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Article

The Critical Hypersurface as a Geometric Origin of Nonsingular Cosmic Expansion

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Abstract

We propose a geometrically motivated framework in which the large-scale evolution of the Universe is described by a coherent multidimensional wavefunction possessing a preferred direction of propagation. Within this formulation, the scalar envelope of the wavefunction defines a critical hypersurface whose temporal evolution provides an effective geometric description of cosmic expansion. The resulting picture naturally incorporates an arrow of time, large-scale homogeneity, and a nonsingular expansion history, without invoking an inflationary phase, a cosmological constant, or an initial singularity. The critical hypersurface takes the form of a three-dimensional sphere whose radius plays the role of a cosmological scale factor. Its evolution leads to a time-dependent expansion rate with a positive but gradually decreasing acceleration. The associated density evolution follows a well-defined scaling law that is consistent with the standard stress–energy continuity equation and corresponds to an effective equation-of-state parameter $w = -1/3$. As a consequence, the total mass–energy contained within the expanding hypersurface increases with time in a manner that remains fully compatible with the continuity relation. Analytical estimates derived from the model yield values for the present expansion rate and mean density that are in close agreement with current observational constraints. Within this geometric interpretation, the gravitational constant emerges as an invariant global potential associated with the critical hypersurface, linking the conserved properties of the wavefunction to observable gravitational coupling. The framework therefore provides a self-consistent, effective description in which cosmic expansion and gravitational dynamics arise from the geometry of a universal wavefunction, suggesting a deep connection between quantum structure, spacetime geometry, and cosmological evolution.

Keywords: cosmology; evolution of the universe; general relativity; gravitation; quantum cosmology

1. Introduction

The origin of the universe remains one of the greatest unsolved mysteries in modern physics. General relativity, widely recognized as the fundamental theory underpinning cosmology, has profoundly enhanced our understanding of spacetime. However, it has never fully explained the universe's inception. Einstein's equations, when extrapolated back to the very beginning of the universe, predict a singularity—a point at which classical physical laws cease to be meaningful. This singularity marks the breakdown of general relativity, necessitating a quantum description. Quantum theory, which primarily addresses phenomena at microscopic scales, is widely believed to be universally applicable, suggesting that the origin of the universe must fundamentally be a quantum event. Although direct observational evidence for quantum gravitational phenomena is on its early stage [1], compelling theoretical arguments indicate that gravity and quantum theory should unify at the Planck scale, approximately defining the initial size of the universe [2–6]. Hence, it is logical to conclude that spacetime itself should be represented by a wavefunction dependent on both matter fields and spacetime geometry.

Over recent decades, significant efforts have focused on mathematically formulating the universe's wavefunction (see [7] for an extensive review). A central challenge in these formulations is defining appropriate boundary conditions for the wavefunction. Among the most influential proposals is the "no-boundary" condition introduced by Hartle and Hawking, suggesting a spacetime without initial boundaries or singularities [8,9]. Despite its conceptual elegance, the no-boundary condition encounters difficulties when interfacing with general relativity. Under reasonable assumptions regarding the matter content of the universe, the celebrated singularity theorems imply that a curvature singularity must have occurred [8,9]. Resolving this issue necessitates a genuine quantum theory of gravity—a formidable challenge that remains unresolved despite significant advances in string theory, loop quantum gravity, and other quantum gravity frameworks [10–14].

To address this fundamental issue, we introduce a novel concept involving combined boundary conditions. In our model, the boundary conditions for 4-dimensional spacetime arise naturally when solving the most general wave equation describing a multidimensional, unrestricted global wavefunction. A key advantage of our approach is its compatibility with current cosmological observations without relying on specific assumptions drawn from quantum theory or general relativity. Both these theories naturally emerge within the logic of the global wavefunction itself. Within our framework, the global wavefunction dictates all evolutionary aspects of the universe, with spacetime curvature—and thus gravity—emerging as an inherent consequence of this evolutionary process, rather than as the fundamental driver of cosmic expansion. A central outcome of our theory is a conservation law governing the integrated intensity of the wavefunction, which serves as an analog to, though not exactly identical with, the total energy of the universe. This conservation law ensures that our model avoids an initial singularity, providing a coherent and physically consistent description of the universe's origins.

To identify the wavefunction, we adapt a well-established methodology from the theory of coherent electromagnetic waves and singular optics [15]. For this purpose, we start from the most general wave equation in (3+1)-dimensional spacetime [16,17]:

$$\square \Phi^a = 0, \quad (1.1)$$

where $\Phi^a(x, y, z, t)$ represents one of the two electromagnetic (EM) vector fields—electric ($a = 1$) or magnetic ($a = 2$), $\square = \nabla^2 - \frac{1}{c^2} \partial_t^2$ is the d'Alembertian operator, and $\nabla = \mathbf{e}_x \partial_x + \mathbf{e}_y \partial_y + \mathbf{e}_z \partial_z$ with $\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$ being Cartesian unit vectors, and c the speed of light.

An infinite coherent EM wave with constant angular frequency ω can be expressed as $\Phi^a(x, y, z, t) = F^a(x, y, z) e^{-i\omega t}$. Substituting this into Eq. (1.1) yields the three-dimensional Helmholtz equation:

$$(\nabla^2 + k^2) F^a = 0, \quad (1.2)$$

where $k = \omega/c$.

The symmetry of coordinates (x, y, z) in Eq. (1.2) leads to an energy divergence in its exact solutions. This is evident in plane, cylindrical, and spherical wave solutions, all of which have infinite total energy, $\int_{\mathbb{R}^3} |F|^2 d\mathbb{R}^3 = \infty$. This divergence is typically managed by limiting the integration domain or using superpositions to compensate. However, for highly directed coherent EM waves such as laser beams, limiting the domain is often impractical [18]. The only efficient approach is to break the coordinate symmetry in Eq. (1.2).

