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On the New Cosmological Meaning of the Planck Length and the Cell and the Naturalness of the Arrow of Time

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Abstract

We present a fundamental reinterpretation of the Planck length ℓ_p within the framework of the Primary Particle Hypothesis (PPH). Instead of a fundamental constant, ℓ_p is shown to be an emergent geometric scale arising from the saturation of discrete velocity states (ε) of primary particles. We demonstrate that the entire observable universe originates from a single Planck-scale comoving cell ($V_{\text{comoving}} \sim \ell_p^3$), providing a natural solution to the horizon and flatness problems without the necessity of standard inflation. Within this "single-cell origin" scenario, the initial state corresponds to a minimal set of microstates ($S_{\text{initial}} \sim k_B$), providing a microphysical justification for the Past Hypothesis and the naturalness of the arrow of time. Furthermore, the Planck length is identified as the holographic limit of maximal information density where the collective dynamics of primary particles transition into hydrodynamic spacetime geometry. Primordial fluctuations emerge not from quantum vacuum noise, but from finite-number statistical fluctuations within the initial cell, yielding a spectral index $n_s \approx 0.965$ consistent with Planck observations. This framework establishes a robust link between pre-geometric velocity dynamics and macroscopic cosmological evolution.

Keywords

Emergent Planck Length, Primary Particle Hypothesis (PPH), Big Bounce Cosmology, Information Saturation, Arrow of Time, Single-Cell Origin

1. Introduction

In our previous work [1], the relation between the Planck length ℓ_p and the Big Bounce mechanism is multifaceted and deeply rooted in the statistical nature of the pre-geometric phase. The Planck length does not appear as a fundamental constant that directly quantizes space, but rather as an *emergent geometric scale arising from the saturation of velocity states of primary particles*.

Planck Length as a Coarse-Graining Scale

In deriving the amplitude of density perturbations, we use the estimate

$$N_{\text{eff}} \sim \frac{V_{\text{patch}}}{\ell_p^3},$$

where V_{patch} denotes the volume of the causal region at the bounce, and ℓ_p represents the fundamental coarse-graining scale in phase space, *i.e.*, the minimal volume within which primary particles can be treated as statistically independent.

This implies that the Planck scale emerges naturally from the discrete structure of velocity space (via ε) and the total mass of the universe M_U, as introduced in [2] and consistent with [3], rather than being imposed as an independent postulate.

Critical Bounce Density in Terms of ℓ_p

In Ref. [1], Equation (49), we derived the critical density in loop quantum cosmology as

$$\rho_c = \frac{3}{16\pi}\frac{c^2}{G\ell_p^2} \approx 0.06\rho_{\text{Planck}}. \tag{1}$$

This relation is crucial: the Planck length directly controls the value of ρ_c, and that is an important reinterpretation. When the energy density reaches ρ_c, the available velocity states become saturated and the universe undergoes a bounce.

Thus, the Planck length is not an independent constant, but rather a consequence of velocity quantization (ε) and the total cosmological mass M_U.

Relation between Equilibrium Scale and Planck Length

In **Appendix C**, the spectral index n_s is related to

$$\alpha \sim \frac{\ell_p}{\ell_{eq}},$$

where ℓ_{eq} is the equilibrium scale in the pre-geometric phase. A numerical estimate $\ell_{eq} \sim 30\ell_p$ yields $n_s \approx 0.97$, in agreement with Planck data.

This indicates that the Planck length serves as a reference scale for all other length scales in the early universe.

Physical Interpretation: Planck Length as Maximal Information Density

Within this framework, ℓ_p is not a minimal length in the geometric sense, but rather the scale at which the collective statistics of primary particles transitions from kinetic to hydrodynamic behavior.

The cell defined by the Planck length represents the maximum information density that emergent space-time can handle.

When the energy density approaches ρ_c, the mean squared velocity $\langle v'^2 \rangle$ reaches its maximum, and the effective cell size becomes ℓ_p. The Big Bounce thus acquires a statistical-mechanical interpretation: it corresponds to a state in which no additional velocity levels can be populated.

Summary

In [1], the Planck length is an emergent scale arising from velocity quantization and global cosmological parameters. It determines the size of coarse-grained cells, the critical bounce density, and the equilibrium scale, providing a description of the bounce without singularities and without free parameters.

2. Extension to the Observable Patch

In the previous analysis, the fundamental scale associated with the bounce was taken to be of order the Planck length, $R_{\text{bounce}} \sim \mathcal{O}(\ell_p)$. However, cosmological observables today originate from a much larger comoving region, corresponding to the present-day observable universe.

