Inflation-Dark Energy unified through Quantum Regeneration

A. de la Macorra and F. Briscese

Instituto de Física, Universidad Nacional Autonoma de Mexico,
Apdo. Postal 20-364, 01000 México D.F., México
Part of the Collaboration Instituto Avanzado de Cosmologia

We study a scalar \( \phi \) field that unifies inflation and dark energy with a long period of a hot decelerating universe in between these two stages of inflation. A key feature is that the transition between the intermediate decelerated phase to the dark energy phase is related to a quantum regeneration of the scalar field \( \phi \) instead to purely classical dynamics. The interaction \( V_{\text{int}}(\phi, \varphi) \) between \( \phi \) and a second scalar field \( \varphi \) allows not only for \( \phi \) to decay at a high energy \( E_I \), even though \( \phi \) does not oscillate around the minimum of its potential, but it also regenerates \( \phi \) at an energy \( E_{BD} \simeq E_I^2 \) close to present time. It predicts extra relativistic energy and an interacting dark energy which may account for a \( w < -1 \). In the model presented here we have \( E_I \simeq 100 \text{TeV} \) and \( E_{BD} \simeq 1 \text{eV} \). The low value of the back decay energy \( E_{BD} \) gives an explanation of the coincidence problem.

In the last few years the existence of two stages of accelerating the universe have been established. The first stage is inflation [1] needed to explain the homogeneity and isotropy of our universe and the second stage corresponds to the dark energy "DE" which dominates the universe at present time [2].

Inflation is associated with a scalar field, the "inflaton", and the energy scale at which inflation occurs is typically of the order of \( E_I = 10^{16} \text{GeV} \) [1] but it is possible to have consistent inflationary models with \( E_I \) as low as \( 10 \text{MeV} \)[3]. On the other hand the energy scale at which DE becomes relevant is much smaller than for inflation, namely \( E_o \simeq 10^{-3} \text{eV} \), and its nature is not known. The present time data are consistent with a cosmological constant but perhaps the most appealing candidate for the DE is that of a scalar field [4]-[5] which interacts weakly with standard model "SM" particles.

We will assume that DE and inflation are given in terms of the same scalar field and we will call this field the "uniton" \( \phi \), from inflaton-dark energy unification. A single scalar field can easily give inflation and DE if the potential is flat at high and low energies (present time)[6]. However, most of the time our universe was decelerating and was not dominated by the uniton field but by radiation and later by matter. Therefore, any realistic model must not only explain the two stages of inflation but also allow for a long period of decelerating universe. This long period of deceleration is not easy to achieve in the context of inflation-dark energy unification. In this letter we study a class of models that achieve these results.

To reheat the universe and obtain a long period of deceleration we couple the uniton to a scalar \( \varphi \). After inflation the uniton will decay into \( \varphi \), reheating the universe, while at low energies (close to present time) \( \varphi \) will decay back and regenerate the uniton. We use for this second decay the same interaction term \( V_{\text{int}} \) as in the first decay. We point out that the appearance of DE is via quantum decay and not classical evolution.