Consider a wave directed predominantly along the z -axis. Then $F^a(x, y, z) = \tilde{F}^a(x, y, z) e^{ikz}$, and Eq. (1.2) becomes [19]:

$$(\nabla^2 + 2ik\partial_z) \tilde{F}^a = 0. \quad (1.3)$$

Under the slowly varying envelope approximation, and neglecting the longitudinal component $\tilde{F}_z^a \ll F_\perp^a$, we approximate $\tilde{F}^a \approx F_\perp^a(x, y, z)$, giving the (2+1)D Schrödinger-type equation:

$$(\nabla_\perp^2 + 2ik\partial_z) F_\perp^a = 0, \quad (1.4)$$

where $\nabla_{\perp} = \mathbf{e}_x \partial_x + \mathbf{e}_y \partial_y$.

Solutions of Eq. (1.4) can be expressed as the product of a vector modulation function and a scalar background envelope [15,20]:

$$\mathbf{F}_{\perp}^a = \mathbf{U}^a(x, y, z) G(x, y, z), \quad (1.5)$$

where the scalar envelope [18,19]:

$$G(x, y, z) = \frac{1}{w_0 \xi(z)} \exp\left(-\frac{x^2 + y^2}{w_0^2 \xi(z)}\right), \quad (1.6)$$

satisfies Eq. (1.4) with $\xi(z) = 1 + iz/z_0$, $z_0 = kw_0^2/2$. The scalar envelope given by Eq. (1.6) represents the complex amplitude of the coherent wave and plays a crucial role in ensuring the wave's finite energy:

$$(2/\pi) \int_0^{\infty} GG^* dS_{\perp} = 1. \quad (1.7)$$

Here the star denotes complex conjugation, and $dS_{\perp}$ is the differential area element in the transverse xy plane.

While G governs spatial evolution of the EM wave, the vector function $\mathbf{U}^a$ captures its topological and polarisation properties. Unlike the scalar envelope G , the modulation function itself does not satisfy the Eq. (1.4). Although $\mathbf{U}^a(x, y, z)$ is, in general, a function of all three Cartesian coordinates, its equation admits a separation of variables, allowing a distinction between longitudinal and transverse degrees of freedom. By changing variables as $X = x/(w_0 \xi)$, $Y = y/(w_0 \xi)$, and substituting expression (1.5) into Eq. (1.4), we obtain the differential equation for the modulation function $\mathbf{U}^a(X, Y, \xi)$ [20]:

$$\nabla_t^2 \mathbf{U}^a - 4\xi^2 \partial_{\xi} \mathbf{U}^a = 0, \quad (1.8)$$

with $\nabla_t = \mathbf{e}_x \partial_X + \mathbf{e}_y \partial_Y$.

This equation admits the separation of variables:

$$\mathbf{U}^a(X, Y, \xi) = \mathbf{u}^a(X, Y) Z(\xi), \quad (1.9)$$

with $Z(\xi) = \exp[K^2(1 - \xi)/4\xi]$ and K is a separation constant.

The function $\mathbf{u}^a(X, Y)$ satisfies the Helmholtz equation in the two-dimensional transverse space (X, Y) :

$$(\nabla_t^2 + K^2) \mathbf{u}^a = 0. \quad (1.10)$$

In the special case $K = 0$, the modulation function $\mathbf{U}^a(X, Y, \xi)$ coincides with the function $\mathbf{u}^a(X, Y)$, becoming independent on the longitudinal coordinate ξ , and Eq. (1.10) reduces to the two-dimensional Laplace equation:

$$\nabla_t^2 \mathbf{u}^a(X, Y) = 0. \quad (1.11)$$

Analyses of possible $\mathbf{u}^a(X, Y)$ are provided in [15].

While Eq. (1.10) represents a two-dimensional analogue of the three-dimensional Helmholtz equation (1.2), its solutions would exhibit similar issues with energy divergence. However, this is not the case for the general solutions of the wave equation (1.5), as all singularities associated with Eq. (1.10) are embedded within the higher-dimensional space defined by the finite-energy Gaussian envelope of Eq. (1.6). The former captures the wave's topological structures, while the latter governs its spatial evolution and energy localization.

2. Results

2.1. Multidimensional Wave

The previous section demonstrated that reducing the coordinate symmetry of the wave equation yields directed electromagnetic (EM) waves with finite energy. In that case, the reduced equation

is effectively three-dimensional, while the complete coherent wave includes a rapidly oscillating time-dependent phase.

We now extend these results to the general case of an abstract $(n + 1)$ -dimensional coherent wave, described by a multicomponent vector function $\Phi^a(x_0, x_1, \dots, x_n)$, where x_0 is the preferred direction of propagation. To do this, we consider the wave equation in its most general form, without assuming any specific physical interpretation:

$$\square \Phi^a = 0, \quad (2.1)$$

where $\square = \sum_{\alpha=1}^n \frac{\partial^2}{\partial x_\alpha^2} \pm \frac{\partial^2}{\partial x_0^2}$ is the $(n + 1)$ -dimensional Laplace or d'Alembert operator, depending on the sign chosen between the transverse coordinates $x_1, \dots, x_n$ and the longitudinal coordinate x_0 , associated with the predominant direction of propagation.

We further assume that the function depends on one of the coordinates, say x_n , only through an oscillatory phase term.

$$\begin{aligned} \Phi^a(x_0, x_1, \dots, x_n) &= \tilde{\Phi}^a(x_0, x_1, \dots, x_{n-1}) \\ &\times \exp(\pm i p_n x_n), \end{aligned} \quad (2.2)$$

where p_n is a positive constant. The sign in the phase, which reflects the two possible oscillation directions, can be chosen arbitrarily. Substituting the expression (2.2) into Eq. (2.1), we obtain the reduced wave equation for $\tilde{\Phi}^a(x_0, x_1, \dots, x_{n-1})$:

$$(\square - p_n^2) \tilde{\Phi}^a = 0, \quad (2.3)$$

where the operator now becomes $\square = \sum_{\alpha=1}^{n-1} \frac{\partial^2}{\partial x_\alpha^2} \pm \frac{\partial^2}{\partial x_0^2}$.

By analogy with directed electromagnetic waves, we can separate out the rapidly oscillating term along the predominant direction x_0 in the function $\tilde{\Phi}^a$:

$$\begin{aligned} \tilde{\Phi}^a(x_0, x_1, \dots, x_{n-1}) &= \Psi^a(x_0, x_1, \dots, x_{n-1}) \\ &\times \exp(\pm i p_0 x_0), \end{aligned} \quad (2.4)$$

where p_0 is a positive constant, and the choice of sign reflects the wave's direction along x_0 .

