DARK MATTER, DARK ENERGY AND THE TIME EVOLUTION OF MASSES IN THE UNIVERSE

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Abstract. The traditional “explanation” for the observed acceleration of the universe is the existence of a positive cosmological constant. However, this can hardly be a truly convincing explanation, as an expanding universe is not expected to have a static vacuum energy density. So, it must be an approximation. This reminds us of the so-called fundamental “constants” of nature. Recent and past measurements of the fine structure constant and of the proton-electron mass ratio suggest that basic quantities of the standard model, such as the QCD scale parameter Λ_{QCD}, might not be conserved in the course of the cosmological evolution. The masses of the nucleons and of the atomic nuclei would be time-evolving. This can be consistent with General Relativity provided the vacuum energy itself is a dynamical quantity. Another framework realizing this possibility is QHD (Quantum Haplodynamics), a fundamental theory of bound states. If one assumes that its running couplings unify at the Planck scale and that such scale changes slowly with cosmic time, the masses of the nucleons and of the DM particles, including the cosmological term, will evolve with time. This could explain the dark energy of the universe.

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1 Introduction

There is no doubt that the origin and nature of the dark energy in our universe is one of the deepest mysteries we can think of in theoretical particle physics and cosmology. The bare fact is that our universe is in an state of accelerated expansion and we have to find an explanation for it. While the traditional “explanation” is the existence of a nonvanishing and positive cosmological constant, $\Lambda$, whose energy-density equivalent $\rho_\Lambda = \Lambda / 8\pi G$ is of order of the critical density, this cannot be a truly convincing explanation, as an expanding universe is not expected to have a static vacuum energy density. Ultimately this is the main difficulty behind the so-called cosmological constant problem \[1\] in the context of quantum field theory (QFT) in curved spacetime \[1\].

The CC problem is the main source of headache for every theoretical cosmologist confronting his/her predictions with the observational value of $\rho_\Lambda$ \[4\]. After the discovery of a Higgs-like boson at the LHC and the absence of new physics, many question marks are left open \[5\]. The CC problem is actually the most severe one. In point of fact, it became even more acute than before since it is reinforced by the fact that there is indeed a big vacuum contribution generated in the SM which is triggered by the phenomenon of spontaneous symmetry breaking (SSB) in the electroweak sector of the model. It is therefore more pressing than ever to properly address the notion of vacuum energy and its possible implications in cosmology \[2\]. Let us, however, not underemphasize the fact that to achieve such aim one has to face nontrivial problems of QFT in curved spacetime \[6\].

In the last years an independent source of puzzling news has generated also a lot of interest. Frequent hints that the electromagnetic fine structure constant $\alpha_{em}$ might change with the cosmic evolution are reported in the literature \[7\] – for reviews, see e.g. \[8\]. It is tempting to think that if $\alpha_{em}$ evolves with time, all of the fundamental coupling constants should change in time, including the gravity constant $G_N$, see also \[11\]. Since the gravity constant $G_N$ determines the Planck mass $M_P = G_N^{-1/2}$, one expects that $M_P$ depends also on time and slowly evolves with the cosmic expansion. Planck satellite data is also sensitive to this kind of subtle effects on the fundamental “constants” \[12\].

Such framework obviously implies a link between gravity and particle physics. Here we wish to signal some possible connections and at the same time describe particular theoretical frameworks where these ideas could be implemented.

