Mini-review on Quantum Gravity and Particles

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Abstract

This review is a phenomenological, introductory mini-review on Quantum Gravity, some Cosmology and visible/dark Particles. As an unforeseen result we obtain arguments that three a priori very distinct ideas, namely Hartle-Hawking initial condition, all order finite Chern-Simons quantum gravity and unbroken global supersymmetry of preons provide the necessary tools for unifying all particles and the four forces. This combined model is a novel, noteworthy candidate for BSM physics.

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Contents

1 Introduction

The Standard Model of particles (SM) describes all the accelerator experimental results well and it gives a premonition of being valid at even higher energies. Going beyond the Standard Model (SM) has turned out to be time consuming task, the main reason being insufficient data of cosmological phenomena like dark matter, baryon asymmetry, quantum gravity, etc. In this situation one may try to look for an insightful change within the SM, or rather in the Minimally Supersymmetric SM (MSSM).

A priori, there does not appear to be any connection between these three distinct ideas of this review: 1. the Hartle-Hawking no-boundary condition (by H. and H.), 2. quantum gravity (by A. Castro et al.), and 3. preons as fundamental particles (by myself and others). The combined model of 1.–3. is, however, a novel, noteworthy candidate for BSM physics. It solves many important shortcomings of the Standard Model as given in section 6.

More explicitly, to handle the classical initial singularity of the universe, its initial state has to be defined. We assume the Hartle-Hawking no-boundary condition for the wave function of the universe.

Secondly, gravitation is based on a non-perturbatively and all-order perturbatively calculable Chern-Simons (CS) quantum gravity model.

Thirly, below quark-lepton level there is a topological level of supersymmetric Chern-Simons preons[1]. All matter is now defined by a supersymmetric vector multiplet.

The resulting combined model is, however, a novel, noteworthy candidate for BSM physics (not presented anywhere before as far as we know). It solves

[1] We have also used the term *chernon* for preons.

many important shortcomings of the Standard Model as given in 6.

The article is organized as follows. In section 2 we briefly review the Hartle-Hawking no-boundary wave function and Wheeler-deWitt equation. Simple inflationary cases are considered in section 3 . Three dimensional Chern-Simons gravity with calculational capability is introduced in section 4 for the very early quantum universe. The Chern-Somons particle model for visible matter and dark sector is summarized in section 5 . Finally, some concluding words are expressed in section 6. This note is intended to be a brief, readable "pocket book" introduction to quantum gravity phenomenology. All text is based on published material of various kind. Any novelty is in the composition of the sources. Readers interested in the subject must go to the brief list of references - and references theirin - for the calculations. Admittedly, much remains to be calculated.

2 The No-Boundary Wave Function

2.1 Ground State of the Universe and Quantum Creation

An excellent review of the Hartle-Hawking no-boundary idea is [1], which we follow. Ground states can be defined in quantum mechanics by considering a Euclidean path integral, and integrating from configurations of vanishing action in the infinite (Euclidean) past,

$$\psi_0(x,0) = \int \mathcal{D}x \, e^{-\frac{1}{\hbar} I_E[x(\tau)]} \,, \tag{2.1}$$

where we ignored an overall normalisation factor and where Euclidean time τ is related to physical time via $t = -i\tau$. The Euclidean action I_E is related to the Lorentzian one via $I_E = -iS$. An integral from the infinite Euclidean past defines the ground state (vacuum state) of the system. Put differently, the integration over Euclidean time is an alternative manner to implement the ground state as initial state. In addition, the replacement $t = -i\tau$ takes one from quantum oscillatory behavior towards semiclassical physics.

What would be an analogous definition when gravity is included? What should play the role of the infinite Euclidean past? As discussed by Hartle and Hawking [2], there are two natural choices (i) Euclidean flat space, and (ii) compact Euclidean metrics. Euclidean flat space can be used for scattering amplitudes, where fields are defined at infinity. In cosmology, instead, we are only measuring the universe at late (finite) times, and we do it from the inside of the universe. Therefore the second option (ii) is more appropriate for cosmology, as proposed by Hartle and Hawking. Note that this prescription then obviates the need to insert an initial state explicitly, the idea being that the Euclidean integral puts the universe in its ground state.

The no-boundary proposal assumes a fully quantum view of spacetime: actual spacetime exists only in interaction with either itself or matter. It is the interactions between different constituents of the universe that result in our perception of classical spacetime with classical laws of evolution. Going back in time towards the putative big bang, one will necessarily encounter departures from the classical evolution.