Substituting Eq. (2.4) into Eq. (2.3) yields, after some algebra, an equation for Ψ^a :

$$\left(\sum_{\alpha=1}^{n-1} \frac{\partial^2}{\partial x_\alpha^2} - \{p_n^2 \pm p_0^2\} \pm 2ip_0 \frac{\partial}{\partial x_0} \pm \frac{\partial^2}{\partial x_0^2} \right) \Psi^a = 0. \quad (2.5)$$

The assumption of predominant propagation along x_0 :

$$\left| \frac{\partial^2}{\partial x_0^2} \Psi \right| \ll p_0 \left| \frac{\partial}{\partial x_0} \Psi \right|, \quad (2.6)$$

allows us to neglect the second derivative with respect to x_0 in Eq. (2.5), resulting in the reduced wave equation:

$$\left(\sum_{\alpha=1}^{n-1} \frac{\partial^2}{\partial x_\alpha^2} - \{p_n^2 \pm p_0^2\} \pm 2ip_0 \frac{\partial}{\partial x_0} \right) \Psi^a = 0, \quad (2.7)$$

Until now, we have not made any assumptions about the signs in the operator $\square$ in Eq. (2.3). Assuming that this operator is the d'Alembertian $\square = \sum_{\alpha=1}^n \frac{\partial^2}{\partial x_\alpha^2} - \frac{\partial^2}{\partial x_0^2}$ and taking into account that $p_0^2 = p_n^2$ for a freely propagating wave, Eq. (2.7) simplifies to:

$$\left(\sum_{\alpha=1}^{n-1} \frac{\partial^2}{\partial x_\alpha^2} \pm 2ip_0 \frac{\partial}{\partial x_0} \right) \Psi^a = 0. \quad (2.8)$$

Equation (2.8) describes one of two possible waves propagating in opposite directions along the coordinate x_0 , depending on the sign in the equation. For clarity, we now consider propagation along the positive direction of the coordinate x_0 , $\Psi^a = \tilde{\Phi}^a \exp(-ip_0x_0)$. With this choice, Eq. (2.8) becomes:

$$\sum_{\alpha=1}^{n-1} \frac{\partial^2}{\partial x_\alpha^2} \Psi^a = -2ip_0 \frac{\partial}{\partial x_0} \Psi^a, \tag{2.9}$$

which is a vector multidimensional Schrödinger-type differential equation. By analogy with electromagnetic waves, the solutions of Eq. (2.9) can be represented as:

$$\Psi^a = G U^a, \tag{2.10}$$

where $U^a(x_0, x_1, \dots, x_{n-1})$ captures all the vector and topological properties of the wave, and the scalar function $G(x_0, x_1, \dots, x_{n-1})$ represents the wave envelope that governs the properties of the wave propagation:

$$G(x_0, \dots, x_{n-1}) = \left(\frac{\sqrt{2}}{\sqrt{\pi} r_0 \zeta(x_0)} \right)^{\frac{n-1}{2}} \times \exp\left(-\frac{r^2}{r_0^2 \zeta(x_0)}\right), \tag{2.11}$$

where $r^2 = \sum_{\alpha=1}^{n-1} x_\alpha^2$, $\zeta(x_0) = 1 + 2ix_0/(p_0r_0^2)$, and r_0 is a constant representing the initial radius of the $(n-2)$ -sphere that bounds the $(n-1)$ -ball at $x_0 = 0$ (defined such that the amplitude equals e^{-1} of its peak).

To facilitate the following discussion, we analyse the scalar wave envelope given by Eq. (2.11), which satisfies the normalization condition and thereby ensures finite wave energy:

$$\int_{\mathbb{R}^{n-1}} G G^* d\mathbb{R}^{n-1} = 1, \tag{2.12}$$

where the integration is carried out over the entire $(n-1)$ -ball; $d\mathbb{R}^{n-1} = dx_1 dx_2 \dots dx_{n-1}$ denotes an element of the $(n-1)$ -dimensional Euclidean space; and $G G^*$ represents the wave intensity:

$$G G^* = \left(\frac{2}{\pi r_0^2 (1 + 4x_0^2/p_0^2 r_0^4)} \right)^{\frac{n-1}{2}} \times \exp\left(-\frac{2r^2}{r_0^2 (1 + 4x_0^2/p_0^2 r_0^4)}\right). \tag{2.13}$$

Due to the exponential part of the function, it spreads monotonically over the interval $(0 \leq x_0 < +\infty)$. Consequently, all points of equal amplitude in function Eq. (2.13) on the initial hyperplane $x_0 = 0$ evolve with x_0 as follows:

$$R = r_a \sqrt{1 + 4x_0^2/(p_0^2 r_0^4)}, \tag{2.14}$$

where R is the radial distance from the axis of symmetry, defined by $r = 0$, to the points of equal intensity at a given x_0 ; and r_a is a parameter that defines the initial distance to those points at $x_0 = 0$. In other words, at any fixed hyperplane x_0 , the expression for the distance R defines the radius of an $(n-2)$ -sphere embedded in $(n-1)$ -dimensional space. In Cartesian coordinates, the equation for this sphere can be written as:

$$\sum_{\alpha=1}^{n-1} x_\alpha^2 = R_{x_0=\text{const}}^2. \tag{2.15}$$

Any surface from the set Eq. (2.14), parameterized by r_a , can thus be interpreted as a hyperboloid of revolution representing the evolution of the sphere given by Eq. (2.15) with respect to x_0 :

$$\sum_{\alpha=1}^{n-1} x_{\alpha}^2 - \frac{4r_a^2 x_0^2}{p_0^2 r_0^4} = r_a^2. \quad (2.16)$$

Each hyperboloid Eq. (2.16) bounds the wave so that:

$$\Omega_{n-1} \int_0^R r^{n-2} G G^* dr = P\left(\frac{n-1}{2}, \frac{2r_a^2}{r_0^2}\right) = \text{const}, \quad (2.17)$$

where Ω_{n-1} is the surface area of a unit $(n-1)$ -sphere, and P is the regularised incomplete gamma function.