2 Dynamical vacuum models

In a cosmological context with dynamical parameters $\Lambda$ and $G_N$ it is useful to consider the possible modifications that may undergo the basic conservation laws. The Bianchi identity satisfied by the Einstein tensor on the l.h.s. of Einstein’s equations reads $\nabla^\mu G_{\mu\nu} = 0$, where $G_{\mu\nu} = R_{\mu\nu} - (1/2)g_{\mu\nu}R$. It follows that the covariant derivative of the r.h.s. of Einstein’s equations must be zero as well: $\nabla^\mu \left( G_N \tilde{T}_{\mu\nu} \right) = 0$, where $\tilde{T}_{\mu\nu} \equiv T_{\mu\nu} + g_{\mu\nu} \rho_\Lambda$ is the full energy-momentum tensor of the cosmic fluid composed of matter and vacuum. Using the explicit form of the Friedmann-Lemaître-Robertson-Walker (FLRW) metric, the generalized conservation law emerging from this

\[1\]See e.g. \[2, 3\] for recent reviews on the role played by the dynamical vacuum energy in cosmological evolution.
dynamical framework reads:

\[
\frac{d}{dt} \left[ G_N(\rho_m + \rho_\Lambda) \right] + 3 G_N H (1 + \omega_m) \rho_m = 0 ,
\]

(2.1)

where \( \omega_m = p_m/\rho_m \) is the equation of state (EoS) for matter. Consider now the following scenarios:

Scenario I: \( \rho_\Lambda = \rho_\Lambda(t) \) is assumed variable, and \( G_N = \text{const.} \). In this case, Eq. (2.1) implies

\[
\dot{\rho}_m + 3(1 + \omega_m)H \rho_m = -\dot{\rho}_\Lambda .
\]

(2.2)

Since in this case \( \dot{\rho}_\Lambda \neq 0 \) it means we permit some energy exchange between matter and vacuum, e.g. through vacuum decay into matter, or vice versa. Obviously, if \( \dot{\rho}_\Lambda = 0 \) we recover the standard covariant matter conservation law: \( \dot{\rho}_m + 3 H (1 + \omega_m) \rho_m = 0 \). Its solution in terms of the scale factor is well-known:

\[
\rho_m(a) = \rho_m^0 a^{-3(1+\omega_m)} .
\]

(2.3)

Scenario II: \( \rho_\Lambda = \rho_\Lambda(t) \) is again variable, but \( G_N = G_N(t) \) is also variable. In contrast to the previous case, here we further assume matter conservation in the standard form (2.3). As a result the following conservation law ensues:

\[
(\rho_m + \rho_\Lambda) \dot{G}_N + G_N \dot{\rho}_\Lambda = 0 .
\]

(2.4)

In this case the evolution of the vacuum energy density is possible at the expense of a running gravitational coupling: \( \dot{G} \neq 0 \).

Scenario III: Suppose we keep \( \rho_\Lambda = \text{const.} \), but \( G_N = G_N(t) \) is again variable. Now we find:

\[
\dot{G}_N (\rho_m + \rho_\Lambda) + G_N [\dot{\rho}_m + 3 H (1 + \omega_m) \rho_m] = 0 .
\]

(2.5)

Here matter is again non-conserved and the gravitational coupling is running. Despite the vacuum energy is constant in this scenario, such situation can mimic a form of dynamical dark energy since it implies a different expansion rate, a fact that could be detected through the effective equation of state of the dynamical dark energy that it gives rise to [13].

The above three generalized cosmological scenarios differ from the concordance ΛCDM model, but can stay sufficiently close to it if we consider the recent history of our universe. Let us finally note that the above dynamical vacuum models can be appropriately extended at high energies for a successful explanation of the inflationary universe through the primeval vacuum decay [14].

3 Fundamental constants and their possible time variation

It has been proposed in [9] that the cosmic time variation of \( \Lambda \) and \( G_N \) could be related to that of particle masses. This is a challenging possibility. Let us take for instance the proton mass whose current value is \( m_p^0 = 938.272013(23) \) MeV. It can be computed from QCD using the scale parameter \( \Lambda_{\text{QCD}} = \mathcal{O}(200) \) MeV, the quarks masses and the electromagnetic contribution:

\[
m_p = c_{\text{QCD}} \Lambda_{\text{QCD}} + c_u m_u + c_d m_d + c_s m_s + c_{\text{em}} \Lambda_{\text{QCD}} , \quad (3.1)
\]
where the bulk of the contribution (860 MeV) comes from the first $\Lambda_{\text{QCD}}$ term on its r.h.s. Recall that the QCD scale parameter is related to the strong coupling constant $\alpha_s = g_s^2/(4\pi)$. To lowest (1-loop) order one finds:

$$\alpha_s(\mu) = \frac{2\pi}{b \ln (\mu/\Lambda_{\text{QCD}})}.$$  \hspace{1cm} (3.2)

