### Dark matter, Mach's ether and the QCD vacuum

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#### Abstract

Here is proposed the idea of linking the dark matter issue (considered as a major problem of contemporary research in physics) with two other theoretical open questions, one, almost centenary about the existence of an unavoidable ether in general relativity agreeing with the Mach's principle, and one, more recent, about the properties of the quantum vacuum in the quantum field theory of strong interactions, Quantum ChromoDynamics (QCD). According to this idea, on the one hand dark matter and dark energy, that according to the current standard model of cosmology, represent about 95% of the universe content can be considered as forming two distinct components of the Mach's ether and, on the other hand, dark matter, as a perfect fluid emerging from the QCD vacuum, could be modeled as a Bose Einstein condensate.

# 1/Introduction

The so-called ACDM new standard model of cosmology has reached a robustness level comparable to the one of the standard model of particle physics. However these two standard models are in conflict about the issue of the *dark matter*, an outcome of the cosmological standard model that is a contribution to the balance of cosmological densities, about five times the one of the ordinary (baryonic) matter, which does not seem to be explainable in terms of the theories of the particle physics standard model. The purpose of the present paper is to put in debate the hypothesis that this conflict could be resolved by linking dark matter with a concept which plays a crucial role in hadronic and nuclear physics, and belongs to the fundamentals of the standard model of particle physics, namely the *QCD vacuum*. Actually, to support this assumption, it appeared useful to revisit an almost centenary debate about a third concept, the *Mach's ether* of general relativity, which led me formulating my hypothesis in the following way: *Mach's ether, dark matter and QCD vacuum are three modes of existence of a same entity.* The idea is that in a quantum field theory like QCD, what one calls "vacuum" is the ground state, the state of minimal energy, namely the state in the Fock space for which all the occupation numbers are zero. But this vacuum is not the

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nothingness: it is a medium in which there is indeed no quantum of energy-momentum, but in which the quantum fields may fluctuate about a vanishing mean value, a medium which, in a cosmological context, could be assimilated to the Mach's ether. This is the way I intend to argue in favor of the assumption raised in the present paper. In the second section I shall analyze the address given by Einstein at the Leiden University in May 1920 [1] devoted to *The ether and the theory of relativity*, in which he claims that "according to the general theory of relativity space without ether is unthinkable", he explains what are the properties he expects of this medium, and he exposes what, from this time, became the research program of his whole life. In the third section, will be shown how the unknown components of the universe, called dark matter and dark energy, that could have some of the expected properties of the ether, became unavoidable to account for observations in astrophysics and cosmology. In the fourth section, one explains why the *dark matter* – *Mach's ether* can be thought of as emerging out of the vacuum of the quantum field theory of strong nuclear interactions of the standard model, Quantum CromoDynamics (QCD). In the fifth and concluding section, one discusses the theoretical implications that may have this conjecture if it turns out to be correct.

# 2/ The Mach's ether of general relativity

#### 2.1 The ether issue

In his Leiden address, Einstein begins by a rapid historical survey of the idea of ether. He asks the question:

"How does it come about that alongside of the idea of ponderable matter, which is derived by abstraction from everyday life, the physicists set the idea of the existence of another kind of matter, the ether?"

and proposes as an answer:

"The explanation is probably to be sought in those phenomena which have given rise to the theory of action at a distance, and in the properties of light which have led to the undulatory theory."

About the first item of this explanation, he notes that the theory of universal gravitation "evoked a lively sense of discomfort among Newton's contemporaries, because it seemed to be in conflict with the principle springing from the rest of experience, that there can be reciprocal action only through contact, and not through immediate action at a distance.

It is only with reluctance that man's desire for knowledge endures a dualism of this kind. How was unity to be preserved in his comprehension of the forces of nature? Either by trying to look upon contact forces as being themselves distant forces which admittedly are observable only at a very small distance and this was the road which Newton's followers, who were entirely under the spell of his doctrine, mostly preferred to take; or by assuming that the Newtonian action at a distance is only apparently immediate action at a distance, but in truth is conveyed by a *medium permeating space* [underlined by me], whether by movements or by elastic deformation of this medium. Thus the endeavor toward a unified view of the

nature of forces leads to the hypothesis of an ether. This hypothesis, to be sure, did not at first bring with it any advance in the theory of gravitation or in physics generally, so that it became customary to treat Newton's law of force as an axiom not further reducible. But the ether hypothesis was bound always to play some part in physical science, even if at first only a latent part."

#### 2.2 The rejection of the luminiferous ether

And about the second item, and after recalling the "wonderful simplification of theoretical principles" made by H.A. Lorentz, who "succeeded in reducing all electromagnetic happenings to Maxwell's equations for free space" he recalls the debate that accompanied the special theory of relativity and led to the rejection of the idea of a luminiferous ether:

"The ether does not exist at all. The electromagnetic fields are not states of a medium, and are not bound down by any bearer, but they are independent realities which are not reducible to anything else, exactly like the atoms of ponderable matter. This conception suggests itself the more reality as, according to Lorentz's theory, electromagnetic radiation, like ponderable matter, brings impulse and energy with it, and as, according to the special theory of relativity, both matter and radiation are but special forms of distributed energy, ponderable mass losing its isolation and appearing as a special form of energy."