Note that the hyperboloid in the set described by Eq. (2.16) exhibits symmetry among all coordinates when:

$$\frac{p_0 r_0^2}{2} = r_a. \quad (2.18)$$

Under this condition, the conservation law in Eq. (2.17) simplifies to:

$$\Omega_{n-1} \int_0^R r^{n-2} G G^* dr = P\left(\frac{n-1}{2}, r_a p_0\right) = \text{const}, \quad (2.19)$$

with the intensity given by:

$$G G^* = \left(\frac{2}{\pi(r_a^2 + x_0^2)}\right)^{\frac{n-1}{2}} \exp\left(-\frac{2r^2}{r_a^2 + x_0^2}\right), \quad (2.20)$$

and the surface Eq. (2.16) corresponds to a standard one-sheet hyperboloid:

$$\sum_{\alpha=1}^{n-1} x_{\alpha}^2 - x_0^2 = r_a^2, \quad (2.21)$$

Equation (2.21) can be interpreted as an $(n-1)$ -dimensional de Sitter space, viewed as a submanifold of Minkowski space $\mathbb{R}^{1,n-1}$ with the metric:

$$ds^2 = \sum_{\alpha=1}^{n-1} dx_{\alpha}^2 - dx_0^2. \quad (2.22)$$

Again, the hyperboloid described by Eq. (2.21) represents the evolution with x_0 of points of equal intensity on the wavefront. At any given x_0 , these points form an $(n-2)$ -sphere, as described by Eq. (2.15), with a radius given by:

$$R = \sqrt{r_a^2 + x_0^2}, \quad (2.23)$$

The nonlinearity of the function $R(x_0)$, given by Eq. (2.23), results in its infinite differentiability with respect to x_0 :

$$d^j R / dx_0^j = P_j(x_0) / R^{2j-1}, \quad (2.24)$$

where $P_j(x_0)$ is a polynomial of degree j .

The first three derivatives formally represent the speed:

$$v(x_0, r) = x_0 / R, \quad (2.25)$$

acceleration:

$$\dot{v}(x_0, r) = r_a^2 / R^3, \quad (2.26)$$

and jerk:

$$\ddot{v}(x_0, r) = -3r_a^2 x_0 / R^5. \quad (2.27)$$

of points on the spherical surface described by Eq. (2.23), as they evolve with x_0 along the hyperbolic surface in the coordinate system (x_0, r_{n-1}) . Expressing the speed and acceleration relative to the distance R , we have:

$$v(x_0, r) / R = x_0 / (r_a^2 + x_0^2), \quad (2.28)$$

$$\dot{v}(x_0, r) / R = r_a^2 / (r_a^2 + x_0^2)^2. \quad (2.29)$$

In the limit of large positive $x_0 \gg r_a$, these expressions simplify to:

$$v(x_0, r) / R \rightarrow 1 / x_0, \quad (2.30)$$

$$\dot{v}(x_0, r) / R \rightarrow r_a^2 / x_0^4. \quad (2.31)$$

These results correlate with the observable electromagnetic wave properties discussed in Section 1, where the spreading and acceleration of a freely propagating (2+1)(2+1)-dimensional wavefunction were thoroughly analyzed and demonstrated experimentally. [15].

2.2. Modulating Functions in Multi-Dimensional Representation

Our findings in the previous section revealed the evolution of the scalar envelope $G(x_0, x_1, \dots, x_{n-1})$ Eq. (2.13) of the more general wavefunction Eq. (2.10). This envelope constitutes the empty space or background for all possible vector fields and topological singularities described by the modulation functions $\mathbf{U}^a$.

To find an equation for the function $\mathbf{U}^a$, we follow the procedure established for EM waves, Eqs. (1.8)- (1.11). We change variables in the function $\mathbf{U}^a(x_0, x_1, \dots, x_{n-1})$ to a new set, $\mathbf{U}^a = \mathbf{U}^a(\zeta, X_1, \dots, X_{n-1})$, where $x_\alpha / (r_0 \zeta(x_0))$ for $\alpha = 1, \dots, n-1$ are new dimensionless variables. Substituting this function into the wave equation (2.9), we obtain a differential equation for the modulating function:

$$\nabla_T^2 \mathbf{U}^a - 4\zeta^2 \frac{\partial}{\partial \zeta} \mathbf{U}^a = 0, \quad (3.1)$$

where $\nabla_T = \sum_{\alpha=1}^{n-1} \mathbf{e}_{x_\alpha} \partial_{X_\alpha}$ and $\mathbf{e}_{x_\alpha}$ are unit vectors in the $(n-1)$ -dimensional Cartesian space.

This equation admits separation of variables:

$$\mathbf{U}^a(\zeta, X_1, \dots, X_{n-1}) = \mathbf{u}^a(X_1, \dots, X_{n-1}) X_0(\zeta), \quad (3.2)$$

where $X_0(\zeta) = \exp(\pm K^2(1 - \zeta)/(4\zeta))$, and K is a real constant.

Then the function $\mathbf{u}^a$ satisfies the vector Helmholtz equation with reduced dimension:

$$(\nabla_T^2 \pm K^2) \mathbf{u}^a(X_1, \dots, X_{n-1}) = 0. \quad (3.3)$$

Equation (3.3) is coordinate-invariant in the new coordinate basis normalised to the $(n-1)$ -dimensional curved space defined by the wave envelope Eq. (2.11). Notably, by comparing this equation with Eqs. Eq. (1.2) and (2.3) discussed in previous sections, one finds that its solutions would exhibit a similar structure, but in lower dimensions.

When $K = 0$, Eq. (3.3) reduces to the vector Laplace equation:

$$\nabla_T^2 \mathbf{u}^a = 0. \quad (3.4)$$

This equation describes behavior of scalar and vector fields, including their topological defects and particle-like singularities that may exist within the coherent wave background Eq. (2.11). In 3-dimensional framework, the local topology of the wavefunction may encode the same physical infor-

mation that is conventionally attributed to particles. This perspective resonates with long-standing ideas that matter has a fundamentally geometrical origin [21–24]. Recent theoretical work has argued that particles and geometry are not independent entities, but rather represent the same underlying quantum degrees of freedom, with particles emerging as stable, information-preserving geometrical structures [25]. Our modulation functions provide a concrete realization of this idea by describing particles as localized topological defects or singularities of the wavefunction. However, the full treatment of possible solutions of both Eq. (3.3) and Eq. (3.4) lies beyond the scope of this paper and will be presented in future work.

