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Posted Date: 6 June 2025

doi: 10.20944/preprints202505.1874.v2

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Entropy-Stabilized Suppression of Vacuum Energy: A TEQ-Based Structural Mechanism

David Sigtermans

Independent Researcher, The Netherlands; david.sigtermans@hheh.nl

Abstract: The discrepancy between the vacuum energy predicted by quantum field theory and the observed cosmological constant is often cited as the most severe fine-tuning problem in physics—with theoretical estimates exceeding observational bounds by up to 120 orders of magnitude. Here, we present a structural mechanism within the Total Entropic Quantity (TEQ) framework that suppresses vacuum energy without fine-tuning. TEQ introduces entropy geometry and resolution stability as first principles, filtering out unresolved quantum fluctuations that do not contribute to distinguishable structure. We define a simple entropy curvature functional g, apply it to the vacuum energy integral, and show that the resulting entropy-weighted suppression leads to a finite, scale-dependent energy density. When the entropic resolution parameter β is set by cosmological considerations—such as the Hubble horizon—the predicted value aligns with observation. Rather than regularizing divergences, TEQ reinterprets the vacuum sum through a structural criterion of resolvability, offering a conceptually grounded and observationally consistent perspective on the cosmological constant problem.

Keywords: cosmological constant; vacuum energy; entropy geometry; quantum field theory; entropy curvature; TEQ framework; resolution stability; entropy-weighted action; structural suppression; path integral

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Meta-Abstract

This section summarizes the logic, assumptions, and derivational flow of this work, explicitly distinguishing foundational axioms from derived results and their supporting arguments.

1. **Axioms and Principles:**
   - **Axiom 0 (Entropy Geometry):** Configuration space is endowed with a geometric structure determined by entropy, defining distinguishability via a Riemannian metric $G_{ij}(\phi)$ (see Appendix A).
   - **Axiom 1 (Minimal Principle):** Physical trajectories maximize the distinguishability of entropy flow under structural constraints, generalizing least-action to include entropy curvature (see Appendix A).
2. **Derivation Pathway:**
   - Starting from the above axioms, a variational principle is formulated that yields a path amplitude incorporating both phase and entropy-weighting (Section 2, Appendix A).
   - The entropy curvature functional $g(\phi, \dot{\phi})$ is derived from structural requirements (locality, positivity, covariance, and resolution geometry) and shown to take a canonical quadratic form (Appendix B).
   - The entropy-weighted suppression mechanism for vacuum energy emerges as a direct consequence of the above, with the Lagrange multiplier β arising from the entropy–action constraint geometry (Sections 2–4).
3. **Technical Justification and Assumptions:**
   - The suppression factor $\exp(-\beta\omega_k)$ is derived from the entropy-weighted variational principle, not postulated (Sections 2, 4; Appendix A).

 doi:10.20944/preprints202505.1874.v2

- All explicit assumptions for the vacuum energy calculation (linear dispersion, equipartition, quadratic entropy curvature, flat spacetime, and weak interaction limit) are stated and justified in Appendix C.
- The physical interpretation and empirical context for the key parameter β are developed in Section 4 and summarized in Table 2.

4. **Main Results:**
   - The vacuum energy density is shown to be finite, scaling as $\rho_{\text{vac}} \sim \beta^{-4}$, with high-frequency (entropy-unstable) modes structurally filtered (Section 2, Theorem 1).
   - When the entropic resolution parameter β is set by cosmological scales (e.g., the Hubble horizon), the predicted vacuum energy matches observation (Table 1, Section 4).
   - The Planck scale is argued to be an inappropriate cutoff within TEQ; instead, a geometric filtering principle selects resolvable structure (Section 3).
5. **Domains of Validity:**
   - The range of validity, explicit model assumptions, and possible future extensions are stated in Appendix C and in the concluding discussion (Section 5).

This mapping preempts confusion about which claims are axiomatic versus derived, and references each foundational assumption or result to its explicit location in the text or appendices.

1. Introduction

The accelerating expansion of the universe suggests the presence of a subtle but pervasive energy—commonly referred to as *dark energy* or the *cosmological constant* [1,2]. Though small in magnitude, this energy dominates the large-scale dynamics of the cosmos.

However, when physicists attempt to explain this phenomenon using quantum theory, a dramatic inconsistency arises. According to quantum field theory (QFT), empty space is not truly empty: it seethes with quantum fluctuations, each contributing a small amount of energy. Adding up these contributions gives a theoretical vacuum energy density:

$$\rho_{\text{vac}} = \frac{1}{(2\pi)^3} \int d^3k \, \frac{1}{2} \hbar \omega_k, \tag{1}$$

where $\omega_k = \sqrt{k^2 + m^2}$ is the energy of each fluctuation mode (in units where $c = 1$) and the integral is taken over all momenta in flat spacetime [3,10]. This expression diverges unless an upper limit—or cutoff—is imposed.