### He notes however that a more careful reflection teaches us

"that the special theory of relativity does not compel us to deny ether. We may assume the existence of an ether, only we must give up ascribing a definite state of motion to it, i.e. we must by abstraction take from it the last mechanical characteristic which Lorentz had still left it. We shall see later that this point of view, the conceivability of which shall at once endeavor to make more intelligible by a somewhat halting comparison, is justified by the results of the general theory of relativity [underlined by me]. (...) [Actually] there is a weighty argument to be adduced in favor of the ether hypothesis. To deny the ether is ultimately to assign that empty space has no physical qualities whatever. The fundamental facts of mechanics do not harmonize with this view. For the mechanical behavior of a corporeal system hovering freely in empty space depends not only on relative positions (distances) and relative velocities, but also on its state of *rotation*, [underlined by me] which physically may be taken as a characteristic not appertaining to the system in itself. In order to be able to look upon the rotation of the system, at least formally, as something real, Newton objectivizes space. Since he classes his absolute space together with real things, for him rotation relative to an absolute space is also something real. Newton might no less well have called his absolute space ``Ether"; what is essential is merely that besides observable objects, another thing, which is not perceptible, must be looked upon as real, to enable acceleration or rotation to be looked upon as something real [underlined by me]."

### 2.3 The Mach's ether

Then comes the reference to the "Mach's way of thinking"

"It is true that Mach tried to avoid having to accept as real something which is not observable by endeavoring to substitute in mechanics a mean acceleration with reference to the totality of the masses in the universe in place of an acceleration with reference to absolute space. But inertial resistance opposed to relative acceleration of distant masses presupposes action at a distance; and as the modern physicist does not believe that he may accept this action at a distance, he comes back once more, if he follows Mach, to *the ether, which has to serve as medium for the effects of inertia* [underlined by me]. But this conception of the ether to which we are led by Mach's way of thinking differs essentially from the ether as conceived by Newton, by Fresnel, and by Lorentz. *Mach's ether not only conditions the behavior of inert masses, but is also conditioned in its state by them* [underlined by me].

"Mach's idea finds its full development in the *ether* of the general theory of relativity. According to this theory the metrical qualities of the continuum of space-time differ in the environment of different points of space-time, and are partly conditioned by the matter existing outside of the territory under consideration. This space-time variability of the reciprocal relations of the standards of space and time, or, perhaps, the recognition of the fact that ``empty space" in its physical relation is neither homogeneous nor isotropic, compelling us to describe its state by ten functions (the gravitation potentials *g*), has, I think, finally disposed of the view that space is physically empty. But therewith the conception of the ether has again acquired an intelligible content, although this content differs widely from that of the ether of the mechanical undulatory theory of light. *The ether of the general theory of relativity is a medium which is itself devoid of all mechanical and kinematical qualities, but helps to determine mechanical (and electromagnetic) events [underlined by me].*"

But Einstein notes that there is a fundamental difference between the gravitational field and the electromagnetic fields from the standpoint of the ether hypothesis:

"There can be no space nor any part of space without gravitational potentials; for these confer upon space its metrical qualities, without which it cannot be imagined at all. The existence of the gravitational field is inseparably bound up with the existence of space [underlined by me]. On the other hand a part of space may very well be imagined without an electromagnetic field; thus in contrast with the gravitational field, the electromagnetic field seems to be only secondarily linked to the ether, the formal nature of the electromagnetic field being as yet in no way determined by that of gravitational ether. From the present state of theory it looks as if the electromagnetic field, as opposed to the gravitational field, rests upon an entirely new formal motif, as though nature might just as well have endowed the gravitational ether with fields of quite another type, for example, with fields of a scalar potential [underlined by me], instead of fields of the electromagnetic type."

#### 2.4 The program of the ether/matter unification

"Since according to our present conceptions the elementary particles of matter are also, in their essence, nothing else than condensations of the electromagnetic field, our present view of the universe presents two realities which are completely separated from each other conceptually, although connected causally, namely, gravitational ether and electromagnetic field, or as they might also be called space and matter."

The lack, in the beginning of the 20<sup>th</sup> century of any theory of the constituents of matter, apart from the electromagnetic interaction, explains why the unification of gravitation and electromagnetism became the main research program of Einstein, the achievement of which would be that

"for the first time the epoch of theoretical physics founded by Faraday and Maxwell would reach a satisfactory conclusion. The contrast between ether and matter would fade away, and, through the general theory of relativity, the whole of physics would become a complete system of thought, like geometry, kinematics, and the theory of gravitation."

However, Einstein expresses the fear he had that quantum physics could raise unsurmountable obstacles to such a program:

"in contemplating the immediate future of theoretical physics we ought not unconditionally to reject the possibility that the facts comprised in the quantum theory may set bounds to the field theory beyond which it cannot pass."

Also, Einstein, who at that time was still believing in a static universe, thought that although "according to the general theory of relativity *space without ether is unthinkable* [underlined by me] (...) the idea of motion may not be applied to ether".

