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Casimir Effect and the Cosmological Constant

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Abstract: Any quantum theory of gravity at the quantum gravity scale has the expectation of the existence of a minimal observable length. It is also expected that this fundamental length has a principal role in nature at the quantum gravity scale. From the uncertainty principle that influences the quantum measurement process, the existence of a minimal measurable length can be heuristically deduced. The existence of this minimal measurable length leads to an apparent discretization of spacetime, as distinguishing below this minimal length becomes impossible. In topologically non-trivial cosmological models, the Casimir effect is significant since it alters the spectrum of vacuum fluctuations and leads to a non-zero Casimir energy density. This suggests that the topology of the Universe could influence its vacuum energy, potentially affecting its expansion dynamics. In this sense, the Casimir effect could contribute to the observed acceleration of the Universe's expansion. Here, we use the Casimir effect to determine the value of the electromagnetic zero-point energy in the Universe, applying it to the regions outside and inside the Universe horizon or Hubble horizon and assuming the existence of this minimal length. The Casimir effect is directly related to the boundary conditions imposed by the geometry and symmetries of the Hubble horizon. The agreement of the obtained value with the observed cosmological constant is not exact and therefore the contribution of non-electromagnetic radiation (gravitational effects) must be take into account.

Keywords: Casimir effect; cosmological constant; discrete spacetime; quantum fluctuations

1. Introduction

Quantum gravity is a field that seeks to reconcile the principles of general relativity with those of quantum mechanics. While progress has been made, we are still far from a complete understanding. Researchers continue to explore novel approaches to shed light on this fundamental force of nature. Despite extensive research spanning several decades and the exploration of various models, such as string theory [1,2], M-theory [3], the brane-world scenario [4], loop quantum gravity [5] and asymptotic safety [6], a comprehensive theory of quantum gravity remains elusive; see [7] for a review of quantum gravity phenomenology during recent years.

In the context of quantum gravity, the quantization of spacetime is anticipated to occur naturally. Specifically, at very small scales, the continuum description of space and time, as outlined by Einstein's general relativity, is expected to break down. This breakdown generates a fluctuating and irregular structure, causing spacetime to be poorly defined in local regions. The connection between spacetime's texture and quantum fluctuations has been thoroughly investigated from multiple angles in recent years. Although there is no consensus on whether spacetime fundamentally possesses quantum features, the unification of quantum theory and general relativity is believed to necessitate the quantization of gravity and spacetime.

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On the other hand, it has been proposed in the literature [8–11] that at the Planck scale, quantum gravity fluctuations and the structure of spacetime could be intricately connected to Einstein–Podolski–Rosen (EPR) [12,13] entangled states through an equivalence with Einstein–Rosen (ER) [14] wormholes. This intriguing conjecture, known as the ER=EPR conjecture, suggests that the seemingly disparate phenomena of entanglement and wormholes might be fundamentally related. The ER=EPR conjecture posits that entangled particles are connected by microscopic wormholes. In other words, EPR entanglement corresponds to the existence of ER bridges. However, as of now, no definitive effects have been observed, suggesting that these fluctuations might occur at even smaller scales. Alternatively, it is possible that our understanding of the interactions between photons and gravitons remains incomplete.

Beginning with the aforementioned assumptions, in [15], it was shown that the quantum measurement process leads to the existence of a fundamental measurable length at the Planck scale, resulting in the apparent discretization of spacetime. Therefore, it does not matter whether spacetime is discrete or not because that is how we perceive it when we interact with it. As an outcome of such a conclusion, in [15], the value of the zero-point energy in the Universe was inferred, which was found to be very close to the observed cosmological constant. In this work, we approach the problem from another point of view in order to determine the electromagnetic component of the cosmological constant.