Typically the inflaton decays while it oscillates around the minimum of its (quadratic) potential [1]. If the inflaton decay is not complete then the remaining energy density of the inflaton redshifts as matter at late times. The amount of residual energy density must be fine tuned if one wants to be interpreted as dark matter. However, in our case the uniton can no longer have a minimum at a finite value for \( \phi \) [5] since it must accelerate the universe at late times. So the decay of \( \phi \) must happen while rolling down its potential. Since the uniton inflates at an early and a late time the potential \( V \) must be flat at high and low energies, we can take \( \phi < -1 \) for inflation and \( \phi > 1 \) for dark energy, and then the uniton evolves through the region \( \phi = 0 \) with a non vanishing potential \( V \neq 0 \). The conditions for instant preheating [7] are then easily met and we have an efficient decay. Of course we want to reheat the universe with particles of the standard model "SM". To achieve this we couple \( \varphi \) to SM particles at high energies, the same energy as the decay of \( \phi \), where all particles of the SM and \( \varphi \) are relativistic. Thermal equilibrium "TE" will be maintained as long as \( \varphi \) 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 it inflates the universe at an early and late epoch and the uniton field evolves through a region (e.g. \( |\phi| \ll 1 \)) where the conditions for instant preheating are met. The field \( \varphi \) remains relativistic until present time and therefore we have more relativistic energy density given by \( \Omega_{\varphi} = \Omega_{\varphi}g_{\varphi}/g_r \) with \( g_{\varphi} = 1, g_r = g_{\varphi} + g_{SM} \) the relativistic degrees of freedom. This extra \( \Omega_{\varphi} \) is favored by the cosmological data [8] and since the interaction between DE and \( \varphi \) 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 [9]. In models where inflation and reheating takes place at a low energy, as in the model presented here with \( E \leq E_I = O(100) \text{TeV} \), the temperature is large to produce all SM particles but low enough so that \( \varphi \) could be produced at LHC. Of course we should be careful not to contradict present day constrained from charged par-
The decaying particle is non-relativistic with the SM. We take the lagrangian $L = L_{SM} + \tilde{L}$, where $L_{SM}$ is the SM lagrangian, $\tilde{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{1}{2} \partial_\mu \phi V(\phi) - V(\phi) - \mathcal{B}(\phi) - V_{\text{int}}(\phi, \phi, \text{SM})$. The uniton potential is $V(\phi)$ while $V_{\text{int}}$ is the complete interaction potential. The potential $\mathcal{B}(\phi)$ may be required to stabilize $\phi$, e.g. $\mathcal{B}(\phi) = \lambda \phi^4$ for $V_{\text{int}}$ in eq. (5). 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. $\phi$, at the inflation epoch and at present time for DE. We also take $V$ such that $\phi$ evolves through regions where instant preheating is possible, e.g. $Q(\phi = 0) \neq 0$. The interaction term $V_{\text{int}}$ has two important consequences. On the classical level it couples the differential equations of $\phi$ and $\overline{\phi}$ through derivatives of $V_{\text{int}}$ while at a quantum level it allows for a particle decay.

We define the energy density and pressure for the field $\phi$ as $\rho_\phi = \frac{1}{2} \dot{\phi}^2 + V$, $p_\phi = \frac{1}{2} \dot{\phi}^2 - V$ and $\rho_\phi = \frac{1}{2} \phi^2 + B + V_{\text{int}}$. The total energy density and pressure are then given by $\rho = \rho_\phi + \rho_\overline{\phi}$. The classical evolution of $\phi$ and $\overline{\phi}$ is governed by the equations of motion, $\dot{\phi} + 3H\dot{\phi} + V' + V_{\text{int}} = 0$, $\dot{\overline{\phi}} + 3H\dot{\overline{\phi}} + B_{\overline{\phi}} + V_{\text{int}} = 0$, with $H^2 = \rho/3$ and $8\pi G = 1$. 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 $n(t) = n_0 e^{-\Gamma (t - t_0)}$ where $\Gamma$ is the transition (constant) rate. The differential transition rate is given by [12] $d\Gamma = \text{Vol} (2\pi)^4 |M_{ab}|^2 \delta^4 (PI - PF) \Pi_a \Pi_b 2E_{a} \Pi_{c} \Pi_{d} 2E_{c} (2\pi)^4$ 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 $E_i = a E_a = b E_b = E_f$ differential transition rate is

$$\Gamma = c_{ab} |M_{ab}|^2 n_{a}^{-1} p_{b}^{-1} E_{a}^{b-3} a$$

(1)

$c_{ab} = (a/b)^{b-2} (1-a-b)(2\pi)^{3-2b}/a$. 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. (1) becomes

$$\Gamma = c_{ab} |M_{ab}|^2 n_{a}^{-1} E_{a}^{b-a-4} = c_{ab} |M_{ab}|^2 n_{a}^{-1} m_{a}^{2-b-a}$$