# 3/ Dark matter and cosmological constant issues

The new cosmological standard model, called ACDM, for Lambda, the usual denomination of the cosmological constant (CC), Cold Dark Matter, also called the "Concordance' cosmology, because it puts in concordance the implications of different methods of observation (the supernovae, the CMB and the modelling of baryon acoustic oscillations) led to a solution of the two problems that were plaguing the so-called simple big bang cosmological model. These two problems are, on the one hand, the too high homogeneity on the full sky of the observed cosmic microwave background (CMB) radiation and the observed approximate vanishing of the spatial curvature which implies, if it is not rigorously exact, an unacceptable fine tuning of the components of the energy density content in the early universe, on the other hand. The recent progresses of observational cosmology that began with the COBE satellite, continued through the WMAP experiment and culminates with the Planck results, led to solving the two problems by validating the so-called *inflation scenario* that was imagined in the Seventies but was hitherto considered as purely speculative. These progresses in observational cosmology provide a remarkably robust evidence about two facts that we consider as the two granted major assets of ACDM, namely the existence of a non-vanishing cosmological constant  $\Lambda$ , and the vanishing of *k*, the spatial curvature.

However ACDM raises new problems of which the most important is the fact that about 95% of the matter content of the universe is not understood by means of the standard model of the microscopic structure of matter: apart from the baryonic matter representing 4.9% of this content, and possibly describable in terms of standard model physics, two components seem to challenge all known physical theories: *the dark energy* (68.3% of the content) and the

*dark matter* (26.8% of the content). If  $\Lambda$  is indeed the cosmological constant it induces through its equation of state a pressure and a density equal in magnitude but of opposite signs, and it can explain the dark energy component. However even in this case, there remains with respect to CC the problem of its value which contradicts all the estimates based on various arguments about the vacuum energy density which it is supposed to account for. Also there remains the problem of dark matter to which is devoted the rest of the present paper.

## 3.1 The assets of the ACDM cosmological model

In this section, we shall adopt the definitions, notations and conventions of reference [2] that we briefly recall.

### The Einstein equation

The starting point of cosmology is the Einstein's equation, in which the cosmological constant term is taken to the right side and interpreted as an effective energy momentum tensor  $\Lambda g_{\mu\nu} / 8\pi G_N$  ( $G_N$  is the Newton's constant, c, the light velocity put to 1) proportional to the metric field for the vacuum

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu} \tag{1}$$

A very important remark is in order about this interpretation: originally, the cosmological term is in the left side of the Einstein's equation; taking it in the right side, the one of the matter source, and interpreting it as an energy momentum tensor proportional to the metric field for the vacuum, implies that this "vacuum" is to be interpreted, as we said above, as an ether rather than as empty space. With this interpretation, *dark energy*, the contribution related to the cosmological constant, can be interpreted as a part of the Mach's ether. We shall come back to this point below.

#### The Robertson-Walker metric

The Robertson-Walker metric allows to describe a homogenous and isotropic universe compatible with the Einstein's equation in terms of two cosmological parameters: the spatial curvature index k, an integer equal to -1, 0 or +1 and the overall dimensional expansion (or contraction) radius of the universe R(t), depending only on time; note that due to the homogeneity, the geometry actually does not depend on the radial relative coordinate r which is dimensionless:

$$ds^{2} = dt^{2} - R^{2}(t) \left[ \frac{dr^{2}}{1 - kr^{2}} + r^{2} \left( d\theta^{2} + \sin^{2} \theta d\phi^{2} \right) \right]$$
(2)

One often uses a dimensionless scale factor  $a(t) = R(t) / R_0$  where  $R_0 \equiv R(t_0)$  is the radius at present-day.

In order to derive the Friedman-Lemaître equations of motion, one assumes that the matter content of the universe is a perfect fluid for which the energy momentum tensor is expressed in terms of the isotropic pressure p, the energy density  $\rho$ , the space time metric  $g_{\mu\nu}$  described in equation (2) and of the velocity vector u = (1,0,0,0) for the isotropic fluid in comoving coordinates

$$T_{\mu\nu} = -pg_{\mu\nu} + (p + \rho)u_{\mu}u_{\nu}$$
(3)

Which leads to the Friedman-Lemaître equations in terms of the Hubble parameter H

$$H^{2} \equiv \left(\frac{\dot{R}}{R}\right)^{2} = \frac{8\pi G_{N}\rho}{3} - \frac{k}{R^{2}} + \frac{\Lambda}{3}$$

$$\tag{4}$$

And

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3} \left(\rho + 3p\right) \tag{5}$$

Energy conservation (via  $T_{;\mu}^{\mu\nu} = 0$ ) leads to a third equation:

$$\dot{\rho} = -3H\left(\rho + p\right) \tag{6}$$

Equation (4) can be given a simple 'Minkowskian' interpretation (in ref.[2], it is said "Newtonian"): interpreting  $-k/R^2$  as the total energy, the cosmic evolution can be seen as resulting from the competition between a negative potential energy (gravitational) and the kinetic energy. If k = 0, as such is the case in  $\Lambda$ CDM, then, according to this interpretation, the total energy is equal to zero.

