The Boundary Theory: A Solution to the Cosmological Constant Problem Through Symmetry Breaking Between Opposing Fields

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Abstract

A solution to the cosmological constant problem is proposed through the existence of opposing fields—one associated with dark energy and the other with quantum fluctuations of the electromagnetic field, i.e., fluctuations of the electric and magnetic components—which possess the same energy density but opposite pressure signs. Both fields are defined over a spacetime quantized in Planck-scale volumes (see Section 4), but only the quantum fluctuation field interacts with matter, as demonstrated by the Casimir effect. This interaction imposes boundary conditions on the quantum fluctuations. The resulting asymmetry breaks the perfect cancellation between both fields, generating a net residual energy that matches the observed dark energy density.

Furthermore, this framework allows quantum fluctuations to exist without violating general relativity, as the absence of cancellation in their energy density would otherwise lead to a gravitational collapse of the universe.

1. Introduction

The cosmological constant problem represents one of the greatest discrepancies between quantum field theory (QFT) and observational cosmology. The vacuum energy density per field predicted by QFT is on the order of 10^113 J/m3, whereas cosmological observations indicate a dark energy density of approximately 5,3×10^−10 J/m3, resulting in a difference of about 120 orders of magnitude.

This work presents a conceptual framework that allows for the reconciliation of both scales without resorting to arbitrary cancellations or exotic mechanisms, relying solely on principles already accepted in theoretical and experimental physics.

2. The Need for Two Opposing Fields: Consistency with Relativity

The existence of quantum vacuum fluctuations implies that spacetime possesses energy even in the absence of matter. However, if only this positive-energy field existed, its total energy density would generate an enormous gravitational curvature that would cause the universe to collapse almost instantly, violating Einstein's general relativity predictions.

For quantum fluctuations to exist while remaining consistent with both general relativity and the observed cosmological stability, a second, opposing field is required—one whose negative pressure counteracts the collapsing tendency of the first. This field corresponds to dark energy, with an equation of state $\omega=-1$, meaning it exerts a negative pressure exactly equal in magnitude (and opposite in sign) to its energy density.

3. Conceptual Foundation

It is postulated that there are two fundamental contributions to the vacuum's energy content:

1- A fluctuating field associated with dark energy, similar in nature to the electromagnetic field, with negative pressure and an energy density of 10^113 J/m3 per each of its two components. This field does not interact with matter and therefore cannot be subject to boundary conditions.
2- A fluctuating field associated with the quantum fluctuations of the electromagnetic field (electric and magnetic components), with positive pressure and an energy density of 10^113 J/m3 per field. This field interacts with matter and can therefore be subject to boundary conditions, as experimentally verified through the Casimir effect.

4. About the Quantization of Space in Planck-Length Units

The present theory is built upon several experimentally verified assumptions, such as the Casimir effect—which demonstrates that quantum fluctuations exist, interact, and are subject to boundary conditions—and cosmological observations that confirm the existence of dark energy and the validity of all known physical laws, including general relativity. However, it introduces one fundamental unverified assumption: that spacetime is quantized in discrete Planck-scale volumes, meaning it has a granular structure at scales of approximately 1.616 x 10^-35m.
Remarkably, the introduction of this assumption, combined with the effect of a cosmic boundary, results in an energy difference between the two fields that exactly matches the observed dark energy density, without the need for arbitrary parameter adjustments.

Since no other free assumptions are introduced in the model, this numerical coincidence cannot reasonably be attributed to chance or artificial fine-tuning. Consequently, this result may be interpreted as strong indirect evidence supporting the quantization of space at the Planck scale. Thus, the theory not only offers a resolution to the cosmological constant problem, but also provides a potentially observable indication of spacetime granularity—something previously thought to be empirically inaccessible.

5. Definition of the Boundary

During the early stages of the universe, when it was dense and opaque (primordial plasma), quantum fluctuations were highly restricted, as the medium limited the development of their modes. When the universe became transparent after recombination, these restrictions disappeared, and space became free to support large-scale quantum modes.

However, information about this "new freedom" cannot propagate instantaneously. According to relativity, information cannot travel faster than the speed of light. This means that, although the potential boundary may have expanded greatly—or even become infinite—after recombination, quantum fluctuations are only defined within the volume that has been causally accessible since that time. In other words, the quantum field can only be defined within the currently visible universe (not to be confused with the broader observable universe), i.e., the maximum distance at which we can observe the cosmic microwave background.
The effective boundary is therefore defined by the current diameter of the visible universe, approximately 45.7×10^9 años luz. $\approx 8{,}6473 \times 10^{26}$m

This sets a finite volume over which quantum fluctuations can exist with well-defined modes. In other words, the visible universe acts as a cavity—analogous to the Casimir effect setup—in which quantum vacuum modes are constrained by the geometric conditions of the system.

This restriction affects only the quantum fluctuation field with positive pressure, as it is the only one that interacts with matter and depends on environmental conditions. In contrast, the dark energy field, which does not interact with matter, has never had restricted modes and has not required adaptation. It is this asymmetry that produces the net energy difference between the two fields, thus explaining the observed dark energy without invoking new fields or unverified mechanisms.

