM} + \rho_\varphi$. If inflation ends with a small value of ϕ than the decay and reheating of the universe will take place immediately afterwards at the energy scale E_I. After inflation the field ϕ is non-relativistic, in the comoving frame its momentum is negligible compared to its mass, and we have $m_\phi^2 > V \simeq \rho_\phi$. Form eq.(10) with $a = 1, b = 3$ and $E_a = E_\phi = m_\phi$ we have

$$\Gamma = \frac{g^2 m_\phi}{192\pi^3}, \; H = \sqrt{\frac{\rho_\phi}{3}}, \quad \frac{\Gamma}{H} = \frac{g^2}{192\pi^3}\sqrt{\frac{3m_\phi^2}{\rho_\phi}}. \tag{18}$$

We see form eq.(18) for as long as $g^4 m_\varphi^2 \gg \rho_\phi$ the field ϕ will decay into φ. If $\Gamma/H \gg 1$ then we will have an efficient decay and ρ_ϕ will be exponentially small. Now, the instant preheating takes place the non adiabaticity condition [8]

$$\left|\frac{\dot{m}_\varphi}{m_\varphi^2}\right| = \left|\left(\frac{\dot{\phi}}{\phi} + \frac{\dot{\varphi}}{\varphi}\right)\frac{1}{2m_\varphi}\right| \geq \left|\frac{V^{1/2}}{m_\varphi \phi}\right| \gg 1 \tag{19}$$

where we have used $\dot{\phi}^2 = 2(1+w_\phi)/(1-w_\phi)V$. After inflation the energy density ρ_ϕ redshifts with an equation of state $w_\phi \neq -1$ and $m_\varphi \phi \approx 0$ for $\phi \approx 0$ giving $|\dot{m}_\varphi/m_\varphi^2| \gg 1$ in eq.(19).

INTERACTION TERM

We will now choose an interaction term which allows for ϕ to decay into a relativistic scalar field φ at a high energy E_I. This field φ is coupled to SM particles denoted by χ and ψ. As soon as φ is produced it decays into χ and ψ, which are also relativistic at the energy E_I. As long as φ, χ or ψ are relativistic they remain in TE. We will assume that φ remains relativistic while it is couple to the SM (otherwise the number density n_φ would be exponentially suppressed and the uniton would not be regenerated). Finally, the φ will regenerate ϕ at a late time when the universe energy is given by E_{BD}, with $E_I \gg E_{BD} > E_o = 10^{-3}eV$. From eq.(11) we see that if want to have a late time regeneration $E \ll 1$ the coupling between φ and ϕ, which are relativistic, must have $a+b < 4.5$ so that the exponent of E in eq.(11), using $H \approx \sqrt{\rho} \sim E^2$, is negative. We take then the simplest interaction potential as [6]

$$V_{int}(\phi,\varphi,SM) = g\,\phi\,\varphi^3 + h\,\varphi^2\chi^2 + \widetilde{h}\,\varphi^2\bar{\psi}\psi. \tag{20}$$

The first term gives rise to the uniton decay into φ at a high energy and a late time regeneration via φ decay. The second and third terms are the coupling of φ with SM particles χ,ψ allowing for reheating our universe. All other SM particles will be produced by χ,ψ. If the fields χ,ψ acquire a large mass then φ will no longer be coupled at $T < m_\chi$ since below this temperature n_χ, n_ψ are exponentially suppressed and Γ/H will be smaller than one. However, the φ temperature will still redshift as $T \sim 1/a(t)$ since it is relativistic.

Let us now describe the three different decay processes, the uniton decay, the SM reheating and the back regeneration of the uniton.

Universe Reheating

The reheating of the universe takes place via the process [6]

$$\varphi+\varphi \;\leftrightarrow\; \chi+\chi \tag{21}$$
$$\varphi+\varphi \;\leftrightarrow\; \psi+\psi \tag{22}$$

with a cross section for relativistic particles $\sigma = h^2/E^2$ (we take the same strength for the χ and ψ) and an interaction rate [6]

$$\Gamma = \frac{h^2 E}{32\pi^3},\;\; H = \sqrt{\frac{\rho_r}{3\Omega_r}} \equiv c_H E^2, \quad \frac{\Gamma}{H} = \frac{c_R h^2}{E} \tag{23}$$

with $T = E, \widetilde{c}_{22} \simeq 1/32\pi^3, c_H^2 \equiv g_r\pi^2/90\Omega_r$ and $c_R \equiv c(E_R), c(E) \equiv (c_H 32\pi^3)^{-1}$. For $E > 10^2 GeV$ we have $g_r \simeq 106, \Omega_r \simeq 1$ and $c_R \simeq 10^{-3}$. Clearly eq.(23) maintains a TE for $E \leq E_R \equiv c_R h^2$. A good choice of h is then $h^2 \simeq E_I$ so that the interaction takes place at $E_R = T_R \simeq E_I$. The amount of ρ_φ can then be easily determined and it is $\Omega_\varphi = \Omega_r/g_r$. In terms of ΔN_ν, extra neutrinos degrees of freedom, we have $\Delta N_\nu = (8/7)(g_\varphi/g_\nu)(T/T_\nu)^4$ with $\Delta N_\nu = 2.2\,(0.57)$ for $T = T_\gamma(T_\nu)$ (if φ decouples at a higher energy than the neutrinos then $\Delta N_\nu < 0.57$). A central value of $0.5 < \Delta N_\nu < 2.1$ is favored by the cosmological data [9].

