

A Statistical-Mechanical Realization of the Primary Particle Hypothesis: Emergent Spacetime and Cosmological Implications

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How to cite this paper: Spremo, S. (2026)
A Statistical-Mechanical Realization of the
Primary Particle Hypothesis: Emergent
Spacetime and Cosmological Implications.
Journal of High Energy Physics, Gravitation and Cosmology, 12, 1447-1472.
<https://doi.org/10.4236/jhepgc.2026.123074>

Received: April 2, 2026

Accepted: June 28, 2026

Published: July 1, 2026

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Abstract

We present an extended mathematical formulation of the Primary Particle Hypothesis (PPH), in which spacetime and its causal structure emerge from a pre-geometric manifold $\mathcal{M}'$ populated by superluminal primary particles. The fundamental invariant speed in $\mathcal{M}'$ is $v_p > c$, while the Lorentzian metric and the limiting velocity c arise statistically through coarse-graining and the central limit theorem applied to the microscopic velocity ensemble. In this sense, special relativity is not violated but extended: Lorentz invariance appears as a universal low-energy fixed point of the underlying transport dynamics. A discrete velocity spectrum with quantum $\varepsilon \approx 2.38 \times 10^{-114} \text{ m} \cdot \text{s}^{-1}$ provides a microscopic foundation for cosmological dynamics. We show that the critical density of Loop Quantum Cosmology is derived from first principles as a consequence of velocity-state saturation, leading to a non-singular Big Bounce. Density perturbations originate from finite-number statistical fluctuations of occupation levels, yielding $\delta\rho/\rho \sim 10^{-5}$ and an approximately scale-invariant scalar spectrum with a small red tilt $n_s \approx 0.97$, consistent with Planck observations. Tensor modes arise from quadrupole anisotropies of the velocity distribution, predicting a suppressed tensor-to-scalar ratio and violation of the slow-roll consistency relation. Time emerges relationally from collective dynamics in $\mathcal{M}'$, rather than being fundamental. The model therefore provides a statistically grounded, microphysical alternative to inflation, with distinctive and testable cosmological signatures.

Keywords

Emergent Spacetime, Pre-Geometric Cosmology, Primary Particle Hypothesis, Primordial Perturbations, Loop Quantum Cosmology, Tensor-to-Scalar Ratio

1. Introduction

In this work, we develop a statistical-mechanical realization of the Primary Particle Hypothesis (PPH), in which spacetime, Lorentz invariance, and primordial cosmological perturbations emerge from the collective dynamics of a pre-geometric ensemble of primary particles. Understanding whether spacetime is fundamental or emergent remains one of the central problems of modern theoretical physics. General Relativity provides a highly successful macroscopic description of gravitational dynamics, yet its singular behavior at early times and its incompatibility with quantum theory strongly suggest that spacetime geometry may arise from a deeper microscopic structure.

Several approaches to quantum gravity, including Loop Quantum Cosmology (LQC) [1] [2], replace the initial singularity with a non-singular bounce. However, the microscopic origin of spacetime, the emergence of Lorentz invariance, and the physical meaning of the critical density remain open questions.

In this work, we develop an extended mathematical formulation of the Primary Particle Hypothesis, in which spacetime and its causal structure emerge from a pre-geometric manifold $\mathcal{M}'$ populated by primary particles with a fundamental invariant velocity scale $v_p > c$.

The key idea of the framework is that Lorentz invariance is not fundamental, but arises as a universal statistical property of coarse-grained microscopic dynamics. Using transport theory and the central limit theorem, we show that the Minkowski metric and the invariant speed c emerge as collective properties determined solely by the second moment of the underlying velocity distribution.

This perspective leads to a hierarchy of causal structures: a fundamental causal cone governed by v_p and an emergent Lorentz cone governed by c . Superluminal microscopic dynamics is therefore compatible with macroscopic relativistic causality.

A central feature of the model is the introduction of a discrete velocity spectrum, which provides a direct microphysical origin for cosmological observables. In particular:

- The critical density of Loop Quantum Cosmology is derived from velocity-state saturation,
- Scalar perturbations arise from finite-number statistical fluctuations, yielding $\delta\rho/\rho \sim 10^{-5}$,
- A nearly scale-invariant power spectrum with a small red tilt emerges without inflation,
- Tensor modes originate from quadrupole anisotropies of the velocity ensemble.

The framework therefore provides a statistically grounded alternative to inflation in which cosmological structure is a direct consequence of microscopic transport dynamics.

Importantly, the model leads to clear observational signatures, including a violation of the inflationary consistency relation and a nearly scale-invariant tensor

spectrum. These predictions make the framework directly testable with upcoming CMB observations.

Finally, time itself emerges as a relational quantity associated with collective dynamics, reinforcing the pre-geometric nature of the theory.

The goal of this work is to establish a mathematically consistent bridge between microscopic velocity dynamics and macroscopic spacetime structure, thereby providing a unified statistical foundation for relativity and cosmology.

2. Pre-Spacetime Structure

We postulate a pre-spacetime manifold $\mathcal{M}'$ endowed with coordinates $(t', \mathbf{r}')$ and characteristic velocity scale $v_p > c$.

The invariant interval in pre-spacetime is defined as

$$ds'^2 = v_p^2 dt'^2 - d\mathbf{r}'^2. \quad (1)$$

It is important to emphasize that Equation (1) should not be interpreted as a physical spacetime metric, but rather as a kinematic quadratic form defining the causal ordering in the pre-geometric manifold $\mathcal{M}'$. The Lorentzian metric of emergent spacetime arises only after statistical coarse-graining, as shown in Section 2.2.

Primary particles follow trajectories

$$\mathbf{r}'(t') = \mathbf{r}'_0 + \mathbf{v}'t', \quad |\mathbf{v}'| < v_p. \quad (2)$$

The distribution function $f(\mathbf{r}', \mathbf{v}', t')$ satisfies the collisionless transport equation:

$$\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = 0. \quad (3)$$

These particles are not bound by the Lorentz invariant, because we introduced a new transformation factor (Section 3).

Fundamental dynamical equation

The fundamental dynamical object of the PPH framework is the distribution function $f(\mathbf{r}', \mathbf{v}', t')$, whose evolution governs both microscopic transport and macroscopic emergence.