6. Calculation of the Net Dark Energy Density

This section presents the calculations that quantify the restriction of quantum modes due to the boundary, yielding the resulting energy difference:

Net Dark Energy = Brute Dark Energy- Energy of quantum fluctuatutions of the electromagnetic field.

The procedure followed to calculate the energy density lost due to discretization is as follows:

First, the wavelengths where the difference between consecutive modes (Δλ) corresponds to specific multiples of Planck's length are identified. These wavelengths are used as UV limits.

For each of these UV limits, the total energy density associated with them it is calculated, and then the density difference between two consecutive limits is determined.

To each difference, a percentage loss is applied, which has been calculated for each specific UV wavelength (not for the interval). Therefore, this percentage represents a loss from or up to that specific limit.

For each interval, a minimum loss is calculated (using the lower limit value) and a maximum loss (using the upper limit value), which allows the real loss within that range to be bounded.

Finally, the arithmetic mean of the minimum and maximum loss is taken as a reasonable estimate of the total loss.

Since these calculations refer only to one of the two components of the electromagnetic field (electric field or magnetic field), the final value must be multiplied by 2 to obtain the total loss corresponding to the complete electromagnetic field.

Many of the calculations have been performed using Python, following all the equations and instructions explained in the document. The links will be provided at the end of the document, as well as the calculations made with much smaller intervals to verify that this holds true in all cases, not just for the intervals presented in this document.

Calculation of the wavelengths in the boundary

To calculate the wavelengths that fit within a boundary, we use this formula:

$\lambda_n = \frac{2L}{n}$ Where L= 8,6473 x 10^26m and n its a whole number, **λ** is the wavelength.

By calculating the number n between two wavelengths of consecutive ones, where there is a specific difference in multiples of Planck's length, we obtain the following values of *n* and λ_n.

We also take the opportunity to calculate the percentage of wavelengths/modes that are lost due to Δλ with this equation:

$$\% \text{ loss} = \left(1 - \frac{1}{\Delta\lambda \ (\text{in multiples of Planck's length})}\right) \times 100$$

	L *(8.6473 x 10^26m)*	Δλ *(in multiples of Planck's length)*	n	λn *(in micrometers)*	percentage of lost modes
AA	8,6473 x 10^26m	1	1,034 x 10^31	167,1900	0%
AB	8,6473 x 10^26m	1,01	1,029 x 10^31	168,0238	0,99%
AC	8,6473 x 10^26m	1,05	1,009 x 10^31	171,3187	4,76%
BA	8,6473 x 10^26m	1,1	9,863 x 10^30	175,3503	9,09%
BB	8,6473 x 10^26m	1,15	9,646 x 10^30	179,2913	13,04%
CA	8,6473 x 10^26m	1,2	9,443 x 10^30	183,1474	16,67%
CB	8,6473 x 10^26m	1,25	9,252 x 10^30	186,9241	20%
D	8,6473 x 10^26m	1,3	9,073 x 10^30	190,6259	23,08%
E	8,6473 x 10^26m	1,4	8,743 x 10^30	197,8218	28,57%
F	8,6473 x 10^26m	1,5	8,446 x 10^30	204,7650	33,33%
G	8,6473 x 10^26m	1,6	8,178 x 10^30	211,4804	37,50%
H	8,6473 x 10^26m	1,7	7,934 x 10^30	217,9890	41,18%
I	8,6473 x 10^26m	1,8	7,710 x 10^30	224,3089	44,44%
J	8,6473 x 10^26m	1,9	7,505 x 10^30	230,4555	47,37%
K	8,6473 x 10^26m	2	7,315 x 10^30	236,4423	50%
L	8,6473 x 10^26m	2,1	7,138 x 10^30	242,2813	52,38%
M	8,6473 x 10^26m	2,2	6,974 x 10^30	247,9828	54,55%
N	8,6473 x 10^26m	2,3	6,821 x 10^30	253,5561	56,52%
O	8,6473 x 10^26m	2,4	6,677 x 10^30	259,0096	58,33%
P	8,6473 x 10^26m	2,5	6,542 x 10^30	264,3505	60%
Q	8,6473 x 10^26m	2,6	6,415 x 10^30	269,5857	61,54%
R	8,6473 x 10^26m	2,7	6,295 x 10^30	274,7211	62,96%
S	8,6473 x 10^26m	2.8	6,182 x 10^30	279,7623	64,29%
T	8,6473 x 10^26m	2,9	6,074 x 10^30	284,7142	65,52%

U	8,6473 x 10^26m	3	5,972 x 10^30	289,5815	66,67%
V	8,6473 x 10^26m	4	5,172 x 10^30	334,3799	75%
W	8,6473 x 10^26m	5	4,626 x 10^30	373,8481	80%
X	8,6473 x 10^26m	6	4,223 x 10^30	409,5301	83,33%
Y	8,6473 x 10^26m	7	3,910 x 10^30	442,3431	85,71%
Z	8,6473 x 10^26m	8	3,657 x 10^30	472,8846	87,50%

Calculation of the energy density for each UV limit.

