Bounded Vacuum Energy: A Spectral Approach to Light, Information, and Spacetime

André J.H. Kamminga

June 9, 2025 version 1.0

Abstract

This article presents a physically motivated limitation of vacuum energy, derived from the spectral properties of photons as information carriers. The vacuum is proposed to support only meaningful electromagnetic fluctuations within a frequency window bounded by thermal effects on the lower end and QCD-related confinement on the upper end. Within these spectral limits, a physically meaningful information field emerges, governed by the causal structure of spacetime. In combination with the theoretical foundation provided in the paper "Vacuum Energy with Natural Bounds"[11], this approach offers a potential solution to the cosmological constant problem without fine-tuning, and integrates thermodynamic, relativistic, and quantum mechanical principles into a unified framework.

1 Introduction

In modern physics, the vacuum is considered a dynamic state full of fluctuating quantum fields [1]. This zero-point energy forms the foundation upon which all physical processes take place [2]. At the same time, fundamental properties of the vacuum remain underexplored, such as the possibility that this energy is not infinite but spectrally bounded by physical limits. This approach builds on previous work. See preprint of the paper: Bounded Vacuum Energy [3].

In this article, we present a model in which the vacuum only supports photons within a physically meaningful frequency domain. Within these bounds, photons function as information carriers, and a bounded yet active structure arises that forms the basis for causality and measurability in spacetime.

[1]See A. Zee, *Quantum Field Theory in a Nutshell*, 2nd edition, Princeton University Press, 2010

[2]See S. Weinberg, "The Cosmological Constant Problem," *Rev. Mod. Phys.*, vol. 61, pp. 1–23, 1989

[3]See also A.J.H. Kamminga, "Vacuum Energy with Natural Bounds: A Spectral Approach without Fine-Tuning," viXra:2505.0208, May 2025, `https://viXra.org/abs/2505.0208`.

2 Physically Motivated Frequency Limits

We propose that the vacuum only carries meaningful fluctuations within a frequency window:

- Lower bound: $\nu_{\text{min}} \approx 10^9$ Hz, associated with the thermal limit at $T \approx 30$ K.
- Upper bound: $\nu_{\text{max}} \approx 3 \times 10^{23}$ Hz, corresponding to an energy of $E \approx 1$ GeV (QCD limit) [4].

The geometric mean gives a characteristic frequency:

$$\nu_0 = \sqrt{\nu_{\text{min}} \cdot \nu_{\text{max}}} \approx 1.7 \times 10^{16} \text{ Hz}$$

3 Spectral Structure of the Vacuum

In quantum theory, vacuum energy is formally infinite unless a cutoff is applied [5].

We propose a cutoff that is physically motivated. The upper bound is determined by quark confinement (QCD) [6], and the lower bound by thermal damping. Only within this frequency domain can photons propagate freely in the vacuum and thus act as genuine carriers of information.

The spectral contribution of photons to vacuum energy can be mathematically represented as:

$$S(\nu) = \exp\left(-\frac{(\log_{10}(\nu/\nu_0))^2}{2\sigma^2}\right)$$

where

$$\nu_0 = \sqrt{\nu_{\text{min}} \cdot \nu_{\text{max}}}, \quad \sigma \approx 3.5$$

This distribution automatically suppresses all frequencies outside the relevant domain. Only physically meaningful fluctuations remain.

4 Energy Estimate

The energy density of the vacuum can be approximated via integration over the spectral contribution of photons:

$$\rho_{\text{vac}} \approx \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} h\nu \cdot S(\nu)\, d\nu$$

Here, the function $S(\nu)$ ensures a natural damping of contributions outside the physically relevant frequency domain. This approach yields a finite energy density on the order of 10^{-10} J/m^3, consistent with the value inferred from measurements of the cosmological constant as reported by the Planck satellite in 2018 [7].

This shows that a physically bounded vacuum structure does not require fine-tuning to explain the observed cosmological energy density. (See figure 1)

[4] See E. W. Kolb and M. S. Turner, *The Early Universe*, Addison-Wesley, 1990

[5] See M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*, Addison-Wesley, 1995

[6] See also C. Rovelli, *Quantum Gravity*, Cambridge University Press, 2004, for context on confinement scales

[7] Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters," *Astronomy & Astrophysics*, vol. 641, A6, 2020

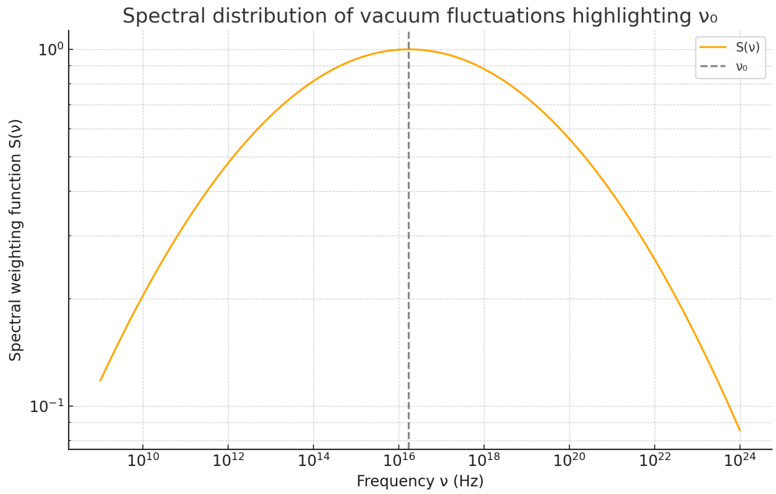

Figure 1: Schematic representation of the spectral distribution $S(\nu)$ (illustrative example).