The wave function is a function of three-dimensional spatial slices. The path integral over compact metrics may then be seen as an amplitude from a slice where the 3−dimensional volume goes to zero, to a final slice with metric h_{ij},

$$\Psi_{HH}[h_{ij}] = \mathcal{N} \int_{\mathcal{C}} \mathcal{D}g_{\mu\nu}\, e^{-I_E[g_{\mu\nu}]}\,, \tag{2.2}$$

where the integral is over all (inequivalent) compact metrics $\mathcal{C}$ that contain a surface with metric h_{ij}. $\mathcal{N}$ here is a normalisation factor. This definition may be given the interpretation of a transition amplitude from zero size to a given final size. It is the amplitude for the universe to tunnel from nothing to a final state. Nothing means here absolute nothing: no space, time or matter.

From the definition (2.2) one has certain consequences. The first is that the wave function is real valued. This can nevertheless lead to definition of probabilities. The second is that from a sum over Euclidean metrics, somehow our Lorentzian universe must come out. This is because the saddle points of the path integral (2.2) will turn out to be complex. Third, by definition the big bang singularity is avoided. This is possible because the geometry is not forced to remain Lorentzian in regions where the universe shrinks to zero size. The origin of the geometry can be viewed more like a point on the surface of a sphere, called the South Pole of the geometry, see figure 1.

2.2 Wheeler-deWitt Equation

The Hamiltonian form of the action of General Relativity is given by [3]

$$S = \int \mathrm{d}^3x\ \mathrm{d}t \left[\dot{h}_{ij}\pi^{ij} - N\mathcal{H} - N^i\mathcal{H}_i\right] \tag{2.3}$$

where $\pi^{ij} = \frac{\delta\mathcal{L}}{\delta\dot{h}^{ij}} = -\frac{\sqrt{h}}{2}\left(K^{ij} - h^{ij}K\right)$ are the momenta conjugate to h_{ij}. The Hamiltonian is a sum of constraints, with the lapse N and shift N^i being Lagrange multipliers. There is the momentum constraint,

$$\mathcal{H}^i = -2D_j\pi^{ij} + \mathcal{H}^i_{matter} = 0\,, \tag{2.4}$$

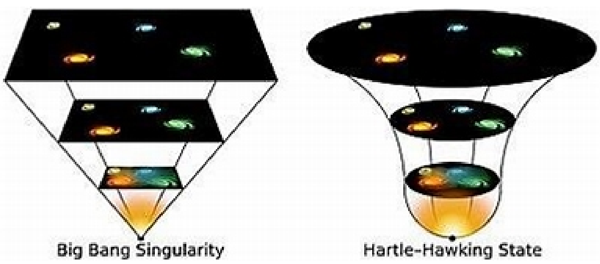

Figure 1: Big Bang Universe and Hartle-Hawking Universe.

and the Hamiltonian constraint

$$\mathcal{H} = 2G_{ijkl}\pi^{ij}\pi^{kl} - \frac{1}{2}\sqrt{h}(^3R - 2\Lambda) + \mathcal{H}_{matter} = 0\,, \tag{2.5}$$

where G_{ijkl} is the DeWitt metric [4]

$$G_{ijkl} = \frac{1}{2\sqrt{h}}\left(h_{ik}h_{jl} + h_{il}h_{jk} - h_{ij}h_{kl}\right)\,. \tag{2.6}$$

These constraints are essentially equivalent to the $0i$ and 00 components of the classical Einstein equations. The constraints play a central role in the canonical quantisation procedure.

Canonical quantisation amounts to imposing the constraints as operator equations, in the field representation with the substitution

$$\pi^{ij} \to -i\frac{\delta}{\delta h_{ij}} \tag{2.7}$$

and similarly for the matter momenta. This results in four equations: the momentum constraint

$$\mathcal{H}^i\Psi = 2iD_j\frac{\delta\Psi}{\delta h_{ij}} + \mathcal{H}^i_{matter}\Psi = 0\,, \tag{2.8}$$

and the Wheeler-DeWitt equation [4, 5] for the wavee function of the universe

$$\mathcal{H}\Psi(h_{ij},\Phi_{matter}) = \left[-G_{ijkl}\frac{\delta}{\delta h_{ij}}\frac{\delta}{\delta h_{kl}} - \sqrt{h}(^3R - 2\Lambda) + \mathcal{H}_{matter}\right]\Psi = 0\,. \tag{2.9}$$

or

$$\hat{H}\Psi = 0 \to \hbar^2\frac{\partial^2\Psi}{\partial q^2} + 12\pi^4(\Lambda q - 3)\Psi = 0\,. \tag{2.10}$$

Two remarks to end this section. Time is treated as a complex number. In the early universe, time behaves like a spatial dimension. This removes the distinction between time and space and allows the geometry of the universe to be smooth and finite in all directions. Imaginary time replaces the singular boundary of the big bang.

