Minimal Causal-Informational Model of Emergent Space-Time (MCIMES)

Sergei Kondrashov

The University of Queensland, Australia

E-mail: sergei.kondrashov@student.uq.edu.au

1. Abstract

Quantum gravity continues to pose significant challenges in theoretical physics, including the reconciliation of general relativity with quantum mechanics, the nature of time, and the small observed value of the cosmological constant. This paper proposes the Minimal Causal-Informational Model of Emergent Space-Time (MCIMES), a new framework that explores quantum information as a possible foundation for physical reality, suggesting that space-time and gravity may emerge from it. Using an abstract interaction graph and drawing on quantum information theory, MCIMES offers a perspective in which space-time arises as an emergent phenomenon, providing potential explanations for its three-dimensionality and the arrow of time through entropic processes. The model suggests an approach to the cosmological constant issue, producing a value aligned with observations without requiring fine-tuning, and puts forward testable predictions, such as a dark energy equation of state parameter $w = -0.97 \pm 0.01$ and specific quantum corrections to black hole entropy. While recognizing its current limitations, MCIMES offers an information-based, background-independent viewpoint that seeks to address key questions in quantum gravity and encourages further exploration and testing.

2. Introduction

Quantum gravity remains one of the most significant unsolved problems in modern theoretical physics [1]. Existing approaches face numerous fundamental difficulties: incompatibility of general relativity (GR) with quantum mechanics, the problem of time, resolution of cosmological singularities, and the mysterious smallness of the cosmological constant (on the order of 10^{-123} in Planck units) [2, 3].

This article presents the Minimal Causal-Informational Model of Emergent Space-Time (MCIMES), offering a relatively new approach to quantum gravity. The model is based on the idea that quantum information, rather than space-time and matter, is the fundamental entity from which all physical structures emerge [6].

The author is fully aware of the weaknesses of the proposed model. Its development was motivated by the following considerations: 1) General relativity demonstrated such a level of relativity in the basic components of classical physics that it calls into question their potential "fundamentality" [7]; 2) Intuition suggests that organizational laws of more complex systems, although not reducible to the properties of their components, nevertheless arise from them and their synergy [8]; 3) Quantum mechanics has demonstrated the highest level of reliability and seems extraordinarily close to the perfect description of the most basic foundations of the physical world [9]; 4) A realistic model unifying quantum and relativistic physics should be sufficiently simple in the sense that it should not contain key elements introduced ad hoc [10].

The proposed model, developed based on the assumptions described above, contains virtually no fundamentally new elements that have not been experimentally verified by modern physics. The author has sought to adhere to the principle of "Occam's razor." In this respect, the model is quite simple and allows for a number of falsifiable predictive hypotheses [13]. However, it relies on the global quantum state as a fundamental object from which space-time emerges. The apparent theoretical elegance of the model is largely related to this, transforming the global quantum state into something of a Deus ex Machina [12]. The ontological problem associated with the interpretation of "quantum information" as the "foundation" of the observable physical world is also evident.

Moreover, the significant number of testable predictions increases to a critical level the risk that the model will demonstrate its fundamental error even at the stage of initial testing [13]. Nevertheless, the author's determination to present this model for discussion stems from the deep conviction that even negative results of testing the predictions of such a model, which combines well-known and repeatedly verified elements in a sufficiently simple and obvious manner, can bring great benefit to our deepening understanding of physical reality [14].

MCIMES differs from other approaches to quantum gravity in the following key features:

- Complete independence from background space-time (background independence) [1, 15]
- Emergent appearance of space-time from quantum-informational relations [6, 16]
- Natural explanation of the three-dimensionality of space [17]
- Explanation of the small value of the cosmological constant without fine-tuning [2, 18]
- Specific quantitatively testable predictions [19]

Unlike many competing theories, MCIMES does not a priori postulate the existence of space-time, but rather derives it as an emergent property of a more fundamental informational structure [6, 21].

The article is organized as follows. Section 2 discusses the philosophical foundations of the model. Section 3 formulates the axiomatic foundations in the form of a system of postulates. Section 4 presents the mathematical formalism of the model. Section 5 describes the mechanism of emergence of space-time and gravity. Section 6 examines the physical consequences and predictions of the model. Section 7 compares it with other approaches to quantum gravity. Section 8 contains the conclusion and discussion of directions for further development of the theory.

3. Philosophical Foundations

MCIMES proposes an ontological shift that may seem radical to some: from the traditional view of space-time and matter as primary elements of reality to quantum information as a more fundamental entity [6, 25]. In this paradigm, space-time is not the primary arena in which physical processes unfold, but emerges from quantum-informational relations between fundamental subsystems [16].

This approach fundamentally differs from most other approaches to quantum gravity. In string theory, space-time is often assumed to be given (although it can be modified) [20], while in loop quantum gravity (LQG), the geometry of space-time is quantized [5]. In MCIMES, space-time is completely derived from more fundamental quantum-informational relations [26].

The philosophical position of MCIMES can be characterized as information monism: information is considered the fundamental substance from which all other physical structures emerge [27]. This has profound implications for understanding the nature of reality and is consistent with some modern interpretations of quantum mechanics, for example, with information-theoretical approaches [28, 29].

The MCIMES approach resonates with Wheeler's ideas of "it from bit" (everything from information) [22], but goes somewhat further, formulating a specific mathematical mechanism for the emergence of space-time from quantum-informational relations [23]. The model also has connections with Rovelli's concept of "relational quantum mechanics," where physical reality is viewed as a network of relations between observers [15].

It is important to note that MCIMES is not a purely philosophical concept, but represents a physical theoretical model with a specific mathematical formalism and testable predictions [19].

4. Axiomatic Foundations

MCIMES is based on the following fundamental postulates:

4.1. Postulate 1 (Primacy of Quantum Information over Geometry)

The fundamental entity of the model is not space-time or matter, but quantum information, from which all physical structures emerge [6, 25].

Mathematical formulation:

(i) The basic object of the model is an abstract interaction graph $G = (V, E)$, not assuming an initial embedding in any physical space [30]:

- V – set of vertices (quantum subsystems)
- $E \subset V \times V$ – set of edges (informational interactions)

(ii) Each vertex $i \in V$ is associated with a local Hilbert space $\mathcal{H}_i$ [9]

(iii) The global Hilbert space is defined as the tensor product of the local ones [24]:

$$\mathcal{H}_G = \bigotimes_{i \in V} \mathcal{H}_i \tag{1}$$

(iv) The global quantum state $|\Psi\rangle \in \mathcal{H}_G$ or density operator ρ completely describes the state of the entire system [35]

4.2. Postulate 2 (Background Independence)

All physical laws and observables must be formulated without relying on a pre-given space-time structure [1, 15].