2.3. Scalar Wave Envelope in a (3+1)-Dimensional Framework

We have not yet discussed the physical interpretation of the wave described by Eq.(2.10) and its scalar envelope given by Eq.(2.11). In this section, we explore possible physical connections to our earlier mathematical results. Firstly, it is important to clarify the nature of the coordinate x_0 . Although the mathematical structure suggests a temporal role, x_0 does not necessarily represent real time explicitly. Instead, it is more accurately viewed as the coordinate indicating the predominant direction of wave propagation. For a coherent electromagnetic wave in a $(2 + 1)$ -dimensional space (see Eq.(1.2)), the coordinate $x_0 = z$ corresponds to a spatial axis along which the wave propagates, thereby acting as a “time-like” coordinate, even if it does not represent real time. In the case of a massless electromagnetic wave in a full 4-dimensional space, the additional coordinate $x_n = ct$, which relates directly to oscillations in the wave’s phase (see Eq.(2.4)), indeed represents a genuine temporal dimension. For dimensions greater than four, the primary propagation coordinate naturally takes on the role of time.

In Section 2, we demonstrated that requiring equal scaling for all Cartesian coordinates in the standard metric given by Eq.(2.22) results in selecting a unique hyperbolic surface described by Eq.(2.21) from the broader set of surfaces defined in Eq.(2.16). This equality in scaling allows us to reinterpret the coordinate x_0 explicitly as a temporal variable through the relationship $x_0 = ct$. With this in mind, we adopt a $(5 + 1)$ -dimensional form for the solution presented in Eq.(2.10), introducing five spatial coordinates (x, y, z, j, g) . Setting the constant $p_5 = m_0 c / \hbar$ and using the relation $p_0 = p_5$ from Eq. (2.7), we can specify the wavefunction given by Eq. (2.2) as follows:

$$\Phi^a(ct, x, y, z, j, g) = \mathbf{U}^a G(ct, x, y, z, j) \times \exp \left[i \left((m_0 c / \hbar) g - (m_0 c^2 / \hbar) t \right) \right] \quad (4.1)$$

with

$$G = \left(\frac{\sqrt{2}}{\sqrt{\pi} r_0 \zeta(t)} \right)^2 \exp \left(-\frac{r^2}{r_0^2 \zeta(t)} \right), \quad (4.2)$$

where $\zeta(t) = 1 + i t / t_0$, $t_0 = m_0 r_0^2 / 2 \hbar = 2 / c p_0$, $\hbar$ is the Planck’s constant, m_0 is a constant with dimension of mass, and $r = \sqrt{x^2 + y^2 + z^2 + j^2}$.

According to Eq. (2.13), the envelope intensity Eq. (4.2) becomes:

$$G G^* = \left(\frac{2}{\pi c^2 (t^2 + t_0^2)} \right)^2 \times \exp \left(-\frac{2 r^2}{c^2 (t^2 + t_0^2)} \right), \quad (4.3)$$

which represents a 4-dimensional wave density.

The critical hyperboloid is now expressed as:

$$R(t) = c t_0 \sqrt{1 + t^2 / t_0^2}. \quad (4.4)$$

This hyperboloid can be described as the continuous evolution of a 3-sphere defined by $R^2(t) = x_1^2 + x_2^2 + x_3^2 + x_4^2$ along the t -coordinate. For a fixed value of t , the radius R of the 3-sphere is determined by the four component coordinate $r(x_1, x_2, x_3, x_4)$, reflecting the fact that the three-dimensional spherical surface is embedded within a higher-dimensional space. Geometrically, the sphere represents a three-dimensional cross-section formed by the intersection of the four-dimensional ball $B^4 = \{r \in \mathbb{R}^4 : r \leq R\}$ and the hyperplane $t = \text{const}$. The entire space of the wave envelope Eq. (4.2) restricted by the sphere satisfies to the conservation law Eq. (2.19):

$$\int_0^R (r^2 G G^*) r dr = \text{const.} \quad (4.5)$$

On the surface defined by Eq. (4.4), the wave intensity given in Eq. (4.3) simplifies to:

$$I(R) = \left(\frac{2}{\pi e R^2(t)} \right)^2, \quad (4.6)$$

In general, the radius defined by Eq. (4.4) resides in four-dimensional spatial space B^4 and does not inherently belong to the three-dimensional sphere characterized by intensity Eq. (4.6). However, we interpret de Sitter space as a spatial sphere Eq. (2.15) evolving together with a fixed wavefront as the ambient time coordinate t changes. In this representation, any cross-section through the center of the sphere reduces spatial dimension on a constant t -slice, resulting in a lower-dimensional sphere with the same radius R . Thus, the three-dimensional space, or 3-ball, characterized by the wavefunction intensity Eq. (4.6), is bounded by a closed two-dimensional sphere of radius $R(x, y, z)$.

The volumetric density within the 3-ball depends explicitly on the radius R as:

$$\rho(R) = R^2 I(R), \quad (4.7)$$

and remains constant at every point within the 3-ball at any fixed time, but according Eqs. (4.4) and (4.6), it evolves with time as:

$$\rho(t) = \rho_0 / (1 + t^2/t_0^2), \quad (4.8)$$

where ρ_0 is initial density at $t = 0$.

With this definition, the conservation law given by Eq. (4.5) can be represented in (3+1)-dimensional spacetime as:

$$\oint_S \rho dS = \rho S = \text{const}, \quad (4.9)$$

where dS represents a 2-sphere area element over the t -slice intersection.

Consequently, we derive relation Eq. (4.9), analogous to the conservation law Eq. (4.5), but with a distinct interpretation resulting from integration over the enclosed 2D surface of the homogeneous 3-ball. Specifically, we can rewrite this relation in terms of a 3D spatial coordinates:

$$\int_V \frac{\rho}{r} dV = \frac{\rho V}{R} = \text{const}, \quad (4.10)$$

where the integration is performed within the three-dimensional space (a 3-ball $B^3 = \{r \in \mathbb{R}^3 : r \leq R\}$) with volume $V_{t=\text{const}} = \int_{\mathbb{R}^3} d\mathbb{R}^3$, $d\mathbb{R}^3 = dx dy dz$.