(2)

On the other hand if all particles involved are relativistic and in TE then eq.(1) with $n_a = c_a T^3$, $c_n = g_a \zeta(3)/\pi^2$ and $E_a = T$ is

$$\Gamma = \bar{c}_{ab} |M_{ab}|^2 E_{a}^{(b-a)-7}$$

(3)

$\bar{c}_{ab} = c_{ab} n_{b}^{-a-1}$. In quantum field theory it is common to take the interaction between two scalar fields as power laws with $V_{\text{int}} = g \phi^m \overline{\phi}^n/2$ 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 $1/\phi^n$. Therefore, we will consider a generic interaction potential $V_{\text{int}}(\phi, \overline{\phi})$. 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 $\phi$ around its classical average $\phi_0(t)$ at any given time, $t(t) = \phi_0(t) + \delta \phi(t)$, 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 $V_{\text{int}} = gh(\phi)\phi^n$ with $n$ not necessarily a positive power law function of $\phi$. If we expand $h$ in a Taylor series around $\phi_0(t)$ the interaction term $V_{\text{int}}$ gives an effective coupling $V_{\text{int}} \simeq gh_0 \phi^n + gh_0 \delta \phi \phi^n + \frac{1}{2} gh_0 \delta \phi^2 \phi^n + ...$ between a quantum fields $\delta \phi$ with $1 \leq a$ and $b$ quantum fields $\delta \phi$ with $1 \leq b \leq n$, after expanding $\phi = \phi_0 + \delta \phi$. Since $\phi$ is dynamically evolving, the expansion point $\phi_0$ 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

$$M_{ab} = \frac{1}{a! b!} \frac{d^n}{d\phi^n} \frac{d^n V_{\text{int}}}{d\overline{\phi}^n}$$

(4)

and the total transition rate is then given by $\Gamma = \sum_{a,b} M_{ab}$ where $a$ takes the value from $1 \leq a \leq a_{\text{max}}$ and $1 \leq b \leq b_{\text{max}}$. Clearly the total transition rate $\Gamma$ will be dominated by the largest $\Gamma_{ab}$. If we take a polynomial potential $V_{\text{int}}(\phi, \overline{\phi}) = g \phi^m \overline{\phi}^n$ with arbitrary values of $m, n$ and use eq.(4) we have $M_{ab} = m_{\text{int}}(m+1)(m+n)/(m_{\text{int}})^2 g^{m_{\text{int}}+n-2b-a} \Gamma_f$ and eq.(1) becomes $\Gamma_{ab} = \Gamma_{f} \Gamma_f^{-3} \Gamma_f^2$ with $\Gamma_f \equiv c_0 g^2 \phi^2 (n-2)/m_{\phi}, \Gamma_f \equiv n_{\phi}/\phi^2 m_{\phi}, \Gamma_f = m_{\phi}^2/\phi^2$ and $c_0 = (a! (m_{\text{int}} - a)! b!(n-2)!)^2 c_{ab}$. The quantity $\Gamma_{12}$ corresponds to the decay with $a = 1, b = 2$, $\Gamma_{f}$ gives the contribution from a larger number of initial decaying particles $\phi$ while $\Gamma_f$ corresponds to a larger number ($b > 2$) of final product particles $\phi$. We clearly see that if $\Gamma_f = n_{\phi}/\phi^2 m_{\phi} > 1$ then a large value of "$a"$ gives a bigger $\Gamma_{ab}$ or if $\Gamma_f = m_{\phi}^2/\phi^2 > 1$ when "$b"$ takes its maximum value $b = n$.

