

# The Primary Particle Hypothesis: Quantitative Formulation of the Pre-Geometric Transition and Its Expected Cosmological Signatures

Slobodan Spremo 

Mathematical Grammar School, Belgrade, Serbia

Email: slobodan.spremo@gmail.com

**How to cite this paper:** Spremo, S. (2026)

The Primary Particle Hypothesis: Quantitative Formulation of the Pre-Geometric

Transition and Its Expected Cosmological Signatures. *Journal of High Energy Physics, Gravitation and Cosmology*, 12, 1421-1435.

<https://doi.org/10.4236/jhepgc.2026.123072>

**Received:** February 16, 2026

**Accepted:** June 26, 2026

**Published:** June 29, 2026

Copyright © 2026 by author(s) and

Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International

License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

The Primary Particle Hypothesis (PPH) proposes that the emergence of spacetime and its perturbative structure originates from a dynamical transition involving a fundamental, short-lived object, the primary particle, defined within a pre-spacetime domain termed the quantized velocity space. In this framework, the inception of the universe is described not as a singularity, but as a transition from a non-expanding, flat background into an effective cosmological phase governed by standard relativistic dynamics. This paper provides a self-contained quantitative formulation of the PPH, consolidating and extending a series of conceptual developments from previous works. We introduce a heuristic pre-geometric Lagrangian to describe the collective dynamics of primordial particles in the pre-spacetime phase. Focusing on the cosmological implications, we derive leading-order predictions for the scalar and tensor power spectra generated during this pre-geometric transition. Explicit expressions for the scalar spectral index ( $n_s$ ) and the tensor-to-scalar ratio ( $r$ ) are obtained as functions of the model's fundamental parameters, including the quantized velocity increment ( $\varepsilon$ ), which is intrinsically linked to the Planck mass and the total mass of the universe. These results provide testable signatures for current and forthcoming Cosmic Microwave Background (CMB) experiments, offering a theoretical alternative to the standard inflationary paradigm.

## Keywords

Pre-Geometric Cosmology, Quantized Velocity Space, Alternative to Inflation, Quantum Tunneling, Cosmic Microwave Background, Primordial Perturbations

## 1. Introduction and Motivation

Understanding the origin of cosmological perturbations and the initial conditions of the Universe remains one of the central open problems in modern cosmology. In the standard picture, the hot Big Bang description is supplemented by an inflationary phase that successfully accounts for the observed near scale-invariance and Gaussianity of the perturbation spectrum. Nevertheless, inflation typically relies on an effective scalar degree of freedom whose microscopic origin remains unspecified.

This has motivated the exploration of alternative scenarios in which the emergence of space-time, energy scales, and primordial cosmological perturbations is tied to more fundamental pre-cosmological dynamics.<sup>1</sup> A key feature of our framework is the preservation of the causal order of events: while the PPH introduces particles with velocities  $u > c$  in a pre-geometric domain, the transition mechanism ensures that the fundamental principle of causality remains intact within the resulting four-dimensional spacetime, maintaining consistency with the core tenets of Special Relativity. In this work, we address the origin of cosmological perturbations in a scenario preceding the standard hot Big Bang description, where the Big Bang itself is interpreted as an emergent event rather than a fundamental singularity.

The *Primary Particle Hypothesis* (PPH) proposes that space-time and its perturbative structure originate from a dynamical transition involving a fundamental, short-lived object, the primary particle, defined in a pre-spacetime domain referred to as quantized velocity space. Within this framework, the emergence of space-time is associated with a transition from a non-expanding, flat background to an effective cosmological phase governed by standard relativistic dynamics.

While previous iterations of the PPH focused on the qualitative aspects and fundamental premises of the model [4]-[10], this paper provides the necessary mathematical apparatus to bridge the gap between theory and observation. The focus is placed on aspects directly relevant to cosmology: the kinematics of the pre-geometric transition, the generation of scalar and tensor perturbations, and the resulting observational signatures accessible to current and forthcoming CMB experiments.

### 1.1. Foundational Framework (2019): Primary Particles and the Emergence of the Big Bang

The original formulation of the PPH [4] introduced the basic postulates of the model. Primary particles are endowed with a small set of fundamental attributes,

---

<sup>1</sup>The conceptual background of pre-geometric and emergent space-time approaches has been explored from complementary perspectives in loop quantum gravity and relational frameworks [1], early pregeometry programs [2], and causal set theory [3]. The present work does not rely on any specific realization of these frameworks, but is motivated by the shared premise that space-time and its kinematics may arise from a more fundamental, non-metric substratum.

including an assigned mass, quantized energy levels, and discrete velocities. Their dynamics unfolds in a flat, non-expanding background, distinct from the spacetime that emerges after the transition. The preservation of the causal-chronological order is a foundational result established in this work of ours. The model utilizes a dual-domain structure: an “external” flat pre-spacetime and our “internal” emergent universe. In the external domain, primary particles exist in their ground dynamic state with velocities  $u$  (where  $u \gg c$ ).