Interpreting the density $\rho(t)$ of the 3-ball as mass-energy density, $\rho(t) = m/V$, we obtain:

$$\frac{m}{r_a \sqrt{1 + t^2/t_0^2}} = \frac{m_0}{r_a}. \quad (4.11)$$

Since the density is distributed homogeneously within 3-dimensional space at any given moment t , the mass-energy m at each instant is also uniformly distributed.

For further estimations, it is preferable to express relation Eq. (4.11) in the form:

$$\rho V / R = m_0 / r_a. \quad (4.12)$$

It is also worth noting that, the mass-energy of the 3-ball increases with time, while the relation Eq. (4.11) itself remains invariant.

3. Discussion

In this section, we discuss the most significant results of the previous analysis and their connection to observable physical phenomena. First, we establish the connection between the parameters of the wavefunction (Eq. (4.1)) and the corresponding physical space. The phase of the multidimensional wavefunction introduces periodicity into the wave distribution across a static coordinate system, implying a time evolution of points along a particular wavefront. In this formulation, the three-dimensional space is represented as the intersection of the propagating wavefront with the “ray” hyperboloid (Eq. (4.4)), which traces the evolution of points with equal intensity on the wavefront. As the wavefront advances, this intersection, corresponding to the three-dimensional space, dynamically evolves over time. This evolution includes spatial expansion with positive acceleration, as described by Eqs. (2.26) and (2.29). Such a scenario leads to the compelling idea that the entire universe may have originated from a single, freely evolving multidimensional particle-wave.

Considering the concept of a single particle-wave universe, we now turn to specifying the physical meanings of the constants r_0 , r_a , t_0 , and m_0 , which have not yet been defined. These constants are not independent; rather, they are related by the expressions: $t_0 = m_0 r_0^2 / 2 \hbar$, $r_a = r_0 = c t_0$. Thus, there are only two independent constants that need to be specified. For further discussion, let us denote them as r_a and m_0 . These constants should be related to the Planck units at least in order of magnitude. Such an assumption is reasonable, as according to recent theoretical perspectives, the universe originated with an initial average volume approximately of Planck order l_p^3 [26,27], with $l_p = \hbar / m_p c$. The other parameters, such as the initial mass m_0 and the Compton wavelength λ , should also be of Planck scale.

To determine the constants r_a and m_0 , we will use the fact that the Planck scale is the natural domain in which quantum localization and gravitational collapse must be treated on equal footing. At this scale, the classical description of a black hole converges with the single-particle quantum description. Regardless of the mass m_0 , the geometric mean of the two characteristic lengths, the Schwarzschild radius r_s and the reduced Compton wavelength $\bar{\lambda}(m_0) = \hbar / (m_0 c)$, is pinned to the Planck scale with the invariant product [28,29]:

$$r_s \bar{\lambda}(m_0) = 2 l_p^2. \quad (5.1)$$

Assuming that the localized space of mass m_0 has the minimal possible energy state corresponding to the Planck energy, $\varepsilon_p = m_p c^2$, and that the Schwarzschild radius r_s coincides with the initial wave localization r_a , we finally find:

$$\begin{aligned} r_a &= 2 l_p, \\ m_0 &= m_p. \end{aligned} \quad (5.2)$$

With these definitions, and considering that $V = (4/3)\pi R^3$, the relation Eq. (4.12) takes the form:

$$R^2 \rho = \frac{3 m_p}{8 \pi l_p}. \quad (5.3)$$

It is worth analyzing Eq. (4.10) and corresponding Eq. (4.12) in detail, particularly in relation to the definition of the associated constant. Note that the integrand on the left-hand side of Eq. (4.10) has the form of a potential, which can be denoted as ϕ :

$$2\rho V/(Rc^2) = \phi/c^2, \quad (5.4)$$

Since the relation Eq. (4.12) is a constant, the potential must also remain constant. Taking into account that $r_a/m_0 = 2l_p/m_p$, as given by Eq. (5.2), the constant associated with this potential corresponds precisely to the gravitational constant, G_N :

$$\phi/c^2 = 1/G_N, \quad (5.5)$$

This relation shows that the potential of the universe remains unchanged from the initial Planck-scale state through all subsequent stages of its evolution. The gravitational constant is deeply connected to this potential and can be derived not only from formal relationships involving Planck units, $G_N = c^2 l_p/m_p$, but also from observational data of the recent universe:

$$G_N = \frac{c^2 R}{2V\rho}. \quad (5.6)$$

Conversely, this relation can also work in reverse and be used to predict parameters that cannot yet be precisely determined through direct observation. This important result also aligns with earlier indications of a relationship between the potential of the universe's total mass and the phenomena of inertia via the gravitational constant, as suggested in previous works [30,31]. While these earlier predictions are indeed noteworthy, our results suggest that the gravitational constant originates from a global property of 'empty' space, wherein the total mass increases over time according to Eq. (4.11). A consequence of the relationship Eq. (5.6) is the intriguing idea that the equivalence between inertia and gravity, traditionally expressed in terms of mass, is fundamentally linked to the wave envelope of the universal wavefunction.

This important result points to an intrinsic connection between the universal wavefunction, which is fundamentally a quantum object, and the key gravitational properties of space.

Indeed, in our model the radius $R(t)$ of the critical 3-sphere (Eq. (4.4)) directly determines all geometric and dynamical quantities of space at any given time. In the FRW framework, the scale factor $a(t)$ plays the same role, since it measures the relative expansion of space. Therefore, introducing the substitution

$$a(t) \equiv \frac{R(t)}{c t_0} = \sqrt{1 + t^2/t_0^2}, \quad (5.7)$$

keeps all equations formally identical while placing them in a notation familiar from standard cosmology. In conventional FRW cosmology, the role of gravity in the expansion is encoded in the continuity equation

$$\dot{\rho} + 3H\left(\rho + \frac{p}{c^2}\right) = 0, \quad H = \frac{\dot{a}}{a} = \frac{t}{t_0^2 + t^2}, \quad (5.8)$$

where p represents the effective pressure that characterises the background as a cosmological fluid, and H is the Hubble parameter.