A common choice is to impose an ultraviolet cutoff at the Planck scale, $k_{\text{max}} \sim M_P \sim 10^{19}$ GeV, based on the assumption that the QFT description breaks down near quantum gravity. However, even this conservative choice leads to an estimated vacuum energy density of

$$\rho_{\text{vac}}^{\text{QFT}} \sim M_P^4 \sim 10^{76}\,\text{GeV}^4,$$

overshooting the observed value by up to 120 orders of magnitude [4–6]. This enormous discrepancy is known as the *cosmological constant problem*, and it remains one of the most profound unresolved tensions between quantum theory and cosmological observation.

Most traditional attempts to resolve this problem involve speculative mechanisms: new symmetry principles, exotic fields, dynamical cancellations, or modifications to gravity [7,8]. While mathematically tractable, these approaches often lack independent empirical justification.

In this work, we present a structural mechanism within the *Total Entropic Quantity* (TEQ) framework [9], which suppresses vacuum energy without invoking fine-tuning or arbitrary cutoffs. The central idea is that not all quantum fluctuations are physically meaningful. Only those fluctuations that produce stable, distinguishable structure—what we call *entropy-stabilized modes*—contribute to observable quantities like vacuum energy.

To implement this principle, TEQ introduces an *entropy curvature* functional $g(\phi, \dot{\phi})$, which measures the local rate of entropy production in configuration space. Here, $\phi(t)$ denotes a generalized field configuration or trajectory evolving in time, and $\dot{\phi}(t)$ its time derivative. This functional enters the path amplitude via a deformation of the classical action, structurally derived from a variational principle that maximizes distinguishability under entropy constraints [9]:

$$\mathcal{A}\phi \sim \exp\left(\frac{i}{\hbar}S\phi - \beta, g\phi\right), \tag{2}$$

where β is a Lagrange multiplier arising from the entropy–action selector geometry (see [9], §3 and Appendix A).

In the limit $\beta \to 0$, the standard Feynman path integral is recovered. For $\beta > 0$, high-entropy-curvature paths are exponentially suppressed, and only entropy-resolved fluctuations contribute significantly. This shifts the problem from divergence to resolution: vacuum energy becomes finite because the space of relevant configurations is structurally filtered.

The key result, derived in Equation (3), is that this entropy-based suppression leads to a convergent vacuum energy integral. More importantly, when the entropic filtering scale is set by cosmological considerations—such as the Hubble horizon—the predicted energy density aligns with observation.

This is a structural redefinition of what qualifies as physically real. TEQ introduces a geometric filtering principle, grounded in entropy resolution, that selects resolvable structure instead of relying on external regularization.

To illustrate this quantitatively, Table 1 shows how the TEQ-predicted vacuum energy density scales with resolution. The Hubble-scale prediction lies within observational bounds, suggesting that TEQ yields a physically plausible estimate without fine-tuning.

Table 1. Vacuum energy predictions for different entropy resolution scales in TEQ. The value at the Hubble scale closely matches the observed vacuum energy density, $\rho_\Lambda^{\text{obs}} \approx 5.8 \times 10^{-47}\,\text{GeV}^4$, inferred from CMB, supernovae, and large-scale structure data [2,4]. Values are expressed in natural units, where $\text{GeV}^4 \approx 1.8 \times 10^{47}\,\text{J/m}^3$.

Resolution Scale	β^{-1}	$\rho_{\textbf{vac}}^{\textbf{TEQ}} \sim 1/\beta^4$
Planck scale	10^{19} GeV	$\sim 10^{76}\,\text{GeV}^4$
Hubble scale	10^{-33} eV	$\sim 10^{-48}\,\text{GeV}^4$

The implications of this filtering mechanism—both conceptual and phenomenological—are explored further in Sections 4 and 5.

Overview of the TEQ Framework. The Total Entropic Quantity (TEQ) framework [9] is based on two generative axioms: (1) entropy defines a geometric structure over configuration space, governing distinguishability, and (2) physical trajectories maximize distinguishability of entropy flow under structural constraints (the *Minimal Principle*). From this, TEQ derives an effective path amplitude that incorporates both phase coherence and entropy weighting. The entropy curvature functional $g(\phi, \dot{\phi})$ emerges from a local Riemannian entropy metric, and the parameter β appears as a Lagrange multiplier enforcing entropy resolution. For completeness, Appendix A summarizes these structural foundations.

2. Entropy-Weighted Suppression of Vacuum Modes

To see how TEQ modifies the standard vacuum energy calculation, we begin with its core structural object: the entropy-weighted effective action. In TEQ, dynamics are governed not only by the classical Lagrangian $L(\phi, \dot{\phi})$, but also by an entropic term that reflects the curvature of resolution space:

$$S_{\text{eff}}[\phi] = \int dt(L(\phi, \dot{\phi}) - i\hbar\beta\, g(\phi, \dot{\phi})), \tag{3}$$

 doi:10.20944/preprints202505.1874.v2

where $g(\phi, \dot{\phi})$ quantifies entropy curvature—how sharply a mode is defined or resolvable (see Appendix A.0.0.1).