# Equation of state of the components of the universe

In terms of the equation of state parameter  $w = p / \rho$ , eq.(6) can be written as  $\dot{\rho} = -3(1+w)\rho \dot{R}/R$  that can be integrated as a general equation of state

$$\rho \propto R^{-3(1+w)},\tag{7}$$

Which allows determining the time dependence of the expansion radius R(t) according to the component that dominates the evolution at a given epoch. At early times, when *R* is small, the less singular term  $k/R^2$  in equation (4) can be neglected as long as w > -1/3. For  $w \neq -1$  and neglecting the curvature and CC terms, equation (4) can be integrated to yield

$$R(t) \propto t^{2/[3(1+w)]}$$
, (8)

Which allows attributing the standard time dependences of the expansion radius, namely

$$w = 1/3; \rho \propto R^{-4}; R(t) \propto t^{1/2}; H = 1/2t$$
, (9)

For a radiation-dominated universe,

$$w = 0; \, \rho \propto R^{-3}; \, R(t) \propto t^{2/3}; \, H = 2/3t \tag{10}$$

For a matter-dominated universe and

$$w = -1; R(t) \propto e^{\sqrt{\Lambda/3}t} , \qquad (11)$$

For a universe dominated by the cosmological constant.

The three phases of the ACDM cosmology

According to ACDM, the cosmic evolution involves three distinct phases namely

- A primeval inflation phase occurring at an energy of about  $10^{16}$  GeV, during which the Hubble radius is constant (about  $10^3$  Planck lengths) whereas the scale factor grows exponentially by about thirty orders of magnitude, so that we can assume that at the end of inflation, the spatial curvature index *k* is compatible with zero  $\left(\Omega_k \equiv -k/R_0^2 H_0^2 = 0.0008^{+0.0040}_{-0.0039}\right)$ . This primeval inflation phase replaces the big bang singularity that actually was the cause of the two problems plaguing the old standard model of cosmology;
- An expansion phase during which the content of the universe obeys the standard Friedman-Lemaître cosmological equations of motion, with an epoch of dominance of radiation  $(L \propto a^2)$  followed by an epoch of dominance of matter  $(L \propto a^{1.5})$
- A late inflation phase driven by the cosmological constant  $\Lambda$ ,  $(w = -1.019^{+0.075}_{-0.080})$ [3].

Definition of the cosmological density parameters

In eq.(4), the density such that k = 0 when  $\Lambda = 0$  is called the critical density:

$$\rho_c = \frac{3H^2}{8\pi G_N} \,. \tag{12}$$

For a given component of the content of the universe, labelled by index i, one defines the cosmological density parameter

$$\Omega_{\rm i} = \rho_{\rm i} \,/\, \rho_c \,, \tag{13}$$

In terms of which one can rewrite eq.(4) as

$$k / R_0^2 = H_0^2 \left( \Omega_m + \Omega_r + \Omega_\Lambda - 1 \right)$$
(14)

Where  $\Omega_{\Lambda} = \Lambda/3H^2$  represents, according of the interpretation of CC in eq.(1), the cosmological density parameter of the vacuum (or the ether), the subscript 0 indicates presentday values, the subscript m refers to matter and the subscript r refers to relativistic particles.

## 3.2 Observational evidence for dark matter

Actually dark matter is a long standing problem in astrophysics, related to the rotation curves of stars in galaxies and galaxies in clusters which show rotation velocities that are almost independent of the distance at large distances. This feature led to the assumption of an unknown component of matter, *acting only gravitationally in a way comparable with Mach's ether*, compensating the centrifugal (inertial!) force which tends to disperse the components of the rotating system. This component is qualified as dark because it seems invisible. This dark matter does not prevent the propagation of light nor the motion of matter. But it seems to modify the propagation of light through the effect of gravitational lensing. Systematic use of this gravitational lensing effect has allowed producing a full sky map of the dark matter [4]. Dark matter seems to spread all over the full sky, being rather concentrated in the halos of the clusters. Also, it appears that in collisions of clusters, dark matter follows inertially the motions of the colliding clusters.

### The flatness sum rule

The existence of an important dark matter component of the universe is definitely confirmed in ACDM. Such a contribution is called *cold* dark matter because, it appears to be non-relativistic. Dark matter seems to be well constrained by the concordance of the observations of the CMB, of the baryonic acoustic oscillations, and of the super novae (very sensitive to CC). If, on the concordance diagram, one draws the straight line representing the flatness sum rule that translates the vanishing of the spatial curvature it goes remarkably well through the blob of best fit of all data with a dark matter component amounting to more than five times the baryonic matter. It is now a common practice to call the sum of baryonic and dark matter densities the matter density ( $\rho_m = \rho_b + \rho_{DM}$ ).

Putting k to zero in eq.(14), and rewriting it in terms of the densities, and assuming that  $\Lambda$  is indeed a cosmological constant with an equation of state w = -1, leading to the vacuum energy density  $\rho_{\Lambda} = \Lambda / 8\pi G_N$  we write the flatness sum rule as:

$$\rho_{\rm m} + \rho_{\rm r} + \rho_{\rm A} - \rho_{\rm c} = 0, \qquad (15)$$

Which translates the conservation of total energy with CC playing the role of an integration constant.