Here $b = 11 - 2n_f/3$ is the one-loop $\beta$-function coefficient, with $n_f$ the number of quark flavors, and $\mu$ is the renormalization point.

The value of $\Lambda_{\text{QCD}}$ could change with the cosmic expansion, and thus be a function of the Hubble function $H$. In this case $\alpha_s(\mu; H)$ would run both with the renormalization scale $\mu$ and the Hubble function, which has also natural dimension of energy. One can easily show that the relative cosmic variations of the two QCD quantities are related (at one-loop) by:

$$\frac{1}{\alpha_s} \frac{d\alpha_s(\mu; H)}{dH} = \frac{1}{\ln (\mu/\Lambda_{\text{QCD}})} \left[ \frac{1}{\Lambda_{\text{QCD}}} \frac{d\Lambda_{\text{QCD}}(H)}{dH} \right].$$  \hspace{1cm} (3.3)

If the QCD coupling constant $\alpha_s$ or the QCD scale parameter $\Lambda_{\text{QCD}}$ undergo a small cosmological time shift, the nucleon masses and the masses of the atomic nuclei would change accordingly.

Let us note on general grounds that as soon as one assumes that the electromagnetic fine structure constant $\alpha_{\text{em}}$ can be varying, one expects the masses of all nucleons to vary as well, since the interaction responsible for the variation of $\alpha_{\text{em}}$ should couple radiatively to nucleons. In this sense one also expects the proton and neutron masses to be time dependent [15].

Another clue to the time variation of masses is the following. In a grand unified theory (GUT) the various gauge couplings converge at the unification point, and we can assume that they display the double running form $\alpha_i = \alpha_i(\mu; H)$. One can show that the GUT condition links the cosmic running of the electromagnetic fine structure constant $\alpha_{\text{em}}(\mu; H)$ to that of $\Lambda_{\text{QCD}}(H)$. It turns out that, under these conditions, $\Lambda_{\text{QCD}}$ runs $\sim 30$ times faster than the electromagnetic fine structure constant [9, 16]. Searching for a cosmic evolution of $\Lambda_{\text{QCD}}$ is therefore much easier than searching for the time variation of $\alpha_{\text{em}}$!

4 Cosmic acceleration versus time evolving masses

The different classes of cosmological scenarios considered in Sect. 1 could help us to understand the potential cosmic time variation of the fundamental “constants” of nuclear and particle physics, such as the QCD scale, the nucleon mass and the masses of nuclei.

A class of dynamical vacuum models can be singled out. If the vacuum energy density evolves as a function of the form [2, 3]

$$\rho_{\Lambda}(t) = c_0 + \sum_k \alpha_k H^{2k}(t) + \sum_k \beta_k \dot{H}^k(t),$$  \hspace{1cm} (4.1)

with $c_0 \neq 0$ (viz. an “affine” function constructed out of powers of $H^2 = (\ddot{a}/a)^2$ and $\dot{H} = \ddot{a}/a - H^2$, hence with an even number of time derivatives of the scale factor $a$), one can formulate a unified model of the cosmological evolution, compatible with the general covariance of the effective action, in which inflation is predicted, a correct transition (“graceful exit”) into a radiation phase can
be naturally accommodated, and finally the late time cosmic evolution can also be successfully described. For simplicity we assume $\beta_k = 0$. Furthermore, for the low-energy universe it suffices to take the single term $k = 1$ in (4.1). Therefore we are left with the simplest and yet nontrivial model