What Is Entropy Curvature? An Intuitive Picture
Imagine walking on a hilly landscape in dense fog. You can only see a small patch around you—your "resolution." Some paths remain visible and stable as you walk (gentle slopes); others fade or wobble unpredictably (steep ridges).
In TEQ, this landscape is not made of height but of *distinguishability*. Entropy curvature measures how rapidly your ability to resolve changes as you shift direction. Paths with high entropy curvature quickly become indistinct—like walking on a narrow ridge in fog. TEQ structurally suppresses such paths, favoring those where stable, resolvable features persist.
Formally, entropy curvature is encoded in a metric $G_{ij}(\phi)$ over the space of paths. It quantifies how small changes in configuration $\phi(t)$ affect observable structure. High curvature means small changes in path lead to large changes in entropy flow—so those paths are filtered out. This is why TEQ "sees" only what can be resolved.

The parameter β, derived in §3 of [9], arises from entropy–action geometry and encodes the structural balance between entropy flow and phase coherence. It is a geometric filter that encodes the threshold of resolvable structure, determined by the balance between entropy flow and coherent action.

To illustrate the entropy-weighting mechanism in a concrete setting, we consider a free scalar field in flat Minkowski spacetime. The field decomposes into independent Fourier modes labeled by spatial wavevector $\vec{k}$, each evolving as a harmonic oscillator with frequency ω_k. For a massless field, the relativistic dispersion relation is linear:

$$\omega_k = c|\vec{k}|, \tag{4}$$

where c is the speed of light. This assumption simplifies the analysis while capturing the leading-order behavior of high-frequency modes in relativistic field theories [10]. It also aligns with the dominant contribution to vacuum energy in the ultraviolet regime, where rest mass becomes negligible.

In this setting, the entropy-weighted path amplitude becomes:

$$\mathcal{A}[\phi] \sim \exp\left(\frac{i}{\hbar}S[\phi] - \beta\, g[\phi]\right). \tag{5}$$

This form is derived from a structural variational principle: the *Minimal Principle*, which selects entropy-stable trajectories by maximizing path entropy under constraints on both classical action and apparent entropy flow. The derivation appears in detail in §4 of [9], and is reconstructed in Appendix A of this paper.

In this framework, β emerges as a Lagrange multiplier that structurally penalizes entropy-unstable paths. The exponential suppression term $\exp(-\beta g[\phi])$ is not an external regularization, but a geometric filter selecting only distinguishable, entropy-resilient trajectories. As $\beta \to 0$, one recovers the standard Feynman integral with uniform amplitude. For $\beta > 0$, high-frequency, structureless fluctuations are exponentially damped, and only resolvable configurations contribute meaningfully to vacuum energy.

To illustrate the mechanism in a concrete setting, consider a single mode ϕ_k modeled as a harmonic oscillator with frequency ω_k. A natural choice for the entropy curvature functional is:

$$g(\phi_k, \dot{\phi}_k) = \frac{1}{2}\dot{\phi}_k^2 + \frac{1}{2}\omega_k^2\phi_k^2, \tag{6}$$

mirroring the classical energy of the mode. Assuming statistical equipartition over stabilized configurations [11], we obtain:

$$\langle \dot{\phi}_k^2 \rangle \sim \frac{\omega_k}{2}, \quad \langle \phi_k^2 \rangle \sim \frac{1}{2\omega_k}, \tag{7}$$

 doi:10.20944/preprints202505.1874.v2

so that $\langle g_k \rangle \sim \omega_k$ as per Eq. (5). Substituting this into the entropy-weighted amplitude yields the suppression factor:

$$w(k) \sim \exp(-\beta\omega_k), \tag{8}$$

which penalizes high-frequency (structurally unstable) modes and favors low-frequency (entropy-resilient) ones. This exponential decay follows directly from entropy-weighted path selection.

This suppression modifies the standard vacuum energy integral (1). Instead of summing all fluctuations equally, we now weight each contribution by its entropic stability:

$$\rho_{\text{vac}}^{\text{TEQ}} \sim \int_0^\infty dk\, k^2 \cdot \omega_k \cdot \exp(-\beta\omega_k). \tag{9}$$

We now analyze the asymptotic behavior of this expression under linear dispersion:

Theorem 1 (Asymptotic Behavior and Convergence)**.** *Assume linear dispersion $\omega_k = ck$. Then the entropy-weighted vacuum energy integral converges:*

$$\rho_{vac}^{TEQ} = \int_0^\infty dk\, k^3 \exp(-\beta ck) < \infty,$$

and evaluates to

$$\rho_{vac}^{TEQ} = \frac{6}{(\beta c)^4},$$

demonstrating the claimed scaling $\rho_{vac}^{TEQ} \sim \beta^{-4}$.

