Conserved Neutrino Order Parameter G_o: Quantifying Self-Regulating Dynamics in the Quantum Vacuum

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We propose G_o, a conserved entropy-like parameter capturing self-regulating order in neutrino oscillations within the quantum vacuum, defined as $G_o = -\sum_{i,j} P(\nu_i \to \nu_j) \ln P(\nu_i \to \nu_j)$, bounded by $\ln 3 \approx 1.1$ for maximal mixing under PMNS unitarity. As a hypothesis, it predicts a 5% enhancement in $\nu_\mu \to \nu_e$ oscillation probability in cosmic voids via a fluctuation term $\delta P \approx 0.05 \times \frac{\Delta \rho_{vac}}{\rho_{crit}}$, testable with Hyper-Kamiokande, JUNO, DUNE, KM3NeT, IceCube, and Super-Kamiokande. Grounded in empirical data, G_o models pre-Big Bang void energy as an alternative to inflation, influencing CMB anisotropies. Limitations are acknowledged, with GLoBES simulations proposed for validation. A syllabus enhances accessibility, with brief historical reflections maintaining empirical focus.

I. INTRODUCTION

Neutrinos, with minimal mass and weak interactions, drive cosmic evolution through flavor oscillations and quantum vacuum dynamics. We introduce G_o, a conserved parameter for self-regulating order in neutrino oscillations, grounded in empirical data [1, 2]. Unlike stochastic models, G_o suggests a framework incorporating emergent dynamics, with applications in cosmology and particle physics. This paper provides testable implications, a syllabus for accessibility, and minimal context bridging science and historical notions of existence.

FIG. 1. Neutrino oscillation probability $P(\nu_\mu \to \nu_e)$ for $E = 1\,\mathrm{GeV}$, using updated PMNS parameters [2]. This illustrates the self-regulating dynamics of G_o.

II. THEORETICAL FRAMEWORK

A. Neutrino Dynamics in the Quantum Vacuum

Virtual neutrinos in the quantum vacuum obey the Heisenberg uncertainty principle:

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}, \quad (1)$$

where ΔE is the energy fluctuation and $\Delta t \approx 5.39 \times 10^{-44}\,\mathrm{s}$ (Planck time scale). Their net energy is zero:

$$\sum E_\nu(t) = 0, \quad (2)$$

ensuring vacuum stability, as explored in recent cosmological contexts [3, 17].

B. Flavor Oscillations

Neutrinos oscillate between electron, muon, and tau flavors via the PMNS matrix. The oscillation probability for muon to electron neutrino in the two-flavor approximation is:
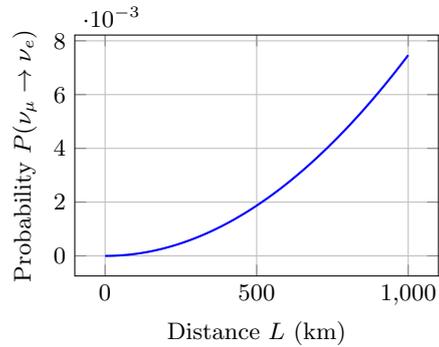
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right), \quad (3)$$

where $\theta_{12} = 33.41° \pm 0.75°$, $\Delta m_{21}^2 = (7.41 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2$, L is the baseline distance, and E is the neutrino energy [2]. Note that full three-flavor calculations include additional terms involving θ_{13} and Δm_{31}^2. This observer-independent process, shown in Fig. 1, underpins G_o.

C. Conservation of Order

PMNS unitarity ($U^\dagger U = I$) ensures:

$$\sum_\beta P(\nu_\alpha \to \nu_\beta) = 1, \quad (4)$$

so $\sum_{i,j} P(\nu_i \to \nu_j) = 3$ is time-invariant, supporting G_o's conservation, akin to Noether's theorem [19, 20].