Back Decay and Quantum Regeneration

Now, let us see the case for the back decay and quantum regeneration of the uniton field ϕ. This process will take place at late time and low energies $E = E_{BD}$. Therefore the classical potential $V \ll E_{BD}$ and $m_\phi \ll E_{BD}$. So the uniton will be relativistic and from eq.(20) the process $\varphi + \varphi \to \varphi + \phi$ gives [6]

$$\Gamma = \frac{g^2 E}{32\pi^3}, \;\; H = \sqrt{\frac{\rho_r}{3\Omega_r}} = c_H E^2, \quad \frac{\Gamma}{H} = \frac{c_{BD}\, g^2}{E} \tag{24}$$

For low energy, $E \ll MeV$, we have $g_r \simeq 5$ and $c_{BD} \equiv c(E_{BD}) \simeq 10^{-3}\sqrt{\Omega_r}$. The process takes place for $E \leq E_{BD} \equiv c_{BD} g^2$. An interesting choice is $g \simeq E_I$, which gives $E_{BD} \ll E_I$. With this choice we reduce the number of free parameters and we relate the energy scale of the back decay to that of the end of inflation

$$\begin{aligned} E_R \equiv c_R h^2 \approx E_I, \qquad & E_{BD} \equiv c_{BD} g^2 \approx E_I^2, \\ g = h^2 \;\; = \;\; & qE_I \end{aligned} \tag{25}$$

with q a proportionality constant. The fine structure constant of these interactions are $\alpha_I \equiv h^2/4\pi = E_I/4\pi$ and $\alpha_{BD} \equiv g^2/4\pi = E_I^2/4\pi$ which for $E_I = 100\,TeV$ gives $\alpha_I = 10^{-14}, \alpha_{BD} = 10^{-27}$ to be compared with $\alpha_{em} = 1/137$, the electromagnetic fine structure constant. The constraint on light particles coupled to electrons from astrophysical considerations is $\alpha < 0.5\ 10^{-26}$ [11] or to baryons from a long range force [12] imply that the SM field χ and ψ must be a neutral particles such as neutrino.

Using eqs.(7) and (18) we have the ϕ decay rate $\Gamma \approx g^2 m_\phi = E_I^2 V_I^{1/2} k$ and

$$\frac{\Gamma}{H} \approx g^2 \sqrt{\frac{m_\phi^2}{\rho_\phi}} \simeq E_I^2 k = 10^{40} \gg 1 \tag{26}$$

and eq.(19) is also satisfied. Therefore we have an efficient decay and the field ϕ ceases to exist until it is regenerated at late time by the back decay process. The universe will therefore be in a decelerating phase for a long period of time, from reheating at $E_I \simeq 100\,TeV$ to φ decay at $E_{BD} = E_I^2 = 1\,eV$ (c.f. eq.(24)) when φ starts to regenerate ϕ giving $\Omega_{\phi BD} = \Omega_{\varphi BD}$ with $\rho_{\varphi BD} \simeq E_{BD}^4 = E_I^8$. For $V \approx \rho_\phi \approx \rho_{\varphi BD}$ we have $\phi > 1/kV_I \simeq 10^{-12}$, using $V \simeq V_I/k\phi$ (valid for $\phi k \geq 1$). Once ϕ is regenerated it will grow and its potential will start dominating the universe with $\phi = O(1)$ for $V \approx V_o$, independent of its initial conditions (tracker behavior). The slow roll conditions are satisfied and the universe will enter an acceleration period or DE domination. This late time decay gives an understanding why DE appears at such a late time.

SUMMARY AND CONCLUSIONS

We have presented a model where inflation at and dark energy can be achieved via a single scalar field ϕ, the uniton. In order to have a long period of hot and decelerating universe we couple ϕ to another field φ. The inflation, reheating and back decay scales, using eq.(25) with $q = 10$, are

$$E_I \simeq 100\,TeV,\;\; E_R \simeq 1\,TeV,\;\; E_{BD} \simeq 1\,eV \tag{27}$$

The scale E_I is very interesting since it is on the upper limit of susy. This inflationary scale E_I is low compared to the standard $10^{16}GeV$ but it is large enough to have a reheating temperature to produce all SM particles and it is within the phenomenological range at LHC. Moreover, it is phenomenological welcome [3] and since it is low scale one does not have gravitino overabundance problems and it has a spectral index $n_s = 0.97$. More relativistic energy and a $w < -1$ are phenomenological favored [9] and our model can explain both since it predicts the existence of Ω_φ and we have an interacting dark energy giving a $w < -1$. The universe is dominated by ρ_ϕ at high energy $\rho_\phi > E_I^4 = (100\,TeV)^4$ and low energy $\rho_\phi \ll \rho_{BD} = (1\,eV)^4$ while radiation or matter dominates the universe otherwise. We stress the fact that the quantum regeneration of the uniton drives the transition between the decelerating universe to the dark energy phase, it is not longer classical but it is essentially due to quantum effects and the low value of E_{BD} explains the coincidence problem.

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