Interaction term- We will now choose an interaction term which allows for $\phi$ to decay into a relativistic scalar field $\phi$ at a high energy $E_f$. This field $\phi$ is coupled to SM particles denoted by $\chi$ and $\psi$. As soon as $\phi$ is produced it decays into $\chi$ and $\psi$, which are also relativistic at the energy $E_f$. As long as $\phi$, $\chi$ or $\psi$ are relativistic they remain in TE. We will assume that $\phi$ remains relativistic while it is coupled to the SM (otherwise the number density $n_{\phi}$ would be exponentially suppressed and the unliton would not be regenerated). Finally, the $\phi$ will
regenerate $\phi$ 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.(3) we see that if want to have a late time regeneration $E \ll 1$ the coupling between $\varphi$ and $\phi$, which are relativistic, must have $a + b < 4.5$ so that the exponent of $E$ in $h^2E^{\alpha+\beta-b} > 10^{-3/2}$ is negative, and we have used $H \approx \sqrt{\rho} \sim E^2$. We take then the simplest interaction potential is

$$V_{int}(\phi, \varphi, SM) = g \phi \varphi^3 + h \varphi^2 \chi^2 + \tilde{h} \varphi^2 \psi \psi.$$  \hspace{1cm} (5)

The first term gives rise to the uniton decay into $\varphi$ at a high energy and a late time regeneration via $\varphi$ decay. The second and third terms are the coupling of $\varphi$ with SM particles $\chi, \psi$ allowing for reheating our universe. All other SM particles will be produced by $\chi, \psi$. If the fields $\chi, \psi$ acquire a large mass then $\varphi$ will no longer be coupled to $T < m_\varphi$ since below this temperature $n_\chi, n_\psi$ are exponentially suppressed and $\Gamma/H$ will be smaller than one. However, the $\varphi$ 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.

Inflaton Decay – In the decay of $\phi$ two different and complementary scenarios take place. On the one hand we have $\Gamma/H \gg 1$ giving an exponentially suppressed $\rho_\phi$ after the decay. In 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 $\phi$ rolls down its potential around the value $\phi = 0$ and the mass of $\varphi$, $m_\varphi^2 = 6g_\phi \varphi$, vanishes. Taking into account these facts we expect an efficient decay of $\phi$ into $\varphi$. Furthermore, since $\varphi$ is coupled to the SM it will decay into SM particles and the resulting energy density $\rho_R$ will essentially vanish giving rise to a relativistic $\rho_R = \rho_{SM} + \rho_\varphi$. If inflation ends with a small value of $\phi$ than the decay and reheating of the universe will take place immediately afterwards at the energy scale $E_I$. After inflation the field $\phi$ is non-relativistic, in the comoving frame its momentum is negligible compared to its mass, and we have $m_\varphi^2 > V \approx \rho_\phi$. Form eq.(2) with $a = 1, b = 3$ and $E_a = E_\phi = m_\phi$ we have

$$\Gamma = \frac{g^2 m_\phi}{192 \pi^3}, \quad \frac{\Gamma}{H} = \frac{g^2}{192 \pi^3} \frac{m_\phi^2}{\rho_\phi}.$$  \hspace{1cm} (6)

We see form eq.(6) for as long as $g^4 m_\varphi^2 > \rho_\phi$ the field $\phi$ will decay into $\varphi$. If $\Gamma/H \gg 1$ then we will have an efficient decay and $\rho_\phi$ will be exponentially small. Now, the instant preheating takes place the non adiabaticity condition [7]

$$\left| \frac{\dot{m}_\varphi}{m_\varphi} \right| = \left( \frac{\dot{\varphi}}{\dot{\phi}} \right) \frac{1}{2 m_\varphi} \geq \left| \frac{V^{1/2}}{m_\varphi \varphi} \right| \geq 1$$  \hspace{1cm} (7)

where we have used $\dot{\varphi}^2 = 2(1 + w_\phi)/(1 - w_\phi) V$. After inflation the energy density $\rho_\phi$ redshifts with an equation of state $w_\phi \neq -1$ and $\rho_\phi \approx 0$ for $\phi \approx 0$ giving $|\dot{m}_\varphi/m_\varphi^2| > 1$ in eq.(7).