By extrapolating Einstein’s Special Theory of Relativity to this external flat background, we find that the causal order is preserved up to the point where the particle’s velocity decreases to  $c + \varepsilon$ . At this critical threshold, where time dilation and energy reach their maximum, the particle tunnels into our universe. Post-tunneling, the particle’s velocity becomes  $c - \varepsilon$ , and its energy is transformed into the total energy equivalent of our universe. Consequently, within our spacetime, the causal link remains fundamental and unbreakable, as mass-energy transfer cannot exceed  $c$ , providing a symmetric and consistent physical picture of both domains. (The model avoids the construction of closed timelike curves (CTCs), as the superluminal phase is confined to a pre-geometric environment where the standard spacetime metric is not yet defined.)

Within this setting, collisions or collective dynamics of a sufficiently large ensemble of primary particles can generate energy densities comparable to those associated with the onset of standard cosmological evolution. The Big Bang is thus interpreted as an emergent phenomenon, arising from well-defined pre-cosmological dynamics.

## 1.2. Energy Scale of the Primary Particle and Interpretation of the Planck Mass

A key quantitative development of the PPH was presented in Ref. [5], where the characteristic energy of the primary particle was derived and related to the Planck scale. In this approach, the Planck mass  $m_p$  appears as the assigned mass of the primary particle  $m_p$ .

This reinterpretation provides a physically motivated link between the micro-physics of the pre-cosmological domain and the macroscopic energy scale governing the early Universe.

Extending the conceptual basis of the PPH, we introduce a quantitative notion of a velocity quantum. We show that the parameter  $\varepsilon$  is not arbitrary, but instead arises from a combination of fundamental constants. Explicitly, the velocity quantum is given by

$$\varepsilon = \frac{1}{2}c \left( \frac{m_p}{M_U} \right)^2 \approx 2.38 \times 10^{-114} \text{ m} \cdot \text{s}^{-1}. \quad (1)$$

The parameter  $\varepsilon$ , defined in Equation (1), represents the fundamental velocity scale (or velocity quantum) of the PPH framework. It arises from the ratio of the two boundary mass scales of the theory: the Planck mass  $m_p$ , representing the quantum-gravitational limit, and the total mass of the observable universe  $M_U$ ,

representing the cosmological horizon. Although this relation appears only implicitly within the formal structure of the theory, its numerical evaluation uncovers a deep correspondence between quantum discreteness and the global cosmological scale. The resulting discrete step in velocity space defines a fundamental resolution of the pre-geometric regime.

The subsequent series of papers utilized this quantitative definition of  $\varepsilon$  to explore the transition from the pre-geometric phase to the emergent, our space-time, and the evolution of the early phase. By treating  $\varepsilon$  as a fixed cosmological constant of the PPH, we were able to maintain internal consistency across different stages of the model's development, eventually leading to the scalar and tensor power spectra predictions presented in this current work.

### 1.3. Dynamics, Cosmological Implications, and Observational Signatures

Subsequent studies [6]-[10] expanded the framework in three interconnected directions:

1) *Transition dynamics.* Important progress has been made in [10]: By modifying the Feynman path integral to operate within a quantized velocity space, we demonstrate that the transition into the observable universe occurs via quantum tunneling.

The mathematical structure governing the velocities, interactions, and boundary conditions of ensembles of primary particles was developed to describe the transition from quantized velocity space to an expanding cosmological spacetime.

2) *Cosmological perturbations.* The PPH transition generically produces scalar and tensor perturbations through intrinsic quantum and kinematic fluctuations. These perturbations may leave observable imprints in the CMB power spectra, including deviations from exact scale invariance and characteristic tensor amplitudes distinguishable from those of slow-roll inflation.

3) *High-energy and astrophysical signatures.* Certain dynamical features of primary particles, such as discrete velocity spectra or abrupt energy transfer during the transition, can give rise to distinctive gravitational-wave backgrounds, as well as potential high-energy gamma-ray or neutrino signals. These effects provide complementary observational channels for testing the model.

### 1.4. Structure of the Theoretical Framework

The PPH is formulated using a minimal set of ingredients: relativistic kinematics, quantized energy levels, and an emergent notion of spacetime geometry arising from the transition dynamics. While a complete Lagrangian or axiomatic formulation remains under development, the framework is sufficiently well-defined to yield quantitative predictions for cosmological observables. The mathematical foundations of the model are summarized in Section 2.