While Equation (3) describes collisionless dynamics, the discrete structure of the velocity spectrum naturally induces stochastic transitions between neighboring velocity states (see **Appendix A**). This leads to an effective coarse-grained evolution equation of Fokker-Planck type:

$$\boxed{\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = D_v \nabla_v^2 f} \quad (4)$$

Equation (4) constitutes the fundamental equation of the PPH framework. All emergent structures, including spacetime geometry, causal structure, and cosmological perturbations, arise from its statistical solutions.

In this sense, spacetime is not a fundamental entity but an effective description of the collective dynamics encoded in f .

Main result: The motion of primary particles generates an emergent space-time with effective velocities with an upper limit velocity c .

Implication: Standard particles and physical laws arise from the collective behavior of primary particles.

2.1. Causal Structure and Consistency of Superluminal Dynamics

The introduction of a characteristic velocity scale $v_p > c$ requires a careful clarification of the causal structure of the pre-spacetime manifold $\mathcal{M}'$.

Pre-geometric light cone

The invariant interval, Equation (1)

$$ds'^2 = v_p^2 dt'^2 - d\mathbf{r}'^2$$

defines a causal cone in $\mathcal{M}'$ with limiting velocity v_p . Causal curves satisfy

$$|\mathbf{v}'| \leq v_p, \quad (5)$$

so that no signal or primary particle trajectory exceeds v_p .

Thus, superluminal motion relative to the emergent velocity c does not violate causality in $\mathcal{M}'$, because c is not the fundamental invariant speed of the pre-geometric phase.

Hierarchy of causal structures

The framework involves two distinct causal cones:

- The fundamental cone in $\mathcal{M}'$, determined by v_p ,
- The emergent Lorentz cone in spacetime, determined by c .

Since $v_p > c$, every Lorentz-causal trajectory is also causal in $\mathcal{M}'$. However, not every $\mathcal{M}'$ -causal trajectory remains causal after coarse-graining.

This establishes a hierarchy:

$$\mathcal{C}_{\text{Lorentz}} \subset \mathcal{C}_{\mathcal{M}'}. \quad (6)$$

Causality in the emergent spacetime is therefore inherited from the stronger pre-geometric causality, not violated by it.

Absence of closed causal curves

Closed causal curves would require violation of the fundamental ordering in t' . However, the transport Equation (3)

$$\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = 0$$

is hyperbolic with respect to t' and admits well-posed initial value formulation on spacelike hypersurfaces of $\mathcal{M}'$.

Given initial data on $t' = \text{const}$, the evolution is uniquely determined, ensuring global hyperbolicity of the pre-spacetime manifold.

Therefore, no closed causal curves arise in $\mathcal{M}'$.

Emergent relativistic causality

The emergent velocity c appears as the root-mean-square velocity of primary particles after coarse-graining:

$$c^2 = \langle v'^2 \rangle. \quad (7)$$

Since coarse-graining integrates over the full distribution, signals in the emergent spacetime propagate only within the effective Lorentz cone.

Superluminal microscopic propagation therefore does not translate into macroscopic superluminal signaling.

Interpretation

Superluminality in this framework is not a violation of causality, but a reflection of the fact that Lorentz invariance is emergent rather than fundamental.

The fundamental invariant structure is governed by v_p , while c characterizes the collective, low-energy limit.

This situation is analogous to condensed-matter systems in which quasiparticles obey an emergent relativistic dispersion relation with limiting velocity lower than the microscopic propagation speed of underlying constituents.

2.2. Emergent Lorentz Symmetry from the Central Limit Theorem

We now show that Lorentz symmetry in the emergent spacetime arises statistically from the collective behavior of primary particle velocities.

Microscopic velocity ensemble

Consider a coarse-grained cell containing N primary particles with velocities $\mathbf{v}'_a$ drawn from a distribution $f(\mathbf{v}')$ defined in $\mathcal{M}'$. Assume:

- The distribution is isotropic in the pre-spacetime manifold,
- Velocities are statistically independent beyond a microscopic correlation length,
- The second moment $\langle v'^2 \rangle$ is finite.

Define the coarse-grained averaged velocity:

$$\bar{\mathbf{v}} = \frac{1}{N} \sum_{a=1}^N \mathbf{v}'_a. \quad (8)$$

By the central limit theorem, as $N \rightarrow \infty$, the distribution of $\bar{\mathbf{v}}$ approaches a Gaussian with covariance matrix determined by the second moment:

$$\langle \bar{v}_i \bar{v}_j \rangle = \frac{1}{N} \langle v'_i v'_j \rangle. \quad (9)$$

Isotropy and covariance structure

For an isotropic microscopic distribution,

$$\langle v'_i v'_j \rangle = \frac{1}{3} \delta_{ij} \langle v'^2 \rangle. \quad (10)$$

Hence,

$$\langle \bar{v}_i \bar{v}_j \rangle = \frac{1}{3N} \delta_{ij} \langle v'^2 \rangle. \quad (11)$$

This covariance tensor is rotationally invariant and uniquely determined by the scalar quantity $\langle v'^2 \rangle$.

Emergent invariant speed

We define the effective limiting velocity in the emergent spacetime as

$$c^2 = \langle v'^2 \rangle,$$

(as in Equation (7)).

The Gaussian fixed point of the central limit theorem ensures that the coarse-grained fluctuations depend only on the quadratic invariant

$$v^2 = \delta_{ij} v_i v_j. \quad (12)$$

As a consequence, the effective quadratic form governing propagation at large scales is

$$ds^2 = c^2 dt^2 - d\mathbf{r}^2, \quad (13)$$

which is invariant under Lorentz transformations with limiting speed c .

Universality of the Gaussian fixed point

The key result is that the Gaussian distribution is the universal attractor for sums of independent random variables with finite variance.

Therefore:

- The emergent symmetry group depends only on the second moment of the microscopic distribution,
- Higher-order details of $f(\mathbf{v}')$ become irrelevant at large scales,
- Lorentz invariance emerges as a universality class of the central limit theorem.

Renormalization-group interpretation

The statistical emergence of Lorentz symmetry admits a natural interpretation in terms of renormalization-group (RG) flow.

At the microscopic level the fundamental dynamics is governed by the velocity scale v_p characterizing the pre-spacetime manifold $\mathcal{M}'$. The distribution of primary particle velocities may in general possess a complicated non-Gaussian structure.

However, the coarse-graining procedure effectively performs a sum over a large number of statistically independent velocity degrees of freedom. According to the central limit theorem, the distribution flows toward a Gaussian fixed point determined only by its second moment.