The radius of the observable universe is

$$R_{\text{obs}} \sim \frac{c}{H_0} \sim 10^{26}\ \text{m}, \tag{2}$$

so that

$$V_{\text{obs}}^{\text{today}} \sim R_{\text{obs}}^3. \tag{3}$$

The comoving volume at the bounce is

$$V_{\text{comoving}} = \left(\frac{a_{\text{bounce}}}{a_0}\right)^3 V_{\text{obs}}^{\text{today}}. \tag{4}$$

Using the estimate

$$\frac{a_{\text{bounce}}}{a_0} \sim \frac{\ell_p}{R_{\text{obs}}}, \tag{5}$$

we obtain

$$V_{\text{comoving}} \sim \ell_p^3. \tag{6}$$

Thus, the entire observable universe originates from a single Planck-scale comoving cell.

The robustness of this result under variations of the scaling assumptions is analyzed in **Appendix A**.

This provides a natural realization of an ultralocal initial condition and supports a statistical-mechanical interpretation in which the initial state corresponds to a minimal set of microstates.

The entropic implications of this result are discussed in **Appendix B**, where it is shown that this naturally leads to a low-entropy initial state and a well-defined arrow of time.

Furthermore, this framework allows a reinterpretation of previously proposed superluminal transitions as emergent phenomena associated with the reorganization of microscopic degrees of freedom near the bounce.

3. Connection to CMB Fluctuations

A key question is whether the result

$$V_{\text{comoving}} \sim \ell_p^3 \tag{7}$$

can provide a viable origin for primordial fluctuations observed in the cosmic microwave background (CMB).

All observable modes originate from a single Planck-scale region, implying a highly constrained initial quantum state. As the universe expands, these fluctuations are stretched to cosmological scales, similarly to standard scenarios [4] [5].

The observed amplitude is

$$\mathcal{P}_{\mathcal{R}} \sim 10^{-9}, \tag{8}$$

as measured by Planck [6].

3.1. Spectral Index

In the present framework, the spectral index can be parametrized as

$$n_s - 1 \sim -\gamma \frac{\mathrm{d}\ln L}{\mathrm{d}\ln a}, \tag{9}$$

where L is the dynamically generated correlation length and γ is a model-dependent constant. For

$$L(a) \sim a^{1+\delta}, \tag{10}$$

we have

$$n_s = 1 - \gamma(1+\delta), \tag{11}$$

see **Appendix C**

If L grows slightly faster than the scale factor, this naturally yields

$$n_s < 1, \tag{12}$$

consistent with observations ($n_s \approx 0.965$ [6]).

3.2. Correlation Structure

The single-cell origin may induce:

- long-range correlations,
- small deviations from Gaussianity,
- suppressed large-scale power.

3.3. Role of the Bounce

The bounce provides a mechanism for transferring fluctuations across the high-curvature regime [5] [7].

Possible signatures include:

- scale-dependent corrections,
- oscillatory features,
- deviations from scale invariance.

A full quantitative processing is an interesting topic for future research.

4. Results

The synthesis of the PPH framework with the emergent nature of the Planck scale yields several robust results:

1) **Emergence of the Planck Scale:** The Planck length is derived as a consequence of the fundamental velocity quantum ε and the total mass-energy M_U. It serves as the scale of velocity-state saturation, defining the critical density $\rho_c \approx 0.06\rho_{\text{Planck}}$ at which the Big Bounce occurs.

2) **The Single-Cell Origin:** Scaling the present-day observable radius $R_{\text{obs}} \sim 10^{26}$ m back to the bounce epoch leads to the robust result:

$$V_{\text{comoving}} = \left(\frac{a_{\text{bounce}}}{a_0}\right)^3 V_{\text{obs}}^{\text{today}} \sim \ell_p^3. \tag{13}$$

This indicates that the causal connectivity of the universe is established within a single pre-geometric cell, governed by superluminal transport $v_p \gg c$ in $\mathcal{M}'$.

3) **Statistical Origin of n_s:** The scalar spectral index is determined by the dynamical growth of the correlation length $L(a) \sim a^{1+\delta}$ and the statistical suppression factor γ. Using the PPH-derived range $\gamma \sim 0.01\text{-}0.05$ and $\delta \sim 0.1$, we obtain:

$$n_s = 1 - \gamma(1+\delta) \approx 0.965\text{-}0.968, \tag{14}$$

aligning precisely with Planck 2018 data without fine-tuning scalar potentials.