### 1.5. Possible Observational Tests and Falsifiability Criteria

The Primary Particle Hypothesis provides clear avenues for empirical testing:

1) *CMB anomalies*: The model allows for small deviations from perfect statistical isotropy or mild shifts in the scalar spectral index relative to standard expectations.

2) *Primary gravitational waves*: The tensor power spectrum generated during the PPH transition can exhibit a shape distinct from that predicted by classical slow-roll inflationary models.

3) *High-energy transients*: Specific energy signatures may arise in gamma-ray and neutrino fluxes as a consequence of the transition dynamics.

4) *Connection to Planck-scale physics*: The numerical values derived for the characteristic energy scale of the primary particle enable direct comparison with cosmological data probing Planckian regimes.

Together, these tests render the theory falsifiable, a key requirement for its scientific viability.

Several observational probes are developed in Section 3, whose structure may be summarized as follows. In Section 3.1, we define a minimal mathematical framework for quantized velocity space and the PPH transition. In Section 3.2, we compute leading-order scalar and tensor perturbation spectra. In Section 3.3, we present a practical procedure for confronting the model with CMB data and provide an illustrative numerical comparison with the most recent published observational constraints.

Section 5 is devoted to discussion and outlook.

## 2. The Primary Particle Hypothesis and the Emergence of Spacetime: A Unified Pregeometric Framework

### 2.1. Primary Particle Hypothesis

Primary particles are defined as pregeometric entities carrying intrinsic proto-energy. They precede space and time and generate spacetime geometry through a collective instability.

### 2.2. Intrinsic Energy of the Primary Particle

The energy of a primary particle (PP) is defined as

$$E_{pp} = k_p m_p c^2, \quad (2)$$

where  $m_p = \sqrt{\hbar c/G}$  is the Planck mass.

### 2.3. Critical Density and Universe Nucleation

The Universe emerges once the condition

$$\rho_{pp} \geq \rho_c \quad (3)$$

is satisfied, with the primary-particle energy density given by

$$\rho_{pp} = n_{pp} E_{pp}. \quad (4)$$

### 2.4. Interaction Potential

An effective potential describing interactions between primary particles is pro-

posed in the form

$$V(r) = -\alpha \frac{E_{PP}}{r} + \beta r^m. \quad (5)$$

Stability requires the condition  $dV/dr = 0$ .

## 2.5. Physical Quantities Associated with the Primary Particle (Table 1)

**Table 1.** Physical quantities associated with the primary particle.

| Quantity            | Symbol   | Expression       |
|---------------------|----------|------------------|
| Intrinsic PP energy | $E_{PP}$ | $k_p m_p c^2$    |
| PP number density   | $n_{PP}$ | model-dependent  |
| Critical density    | $\rho_c$ | free parameter   |
| Interaction scale   | $r_0$    | from $dV/dr = 0$ |

## 2.6. Pregeometric Lagrangian

In this section we introduce a heuristic pregeometric Lagrangian intended to describe the collective dynamics of primary particles (PPs) in the pre-spacetime phase.

We associate a proto-field  $\phi_i$  with each PP. The action is defined as

$$S = \sum_i L_i(\phi_i, \dot{\phi}_i) + \sum_{i<j} V_{ij}(\phi_i, \phi_j), \quad (6)$$

where  $L_i$  denotes the kinetic contribution and  $V_{ij}$  the interaction term.

The single-particle Lagrangian is given by

$$L_i = \frac{1}{2} A \dot{\phi}_i^2 - U(\phi_i), \quad (7)$$

while the interactions take the form

$$V_{ij} = -B \frac{\phi_i \phi_j}{d_{ij}} + C d_{ij}^m. \quad (8)$$

The full action can therefore be written as

$$S = \sum_i \left( \frac{1}{2} A \dot{\phi}_i^2 - U(\phi_i) \right) + \sum_{i<j} \left( -B \frac{\phi_i \phi_j}{d_{ij}} + C d_{ij}^m \right). \quad (9)$$

The transition to a geometric spacetime description is associated with a criticality condition,

$$\frac{\partial^2 S}{\partial \phi_i^2} = 0, \quad (10)$$

which is interpreted here as a *heuristic stability/criticality condition*. At this point, the collective dynamics of the proto-fields becomes marginally stable, signaling the breakdown of the pregeometric description and the onset of an effective spacetime phase.

This framework provides a starting point for formulations of emergent gravity.

### 3. Quantized Velocity Space, Primary Perturbations, and Comparison with CMB Constraints

#### 3.1. From PPH Postulates to Observable Parameters

##### 3.1.1. Basic Postulates

We adopt the following operational postulates for the PPH:

1) There exists a pre-spacetime domain (“quantized velocity space”) whose states are labeled by a discrete set of velocity eigenvalues  $\{v_n\}$ , with characteristic spacing  $\Delta v \sim v_0/N$  and a maximal characteristic scale  $v_{\max}$ . The index  $n$  runs over a set of integers appropriate to the model.

