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Dark Matter Explained in Terms of a Gluonic Bose–Einstein Condensate in an Anti-de Sitter Geometry

G. Cohen-Tannoudji*

*Laboratoire de Recherche sur les Sciences de la Matière CEA, Université de Paris-Saclay,
Saint-Aubin, 91190 France*

**e-mail: Gilles.cohentannoudji@gmail.com*

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Abstract—The Λ CDM standard model of cosmology involves two dark components of the universe, dark energy, and dark matter. Whereas dark energy is usually associated with the (positive) cosmological constant Λ associated with a de Sitter geometry, we propose to explain dark matter as a pure QCD effect, namely a gluonic Bose–Einstein condensate with the status of a Cosmic Gluonic Background (CGB). This effect is due to the trace anomaly viewed as an effective negative cosmological constant determining an Anti de Sitter geometry and accompanying baryonic matter at the hadronization transition from the quark gluon plasma phase to the colorless hadronic phase. Our approach also allows to assume a ratio Dark/Visible equal to 11/2.

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INTRODUCTION

The standard model of cosmology (CSM) known as the cosmology of concordance or Λ CDM (for Λ —the cosmological constant—Cold Dark Matter) involves together with the visible matter, also called baryonic matter, a *dark universe*, consisting of two components, the dark energy, and the dark matter. The common belief is that whether dark energy can be found in the contribution of the cosmological constant, the explanation of dark matter is considered as a major challenge, a possible taking of which is the object of the present contribution. We propose to explain dark matter, by linking its content, in the early universe, with the one of the standard model (SM) of particle physics.

If one assumes that the fundamental theoretical framework embedding both particle physics and cosmology, is the quantum theory of fields that implies the PCT symmetry (product of charge conjugation C , space parity P and time reversal T), one is obliged to assume that at least, time reversal and charge conjugation are spontaneously broken in the early universe, since there is no viable causal universe (i.e. without an arrow of time) and empty of any astronomical object (star, galaxy, or galaxy cluster made of anti-matter) without such a symmetry breaking. Now, since the energy of the ground state in quantum field theory is defined up to an arbitrary additive constant, one can always set this constant in such a way that, up to a very high energy, there is no negative energy or frequency in the observable universe. This does not mean that anti-matter does not exist, it exists, but only virtually, in the dark universe, that can be identified as the ground state of the quantum field theory underlying the SM

and the CSM. Now, according to the theory of spontaneous symmetry breaking, the components of this ground state must have well defined symmetry properties under the exchange of matter and anti-matter. So, the explanation that we propose mainly relies on relating the two components of the dark universe, namely dark energy, and dark matter, not only with the cosmological constant Λ , but also with a virtual anti-matter. In the rest of the present paper, we firstly make more precise the well accepted belief that dark energy is identified with Λ by noting that it cannot be limited to the contribution of the cosmological constant but that it contains a contribution of the anti-baryons that is necessarily virtually present, as a dark energy component in the observed baryonic matter. Then, reviewing all the possibilities offered by the standard model (SM) of particle physics, and apart from the photon, the u - d -quarks and the electron which form the baryonic matter, we are led [1, 2] to conjecture that dark energy is carried by the SM lightest neutral stable fermions, namely neutrinos and antineutrinos, and dark matter is carried by the only SM stable bosons, the gluons. Finally, we shall briefly discuss some possible implications of our work in the context of the *gauge-gravity duality paradigm* [Conceptual aspects of gauge-gravity duality].

A BRIEF HISTORICAL SURVEY

We begin this presentation by a short historical reminder about the first two cosmological models which were imagined by Einstein and de Sitter to satisfy the principle of the relativity of inertia that is considered as foundational in the general theory of relativity. These two models relayed on the gedanken exper-

iment consisting in removing the whole of the matter observed in the universe: according to the Einstein's model (called by de Sitter "system A"), to the observed matter one must add the contribution of a positive cosmological constant (CC) leading to a negative pressure (called a "cosmic repulsion" by Lemaître) able to prevent the Einstein's static universe to collapse due to its own gravitation; and according to the de Sitter's model (that he called "system B") the universe to which the observed matter has been removed is empty apart from the contribution of a positive CC. We intend to show that Λ CDM the new standard model of cosmology somehow reconciles these two models.