Universe Reheating – The reheating of the universe takes place via a process $\varphi + \varphi \leftrightarrow \chi + \chi$ (or $\varphi + \varphi \leftrightarrow \psi + \psi$) with a cross section for relativistic particles $\sigma = h^2/E^2$ (we take the same strength for the $\chi$ and $\psi$) and an interaction rate

$$\Gamma = \frac{h^2 E}{32 \pi^3}, \quad H = \sqrt{\frac{\rho_\varphi}{3 \Omega_\varphi}} = c_H E^2, \quad \frac{\Gamma}{H} = \frac{c_R h^2}{E}$$  \hspace{1cm} (8)

with $T = E$, $c_\varphi = g_i/2(32 \pi^3)^{1/2} \equiv g_i / \sqrt{30} \Omega_\varphi$ and $c_\varphi \equiv c(E_R), c(E) \equiv (c_H (32 \pi^3))^{-1}$. For $E > 10^2 GeV$ we have $g_i \approx 106, \Omega_\varphi \approx \rho_\varphi$ and $c_R \approx 10^{-2}$. Clearly eq.(8) maintains a TE for $E \leq E_R \equiv c_R h^2$. A good choice of $h$ is then $h^2 \approx E_I$ so that the interaction takes place at $E_R = T_R \approx E_I$. The amount of $\rho_\varphi$ can then be easily determined and it is $\Omega_\varphi = \Omega_\varphi / g_i$. In terms of $\Delta N_\nu$, extra neutrinos degrees of freedom, we have $\Delta N_\nu = (8/7)(g_i / g_\varphi)(T/T_\nu)^4$ with $\Delta N_\nu = 2.2 (0.57)$ for $T = T_c (T_\nu)$ (if $\varphi$ 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 [8].

Back Decay and quantum regeneration – Now, let us see the case for the back decay and quantum regeneration of the uniton field $\phi$. This process will take place at late time and low energies $E = E_{BD}$. Therefore the classical potential $V \ll E_{BD}$ and $m_\varphi \ll E_{BD}$. So the uniton will be relativistic and from eq.(5) the process $\varphi + \varphi \rightarrow \varphi + \phi$ gives

$$\Gamma = \frac{g^2 E}{32 \pi^3}, \quad H = \sqrt{\frac{\rho_\varphi}{3 \Omega_\varphi}} = c_H E^2, \quad \frac{\Gamma}{H} = \frac{c_{BD} g^2}{E}$$  \hspace{1cm} (9)

For low energy, $E \ll MeV$, we have $g_i \approx 5$ and $c_{BD} \approx 10^{-3} \sqrt{30}$. The process takes place for $E \leq E_{BD} \equiv c_{BD} g^2$. An interesting choice is $g \approx E_I$, 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

$$E_R \equiv c_{R} g^2 \approx E_I^2, \quad E_{BD} \equiv c_{BD} h^2 \approx E_I,$$

$$g = h^2 = q E_I$$  \hspace{1cm} (10)

with $q$ a proportionality constant. The fine structure constant of these interactions are $\alpha_I \equiv h^2/4\pi = E_I^2/4\pi$ 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 $\alpha < 0.5 \times 10^{-26}$ [10] or to baryons from a long range force [11] imply that the SM field $\chi$ and $\psi$ must be a neutral particles such as neutrino.

Uniton potential $V(\phi)$ – 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 $\phi$ go through values where $V \neq 0$ with $m_\phi \approx 0$ so that $|\dot{m}_\varphi/m_\varphi^2| > 1$. However, to
be more specific we present as an example the potential

$$V(\phi) = \frac{V_I}{2} \left( 1 - \frac{2}{\pi} \arctan[k\phi]\right)$$  \hspace{1cm} (11)$$

with $V_I, k$ constant parameters. The potential in eq.(11) can be motivated by the interaction $AB \to C \to A'B'$, with the exchange of a scalar particle with propagator $1/(E^2 - p^2 - m^2)$. The Yukawa potential $V_{Y} \propto e^{-m_{\tau}/r}$ 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 $E_{c} = i\bar{E}$ we get a potential
to the standard $10^{16}$

