

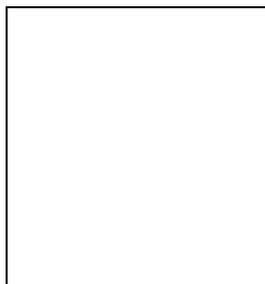
HIGH ENERGY PHYSICS AND QUINTESSENCE^a

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It is shown that any realistic model of quintessence should be based on Supergravity (SUGRA) since the value of the quintessence field on the attractor is approximately the Planck mass. Under very general assumptions, the typical shape of a SUGRA tracking potential is derived. Cosmological implications are investigated. In particular, it is demonstrated that, generically, the equation of state parameter is driven to a value close to -1 in agreement with recent observations.

If confirmed, the discovery that our Universe is presently undergoing a phase of accelerated expansion¹ has clearly important implications for Cosmology and High Energy Physics. In particular, a crucial question is to identify the physical nature of the dark matter component responsible for this acceleration which would represent 70% of the matter content of the Universe. A natural candidate is obviously the cosmological constant. The cosmological constant energy density includes in fact contributions from two origins. The first contribution is due to the bare cosmological, Λ_0 , which appears in the Einstein equations as a “free parameter” and the second one is due to the zero-point fluctuations of the quantum fields. This gives rise to energy densities respectively equal to $\Lambda_0 c^4 / (8\pi G)$ and $(\hbar c/2) \int d^3k k / (2\pi)^3 \approx \hbar c k_{\max}^4 / (16\pi^2)$. In the last expression, k_{\max} is a cut-off which can naturally be taken as the Planck wavenumber. As a consequence, the second contribution becomes huge. Since the observed value is tiny (0.7 times the critical energy density ρ_c), one needs to fine-tune very accurately the value of the bare constant Λ_0 such that the previous simple theoretical predictions be compatible with observational data. Let us emphasize that the discovery that the Universe is accelerating renders this problem even worse than before. Indeed, it is probably easier to explain why there is an exact cancellation between the two contributions such that $\rho_\Lambda = 0$ (due, for example, to some

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so far unknown symmetry in quantum gravity) than finding a reason for a non-vanishing tiny value $\rho_\Lambda = 0.7 \times \rho_c \neq 0$.

This problem motivates the search for alternative explanations. Among them is the quintessence hypothesis. It consists in assuming that the dark matter component is an homogeneous scalar field $Q(t)$, named quintessence, such that $\Omega_Q = 0.7$ (and therefore $\Omega_\Lambda = 0$). However, this is not sufficient to be an interesting proposal. In addition, the shape of the potential $V(Q)$ must possess some typical features. Roughly speaking, the parameter Γ defined by the expression $\Gamma \equiv (d^2V(Q)/dQ^2)V(Q)/(dV(Q)/dQ)^2$ must be greater than one and almost constant². The prototype of such a potential is given by $V(Q) = \Lambda^{4+\alpha}/Q^{\alpha}$ ^{3,4} where Λ and $\alpha > 0$ are two free parameters.

Let us now examine briefly what are the main properties of this “tracker” quintessence field. In order to have $\Omega_Q = 0.7$, we must tune the value of Λ . For example, if $\alpha = 6$, one has $\Lambda \approx 10^6 \text{ GeV}$, a scale compatible with the typical scales of High Energy Physics. In this sense, the fine-tuning problem is less important than for the cosmological constant since the free parameter of the potential can now take a “natural” value. This would not have been the case for the potential $V(Q) = (1/2)m^2Q^2$ where the only free parameter must be chosen such that $m \approx 10^{-33} \text{ eV}$, certainly an “unnatural” value. For the tracking potential the situation is different since the mass, defined as the second derivative of the potential, has also this small value; but, as we have seen, this is not the result of an artificial choice. This is rather the consequence of the shape of the potential and of the reasonable value of the free parameter Λ . Therefore, even if the problem has not been completely overcome, something has been gained.

Having fixed the value of Λ and α , we now turn to the study of the dependence of the final result on the initial conditions. This is the most interesting property of the tracking potential. It can be shown that, due to the presence of an attractor, the final result is completely independent of the initial conditions. The initial value of the energy density can vary in a range of 100 orders of magnitude: $10^{61} \text{ GeV}^4 < \rho_Q < 10^{-37} \text{ GeV}^4$. Another nice property of such models is that it turns out that the equation of state parameter, $\omega_Q \equiv p_Q/\rho_Q$, is naturally such that $-1 < \omega_Q < 0$. However, it is not possible to obtain a value less than $\omega_Q = -0.7$ which could be a problem since observations seem to suggest a value close to -1 ⁵.

One of the most interesting challenge is to derive the tracking properties from generic High Energy Physics considerations. We now show briefly that this is indeed possible and that this leads to a different shape for the potential for which all the previous nice properties are preserved. In addition some of the problems of the previous approach are overcome. Let us consider several possible options for the particle physics origin of the quintessence field. For that it is relevant to express the mass of the quintessence field in terms of the Hubble constant

$$\frac{d^2V(Q)}{d^2Q} = \frac{9}{2} \frac{1+\alpha}{\alpha} (1 - \omega_Q^2) H^2. \quad (1)$$

This has two immediate consequences. First of all, as already mentioned above, the mass of the quintessence field is extremely light compared to the particle physics scales. This implies that the quintessence field could mediate an extremely long range fifth force. This violates experimental results entailing that the quintessence field must be decoupled from ordinary matter. On the other hand, the value of Q now (at vanishing redshift) is of order m_{Pl} as can be seen on the previous formula. This strongly suggests that High Energy Physics must be taken into account in trying to find the origin of the quintessence field. We will only consider models beyond the standard model of particle physics which incorporate supersymmetry. Moreover we shall explicitly consider the supergravity effects as they cannot be neglected for $Q \approx m_{\text{Pl}}$. Within this scheme several possibilities can be envisaged. The quintessence field could spring from the meson field after the gauge breaking of supersymmetric gauge theory⁶, it could also be the dilaton or one of the compactification moduli. It is easy to see that the supergravity