## 3.3 The cosmological constant issue

The cosmological constant as an integration constant

Actually, this way of interpreting the energy conservation sum rule corresponds to the one adopted by Georges Lemaître in his debate with Einstein about the cosmological constant [5]:

"Newtonian gravitation depends on the mass (through the density  $\rho$ ) and it produces on the planets a definite acceleration proportional to the attractive mass. Mass is but a form of energy and any form of energy has to be counted as mass. But energy essentially contains an arbitrary constant; it can be counted from a zero level which can be chosen arbitrarily. Therefore, if gravitational mass, which has a definite effect, viz., the Newtonian attraction, must be identified with energy, which is defined but for an additive arbitrary constant, it is necessary that the theory should provide some possibility of adjustment when the zero level from which energy is counted is changed arbitrarily. Poisson's equation in its original form does not meet this requirement; but in the modified equation the density comes out as  $\rho - \rho_0$  only. The arbitrary change of  $\rho$ , arising from the change of zero level, can then be compensated by an equivalent change in the unknown  $\rho_0$  or in lambda. In this way, no modification results in the gravitational attraction."

## The holographic equipartition principle of T. Padmanabhan

Now it turns out that this interpretation of CC as an integration constant has been put on a very solid theoretical ground by T. Padmanabhan [6] in works he has performed for more than fifteen years and published in scores of papers. One of the leitmotiv of his approach is that [7]

"The key new ingredient arises from the fact that properties of the vacuum state depends on the scale at which it is probed and it is not appropriate to ask questions without specifying this scale. If the spacetime has a cosmological horizon which blocks information, the natural scale is provided by the size of the horizon,  $L_{\Lambda}$  and we should use observables defined within the accessible region."

Which implies that, once the presence of horizons is taken into account, *vacuum fluctuations* of energy density can lead to the observed cosmological constant [8]. The very simple argument used for this statement deserves to be reproduced here: in the two regions 1 and 2, separated by a horizon and described by a Hamiltonian  $H = H_1 + H_2$  the dispersions in the energies  $(\Delta E_1)^2 = \langle 0 | (H_1 - E_1)^2 | 0 \rangle$  and  $(\Delta E_2)^2 = \langle 0 | (H_2 - E_2)^2 | 0 \rangle$  are equal because the expectation values of (H - E) and  $(H - E)^2$  vanish in any energy eigenstate; but since the two regions only share the bounding surface, the two dispersions have to be proportional to the area of the surface, and thus to scale as the square of the radius of the horizon. So the fluctuation of the

density  $\Delta \rho_{\text{vac}} \propto \Delta E / L_H^3$  scales as the inverse surface area,  $\Delta \rho_{\text{vac}} \propto (L_P L_H)^{-2} \propto H^2 / G_N$  which is compatible with the observed value of CC.

However, the author notes that this argument, although suggestive "leaves significant scope for improvement – not in the least because one is dealing with formally divergent quantities." That is why he uses an alternative way of presenting the argument. The Hamiltonian, limited to the region bounded by a cosmological horizon, exhibits energy fluctuations  $\Delta E$  because the vacuum state is not an eigenstate of this operator. Now these fluctuations in the energy density  $\Delta \rho \propto (\Delta E)/L_H^3$  depend on both the ultraviolet cutoff and on  $L_H$ . Now, when used as the source of gravity, this  $\Delta \rho$  should lead, in a sort of a "bootstrap", to a spacetime with the horizon size  $L_H$  playing the role of an infrared cutoff in the computation of  $\Delta \rho$ , allowing to get rid of the contribution of the mean density, and leading to the  $\Delta \rho \propto (L_P L_H)^{-2}$  scaling law. On the whole, if this argument holds true it means that any energy density, with this scaling law, that can be interpreted in terms of vacuum energy density, has to be attributed to the fluctuations of the density and not to its mean value.

In a more recent work which synthesizes his whole work on the subject, and which gives a full justification of the argument discussed just above, T. Padmanabhan proposes a reformulation, ab initio, of *general relativity from a thermodynamic perspective* [9] from which he derives a series of very important results related to the concept of *holography* interpreted as "the deep inter-relationship between gravitational dynamics and horizon thermodynamics". From this work, I retain<sup>b</sup> the fact that "when the equations of motion hold, the total energy of the gravity plus matter system in a bulk region is equal to the boundary heat content." Which means that the total energy density (including the vacuum energy density) scales as the boundary heat content, that is as the inverse of the area of the bounding surface. In my opinion, this feature is enough to solve the CC problem [10] because it means that the gravity induced by the bulk vacuum energy does not come from its mean density but only from the fluctuations: if such is the case, we understand

- 1. Why the cosmological constant has a value that is as small as the observed one, and
- 2. Why the vacuum energy density depends on the cosmic time since it scales as the inverse of the area of the Hubble horizon, which of course depends on time: how Weinberg says in [10] "We want to explain why the effective cosmological constant is

<sup>&</sup>lt;sup>b</sup> For the moment, because I will come back to it in a work in preparation.

small now, *not* why it was always small." In other words, the observed small value of CC is not the result of an unacceptable fine-tuning, but simply the present-day value of a *running effective cosmological "constant"*, the running being driven by the Friedman-Lemaître equations, in the same way as the running of the strong fine structure "constant"  $\alpha_s(Q^2)$  in driven by the renormalization group equations of QCD. In fact, at the end of the primeval inflation phase the effective cosmological constant is large and positive, and it has to be compensated by a negative contribution induced by another component of the vacuum energy, decreasing in absolute value along the cosmic evolution driven by the Friedman equations, in order to reach its small present-day value.