Because the covariance tensor of the velocity ensemble is isotropic, Equation (10)

$$\langle v'_i v'_j \rangle = \frac{1}{3} \delta_{ij} \langle v'^2 \rangle,$$

the effective quadratic invariant controlling large-scale propagation becomes (13), *i.e.*

$$ds^2 = c^2 dt^2 - d\mathbf{r}^2,$$

where the emergent limiting velocity is given as in Equation (7) with

$$c^2 = \langle v'^2 \rangle.$$

In this sense Lorentz symmetry appears as a stable fixed point of the statistical coarse-graining of the underlying velocity ensemble. The invariant speed c therefore represents an effective propagation scale emerging from the renormalization of microscopic superluminal dynamics rather than a fundamental constant of the pre-geometric theory.

The emergence of Lorentz invariance should be understood as a property of the effective propagation law of collective excitations, rather than a direct consequence of Gaussianity alone.

Interpretation

Lorentz symmetry is not fundamental in this framework. It arises as the unique quadratic invariant compatible with isotropic Gaussian statistics of coarse-grained velocity ensembles.

In this sense, the Lorentz group plays the role of a renormalization-group fixed symmetry of the pre-geometric velocity dynamics.

Physical interpretation

Lorentz invariance is not a fundamental symmetry of $\mathcal{M}'$, but a universal property of collective excitations of the velocity ensemble.

In this sense, spacetime geometry arises as the effective propagation structure of coarse-grained degrees of freedom, rather than as a primary geometric entity.

3. Generalized Transformations

Between inertial frames S and S' in $\mathcal{M}'$ moving with velocity v , we define the transformation:

$$x' = \gamma_p (x - vt), \quad (14)$$

$$t' = \gamma_p \left(t - \frac{v}{v_p^2} x \right), \quad (15)$$

where

$$\gamma_p = \frac{1}{\sqrt{1 - \frac{v^2}{v_p^2}}}, \quad (16)$$

and we obtained this transformation similarly to Equation (14), Ref. [3].

For $v_p \rightarrow c$, standard Lorentz transformations are recovered.

Main result: These transformations remain consistent for velocities higher than c , thus extending standard relativity.

From Distribution to Metrics

We now construct the emergent spacetime metric as a statistical object derived from the microscopic velocity ensemble.

Let $\eta'_{\alpha\beta}$ denote the quadratic form defined in the pre-spacetime manifold $\mathcal{M}'$. The effective metric in the emergent spacetime is defined as an expectation value over the distribution function:

$$g_{\mu\nu}(x) = \int \eta'_{\alpha\beta} \frac{\partial x^\alpha}{\partial x'^\mu} \frac{\partial x^\beta}{\partial x'^\nu} f(x', v') d^3v'. \quad (17)$$

This expression shows that the spacetime metric is not fundamental, but arises as a collective statistical observable of the underlying microscopic dynamics.

In particular:

- The metric depends only on coarse-grained properties of the velocity ensemble,
- Local Lorentz invariance emerges from isotropy of the second moment,
- Deviations from equilibrium correspond to deviations from classical spacetime geometry.

Thus, geometry is promoted from a primary structure to an emergent effective field determined by the distribution function f .

4. Emergent Spacetime

We define emergent spacetime coordinates as coarse-grained averages:

$$x^\mu = \langle x'^\mu \rangle_f, \quad (18)$$

where averaging is performed over the distribution f .

Effective limiting speed in emergent spacetime:

$$c^2 = \frac{d\mathbf{r}'^2}{dt'^2}. \quad (19)$$

The emergent metric tensor is obtained via statistical averaging:

$$g_{\mu\nu} = \langle \eta'_{\mu\nu} \rangle. \quad (20)$$

5. CMB Homogenization Mechanism

Fast equilibration in pre-spacetime occurs over scale

$$\tau_{eq} \sim \frac{L}{v_p}, \quad (21)$$

with $v_p \gg c$, ensuring causal contact before emergence.

The resulting density contrast satisfies

$$\delta\rho/\rho \sim \mathcal{O}(10^{-5}), \quad (22)$$

consistent with observed CMB anisotropies (see Equation (27), **Appendix A** and Equation (29)).

Main result: This rapid dynamics creates a quasi-isotropic distribution that, upon emergence into our spacetime, appears as a homogeneous CMB.

Statistical Origin and Scale Structure of the Density Contrast

In the present framework, density fluctuations do not originate from vacuum fluctuations of a scalar field, but from statistical fluctuations of the discrete velocity states of primary particles.

We introduced that the velocity spectrum is quantized:

$$v'_n = n\varepsilon, \quad n \in \mathbb{Z}, \quad (23)$$

as a postulate of our model, and is analogous to the quantization of energy in a potential well.

Explicitly, the velocity quantum is given in Equation (1), [4] (*i.e.* implicitly in Equations. (6), (8) and (9) in [5]) as

$$\varepsilon = \frac{1}{2} c \left(\frac{m_p}{M_U} \right)^2 \approx 2.38 \times 10^{-114} \text{ m} \cdot \text{s}^{-1}, \quad (24)$$

where m_p is the Planck mass, $M_U \approx 1.73 \times 10^{53} \text{ kg}$ denotes the total mass of matter (baryonic + dark matter) contained in the visible Universe, obtained from the cosmological matter density parameter Ω_m and here it is viewed as a global invariant of the system, and the energy density is

$$\rho = \sum_n f_n \frac{1}{2} m_p v_n'^2. \quad (25)$$

For a coarse-grained region containing a large number of primary particles, the mean energy density reads

$$\bar{\rho} = \frac{1}{2} m_p \langle v'^2 \rangle = \frac{1}{2} m_p \sum_n f_n (n\varepsilon)^2. \quad (26)$$

Since the density is quadratic in the discrete velocity levels, its statistical variance is determined by fluctuations in the occupation numbers f_n . If the coarse-grained region contains N_{eff} statistically independent microscopic cells, the central limit theorem implies

$$\frac{\delta\rho}{\rho} \sim \frac{1}{\sqrt{N_{\text{eff}}}}, \quad (27)$$

which we showed in **Appendix A**.

Effective number of degrees of freedom

In the pre-emergent phase, causal contact is established at the characteristic scale (Equation (21))

$$\tau_{\text{eq}} \sim \frac{L}{v_p},$$

with $v_p \gg c$, allowing statistical equilibration within a horizon-sized patch prior to the geometric phase transition.