According to the Big Bang Theory, the Universe began from a singularity. At that moment, spacetime and matter all came into existence. The Universe rapidly expanded from this initial state, and crucial data evidence supports such an expanding Universe. This expansion implies the existence of a cosmological horizon or Hubble horizon. The cosmological horizon, or the cosmic light horizon, represents the maximum distance from which light (or any other form of radiation) could have traveled to an observer since the beginning of the Universe. It serves as the boundary between the observable and unobservable regions of the Universe. In other words, it defines the size of the observable universe. In terms of the comoving distance, the cosmological horizon is equal to the conformal time that has passed since the Big Bang, multiplied by the speed of light. Essentially, the cosmological horizon represents the furthest distance from which we can retrieve information about events in the past, defining what we can observe in the Universe. In summary, the cosmological horizon represents the boundary beyond which information cannot be obtained due to the finite speed of light. It plays a crucial role in defining what we can observe in our vast and ever-expanding Universe.

The Casimir effect is usually interpreted as arising from the modification of the zero-point energy of quantum electrodynamics (QED) when two perfectly conducting plates are put very close to each other, and is considered as proof of the physical reality of this zero-point energy. The cosmological constant, which is necessary to explain the acceleration of the expansion of the Universe, is sometimes viewed as another proof of the same reality; see [16]. In fact, Zel'dovich [17] already conjectured that these two empirical facts, the cosmological constant and the Casimir force, must have a common theoretical explanation, but all attempts of deriving both from a unified theory have not been successful so far. Lifshitz theory has been the standard theoretical tool for describing the measured forces of the Casimir effect. In [18], a version of Lifshitz theory is developed in order to account for the electromagnetic contribution to the cosmological constant. The theory does not predict a specific cosmological constant Λ, as Λ depends on dynamics, which implies that it may have had different values throughout the history of the Universe. Here, we try to heuristically determine the present value of the cosmological constant in terms of a global Casimir effect applied to the cosmological horizon.

The existence of such a cosmological horizon implies the existence of two different regions in the Universe. Hence, we can study the Casimir effect of the quantum fluctuations inside the horizon and over the boundary defined by the cosmological horizon. It is implicitly understood that we made several assumptions in order to apply the Casimir effect to such a configuration. The boundary conditions imposed by the geometry and symmetries of the cosmological horizon affect the application of the Casimir effect. These symmetries determine which vacuum modes are allowed, affecting the vacuum energy density in the confined region inside the horizon and outside of it. As a practical application stemming from our research, we obtain the value of the electromagnetic zero-point energy of the Universe close to the value of the present cosmological constant obtained from the observations, but not the same. The conclusions and outlook are finally summarized in Section 3.

In summary, recent advances in quantum gravity suggest the existence of a minimal measurable length, implying an effective discretization of spacetime at the Planck scale. The existence of a minimum measurable length associated with the quantum measure—typically associated with the Planck scale—implies an effective discretization of spacetime and has profound implications for quantum field theory and cosmology. In this work, we investigate how the Casimir effect—a physical manifestation of vacuum fluctuations—can be extended to cosmological scales, particularly in the presence of the Hubble horizon, which acts as a natural boundary. By applying Casimir energy calculations to the observable universe, we estimate the electromagnetic contribution to the zero-point energy and compare it with the observed value of the cosmological constant. Our results show that the electromagnetic Casimir energy accounts for approximately 56% of the observed cosmological constant, suggesting that additional contributions, likely from quantum gravitational effects, are necessary to fully explain dark energy. Importantly, this framework offers a novel perspective on how vacuum fluctuations may have influenced the early expansion of the Universe, providing insight into the intersection between quantum field theory and cosmology.

2. Casimir Effect and Cosmological Constant

We use the apparent discretization of spacetime and the Casimir effect to estimate the cosmological constant. Several proposals have been made to establish the relationship between the cosmological constant problem and quantum fluctuations [19–21]. In [15], using a heuristic derivation of the Unruh effect [22] given in [23], the Heisenberg uncertainty relation and the apparently granulated spacetime at Planck scale, a value for the cosmological constant was given. The apparently granulated spacetime at the Planck scale means that not any points of the continuum spacetime can resonate but only points that have a Planck distance between them can resonate; consequently, such resonant points are the only contribution to the zero-point energy of the Universe. This is similar to what happens with the energies of the electrons of an atom, which are quantized and cannot take any value. Using the same idea, quantized spacetime implies that quantum fluctuations can only occur at certain points of the Universe. This discretization results in a finite value for the cosmological constant and avoids a vacuum catastrophe.