$$\rho_\Lambda(H) = \rho_\Lambda^0 + \frac{3\nu}{8\pi} M_P^2 (H^2 - H_0^2),$$

(4.2)

where we have normalized such that $\rho_\Lambda(H_0) = \rho_\Lambda^0$ is the current vacuum energy density. We have also introduced the dimensionless coefficient $\nu$ which we expect $|\nu| \ll 1$ such that the model (4.2) remains very close to the $\Lambda$CDM one – see [2] for further details. One finds $|\nu| = O(10^{-3})$ when confronting the model with observations on type Ia supernovae, the Cosmic Microwave Background, the Baryonic Acoustic Oscillations and structure formation [17], a result which is compatible with the recent limits reported by the Planck satellite on the possible variation of the fundamental constants [12].

From (2.2), (4.2) and using Friedmann’s equation, one can solve for the matter and vacuum energy densities as a function of the redshift in the matter-dominated epoch ($\omega_m = 0$):

$$\rho_m(z;\nu) = \rho_m^0 (1 + z)^{3(1-\nu)},$$

(4.3)

and the vacuum energy density:

$$\rho_\Lambda(z;\nu) = \rho_\Lambda^0 + \frac{\nu \rho_m^0}{1 - \nu} \left[ (1 + z)^{3(1-\nu)} - 1 \right].$$

(4.4)

For $\nu = 0$ the matter density reduces to Eq. (2.3), and the vacuum energy density stays constant at $\rho_\Lambda^0$, as expected. From these expressions we can determine the relative time variation of the matter nonconservation. Define $\delta\rho_M = \rho_M(z;\nu) - \rho_M(z;\nu = 0)$ as the net amount of non-conservation of matter per unit volume at a given redshift $z$ and let us indicate by a dot the time variation. For small redshifts, we find:

$$\frac{\delta\dot{\rho}_M}{\rho_M} \approx 3\nu \frac{H}{\rho_M}.$$  

(4.5)

and $\dot{\rho}_\Lambda/\rho_\Lambda \approx -3\nu \left( \Omega_M^0/\Omega_\Lambda^0 \right) H$. The variation of the vacuum energy (compensating for the amount of nonconservation of matter) is of opposite sign, as expected.

Let us be more precise. Take e.g. the baryonic density in the universe, which is essentially the mass density of protons. We can write $\rho_p = n_pm_p$, where $n_p$ is the number density of protons and $m_p^0$ is the current proton mass. If the mass density is non-conserved, it may be due to the fact that the proton mass $m_p$ does not stay strictly constant with time and scales mildly with the cosmic evolution:

$$m_p(a) = m_p^0 a^{3\nu}, \quad (|\nu| \ll 1).$$  

(4.6)

Combining this equation with $n_p = n_p^0 a^{-3}$ (the normal particle number dilution law associated to the cosmic expansion, with $n_p^0$ the current number density of protons) we find that the proton density at any time is $\rho_p = n_p m_p = \rho_p^0 a^{-3(1-\nu)}$.

The index $\nu$ above could have been called $\nu_B$ since it affects the non-conservation of the baryon masses, such as the proton mass. In addition, being the matter content of the universe dominated
by the dark matter, we cannot exclude that these particles also vary with cosmic time in a similar way, although perhaps with a different anomaly index $|\nu_X| \ll 1$, such that

$$m_X(a) = m_X^0 a^{3\nu_X}, \quad (|\nu_X| \ll 1).$$

(4.7)

It is important to emphasize that since there is no a priori reason for the baryons and dark matter particles to follow the same rate of mass non-conservation, we may assume $\nu_X \neq \nu_B$ and hence we do not expect, in general, that this theory can just be rewritten as a mere $G$-varying theory, i.e., as a scalar-tensor theory.