If the coarse-graining volume corresponds to a Planck-scale cellular structure at the bounce, the effective number of independent cells inside a causal patch is

$$N_{\text{eff}} \sim \frac{V_{\text{patch}}}{\ell_p^3}. \quad (28)$$

Using standard LQC estimates for the horizon volume near the bounce scale, a representative estimate yields

$$N_{\text{eff}} \sim 10^{10}. \quad (29)$$

(The precise value of N_{eff} depends on the detailed coarse-graining prescription, and we consider this to be an order of magnitude estimate.)

That's how we get

$$\frac{\delta\rho}{\rho} \sim 10^{-5}. \quad (30)$$

Thus, the observed amplitude of CMB anisotropies emerges naturally as a sta-

tistical residual of the discrete velocity structure of primary particles.

Approximate scale invariance

To examine the scale dependence, consider a fluctuation mode characterized by comoving wavenumber k . The corresponding physical volume at the onset of the emergent phase is

$$V_k \sim k^{-3}. \quad (31)$$

The effective number of microscopic cells contributing to that mode scales as

$$N_{\text{eff}}(k) \sim \frac{V_k}{\ell_p^3} \sim \frac{k^{-3}}{\ell_p^3}. \quad (32)$$

Using Equation (27), the variance of density fluctuations per mode scales as

$$\left(\frac{\delta\rho}{\rho} \right)_k^2 \sim \frac{1}{N_{\text{eff}}(k)} \sim k^3. \quad (33)$$

The dimensionless power spectrum is defined as

$$\mathcal{P}_\delta(k) \sim k^3 |\delta_k|^2. \quad (34)$$

Substituting the above scaling yields

$$\mathcal{P}_\delta(k) \sim \text{const}. \quad (35)$$

Therefore, the discrete velocity structure naturally produces an approximately scale-invariant spectrum without invoking an inflationary phase. Deviations from exact scale invariance arise from mild k -dependence in the equilibration process and in the occupation number distribution f_n , leading to a small spectral tilt.

6. Statistical Origin of Scalar and Tensor Spectra

In the PPH framework, both scalar and tensor perturbations arise from statistical fluctuations of the discrete velocity distribution of primary particles. Scalar modes originate from density fluctuations, while tensor modes arise from fluctuations of the traceless anisotropic stress tensor.

Scalar fluctuations

The energy density is given by Equation (25)

$$\rho = \sum_n f_n \frac{1}{2} m_p v_n'^2.$$

For a coarse-grained region containing N_{eff} statistically independent microscopic cells, the central limit theorem implies Equation (27),

$$\frac{\delta\rho}{\rho} \sim \frac{1}{\sqrt{N_{\text{eff}}}}.$$

Near the bounce, taking

$$N_{\text{eff}} \sim \frac{V_{\text{patch}}}{\ell_p^3} \sim 10^{10}, \quad (36)$$

is obtained as in Equation (30)

$$\frac{\delta\rho}{\rho} \sim 10^{-5},$$

in agreement with the observed amplitude of CMB anisotropies.

Tensor fluctuations from multipole statistics

Tensor modes are sourced by the traceless part of the stress tensor

$$\Pi_{ij} = m_p \int v'_i v'_j f(\mathbf{v}') d^3 v'. \quad (37)$$

The tensor component corresponds to the quadrupole ($\ell = 2$) moment of the angular distribution of velocities.

Let the angular distribution be expanded in spherical harmonics:

$$f(\theta, \phi) = f_0 \left[1 + \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi) \right]. \quad (38)$$

For an almost isotropic distribution, the multipole coefficients satisfy

$$\langle |a_{\ell m}|^2 \rangle \sim \frac{1}{N_{\text{ang}}}, \quad (39)$$

where N_{ang} is the effective number of independent angular cells contributing to isotropization.

Since tensor modes are sourced by the quadrupole,

$$\mathcal{P}_t \sim \langle |a_{2m}|^2 \rangle \sim \frac{1}{N_{\text{ang}}}. \quad (40)$$

PPH prediction for the tensor-to-scalar ratio

An important feature of the PPH framework is the existence of a consistency relation between scalar and tensor perturbations, analogous in spirit to the inflationary consistency relation $r = -8n_t$.

In the PPH model, scalar and tensor perturbations originate from different statistical aspects of the same microscopic system. Scalar fluctuations arise from volumetric density fluctuations of primary particles, while tensor modes originate from the quadrupole anisotropy of the velocity distribution.

The scalar power scales as

$$\mathcal{P}_s \sim \frac{1}{N_{\text{eff}}}, \quad (41)$$

where N_{eff} is the effective number of independent microscopic cells contributing to a coarse-grained region.

Tensor modes arise from angular multipole fluctuations, leading to

$$\mathcal{P}_t \sim \frac{1}{N_{\text{ang}}}, \quad (42)$$

where N_{ang} denotes the number of independent angular cells participating in the isotropization of the velocity distribution.

The tensor-to-scalar ratio therefore satisfies

$$r = \frac{\mathcal{P}_t}{\mathcal{P}_s} = \frac{N_{\text{eff}}}{N_{\text{ang}}}. \quad (43)$$

This relation constitutes a characteristic prediction of the PPH framework.

Efficient angular mixing implies $N_{\text{ang}} \gg N_{\text{eff}}$, which naturally suppresses tensor modes.

Using the representative estimates

$$N_{\text{eff}} \sim 10^{10}, \quad N_{\text{ang}} \sim 10^{12}, \quad (44)$$

which should be understood as an order of magnitude characterization rather than a precise prediction, we obtain

$$r \sim 10^{-2}, \quad (45)$$

with stronger isotropization yielding

$$r \lesssim 10^{-3}. \quad (46)$$

This result provides a direct microphysical interpretation of tensor suppression in terms of the statistical structure of the primary particle ensemble.

Key predictions

The statistical structure of the PPH model therefore predicts:

- Scalar amplitude $\delta\rho/\rho \sim 10^{-5}$,
- Nearly scale-invariant scalar and tensor spectra,
- Tensor-to-scalar ratio r suppressed by angular isotropization,
- Absence of the slow-roll consistency relation.

The suppression of r is controlled by the ratio between volumetric and angular statistical degrees of freedom, providing a clear physical interpretation and a falsifiable prediction.

Consistency with LQC bounce dynamics

In effective Loop Quantum Cosmology, the modified Friedmann equation reads

$$H^2 = \frac{8\pi G}{3} \rho \left(1 - \frac{\rho}{\rho_c}\right). \quad (47)$$

Within the PPH framework, the critical density is derived from the quantized velocity scale:

$$\rho_c = \frac{3}{8\pi G} \frac{c \cdot \mathcal{E}}{\ell_p^2} \left(\frac{M_U}{m_p}\right)^2. \quad (48)$$

When we replace $\left(\frac{M_U}{m_p}\right)^2$ with $\frac{c}{2\mathcal{E}}$ from Equation (24) we obtain:

$$\rho_c = \frac{3}{16\pi} \frac{c^2}{G \ell_p^2} \approx 0.06 \rho_{\text{Planck}}. \quad (49)$$

The agreement with the standard LQC value should be interpreted at the level of scaling and order of magnitude, rather than as an exact numerical derivation.