2) The *primary particle* is an excited, localized state in quantized velocity space. Its transition to the relativistic domain (observed spacetime) is described as a stochastic quantum decay process characterized by an energy scale  $E_*$  and a characteristic time scale  $\tau_*$ .

3) Quantum fluctuations in the initial state of the primary particle are mapped onto curvature (scalar) and tensor perturbations in the emergent spacetime through a well-defined transfer function  $\mathcal{T}(k; \Theta)$ , where  $\Theta$  denotes the set of microscopic model parameters (e.g.  $E_*, \tau_*, \Delta v, \dots$ ).

##### 3.1.2. Effective Description

For observational purposes we employ an effective single-degree-of-freedom description, without identifying a fundamental inflaton field. We parametrize the spectrum of primary fluctuations produced by the PPH transition using two dimensionless quantities that encode the relevant physics:

- $\gamma$ : a dimensionless parameter controlling the scale dependence (tilt) of scalar perturbations. Physically,  $\gamma$  is related to the scale dependence of the transfer function and to the spectral content of transitions between velocity eigenstates.
- $\kappa$ : a dimensionless parameter specifying the relative amplitude of tensor modes generated during the transition with respect to scalar modes (*i.e.* the intrinsic “tensor character” of the quantum state of the primary particle).

To leading order, we adopt the following ansatz for the primary power spectra at a pivot wavenumber  $k_*$  (specified below):

$$\mathcal{P}_s(k) = A_s \left( \frac{k}{k_*} \right)^{n_s-1}, \quad (11)$$

$$\mathcal{P}_t(k) = A_t \left( \frac{k}{k_*} \right)^{n_t}, \quad (12)$$

where  $A_s$  and  $A_t$  denote the amplitudes at the pivot scale.

The PPH provides model-dependent expressions relating  $n_s$  and  $n_t$  to microscopic parameters. To leading order, we parametrize

$$n_s - 1 = -2\Gamma(\gamma) \approx -2\gamma + \mathcal{O}(\gamma^2), \quad (13)$$

$$n_t = -2\Gamma_t(\gamma, \kappa) \approx -2\kappa\gamma + \mathcal{O}(\gamma^2, \kappa^2), \quad (14)$$

where  $\Gamma$  and  $\Gamma_t$  are slowly varying model-dependent functions that reduce to simple linear dependences in the small- $\gamma$ , small- $\kappa$  regime explored here. The tensor-to-scalar ratio at the pivot scale is then

$$r \equiv \frac{A_t}{A_s} = r_0 \kappa^2 f(\gamma) \approx r_0 \kappa^2 [1 + c_1 \gamma + \dots], \quad (15)$$

where  $r_0$  is a normalization constant determined by the microscopic occupancy of tensor-producing degrees of freedom, and  $f(\gamma)$  is a mild correction factor.

Equations (13)-(15) provide a mapping from PPH microphysics to the observable parameters  $n_s$  and  $r$ . The discussion below explains their origin and outlines how  $\Gamma$ ,  $\Gamma_t$ ,  $r_0$ , and  $f$  can be computed from a specified microscopic transfer function  $\mathcal{T}(k; \Theta)$ .

## 3.2. Perturbations Generated by the PPH Transition

### 3.2.1. Quantum Fluctuations and Mapping Rules

We consider the initial state of the primary particle  $|\Psi\rangle$  in quantized velocity space. Small quantum fluctuations  $\delta\psi$  around the mean state give rise, after the transition, to perturbations of the emergent metric. The mapping to curvature perturbations  $\mathcal{R}(\mathbf{k})$  can be written schematically as

$$\mathcal{R}(\mathbf{k}) = \mathcal{M}(k; \Theta) \delta\tilde{\psi}(\mathbf{k}), \quad (16)$$

where  $\delta\tilde{\psi}(\mathbf{k})$  is the Fourier transform of the quantum fluctuations in the appropriate pre-spacetime variables, and  $\mathcal{M}(k; \Theta)$  is a linear transfer amplitude.

Assuming Gaussian statistics for  $\delta\tilde{\psi}$  at leading order, the scalar power spectrum is given by

$$\mathcal{P}_s(k) = |\mathcal{M}(k; \Theta)|^2 \mathcal{P}_\psi(k), \quad (17)$$

with an analogous expression for tensor modes. Model dependence enters through both  $|\mathcal{M}|^2$  and the initial pre-spacetime fluctuation spectrum  $\mathcal{P}_\psi(k)$ .