5 Numerical Evaluation of the Vacuum Energy Density

The energy density of the vacuum can be estimated numerically using the spectral function $S(\nu)$ defined above. This section presents the main result of the integration, followed by an analysis of the frequency-dependent contributions.

The vacuum energy density in the proposed model is calculated via the integral:

$$\rho_{\text{vac}} = \int_{\nu_{\min}}^{\nu_{\max}} h\nu \cdot S(\nu)\, d\nu$$

with:

$h = 6{,}626 \times 10^{-34}$ J·s (Planck's constant),

$\nu_{\min} = 10^9$ Hz (thermal lower bound),

$\nu_{\max} = 3 \times 10^{23}$ Hz (QCD upper bound),

$\nu_0 = \sqrt{\nu_{\min} \cdot \nu_{\max}} \approx 1.73 \times 10^{16}$ Hz,

$S(\nu) = \exp\left(-\frac{[\log_{10}(\nu/\nu_0)]^2}{2\sigma^2}\right)$,

$\sigma = 3.5$.

5.1 Result of the Integration

The integral was numerically evaluated using quadrature methods and yields:

$$\rho_{\text{vac}} \approx 4.01 \times 10^{-10}\ \text{J/m}^3$$

This value corresponds, as already noted, to the vacuum energy density inferred from measurements of the cosmological constant (Planck 2018). The numerical evaluation aligns with a previously developed method [11]. See also the introduction.

5.2 Frequency Distribution of the Contribution

The differential contribution per frequency interval was analyzed. It shows that:

- The largest energy contribution originates from the range between 10^{14} and 10^{18} Hz.
- Frequencies below 10^{12} Hz and above 10^{21} Hz contribute negligibly.
- Around $\nu \approx 10^{16}$ Hz (visible-UV range) lies the maximum of the spectral weight distribution.
- The cumulative contribution to ρ_{vac} reaches 95% by $\nu \approx 10^{19}$ Hz.

5.3 Interpretation

This numerical evaluation confirms that:

- The spectral limitation provides a physically consistent and effective cutoff.
- The model requires no fine-tuning to reproduce the observed vacuum energy density.
- Only physically meaningful frequencies contribute to the total vacuum energy.

6 Information-Carrying Fluctuations and Causality

Within the physically bounded frequency window, electromagnetic fluctuations behave as information-carrying photons. These photons can transmit properties such as frequency, polarity, phase, and energy, thereby forming the basis for quantum mechanical processes such as interference and entanglement.

The vacuum defines the conditions for this information transfer. The universal speed of light can be derived from the relation:

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

This speed of light imposes an absolute limit on information transfer [8]. In relativistic theory, c also defines the causal structure of spacetime: only events within each other's light cone can physically influence one another.

7 Cosmological Implications

The proposed limitation provides a physical framework for a finite vacuum energy density [9]. During the evolution of the universe, long-wavelength fluctuations are thermally suppressed, reducing their contribution to vacuum energy.

Future observations, such as precision measurements of the cosmic microwave background or laboratory detection of low-temperature vacuum fluctuations, may provide empirical tests for this model.

[8] See E. Verlinde, "On the Origin of Gravity and the Laws of Newton," *JHEP*, vol. 2011, no. 4, p. 029

[9] See P. J. E. Peebles and B. Ratra, "The Cosmological Constant and Dark Energy," *Rev. Mod. Phys.*, vol. 75, pp. 559–606, 2003

8 Conclusion

The image of a spectrally bounded and information-carrying vacuum offers a fundamental perspective on the structure of the universe. In this model, the vacuum is not empty space, but an active medium that carries light, organizes information, and defines the limits of causality and interaction.

This approach unifies concepts from energy physics, information theory, and relativity into a coherent physical framework. Future research, both theoretical and observational, can further substantiate this model and explore its implications for our view of space, time, and reality.

References

[1] S. Weinberg, "The Cosmological Constant Problem," *Rev. Mod. Phys.*, vol. 61, pp. 1–23, 1989.

[2] P. J. E. Peebles and B. Ratra, "The Cosmological Constant and Dark Energy," *Rev. Mod. Phys.*, vol. 75, pp. 559–606, 2003.

[3] A. Zee, *Quantum Field Theory in a Nutshell*, 2nd edition, Princeton University Press, 2010.

[4] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*, Addison-Wesley, 1995.

[5] H. B. G. Casimir, "On the Attraction Between Two Perfectly Conducting Plates," *Proc. Kon. Ned. Akad. Wet.*, 1948.

[6] E. W. Kolb and M. S. Turner, *The Early Universe*, Addison-Wesley, 1990.

[7] S. M. Carroll, "The Cosmological Constant Problem" *Living Reviews in Relativity*, vol. 4, no. 1, 2001.

[8] T. Padmanabhan, "Understanding Our Universe: Current Status and Open Issues," *Current Science*, vol. 88, 2005.

[9] C. Rovelli, *Quantum Gravity*, Cambridge University Press, 2004.

[10] E. Verlinde, "On the Origin of Gravity and the Laws of Newton," *JHEP*, vol. 2011, no. 4, p. 029, 2011.

[11] A.J.H. Kamminga, "Bounded Vacuum Energy: A Spectral Approach without Fine-Tuning," viXra:2505.0208, May 2025. `https://viXra.org/abs/2505.0208`