An element of the model X is background-independent if and only if:

(i) The definition of X contains no references to space-time concepts

(ii) X is invariant with respect to all automorphisms of the algebraic structure

(iii) The physical interpretation of X does not depend on the specific representation of the structure

(iv) The properties of X can be fully expressed through informational functionals [11]

4.3. Postulate 3 (Emergence of Space-Time)

Space-time and its metric structure are not postulated a priori, but arise from the dynamics of information-causal relations between quantum subsystems [16, 31].

Mathematical formulation:

(i) **Emergent metric**: The metric structure of emergent space-time is defined through informational distances between subsystems [23, 36]:

$$d_I(i,j) = \sqrt{-\ln\left(\frac{I(i:j)}{\sqrt{S(\rho_i)S(\rho_j)}}\right)} \tag{2}$$

where $I(i:j)$ is the mutual information between subsystems, $S(\rho_i)$ is the von Neumann entropy.

(ii) **Entropic time**: The direction and "pace" of time are defined through the change of entanglement entropy [19, 37]:

$$t_{\text{entr}} = \int_0^t F\left(\sum_{p=0}^{2} w_p \frac{dS^{(p)}(t')}{dt'}\right) dt' \tag{3}$$

where $S^{(p)}(t')$ is the entanglement entropy of patterns of degree p.

4.4. Postulate 4 (Principle of Minimal Information Loss)

The structure of fundamental interactions and the dynamics of the system are optimized according to the criterion of minimizing the loss of quantum information when dividing the global system into subsystems [21, 39].

Mathematical formulation:

(i) Information loss functional for an abstract graph:

$$L(G) = \sum_{i \in V} S(\rho_i) - S(\rho) \tag{4}$$

where $S(\rho_i) = -\mathrm{Tr}(\rho_i \ln \rho_i)$ is the von Neumann entropy of the reduced state, and $S(\rho)$ is the entropy of the global state [36].

(ii) The optimal structure of the interaction graph minimizes this functional:

$$G_{\text{opt}} = \arg\min_G L(G) \tag{5}$$

4.5. Postulate 5 (Physical Realism of Interactions)

Physically realistic interactions between subsystems must satisfy the principles of locality, finite energy, and extensivity [22, 40].

An interaction graph $G = (V, E)$ satisfies the principle of locality if:

(i) It is sparse: $\forall v \in V : \deg(v) = O(\log |V|)$

(ii) The strength of interaction (correlation) between subsystems decreases with distance

(iii) The graph allows embedding in a space of small fixed dimension with low metric distortion [17]

4.6. Postulate 6 (Quantum Evolution and Discrete Covariance)

The dynamics of the system obeys the laws of quantum theory and possesses invariance with respect to different "trajectories" of growth of the interaction graph [9, 42].

Mathematical formulation:

(i) **Quantum dynamics**: At each elementary step of evolution:

$$|\Psi_{n+1}\rangle = \hat{U}_n |\Psi_n\rangle \tag{6}$$

where $\hat{U}_n$ is a local unitary operator [24].

(ii) **Discrete covariance**: Different sequences of local transformations leading to isomorphic final graphs are physically equivalent [43].

4.7. Postulate 7 (Cosmological Constant as a Measure of Quantum Relative Entropy)

The cosmological constant emerges as a measure of quantum relative entropy between the current and reference states of the global system [2, 23].

Mathematical formulation: The cosmological constant is defined by the expression [36, 44]:

$$\Lambda = \frac{1}{2\kappa}\mathrm{Tr}_{\mathcal{H}}[D(|\psi\rangle\langle\psi| \,||\, |\psi_{\mathrm{ref}}\rangle\langle\psi_{\mathrm{ref}}|)] \tag{7}$$

where $D(\rho||\sigma) = \mathrm{Tr}(\rho\ln\rho - \rho\ln\sigma)$ is quantum relative entropy, $|\psi\rangle$ is the global quantum state, $|\psi_{\mathrm{ref}}\rangle = \bigotimes_{i\in V}|0_i\rangle$ is the reference state with minimal correlations, and $\kappa = \frac{\ell_P^2}{8\pi G}$.

4.8. Postulate 8 (Entropic Initial State and Clock Subsystems)

The arrow of time manifests only in the presence of a correlation gradient, which requires low entropy in the initial state of the system [19, 37].

5. Mathematical Formalism

5.1. Abstract Algebraic Structure of Relations

The fundamental object of the model is the algebraic structure of relations $\mathcal{A} = (S, \mathcal{R})$, where S is an abstract set of indices corresponding to elementary algebraic objects, and $\mathcal{R} \subset S \times S$ is the connectivity relation between indices, defining informational interactions [30].

This structure can be represented by an equivalent interaction graph $G = (V, E)$, where:

- $V = S$ – set of vertices corresponding to elementary subsystems
- $E = \{(i, j) \in S \times S \mid (i, j) \in \mathcal{R}\}$ – set of edges corresponding to informational interactions

It is fundamentally important that the graph G does not assume an initial embedding in any physical space, but represents a purely algebraic structure, which is consistent with the principle of background independence [1, 18].

For each index $i \in S$, an elementary algebraic subspace $\mathcal{H}_i$ is defined as an abstract Hilbert space with inner product $\langle\cdot,\cdot\rangle_i : \mathcal{H}_i \times \mathcal{H}_i \to \mathbb{C}$ [35].

The composite algebraic space is defined as the tensor product of elementary subspaces:

$$\mathcal{H}_{\mathcal{A}} = \bigotimes_{i\in S}\mathcal{H}_i \tag{8}$$

The global quantum state $|\Psi\rangle \in \mathcal{H}_{\mathcal{A}}$ is defined as a unit norm vector ($\langle\Psi|\Psi\rangle = 1$). Alternatively, the state can be specified by a density operator $\rho : \mathcal{H}_{\mathcal{A}} \to \mathcal{H}_{\mathcal{A}}$, where $\rho = \rho^\dagger \geq 0$ and $\mathrm{Tr}(\rho) = 1$ [24].

For a subset of vertices $A \subset V$, the reduced algebraic state ρ_A is defined as the partial trace of the global state ρ over the complementary degrees of freedom:

$$\rho_A = \mathrm{Tr}_{V\setminus A}(\rho) \tag{9}$$

The operator algebra $\mathcal{B}(\mathcal{H}_{\mathcal{A}})$ consists of all bounded linear operators on $\mathcal{H}_{\mathcal{A}}$. For each subsystem $i \in S$, a local operator algebra $\mathcal{B}(\mathcal{H}_i)$ is defined, acting non-trivially only on $\mathcal{H}_i$ [46].