Classicalization is explained by a Wentzel-Kramers-Brillouin (WKB) semi-classical phenomenon and decoherence due to interactions, see [1] for details.

3 Simple Inflationary Examples

We review briefly a simplified inflationary case of the universe following [1]. It is known that path integrals can be well approximated by their saddle points, but do compact and regular saddle point solutions actually exist?

The relevant situation is gravity coupled to a scalar field ϕ with potential $V(\phi)$ and action

$$S = \int_{\mathcal{M}} \mathrm{d}^4 x \sqrt{-g} \left(\frac{R}{2} - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right) + \int_{\partial \mathcal{M}} \mathrm{d}^3 y \sqrt{h} K \,. \tag{3.1}$$

We will assume Friedmann-Lemaître-Roberston-Walker (FLRW) backgrounds

$$\mathrm{d}s^2 = -\tilde{N}^2(t)\mathrm{d}t^2 + a^2(t)\mathrm{d}\Omega_3^2 \,, \tag{3.2}$$

where $\tilde{N}$ is the lapse function and $\mathrm{d}\Omega_3^2$ the metric on the unit three-sphere. This symmetry reduced setting is an example of minisuperspace.

We redefine the time coordinate $\tilde{N}\mathrm{d}t = -i\mathrm{d}\tau$. $\tau \subset \mathbb{R}$ corresponds to Euclidean time, it will be useful to consider $\tau \subset \mathbb{C}$ in general. The metric ansatz is then very

$$\mathrm{d}s^2 = \mathrm{d}\tau^2 + a^2(\tau)\mathrm{d}\Omega_3^2 \,, \tag{3.3}$$

and the Euclidean action $I_E = -iS$ becomes

$$I_E = 2\pi^2 \int \mathrm{d}\tau \left(-3aa'^2 - 3a + a^3 \left(\frac{1}{2}\phi'^2 + V \right) \right) \,, \tag{3.4}$$

where $' \equiv \mathrm{d}/\mathrm{d}\tau$. The equations of motion are

$$\phi'' + 3\frac{a'}{a}\phi' - V_{,\phi} = 0 \,, \tag{3.5}$$

$$a'' + \frac{a}{3}\left(\phi'^2 + V\right) = 0 \,, \tag{3.6}$$

while the constraint, arising from time reparameterisation invariance, is

$$a'^2 - 1 = \frac{a^2}{3}\left(\frac{1}{2}\phi'^2 - V \right) \,. \tag{3.7}$$

which is called the Friedmann equation. Using this equation, we can simplify the action when it is evaluated on a solution of the equations of motion

$$I_E^{on-shell} = 4\pi^2 \int \mathrm{d}\tau \, \left(-3a + a^3 V \right) \,. \tag{3.8}$$

The no-boundary wave function is the path integral

$$\Psi(b,\chi) = \int_{\mathcal{C}} \mathcal{D}a \mathcal{D}\phi \, e^{-I_E(a,\phi)} \sim \sum e^{-I_E(b,\chi)} \,, \tag{3.9}$$

depends on b and χ, the (late-time) values of the scale factor and scalar field on the final hypersurface. We assume that it can be approximated by (a sum of) saddle point contributions. These saddle points must satisfy a number of mathematical and physical requirements [6]: evidently, they must satisfy the equations of motion and constraints. But moreover, we would like them to be physically meaningful, and for this reason they should yield normalisable wave functions. Moreover, they should lead to physically sensible results, implementing in particular the idea that in the early universe matter fields were in their ground states.

The solutions $(a(\tau), \phi(\tau))$, must satisfy the several conditions [7, 8]. The solution must be compact, we must have $a(0) = 0$ somewhere. The time coordinate is defined such that $\tau = 0$ corresponds to the South Pole of the solution. There the solution must also be regular. The Friedmann equation (3.7) then implies $a'(0) = \pm 1$, meaning that the geometry must be Euclidean at the South Pole. The choice of sign for a' is important, for normalisability we must choose $a'(0) = +1$. The equation of motion (3.6) implies that $a = \tau + \mathcal{O}(\tau^3)$. Meanwhile, the equation of motion for ϕ, Eq. (3.5), shows that no-boundary solutions can be characterised by the value of the scalar field at the South Pole, $\phi_{SP} = \phi(0)$, which is complex in general.