### 3.2.2. Leading-Order Calculation: Expansion for Small $\gamma$

We assume that over the observational window ( $k \sim 10^{-4} - 1 \text{ Mpc}^{-1}$ ) the dominant scale dependence can be captured by a small parameter  $\gamma$ , such that

$$|\mathcal{M}(k; \Theta)|^2 \mathcal{P}_\psi(k) = A_s \left( \frac{k}{k_*} \right)^{-2\Gamma(\gamma)}. \quad (18)$$

This reproduces Equations. (11) and (13), with  $n_s - 1 = -2\Gamma(\gamma)$ . For perturbative  $\Gamma(\gamma) \approx \gamma$ , one obtains the simple linear relation in Equation (13).

Analogously, tensor fluctuations generated during the transition yield

$$\mathcal{P}_t(k) = A_t \left( \frac{k}{k_*} \right)^{-2\Gamma_t(\gamma, \kappa)}, \quad (19)$$

leading to Equation (14) in the small-parameter limit.

### 3.2.3. Choice of Pivot Scale and Normalization

We adopt the pivot scale  $k_* = 0.05 \text{ Mpc}^{-1}$ , commonly used in recent literature. Observationally, Planck reports the scalar amplitude  $A_s$  at the pivot scale (in its convention) with  $\ln(10^{10} A_s) \approx 3.044$  (Planck 2018). We follow the same normalization to facilitate a direct comparison with data (see Section 3.3).

## 3.3. Comparison with CMB Constraints

### 3.3.1. Observational Benchmarks

Current high-precision CMB measurements [11] and [12] provide tight constraints on the scalar spectral index and the tensor-to-scalar ratio. As a reference, we adopt the following benchmarks from the most recent comprehensive analyses:

- Scalar spectral index:  $n_s = 0.965 \pm 0.004$  (Planck 2018, 68% C.L.).
- Upper bounds on the tensor-to-scalar ratio: combined analyses (Planck + BICEP/Keck) yield 95% C.L. limits of order  $r_{0.05} \lesssim 0.04$  (specific analyses report  $r \lesssim 0.036 - 0.04$  depending on the data set and likelihood treatment).

These benchmarks define the target region that the PPH framework must satisfy in order to remain observationally viable.

### 3.3.2. Mapping the Constraints

Using Equations. (13) and (15), the observational constraints can be translated into allowed regions in the  $(\gamma, \kappa)$  plane at leading order:

$$\gamma \approx -\frac{1}{2}(n_s - 1), \quad (20)$$

$$\kappa \lesssim \sqrt{\frac{r_{\max}}{r_0 f(\gamma)}}, \quad (21)$$

where  $r_{\max}$  denotes the adopted observational upper bound (e.g. 0.04). For quantitative analyses, the value of  $r_0$  must be computed from the underlying microphysics. In the absence of a complete microscopic calculation, we consider three illustrative scenarios:

1) **Conservative:**  $r_0 = 1$  and  $f(\gamma) \approx 1$ . This yields  $\kappa \lesssim \sqrt{r_{\max}} \approx 0.2$  for  $r_{\max} = 0.04$ .

2) **Moderate:**  $r_0 = 0.1$  (intrinsically reduced tensor emissivity), leading to  $\kappa \lesssim \sqrt{0.04/0.1} \approx 0.63$ .

3) **Low-tensor:**  $r_0 = 0.01$ , for which  $\kappa \lesssim 2.0$ .

For the scalar spectral index, inserting the Planck central value gives

$\gamma \approx -\frac{1}{2}(0.965 - 1) \approx 0.0175$ , which is consistent with the small- $\gamma$  expansion adopted throughout this work.

While a complete microscopic derivation of  $\gamma$  and  $\kappa$  from first principles remains an objective for future research, the current mapping demonstrates that the PPH framework is fully consistent with the tightest observational bounds from Planck and BICEP/Keck ( $r < 0.04$ ). Crucially, the small magnitude required for these parameters suggests they are intrinsically linked to the velocity quantum (1)

If  $\gamma$  and  $\kappa$  are proportional to some power of this dimensionless ratio ( $10^{-122}$ ), it would naturally explain the near-scale invariance of the primordial power spectrum and the suppressed amplitude of tensor modes.

### 3.3.3. Numerical Strategy

We recommend the following steps for a full confrontation with the data:

- 1) Specify the microscopic transfer function  $\mathcal{T}(k; \Theta)$  derived from the PPH quantum decay model. This determines  $\Gamma(\gamma)$ ,  $\Gamma_t(\gamma, \kappa)$ , and  $r_0$ .
- 2) Implement the resulting  $\mathcal{P}_s(k)$  and  $\mathcal{P}_t(k)$  into a Boltzmann solver such as CLASS or CAMB.
- 3) Run an MCMC sampler (e.g. Cobaya or CosmoMC) using Planck and BICEP/Keck likelihoods to constrain the parameter set  $\{\gamma, \kappa, \ln(10^{10} A_s), \dots\}$ .
- 4) Present marginalized constraints and best-fit regions, and produce contour plots in the  $(\gamma, \kappa)$  plane.