For each pair of interacting subsystems $(i, j) \in \mathcal{R}$, an interaction operator is defined as:

$$\hat{T}_{ij} = \sum_{\alpha} \hat{O}_i^{\alpha} \otimes \hat{O}_j^{\alpha} \otimes \mathbb{I}_{S\setminus\{i,j\}} \tag{10}$$

where $\hat{O}_i^{\alpha} \in \mathcal{B}(\mathcal{H}_i)$, $\hat{O}_j^{\alpha} \in \mathcal{B}(\mathcal{H}_j)$, and $\mathbb{I}_{S\setminus\{i,j\}}$ denotes the identity operator on all other subspaces [40].

This formalism fully implements the principle of primacy of quantum information over geometry, since space-time is not postulated a priori, but emerges from informational relations between quantum subsystems [6, 25]. All physical dynamics are formulated in terms of changes in quantum correlations, not in terms of a pre-existing space-time structure.

5.2. Reduced States and Information Measures

For a subset of vertices $A \subset V$, the reduced algebraic state ρ_A is defined as the partial trace of the global state ρ over the complementary degrees of freedom:

$$\rho_A = \mathrm{Tr}_{V\setminus A}(\rho) \tag{11}$$

The von Neumann entropy for the reduced state ρ_A is defined as [36]:

$$S(\rho_A) = -\mathrm{Tr}(\rho_A \ln \rho_A) = -\sum_i \lambda_i \ln \lambda_i \tag{12}$$

where λ_i are the eigenvalues of the operator ρ_A.

The mutual information between two subsystems $A, B \subset V$ is defined as [47]:

$$I(A : B) = S(\rho_A) + S(\rho_B) - S(\rho_{A\cup B}) \tag{13}$$

5.3. Information Distance and Emergent Metric

The information distance between subsystems i and j is defined as [25, 48]:

$$d_I(i, j) = \sqrt{-\ln\left(\frac{I(i:j)}{\sqrt{S(\rho_i)S(\rho_j)}}\right)} \tag{14}$$

provided that $I(i:j) > 0$ and $S(\rho_i), S(\rho_j) > 0$.

In the thermodynamic limit ($|V| \to \infty$), the information distance d_I satisfies all the axioms of a metric:

(i) Non-negativity: $d_I(i,j) \geq 0$

(ii) Identity of indiscernibles: $d_I(i,j) = 0 \iff i = j$

(iii) Symmetry: $d_I(i,j) = d_I(j,i)$

(iv) Triangle inequality: $d_I(i,k) \leq d_I(i,j) + d_I(j,k)$

The most important result arising from the presented approach is the fact that the emergent metric structure of space-time is completely determined through informational distances between quantum subsystems. In particular, the introduced formula [16, 31]

$$d_I(i,j) = \sqrt{-\ln\left(\frac{I(i:j)}{\sqrt{S(\rho_i)S(\rho_j)}}\right)} \tag{15}$$

defines a metric distance, where $I(i:j)$ represents the mutual information between subsystems i and j, and $S(\rho_i)$ and $S(\rho_j)$ are the von Neumann entropies of their reduced states. This formula not only satisfies all the axioms of a metric space (non-negativity, symmetry, identity of indiscernibles, and triangle inequality), but also emphasizes that the geometric structure of emergent space-time arises directly from the correlation structure of the quantum state of the system.

The metric operator $\hat{D}_{\mu\nu}$ on the graph $G = (V, E)$ has the form [49]:

$$\hat{D}_{\mu\nu} = \sum_{i,j \in V} \sum_{p,q=0}^{2} c_{ij}^{(p,q)} (\hat{O}_i^{\mu})^{(p)} \otimes (\hat{O}_j^{\nu})^{(q)} \tag{16}$$

where $c_{ij}^{(p,q)}$ are coefficients determined by quantum correlations, and $(\hat{O}_i^{\mu})^{(p)}$ are operators corresponding to information patterns of degree p.

For the time component, we define $(\hat{O}_i^0)^{(p)} = i\hat{p}_i^{(p)}$ (imaginary unit multiplied by the momentum operator), and for spatial components $(\hat{O}_i^k)^{(p)} = \hat{q}_i^{k(p)}$ (coordinate operators).

The emergent metric is defined as the quantum average of the metric operator:

$$g_{\mu\nu}(x) = \langle \hat{D}_{\mu\nu}(x) \rangle \tag{17}$$

5.4. Information Loss Functional

For a quantum system described by a global quantum state ρ on an interaction graph $G = (V, E)$, the information loss functional $L(\rho, G)$ is defined as [21, 39]:

$$L(\rho, G) = \sum_{i \in V} S(\rho_i) - S(\rho) \tag{18}$$

In the class of physically admissible information functionals, only a functional of the form $L(G) = \alpha \left(\sum_{i \in V} S(\rho_i) - S(\rho) \right)$, where $\alpha > 0$ is a positive constant, satisfies the conditions of invariance, additivity, monotonicity, and positivity [36].

5.5. Inevitability of Lorentzian Signature

In the thermodynamic limit, the emergent metric $g_{\mu\nu}(x) = \langle \hat{D}_{\mu\nu}(x) \rangle$ inevitably acquires a Lorentzian signature $(-,+,+,+)$ for physically realizable quantum states with positive correlations [50].

Proof (scheme): For the metric operator, defined through the time component $(\hat{O}_i^0)^{(p)} = i\hat{p}_i^{(p)}$ and spatial components $(\hat{O}_i^k)^{(p)} = \hat{q}_i^{k(p)}$, when calculating expectation values we get [49]:

(i) Time component: $g_{00} = -\sum_{i,j} \sum_{p,q} c_{ij}^{(p,q)}(x) \langle \hat{p}_i^{(p)} \otimes \hat{p}_j^{(q)} \rangle < 0$, since $c_{ij}^{(p,q)}(x) > 0$ and $\langle \hat{p}_i^{(p)} \otimes \hat{p}_j^{(q)} \rangle > 0$.

(ii) Spatial components: $g_{kk} = \sum_{i,j} \sum_{p,q} c_{ij}^{(p,q)}(x) \langle \hat{q}_i^{k(p)} \otimes \hat{q}_j^{k(q)} \rangle > 0$.

(iii) Mixed components: $g_{0k} \approx 0$ due to the different parity of the operators [46].

Thus, the metric has a diagonal form with signature $(-,+,+,+)$.

5.6. Categorical Representation of Relation Structure and Functor Transition

For a deeper understanding of the background-independent nature of MCIMES, a categorical approach is needed, which creates a rigorous mathematical bridge between the algebraic structure of relations and the quantum dynamics of the system [43].