On the final hypersurface we must have

$$a(\tau_f) = b \quad \text{and} \quad \phi(\tau_f) = \chi, \tag{3.10}$$

with b, χ being the arguments of the wave function. It must be required that the fields take the specified values simultaneously. Otherwise, no solution exists.

The phases of very early universe, $0 \leq t \leq 10^{-32}$ s, in the preon model are: 1. nucleation, 2. appearance of scalar field, 3. scalar field produces preon–anti-preon pairs, and 4. reheating producing SM fermions (more details in [9] together with the baryon asymmetry mechanism). At the nucleation of the universe, only scalar fields may have a non-zero energy density. This follows from the equation of continuity $\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0$. At zero scale factor this equation remains regular only if $\rho + p$ vanishes, which only a scalar field can achieve, when its kinetic energy is zero. Other matter fields must be created later during reheating.

The black hole information paradox is wiped away in the present scenario. Black holes with an initial mass less than about 10^{15} g have completely evaporated by now, i.e. in about 13.8 billion years. When the surface temperature of a decaying hole reaches the temperature of about $\Lambda_{cr} \sim E_R \sim 10^{15}$ GeV falling quarks and leptons transform into preons with vacuum quantum numbers. These in turn form scalars. The stuff ultimately ends up into a point, the South Pole. The Pole begins the process of the previous paragraph (inflation) from phase 2 producing matter and radiation like in the present universe. The baryon asymmetry may be slightly different from what is now observed. No physical information is lost.

4 Quantum Gravity

The CS model of quantum gravity by Castro et al. [10, 11] and the supersymmetric model for (left handed) particles in [12] were reviewed and their actions compared [13]. The former model is summarized below. In section 5 the particle model is recapped.

In Euclidean space, the fermions ψ and $\bar{\psi}$ are independent and they transform in the same representation of the Lorentz group. Their index structure is [14]

$$\psi^{\alpha}, \quad \bar{\psi}^{\alpha}. \tag{4.1}$$

We will take γ_μ to be the Pauli matrices, which are hermitian, and

$$\gamma_{\mu\nu} = \frac{1}{2}[\gamma_\mu, \gamma_\nu] = \mathrm{i}\epsilon_{\mu\nu\rho}\gamma^{\rho}. \tag{4.2}$$

The three dimensional Euclidean $\mathcal{N} = 2$ vector superfield V has the following content

$$V : \qquad A_\mu,\ \sigma,\ \lambda,\ \bar{\lambda},\ D, \tag{4.3}$$

where A_μ is a gauge field, σ is an auxiliary scalar field, λ, $\bar{\lambda}$ are two-component complex Dirac spinors, and D is an auxiliary scalar. This is just the dimensional reduction of the $\mathcal{N} = 1$ vector multiplet in 4 dimensions, and σ is the reduction of the fourth component of A_μ. All fields are valued in the Lie algebra $\mathfrak{g}$ of the gauge group G. For $G = U(N)$ our convention is that $\mathfrak{g}$ are Hermitian matrices. It follows that the gauge covariant derivative is given by

$$\partial_\mu + \mathrm{i}[A_\mu, .] \tag{4.4}$$

while the gauge field strength is

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + \mathrm{i}[A_\mu, A_\nu]. \tag{4.5}$$

The question of gravity-matter coupling is resolved in [15]. The major result of [10] is the expression of the one-loop determinant (or partition function) of a massive scalar field minimally coupled to a background metric, $g_{\mu\nu}$, as a gauge invariant object of the Chern-Simons connections, $A_{L/R}$

$$Z_{\text{scalar}}[g_{\mu\nu}] = \exp\frac{1}{4}\mathbb{W}[A_L, A_R]\ . \tag{4.6}$$

The object $\mathbb{W}[A_L, A_R]$, coined the Wilson spool, is a collection of Wilson loop operators W

$$\mathrm{Tr_R Pexp}\Big(\mathrm{i}\int_\gamma \mathrm{A_\mu dx^\mu}\Big) \tag{4.7}$$

where γ is a closed loop in space-time and R is a representation of the gauge group G, wrapped many times around cycles of the base geometry. Supersymmetric localization for the evaluation of Wilson loop expectation values [14] with the Wilson spool inserted into the path integral allows a precise and efficient calculation of the quantum gravitational corrections to Z_{scalar} at any order of perturbation theory of Newton's constant G_N. The equality in (4.6) is expected to apply to three-dimensional gravity of either sign of cosmological constant.