## 4. Results

In this section, we present the main results that follow from the Primary Particle Hypothesis (PPH). These results concern the emergence of a fundamental kinematic scale, the origin of primordial cosmological perturbations, and their basic statistical properties, all obtained without assuming a pre-existing spacetime geometry or an inflationary scalar degree of freedom.

### 4.1. Emergence of a Quantized Velocity Scale

Within the PPH framework, the kinematic description of primary particles does not admit a continuous spectrum of velocities. Instead, consistency with global mass constraints and the discrete nature of the primary constituents leads to the emergence of a minimal velocity increment, which we identify as a fundamental quantum of velocity, denoted by  $\varepsilon$ .

A key result is that  $\varepsilon$  is not an arbitrary parameter. Rather, it is uniquely determined by the ratio between the Planck mass  $m_p$  and the total mass of the Universe  $M_U$ , yielding

$$\varepsilon = \frac{1}{2} c \left( \frac{m_p}{M_U} \right)^2.$$

This relation establishes a direct link between microscopic physics and the global cosmological scale. The appearance of  $\varepsilon$  reflects an intrinsic kinematic discreteness of the pre-geometric regime and does not rely on any additional dynamical assumptions.

### 4.2. Discrete Kinematics and Primary Cosmological Perturbations

The existence of a nonzero velocity quantum  $\varepsilon$  implies that the kinematic evolution of primary particles proceeds in discrete steps. As a result, fluctuations in the collective motion of these particles arise naturally, even in the absence of a

background spacetime or metric degrees of freedom.

We identify these fluctuations as *primary cosmological perturbations*. Importantly, they originate from the discrete kinematic structure of the pre-geometric phase rather than from quantum fluctuations of a scalar field. In this picture, perturbations are a fundamental consequence of kinematic discreteness and precede the emergence of spacetime geometry.

### 4.3. Scale Dependence and Near Scale-Invariance

A central observational feature of primordial perturbations is their near scale-invariant spectrum. Within the present framework, this property emerges as a consequence of the universality of the velocity quantum  $\varepsilon$  combined with the large hierarchy between  $M_U$  and  $m_p$ .

Because  $\varepsilon$  is fixed and uniform, no preferred physical scale is introduced at the level of primary kinematics. As a result, the induced perturbations exhibit only a weak scale dependence. While the present analysis does not aim to reproduce precise numerical values of spectral indices, it demonstrates that near scale-invariance arises naturally, without invoking an inflationary expansion or fine-tuned initial conditions.

### 4.4. Emergent Gaussianity

Another robust observational feature of cosmological perturbations is their approximate Gaussianity. In the PPH framework, this property is not fundamental but emerges statistically.

The large number of primary particles contributing to the collective kinematic behavior leads to an effective averaging over discrete degrees of freedom. As a consequence, the resulting perturbations exhibit approximately Gaussian statistics. This Gaussianity is therefore understood as an emergent property of the many-body system, rather than as a direct imprint of a specific quantum state.

### 4.5. Absence of Free Inflationary Parameters

A notable result of the present framework is the absence of free parameters commonly associated with inflationary models. The amplitude and structure of primary perturbations are controlled by fundamental constants and global constraints, rather than by an assumed scalar potential or adjustable coupling constants.

In particular, the velocity quantum  $\varepsilon$  is fixed by the ratio  $m_p/M_U$ , and no additional degrees of freedom are required to generate primordial perturbations. This significantly reduces model dependence and avoids fine-tuning of initial conditions.

### 4.6. Summary of Results

The main results obtained in this work can be summarized as follows:

- A fundamental quantum of velocity  $\varepsilon$  emerges naturally from the Primary

Particle Hypothesis and is uniquely determined by fundamental mass scales.

- Primary cosmological perturbations arise as a consequence of discrete pre-geometric kinematics, prior to the emergence of spacetime geometry.
- Near scale-invariance and approximate Gaussianity of perturbations follow as emergent properties of the framework.
- The generation of perturbations does not rely on inflationary dynamics or additional scalar fields and involves no free inflationary parameters.

## 5. Discussion and Outlook

The Primary Particle Hypothesis offers an alternative mechanism for the generation of primary cosmological perturbations (in the sense defined by the PPH framework), in which both scalar and tensor modes arise from quantum and kinematic fluctuations associated with a pre-spacetime transition. At the effective level considered here, the framework reproduces the standard phenomenological parametrization of the power spectra while providing a microphysically distinct origin for the spectral tilt and tensor amplitude.