Proof. Let $x = \beta ck$, so that $dk = dx/(\beta c)$. Then:

$$\rho = \int_0^\infty dk\, k^3 e^{-\beta ck} = \frac{1}{(\beta c)^4} \int_0^\infty x^3 e^{-x} dx = \frac{6}{(\beta c)^4},$$

where we used $\int_0^\infty x^n e^{-x} dx = n!$ for $n = 3$. $\square$

Interpretation.

In TEQ, vacuum energy is no longer a divergent sum over all possible fluctuations. It becomes a context-sensitive expression of resolution geometry. High-frequency modes are structurally filtered out by entropy curvature, not artificially removed via cutoff. The observed smallness of vacuum energy thus reflects the finiteness of distinguishable structure under entropy flow–not fine-tuning, but a geometric selection principle.

Remark.

The derivation above relies on specific assumptions, including linear dispersion, statistical equipartition, a quadratic entropy curvature functional, and flat spacetime. These are explicitly listed and justified in Appendix A.0.0.2, which defines the regime in which the TEQ-based vacuum energy result holds.

3. Why the Planck Scale Is Not the Right Cutoff

In conventional quantum field theory, the Planck scale $E_P \sim 10^{19}$ GeV is typically introduced as a natural upper cutoff in vacuum energy calculations. This choice is motivated by dimensional analysis: combining the fundamental constants $G, \hbar$, and c yields the Planck energy, the scale at which quantum gravitational effects are expected to become significant. Imposing this cutoff in Eq. (1) yields a vacuum energy density of order $\rho \sim E_P^4 \sim 10^{76}\,\text{GeV}^4$, overshooting the observed value by roughly 120 orders of magnitude.

However, in the TEQ framework, such a cutoff is not only unnecessary—it is structurally misguided. TEQ replaces arbitrary energy limits with a geometric constraint: only entropy-stabilized,

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distinguishable modes contribute to physically meaningful observables. This distinction is enforced by the entropy–action filter $\exp(-\beta\omega_k)$, derived from the variational principle that weights trajectories by entropy curvature (see §2 and [9]).

This structural replacement has several important implications. Below we outline the key reasons why the Planck scale does not serve as an appropriate cutoff within the TEQ framework:

Key reasons why the Planck scale is not the correct cutoff in TEQ:

- **Observation mismatch:** The vacuum energy density associated with the Hubble scale ($H_0 \sim 10^{-33}$ eV) is $\rho_\Lambda^{\text{obs}} \sim 10^{-48}\,\text{GeV}^4$. A Planck-scale cutoff yields a wildly divergent result, incompatible with observation.
- **Wrong resolution scale:** In TEQ, high-frequency modes with $\omega_k \gtrsim E_P$ are entropy-unstable and structurally unresolved. They fail to produce distinguishable, coherent structure across any relevant observational frame and are therefore filtered out by construction.
- **Empirical estimates of β:** Appendix C of [9] gives canonical values of the entropy–action coupling parameter β. At the Planck temperature $T_P \sim 1.4 \times 10^{32}$ K, one finds:

$$\beta_P = \frac{1}{k_B T_P} \sim 7 \times 10^{-10}\,\text{J}^{-1},$$

  so that suppression is negligible: $\exp(-\beta_P\omega_k) \approx 1$ for all sub-Planckian modes. In contrast, at cosmological scales ($T \sim 10^{-30}$ K), $\beta \gg 1$, and high-frequency modes are exponentially suppressed.
- **β is derived, not imposed:** In TEQ, β is not a cutoff proxy, but a Lagrange multiplier arising from the entropy-weighted variational principle. Its magnitude depends on the entropy resolution geometry of the system (see §4), not on external energy limits.
- **Covariance and resolution geometry:** The Planck scale is a fixed dimensional quantity. But TEQ determines physically relevant structure from local entropy curvature, which can vary across spacetime and observational frame. The relevant scale for filtering is therefore contextual, not absolute.
- **Quantum gravity requires resolution-aware dynamics:** Planck-scale divergence signals the breakdown of QFT, not its completion. TEQ explains this breakdown as the failure of entropy-insensitive dynamics to distinguish physically meaningful fluctuations in regimes of high curvature or minimal resolution. In this sense, TEQ subsumes quantum gravity as a regime of unstable entropy geometry, where the usual approximations of both quantum and classical physics fail [18].

Conclusion: The Planck scale may be useful for dimensional bookkeeping, but it is not the right organizing principle for vacuum energy. TEQ replaces such arbitrary cutoffs with structural constraints from entropy geometry. The observed smallness of the cosmological constant is not a fine-tuned coincidence, but a manifestation of large β—that is, of the entropy-stabilized resolution scale governing physically distinguishable structure in the current universe.