3. Moreover, we understand why the "vacuum" which has gravitational or cosmological effects, namely that can be considered as a part of an ether, is necessarily a *quantum vacuum, because it is in the framework of quantum fields theory that the fields in the ground state fluctuate.* Actually, in a 2008 article [11] Padmanabhan noted that "any observed value of the cosmological constant has to be necessarily a quantum phenomenon arising as a relic of microscopic spacetime fluctuations;"

# 4/ Quantum vacuum as Mach's ether

In his work, Padmanabhan did not address the dark matter issue, he left it to particle physics, and what I want to do now is to explore the possibility of extending his approach to the dark matter issue. I am encouraged to do it because if it is the quantum nature of spacetime geometry fluctuations that leads to a small cosmological constant at the origin of dark energy, then, a fortiori one can expect that the fluctuations of the quantum fields of the particle physics standard model have all the reasons to contribute also to the vacuum energy. I thus assume that the vacuum has two components<sup>c</sup>, one coming from the quantum fluctuations of the spacetime geometry (or of quantum gravity) leading to dark energy, and one coming from the fluctuations of the quantum fields of the standard model, in particular those of QCD, possibly leading to dark matter.

<sup>&</sup>lt;sup>c</sup> Such an assumption is not common in the literature, but since the vacuum is not the nothingness, but is rather a medium, which has not to be unique, I think it is legitimate: "From which one can see that there is as much difference between nothingness and empty space, as between empty space and matter; and that empty space holds the middle between matter and nothingness. That is why the maxim of Aristoteles you are talking about, 'that the non-beings are not differing' applies only to the nothingness" Blaise Pascal, answer to rev. father Noël, Paris, on October 29<sup>th</sup> 1647 (oeuvres completes, p. 384)

#### 4.1 Confinement in QCD

I first concentrate on QCD because it is an unbroken non abelian renormalisable gauge theory, which is asymptotically free at short distance, and singular at large distance. This behavior at large distance is believed to be the key to the understanding of color confinement, and also for the possibility of cosmological implications. Quantum radiative corrections involve quantum fluctuations represented by Feynman diagrams involving quark and gluon loops, contributing to the polarization of the vacuum. Now, contrary to quantum electrodynamics (QED) for which the gauge field, the photon, is neutral, the gluon is color charged and gluon loops produce an anti-screening effect which overpass the screening effect induced by quark loops. On the whole, the fluctuations of the QCD fields make of the QCD vacuum a medium that repels the chromo-electric field, what T. D. Lee calls a "perfect color diaelectric" [12] in the same way as a QED superconductor, a "perfect diamagnetic", repels the magnetic field. It would cost an infinite amount of energy to put an isolated color charge (a quark or a gluon) inside such a medium. However a color singlet hadron (a quark-antiquark meson, a three quark baryon or a gluonium) can create in the medium a cavity in which the mass energy of the hadron would equilibrate the pressure of the external medium. Let us note that this pressure exerted by the QCD vacuum has a sign opposite to the one equivalent to the dark energy: the spacetime in which live quarks and gluons is an anti-de Sitter (AdS) rather than a de Sitter spacetime, corresponding to a negative effective cosmological constant (see item 2 in paragraph 3.3). In the seventies the hadronic string heuristic model picturing hadrons as open strings the end points of which are confined quarks or antiquarks provided a hint toward a sub-hadronic confining theory. When QCD was discovered, this picture became more ambitious following the work of G. 't Hooft [13] who conjectured that at the limit when the number of colors  $N_c$  goes to infinity with fixed  $g^2 N_c$  ( $g^2$  being the squared of the QCD coupling constant), QCD confines quarks and antiquarks as the end points of color singlet hadronic strings: if one tries to separate the quark and the antiquark by rotating a meson at high speed, they will remain attached by a color flux tube acting as a string, the tension of which is a universal constant of the hadronic world, the amount of energy per unit of length necessary for compensating the centrifugal force<sup>d</sup>. A string tension of about 1 GeV<sup>2</sup> is favored by the phenomenology of soft hadronic reactions and by lattice gauge simulations.

<sup>&</sup>lt;sup>d</sup> Is that not similar to the effect of dark matter compensating the centrifugal force in the rotation of stars in galaxies and galaxies in clusters?!

### 4.2 Conformal anomaly

On a more quantitative ground, the properties of the QCD vacuum have been thoroughly studied. The QCD Lagrangian, without quarks or with massless quarks (in the so-called chiral limit), is scale invariant since the coupling constant is dimensionless. But through quantization, this symmetry is broken, one says that it is dynamically broken: this phenomenon is called *conformal (or trace) anomaly*, because even if the trace of the energy-momentum tensor vanishes classically in QCD at the chiral limit, it becomes different from zero through quantization of the theory.

The dynamical breaking of scale invariance is apparent in the fact that "the renormalization has replaced a one-parameter family of unrenormalized theories, characterized by their values of the dimensionless unrenormalized gauge coupling,  $g_0$ , by a one-parameter family of renormalized theories, characterized by their value of the dimension-one [renormalization group invariant] scale mass  $\mathcal{M}(g,\mu)$ "[14]. This scale mass, independent of the energy  $\mu$  at which renormalization is performed, appears as a non-vanishing trace of the renormalized energy-momentum tensor; it is completely physical; it is related to the hadron masses or to the above mentioned string tension; but, and this is the main point of our proposal, it does have cosmological implications.