MATCHING THE STANDARD MODELS OF PARTICLE PHYSICS AND COSMOLOGY

What we call *scientific cosmogony* [time and science] in our contribution to the book *Time and Science*, is the scientific theory of the beginning of the universe that could result from the matching of the two standard models of particle physics (the famous standard model SM) and the new standard model of cosmology (CSM) known as the *Concordance cosmology* or Λ CDM.

The Assets of the Standard Model of Cosmology

From the metric

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

involving the "radius of the universe" $R(t)$ and the spatial curvature index k , solution of the Einstein equation that relates the tensor and scalar curvatures of spacetime in its left hand side to the sum of the stress energy tensor of matter $T_{\mu\nu}$ and of the cosmological term in its right hand side,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu} \quad (2)$$

one derives the Friedman–Lemaître equations of the dynamics of a perfect isotropic fluid involving a density ρ and a pressure P , where H is the Hubble parameter and a the scale parameter $a(t) = \frac{R(t)}{R(0)}$, the space

metric $g_{\mu\nu}$ and the velocity vector $u = (1, 0, 0, 0)$ in comoving coordinates

$$T_{\mu\nu} = -P g_{\mu\nu} + (P + \rho) u_\mu u_\nu, \quad (3)$$

$$H^2 \equiv \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G_N \rho}{3} - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}, \quad (4)$$

$$\ddot{a}/a = \frac{\Lambda c^2}{3} - \frac{4\pi G_N}{3} \left[\rho + 3 \frac{P}{c^2} \right], \quad (5)$$

$$\dot{\rho} + 3H \left[\rho + \frac{P}{c^2} \right] = 0. \quad (6)$$

Following the terminology introduced by de Sitter in 1917 [3] we call *world-matter*, a form of matter with no interaction except for gravitation, i.e. a form of matter the energy-tensor of which reduces to a pure pressure multiplying the metric tensor of spacetime; when this pressure is negative, the world-matter (WM) is said a *normal de Sitter WM*, because it is the WM induced by a positive cosmological constant, and when the pressure is positive, it is said an *anti de Sitter WM* (negative CC). In terms of these two components of the dark universe, the assets of Λ CDM can be summarized in the following way:

- The comeback of the cosmological constant (CC);
- Compatibility with the *primordial inflation scenario* [reference];
- Agreement with the Hot Big Bang Model (HBBM) in the expansion stage;
- Discovery of the two-component world-matter.

Figure 1 in which the Hubble radius L is plotted versus the scale parameter a in logarithmic scales shows the three stages of Λ CDM: a primordial inflation stage (beyond the standard models) from point α to point β ; an expansion stage from point β to point ψ which is the stage when the matching of the two standard models can occur and the late inflation stage from point ψ to point ω .

The Visible Matter Set to Zero

Of course, the content of the universe in the expansion stage is not directly accessible to observation, but one can figure out what it is by means of the methodology of effective theories according to which if in a theory a given quantity or parameter is very small (or very large) it may be useful to let it be equal to zero (or infinity) in order to make more reliable the theory. In this respect, if the visible matter that seems to amount to less than 5% of the full content of the universe, is set to zero, one can consider the expansion $\beta \rightarrow \psi$ as a succession of *effective universes* that are dark (since the visible matter has been set to zero) and that are indexed by a comoving or *induced cosmological "constant"* $\Lambda(a)$ which varies according to the scale factor a and which retains all their properties. The relation $L(a)$ must in fact ensure that each of these effective universes can be assimilated at each value of a , to the real universe.

For each of these effective universes, the vanishing of the spatial curvature is expressed by the flatness sum-rule:

$$\rho_{\text{eff}}(a) = \rho_M(a) + \rho_\Lambda(a) = \rho_c(a) \quad (7)$$

equating its total energy density to the so-called critical density $\rho_c(a)$, which reduces to the sum of dark matter and dark energy densities in the absence of observable matter (which is meant by the superscript 0 in the subsequent equations):