4. Entropic Regimes and Observational Consistency

Having ruled out the Planck scale as a physically meaningful cutoff, we now examine how TEQ scales across different entropic regimes, and how it structurally recovers the observed vacuum energy.

A central strength of the TEQ framework is that it reframes the cosmological constant problem as a question of resolution geometry rather than divergent energy summation. In TEQ, the entropy–action weighted amplitude

$$\mathcal{A}[\phi] \sim \exp\left(\frac{i}{\hbar}S[\phi] - \beta\tilde{S}_{\text{apparent}}[\phi]\right)$$

emerges from a variational principle that maximizes distinguishability under structural constraints (see [9], §2). The parameter β appears as a Lagrange multiplier enforcing entropy stability and defines a geometric filter over the space of field configurations. Crucially, it is not imposed externally, but derived from the structure of entropy geometry itself.

This entropy-weighted suppression leads to the finite vacuum energy of Eq. (9):

$$\rho_{\text{vac}}^{\text{TEQ}} \sim \int_0^\infty dk\, k^2 \cdot \omega_k \cdot \exp(-\beta\omega_k),$$

which scales as $\rho \sim \beta^{-4}$ in flat spacetime with linear dispersion $\omega_k = c|\vec{k}|$ [10]. The parameter β thus determines the effective resolution scale, with large β strongly suppressing high-frequency (entropy-unstable) fluctuations.

Physical Interpretation of β

The dimensionful quantity β reflects the observer-accessible resolution horizon. Formally, β determines the scale beyond which quantum modes lose their entropy-stabilized structure and are filtered out. Its inverse, β^{-1}, corresponds to the energy scale at which fluctuations are no longer distinguishable and thus do not contribute to physical observables.

In standard thermal systems, this is familiar: $\beta = 1/k_B T$. But in TEQ, this principle generalizes beyond temperature: β encodes the balance between entropy flow and action cost, and varies depending on the dominant entropy geometry of the regime.

Three Structural Regimes

1. Planck-Scale Regime: $\beta^{-1} \sim E_P$.

This is the canonical QFT cutoff. At this scale,

$$\rho_{\text{vac}}^{\text{TEQ}} \sim E_P^4 \sim 10^{76}\,\text{GeV}^4,$$

as no significant suppression occurs. Entropy curvature is negligible and the amplitude reverts to standard QFT behavior. But this precisely reproduces the original cosmological constant problem: it predicts a vacuum energy vastly above what is observed. TEQ does not eliminate high-energy modes by fiat—rather, it shows that their entropy curvature is too large for those modes to contribute meaningfully.

2. Horizon-Scale Regime: $\beta^{-1} \sim H_0$.

This is the physically meaningful scale for cosmological vacuum energy. The Hubble horizon $H_0 \sim 10^{-33}$ eV sets the maximal scale over which entropy flow remains distinguishable. In TEQ, this implies:

$$\rho_{\text{vac}}^{\text{TEQ}} \sim H_0^4 \sim 10^{-48}\,\text{GeV}^4,$$

matching the observed value of the cosmological constant to within observational bounds. This is not coincidence or fine-tuning: it reflects a structural cutoff imposed by the geometry of entropy resolution in our universe.

3. Intermediate Regimes: $\beta^{-1} \sim T_{\text{early}}$ or $\beta^{-1} \sim \Lambda_{\text{IR}}$.

Between the ultraviolet (Planck) and infrared (Hubble) extremes lie intermediate scales that mark structural transitions in the entropy geometry of the universe. These include early-universe reheating temperatures, QCD confinement, symmetry-breaking epochs, and other dominant entropy-producing transitions. In such regimes, β is set by the energy scale at which distinguishable structure emerges.

Clarification of Terms. The ultraviolet (UV) extreme refers to the highest energy physics, typically associated with the Planck scale:

$$E_{\text{UV}} \sim E_P \sim 10^{19}\,\text{GeV},$$

where quantum gravitational effects dominate. The infrared (IR) extreme corresponds to the lowest accessible energy scale, such as the current Hubble horizon:

$$E_{\mathrm{IR}} \sim H_0 \sim 10^{-33}\,\mathrm{eV}.$$

The intermediate scales are:

- T_{early}: Temperatures associated with reheating after inflation ($\sim 10^9 - 10^{15}$ GeV) and symmetry-breaking epochs (e.g., electroweak at $\sim 10^2$ GeV, QCD at ~ 0.2 GeV).
- Λ_{IR}: Infrared scales arising in effective theories, such as the CMB temperature ($\sim 10^{-4}$ eV) or matter–radiation equality.

In these regimes, the TEQ parameter β dynamically adjusts to reflect the dominant entropy geometry, enabling smooth interpolation between early-universe physics and late-time cosmological observables. These values determine temporary or context-specific vacuum-like effects—analogous to effective potentials or phase transitions in cosmology [12]—without requiring a change in the underlying formalism.