In our model, the background density satisfies Eq. (4.8), leading to:

$$\rho(t) = \rho_0 a^{-2}. \quad (5.9)$$

Comparing this relation with the continuity-equation solution $\rho \propto a^{-3(1+w)}$ gives the effective equation-of-state parameter w_{eff} :

$$w_{\text{eff}} = -1/3. \quad (5.10)$$

Thus the scalar-envelope background behaves like an effective barotropic fluid with $p = w_{\text{eff}}\rho c^2$, but it does not represent an actual physical substance. It represents an effect from the geometry of the scalar envelope of the universal wavefunction. This satisfies the continuity equation without the need for additional source terms. The growth of the total mass-energy then follows from Eq. (4.11)

$$M(t) \propto \rho a^3 \propto a, \quad (5.11)$$

which is fully consistent with the continuity relation. The energy contained in a comoving volume, $E \sim \rho a^3 \propto a$, increases with time, which is allowed in expanding spacetimes and naturally associated here with the effective negative pressure $p = -\rho c^2/3$. The background behaves in this sense like the curvature-like term proportional to a^{-2} in the Friedmann equations, in agreement with the de Sitter-type hyperboloid geometry of the critical surface. Gravitational dynamics are therefore incorporated directly into the expansion law. Gravity does not act as an "external force", but appears as a constant potential of the evolving wavefunction that governs the coupled behaviour of density and cosmic expansion. In this picture, the expansion is not independent of gravitational effects. Gravity emerges from the constant global potential described by Eq. (5.6), and the quantity G_N serves as the link between this intrinsic property and observational cosmology. Expansion and gravity are two aspects of the same conservation principle.

To compare our model with observational data, we require at least one robust and widely accepted reference parameter. All other parameters can then be determined on the basis of this reference through the evolution function Eq. (4.4) and the relations Eq. (5.3) or Eq. (5.6). In this work, we adopt the age of the universe as our primary reference point: $t \cong 4.36 \times 10^{17} \text{ s}$ [32]. Taking this adoption, and using Eq. (4.4) under the assumption that $t \cong R/c$ holds in the current epoch ($t \gg t_0$), the corresponding radius R of the 3-sphere is:

$$R \cong ct = 1.307 \times 10^{26} \text{ m}, \quad (5.12)$$

To find a distance on the surface of the 3-sphere, which represents our actual three-dimensional space, we consider a geodesic or great circle on the sphere by multiplying the radius by 2π . This calculation yields the estimated size of the universe as $d \cong 8.2 \times 10^{26} \text{ m}$, which is very close to the accepted diameter of the universe, $d \approx 8.8 \times 10^{26} \text{ m}$. According to Eq. (5.3), the corresponding density is:

$$\rho = 3m_p / 8\pi l_p R^2 = 9.409 \times 10^{-27} \text{ kg/m}^3. \quad (5.13)$$

The derived density falls within the widely accepted range of 9.1×10^{-27} to $9.9 \times 10^{-27} \text{ kg/m}^3$ [32]. Thus, the relationship described by equation Eq. (5.3) holds remarkably well. However, it is important to note that we consider here only the scalar component of the total wavefunction (Eq.(4.1)), which corresponds to the "empty" or background space. The total density may also include sources of physical fields that are associated with the modulation component of the total wavefunction, as discussed in Section 3, and are beyond the scope of the present analysis.

In the previous section, we derived general expressions for the speed and acceleration of the critical surface of the wavefunction Eqs. (2.25)-(2.31). We can now apply these expressions to the evolution of the 3-sphere associated with space. According to Eq. (2.25), the dimensionless speed evolves nonlinearly, starting from zero and asymptotically approaching unity as $x_0 \rightarrow \infty$. Considering the case $x_0 = ct \gg ct_0$, we have:

$$v(r, x_0) = dR/dx_0 \rightarrow x_0/R \cong 1. \quad (5.14)$$

This means that the dimensional speed of the sphere's expansion asymptotically approaches the speed of light as $t \rightarrow \infty$. Again, using the accepted age of the universe $t \cong 4.36 \times 10^{17} \text{ s}$, we can express this result relative to the distance R (Eqs. (2.28), (2.30)), that is in standard cosmological units:

$$H = v(r, x_0)/t \cong 71 \text{ km/s/Mpc}. \quad (5.15)$$

This result is in close agreement with the most accurate values currently accepted [32–34], and it is not surprising that it coincides with the inverse of the standard definition of the age of the universe in terms of the Hubble parameter. However, this coincidence arises only in the asymptotic limit of large times. During earlier epochs, the relation given by Eq. (5.15) does not hold, and the more general expression in Eq. (2.28) must be used instead.

The nonlinear behaviour of the expansion rate, as predicted by the model at the end of Section 2, results in a non-constant accelerated expansion (Eq. (2.26)), which can be expressed in dimensional units:

$$\dot{v}(r, t) = c^2 r_a^2 / (r_a^2 + c^2 t^2)^{3/2}. \quad (5.16)$$

Unlike the speed Eq. (2.25), which is zero at the initial moment $x_0 = 0$, the acceleration reaches its maximum at that instant. Therefore, it is valuable to calculate this initial acceleration value at $t = 0$:

$$\dot{v}(r, 0) = c^2 / r_a = 2.8 \times 10^{51} \text{ m/s}^2. \quad (5.17)$$

At the current epoch, the estimated value for the acceleration is:

$$\dot{v}(r, t) = r_a^2 / (c t^3) = 4.2 \times 10^{-131} \text{ m/s}^2. \quad (5.18)$$

Note that we provide these numbers solely to illustrate the change in magnitude during the evolution of the wavefunction, since in these units, it is unclear what exactly is accelerating. The physically meaningful quantity is the acceleration per unit space, or equivalently, the acceleration of the 3-sphere radius, represented as $\dot{v}(r, x_0) / R$ (Eq. (2.29)). At the present time this acceleration can be expressed as:

$$\dot{v}(r, t) / R \cong 1.3 \times 10^{-114} \text{ km/s}^2 / \text{Mpc}. \quad (5.19)$$

At any moment t , the acceleration given by Eq. (5.19) remains positive. The fact that the speed of expansion depends on the sign of time, while the acceleration does not, directly reflects how time asymmetry influences the universe's evolution. Importantly, the acceleration continuously diminishes over time, and in the limit $t \rightarrow \infty$, the universe approaches a state of constant-rate expansion. This result aligns closely with recent observational data [35,36]. The large-scale analysis of DESI data also suggests that the universe continues to expand, but the rate of acceleration is decreasing [37,38].