$$\rho_c^0(a) = \rho_{\text{DM}}^0(a) + \rho_{\text{DE}}^0(a). \quad (8)$$

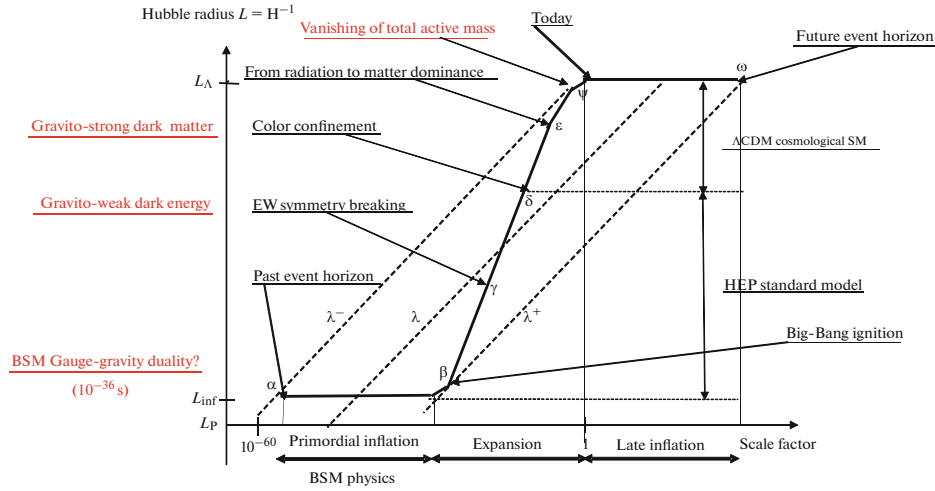


Fig. 1. The Hubble radius L as a function of the scale parameter a in log scales. The Greek letters along the thick line denote important events that occurred in the history of the universe. The dotted lines λ^+ and λ^- denote the limits of the visible universe, and the one, denoted λ represents the wavelength of a typical fluctuation that exits the horizon between α and β , re-enters it between β and ψ , and re-exits it between ψ and ω .

If one wants to relate this critical density with the effective cosmological constant, one must not forget that the effective dark universe also virtually contains anti-matter. Keeping in mind the well accepted belief that dark energy is identified with the contribution of the cosmological constant, we can also relate to it $\rho_{DM}^0(a)$ by making explicit the contributions of matter and anti-matter in Eqs. (7) and (8) to the density of the effective dark universe. Now, since in the dark universe the visible matter is set to zero, matter is reduced to dark matter which is necessarily related to anti-matter. Actually, let us first equate the density of dark matter, that we interpret as the density of a *missing mass* with the opposite of the density that we interpret as the density of a missing anti-matter, $\rho_{DM}^0 = -\rho_M^0 = P_M^0$ which means that, since the pressure of the missing anti-matter is positive, dark matter is necessarily an *anti-de Sitter world-matter*, whereas dark energy associated with a positive CC is a *normal de Sitter world-matter*. Then, since $\rho_M^0 + \rho_M^0 = 0$, we can express the vanishing of the active mass in the effective dark universe: with $\rho_M^0 = -\rho_M^0 = P_M^0 = -P_M^0$ and $\rho_{DE}^0 = \rho_\Lambda^0 = \rho_M^0 + P_M^0 = 2\rho_M^0$ one obtains:

$$\rho_c^0 = \rho_{DM}^0 + \rho_{DE}^0 = \frac{3}{2}\rho_\Lambda^0. \quad (9)$$

This relation appears well satisfied in Fig. 2.

Re-Introduction of the Visible Matter

As a preliminary issue related to the re-introduction of the visible matter, one must answer the question: what is the relevant cosmological constant that enters in the statement that “dark energy is identified

with the contribution of the cosmological constant.” The fact that, in Fig. 2, the point possibly representing the actual content of the universe cannot coincide with the intersection point of the flatness and zero active mass straight lines means that the cosmological constant that occurs in the definition of the critical density is rather the one which appears in what we call ρ_Λ^0 , that could be its value at point ω of Fig. 2, and not the value that can be associated with the observation of the present day universe. More generally, the issue of the compatibility of the standard models of particle physics and of cosmology cannot be addressed without identifying what is the content of the dark universe in terms of the elementary constituents of the standard model of particle physics. That is what we intend to do in the present section.