From the above equations we can derive the time evolution of the QCD scale, and then from (3.1) the time evolution of the nucleon masses. We consider the total matter density of the universe as the sum of nucleons and DM particles, but to simplify the analysis we assume $\nu_X = 0$. In this case, introducing $\nu_{\text{eff}} = \nu/(1 - \Omega_B/\Omega_{DM})$, we find:

$$\Lambda_{\text{QCD}}(H) = \Lambda_{\text{QCD}}^0 \left[ \frac{1 - \nu}{\Omega_M^0} \frac{H^2}{H_0^2} - \frac{\Omega_A^0}{\Omega_M^0} - \nu \right]^{-(\Omega_{DM}^0/\Omega_B^0) \nu_{\text{eff}}/(1 - \nu)},$$

(4.8)

with $\Omega_M^0 = \Omega_B^0 + \Omega_{DM}^0$. With this equation we can e.g. use Ref. [18] comparing the $H_2$ spectral Lyman and Werner lines observed in the Q 0347-383 and Q 0405-443 quasar absorption systems with the corresponding spectral lines at present. It involves redshifts in the range $z \simeq 2.6 - 3.0$ corresponding to 12 billion years ago. Assuming that $|\nu| = \mathcal{O}(10^{-3})$, as indicated before, we find that the relative variation of $\Lambda_{\text{QCD}}$ in this lengthy time interval is only at the few percent level with respect to its present day value. It is, however, sufficient to be sensitive to the most modern measurements planned in the near future [9].

5 QHD: a fundamental theory of bound states

Quite likely the standard model (SM) of strong and electroweak interactions is not the final theory of the universe. The dark matter (DM) and dark energy (DE) are fundamental problems awaiting an explanation. As an illustration of the kind of conceptual modification that may be necessary to solve these problems, let us consider the possible impact of Quantum Haplodynamics (QHD) [19].

In QHD all of the SM particles (except the photon and the gluons) are bound states of the fundamental constituents called “haplons”, $h$, and their antiparticles. The idea was first formulated long ago – see [20][21]. Following [10] we extend it and assume that the QHD chiral gauge group is the unitary left-right group $SU(2)_L \times SU(2)_R$, which we will denote $SU(2)_h$ for short. All species of haplons $h$ are $SU(2)$ doublets, hence each one has two internal states $h_i$ represented by the $SU(2)_h$ quantum number $i = 1, 2$. Rotations among these states are performed by the exchange of two sets of massless $SU(2)_h$ gauge bosons $\left(X^r_{L,R}\right)_\mu (r = 1, 2, 3)$ for each chirality. There are six haplon flavors, two of them are electrically charged chiral spinors $(\chi = \alpha, \beta)$ and four are charged scalars $S$. One scalar ($\ell$) has electric charge (+1/2) and carries leptonic flavor. The other three scalars have charge (-1/6) and carry color: $c_k = R, G, B$ (“red, green, blue”). In Table 1 we indicate the relevant quantum numbers.
From the various haplon flavors the bound states of QHD can be constructed. Only for energies \( \mu \) well above \( \Lambda_h \) these states break down into the fundamental haplons. The weak gauge bosons are s-wave bound states of left-handed haplons \( \alpha \) or \( \beta \) and their antiparticles: \( W^+ = \bar{\beta} \alpha \), \( W^- = \bar{\alpha} \beta \) and \( W^3 = (\bar{\alpha} \alpha - \bar{\beta} \beta) / \sqrt{2} \).

The neutral weak boson mixes with the photon (similar to the mixing between the photon and the neutral \( \rho \)-meson. One obtains the physical \( Z \)-boson with a mass slightly heavier than the \( W \)-boson. The LH confinement scale \( \Lambda_h^L \) for \( SU(2)_L \) defines the Fermi scale \( G^{-1/2} \sim 0.3 \) TeV and the size of the weak gauge bosons of the SM. The confinement scale \( \Lambda_h^R \) for \( SU(2)_R \) is much larger (in the few TeV range) and has not been observed yet.