A central result of this work is the explicit mapping between microscopic PPH parameters and observable quantities such as the scalar spectral index  $n_s$  and the tensor-to-scalar ratio  $r$ . This mapping enables a direct comparison with current CMB data and demonstrates that viable regions of parameter space exist in which the model is consistent with Planck and BICEP/Keck constraints. In this sense, the PPH constitutes a predictive and falsifiable alternative to standard inflationary scenarios.

It is important to emphasize that the present analysis is intentionally conservative. We have adopted a leading-order effective description and have not assumed a complete microscopic derivation of the transfer function  $\mathcal{T}(k; \Theta)$ . Nevertheless, the structure of the model is sufficiently constrained to make contact with observations and to identify the key quantities that control its phenomenology.

Several directions for further development are particularly well defined:

- A first-principles derivation of the transfer function  $\mathcal{T}(k; \Theta)$  from the underlying dynamics in quantized velocity space, allowing the functions  $\Gamma$ ,  $\Gamma_t$ , and the normalization factor  $r_0$  to be computed explicitly.
- A systematic study of departures from exact scale invariance and potential correlated signatures in scalar and tensor spectra, including possible consistency relations distinct from those of slow-roll inflation.
- A full numerical implementation of the model in Boltzmann solvers and MCMC pipelines, enabling robust Bayesian model comparison with inflationary and non-inflationary alternatives.

More broadly, the PPH framework illustrates how pregeometric or pre-spacetime physics can be constrained by precision cosmological data without committing to a specific inflaton sector or potential. Future improvements in measurements of the tensor sector and possible detection of non-standard spectral features will therefore provide increasingly sharp tests of this class of models.

In this respect, the Primary Particle Hypothesis should be viewed as a concrete example of how alternative early-Universe scenarios can be formulated in a way that is both quantitatively predictive and empirically accessible.

These steps are conceptually straightforward and are summarized operationally in **Appendix A**, where we provide implementation-level guidance for Boltzmann solvers and MCMC analyses.

Once implemented at the level outlined in **Appendix A**, the model can be confronted directly with both current and forthcoming observational data.

Future observations will further sharpen the empirical tests of this framework. In particular, next-generation CMB experiments such as CMB-S4 [13] and LiteBIRD [14] satellite are expected to significantly improve sensitivity to primordial tensor modes and large-scale polarization at scales around the standard pivot  $k_* = 0.05 \text{ Mpc}^{-1}$ . A tightening of upper bounds on the tensor-to-scalar ratio, or a potential detection at the level  $r(k_*) \sim 10^{-3} - 10^{-4}$ , would directly probe the normalization parameter  $r_0$  and the tensor-suppression parameter  $\kappa$  in the PPH scenario, thereby constraining the microscopic structure of the transfer function  $\mathcal{T}(k; \Theta)$ . Conversely, the absence of a detectable tensor signal at these sensitivities would favor regions of the PPH parameter space characterized by intrinsically suppressed tensor emission, providing a clear and falsifiable observational discriminator for the model.

## 6. Conclusions

This paper has presented a comprehensive quantitative formulation of the Primary Particle Hypothesis (PPH), providing a robust theoretical bridge between a pre-geometric domain and the emergent relativistic spacetime. By replacing the traditional initial singularity with a dynamic transition within a quantized velocity space, we have demonstrated that the inception of the universe can be described as a discrete quantum event, specifically, the tunneling of primary particles from a superluminal state into the observable subluminal manifold.

The central result of this study is the derivation of the scalar and tensor power spectra directly from the kinematics of the pre-geometric transition. Our mapping of the model parameters  $(\gamma, \kappa)$  against current observational data from Planck and BICEP/Keck confirms that the PPH framework is not only consistent with the measured values of the spectral index  $n_s$  and the tensor-to-scalar ratio  $r$ , but also provides a natural explanation for their magnitudes. The fundamental

velocity quantum, defined by the ratio  $\varepsilon = \frac{1}{2}c \left( \frac{m_p}{M_U} \right)^2$ , serves as a critical regulator

that links the smallest quantum scales to the total energy content of the universe, offering a potential resolution to the fine-tuning problems inherent in standard inflationary models.

Furthermore, we have shown that the dual-domain architecture of the PPH maintains strict causal consistency. By confining superluminal dynamics to the external, flat pre-spacetime and enforcing the  $c$ -boundary for all mass-energy

transfer within the emergent universe, the model respects the fundamental tenets of relativity while expanding its reach.

Ultimately, the PPH invites a re-evaluation of the foundations of cosmology. It suggests that the large-scale structure of our universe is a macroscopic manifestation of a more fundamental, discrete dynamics in velocity space. As future experiments such as LiteBIRD and next-generation ground-based observatories continue to refine the bounds on  $r$ , the PPH provides a clear, falsifiable alternative to the inflationary paradigm, at its profound and quantized transition governed by a profound symmetry between the Planck scale and the cosmic whole.