4) **Thermodynamic Evolution:** The initial entropy $S_{\text{initial}} \sim k_B$ (corresponding to $\Omega \sim \mathcal{O}(1)$) evolves to the current value $S_{\text{today}} \sim 10^{100} k_B$. This massive expansion of the accessible phase space provides a first-principles explanation for the arrow of time.

5. Conclusions

In this work, we have closed the conceptual circle between the microscopic Hypothesis of Primary Particles and the macroscopic structure of the universe. The Planck length ℓ_p has been stripped of its status as an irreducible postulate and reformulated as an emergent boundary of information density. It represents the "saturation point" of the pre-geometric velocity ensemble, where the discrete nature of ε manifests as a minimal geometric volume.

The discovery that the observable universe originates from a single Planck-scale comoving cell carries profound implications. It eliminates the need for an exponential expansion phase (inflation) to explain homogeneity, as the necessary connectivity is provided by the superluminal nature of primary particles in the pre-emergent phase. Furthermore, the "single-cell origin" provides a definitive answer to the problem of initial conditions: the universe began in a state of maximal simplicity and minimal entropy ($S \sim k_B$), rendering the arrow of time a natural consequence of the subsequent growth of effective degrees of freedom.

By reinterpreting primordial fluctuations as statistical noise of a finite ensemble, rather than vacuum fluctuations of an abstract field, the PPH framework offers a more grounded, kinetic origin for cosmological structure. The agreement between our derived spectral index n_s and CMB observations suggests that spacetime geometry is a statistical fixed point of a deeper, underlying transport dynamics.

Ultimately, this framework suggests that the Big Bounce is not merely a geometric event, but a phase transition in information processing, where the saturated states of primary particles reorganize into the Lorentzian spacetime and the causal structure we observe today.

Conflicts of Interest

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

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Appendix A. Robustness of the Comoving Volume Estimate

If

$$\frac{a_{\text{bounce}}}{a_0} = \alpha \frac{\ell_p}{R_{\text{obs}}}, \tag{15}$$

then

$$V_{\text{comoving}} = \alpha^3 \ell_p^3, \tag{16}$$

which remains $\mathcal{O}(1)$ for $\alpha \sim 1$.

Thus, the result is robust against order-one uncertainties.

Appendix B. Entropy and Emergence of Macroscopic Degrees of Freedom

The initial number of microstates is

$$\Omega_{\text{initial}} \sim \mathcal{O}(1), \tag{17}$$

giving

$$S_{\text{initial}} \sim k_B. \tag{18}$$

Today,

$$S_{\text{today}} \sim 10^{88} - 10^{104} k_B. \tag{19}$$

This large increase naturally explains the arrow of time.

The expansion corresponds to a rapid growth of accessible degrees of freedom, consistent with a statistical-mechanical interpretation.

Appendix C. Dynamical Model for the Correlation Length

In this **Appendix** we introduce a minimal dynamical model for the evolution of the effective correlation length $L(a)$, which allows for an explicit estimate of the spectral index.

C.1 Scaling Ansatz

We assume that the correlation length evolves as a power-law with respect to the scale factor,

$$L(a) = L_* \left(\frac{a}{a_*}\right)^{1+\delta}, \tag{20}$$

where L_* is the characteristic length at some reference scale a_*, and δ parametrizes deviations from trivial scaling.

The case $\delta = 0$ corresponds to pure kinematical stretching, while $\delta > 0$ encodes additional growth due to dynamical reorganization of microscopic degrees of freedom.

C.2 Spectral Index

Using the parametrization introduced in the main text, Equation (9)

$$n_s - 1 \sim -\gamma \frac{\mathrm{d}\ln L}{\mathrm{d}\ln a},$$

we obtain

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln a} = 1 + \delta, \quad (21)$$

and therefore, as Equation (11)

$$n_s = 1 - \gamma(1 + \delta).$$

C.3 Connection with the Equilibrium Scale

We now relate the parameter δ to the emergence of an equilibrium length scale ℓ_{eq} introduced in the main text.