The algebraic structure of relations $\mathcal{A} = (S, \mathcal{R})$ can be represented as a category $\mathbf{C}_{\mathcal{A}}$, where [45]:

- Objects of the category – elements of the set S (elementary subsystems)
- Morphisms of the category – for each pair $(i,j) \in \mathcal{R}$ there exists a morphism $f_{ij} : i \to j$
- Composition of morphisms $f_{jk} \circ f_{ij} = f_{ik}$ is defined for all $(i,j), (j,k) \in \mathcal{R}$ through the transitive closure of the relation $\mathcal{R}$
- Identity morphisms $\mathrm{id}_i : i \to i$ are defined for each $i \in S$

The connection between the categorical and graph representations is established by the theorem that the category $\mathbf{C}_{\mathcal{A}}$ is isomorphic to the path category of the directed graph $G = (V, E)$, where $V = S$ and $E = \{(i,j) | (i,j) \in \mathcal{R}\}$.

The category of quantum processes **QProc** is defined as follows [42]:

- Objects – graph configurations $G_t = (V_t, E_t)$, indexed by the evolution parameter t

- Morphisms – $\mathcal{E}_{t_1 \to t_2} : G_{t_1} \to G_{t_2}$ – quantum processes that transform one configuration into another
- Composition – $\mathcal{E}_{t_2 \to t_3} \circ \mathcal{E}_{t_1 \to t_2} = \mathcal{E}_{t_1 \to t_3}$ – sequential application of processes

The category **QProc** is a symmetric monoidal category with the following structures:

- Tensor product of objects: $G_1 \otimes G_2$ represents the independent coexistence of configurations
- Tensor product of morphisms: $\mathcal{E}_1 \otimes \mathcal{E}_2$ represents the parallel execution of processes
- Natural isomorphisms of associativity, unitarity, and commutativity

The quantization functor $\mathcal{Q} : \mathbf{C}_{\mathcal{A}} \to \mathbf{Hilb}$ from the category of relation structure to the category of Hilbert spaces **Hilb** is defined as [24]:

- For each object $i \in \mathbf{C}_{\mathcal{A}}$, the functor $\mathcal{Q}$ assigns a Hilbert space $\mathcal{Q}(i) = \mathcal{H}_i$
- For each morphism $f_{ij} : i \to j$, the functor $\mathcal{Q}$ assigns a linear operator $\mathcal{Q}(f_{ij}) : \mathcal{H}_i \to \mathcal{H}_j$

The state functor $\mathcal{S} : \mathbf{QProc} \to \mathbf{DensOp}$ from the category of quantum processes to the category of density operators **DensOp** is defined as:

- For each object $G_t \in \mathbf{QProc}$, the functor $\mathcal{S}$ assigns a density operator $\mathcal{S}(G_t) = \rho(G_t)$
- For each morphism $\mathcal{E}_{t_1 \to t_2}$, the functor $\mathcal{S}$ assigns a quantum channel $\mathcal{S}(\mathcal{E}_{t_1 \to t_2})$

The functors $\mathcal{Q}$ and $\mathcal{S}$ are coordinated in the sense that for any two configurations G_1 and G_2 connected by evolution $\mathcal{E}_{1 \to 2}$, the corresponding change in quantum state is described by a quantum channel:

$$\rho(G_2) = \mathcal{S}(\mathcal{E}_{1 \to 2})[\rho(G_1)] \tag{19}$$

The causal structure of the category **QProc** is expressed through a partial order on objects and a "forgetting the future" functor, which implements the axiom of minimal initial conditions and ensures causality of the emergent space-time [15, 37].

The categorical approach allows establishing the invariance of the theory with respect to isomorphisms of the category, which confirms its background independence and ensures the independence of physical predictions from the choice of a specific parameterization of the causal order of events.

5.7. Hamiltonian Evolution and Dynamics of the Interaction Graph

The central element of the dynamic description of the MCIMES model is the construction of the global Hamiltonian of the system, which determines the evolution of the quantum state of the interaction graph. A fundamental feature of this approach is the possibility of representing the global Hamiltonian as a sum of local and pairwise interactions [40].

For an interaction graph $G = (V, E)$, the global Hamiltonian has the form:

$$\hat{H}_G = \sum_{i \in V} \hat{H}_i + \sum_{(i,j) \in E} \hat{H}_{ij} \tag{20}$$

where $\hat{H}_i$ are operators acting only on individual subsystems i, and $\hat{H}_{ij}$ are interaction operators between subsystems i and j.

Such a decomposition of the Hamiltonian naturally arises from the expansion of operators in a basis, taking into account the principle of locality of interactions. For physically realistic systems, the coefficients for many-body interactions (three- and more-body) decrease exponentially with the increase in the number of involved subsystems, which allows us to limit ourselves in the first approximation to only one- and two-body interactions.

It is important to emphasize that the structure of the graph $G = (V, E)$ is not given a priori, but is determined by the structure of the Hamiltonian itself — edges (i, j) exist only between those vertices for which the corresponding interactions $\hat{H}_{ij}$ are non-trivial. Thus, the interaction graph arises directly from the structure of quantum-informational correlations.

The dynamics of the system is determined by the quantum evolution of the state $|\Psi\rangle$ according to the Schrödinger equation [9, 40]:

$$i\hbar \frac{d\,|\Psi\rangle}{dt} = \hat{H}_G\,|\Psi\rangle \tag{21}$$

In the discrete representation, at each elementary step of evolution:

$$|\Psi_{n+1}\rangle = \hat{U}_n\,|\Psi_n\rangle \tag{22}$$

where $\hat{U}_n$ is a local unitary operator acting only on a limited subset of vertices and edges of the graph.

The sequential application of such local unitary transformations generates global dynamics which, according to the principle of minimal information loss, tends toward configurations with an optimal structure of quantum correlations. It is this dynamics that ensures the emergent appearance of metric structure, preservation of causal order, and self-consistency of evolution with covariance conditions.

The variational principle for the total action of the system [23, 39]:

$$\mathcal{S}_{\text{total}} = \mathcal{S}_{\text{quantum}} + \mathcal{S}_{\text{geom}} + \mathcal{S}_{\text{constraint}} \tag{23}$$

where the quantum part of the action has the form:

$$\mathcal{S}_{\text{quantum}} = \int dt \left(\langle\psi|i\hbar\partial_t|\psi\rangle - \langle\psi|\hat{H}_G|\psi\rangle \right) \tag{24}$$

leads to a coupled system of equations for quantum and geometric degrees of freedom, which ensures the self-consistency of the evolution of the entire system.

Thus, the Hamiltonian, constructed on the basis of local and pairwise interactions, not only determines the energy structure of the system but also provides the dynamic evolution of the interaction graph, which ultimately leads to the emergent appearance of space-time geometry with the necessary symmetries and conservation laws [16].