2.1. The Casimir Effect

The main macroscopic and measurable consequence of quantum fluctuations is the Casimir effect. See the textbook [24] for a good survey of the latest results of the Casimir effect. The Casimir effect is a small attractive force that acts between two close parallel uncharged conducting plates. Casimir theorized it in 1948 from the quantum vacuum fluctuations of the electromagnetic field based on the mode summation technique. The Casimir force appears between two plates as a consequence of the imbalance between the radiation pressure of vacuum fluctuations inside and outside the plates. This imbalance gives the following expression:

$$E = \frac{\pi^2 \hbar c A}{720 d^3} \tag{1}$$

where d is the distance between the plates and A is their surface area. The heuristic deduction of the Casimir effect between the plates from the uncertainty principle can be seen in [25–27]. Photons are the dominant virtual particles of quantum fluctuations, but not the unique ones. Hereunder, other contributions must be taken into account, such as the graviational quantum fluctuations.

2.2. Casimir Effect for a Spherical Shell

In this section, we consider a spherical shell of a finite radius enclosed in a larger shell of infinite radius that corresponds to the whole space.

A first approximation was made by Casimir, which was computed from the electromagnetic normal modes inside the shell in an analogy with the parallel plates, obtaining the result

$$E \sim -0.09\,\frac{\hbar c}{2a}, \tag{2}$$

by substituting the distance d for a and the area of the plate as πa^2 in Equation (1), which, as we see, is in good agreement considering the rough approximation made, but there is a contrary sign.

The first correct computations were made by Boyer [28], and the energy found was just of contrary sign, i.e., tending to expand the shell, and its value is given by

$$E \cong +0.09\,\frac{\hbar c}{2a}. \tag{3}$$

Therefore, the Casimir energy for the sphere was found to be positive, thereby implying a repulsive force rather than the attractive force observed in the case of two plates. Boyer's [28] result was later verified by other authors [29–31].

The Casimir effect has its origin in the expression for the energy of the uncoupled electromagnetic field, which is well known to have the form

$$E = \sum_{\mathbf{k},\lambda} (\frac{1}{2} + n_{\mathbf{k},\lambda}) \hbar\, w_{\mathbf{k}}^{(\lambda)} \tag{4}$$

where $w_{\mathbf{k}}^{(\lambda)} = |\mathbf{k}|$ and $n_{\mathbf{k},\lambda}$ is the photon occupation number in the mode with wave number $\mathbf{k}$ and polarization λ. The sum is to be taken over all allowed $\mathbf{k}$ and λ. In the absence of radiation, this reduces to the zero-point vacuum energy or

$$E = \sum_{\mathbf{k},\lambda} \frac{1}{2} \hbar\, w_{\mathbf{k}}^{(\lambda)} \tag{5}$$

Clearly, this is a divergent expression that can be finite by using a cutoff or convergent factor, and produces measurable effects when boundary surfaces are used to modify the allowed set of modes in Equation (5).

In [32], a direct mode summation approach to determine the Casimir energy of a spherical shell is proposed using Cauchy's theorem, which transforms a sum over modes into an integral in the complex plane. Indeed, Cauchy's theorem establishes that for two analytic functions $f(z)$ and $g(z)$ within a closed contour C, where $f(z)$ has isolated zeros at $x_1, x_2, \ldots, x_n$, then

$$\frac{1}{2\pi i}\oint_C g(z)\frac{f_l'(z)}{f_l(z)}dz = \sum_i g(x_i). \tag{6}$$

However, the standing waves exterior to the sphere were not found correctly in [32]. The correct computation is made in [33]. The mode summation for a spherical shell using Cauchy's theorem works as follows.