5 Particle Model

The localization procedure [14] is not only a calculational method but the vectormultiplet $\{A_\mu, \sigma, \mathfrak{D}, \lambda, \bar{\lambda}\}$ of section 4 should be realized also on the topological matter sector of the particle model. In fact, this kind of supersymmetric mattter structure was anticipated on phenomenological basis some time ago in [16, 12, 9]. The setup for this scenario is recapped below:

Unbroken supersymmetry is adopted for fundamental particles. The divisive point between the Minimal Supersymmetric SM and our model (for visible and dark matter) is the following: supersymmetry is unbroken and superpartners are included in constructing the Standard Model particles. There are no squarks or sleptons to be dicovered.[2] This can be achieved only if Standard Model fermions are split into three preons. A binding mechanism for preons has been constructed using spontaneously broken 3d Chern-Simons theory.
Preons, or here preons, are free particles above the energy scale Λ_{cr}, numerically abou t $\sim 10^{10} - 10^{16}$ GeV. It is close to reheating scale T_R and the grand unified theory (GUT) scale. At Λ_{cr} preons make a phase transition by an attractive Chern-Simons model interaction into composite states of Standard Model quarks and leptons, including gauge interactions. preons have undergone "second quarkization".

To make the preon scenario compatible with the SM we consider the following Lagrangians 5.1 anf 5.2. To include charged matter we define the charged chiral field Lagrangian for fermion m^-, complex scalar s^- and the electromagnetic field tensor $F_{\mu\nu}$[3]

$$\mathcal{L}_{QED} = -\frac{1}{2}\bar{m}^-\gamma^\mu(\partial_\mu + ieA_\mu)m^- - \frac{1}{2}(\partial s^-)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \; . \tag{5.1}$$

We assign color to the neutral fermion $m \to m_i^0$ $(i = R, G, B)$. The color sector Lagrangian is then

$$\mathcal{L}_{QCD} = -\frac{1}{2}\sum_{i=R,G,B}\left[\bar{m}_i^0\gamma^\mu(\partial_\mu + igG_\mu^a t_a)m_i^0\right] - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \; . \tag{5.2}$$

We now have the supermultiplets shown in table 1.

[2] The MSSM leads rather to particle "double counting".
[3] The next two equations are in standard 4D form. They are not used quantitatively below.

Multiplet	Particle, Sparticle
chiral multiplets spins 0, 1/2	s^-, m^-; σ_i, m_i^0; a, n
vector multiplets spins 1/2, 1	m^0, γ; m_i^0, g_i

Table 1: The particle s^- is a charged scalar particle. The particles m^-, m^0 are charged and neutral, respectively, Dirac spinors. The a is axion and n axino [17, 18, 19]. m^0 is color singlet particle and γ is the photon. m_i and g_i (i = R, G, B) are zero charge color triplet fermions and bosons, respectively.

Note that in table 1 there is a zero charge quark triplet m_i but no gluon octet. Instead, supersymmetry demands the gluons to appear only in triplets at this stage (before reheating) of cosmological evolution. The dark sector we get from axion sector {a, n} in table 1 (if axion(s) are found).

The matter-preon correspondence for the first two flavors (r = 1, 2; i.e. the first generation) is indicated in table 2 for left handed particles.

SM Matter 1st gen.	Preon state
ν_e	$m_R^0 m_G^0 m_B^0$
u_R	$m^+ m^+ m_R^0$
u_G	$m^+ m^+ m_G^0$
u_B	$m^+ m^+ m_B^0$
e^-	$m^- m^- m^-$
d_R	$m^- m_G^0 m_B^0$
d_G	$m^- m_B^0 m_R^0$
d_B	$m^- m_R^0 m_G^0$
W-Z Dark Matter	Particle
boson (or BC)	s, axion(s)
e'	axino n
meson, baryon o	$n\bar{n}, 3n$
nuclei (atoms with γ')	multi n
celestial bodies	any dark stuff
black holes	anything (neutral)

Table 2: Visible and Dark Matter with corresponding particles and preon composites. m_i^0 (i = R, G, B) is color triplet, $m^\pm$ are color singlets of charge $\pm 1/3$. e' and γ' refer to dark electron and dark photon, respectively. BC stands for Bose condensate. preons obey anyon statistics.