6. Emergence of Space-Time and Gravity

6.1. Mechanism of Geometry Emergence

The central idea of MCIMES is that space-time is not fundamental, but emerges from quantum-informational relations between elementary subsystems [6, 16]. Let's consider in more detail the mechanism of this emergence.

The abstract interaction graph $G = (V, E)$ describes the structure of informational relations between elementary quantum subsystems. This graph is initially not embedded in any space, but represents a purely algebraic structure [30].

On this graph, informational measures are defined, such as the von Neumann entropy $S(\rho_i)$ for individual subsystems and the mutual information $I(i:j)$ between subsystems. These informational measures allow defining the information distance $d_I(i,j)$ between subsystems according to the formula [25, 48]:

$$d_I(i,j) = \sqrt{-\ln\left(\frac{I(i:j)}{\sqrt{S(\rho_i)S(\rho_j)}}\right)} \tag{25}$$

In the thermodynamic limit ($|V| \to \infty$), this information distance satisfies all the axioms of a metric, which allows considering the set of graph vertices as a metric space.

The optimal structure of the interaction graph, minimizing the information loss functional $L(G)$ [21], turns out to be embeddable in three-dimensional space with small metric distortions. This explains why the observed physical space is three-dimensional: this dimensionality optimizes the balance between locality of interactions and information capacity [17, 51].

Quantum correlations between subsystems generate not only spatial metric but also the time dimension through entropic time [19, 37]:

$$t_{\text{entr}} = \int_0^t F\left(\sum_{p=0}^{2} w_p \frac{dS^{(p)}(t')}{dt'}\right) dt' \tag{26}$$

The direction of time is determined by the growth of entanglement entropy, which provides a natural explanation for the arrow of time [38, 53].

6.2. Connection with Einstein's Equations

In the continuum limit, minimization of the information functional leads to equations isomorphic to Einstein's equations [7, 18]:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \tag{27}$$

where $G_{\mu\nu}$ is the Einstein tensor, and $T_{\mu\nu}$ is the energy-momentum tensor.

The principle of minimal information loss is a key element of the MCIMES model, since it determines the optimal configuration of the interaction graph, minimizing the leakage of information when decomposing the global quantum state into local subsystems. Mathematically, this principle is expressed through the functional [23, 54]:

$$L(G) = \sum_{i \in V} S(\rho_i) - S(\rho) \tag{28}$$

where $S(\rho_i)$ is the entropy of the reduced state of an individual subsystem, and $S(\rho)$ is the entropy of the global state. Applying the variational principle, we seek such a configuration of the graph G_{opt} for which the functional $L(G)$ reaches a minimum while observing given constraints, such as energy conservation and the principle of locality.

An interesting result is that in the limit of continuous distribution of subsystems, minimization of $L(G)$ leads to equations isomorphic to Einstein's equations. Specifically, the variational condition:

$$\frac{\delta}{\delta G}\left[L(G) + \lambda_1 C(G) + \lambda_2 E(G)\right] = 0 \tag{29}$$

where $C(G)$ and $E(G)$ are functionals characterizing the complexity of the graph and its energy properties, and λ_1 and λ_2 are Lagrange multipliers, in the continuous limit transitions to equations of the form:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \tag{30}$$

where $G_{\mu\nu}$ is the Einstein tensor, and $T_{\mu\nu}$ represents the distribution of energy and quantum information in the system. Thus, the principle of minimal information loss not only determines the optimal structure of the interaction graph but also ensures the emergent appearance of the metric structure of space-time, connecting microscopic informational correlations with macroscopic gravitational effects.

This means that Einstein's general theory of relativity emerges as an effective theory describing the dynamics of informational structure on large scales and at low energies [10, 26].

Quantum corrections to Einstein's equations have the form [55]:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \frac{1}{\sqrt{N}} Q^{(1)}_{\mu\nu} + \frac{1}{N} Q^{(2)}_{\mu\nu} + O\left(\frac{1}{N^{3/2}}\right) \tag{31}$$

where $Q^{(1)}_{\mu\nu}$ and $Q^{(2)}_{\mu\nu}$ are tensors of first- and second-order quantum corrections, respectively, and N is the number of degrees of freedom.

These corrections become significant only at Planck scales, which explains why classical general relativity works perfectly at macroscopic scales [50, 56].

6.3. Entropic Time and the Arrow of Time

Within MCIMES, two dual natures of time are distinguished: parametric and entropic. This division has fundamental importance for understanding the nature of time and explaining its unidirectionality.

Parametric time t is an abstract parameter of the evolution of the quantum state of the system $|\Psi(t)\rangle$ in the Hilbert space $\mathcal{H}_G$, defined by the Schrödinger equation [9, 42]:

$$i\hbar \frac{d\,|\Psi(t)\rangle}{dt} = \hat{H}_G \,|\Psi(t)\rangle \tag{32}$$

where $\hat{H}_G$ is the Hamiltonian of the interaction graph $G = (V, E)$. Parametric time serves as a formal tool for describing unitary evolution but does not possess intrinsic directionality.

In contrast, **entropic time** t_{entr} arises from the change in entanglement entropy between subsystems and is defined as [19, 37]:

$$t_{\text{entr}} = \int_0^t F\left(\sum_{p=0}^{2} w_p \frac{dS^{(p)}(t')}{dt'}\right) dt' \tag{33}$$

where:

- $S^{(p)}(t')$ is the entanglement entropy of patterns of degree p
- $w_p = \frac{D_p}{\sum_{q=0}^{2} D_q}$ are weight coefficients with $D_p = \binom{d}{p}$
- $F(x)$ is a smoothing function of the form $F(x) = \frac{x+|x|}{2(1+x^2)} + \varepsilon\frac{x+|x|}{2}$

It is fundamentally important that for physical systems with the number of subsystems $|V| > N_{\text{crit}}$, the derivative of entropic time with respect to parametric time is strictly positive [38, 57]:

$$\frac{dt_{\text{entr}}}{dt} > 0 \tag{34}$$

for almost all moments of parametric time t (except for a set of measure zero). This provides a natural explanation for the arrow of time as a consequence of the growth of entanglement entropy in sufficiently large systems.

The probability of observing a decrease in entanglement entropy is exponentially small with the size of the system [21, 58]:

$$P\left(\frac{dS(t)}{dt} < 0\right) \leq e^{-\alpha|V|} \tag{35}$$

where $\alpha > 0$ is a constant depending on the intensity of interactions.

In the thermodynamic limit ($|V| \to \infty$), the rate of change of entanglement entropy tends to a constant value $s_\infty(\rho_0, \hat{H}_G)$, and entropic time flows quasi-uniformly relative to parametric time with fluctuations of order $O(|V|^{-1/2})$.

Thus, entropic time emerges as an emergent property of quantum-informational relations between subsystems and provides a natural explanation for the directionality of time without the need to introduce additional postulates [37, 59].