Taking into account that each mode is $2l+1$-fold generate, then Equation (5) gives

$$E = \sum_{l=1}^{\infty}(l+\frac{1}{2})\sum_{n=1}^{\infty}\sum_{\lambda=1,2} w_{n,l}^{(\lambda)} \tag{7}$$

where the eigenfrequencies $w_{n,l}^{(\lambda)}$ are determined by imposing the boundary conditions on the multipole fields. These boundary conditions are for the transverse electric modes ($\lambda = 1$):

$$f_l^{(1)}(z) = j_l(z), \quad f_l^{(2)} = j_l(z) + \tan\delta_l(z)n_l(z), \tag{8}$$

and for the transverse magnetic modes ($\lambda = 2$):

$$f_l^{(3)}(z) = \frac{d}{dz}[zj_l(z)], \quad f_l^{(4)} = \frac{d}{dz}[z[j_l(z) + \cot\delta_l(z)n_l(z)]], \tag{9}$$

where $f_l^{(1)}$ and $f_l^{(3)}(z)$ are for the interior $(r < a)$ modes and $f_l^{(2)}$ and $f_l^{(4)}$ are for the exterior $(r > a)$ modes. Moreover, $j_l(z)$ and $n_l(z)$ are spherical Bessel functions with $z = wa$, and for sufficiently large R, we have that $\delta_l(z) = (2z(R/a) - l\pi)/2$. Now, defining the analytic function as

$$f_l(z) = z^2\prod_{i=1}^{4} f_l^{(i)}(z), \tag{10}$$

and applying Cauchy's theorem, that is Equation (6) with $g(z) = ze^{-\sigma z}$ where $\sigma > 0$, to Equation (7), we have

$$E = \lim_{\sigma\to 0}\frac{1}{2\pi i a}\sum_{l=1}^{\infty}(l+\frac{1}{2})\oint_C ze^{-\sigma z}\frac{d}{dz}\ln f_l(z)dz, \tag{11}$$

where the function $e^{-\sigma z}$ is a cutoff in order to ensure that all the integrals are well defined and C is an appropriate contour; see details in [33]. Finally, the computations of E must be divided into a finite part E_f (taking a uniform expansion of the integrand) and the cutoff part E_σ, and the computations yield

$$E = E_\sigma + E_f = \frac{3\hbar c}{64a} + E_f, \tag{12}$$

and taking into account the numerical value of E_f, the expression of the Casimir energy is

$$E \cong +0.09235\frac{\hbar c}{2a}. \tag{13}$$

In summary, the Casimir effect between plates led to the energy being negative, while the Casimir effect energy for a spherical shell found for the first time by Boyer was proved to be positive, and therefore, it would cause an expansion of the spherical shell if this spherical shell could be deformed. It is known that the energy densities in the Casimir effect for a spherical shell in the interior and exterior regions are not uniform. Indeed, they are complicated functions of the radial coordinate (given in terms of integrals involving the spherical Bessel functions). Furthermore, the Casimir energy density is negative inside the sphere and positive outside the sphere. However, Equation (13) is the total energy imbalance, which is positive in a similar way that the total energy is associated with the cosmological constant.

2.3. Casimir Effect Due to the Cosmological Horizon

We recall that for any observer in the Universe, there exists a cosmological horizon due to the expansion of the Universe, i.e., there exists distances beyond which the observer cannot exchange information with the region beyond those distances. Now, we assume that the existence of a Casimir effect due to this cosmological horizon, which takes the role of a spherical shell. Recall that in the Casimir effect, the corresponding energy describes the balance between energy inside a spherical shell and outside of it. Here, we assume that the cosmological horizon establishes a similar boundary condition and that the perfectly conducting spherical shell of the Casimir effect in the previous section does not affect the result. Indeed, the Casimir force between non-conducting plates is typically weaker than that between conducting plates due to the different boundary conditions and the nature of the material interactions. Hence, we assume that the cosmological horizon is really a boundary condition and acts in a similar way to the Casimir effect for a conducting spherical shell for the observer that sees the cosmological horizon.

The sign of the Casimir energy (negative for plates, positive for a conducting sphere) arises from the geometry and the allowed electromagnetic mode spectrum. In the case of two parallel plates, the boundary conditions exclude more modes inside than outside, lowering the energy between the plates and leading to an attractive force. For a perfectly conducting spherical shell, Boyer's result shows the opposite: the boundary conditions lead to a net increase in the energy inside the sphere compared with the vacuum, producing a repulsive force. Despite this difference in sign, both energies are computed in stationary configurations and reflect an equilibrium state of the quantum fields subject to their respective boundaries. Regarding the cosmological horizon, the analogy lies in the role of the horizon as a boundary that constrains vacuum fluctuations for a given observer. In this manuscript, we extend the concept of the Casimir effect by treating the cosmological horizon as a physical boundary condition—similar in spirit to the conducting shell—which modifies the vacuum energy. This modification is then interpreted as a possible contributor to the observed cosmological constant. The spherical symmetry and observer-dependent nature of the horizon support the analogy with the spherical shell case.