After quarks have been formed by the process described in [9] the SM octet of gluons will emerge because it is known that fractional charge states have not been observed in nature. To make observable color neutral, integer charge states (baryons and mesons) possible we proceed as follows. The local $SU(3)_{color}$ octet structure is formed by quark-antiquark composite pairs as follows (with only color charge indicated):

$$\text{Gluons : } \mathrm{R\bar{G}, R\bar{B}, G\bar{R}, G\bar{B}, B\bar{R}, B\bar{G}}, \frac{1}{\sqrt{2}}(\mathrm{R\bar{R} - G\bar{G}}), \frac{1}{\sqrt{6}}(\mathrm{R\bar{R} + G\bar{G} - 2B\bar{B}}) \ . \quad (5.3)$$

With the gluon triplet the first hunch is that they form, with octet gluons now available, the $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$ bosonic states with spins 1 and 3. These three gluon coupling states would need a separate investigation.

Finally, we introduce the weak interaction briefly and heuristically - the scalar sector is rather complex. After the SM quarks, gluons and leptons have been formed at scale Λ_{cr} there is no more observable supersymmetry in nature [20]. To avoid a more complicated vector supermultiplet in table 1, we may append the Standard Model electroweak interaction in our model as a $SU(2)_Y$ Higgs extension with the weak bosons presented as composite pairs like gluons in (5.3).

Standard Model and dark matter is formed by preon composites in the very early universe at temperature about the reheating value T_R. Due to spontaneous symmetry breaking in three dimensional QED_3 by a heavy Higgs-like particle the Chern-Simons action can provide a binding force stronger than Coulomb repulsion between equal charge preons. Details of preon binding and a mechanism for baryon asymmetry in the universe are presented in [9, 21].

Chern-Simons theory with larger groups like $G = U(N_c)$ with fundamental matter and flavor symmetry group $SU(N_f) \times SU(N_f)$ have been studied, e.g. [22], but they are beyond the scope of this review.

6 Conclusions and Outlook

Starting from the beginning of time without singularity we have obtained heuristically a rather comprehensive picture of the cosmological evolution of the universe from nothing to the present time.

Properties of the scenario include

- perturbatively all order calculable quantum gravity,
- there are no initial or black hole singularities due to no-boundary condition,
- dark sector is predicted, see table 1 (axion, n),
- time is treated as a complex number,
- classicalization is explained by a Wentzel-Kramers-Brillouin (WKB) semiclassical phenomenon and decoherence due to interactions,
- cosmic expansion is possible by inflation or ekpyrotic model,
- mechanism for baryon asymmetry has been constructed,

- "light" black hole radiates back the same matter (as preons) it has swallowed earlier (depending on the flux of falling matter),
- dark sector is obtained, see table 1 (axion, n),
- Standard Model of particles is obtained after reheating,
- flavor symmetry $SU(N_f)$ is appendable,
- all particles and interactions originate equally on topological level (near Planck scale) from **supermultiplets** of table 1 and **CS action** of (A.2) (this is the novelty in the article),
- numerical techniques are available.

The present discussion is precursory. Details of this framework have to be studied systematicallytly. For example, why are dimensions of spacetime approaching zero as we go towards the initial state of the universe.

A single CS basic action to build all particles and interactions combined with Hartle-Hawking initial conditions for cosmic expansion indicates an element of a theory of "everything" - to the extent it can be defined.

A Chern-Simons Action

In accordance with the split structure of the isometry group, one describes Euclidean dS_3 gravity with a pair of $SU(2)$ Chern-Simons theories [10]

$$S = k_L\, S_{CS}[A_L] + k_R\, S_{CS}[A_R] \;, \tag{A.1}$$

with

$$S_{CS}[A] = \frac{1}{4\pi}\mathrm{Tr}\int \left(\mathrm{A}\wedge \mathrm{dA} + \frac{2}{3}\mathrm{A}\wedge\mathrm{A}\wedge\mathrm{A}\right) \;, \tag{A.2}$$

and the trace taken in the fundamental representation. This topological expression is a key element for unification. The other is unbroken supersymmetry.

The gravitational Chern-Simons term I_{GCS} is

$$I_{\mathrm{GCS}} = \frac{1}{2\pi}\mathrm{Tr}\int \left(\omega\wedge \mathrm{d}\omega + \frac{2}{3}\omega\wedge\omega\wedge\omega\right) + \frac{1}{2\pi\ell_{\mathrm{dS}}^2}\mathrm{Tr}\int \mathrm{e}\wedge\mathrm{T} \;, \tag{A.3}$$

with T the torsion two-form and ℓ_{dS} is deSitter radius.

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