# 4.3 QCD in the cosmological context

### Conformally flat cosmologies

All cosmologies which are homogeneous and isotropic are said to be *conformally flat*, which means that the metric is Minkowskian up to a multiplicative factor related to its determinant |g| which is the part of the metric tensor that is relevant in cosmology

$$ds^{2} = f(x) \left( ds \right)_{\text{Minkowski}}^{2}; \left| g \right| = f^{4} \left| g \right|_{\text{Minkowski}}.$$
 (16)

Now, since the determinant is just a function depending of the spacetime point, it can be replaced by a scalar field, called the *dilaton*, and cosmology can be studied in a Minkowski spacetime, i.e. in a flat spacetime. This possibility has been used by Gürsey [15] who has proposed a *reformulation of general relativity in accordance with Mach's principle* (again the Mach's way of thinking!): according to this reformulation, the metric tensor is factorized into a scalar density and a tensor density with unit determinant. The scalar density describes the cosmological structure whereas the tensor density refers to gravitational phenomena. On the other hand, the possibility offered by conformally flat cosmologies has been used by R. Brout, F. Englert and E. Gunzig (BEG) to propose a model in which "quantum creation of massy

particles can occur in the cosmological context without cost of energy" [16], a model that turned out to be quite compatible with the primeval inflation phase of the ACDM model. In the BEG model, the field associated with the determinant of the metric gives an unconventional negative energy density, such that, "matter –carrying positive energy– can be created, yet the total Minkowskian energy kept fixed and equal to that of empty space." By the way, they show that despite this unconventional negative density, their model is perfectly compatible with general relativity, since through a Weyl transformation (a rescaling of the metric and the matter fields) that is analogous to the transformation to a unitary gauge in the BEH (Brout Englert Higgs) mechanism in electroweak symmetry breaking, the ghost that appears in the Minkowski action is cancelled in the generally covariant action.

### The dilaton as the Nambu-Goldstone boson of spontaneous scale invariance breaking

In QCD, neglecting the quark contribution, this trace is related to the *renormalized* gluon condensate, or gluon pairing amplitude:

$$\left\langle T^{\mu}_{\mu}\right\rangle_{0} = \left\langle \frac{\beta(g)}{2g} \left( F^{i}_{\lambda\sigma} F^{i\lambda\sigma} \right)^{r} \right\rangle_{O}$$
(17)

Which is proportional to the fourth power of the scale mass introduced above  $\mathcal{M}(g,\mu)$ .

What is particularly important for us is that in case of a spontaneous breaking of scale invariance (SBSI), leading to a non-vanishing trace for the energy-momentum tensor of the matter field, the determinant of the induced metric that describes the cosmological structure, is nothing but the *Nambu-Goldstone boson*  $\phi$  *implied by SBSI*, the equation of motion of which is

$$\phi \Box \phi = \left( L_P \phi \right)^4 t \tag{18}$$

where *t* is the vacuum expectation value of the trace of the energy-momentum tensor eq.(17). *QCD in an anti de Sitter background: Bose-Einstein condensation of the gluons* 

After huge developments in research about string theory applied to quantum gravity, the interest to string theory came back to the research of the string theories equivalent to QCD, and that is how emerged the concept of gauge/gravity duality [17] through the so-called ADS/CFT (Anti de Sitter/Conformal Field Theory) correspondence of J.M. Maldacena [18]. This correspondence now appears as the most reliable approach to QCD in the non-perturbative regime [19], and it provides us with a hint about the cosmological implications of QCD at the color confinement scale. In ref. [20], Maldacena has explained some of the qualitative features of QCD in an anti de Sitter background which we adapt for our purpose of explaining how the QCD vacuum repels color: any massless gluon moving towards the boundary hits this boundary and is sent back just like by a mirror in a finite time. The Hubble horizon at the confinement

scale which has a radius of about  $L_H \approx 10^{-6} s$ , corresponding to a temperature (or an acceleration in units where  $\hbar = k_B = c = 1$ ) of about  $10^{-9} eV$ , precisely acts as such a mirror, blocking color information (by sending back the gluon) but not the full four-momentum carried by the initial gluon. The missing four-momentum, equal to  $1/2k_BT$ , is carried by a quantum of the dilaton field, which we interpret as the Bose-Einstein gluon condensate: a spherical wave function with a wave length equal to the Hubble radius.

# Baryonic to dark matter ratio and the quark-gluon parton model

To conclude this section, I want to present an argument in favor of the assimilation of dark matter with the QCD vacuum. In deep inelastic lepton-nucleon experiments, one probes, with a resolution of the order of the color confinement scale (about 1 to 2  $\text{Gev}^2$ ), the quark-parton structure of the nucleon in a large momentum frame (light cone) for the nucleon. The results of these experiments show that the three valence quarks carry only a small fraction (about one quarter to one fifth) of the total momentum of the nucleon, the rest being carried by the quark anti-quark pairs of the sea and by the gluons, i.e. by the QCD vacuum, which is quite compatible with the baryonic to dark matter ratio.