Indeed, the perfect conductor boundary condition in its covariant form is written as $n_i\,{}^*F^{ik} = 0$, where n_i is the normal to the boundary and ${}^*F^{ik}$ is the dual of the field strength tensor. In accordance with our assumption for an observer at $r = 0$ (in FRW coordinates), the boundary condition is imposed on the Hubble horizon corresponding to $r = r_H$. But for an observer residing at $r = r_H$, the horizon passes through the point $r = 0$, and the boundary condition should be imposed for $r = 0$ with the corresponding normal. Thus, any point in the FRW universe is a horizon point for some observer and the boundary condition at that point should be imposed with all directions of the normal. In fact, this implies that ${}^*F^{ik} = 0$ everywhere in the space, which is what really happens. Our boundary condition is observer-dependent and, in fact, it is only perceived by each observer at a different place.

Therefore, we assume that in the cosmological context, the same boundary conditions are present in the sense of the allowed modes of vibration. Therefore, from Equation (13), we obtain the following total energy imbalance:

$$E \cong +0.09235\frac{\hbar c}{2r_H}. \tag{14}$$

where r_H is the horizon distance or Hubble radius, i.e., $r_H = c/H_0$, where H_0 is the present value of the Hubble parameter. Now, we take into account that spacetime is apparently granulated at the Planck scale and each point of Planck size is a resonant point of spacetime. Next, following [15,23], in a linear distance r_H, the number of resonant points is $N_0 = r_H/\ell_P$. Hence, Equation (14) becomes

$$E \cong +0.09235\frac{\hbar c}{2\ell_P N_0}\,. \tag{15}$$

Then, any resonant point of the cosmological horizon contributes to the vacuum energy with

$$E_i = \frac{E}{N_0} \cong +0.09235\frac{\hbar c}{2\ell_P N_0^2} \simeq +0.09235\frac{\hbar c\,\ell_P}{2r_H^2}. \tag{16}$$

Here, we assume that every point at the cosmological horizon contributes in the same way by the homogeneity and isotropy of the Universe.

2.4. Cosmological Constant and Cosmological Casimir Effect

The cosmological constant, introduced into Einstein's equations, represents a uniform vacuum energy density that influences the expansion of the Universe. Symmetry plays a crucial role in the formulation of cosmological theories, as the solutions to Einstein's field equations typically assume specific spatial and temporal symmetries. These symmetries help simplify the equations and model the Universe on a large scale.

The cosmological constant problem, also referred to as the vacuum catastrophe, arises from the significant discrepancy between the observed vacuum energy density (which corresponds to a small value of the cosmological constant) and the much larger theoretical value of the zero-point energy predicted by quantum field theory. This discrepancy is estimated to be between 50 and 120 orders of magnitude greater than what is actually observed. The task at hand involves determining the value of the cosmological constant Λ within the Einstein's field equations

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}\,, \tag{17}$$

to ensure that the dynamic model aligns with the observed accelerated expansion of the present Universe, considering that the cosmological constant Λ has an effect equivalent to an intrinsic vacuum energy density characterized by a negative pressure. Indeed, the introduction of the term $\Lambda g_{\mu\nu}$ is a symmetry that Einstein's field equations have, but Einstein, in his desire for a stable Universe, mistakenly determined that Λ had to be zero.