Energy “at Rest” in the Anti-de Sitter Geometry

Since the dark universe can be interpreted as the quantum vacuum (ground state) of the system of quantum fields of the standard model, it is possible to relate the quantum statistics of a particle of the SM to which component of the dark universe its energy contributes. Since, as stated above, if the vacuum energy is set to zero, only quantum fluctuations represented, at the lowest quantum approximation (semi-classical approximation) by Feynman diagrams containing one closed loop (namely creation of particle-antiparticle pair, immediately followed by its annihilation), we have shown in [2] that a free particle moving in an AdS spacetime gets an “at rest” energy *equal to

$$E_{AdS^{1/2}}^{\text{rest}} = \left[m^2 c^4 + \hbar^2 c^2 (s - 1/2)^2 \right]^{1/2} + \frac{3}{2} \hbar \sqrt{\frac{\Lambda_{AdS}}{3}} c. \quad (10)$$

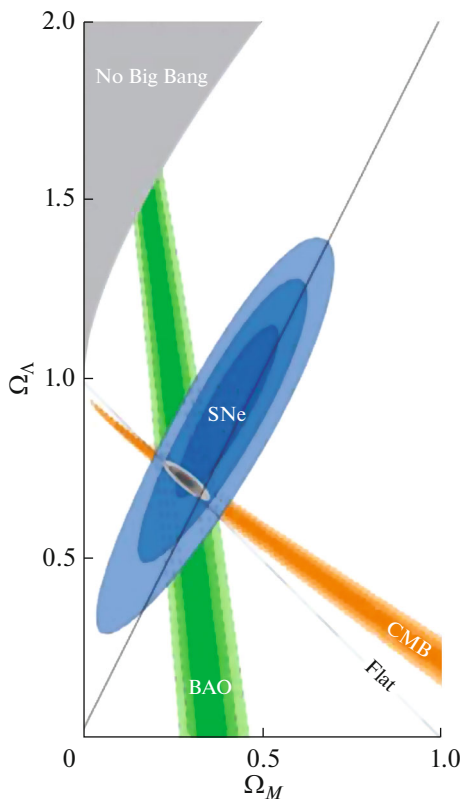


Fig. 2. (From M. Kowalski et al., Improved cosmological constraints from new, old, and combined super-nova data sets, *Astrophys. J.* 686, 749 (2008) doi:10.1086/589937.68.3, 95.4 and 99.7%) In this figure, representing the assets of the “concordance cosmology” (the other name of Λ CDM),

the cosmological parameter $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c}$ of the cosmological constant Λ , and the one of matter (observed + dark) $\Omega_M = \frac{\rho_M}{\rho_c}$, obtained from CMB, BAO and the SN, where

the equation of state parameter $w \equiv \frac{P}{\rho}$ is set to -1 . The straight line $\Omega_\Lambda + \Omega_M = 1$ which is marked “flat” corresponding to a spatially flat Universe, and the straight line $\Omega_\Lambda = 2\Omega_m$ corresponding to the vanishing of the total active mass intersect at the point $\Omega_M^0 = 1/3$; $\Omega_\Lambda^0 = 2/3$ corresponding to a dark (i.e. without visible matter) universe, provided that $\rho_c^0 = \frac{3}{2}\rho_\Lambda^0$.

An argument developed in [4] see Fig. 3, leads to the assignment that the energies of SM bosons contribute to the dark matter, and only to it, whereas the

energies of SM fermions that contribute to the visible energy also contribute to the dark energy. We can thus proceed to the re-introduction of the visible matter. The matter-energy density of the visible matter is contributed to equal amounts by the fermions through the density and anti-fermions through the pressure P : $\Omega_{\text{vis}} = \Omega_F + \Omega_{\bar{F}}$ where $\Omega_F = \rho_F/\rho_c = \Omega_{\bar{F}} = P_{\bar{F}}/\rho_c$. Since, by assumption, anti-matter is only present in the dark universe, only half of Ω_{vis} is “visible”, and the other half $\Omega_{\bar{F}} = P_{\bar{F}}/\rho_c$ is part of the dark energy, so

$$\begin{aligned} \rho_{\text{DE}} &= \rho_{\text{DE}}^0 + 1/2\rho_{\text{vis}} = \rho_{\text{DE}}^0 + P_{\bar{F}}, \\ \rho_M &= \rho_M^0 - 1/2\rho_{\text{vis}} = \rho_M^0 - P_{\bar{F}}. \end{aligned} \quad (11)$$

Moreover, since $\rho_{\text{DM}} = \rho_M - \rho_{\text{vis}}$, and since $\rho_F = -3P_F$

$$\begin{aligned} \rho_{\text{DM}} &= \rho_M^0 - 3P_{\bar{F}} \\ &= \rho_M^0 + \rho_{\bar{F}} = -(\rho_{\bar{M}} - \rho_{\bar{F}}) = \rho_{\bar{B}}. \end{aligned} \quad (12)$$

Which means that as expected, dark matter is the bosonic part of anti-matter, namely is, in the QCD context, the gluonic part: Quod Erat Demonstrandum!