The bounce occurs when $\rho = \rho_c$, corresponding physically to saturation of accessible velocity states:

$$\langle v'^2 \rangle \rightarrow v_{p,\text{max}}^2. \quad (50)$$

Hence, the LQC bounce condition acquires a microscopic interpretation: it corresponds to the maximal occupation of discrete velocity levels. The non-singular evolution is therefore not merely a geometric artifact of quantum gravity corrections, but a statistical consequence of the finite velocity spectrum of primary particles.

This establishes a closed bridge between PPH microphysics and effective LQC dynamics, linking:

- quantized velocity levels (ε),
- statistical density fluctuations ($\delta\rho/\rho$),
- and the critical bounce density (ρ_c).

Comment: The critical density ρ_c at which the Big Bang occurs is usually treated as a free parameter in the effective LQC. However, in the PPH framework, we can derive ρ_c by considering the interaction between the fundamental velocity quantum ε and the global mass-energy content of the universe M_U . Substituting Equation (24) into the modified Friedmann dynamics, we find that the big bang is triggered exactly when the energy density reaches a threshold defined by the saturation of the velocity state of the primary particles $\rho = \rho_c$. This leads to a non-singular evolution where the Planck scale density is restored as a natural consequence of the velocity quantization.

Main result: The model predicts an escape from the singularity (Big Bang $\rightarrow$ Big Bounce).

Implication: We can compare current observational constraints from the Planck 2018 full-mission analysis and combined Planck + BICEP/Keck ([6] and [7]) limits on primordial tensors with representative predictions of the PPH framework developed in this work. The PPH predictions are not single-point fits but representative ranges derived from the microscopic parameters (ε , N_{eff} , N_{ang} and the equilibration scale ℓ_{eq}). Importantly, the scalar amplitude and tilt produced by finite-number statistical fluctuations and transport-induced equilibration lie naturally in the Planck-preferred region, while the tensor-to-scalar ratio is generically suppressed (typical $r \sim 10^{-3} - 10^{-2}$) and therefore consistent with present upper limits. Therefore, these results motivate a full numerical implementation and MCMC confrontation described in **Appendix B**.

7. Distinctive Observational Predictions

A crucial question for any alternative to inflation is whether it makes observational predictions that distinguish it from slow-roll scenarios.

Absence of the inflationary consistency relation

In standard single-field slow-roll inflation the tensor-to-scalar ratio and the tensor spectral index satisfy the well-known consistency relation

$$r = -8n_t, \quad (51)$$

which follows directly from the slow-roll relations $r = 16\epsilon$ and $n_t = -2\epsilon$ [8]-[10].

In the PPH framework, scalar and tensor modes originate from distinct statis-

tical aspects of the same pre-geometric system:

- Scalar modes arise from density fluctuations,
- Tensor modes arise from anisotropic stress fluctuations.

As a result, we obtain

$$n_t \approx 0, \quad r \sim \frac{1}{N_{\text{ang}}}, \quad (52)$$

with no fundamental relation between r and n_t .

Therefore, the inflationary consistency relation is generically violated in the PPH scenario. Also, the PPH expectation is that the frequency (temperature) of a hyperenergetic spherical wave of pre-geometric origin, from the very initial moment of exiting the singularity (Big Bang $\rightarrow$ Big Bounce), decreases sharply until the epoch of nucleogenesis as in Ref. [11].

Spectral structure

The scalar spectral index is given by

$$n_s - 1 = -\alpha, \quad (53)$$

where α originates from finite equilibration effects in quantized velocity space, and an additional, cosmological estimate of the spectral tilt is shown in **Appendix C**.

The tensor spectrum remains approximately scale-invariant at leading order:

$$n_t \approx 0. \quad (54)$$

This separation of scalar and tensor tilt provides a clear observational discriminator.

Non-Gaussianity scaling

Since fluctuations arise from finite-number statistical effects, residual non-Gaussianity scales as

$$f_{NL} \sim \frac{1}{N_{\text{eff}}}, \quad (55)$$

differing structurally from the slow-roll expectation.

Summary

The PPH framework predicts:

- Violation of the inflationary consistency relation,
- Suppressed tensor-to-scalar ratio,
- Nearly scale-invariant tensor spectrum,
- Scalar tilt determined by transport dynamics,
- Distinct statistical origin of non-Gaussianity.

Future measurements of n_t and r , such as [12] and [13], therefore provide a direct test of the model.

Primary falsifiable prediction

A central, model-independent prediction of the PPH framework is the following:

$$n_t \approx 0 \text{ independently of } r. \quad (56)$$

Prediction: A future detection of a tensor-to-scalar ratio $r \gtrsim 10^{-3}$ together with a nearly scale-invariant tensor spectrum ($n_t \approx 0$) would violate the inflationary consistency relation $r = -8n_t$ and provide strong evidence in favor of the PPH framework.

Conversely, a confirmed detection of a red tensor tilt satisfying $r = -8n_t$ would falsify the present statistical origin of tensor modes.

This establishes a direct and decisive observational test of the model.

8. Emergent Time

Time is defined relationally:

$$\Delta t = \frac{\Delta s'}{\langle v' \rangle}. \quad (57)$$

Thus time arises from collective dynamics rather than being fundamental.

Main result: Time in our space results from the average dynamics of primary particles in prespace.

9. Conclusions

We have developed an extended mathematical formalism of the Primary Particle Hypothesis in which Lorentzian spacetime, relativistic causality, and cosmological perturbations emerge from a superluminal pre-geometric manifold governed by transport dynamics. Special relativity appears as a universal statistical limit, rather than a fundamental postulate.

The discrete velocity spectrum provides a microscopic derivation of the LQC critical density and predicts a non-singular Big Bounce. Scalar and tensor perturbations arise from finite-number statistical fluctuations, yielding Planck-compatible amplitude and tilt while generically violating inflationary consistency relations.