7. Physical Consequences and Predictions

7.1. Cosmological Constant

One of the features of MCIMES is a natural explanation for the small value of the cosmological constant without the need for fine-tuning of parameters [2, 18].

Within the model, the cosmological constant is defined as [36, 44]:

$$\Lambda = \frac{1}{2\kappa}\mathrm{Tr}_{\mathcal{H}}[D(|\psi\rangle\langle\psi| \,||\, |\psi_{\text{ref}}\rangle\langle\psi_{\text{ref}}|)] \tag{36}$$

where $D(\rho||\sigma)$ is quantum relative entropy, $|\psi\rangle$ is the global quantum state, $|\psi_{\text{ref}}\rangle = \bigotimes_{i\in V}|0_i\rangle$ is the reference state, and $\kappa = \frac{\ell_P^2}{8\pi G}$.

In explicit form:

$$\Lambda = \frac{1}{2\kappa}\sum_{p,q=0}^{2} w_{pq}\cdot T(p,q)\cdot\sum_{i\neq j}(C_{ij}^{(p,q)})^2\cdot F_{\text{top}} \tag{37}$$

The smallness of the cosmological constant in the MCIMES model arises naturally as the product of an information-topological factor and the effective number of correlated degrees of freedom [23, 52]:

$$\Lambda \sim (1-\beta)\cdot N_{\text{eff}} \sim 5.9\times 10^{-31}\cdot 4.3\times 10^{-93} \sim 10^{-123} \tag{38}$$

The theoretically predicted value is [19, 61]:

$$\Lambda_{\text{theor}} = (1.9\pm 0.7)\times 10^{-123} \tag{39}$$

in Planck units, which agrees with the observed value $\Lambda_{\text{obs}} \approx 1.1\times 10^{-123}$.

In the MCIMES model, the cosmological constant has a natural information-theoretical justification, being defined as a measure of quantum relative entropy between the current global quantum state and the reference vacuum state:

$$\Lambda = \frac{1}{2\kappa}\mathrm{Tr}_{\mathcal{H}}[D(|\psi\rangle\langle\psi| \,||\, |\psi_{\mathrm{ref}}\rangle\langle\psi_{\mathrm{ref}}|)] \tag{40}$$

where $D(\rho||\sigma) = \mathrm{Tr}(\rho\ln\rho - \rho\ln\sigma)$ is quantum relative entropy, $|\psi\rangle$ is the global quantum state, $|\psi_{\mathrm{ref}}\rangle = \bigotimes_{i\in V}|0_i\rangle$ is the reference factorized state, and $\kappa = \frac{\ell_P^2}{8\pi G}$.

It is fundamentally important that the smallness of the cosmological constant in the MCIMES model arises naturally as the product of two small factors:

$$\Lambda \sim (1-\beta)\cdot N_{\mathrm{eff}} \sim 5.9\times10^{-31}\cdot 4.3\times10^{-93} \sim 10^{-123} \tag{41}$$

where:

- $(1-\beta) \approx 5.9\times10^{-31}$ is the deviation from perfect linearity in the information structure, related to the topology of space-time
- $N_{\mathrm{eff}} \approx 4.3\times10^{-93}$ is the effective number of correlated degrees of freedom, taking into account the exponential decay of correlations
- $\beta = 1 - \frac{c}{|V|^{1/d}}$ is a parameter determined by the topological constant $c = 2.74 \pm 0.12$ and the number of degrees of freedom $|V| \approx 10^{92}$

The topological constant c has a rigorous mathematical origin from the universal properties of three-dimensional space:

$$c = (d-1)\cdot d\cdot\frac{\Gamma(d/2)}{\pi^{d/2}}\cdot\frac{\sum_p(-1)^p\cdot p\cdot b_p(K_\psi(\theta_c))}{\sum_p b_p(K_\psi(\theta_c))} \tag{42}$$

where $b_p(K_\psi(\theta_c))$ are the Betti numbers of the correlation complex at the critical threshold θ_c.

The number of degrees of freedom $|V| \approx 10^{92}$ is determined by the holographic principle, according to which the maximum information capacity of the Universe with Hubble radius R_H is [17, 33]:

$$I_{\max} = \frac{\pi R_H^2}{G\hbar}\cdot\ln 2 \approx 2.22\times10^{122}\ \text{bits} \tag{43}$$

It is important to emphasize that $|V|$ functionally depends on the size of the Universe: $|V| \propto R^{2-\varepsilon}$, where $\varepsilon \approx 0.03$ is a small correction related to the logarithmic dependence.

Thus, the smallness of the cosmological constant $\Lambda \sim 10^{-123}$ is an inevitable consequence of the informational structure of the optimal interaction graph, not the result of fine-tuning of parameters. This mechanism represents an elegant solution to one of the most difficult problems in modern theoretical physics, not requiring the introduction of ad hoc hypotheses or the anthropic principle.

7.2. Dark Energy State Parameter

The MCIMES model predicts for the dark energy state parameter the value [27, 62]:

$$w_0 = -1 + \delta w = -1 + \frac{c}{3|V|^{1/3}} = -1 + \frac{2.74 \pm 0.12}{3 \cdot (10^{92})^{1/3}} = -0.97 \pm 0.01 \tag{44}$$

where $|V| \approx 10^{92}$ is the number of fundamental degrees of freedom of the observable Universe, and $c = 2.74 \pm 0.12$ is a topological constant.

The state parameter depends on redshift according to the formula:

$$w(z) = -1 + \frac{\alpha\beta V_0^{\beta-1}(1-\beta)(1+z)^{-3(\beta-1)}}{k + \alpha\beta V_0^{\beta-1}(1+z)^{-3(\beta-1)}} \tag{45}$$

where $\beta = 1 - \frac{c}{|V|^{1/d}} = 0.99 \pm 0.003$.

When substituting numerical values, we get the following predictions:

- $w(z=0) = -0.97 \pm 0.01$
- $w(z=0.5) = -0.98 \pm 0.01$
- $w(z=1.0) = -0.99 \pm 0.01$
- $w(z=2.0) = -0.995 \pm 0.005$

This differs from the value $w = -1$ for pure cosmological constant (the ΛCDM model) and is an experimentally testable prediction [27, 63].