Comparison with Planck 2018 Data

In Table 1 is shown the comparison of the yields of our model with the Planck 2018 data; the agreement is better than 1%.

GAUGE GRAVITY DUALITY

Gauge-Gravity Duality and the Reconciliation of the Historical Einstein' and de Sitter' Models

About gauge-gravity duality, we have been inspired by the seminal paper of Adler [5] according to which, following an idea of Sakharov [6], the Einstein's gravity can be interpreted as a spontaneous symmetry breaking effect in a conformally symmetric theory involving only massless fields and dimensionless couplings. In such a theory Adler shows, thanks to the gauge theory/super-conductor analogy in spontaneous symmetry breaking, that the gauge theories of the SM can induce gravitational effects relevant in the CSM. For instance, in QCD the trace anomaly

$$\langle T_\mu^\mu \rangle = -\frac{1}{8}[11N_c - 2N_f] \left\langle \frac{\alpha_s}{\pi} (F_{\mu\nu}^a F_{\mu\nu}^{a\mu\nu}) \right\rangle \quad (13)$$

Table 1. Comparison of the yields of our model with the Planck's 2018 results [7] (with Ω_{vis} taken from the data)

	Our model		Planck 2018
Matter	$\Omega_M = 0.3333 - \Omega_{\text{vis}}/2$	0.3088	0.3111
CC	$\Omega_\Lambda = 0.6666 + \Omega_{\text{vis}}/2$	0.6911	0.6889
Dark Matter	$\Omega_{\text{DM}} = 0.3333 - 1.5\Omega_{\text{vis}}$	0.2599	0.2607

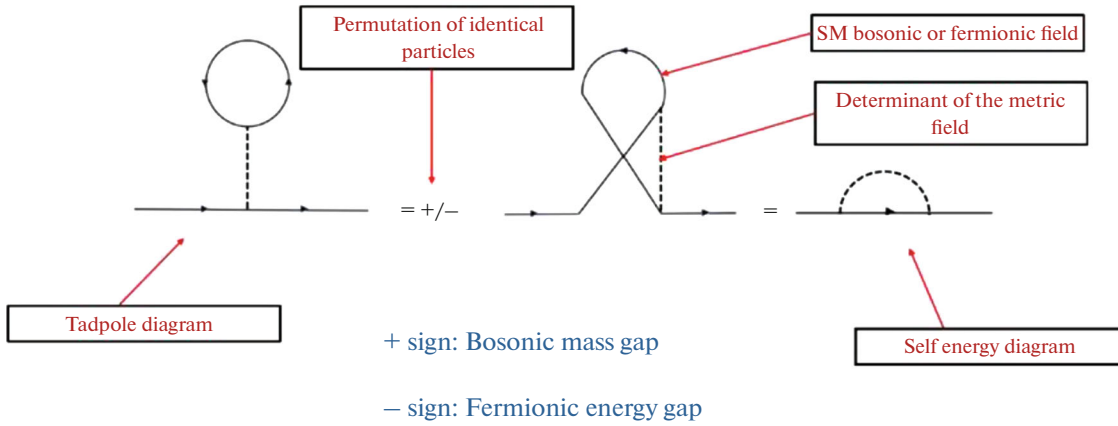


Fig. 3. Dark matter-energy in AdS spacetime.

yields a *negative induced cosmological constant*, that can be a good candidate of an anti-de Sitter world-matter. In the trace anomaly the prefactor $[11N_c - 2N_f]$ in which the term in N_c represents the contribution of gluon loops to the dark matter and the term in N_f represents the contribution of flavored quark loops to the baryonic matter. This prefactor, present in the contributions of all the QCD condensates leads to possible

predictions on the ratios visible to dark matter of dark matter to dark energy.