Empirical Resolution Scales and Vacuum Energy Suppression

Appendix C of [9] provides canonical estimates for the entropy–action parameter β across different physical regimes. These values emerge from the structural variational principle governing entropy-weighted dynamics. As such, TEQ does not impose cutoffs externally, but derives context-sensitive suppression from entropy geometry itself.

The observed smallness of the vacuum energy is explained as a structural consequence of:

- Entropy curvature filtering unstable, high-frequency fluctuations;
- A resolution threshold governed by β, derived from entropy geometry;
- Suppression scaling as $\rho_{\mathrm{vac}} \sim \beta^{-4}$.

This explains why the cosmological constant corresponds not to the Planck scale, but to the horizon-scale value of β. As the entropy geometry of the universe evolves, so does β, implying that the vacuum energy may in principle be dynamic. Representative values of β are summarized in Table 2.

Table 2. Representative values of β across physical regimes, illustrating the entropy–coherence spectrum. Real values of β suppress unstable entropy flow; the imaginary value $i/\hbar$ represents the unitary quantum limit.

Regime	Representative β	Interpretation
Hubble scale ($H_0 \sim 10^{-33}$ eV)	$\sim 6 \times 10^{33}\,\mathrm{J}^{-1}$	Cosmological resolution
CMB temperature ($T \approx 2.7$ K)	$\sim 2.7 \times 10^{22}\,\mathrm{J}^{-1}$	Weak entropy flow
Room temperature ($T \approx 300$ K)	$\sim 2.4 \times 10^{20}\,\mathrm{J}^{-1}$	Classical–thermal
Planck temperature ($T_P \sim 1.4 \times 10^{32}$ K)	$\sim 7 \times 10^{-10}\,\mathrm{J}^{-1}$	Action-dominated
Quantum limit (unitary weight)	$\beta = \frac{i}{\hbar} \sim i \times 10^{34}\,\mathrm{J}^{-1}$	Pure phase coherence

5. Structural Resolution of Vacuum Energy: Outlook and Implications

The cosmological constant problem is often described as a discrepancy between theory and observation—a mismatch in how much vacuum energy quantum field theory (QFT) predicts versus how much the universe actually displays. But in the TEQ framework, we reinterpret the issue more fundamentally: it is not a mistake in energy accounting, but a misunderstanding of what should be counted in the first place.

Standard QFT includes contributions from all possible quantum fluctuations, regardless of whether they give rise to stable, distinguishable features. In contrast, TEQ introduces a filtering principle based on entropy curvature. Only those modes that are entropy-stabilized—that is, which contribute to resolvable physical structure—are allowed to influence observable quantities like vacuum energy.

Although the present model is simplified, the core result is structurally nontrivial: it reproduces the observed scale of vacuum energy without resorting to arbitrary cutoffs or fine-tuned cancellations. The filtering mechanism arises from a first-principles variational argument, not from phenomenological adjustments.

The entropy curvature functional $g(\phi, \dot{\phi})$, central to the suppression mechanism, has already been derived from minimal geometric constraints in Appendix A.0.0.1 and [9]. It appears as a quadratic form over the tangent bundle governed by an entropy-induced metric $G_{ij}(\phi)$, encoding local resolution structure.

To fully develop this approach, several extensions remain:

- A covariant formulation of the entropy filter, clarifying how TEQ behaves under changes of frame or slicing;
- A reformulation of gravitational coupling, consistent with TEQ's principle that only entropy-resolved modes contribute to physically meaningful dynamics;
- Exploration of possible observable consequences in systems with varying entropy curvature, such as early-universe cosmology or black hole evaporation.

The entropic scale β is not a fixed parameter but emerges from the structure of entropy geometry, as shown in Table 2 and in [9], §3. It governs the threshold across which fluctuations cease to contribute to resolvable structure, and it varies depending on the entropy–action balance in a given regime.

TEQ vs Standard QFT: A Structural Comparison

To clarify how the Total Entropic Quantity (TEQ) framework departs from traditional quantum field theory (QFT) in its treatment of vacuum energy, the table below summarizes the key structural distinctions. Whereas standard QFT relies on external cutoffs and includes all modes in its energy accounting, TEQ derives suppression from entropy geometry and resolution stability.

Table 3. Comparison between standard quantum field theory (QFT) and the Total Entropic Quantity (TEQ) framework in their treatment of vacuum energy.

Standard QFT	**TEQ Framework**
All quantum modes up to a chosen cutoff (e.g., Planck scale) are counted equally in vacuum energy summation.	Only entropy-stabilized (resolvable) modes contribute. Entropy-unstable fluctuations are structurally filtered.
Vacuum energy generically diverges unless artificial cutoffs or fine-tuned cancellations are applied.	Vacuum energy is finite, scaling as $\rho_{\text{vac}} \sim \beta^{-4}$. Suppression arises structurally via entropy weighting.
Energy cutoffs are imposed externally, often based on dimensional analysis rather than structural necessity.	The suppression factor $\exp(-\beta\omega_k)$ emerges from a variational principle over entropy–action geometry [9].
High-frequency (short-wavelength) modes dominate the energy integral.	High-frequency modes are exponentially suppressed due to large entropy curvature. Only stable, low-frequency modes remain.
Structure is assumed; all mathematically allowed paths contribute equally in modulus.	Structure emerges from resolution: only entropy-stable paths contribute significantly to physical amplitudes.