Hence, we estimate the energy per any resonant point from the cosmological constant. The cosmological constant is equivalent to the intrinsic density energy of the vacuum through the equation

$$\rho_{vac} = \frac{\Lambda c^4}{8\pi G}. \tag{18}$$

The result given in (14) is the total energy imbalance of the vacuum induced by a perfectly conducting spherical shell in the Minkowski spacetime. But, the source of the expansion in the Friedmann equations is the energy density and not the total energy. Therefore, in order to compute the total vacuum energy, we must multiply by the volume inside the cosmological horizon, i.e.,

$$E_T = \rho_{vac}\, V = \rho_{vac}\,\frac{4}{3}\pi r_H^3\,. \tag{19}$$

In this context, V represents the volume enclosed by the cosmological horizon. Additionally, we now consider the number of resonant points inside the volume enclosed by the cosmological horizon $N = \frac{4}{3}\pi r_H^3/\ell_P^3$. We remark that this number N is distinct from the previously introduced N_0 (the number of resonant points at the distance r_H). Hence, we can express the energy associated with each resonant point as follows:

$$\frac{E_T}{N} = \rho_{vac}\,\ell_P^3\,. \tag{20}$$

Ultimately, we note that any resonant point p within the Universe must resonate with the same energy. This consistency arises because any point p of the Universe either lies on the cosmological horizon or resides within the region enclosed by the cosmological horizon, depending on the observer's location. Hence, depending on the observer, the same point p can be at the cosmological horizon or inside of it. Indeed, any observer has its own associated cosmological horizon. Therefore, we can equate Equations (16) and (20) since they represent the same energy of the resonant point p. Finally, equating Equations (16) and (20), we obtain

$$\Lambda = 0.09235\frac{4\pi G\hbar}{c^3\ell_P^2 r_H^2} = 1.1605\frac{1}{r_H^2} = 1.1605\frac{H_0^2}{c^2}\,. \tag{21}$$

This result must be compared with the widely recognized expression

$$\Lambda = 3\Omega_\Lambda\frac{H_0^2}{c^2}\,, \tag{22}$$

where Ω_Λ is the ratio between the energy density due to the cosmological constant and the critical density of the Universe. Using the value known for $\Omega_\Lambda \simeq 0.69$ [34], this leads to

$$\Lambda \simeq 2.07\frac{H_0^2}{c^2}, \tag{23}$$

which is in partial agreement with Equation (21). Indeed the electromagnetic zero-point energy only explains 56% of the contribution to the total zero-point energy of the Universe. This contribution is obtained by comparing Equation (21) with Equation (23). The remaining portion must be due to quantum gravity effects. Indeed the spacetime discreteness is assumed to be of the Planck length in all the computations, while it could be proportional to it. The reference to the Planck length for the effects of quantum gravity is generally in terms of the order of magnitude, which would end up explaining the discrepancy.

3. Discussion and Conclusions

In many existing models of quantum gravity, a fundamental feature is the emergence of a minimal length scale at the Planck scale. Consequently, space and time become quantized. According to these models, Einstein's general relativity, which describes continuous spacetime, breaks down at extremely small scales. This breakdown leads to a fluctuating and non-smooth structure where local spacetime is not well defined. Despite the apparent inconsistency with special relativity, researchers have made preliminary efforts to address the challenge of maintaining Lorentz invariance at this minimal length scale [35–37].

Recent investigations into the discreteness of spacetime often assume the existence of a minimal length and a modified uncertainty principle [27,38–46]. These assumptions play a crucial role in understanding the fundamental structure of spacetime at small scales, and they continue to be an active area of research that explores the related implications. Conversely, significant research has focused on constructing a discrete curved spacetime through the causal set approach to quantum gravity; see [47,48]. Despite these efforts, experimental verification of this prediction has remained largely elusive [49,50]. In fact, the causal set theory provides an intriguing perspective on the fundamental structure of spacetime, but empirical validation remains an ongoing challenge for the field.