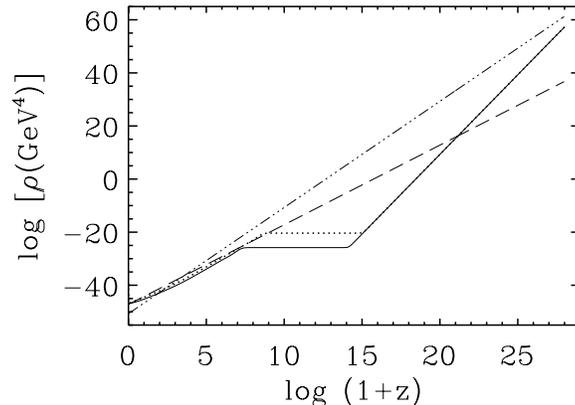


Figure 1: Evolution of the different energy densities. The dashed-dotted line represents the the energy density of radiation whereas the dashed line represents the energy density of matter. The solid line is the energy density of quintessence in the SUGRA model with $\alpha = 11$. The dotted line is the energy density of quintessence for the potential $V(Q) = \Lambda^{4+\alpha} Q^{-\alpha}$ with the same α . The initial conditions are such that equipartition, i.e. $\Omega_{Qi} \approx 10^{-4}$ is realized just after inflation.

potential of the meson field leads to nonsensical negative energy densities. The potential for the dilaton S is of the type $\exp(\exp -S)$ which is far too flat. The potential for the moduli T is of exponential type $\exp(-\lambda T)$ which leads to a small value of $\Omega_Q \leq 0.15^7$. We are thus lead to postulate the existence of a quintessence field whose physical origin is not clear from the string point of view. Nevertheless, one can adopt an effective theory point of view and look for a general class of supegravity models leading to a quintessence behaviour^{8,9}. For that it is only necessary to specify two functions, the superpotential W which is a holomorphic function of the fields and the Kähler potential governing the kinetic terms. The Lagrangian depends on the combination $G = \kappa K + \ln(\kappa^3 |W|^2)$ where $\kappa \equiv 8\pi/m_{\text{Pl}}^2$. The scalar potential is given by $V = \kappa^{-2} e^G (G^i G_i - 3) + V_D$ where V_D is a positive contribution from the gauge sector of the models. From this one can analyse the typical behaviour of the scalar potential in a supergravity quintessence model. First of all for a general polynomial K the exponential term e^G will be negligible throughout the cosmic evolution of Q at least until $Q \approx m_{\text{Pl}}$. This implies that one looks for models where the $G^i G_i$ term is responsible for the tracking potential. It is only at low red shift that the e^G supergravity correction starts contributing by slowing the evolution of Q hence pushing the value of the equation of state towards -1 . In Refs.^{8,9} string inspired Kähler and superpotentials were proposed along these lines. They lead to the SUGRA tracking potential of the form

$$V(Q) = \frac{\Lambda^{4+\alpha}}{Q^\alpha} e^{\frac{\kappa}{2} Q^2}. \quad (2)$$

The cosmological implications of these potentials follow. First of all, the value of Λ necessary to obtain $\Omega_Q \approx 0.7$ is still the same, i.e. comparable to the scales of particles physics. Secondly, the mass of this potential is now given by $m \approx \sqrt{\rho_c}/m_{\text{Pl}} e^{2\pi}$. It is therefore still very small even if we have gained a factor $e^{2\pi}$. Thirdly, we see that the coincidence problem is still solved since, during almost all the cosmic evolution, the exponential factor plays no role. Hence, the attractor is still present. This behaviour is illustrated in Fig. (1) where the evolution of the energy density of the quintessence field is displayed.

As already mentioned above, the most interesting cosmological implications concern the equation of state parameter. Its evolution is displayed in Fig. (2). It is clear that the equation of state parameter is driven towards -1 at very small redshifts due to the presence of the expo-

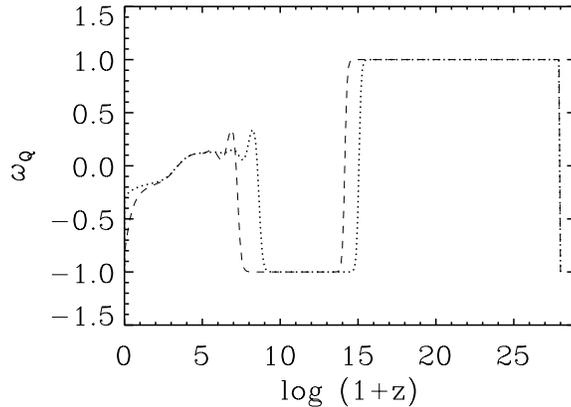


Figure 2: The dotted line represents the evolution of ω_Q for the potential given by $V(Q) = \Lambda^{4+\alpha} Q^{-\alpha}$ with $\alpha = 11$ whereas the dashed line represents the evolution of ω_Q for the SUGRA tracking potential with the same value of α .

nential factor. Numerical integration shows that, for the SUGRA tracking potential, its precise value is given by

$$\omega_Q \approx -0.82. \quad (3)$$

It should be emphasized that this value is independent of the free parameter α .

In conclusion, we have shown in this article that a realistic model of quintessence must be based on SUGRA since the value of the field is $\approx m_{\text{Pl}}$ on the attractor. There are of course questions which remain to be addressed, in particular the issue of SUSY breaking¹⁰.

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