Time itself emerges relationally from collective dynamics in $\mathcal{M}'$. The resulting framework constitutes a microphysically grounded cosmological model with distinctive observational signatures, offering a testable alternative to inflationary paradigms. We expect that recent analyses of the cosmological signatures of the LiteBIRD and CMB-S4 missions will provide a clear discrimination between the PPH framework and inflationary models.

While several elements of the framework remain at the level of leading-order effective description, the internal consistency of the model and its clear observational signatures provide a well-defined basis for further quantitative development.

Conflicts of Interest

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

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Appendix A. Transport Origin of Statistical Fluctuations

Because the velocity spectrum is discrete, statistical redistribution among neighboring velocity levels produces an effective diffusion in velocity space, leading to a Fokker-Planck type evolution of the distribution function [14]-[16].

The statistical fluctuations responsible for primordial density perturbations can be derived directly from the transport equation governing the distribution of primary particles.

Let the distribution function be decomposed as

$$f(\mathbf{r}', \mathbf{v}', t') = f_0(\mathbf{v}') + \delta f, \quad (58)$$

where f_0 is the isotropic equilibrium distribution and δf represents small fluctuations.

Substituting into the transport Equation (3)

$$\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = 0$$

and linearizing yields

$$\frac{\partial \delta f}{\partial t'} + \mathbf{v}' \cdot \nabla' \delta f = 0. \quad (59)$$

From discrete velocity transitions to Fokker-Planck dynamics

The effective diffusion term appearing in the transport equation can be justified from the discrete structure of the velocity spectrum.

In the PPH framework, the velocity states are quantized as in Equation (23)

$$\mathbf{v}'_n = n\boldsymbol{\varepsilon},$$

so that the distribution function evolves through transitions between neighboring velocity levels. The statistical evolution of the distribution can therefore be written in the form of a master equation

$$\partial_{t'} f(\mathbf{v}') = \sum_{\Delta n} [W_{\Delta n} f(\mathbf{v}' - \Delta \mathbf{v}) - W_{-\Delta n} f(\mathbf{v}')], \quad (60)$$

where $W_{\Delta n}$ denotes the transition probability between adjacent velocity states.

Expanding the right-hand side in powers of $\Delta \mathbf{v}$ leads to the Kramers-Moyal expansion

$$\partial_{t'} f = -\partial_v (Af) + \frac{1}{2} \partial_v^2 (Bf) + \dots, \quad (61)$$

with coefficients determined by the transition moments of the underlying stochastic process.

Because the velocity quantum $\boldsymbol{\varepsilon}$ is extremely small, higher-order terms are strongly suppressed and the expansion can be truncated at second order. The evolution equation therefore reduces to the Fokker-Planck form

$$\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = D_v \nabla_v^2 f. \quad (62)$$

This result provides a microscopic justification for the diffusive term used in

the main text and shows that the statistical fluctuations of the primary particle ensemble naturally obey a Fokker-Planck type dynamics (*i.e.* Equation (4)).

Also: Because the velocity spectrum is discrete, statistical redistribution among nearby velocity levels leads to an effective diffusion in velocity space. The transport equation therefore acquires a Fokker-Planck form, *i.e.* Equation (4)

$$\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = D_v \nabla_v^2 f. \quad (63)$$

For the perturbations this becomes

$$\frac{\partial \delta f}{\partial t'} + \mathbf{v}' \cdot \nabla' \delta f = D_v \nabla_v^2 \delta f. \quad (64)$$

Fourier transforming in space leads to

$$\partial_{t'} \delta f_k + i\mathbf{k} \cdot \mathbf{v}' \delta f_k = D_v \nabla_v^2 \delta f_k. \quad (65)$$

The solution of this equation shows that the variance of coarse-grained density fluctuations scales as

$$\langle \delta f^2 \rangle \propto \frac{1}{N_{\text{eff}}}, \quad (66)$$

which directly leads to

$$\frac{\delta \rho}{\rho} \sim \frac{1}{\sqrt{N_{\text{eff}}}},$$

and that is the same as (27)

Thus the amplitude of primordial density perturbations emerges as a statistical consequence of the transport dynamics of the primary particle ensemble.

Appendix B. Spectral Tilt from Non-Uniform Occupation Numbers

In the main text, approximate scale invariance was obtained under the assumption of nearly uniform occupation numbers f_n for the discrete velocity levels. We now relax this assumption and allow for a mild scale dependence in the form

$$f_n \propto n^{-\alpha}, \quad \alpha \ll 1. \quad (67)$$

Such a deviation may arise from incomplete equilibration in the pre-emergent phase or from residual dynamical bias in the velocity distribution.

Modified variance

The mean squared velocity becomes

$$\langle v'^2 \rangle = \varepsilon^2 \sum_n n^{2-\alpha}. \quad (68)$$

Approximating the sum by an integral up to $n_{\max}$, we obtain

$$\langle v'^2 \rangle \sim \varepsilon^2 \int n^{2-\alpha} dn \sim \varepsilon^2 n_{\max}^{3-\alpha}. \quad (69)$$

The effective number of states contributing to a fluctuation mode of comoving wavenumber k scales as

$$n_{\max}(k) \sim k^{-1}. \quad (70)$$

Hence,

$$\langle v'^2 \rangle(k) \sim \varepsilon^2 k^{-(3-\alpha)}. \quad (71)$$

Power spectrum

The density contrast variance scales inversely with the effective number of independent cells,

$$\left(\frac{\delta\rho}{\rho} \right)_k^2 \sim \frac{1}{N_{\text{eff}}(k)} \sim k^{3-\alpha}. \quad (72)$$

The dimensionless power spectrum is

$$\mathcal{P}(k) \sim k^3 |\delta_k|^2. \quad (73)$$

Substituting the above scaling yields

$$\mathcal{P}(k) \sim k^\alpha. \quad (74)$$

Therefore, the spectral index is

$$n_s - 1 = \alpha. \quad (75)$$

Magnitude of the tilt

For small α , the deviation from exact scale invariance is mild. Matching observational data,

$$n_s \approx 0.965, \quad (76)$$

implies

$$\alpha \approx -0.035. \quad (77)$$

Thus, a slight suppression of higher velocity levels in the occupation distribution naturally produces a red spectral tilt consistent with current cosmological observations.

This result demonstrates that the PPH framework not only reproduces approximate scale invariance, but also accommodates a small spectral tilt through minimal deviations from uniformity in the discrete velocity distribution.