Even in this minimal form, the central insight is clear: TEQ does not impose structure—it identifies which fluctuations are physically meaningful based on their stability under entropy flow. This reframes vacuum energy not as a sum over all modes, but as the trace left by those that remain resolvable.

In this framework, vacuum energy is finite because indistinct, high-frequency modes are structurally excluded. Only resolved, entropy-stabilized contributions remain. The result is not a fine-tuned cancellation, but a context-dependent outcome of resolution geometry.

 doi:10.20944/preprints202505.1874.v2

Closing Remark.

The cosmological constant, in the TEQ framework, is not a fixed property of empty space. It is the residual imprint of all the fluctuations that fail to resolve into distinguishable structure. Rather than signaling the presence of hidden fields or miraculous cancellations, it reflects a boundary in the fabric of resolution itself. In this light, the smallness of vacuum energy is not an unexplained anomaly—it is what the absence of structure looks like, measured at cosmological scales.

Acknowledgments: This work was carried out independently during a period of cognitive and physical rehabilitation following a brain hemorrhage. It reflects part of a personal recovery process rather than a formal research program. ChatGPT was used for language refinement and structural organization; all theoretical content is the author's own. The ideas are offered with no claim to certainty—only the hope that their structure may prove useful or clarifying to others.

Appendix A. Summary of the TEQ Framework

This appendix provides a self-contained summary of the structural foundations of the Total Entropic Quantity (TEQ) framework [9], which underlie the entropy-weighted suppression mechanism developed in the main text.

Axioms and Geometric Assumptions

The TEQ framework is built on two generative principles:

- **Axiom 0 (Entropy Geometry):** Configuration space carries a geometric structure induced by entropy. Distinguishability is defined via a Riemannian metric $G_{ij}(\phi)$, governing how changes in system state affect observable structure.
- **Axiom 1 (Minimal Principle):** Physical trajectories maximize distinguishability of entropy flow under structural constraints. This generalizes the least-action principle to account for entropy curvature and resolution stability.

These axioms lead to an entropy-weighted variational principle, where the classical action $S[\phi]$ is supplemented by a functional measuring the apparent entropy production along the path.

Variational Derivation of the Path Amplitude

Let $\rho[\phi]$ denote the probability density over paths $\phi(t)$. To select the most probable path distribution, we extremize the path entropy subject to constraints on average action and average entropy production:

$$\mathcal{S}[\rho] = -\int \mathcal{D}[\phi]\,\rho[\phi]\ln\rho[\phi], \tag{A1}$$

subject to

$$\int \mathcal{D}[\phi]\,\rho[\phi] = 1, \tag{A2}$$

$$\int \mathcal{D}[\phi]\,\rho[\phi]\,S[\phi] = \bar{S}, \tag{A3}$$

$$\int \mathcal{D}[\phi]\,\rho[\phi]\,\tilde{S}_{\text{apparent}}[\phi] = \bar{\Sigma}. \tag{A4}$$

Introducing Lagrange multipliers λ and β, variation yields:

$$\rho[\phi] = \frac{1}{Z}\exp\left(\frac{i}{\hbar}S[\phi] - \beta\tilde{S}_{\text{apparent}}[\phi]\right). \tag{A5}$$

 doi:10.20944/preprints202505.1874.v2

This defines the TEQ path amplitude as:

$$\mathcal{A}[\phi] = \exp\left(\frac{i}{\hbar}S[\phi] - \beta g[\phi]\right), \tag{A6}$$

where $g[\phi] \equiv \tilde{S}_{\text{apparent}}[\phi]$ is approximated by a local functional

$$g(\phi, \dot{\phi}) = \frac{1}{2}G_{ij}(\phi)\,\dot{\phi}^i\dot{\phi}^j.$$

Interpretation

The term $\frac{i}{\hbar}S[\phi]$ encodes coherent phase evolution, while $\beta g[\phi]$ governs entropy-weighted suppression. The parameter β is not imposed arbitrarily; it emerges from the entropy–action constraint geometry and sets the resolution threshold. In the limit $\beta \to 0$, all paths contribute equally in magnitude, recovering the standard Feynman path integral. In the large-β regime, only entropy-resolved, stable fluctuations remain.

Conclusion.

This derivation shows that entropy-weighted suppression is not an ad hoc modification but a structural consequence of constrained distinguishability. The TEQ framework thereby provides a principled mechanism for filtering vacuum modes without introducing external cutoffs.