# 5/ Discussion and conclusion

We thus see that SBSI in QCD may lead, in the cosmological context, to a possible interpretation of dark matter as a scalar gravitation field modeling a Mach's ether component, or as emerging, through a Bose-Einstein condensation mechanism, out of the quantum vacuum. Before discussing possible theoretical implications of this scheme, let us see whether there exists in the current literature, some works which comfort or invalidate it.

Let us note, in this respect the work of ref. [21], in which it is shown that with a scalar graviton, called a "systolon" one can reproduce the rotation curves of objects in the halos of galaxies or clusters, that are usually attributed to dark matter, which rather comfort the interpretation of dark matter as a scalar Mach's ether.

Let us also note that Bose Einstein condensation has been considered in Hydrodynamic simulations or phenomenological [22] interpretations of the heavy ion collision experiments which suggest that the quark-gluon plasma, the state of matter from which is supposed to emerge baryonic matter and, if our conjecture is correct, dark matter, behaves as a low viscosity fluid due to the formation of gluon and quark condensates.

Also, it turns out that several attempts have been made to model dark matter as a Bose Einstein condensate of particles belonging to extensions of the standard model, of which the most favored is the *axion*, the Nambu-Goldstone scalar associated with the Peccei-Quinn solution to the strong CP problem [23]. In ref. [24], it is interesting to note that in order for the proposed dark matter model to work, QCD has to play a role by inducing at the color confinement scale a potential in which the axion condenses and acquires a time (or temperature) dependent mass. In this model, the properties (mass and coupling to  $2 \gamma$ ) have to be fine-tuned in order to explain why such a particle has not been discovered yet. However one may ask the question whether it is the hypothetical axion or QCD that is at the origin of dark matter.

On the other hand, in ref. [25], the authors propose an axion-like BEC model for dark matter of which they show, by means of high precision simulations, that it agrees with the conventional cold dark matter model in the description of large scale structures in the distribution of galaxies and works much better than it in the description of small scale structures thanks to interferences between the "dark quantum waves" and some waves arising in hydro-dynamical models (Jeans instability effect). The proposed model depends on just one free parameter, the axion mass which turns out to be about 8.1 10<sup>-23</sup> eV. Let me note that whereas such a small "mass" is very difficult to accept for a genuine elementary particle, it turns out to be of the same order of magnitude as the temperature of the present-day Hubble horizon, and thus more in favor of an interpretation in terms of a dilaton, a quasi-particle with a time (or temperature) dependent mass representing the collective gravitational effect of the Bose-Einstein gluon condensate.

If one agrees with the idea that dark matter emergent from the QCD vacuum contributes, together with dark energy, to the Mach's ether, one can ask the question whether another component of the Mach's ether emerges from the electroweak quantum vacuum. I think that this is possible but that it is difficult to distinguish such a component from the standard radiation contribution of which we know that it is very small in the present-day balance of the cosmological density parameters (about  $2.10^{-5}$ ). So, if our conjecture is correct, one can say that the main discovery of  $\Lambda$ CDM is that the Mach's ether (dark matter + dark energy) not only exists, which hitherto had never been clearly established, but also represents 95% of the content of the universe. What a beautiful confirmation of the Einstein's statement that "according to the general theory of relativity, space without ether is unthinkable"!

Clearly, much more work is needed to make the heuristic and qualitative arguments presented here more quantitative and better theoretically founded. The necessary work that would be needed to put on experimental or observational tests the proposed idea, would have to be largely interdisciplinary, with collaborations of experts in particle physics, astrophysics, hydrodynamics, computer simulations, and ultra-low temperature physics. Also, if the attempts to discover a clear evidence in favor of other ways of addressing the dark matter issue, such as neutralinos, MOND, or warm dark matter with sterile neutrinos, continue to fail, and if our conjecture gets a better ground, then one would have to have a thorough strategic reflection about large scale experimental long term programs.

In conclusion, let me say that due to the impossibility of proposing a clear-cut experimental or observational test allowing to definitely rule it out, this conjecture only makes sense as an element of a *cosmogonic narrative*. True, a narrative has not the same value as a predictive quantitative theory, but it may have an important philosophical range because it touches on *ontology*. For instance, one can say that the Brout Englert Higgs (BEH) mechanism is more than a clever ad hoc trick to solve the purely epistemic problem of making possible the electroweak unification, because, in the framework of a cosmogonic narrative, it is associated with a cosmic event in which particles that hitherto were massless, became massive. In the same way, one can say that our way of interpreting color confinement in QCD, not simply as an epistemic solution to the problems of non-perturbative QCD, but as the emergence occurring at a precise moment of the cosmic evolution of both the baryonic matter and the dark matter, has an important epistemological range because it relates this emergence with the longstanding issue of the ether of general relativity.

Now with respect to alternative approaches, ours has a methodological advantage, namely that it avoids any fine-tuning [26] to add to the initial conditions that, according to the definition of a cosmogonic theory given by Georges Lemaître [27], are necessary in any cosmogonic narrative.

"The object of a cosmogonic theory is to look for ideally simple initial conditions from which can have resulted, through the interplay of known physical forces, the current world in its full complexity."

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