Appendix C. Transport Origin and Cosmological Estimate of the Spectral Tilt

Transport-induced deviation from uniformity

The distribution function of primary particles satisfies the collisionless transport equation (3)

$$\frac{\partial f}{\partial t'} + \mathbf{v}' \cdot \nabla' f = 0.$$

In a finite causal domain of size L , equilibration occurs over

$$\tau_{eq} \sim \frac{L}{v_p}.$$

Modes with higher discrete velocity $v'_n = n\varepsilon$ have shorter crossing time

$$\tau_n \sim \frac{L}{n\varepsilon}. \quad (78)$$

Incomplete equilibration leads to a mild suppression of large- n occupation numbers, yielding

$$f_n \propto n^{-\alpha}. \quad (79)$$

Relation to density power spectrum

As given in Equation (53),

$$n_s - 1 = -\alpha.$$

We now estimate α from cosmological scales.

Equilibration length and horizon scale

Let the equilibration length in the pre-emergent phase be

$$\ell_{eq} \sim v_p \tau_{eq}. \quad (80)$$

Near the bounce, the characteristic geometric scale is Planckian:

$$H_{bounce}^{-1} \sim \ell_p. \quad (81)$$

A finite ratio between the horizon size and equilibration length generates residual scale dependence:

$$\alpha \sim \frac{\ell_p}{\ell_{eq}}. \quad (82)$$

Numerical estimate

If equilibration occurs over a scale moderately larger than the Planck length, for example

$$\ell_{eq} \sim 30 \ell_p, \quad (83)$$

then

$$\alpha \sim \frac{1}{30} \sim 0.03. \quad (84)$$

This corresponds to

$$n_s \approx 0.97, \quad (85)$$

in excellent agreement with current CMB observations.

Interpretation

The small red tilt therefore arises from incomplete but nearly efficient equilibration in quantized velocity space. It is controlled by the ratio of the microscopic equilibration scale to the geometric horizon scale at the bounce.

No fine-tuning of parameters or scalar potentials is required. The observed deviation from exact scale invariance is a direct statistical imprint of the finite transport dynamics in the pre-geometric phase.

Statistical Origin of the Running of the Spectral Index

A further refinement of the PPH framework involves the scale dependence of the spectral tilt, known as the running of the spectral index, $\alpha_s = dn_s/d\ln k$. In our model, this parameter is not an independent constant but a direct probe of the “texture” of the primary particle distribution f_n . If we relax the assumption of a strict power-law and allow the occupation exponent α to vary logarithmically with the velocity level n , we can write:

$$f_n \propto n^{-\left(\alpha_0 + \frac{1}{2}\beta \ln n\right)}, \quad (86)$$

where β represents a second-order correction to the equilibration process in $\mathcal{M}'$. Given the inverse relationship between the microscopic state index and the cosmological wavenumber, $n \sim (k\ell_p)^{-1}$, the running is derived as:

$$\alpha_s = \frac{dn_s}{d\ln k} = \frac{d\alpha}{d\ln n} \cdot \frac{d\ln n}{d\ln k} = -\beta. \quad (87)$$

Current observations from the Planck mission constrain $\alpha_s \approx -0.006 \pm 0.007$. In the PPH context, the smallness of this value is naturally explained by the vast range of available velocity states ($n_{\max} \sim 10^{122}$), which suppresses higher-order logarithmic deviations. A non-zero α_s would therefore provide a direct measurement of the non-ideal statistical equilibration of the primary particle gas during the pre-emergent phase, offering a concrete observational test that distinguishes PPH from standard slow-roll inflation.

Discussion

The extended PPH framework presents a coherent extrapolation of special relativity rather than its breakdown. The invariant structure of the pre-spacetime manifold is governed by v_p , while the Lorentz cone with limiting speed c emerges statistically as a coarse-grained fixed point. This hierarchical causal structure ensures global hyperbolicity at the fundamental level and preserves relativistic causality in the emergent phase. Superluminality is therefore not paradoxical but reflects the deeper invariant structure of $\mathcal{M}'$.

A central achievement of the model is the derivation of cosmological signatures directly from microphysics. The amplitude of scalar perturbations follows from central-limit scaling of discrete velocity occupation numbers, producing $\delta\rho/\rho \sim 10^{-5}$ without invoking vacuum fluctuations of a scalar field. The small red spectral tilt arises from finite equilibration effects governed by transport dy-

namics, yielding values consistent with Planck measurements. Tensor modes originate from quadrupole anisotropies of the velocity distribution and predict a suppressed tensor-to-scalar ratio, generically violating the slow-roll consistency relation.

The quantized velocity scale ε establishes a direct bridge between microscopic structure and the effective LQC Friedmann equation, providing a physical interpretation of the critical density as velocity-state saturation. In this sense, the Big Bounce acquires a statistical-mechanical origin.

Finally, the relational emergence of time highlights the pre-geometric nature of the framework: temporal ordering arises from collective dynamics rather than being fundamental. This statistical-mechanical perspective on spacetime suggests a new route toward quantum gravity in which Lorentz symmetry and cosmological structure are emergent phenomena. In this picture the Lorentz group emerges as the universal symmetry of the Gaussian fixed point of the underlying velocity ensemble.

We present a concise, comparative overview of the most important features that distinguish the standard inflationary scenario from our PPH framework in the **Table A1**.

Table A1. Comparison of cosmological paradigms: inflationary scenario vs. Primary Particle Hypothesis (PPH).

Feature	Standard Inflation	PPH Framework
Fundamental Field	Inflaton (scalar field ϕ)	Primary particle ensemble (gas)
Mechanism	Exponential expansion of space	Superluminal pre-spacetime transport
Initial Singularity	Often present ($t \rightarrow 0$)	Non-singular Big Bounce (LQC)
Origin of $\delta\rho/\rho$	Quantum vacuum fluctuations	Statistical coarse-graining ($1/\sqrt{N_{\text{eff}}}$)
Lorentz Invariance	Fundamental postulate	Emergent Gaussian fixed point
Consistency Relation	$r = -8n_t$ (Strict)	Violated ($r \approx N_{\text{eff}}/N_{\text{ang}}$)
Tensor Index (n_t)	$n_t = -r/8$ (Red tilt)	$n_t \approx 0$ (Scale-invariant)
Critical Density ρ_c	Phenomenological parameter	Derived from ε and M_U
Nature of Time	Fundamental background	Relational/Emergent dynamics

The exact expectations for future analysis of cosmological signatures are given in **Appendix D**.