A particularly intriguing aspect of quantum field theory is the existence of vacuum fluctuations—quantum fluctuations that persist even in the absence of matter. One of the most striking physical manifestations of these fluctuations is the Casimir effect, a phenomenon where boundary conditions on a quantum field (e.g., due to conducting plates) lead to measurable forces arising from the altered zero-point energy. This effect has been experimentally verified with high precision in laboratory settings, establishing it as a real and observable consequence of quantum vacuum physics. The motivation for invoking the Casimir effect in a cosmological context stems from the observation that the cosmological horizon, such as the Hubble radius, naturally acts as a boundary for an observer's accessible Universe. This boundary could, in principle, modify the vacuum energy modes in a way analogous to the Casimir setup. As such, we propose that the global structure of spacetime may influence the vacuum fluctuations, and that this influence could provide a natural, physically motivated framework for estimating the contributions to the cosmological constant—the observed energy density of the vacuum driving the accelerated expansion of the Universe. Importantly, the cosmological constant problem—the enormous mismatch between the theoretical vacuum energy estimates and the observed value—remains one of the deepest puzzles in modern theoretical physics. Traditional quantum field theory predictions yield a vacuum energy density over 100 orders of magnitude larger than what the cosmological observations allow. By adapting the Casimir approach to the cosmological setting, we seek a more grounded, geometry-sensitive estimate that captures the finite electromagnetic component of the vacuum energy, while also highlighting the need for additional contributions, possibly from quantum gravity effects. Although the application of the Casimir effect to cosmological horizons involves theoretical extrapolation, the analogy is physically meaningful: both involve vacuum fluctuations constrained by boundary conditions. The value of this approach lies not only in its predictive potential, but also in the insight it offers into the interplay between quantum field theory, geometry and the large-scale structure of the Universe. In this work, we use the Casimir effect to estimate the electromagnetic contribution to the vacuum energy within the observable Universe, considering the Hubble horizon as a dynamic boundary condition. We then compare this result to the observed cosmological constant to quantify the role of quantum vacuum fluctuations in cosmic acceleration.

In a previous work [15], it was argued that quantum measurements imply the existence of a minimal length at the Planck scale, leading to the apparent discretization of spacetime. This perspective aligns with recent findings reported in [51]. Hence, irrespective of whether spacetime is intrinsically discrete, our perception arises from the idiosyncrasies of quantum measurements. Consequently, quantum fluctuations exhibit behavior akin to their creation at discrete locations on the Planck scale. The idea to explain the cosmological constant in terms of the Casimir effect is not new; see [18]. As an example, in [52], it was shown that in order to make the zero-point energy finite, a suitable cut-off must be introduced of the order of $L = 0.1$ mm. Modes coupling to gravity thus lead to a cosmological constant that is 10^{12} orders greater than the one actually observed. Moreover, on scales greater than $L = 0.1$ mm, it is expected that thermodynamic fluctuations completely overcome the quantum ones.

In this context, here, the zero-point energy inferred from the Casimir effect is linked to the existence of a cosmological constant in the Universe. In the heuristic analysis, the cut-off scale length is substituted for the apparent discretization of spacetime, and hence, we do not have a harmonic oscillator at any point of the spacetime, only at the points with a Planck distance between them. Remarkably, the value obtained aligns closely (but not totally) with the observed value of the cosmological constant. Nevertheless, the exact value is not obtained, suggesting that other contributions (non-electromagnetic ones) must be taken into account. The findings suggest that additional quantum fluctuations play a significant role, yet our comprehension of the interplay between photons and gravitons remains incomplete.

While our approach demonstrates that the electromagnetic Casimir energy accounts for approximately 56% of the observed cosmological constant, the remaining contribution must arise from non-electromagnetic vacuum sources. These include quantum gravitational fluctuations, which are often discussed in the context of spacetime discreteness and modified uncertainty principles [27,42], as well as scalar field contributions arising from inflationary models or evolving dark energy fields, such as quintessence [53]. Additionally, neutrino mixing has been shown to produce non-trivial vacuum condensates and a Casimir-like effect [54] that mimic the behavior of a cosmological constant and may offer a natural explanation for a portion of the dark energy [55]. The precise interplay between these mechanisms remains an open question in theoretical physics. Nevertheless, our approach provides a concrete, physically motivated electromagnetic baseline, suggesting that any comprehensive resolution of the cosmological constant problem must incorporate these broader quantum contributions.

Furthermore, the evolution of the cosmological horizon directly influences the observable universe's development. Therefore, the correct formulation is a dynamic Casimir effect and we have only seen the agreement with the current value of Λ. Ongoing research in this area, along with other related directions, is currently under review and will be presented in future work.

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