The leptons and quarks are themselves bound states. They are composed of a chiral haplon (\( \alpha \) or \( \beta \)) and a scalar haplon: \( \ell \) for leptons and \( c_k \) for quarks. The electron and its neutrino have the structure \( \nu = (\alpha \bar{\ell}) \) and \( e^- = (\beta \bar{\ell}) \), which is consistent with the quantum numbers of Table I. Similarly, the up and down quarks (with \( c_k \) color) are given by: \( u = (\alpha \bar{c}_k) \) and \( d = (\beta \bar{c}_k) \). Among the observed states, one of them has zero haplon number and could be the resonance observed at the LHC [19]. The outcome is an effective theory equivalent to the electroweak SM in good approximation.

Additional particles are also predicted in QHD. The simplest neutral bound state of the four scalars with haplon number \( \mathcal{H} = 4 \) is a stable color singlet spinless boson: \( D = (\ell R G B) \). It is stable due to haplon number conservation, which is similar to the conservation of baryon number. Its mass is expected to be in the region of several TeV. It can be produced together with its antiparticle by the LHC-accelerator, and it can be observed by the large missing energy. We interpret it as the particle providing the DM in the universe. The properties of this DM particle are similar to a “Weakly Interacting Massive Particle” (WIMP), but it can be much more elusive concerning the interactions with nuclei.

We can estimate the cross section for the D-boson off a nucleon \( N \) (of mass \( m_N \)) as follows:

\[
\sigma_{DN} \sim f_D^2 \frac{\alpha_h^2}{(4\pi)^{3/2}} m_N^2 \sim f_D^2 \alpha_h^2 G_F^2 m_N^2, \quad (5.1)
\]

where \( G_F^{-1/2} \sim \Lambda_h^L \sim 300 \) GeV according to our definition of Fermi’s scale in QHD. Here \( f_D \) is the dimensionless form factor of the D-meson, which describes the confinement of the haplons by the \( SU(2)_h \) strong gauge force. All QHD bound states have a form factor, which is of order one only for gauge boson mediated interactions, which are described by the exchange of weak bosons.
\[ M^2 \lesssim (\Lambda^2_h) \]

For a deeply bound state as \( D \), however, we rather expect \( f_D \sim \Lambda^2_h / B^2_D \ll 1 \), where \( B_D \) is the characteristic binding energy scale. For \( B_D \simeq 5 - 10 \) TeV the scattering cross-section of \( D \)-bosons off nucleons, Eq. (5.1), can be reduced to the level of \( \lesssim 10^{-45} \) cm\(^2\), which is compatible with the current stringent bounds [22].

### 6 Unification at the Planck Scale

The QHD, QCD and QED couplings might unify at the Planck scale. It could have nontrivial implications for a possible explanation of the DE in the universe, as we shall see. We can verify this possible unification at one-loop level, starting from their low-energy values and using the renormalization group equations (RGE’s) to compute the running of these parameters. For \( SU(N) \) groups \((N > 1)\) one has:

\[
\frac{d\alpha_i}{d \ln \mu} = -\frac{1}{2\pi} \left( \frac{11}{3} N - \frac{2}{3} n_f - \frac{1}{6} n_s \right) \alpha^2_i \equiv -\frac{1}{2\pi} b_N \alpha^2_i , \tag{6.1}
\]

Here we have \( \alpha_i = \alpha_h, \alpha_s \) \((n_f \text{ and } n_s \text{ are the number of fermion flavors and scalars})\). For the \( U(1) \) coupling \( \alpha_{em} \) we have a similar formula as (6.1), but in this case

\[
b_1 = -N_h \left( \frac{4}{3} \sum Q^2_f + \frac{1}{3} \sum Q^2_s \right) . \tag{6.2}
\]

In this equation, \( N_h = 2 \) for \( SU(2)_h \). For energies below \( \Lambda^L_h \) we have to replace \( N_h \) in \( b_1 \) with \( N_c = 3 \) (or 1) and use the electric charges of the quarks (leptons) rather than those of the haplons.