Appendix D. Observational Discrimination: PPH vs. Inflation in the LiteBIRD Era

The Primary Particle Hypothesis (PPH) provides a distinct set of signatures in the Cosmic Microwave Background (CMB) B-mode polarization that allow for a direct, model-independent test against the standard inflationary paradigm. With the upcoming LiteBIRD mission (expected launch ~ 2030), the precision in measuring the tensor-to-scalar ratio r will reach $\delta r < 0.001$, providing the ideal laboratory for testing the PPH prediction for the tensor-to-scalar ratio as in Section 6.

D.1. The Breakdown of the Inflationary Consistency Relation

In single-field slow-roll inflation, the tensor spectral index n_t and the tensor-to-scalar ratio r are strictly coupled via:

$$r = -8n_t, \quad (88)$$

and we used this well-known relation in Section 7 as the Equation (51). Since $r > 0$, inflation fundamentally predicts a red-tilted tensor spectrum ($n_t < 0$).

In contrast, the PPH framework derives tensor modes from the quadrupole fluctuations of the discrete velocity ensemble. As shown in Section 6, the tensor spectrum is generated by the statistical properties of the primary particle gas, leading to:

$$n_t \approx 0, \quad r \sim \frac{N_{\text{eff}}}{N_{\text{ang}}}. \quad (89)$$

The PPH model predicts a nearly scale-invariant tensor spectrum, fundamentally violating Equation (88). A detection of $r \sim 10^{-3}$ with $n_t \approx 0$ by LiteBIRD would constitute a would strongly favor for PPH and a strongly disfavors standard single-field slow-roll inflation.

D.2. B-Mode Power Spectrum Morphology

The angular power spectrum of B-mode polarization, C_ℓ^{BB} , exhibits two primary peaks: the reionization bump ($\ell < 10$) and the recombination peak ($\ell \sim 80$).

Due to the absence of a red tilt ($n_t \approx 0$), PPH predicts higher power in the recombination peak relative to the reionization bump compared to inflationary models with the same r . This morphological difference is quantifiable. We define the power ratio:

$$\mathcal{R}_{BB} = \frac{C_{\ell=80}^{BB}}{C_{\ell=2}^{BB}}. \quad (90)$$

For PPH, $\mathcal{R}_{BB}$ is higher than the inflationary value, reflecting the persistence of tensor power toward smaller scales (higher ℓ). In PPH, $n_t \approx 0$, so the tensor spectrum is scalar invariant, so the ratio $\mathcal{R}_{BB}$ tends to the value ≈ 1 , while in inflation with $n_t < 0$ this ratio is $\mathcal{R}_{BB} < 1$.

D.3. LiteBIRD Sensitivity and Falsifiability

LiteBIRD is designed to map the CMB polarization over the full sky with unprec-

edented sensitivity. The PPH framework is falsifiable within this experimental setup under the following conditions:

- **Scenario A:** LiteBIRD measures $n_t < 0$ consistent with $r = -8n_t$. This would invalidate the current PPH statistical derivation of tensor modes.
- **Scenario B:** LiteBIRD measures $n_t \approx 0$ with $r \geq 10^{-3}$. This would strongly favor PPH as it provides a natural microphysical explanation for scale-invariance without fine-tuning a potential $V(\phi)$.
- **Scenario C:** No B-modes are detected ($r < 10^{-3}$). This would constrain the ratio $N_{\text{eff}}/N_{\text{ang}}$, implying a much more efficient angular isotropization in the pre-geometric phase than currently estimated.

D.4. Summary of Observational Features

Table A2 summarizes the key discriminators that will be targeted in the forthcoming analysis of LiteBIRD data.

Table A2. Expected LiteBIRD results for Inflation vs. PPH.

Observable	Slow-Roll Inflation	PPH Framework
Tensor Tilt (n_t)	Red-tilted ($n_t = -r/8$)	Scale-invariant ($n_t \approx 0$)
Consistency Relation	$r + 8n_t = 0$	$r + 8n_t \neq 0$ (Violated)
B-mode morphology	Lower power at high ℓ	Persistent power at high ℓ
Microscopic Origin	Vacuum fluctuations	Velocity ensemble statistics

D.5. Statistical Origin and Precise Calculation of the Running of the Spectral Index

A further refinement of the PPH framework involves the scale dependence of the spectral tilt, known as the running of the spectral index, $\alpha_s = dn_s/d\ln k$. In the context of the Primary Particle Hypothesis, this parameter is not an independent phenomenological constant but a direct probe of the microscopic texture of the primary particle distribution f_n .

Logarithmic Deviations in the Velocity Ensemble

While the leading-order spectral tilt $n_s - 1 \approx -\alpha$ arises from the power-law suppression of occupation numbers ($f_n \propto n^{-\alpha}$), a more precise treatment must account for second-order equilibration effects. If the occupation exponent α varies slowly with the velocity level n due to the logarithmic nature of transport-induced entropy production in $\mathcal{M}'$, we can generalize the distribution as given in Equation (86):

$$f_n \propto n^{-\left(\alpha_0 + \frac{1}{2}\beta \ln n\right)},$$

where β represents the second-order correction to the equilibration process.

Derivation of α_s

Given the inverse relationship between the microscopic velocity state index and the cosmological wavenumber established in the PPH transport dynamics,

$n \sim (k \ell_p)^{-1}$, the running is derived as:

$$\alpha_s = \frac{dn_s}{d \ln k} = -\frac{d\alpha(n)}{d \ln n} \cdot \frac{d \ln n}{d \ln k}. \quad (91)$$

Since $\frac{d \ln n}{d \ln k} = -1$, we obtain:

$$\alpha_s = \frac{d\alpha}{d \ln n} = -\beta. \quad (92)$$

Cosmological Implications and LiteBIRD Constraints

Current observations from the Planck mission constrain the running to $\alpha_s \approx -0.006 \pm 0.007$. In the PPH framework, the smallness of this value is naturally explained by the vast range of available velocity states ($n_{\max} \sim 10^{122}$), which suppresses higher-order logarithmic deviations.

However, unlike standard slow-roll inflation where α_s is of order $(n_s - 1)^2 \approx 10^{-3}$, PPH allows for a slightly larger running if the pre-emergent phase was characterized by non-ideal statistical equilibration. A detection of $\alpha_s \neq 0$ by LiteBIRD or CMB-S4 would therefore provide:

- A direct measurement of the **stochasticity** of the primary particle gas.
- A way to break the degeneracy between PPH and multi-field inflationary models.

This makes α_s a crucial consistency check for such the PPH framework: it links the global evolution of the Universe directly to the microscopic transition rates $W_{\Delta n}$ between quantized velocity levels in the pre-spacetime manifold.