The success of the comparison of the yields of our model with the data suggests a possible reconciliation of the cosmological models developed, in 1917 by Einstein (static universe thanks to the re-introduction of the cosmological constant) and by de Sitter (universe without matter but with a cosmological constant) [3]

$$\text{Flatness sum rule } \rho_{\text{vis}} + \rho_{\text{DM}} + \rho_{\text{DE}} = \rho_c = \rho_\phi = \frac{3}{2}\rho_\Lambda$$

Equation of state of dilaton field (determinant of the metric) ϕ

$$W_\phi = \frac{P_\phi}{\rho_\phi} = -1/3$$

$$\rho_{\text{vis}} + \rho_{\text{DM}} \equiv \rho_M = -P_\phi; \quad \rho_{\text{DE}} = -2P_\phi$$

$$\rho_M = \frac{1}{2}\rho_\Lambda$$

$$\Rightarrow \rho_M + P_M = 0 \text{ (Einstein model, static universe)}$$

$$\Rightarrow \rho_M + \rho_{\bar{M}} = 0 \text{ (de Sitter model, pure cosmological constant).}$$

In [time and science] we sketched the landscape of quantum cosmogony involving the three theoretical frameworks that are kinematics (the structure of spacetime), phenomenology, and dynamics determined by considering five universal fundamental constants (UFC), \hbar , c , G_N , k_B , Λ . We want here to make more precise what we mean by the structure of spacetime implied by quantum cosmogony by answering the question: does the proposed theory need or not a *continuous spacetime*? One can guess that our answer is no, because with the five UFC put to one, cosmogony would be expressible in terms of pure numbers, which means that it implies calculations that can be performed with a computer involving not a continuous spacetime but a digitized spacetime. In the two papers Gazeau, Habonimana, Shabani, and Cohen-Tan-

noudji have been shown that a quantum model à la Gabor can be used for the metric of such a digitized spacetime.

Holographic Equipartition, Anti-de Sitter Black Hole/Bose–Einstein Condensate Duality

The foundational principle of general relativity is the equality of the inertial mass m_i and the gravitational mass m_g , two meanings of the concept of mass to which are associated the two lengths, $\lambda_c = \frac{\hbar}{m_i c}$, the Compton wavelength of the inertial mass, and $\lambda_g = \frac{G_N m_g}{c^2}$, the Schwarzschild radius of the gravita-

tional mass. The equality of the inertial and gravitational mass leads to a relation between these two lengths that is independent of the value of the mass

$$m_i = m_g \Rightarrow \lambda_c \lambda_g = L_p^2 = \frac{\hbar G_N}{c^3} \text{ independent of } m.$$

We take advantage of this relation to explain the meaning of what is called *holographic equipartition*,

$$N_{\text{bulk}} = \frac{|E|}{1/2 k_B T}; \quad k_B T = \frac{H}{2\pi}; \quad |E| = |\rho + 3P|V; \quad V = \frac{4\pi}{3H^3}$$

$$\Rightarrow N_{\text{bulk}} = -\frac{E}{1/2 k_B T} = -\frac{2(\rho + 3P)V}{k_B T} \text{ (for positive } \rho).$$

Which, if $P = -\rho$ (vacuum) gives the holographic relation

$$H^2 = 8\pi L_p^2 \rho/3 \Leftrightarrow N_{\text{bulk}} = N_{\text{sur}}.$$

We thus see that in the whole expansion stage our effective dark universe the radius of which coincides with the Hubble radius can be interpreted either as

(i) an anti-de Sitter black hole¹ satisfying the Bekenstein (entropy) and Hawking (temperature) thermodynamics;

(ii) or a Bose–Einstein condensates since the bulk d.o.f. with energy $1/2 k_B T$ have a length of coherence also equal to the Hubble radius.

CONCLUSIONS

As a conclusion, we can quote the conclusion of [2] “We have tentatively explained dark matter by actually asking a simple question (!): what becomes the huge amount of gluons after the transition from QGP period to hadronization? Similarly to the emergence of the two validated CMB (QED effect) and CNB (electroweak effect), we propose to consider Dark Matter, observed through its gravitational effects, as a pure QCD effect. From our viewpoint it would be legitimate to replace the puzzling expression “Dark Matter” with the realistic *Cosmic Gluonic Background*.”

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¹ See [8] and [9].

namely the equality, in the whole expansion stage, from point β to point ψ , of the surface number of degrees of freedom (d.o.f.) $N_{\text{sur}} = \frac{4\pi}{L_p^2 H^2}$ (H is the

Hubble parameter) residing at the boundary of the observable universe and the one of those residing in its bulk

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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