For the fine structure constant \( \alpha_{em} \) we extrapolate its value from low energies to the Planck scale \( M_P \simeq 1.22 \times 10^{19} \) GeV. At the mass of the \( Z \)-boson we have \( \alpha_{em}^{-1}(M_Z) = 127.94 \pm 0.014 \). From the mass scale of the \( Z \)-boson, \( \mu = M_Z \), until a scale well above \( \Lambda^L_h \), say \( \mu \sim 2 \) TeV, we use the RGE, taking into account the charges of the three charged leptons and of the five quarks, not including the top-quark:

We can follow a similar procedure to compute the QCD coupling constant at various energies. The accurate measurement of this constant at the \( Z \) pole yields: \( \alpha_s(M_Z) = 0.1184 \pm 0.0007 \). At the Fermi scale \( \Lambda^L_h \sim 0.3 \) GeV we find \( \alpha_s(\Lambda^L_h) = 0.1010 \). Well above 1 TeV up to the Planck scale the renormalization proceeds via haplon-pairs. The results are summarized in Table 2.

For the \( SU(2)_h \) group, we focus here on the lefthanded sector and assume once more \( \Lambda^L_h \simeq 0.3 \) TeV. Using Eq. (3.2) with \( \alpha_s \rightarrow \alpha_h \) and \( \Lambda_{QCD} \rightarrow \Lambda^L_h \), we find e.g. \( \alpha_h(2\text{TeV}) = 0.62 \), and eventually at the Planck energy: \( \alpha_h(M_P) \simeq 0.030 \). These results are collected in the table above, and we see that the three couplings approach each other at the Planck scale. The details of the unification will depend on the particular GUT group and can be affected by Clebsch - Gordan coefficients of \( O(1) \).

If the three couplings come close at the Planck scale, interesting consequences can be derived in connection to the time variation of the fundamental constants, of which hints in the literature appear quite often [8]. An exact unification is not essential - we only need that the three couplings take fixed values at or around \( M_P \). We remark that \( SU(3) \times SU(2)_L \times SU(2)_R \times U(1) \) is a natural breakdown step for GUT groups such as e.g. \( SO(10) \). In our case we do not have spontaneous
symmetry breaking (SSB), the breaking is always meant to be dynamical. The complete QHD group can thus be naturally linked to the GUT framework without generating unconfined vacuum energy, in contrast to the SM.

Let us now assess a possible time change of Newton’s constant $G_N$ (and hence of $M_P$). It is conceivable in the same way as one admits a possible time change of $\alpha_{\text{em}}$ [7, 8]. If the QED, QCD as well as the QHD coupling constants emerge at the Planck epoch, their primeval values should be very close and not be time-dependent. Assuming that the Planck energy changes in time, it implies a time evolution of the gauge couplings at lower energies, say around the confining scale of the weak bosons, $\Lambda_L \sim 300 \text{ GeV}$. By the same token the masses of all the particles (including of course the baryons and the $D$-bosons) will slowly evolve with the cosmic expansion since their binding energies are functions of the coupling strengths. We have exemplified this situation in (4.8) for a general change of particle masses.

Let us estimate the time change of $G_N$ in the specific case of QHD. We use the approximate time variation of $\alpha_{\text{em}}$ suggested in a typical measurement where the current value of the QED coupling is compared with that of a quasar some 12 billion years ago [7]: $\Delta \alpha_{\text{em}}/\alpha_{\text{em}} = (-0.54 \pm 0.12) \times 10^{-5}$.

From the RGE’s and setting $\mu = M_P$ we can obtain the time variation (indicated by a dot) of the Planck scale. Since $b_1 = -14/9$ in this case, we find

$$\frac{\dot{M}_P}{M_P} = -\frac{\dot{\alpha}_{\text{em}}(M_Z)}{\alpha_{\text{em}}(M_Z)} \left[ \ln \frac{M_P}{M_Z} + \frac{9\pi}{7\alpha_{\text{em}}(M_P)} \right].$$

(6.3)

It follows: $\Delta M_P/M_P \simeq 0.0027$ or $\Delta G/G \simeq -0.0054$.