$$V \propto \int_{-\infty}^{\infty} dE_{c}/(E_{c}^2 - m_{c}^2) = -\pi/m_{c}$$

and an euclidian action $S_E = -i S \propto -i V_{s} \propto -\pi/m_{c}$. 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 splheron configuration. If we take the integration limits as $E_{max} = m_{A} - m_{B} = \phi$ we have $V \propto \int_{\phi}^{\infty} dE_{c}/(\bar{E}_{c}^2 + m_{c}^2) = 2\arctan[\phi]/m_{c}$ corresponding to $V$ in eq.(11). 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.(11) by demanding that during inflation $\delta\rho/\rho = V^{3/2}/V' = 5.2 \times 10^{-4}$ and at present time the DE density $V(\phi_o) = \simeq V_o = (2 \times 10^{-3} eV)^4$. The inflation, reheating and back decay scales, using eq.(10) with $q = 10$, are

$$E_I \simeq 100 TeV, \hspace{.2cm} E_R \simeq 1 TeV, \hspace{.2cm} E_{BD} \simeq 1 eV$$  \hspace{1cm} (12)$$

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 $n_s = 0.97$. It would be interesting to relate the coupling $E_{BD} = 1 eV$ to the neutrino mass [14].

The potential in eq.(11) has $V' = \frac{-V_I k}{[\pi(1 + k^2 \phi^2)]}$, $m_{50}^2 = V'' = 2V_I k^3 \phi/[\pi(1 + k^2 \phi^2)^2]$ 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 $V_{1/2}/V' \simeq V_I^{1/2} k^{1/3}$ while for $\phi \simeq 1$ we have $V(\phi_o \simeq 1) = V_o \simeq V_I/k$. We then obtain the values $k \simeq 10^{60} \gg 1$ 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 $k/[E] = 1/\sqrt{E}$ and $1/k = O(E_I (V_I/m_{50}^2)) = O(E_{BD}^4)$. Using eq.(6) we have the $\phi$ decay rate $\Gamma \simeq g^2 m_{\phi} = E_I^2 V_I^{1/2} k$ and

$$\frac{\Gamma}{H} \simeq \frac{g^2}{10^{40}} \frac{m_{\phi}^2}{\rho_o} \simeq \frac{E_I^2}{k} k = 10^{40} \gg 1$$  \hspace{1cm} (13)$$

and eq.(7) is also satisfied. Therefore we have an efficient decay and the field $\phi$ 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 $\varphi$ decay at $E_{BD} = E_I^2 = 1 eV$ (c.f. eq.(9)) when $\varphi$ starts to regenerate $\phi$ giving $\Omega_{\phi BD} = \Omega_{\varphi BD}$ with $\rho_{\varphi BD} \simeq E_I^4 = E_I^2$. For $V \simeq \rho_{\phi} \simeq \rho_{\varphi BD}$ we have $\phi > 1/k \phi \simeq 10^{-6}$, using $V \simeq V_I/k \phi$ (valid for $dk \geq 1$). Once $\phi$ is regenerated it will grow and its potential will start dominating the universe with $\phi = O(1)$ for $V \simeq V_o$, 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 $\phi$, the uniton. In order to have a long period of hot and decelerating universe we couple $\phi$ to another field $\varphi$. This coupling allows for the reheating of our universe right after inflation at $E_I = 100 TeV$, a reheating scale $E_R = 1 TeV \simeq E_I$ and a late time regeneration of $\phi$ at a low energy $E_{BD} = 1 eV \simeq E_I^2$ which could be related to the neutrino mass. More relativistic energy and a $w < -1$ are phenomenological favored [8] and our model can explain both since we have an interacting dark energy, which may account for a $w < -1$, and predicts the existence of $\Omega_{\phi}$. The universe is dominated by $\rho_{\phi}$ at high energy $\rho_{\phi} > E_I^4 = (100 TeV)^4$ and low energy $\rho_{\phi} \ll \rho_{\varphi BD} = (1 eV)^4$ 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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