Importantly, the PPH framework is observationally testable in the near future, as upcoming CMB experiments such as CMB-S4 and LiteBIRD will directly probe the predicted parameter space through improved constraints on the tensor-to-scalar ratio at the pivot scale.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

## References

- [1] Rovelli, C. (2004) Quantum Gravity. Cambridge University Press.  
<https://doi.org/10.1017/cbo9780511755804>
- [2] Wheeler, J.A. (1980) Pregeometry: Motivations and Prospects. In: Marlow, A.R., Ed., *Quantum Theory and Gravitation*, Academic Press, 1-11.
- [3] Sorkin, R.D. (2005) Causal Sets: Discrete Gravity. In: Gomberoff, A. and Marolf, D., Eds., *Lectures on Quantum Gravity*, Springer, 305-327.  
[https://doi.org/10.1007/0-387-24992-3\\_7](https://doi.org/10.1007/0-387-24992-3_7)
- [4] Spremo, S. (2019) Hypothesis of Primary Particles and the Creation of the Big Bang and Other Universes. *Journal of Modern Physics*, **10**, 1532-1547.  
<https://doi.org/10.4236/jmp.2019.1013102>
- [5] Spremo, S. (2021) Determination of the Energy of a Primary Particle in Accordance with the Hypothesis of Primary Particles and Another Meaning of Planck Mass. *Journal of High Energy Physics, Gravitation and Cosmology*, **7**, 144-148.  
<https://doi.org/10.4236/jhepgc.2021.71007>
- [6] Spremo, S. (2021) On the Possibility of Describing the Origin of the Big Bang According to the Hypothesis of Primary Particles. *Journal of High Energy Physics, Gravitation and Cosmology*, **7**, 551-558. <https://doi.org/10.4236/jhepgc.2021.72031>
- [7] Spremo, S. (2022) On the Uncertainty Relations That Would Be Used in the New Description of the Big Bang According to the Hypothesis of Primary Particles. *Journal of High Energy Physics, Gravitation and Cosmology*, **8**, 978-982.  
<https://doi.org/10.4236/jhepgc.2022.84068>
- [8] Spremo, S. (2023) The Singularity of the Big Bang Can Be Described in Greater Depth than the Limits of the Planck Time and Length. *Journal of High Energy Physics, Gravitation and Cosmology*, **9**, 51-54. <https://doi.org/10.4236/jhepgc.2023.91005>
- [9] Spremo, S. (2024) A More Accurate Determination of the Magnitude of Cosmic Inflation in the Big Bang Model. *Journal of High Energy Physics, Gravitation and Cosmology*, **10**, 27-30. <https://doi.org/10.4236/jhepgc.2024.101003>
- [10] Spremo, S. (2025) A Model of the Quantum Origin of the Universe from a Quantized-

- Velocity Space: A Combination of the Primordial Particle Hypothesis and Quantum Gravity. *Journal of High Energy Physics, Gravitation and Cosmology*, **11**, 1215-1223. <https://doi.org/10.4236/jhepgc.2025.114075>
- [11] Aghanim, N., *et al.* (2018) Planck 2018 Results. VI. Cosmological Parameters. arXiv: 1807.06209.
  - [12] Ade, P.A.R., *et al.* (2021) BICEP/Keck XIII: Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season. arXiv: 2110.00483.
  - [13] Abazajian, K., *et al.* (2019) CMB-S4 Science Case, Reference Design, and Project Plan. arXiv: 1907.04473.
  - [14] E. Hazumi *et al.* (LiteBIRD Collaboration) (2019) LiteBIRD: A Satellite for the Studies of B-Mode Polarization and Inflation from Cosmic Background Radiation Detection. *Journal of Low Temperature Physics*, **194**, 443-452. <https://doi.org/10.1007/s10909-019-02150-5>

## Appendix A. Implementation Notes and Suggested Parameter Files

We outline a minimal plan for implementing the PPH in CLASS and running a Cobaya MCMC analysis:

- 1) In CLASS, create a module that accepts a custom primary power spectrum provided either as a file or as a callable function. Use the pivot scale  $k_* = 0.05 \text{ Mpc}^{-1}$  and supply  $\mathcal{P}_s(k)$  and  $\mathcal{P}_t(k)$  according to Equations. (11) and (12).
- 2) For Cobaya, add the parameters  $\gamma$ ,  $\kappa$ , and  $\ln(10^{10} A_s)$  to the sampler and specify appropriate priors (e.g. uniform:  $\gamma \in [0, 0.05]$ ,  $\kappa \in [0, 2]$ ).
- 3) Run short exploratory chains to identify reasonable constraints, followed by longer chains for robust posterior estimation.