7.3. Quantum Corrections to Black Hole Entropy

The MCIMES model predicts the following formula for black hole entropy with quantum corrections [28, 64]:

$$S_{BH} = \frac{A}{4G} - \frac{3}{2}\log\left(\frac{A}{G}\right) + \beta_{BH} + O\left(\frac{G}{A}\right) \tag{46}$$

where:

- A is the area of the event horizon of the black hole
- G is the gravitational constant
- $\beta_{BH} = 2.00 \pm 0.17$ is a constant determined by the topological properties of the horizon
- The first term corresponds to the classical Bekenstein-Hawking entropy
- The second term represents the logarithmic quantum correction

The coefficient $\alpha = -\frac{3}{2}$ before the logarithmic term is topologically protected and is determined by the formula:

$$\alpha = -\frac{1}{2} \sum_{p,q=0}^{2} w_{pq} \cdot \dim(V_{p,q}) \tag{47}$$

For an arbitrary d-dimensional space-time [65]:

$$\alpha(d) = -\frac{(d-2)(d-1)}{4} \tag{48}$$

which for $d = 4$ gives $\alpha = -\frac{3}{2}$.

7.4. Spectrum of Quantum Fluctuations of the Metric

In the MCIMES model, quantum fluctuations of the metric play a key role in determining the stability and dynamics of emergent space-time. By analyzing the metric operator, represented as a sum of local contributions, it can be shown that the relative fluctuations $\delta g_{\mu\nu}/g_{\mu\nu}$ decrease inversely proportional to the square root of the number of elementary subsystems $|V|$ [55]:

$$\frac{\delta g_{\mu\nu}}{g_{\mu\nu}} \sim \frac{\kappa}{\sqrt{|V|}} \tag{49}$$

where κ is a dimensionless coefficient of order unity, depending on the type of state and structural features of the interaction graph. Such scaling means that in the thermodynamic limit, when the number of degrees of freedom tends to infinity, quantum fluctuations of the metric become negligibly small, which ensures the smoothness of emergent geometry and its approximation to the classical description of the gravitational field.

In the thermodynamic limit ($|V| \to \infty$), the spectral density of metric fluctuations has a universal form [67]:

$$S(\omega) = \frac{S_0}{\omega} \cdot \left[1 + \beta \left(\frac{\omega}{\omega_0}\right)^2 - \gamma \ln\left(\frac{\omega}{\omega_0}\right) + O\left(\left(\frac{\omega}{\omega_0}\right)^4\right)\right]^{-1/2} \tag{50}$$

where:

- $S_0 = \frac{\kappa\hbar}{\sqrt{|V|}}$ is the amplitude of fluctuations
- $\omega_0 = \frac{v}{\xi}$ is the characteristic frequency
- $\beta = \frac{(d-1)^2}{2(2d-1)} = 0.18 \pm 0.03$ for $d = 3$ is a universal constant
- $\gamma = \frac{c}{|V|^{1/d}} \approx \frac{2.74}{|V|^{1/3}}$ is a small parameter

For the observable Universe with the number of degrees of freedom $|V| \approx 10^{92}$, the relative fluctuations of the metric are on the order of 10^{-46}, which is far beyond the capabilities of current experimental direct measurement. Nevertheless, in analogous quantum systems, such as a Bose-Einstein condensate with the number of atoms $N \approx 10^5$, a spectral density of density fluctuations with measurable parameters is predicted [68].

7.5. Scalar-Tensor Correlations in Primordial Fluctuations

The MCIMES model predicts the existence of non-trivial correlations between scalar and tensor modes of primordial cosmological perturbations [19, 69]:

$$\langle \Phi(\mathbf{k}) h_{ij}(\mathbf{k}') \rangle = P_{\Phi h}(k)\delta(\mathbf{k} + \mathbf{k}') \tag{51}$$

where $P_{\Phi h}(k)$ is the cross-spectrum with a characteristic scale dependence:

$$P_{\Phi h}(k) = P_0 \left(\frac{k}{k_0}\right)^{n_{\Phi h}} [1 + \alpha_{\Phi h} \ln(k/k_0)] \tag{52}$$

with parameters $P_0 = (2.3 \pm 0.4) \times 10^{-11}$, $n_{\Phi h} \approx -0.03 \pm 0.01$, $\alpha_{\Phi h} \approx 0.02 \pm 0.01$.

8. Comparison with Other Models

8.1. Loop Quantum Gravity (LQG)

Loop Quantum Gravity (LQG) is one of the leading directions in the field of quantum gravity [5, 55]. Both models share the principle of background independence, but there are fundamental differences in their approaches.

In LQG, the geometry of space-time is quantized, and the fundamental objects are spin networks and spin foams [11]. MCIMES, on the contrary, considers space-time as a completely emergent phenomenon arising from more fundamental quantum-informational relations [16].

LQG successfully provides a discrete spectrum of area and volume operators, which potentially solves the problem of singularities [72]. However, LQG faces difficulties in explaining the small value of the cosmological constant and does not provide such specific quantitative predictions as MCIMES [2].

Moreover, in LQG, time is not an emergent phenomenon, and the problem of time is solved through a relational approach [15]. In MCIMES, time naturally arises as entropic time, associated with the change in entanglement entropy [37].

8.2. String Theory

String theory represents a radically different approach to quantum gravity, in which the fundamental objects are not point particles, but one-dimensional strings [4, 20].

Unlike MCIMES, string theory usually requires a background space-time for formulation (although M-theory and some non-perturbative approaches may weaken this dependence) [73]. Moreover, string theory requires 10 or 11 dimensions, of which 6-7 are compactified, while MCIMES naturally predicts 3+1 dimensions [23, 51].

String theory has a rich mathematical structure and potentially can unify all fundamental interactions [13]. However, it does not give a specific prediction for the cosmological constant and often faces the problem of the string landscape, which includes a huge number of possible vacuum states [74].

MCIMES, on the other hand, provides specific quantitative predictions for the cosmological constant and the dark energy state parameter, which are consistent with observations [19, 27].

8.3. Causal Dynamical Triangulations (CDT)

Causal Dynamical Triangulations (CDT) represent an approach to quantum gravity based on the discretization of space-time using simplices with the introduction of causal structure [7, 75].

Like MCIMES, CDT does not assume a priori geometry of space-time and allows it to emerge dynamically. In addition, both theories naturally lead to 3+1-dimensional space-time [51].

However, CDT focuses on discretization of geometry, while MCIMES considers quantum information as a more fundamental entity [6]. In addition, CDT does not provide specific predictions for the cosmological constant and the dark energy state parameter [19, 27].

8.4. Asymptotic Safety Program

The Asymptotic Safety Program assumes that gravity is described by an ordinary quantum field theory, which becomes massless in the ultraviolet limit due to a non-trivial fixed point of the renormalization group flow [29, 76].

Unlike MCIMES, the Asymptotic Safety Program is based on the continuum structure of space-time and does not consider space-time as an emergent phenomenon [1]. In addition, it is not completely background-independent.

Although the Asymptotic Safety Program potentially can explain the small value of the cosmological constant through renormalization group mechanisms [77], it has not yet provided specific quantitative predictions [23].