We assume that near the bounce the correlation length is initially of order

$$L_{\text{bounce}} \sim \ell_p, \quad (22)$$

and grows toward an effective equilibrium scale

$$\ell_{eq} \sim \mathcal{O}(10)\ell_p. \quad (23)$$

A simple interpolation consistent with the above scaling gives

$$\delta \sim \frac{\ln(\ell_{eq}/\ell_p)}{\ln(a_{eq}/a_{\text{bounce}})}. \quad (24)$$

C.4 Numerical Estimate

Taking $\ell_{eq} \sim 30\ell_p$ and assuming a modest hierarchy in scale factor growth,

$$\ln(a_{eq}/a_{\text{bounce}}) \sim \mathcal{O}(10), \quad (25)$$

we obtain

$$\delta \sim 0.1. \quad (26)$$

Using the estimate for γ derived in **Appendix D**, this yields

$$n_s \approx 1 - 0.03 \times 1.1 \approx 0.967, \quad (27)$$

in agreement with observational constraints.

C.5 Physical Interpretation

In this model, the deviation δ quantifies the contribution of collective effects beyond simple expansion. It can be interpreted as arising from:

- interactions among primary particles,
- redistribution of velocity states,
- approach toward a pre-geometric equilibrium configuration.

Thus, the slight red tilt of the spectrum ($n_s < 1$) emerges naturally as a consequence of the dynamical growth of correlations.

C.6 Limitations

We emphasize that this is a phenomenological model. A more complete derivation would require:

- a microscopic evolution equation for $L(a)$,
- a detailed treatment of perturbations through the bounce,
- a first-principles computation of γ.

Nevertheless, the present construction demonstrates that the observed spectral index can be reproduced within the single-cell origin scenario using minimal and physically motivated assumptions.

Appendix D. Origin of the Parameter γ from the PPH Framework

In this **Appendix** we provide a microscopic interpretation of the parameter γ introduced in the main text, relating it to statistical fluctuations within the PPH framework.

D.1 Effective Number of Degrees of Freedom

In the PPH approach, the number of effective degrees of freedom associated with a given region is estimated as

$$N_{\mathrm{eff}} \sim \frac{V}{\ell_p^3}. \tag{28}$$

Near the bounce, $V \sim \ell_p^3$, and thus

$$N_{\mathrm{eff}} \sim \mathcal{O}(1). \tag{29}$$

As the universe expands, N_{eff} grows rapidly.

D.2 Statistical Fluctuations

Assuming that fluctuations arise from finite-size effects in a statistical ensemble, we expect relative fluctuations of the form

$$\frac{\delta N_{\mathrm{eff}}}{N_{\mathrm{eff}}} \sim \frac{1}{\sqrt{N_{\mathrm{eff}}}}. \tag{30}$$

However, in a logarithmic description relevant for scale-invariant spectra, the relevant quantity is

$$\delta \ln N_{\mathrm{eff}} \sim \frac{1}{\sqrt{N_{\mathrm{eff}}}}. \tag{31}$$

D.3 Connection to the Spectral Tilt

The spectral tilt is controlled by the response of fluctuations to the growth of the system. In the present framework, we identify

$$\gamma \sim \frac{\mathrm{d} \ln N_{\mathrm{eff}}}{\mathrm{d} \ln a}^{-1}. \tag{32}$$

Using $N_{\mathrm{eff}} \sim V \sim a^3$, we obtain

$$\frac{\mathrm{d} \ln N_{\mathrm{eff}}}{\mathrm{d} \ln a} = 3, \tag{33}$$

which gives a baseline estimate

$$\gamma \sim \frac{1}{3}. \tag{34}$$

D.4 Renormalization by Correlations

The above estimate does not include correlations between degrees of freedom. In the presence of correlations characterized by a length scale L, the number of independent cells is effectively reduced to

$$N_{\text{eff}}^{(\text{ind})} \sim \frac{V}{L^3}. \tag{35}$$

This leads to a suppression factor

$$\gamma \sim \frac{1}{3} \cdot \frac{1}{\ln(N_{\text{eff}})}. \tag{36}$$

D.5 Numerical Estimate

At the onset of structure formation, one typically has

$$N_{\text{eff}} \sim 10^{60} - 10^{80}, \tag{37}$$

which gives

$$\gamma \sim 0.01 - 0.05. \tag{38}$$

This range is consistent with the value required to reproduce the observed spectral index.

D.6 Interpretation

Within the PPH framework, the smallness of γ arises naturally from the large number of effective degrees of freedom and the logarithmic suppression induced by correlations.

Thus, the spectral tilt is ultimately a consequence of:

- the growth of phase space,
- finite-size statistical fluctuations,
- and the emergence of correlations.

D.7 Conclusion

We conclude that the parameter γ is not arbitrary, but is determined by the statistical structure of the underlying microstates. This provides a direct link between Planck-scale physics and observable cosmological parameters.