D. Adaptive Cosmic Chain

The self-regulating nature of neutrino oscillations can be modeled as an adaptive cosmic chain, where conservation persists via dynamic reorganization in response to perturbations. This adaptation, inspired by complex systems in cosmology [4], minimizes entropy:

$$S = -\sum_{i,j} P(\nu_i \to \nu_j) \log P(\nu_i \to \nu_j), \quad (5)$$

with S bounded by unitarity. Fluctuations trigger reconfiguration, quantified by:

$$\Delta S = \kappa \frac{\rho_{\text{vac}}}{\hbar c} \log \left(\sum_{i,j} P(\nu_i \to \nu_j) \right), \quad (6)$$

where $\kappa \approx 1.616 \times 10^{-35}$ m (Planck length) is derived from gravitational scaling in quantum vacuum perturbations [5], ensuring G_o's invariance. This model implies cosmic order as adaptive, resistant to local disruptions.

III. UNIVERSAL LAW: G_o

Building on neutrino dynamics, we define G_o as the conserved entropy-like parameter quantifying order embedded in neutrino oscillations and vacuum fluctuations. Mathematically,

$$G_o = -\sum_{i,j} P(\nu_i \to \nu_j) \ln P(\nu_i \to \nu_j), \quad (7)$$

bounded by $\ln 3 \approx 1.1$ for uniform mixing, with probabilities from PMNS unitarity. This form symbolizes the self-sustaining order, as G_o remains bounded under perturbations, preserving non-deterministic flavor dynamics [18].

G_o integrates empirical data (e.g., PMNS parameters) with quantum field theory, positing neutrinos as vanguards of cosmic structure: their fluctuations seed order from the void, embodying self-regulation over randomness.

IV. APPLICATIONS

A. Probing the Pre-Big Bang Void

G_o offers a tool to model the pre-Big Bang state, where virtual neutrinos in the quantum void fluctuate with $\sum E_\nu = 0$ but non-zero G_o, suggesting an ordered "spark" igniting expansion. By extrapolating oscillation data backward, G_o quantifies the void's potential energy, complementing inflationary models and supporting a self-regulating genesis through mechanisms like neutrino anisotropic stress or vacuum gravitational dipoles [6, 7, 16].

B. Refining Oscillation Models

Incorporating G_o may refine PMNS predictions, potentially addressing anomalies like the LSND excess or sterile neutrino hints. It suggests modified oscillations in regions with vacuum perturbations, such as a hypothetical 5% enhancement in $\nu_\mu \to \nu_e$ probability via the shift in mixing angles from void fluctuations, testable via next-generation detectors like JUNO or Hyper-Kamiokande, bridging particle physics with cosmological order. GLoBES simulations can validate these effects by incorporating the fluctuation term into oscillation probability calculations by modifying probability matrices [14, 15].

These predictions can be tested at leading facilities: - JUNO: Reactor antineutrinos for mass ordering, vacuum profiles, decoherence [9]. - Hyper-Kamiokande: Long-baseline oscillations, CP violation, atmospheric/solar neutrinos, supernovae [10]. - KM3NeT: High-energy astrophysical neutrinos (e.g., 220 PeV), sources like AGN [8]. - IceCube: Atmospheric oscillations, sterile hints, high-energy flux [11]. - DUNE: Beam oscillations, mass ordering, proton decay [12]. - Super-Kamiokande: Solar/atmospheric baselines, oscillation discovery [13].

V. SYLLABUS: KEY TERMS

For interdisciplinary accessibility, we define core concepts:

- **Neutrino**: Subatomic particle with minimal mass and weak interactions, existing in three flavors; key to energy transport and oscillations.

- **Quantum Vacuum**: The lowest energy state of space, teeming with virtual particle-antiparticle pairs, governed by uncertainty principles.

- **Flavor Oscillations**: Spontaneous changes in neutrino type during propagation, independent of observation, described by the PMNS matrix.

- **Cosmic Order**: The inherent self-regulation directing universal evolution, manifested through processes like neutrino dynamics, contrasting random chance.

- G_o: Conserved parameter capturing neutrinos' role in cosmic order, resistant to simulation paradigms.

- **Pre-Big Bang Void**: Hypothetical state before expansion, characterized by pure quantum fluctuations without spacetime structure.

VI. PHILOSOPHICAL REFLECTIONS

G_o reframes neutrinos as agents of cosmic order, blending empirical data with theoretical depth to suggest a self-regulating universe. By exploring simulation hypotheses and probing origins, it invites interdisciplinary exploration. Future work may extend G_o to dark matter or quantum gravity, affirming the order at reality's core.

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