Derivation of the Entropy Metric $g(\phi, \dot{\phi})$

This appendix provides a condensed summary of Appendix B in [9]

In the TEQ framework, the effective action includes an entropy-weighted deformation term:

$$S_{\text{eff}}[\phi] = \int dt\left(L(\phi, \dot{\phi}) - i\hbar\beta\, g(\phi, \dot{\phi})\right), \tag{A7}$$

where $g(\phi, \dot{\phi})$ quantifies the entropy flux associated with the path $\phi(t)$, as accessible to a finite-resolution observer.

To determine a minimal and general form for g, we impose four structural requirements:

1. **Locality:** g depends only on ϕ and $\dot{\phi}$.
2. **Positivity:** $g \geq 0$, encoding entropy production or suppression.
3. **Covariance:** g is a scalar under reparametrizations of configuration space.
4. **Resolution Geometry:** Entropy flow induces a Riemannian structure over the tangent bundle.

These constraints imply a canonical quadratic form:

$$g(\phi, \dot{\phi}) = \frac{1}{2}G_{ij}(\phi)\,\dot{\phi}^i\dot{\phi}^j, \tag{A8}$$

where $G_{ij}(\phi)$ is a positive-semidefinite tensor encoding entropy curvature—i.e., the local geometry of distinguishability. This structure is:

- **Minimal:** No higher-order or nonlocal terms;
- **Invariant:** Covariant under field reparametrization;
- **Familiar:** Analogous to kinetic energy, but with a geometric rather than inertial interpretation.

This formulation aligns with the Fisher information metric in information geometry:

$$G_{ij}(\phi) = \mathbb{E}\left[\partial_i \log p(x;\phi)\,\partial_j \log p(x;\phi)\right], \tag{A9}$$

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where $p(x;\phi)$ defines a family of distributions over observable states [13,14]. Here, entropy curvature measures how sharply variations in ϕ affect resolvability—paralleling thermodynamic and quantum information geometry [15–17].

The entropy curvature tensor also governs local stability:

$$\kappa = \frac{\partial^2 g}{\partial \dot{\phi}^2} = G_{ij}(\phi), \tag{A10}$$

appearing in the deformed Poisson structure and quantization conditions (see §3 of [9]). In this sense, G_{ij} functions as an entropic analogue of an inertial tensor, weighting trajectories by their geometric stability.

Conclusion.

Under general constraints, the entropy deformation g must take the form of a velocity-squared term with entropy-induced metric coefficients. This provides the foundation for entropy-weighted dynamics and structurally derived quantization.

Explicit Assumptions and Validity Domains

This appendix outlines the key mathematical and physical assumptions underlying the TEQ-based suppression of vacuum energy, along with their justification and domains of validity.

1. **Linear Dispersion Relation:**
$$\omega_k = c|\vec{k}|$$
We assume relativistic, linear dispersion. This simplification holds in the ultraviolet limit (high-frequency modes), where mass and nonlinear interactions become negligible relative to kinetic energy terms [10]. While physically realistic for massless or ultrarelativistic fields, it may require corrections for massive or strongly interacting fields at lower energies.
2. **Equipartition Approximation:** Statistical equipartition of stabilized configurations is assumed:
$$\langle \dot{\phi}_k^2 \rangle \sim \frac{\omega_k}{2}, \quad \langle \phi_k^2 \rangle \sim \frac{1}{2\omega_k}$$
This approximation, standard in statistical mechanics [11], is justified for entropy-stable modes that equilibrate locally. Departures from local equilibrium or coherent quantum states (e.g., squeezed vacuum states or early-universe inflationary modes) could require adjustments.
3. **Quadratic Form of Entropy Curvature:** Entropy curvature $g(\phi,\dot{\phi})$ is taken as a quadratic functional:
$$g(\phi,\dot{\phi}) = \frac{1}{2} G_{ij}(\phi)\, \dot{\phi}^i \dot{\phi}^j$$
This form arises naturally from minimal assumptions of locality, covariance, and positivity (Appendix A.0.0.1). Non-quadratic or nonlocal entropy metrics might appear in regimes with strong gravitational or quantum-gravitational effects [18].
4. **Flat Spacetime Background:** The current derivation explicitly assumes a flat Minkowski spacetime background. In curved spacetimes or near gravitational sources, the entropy geometry might couple to spacetime curvature [10]. A fully covariant generalization remains a key area for future development.
5. **Weak Interaction Limit:** Interactions between modes or nonlinear field interactions are neglected. This assumption allows analytical tractability, but limits immediate applicability to strongly coupled or interacting theories. Future extensions of TEQ could integrate perturbative or nonperturbative interactions explicitly.

 doi:10.20944/preprints202505.1874.v2

By transparently stating these assumptions, we clarify the conditions under which TEQ-derived vacuum energy predictions are robust and physically relevant. Deviations from these assumptions highlight potential areas for theoretical refinement and further empirical testing.

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