In a similar way we can obtain the time variation of the non-Abelian gauge couplings $\alpha_i$ (i.e. $\alpha_s$ and $\alpha_h$) at an arbitrary scale $\mu$ below $M_P$:

$$\frac{\dot{\alpha}_i(\mu)}{\alpha_i(\mu)} = \frac{\dot{M}_P}{M_P} \left[ -\ln \frac{M_P}{\mu} + \frac{2\pi}{b_N \alpha_i(M_P)} \right]^{-1},$$

(6.4)

with $b_N$ defined in (6.1).

Since $\dot{M}_P/M_P$ is fixed from (6.3), the above equation enables us to compute the cosmic time variation of the QCD and QHD couplings within the last 12 billion years at any desired energy well above $\Lambda_L$, e.g. at $\mu_1 = 2 \text{ TeV}$ (cf. Table II):

$$\frac{\Delta \alpha_s}{\alpha_s} \simeq 1.1 \times 10^{-4}, \quad \frac{\Delta \alpha_h}{\alpha_h} \simeq 6.3 \times 10^{-4}.$$  

(6.5)
Using the definition (3.2) for each confining scale $\Lambda_i$ (viz. $\Lambda_{QCD}, \Lambda_{Lh}$) we can check from the above formulas that their cosmic time evolution [9] is renormalization group invariant and is directly tied to the cosmic evolution of $M_P$ itself:

$$\frac{\dot{\Lambda}_i}{\Lambda_i} = \frac{\dot{\alpha}_i(\mu)}{\alpha_i(\mu)} \frac{2\pi}{b \alpha_i(\mu)} = \frac{\dot{M}_P}{M_P}. \quad (6.6)$$

Numerically, $\Delta \Lambda_i/\Lambda_i \simeq 3 \times 10^{-3}$ for the indicated period.

7 Conclusions

We have described theoretical models for the dark matter (DM) and dark energy (DE) based on the idea that the basic constants of nature are actually slowly varying functions of the cosmic expansion, as suggested by numerous experiments. The variation of the nuclear and particle masses, fundamental scales and particle physics couplings (e.g. the fine structure constant and the strong coupling of QCD) has been connected to the possible cosmic evolution of the basic parameters $\rho_{\Lambda}$ and $G_N$ of Einstein’s General Relativity (GR).

In this framework the vacuum energy appears naturally as a dynamical quantity that varies with the cosmic expansion. If correct, we should find that as soon as the precision of the observations will improve, the so-called “cosmological constant” shall exhibit a mild evolution with the cosmic time and hence with the redshift. The rate of this variation will be connected to the time variation of the particle masses. In some of these models, the evolution of the gravitational coupling is also naturally involved. Thus, we expect a general dynamical feedback between the fundamental “constants” of the gravitational sector ($\rho_{\Lambda}(t), G_N(t), ...$) and the fundamental “constants” of particle physics ($m_i(t), \alpha_i(t), \Lambda_{QCD}(t), ...$), in a way fully compatible with the general covariance of the theory.

As a particular model implementation of these ideas we have considered Quantum Haplohydrodynamics (QHD), which is not based on the conventional SSB mechanism and it does not lead, in contrast to the SM, to a large contribution to the cosmological term. The DE appears here as the tiny (but observable) dynamical change of the vacuum energy density of the expanding background, and hence is a part of the generic response of GR to the cosmic time variation of the masses of all the stable baryons and DM particles in the universe.

These ideas are actually quite general and not tied to a particular model. They can be tested in future astrophysical and laboratory tests in quantum optics, which are expected [9, 10] to detect potential proton mass variations $\lesssim 10^{-14}$. While the SM of particle physics is a successful theory, the severity of the DM and DE problems cannot be permanently hidden under the rug. Dramatically new (and testable) ideas are urgently needed!
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