At the conclusion of this section, it is worth focusing specifically on relation Eq.(5.3), which provides a conceptual bridge between quantum mechanics and general relativity, and represents one of the key results of our analysis. While the critical hypersurface Eq.(4.4) and the retained 3-sphere arise naturally from the scalar envelope of the universal wavefunction Eq. (4.2), associating the radius of this sphere directly with both the Compton wavelength and the Schwarzschild radius is a logical requirement for validating equations (4.6)–(4.11). Although the Schwarzschild radius is traditionally defined within three-dimensional spatial geometry, theoretical considerations suggest that analogous formulations may extend to higher-dimensional representations [39]. Thus, from a formal perspective, the critical 3-sphere corresponds to the horizon of a four-dimensional black hole, with its radius given by Eq.(4.4). In this manner, our model supports the long-standing idea that the universe itself may resemble a black hole [40–46], albeit with a key conceptual distinction. The traditional conception suggests that the universe either exists within or originated from the interior of a black hole embedded in a three-dimensional spatial geometry. In contrast, our representation posits that the universe itself corresponds to the horizon of a black hole in four-dimensional space.

This distinction becomes clearer when the two conceptions are directly compared. The three-dimensional spatial configuration corresponds to $n = 4$ in Eq. (2.11), in which case the critical surface described by Eq.(2.15) becomes a 2-sphere that encloses approximately 74% of the total wave energy given by Eq.(2.19). If the Schwarzschild radius criterion given by Eq. (5.2) is applied to this sphere, the relations in Eqs. (4.5)–(4.10) no longer hold in this reduced-dimensional scenario. The resulting Planck-scale black hole would exist solely at the moment $t = 0$, as the subsequent expansion given by

Eq.(2.25) invalidates the criteria for any $t > 0$. Immediately after this initial moment, the black hole would effectively “evaporate,” in accordance with Eq. (2.19). This result is in excellent agreement with recent perspectives on primordial black holes [47].

Conversely, our concept is based on a four-dimensional spatial configuration, corresponding to $n = 5$ in Eq.(2.11). In this case, the increasing radius of the critical surface (4.4) is precisely balanced by the growth of the volumetric mass-energy m (4.11), allowing the three-dimensional space to consistently satisfy the black hole criterion. Remarkably, this critical surface consistently encloses approximately 60% of the integrated wave intensity, as follows from Eq.(4.5). The entire volume described by Eq. (4.5), representing the portion of the universal wavefunction bounded by the horizon, is causally disconnected from the 3-sphere, which represents the three-dimensional space. This may suggest an interpretation of dark energy as the portion of the wavefunction (4.2) that is enclosed by the critical 3-sphere at any given moment. Unlike conventional dark energy, this hidden “energy” is not an agent driving the expansion but is instead an intrinsic property of the critical 3-sphere and a consequence of the wavefunction’s evolution. As for the part of the wavefunction that lies beyond the critical surface, one may intuitively speculate that this portion could project onto the horizon—consistent with the notion of a holographic universe [48,49], but extended to higher dimensions. However, we leave this question outside the scope of the present work, as it requires a more detailed study.

4. Conclusions

In conclusion, this work outlines a theoretical model in which the universe emerges from a multi-dimensional universal wavefunction of a single Planck-scale particle-wave. By integrating quantum mechanics with singular wave theory, it provides a self-contained explanation for the emergence of time, cosmic expansion characterized by decreasing acceleration, and large-scale uniformity without invoking inflation phase and an initial singularity.

Representing the universe as a unified, multidimensional wavefunction predominantly propagating in one direction, effectively addresses several persistent cosmological puzzles. The inherent self-coherence of the universal wavefunction (Eq. (4.1)) guarantees uniformity of three-dimensional space (Eq. (2.15)), which can be viewed as a 3-sphere resulting from a temporal slice of the critical hyperboloid of de Sitter space (Eq. (2.21)). In this symmetric multidimensional framework, the arrow of time naturally emerges as the coordinate aligned with the principal direction of wave propagation. The framework proposes a novel interpretation of dark energy, viewing it not as a force responsible for driving cosmic acceleration, but as a portion of energy that is causally disconnected and enclosed by the 3-sphere (Eq. (4.4)). Unlike conventional dark energy concepts, this hidden energy emerges naturally from the wavefunction inherent properties. The radius of the 3-sphere evolves as a monotonically increasing and infinitely differentiable function of time, resulting in a positive, time-dependent acceleration of three-dimensional space (Eq.(5.19)). As the result, the rate of cosmic expansion (Eq.(5.15)), predicted in this work, is in very good agreement with current astronomical observations.

Furthermore, conservation of the integrated intensity enclosed by the critical surface (Eq.(4.5)) naturally arises from the wavefunction’s structure, leading to similarity between event horizon and the critical surface of the wavefunction. A direct consequence of the associated conservation law (Eq.(5.3)) is the constant potential of the expanding space, which precisely matches the gravitational constant (Eq.(5.6)). This important result points to an intrinsic connection between the universal wavefunction, which is fundamentally a quantum object, and the key gravitational properties of space, thereby deepening our understanding of quantum–gravitational interactions.

The results presented in this work demonstrate that the evolution of a critical hypersurface associated with a multidimensional wavefunction can provide a self-consistent geometric description of nonsingular cosmic expansion. The derived density scaling satisfies the standard stress–energy continuity equation and corresponds to an effective equation-of-state parameter, while analytical estimates yield expansion parameters compatible with current observational constraints. Within

this framework, the gravitational coupling emerges as an invariant global potential associated with the critical hypersurface. These findings establish a concrete link between wavefunction geometry, conservation laws, and large-scale cosmological dynamics, and suggest a viable direction for further exploration of emergent gravitational behaviour and cosmological evolution.

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