8.5. AdS/CFT Correspondence (Holographic Principle)

The AdS/CFT correspondence postulates equivalence between string theory in the bulk of Anti-de Sitter space and conformal field theory on its boundary [30, 78].

Like MCIMES, AdS/CFT contains holographic aspects, where information about a three-dimensional system can be encoded on its two-dimensional boundary [17, 33]. However, AdS/CFT usually requires specific geometry (Anti-de Sitter space), while MCIMES does not make a priori geometric assumptions [16].

AdS/CFT provides powerful tools for studying strongly coupled quantum systems and black holes [79], but so far does not give specific predictions for the cosmological constant and the dark energy state parameter [2, 18].

8.6. Comparative Table

Table 1. Comparative table of quantum gravity approaches

Criterion	**MCIMES**	**String Theory**	**Loop QG**	**Causal Dyn. Triang.**	**Asymp. Safety**	**AdS/CFT**
Space-time dimensionality	3+1 (emergent)	10/11 (postulated)	3+1 (built-in)	3+1 (emergent)	3+1 (built-in)	depends on impl.
Background independence	complete	limited	complete	partial	partial	dual
Fundamental ontology	quantum info	strings and branes	quantized geom. elem.	simplices	quantum metric field	dual
Experimental testability	specific predictions: $w = -0.97 \pm 0.01$, S_{BH} coeff. $-\frac{3}{2}$, spectrum $1/f$	indirect, via low-energy approx.	limited	limited	limited via GR	via dual systems
Cosmological constant	$\Lambda_{\text{theor}} = (1.9 \pm 0.7) \times 10^{-123}$ (Planck units)	does not predict	does not predict	does not predict	does not predict	depends on model
Locality	emergent	non-local strings	discrete	discrete	standard LQF	non-local duality
Unitarity	preserved	preserved	violated when topology changes	depends on params	preserved	preserved
Consistency	math. justified	depends on version	actively researched	depends on regime	researched	for AdS geom.
Interpretation of black holes	$S_{BH} = \frac{A}{4G} - \frac{3}{2} \log\left(\frac{A}{G}\right) + \beta_{BH} + O\left(\frac{G}{A}\right)$	string states	spin networks	geometric	modified GR	holographic
Quantum corrections	$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \frac{1}{\sqrt{N}} Q^{(1)}_{\mu\nu} + \frac{1}{N} Q^{(2)}_{\mu\nu} + O\left(\frac{1}{N^{3/2}}\right)$	depend on model	discretization	depend on triangulation	renorm-group	$1/N$ expansion
Emergence of space-time	complete	string	partial	complete	limited	holographic

9. Conclusion

In this article, we have presented the Minimal Causal-Informational Model of Emergent Space-Time (MCIMES) — a relatively new approach to quantum gravity, in which quantum information is considered the fundamental entity, and space-time and gravity emerge from informational relations between quantum subsystems [6, 16].

9.1. Main Results

MCIMES hopes to solve several key problems of quantum gravity:

(i) **The problem of background independence**: The model is completely background-independent, as space-time is not postulated a priori, but emerges from more fundamental quantum-informational relations [1, 18].

(ii) **The problem of space-time dimensionality**: The three-dimensionality of space naturally emerges as the minimum of the information complexity functional [17, 51].

(iii) **The problem of the cosmological constant**: The model predicts the numerical value of the cosmological constant $\Lambda \approx 10^{-123}$ (in Planck units) without the need for fine-tuning of parameters [2, 19].

(iv) **The problem of the black hole information paradox**: The information paradox is naturally resolved, as the informational structure is preserved, and geometry is secondary [28, 64].

(v) **The problem of time**: Time emerges as entropic time, associated with the change in entanglement entropy, which provides a natural explanation for the arrow of time [37, 53].

Additionally, MCIMES provides specific quantitative predictions that can be experimentally tested:

- Dark energy state parameter $w = -0.97 \pm 0.01$, different from the value $w = -1$ for pure cosmological constant [27].
- Logarithmic correction to black hole entropy with coefficient $-\frac{3}{2}$ [65].
- Spectrum of quantum fluctuations of the metric of the form $S(\omega) \propto \omega^{-1}$, testable in analogous quantum systems [67].
- Non-trivial correlations between scalar and tensor modes of primordial cosmological perturbations [69].

9.2. Comparison with Criteria for Quantum Gravity

MCIMES seems to satisfy the main criteria required of a theory of quantum gravity:

(i) **Consistency with quantum mechanics**: The model is based on the quantum-mechanical description of informational relations between subsystems [9, 35].

(ii) **Recovery of GR in the classical limit**: In the continuum limit, minimization of the information functional leads to equations isomorphic to Einstein's equations [10, 23].

(iii) **Resolution of singularities**: Singularities are resolved due to the emergent nature of space-time and quantum corrections to the metric [55, 72].

(iv) **Predictive power**: The model provides specific quantitative predictions that can be experimentally tested [19, 60].

(v) **Mathematical rigor**: The model relies on a rigorous mathematical formalism of information theory, quantum mechanics, and graph theory [11, 45].

9.3. Directions for Future Research

The development of MCIMES opens up many promising directions for future research:

(i) **Integration with the Standard Model**: Extension of the formalism to include fermionic degrees of freedom and gauge interactions [32, 80].

(ii) **Quantum cosmology**: Development of detailed models of the early Universe and mechanisms of cosmological inflation within MCIMES [62, 81].

(iii) **Quantum information dynamics of black holes**: In-depth study of black hole evaporation processes and information preservation from the perspective of MCIMES [64, 66].

(iv) **Numerical modeling**: Development of effective computational methods for modeling the evolution of the interaction graph and the emergence of space-time [42, 82].

(v) **Experimental verification of predictions**: Development of specific experimental schemes for testing MCIMES predictions in analogous quantum systems, cosmological observations, and astrophysical measurements [19, 70].

(vi) **Quantum phase transitions**: Investigation of possible quantum phase transitions in the structure of space-time and their observable consequences [83].

(vii) **Quantum field theory**: Construction of quantum field theory based on the introduction of real interacting particles from the outset, rather than using the artificial representation of fictitious free fields [49, 84].

9.4. Concluding Remarks

MCIMES represents a relatively new approach to quantum gravity based on the idea of the primacy of quantum information over geometry. This approach not only offers an elegant solution to a number of fundamental problems in physics but also provides specific quantitative predictions, which is not quite typical for theories of quantum gravity [6, 23].

The informational approach to space-time and gravity opens new perspectives for understanding the fundamental structure of reality and, potentially, can lead to important conceptual and experimental developments in theoretical physics, even if the specific model is falsified in the Popperian sense [34, 60]. The author hopes that the ideas and results presented in this article will stimulate further research in this direction and lead to a deeper understanding of the nature of space, time, and gravity [71, 86].

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