First, we need to convert micrometers to meters:

λ m =λ μm × 10^−6

We calculate the angular frequency associated with that wavelength:

$$\omega = \frac{2\pi c}{\lambda}$$

Where:
c is speed of light in vacuum
ω is angular frequency
λ is wavelength in meters

And now we can calculate the energy density:

$$p = \frac{\hbar\omega^4}{8\pi^2 c^3}$$

Where:
ℏ: is the reduced planck constant
ω is the angular frequency previously calculated
ρ is the energy density (J/m³).

Using these equations, we calculate the density for each UV limit *(λn becomes the UV limit)*

	λn *(micrometers)*	Energy density *(J/m3)*
AA	167,1900	7.987031802310311 x 10^-10

AB	168,0238	7.829668864849797 x 10^-10
AC	171,3187	7.244485105969158 x 10^-10
BA	175,3503	6.600860457544379 x 10^-10
BB	179,2913	6.039343615251231 x 10^-10
CA	183,1474	5.546558194453195 x 10^-10
CB	186,9241	5.111700635594404 x 10^-10
D	190,6259	4.726057228765738 x 10^-10
E	197,8218	4.075022470371456 x 10^-10
F	204,7650	3.549798503121997 x 10^-10
G	211,4804	3.119939065978542 x 10^-10
H	217,9890	2.763683389711476 x 10^-10
I	224,3089	2.465134287561701 x 10^-10
J	230,4555	2.212474609194942 x 10^-10
K	236,4423	1.996760162940389 x 10^-10
L	242,2813	1.811119154353903 x 10^-10
M	247,9828	1.650214380420531 x 10^-10
N	253,5561	1.509838001646407 x 10^-10
O	259,0096	1.386638199359019 x 10^-10
P	264,3505	1.277927041424811 x 10^-10
Q	269,5857	1.181514887804750 x 10^-10
R	274,7211	1.095616433472236 x 10^-10
S	279,7623	1.018755216926332 x 10^-10
T	284,7142	9.497079927116147 x 10^-11
U	289,5815	8.874488914958372 x 10^-11
V	334,3799	4.991900847971677 x 10^-11
W	373,8481	3.194816315548408 x 10^-11

X	409,5301	2.218621897457171 x 10^-11
Y	442,3431	1.630007399664216 x 10^-11
Z	472,8846	1.247975101837743 x 10^-11

Calculation of the energy density difference.

Now, we calculate the difference in energy density between consecutive UV limits.

Subtraction	subtraction	Difference *(J/M3)*
AA-AB	7.987031802310311 x 10^-10 - 7.829668864849797 x 10^-10	1.573629374605140 x 10^-11
AB-AC	7.829668864849797 x 10^-10 - 7.244485105969158 x 10^-10	5.851837588806392 x 10^-11
AC-BA	7.244485105969158 x 10^-10 - 6.600860457544379 x 10^-10	6.436246484247782 x 10^-11
BA-BB	6.600860457544379 x 10^-10 - 6.039343615251231 x 10^-10	5.615168422931481 x 10^-11
BB-CA	6.039343615251231 x 10^-10 - 5.546558194453195 x 10^-10	4.927854207980365 x 10^-11
CA-CB	5.546558194453195 x 10^-10 - 5.111700635594404 x 10^-10	4.348575588587904 x 10^-11
CB-D	5.111700635594404 x 10^-10 - 4.726057228765738 x 10^-10	3.856434068286667 x 10^-11
D-E	4.726057228765738 x 10^-10 - 4.075022470371456 x 10^-10	6.510347583942819 x 10^-11
E-F	4.075022470371456 x 10^-10 - 3.549798503121997 x 10^-10	5.252239672494590 x 10^-11
F-G	3.549798503121997 x 10^-10 - 3.119939065978542 x 10^-10	4.298594371434549 x 10^-11
G-H	3.119939065978542 x 10^-10 - 2.763683389711476 x 10^-10	3.562556762670661 x 10^-11

H-I	2.763683389711476 x 10^-10 - 2.465134287561701 x 10^-10	2.985491021497748 x 10^-11
I-J	2.465134287561701 x 10^-10 - 2.212474609194942 x 10^-10	2.526596783667591 x 10^-11
J-K	2.212474609194942 x 10^-10 - 1.996760162940389 x 10^-10	2.157144462545529 x 10^-11
K-L	1.996760162940389 x 10^-10 -1.811119154353903 x 10^-10	1.856410085864861 x 10^-11
L-M	1.811119154353903 x 10^-10 - 1.650214380420531 x 10^-10	1.609047739333721 x 10^-11
M-N	1.650214380420531 x 10^-10 - 1.509838001646407 x 10^-10	1.403763787741238 x 10^-11
N-O	1.509838001646407 x 10^-10 - 1.386638199359019 x 10^-10	1.231998022873881 x 10^-11
O-P	1.386638199359019 x 10^-10 - 1.277927041424811 x 10^-10	1.087111579342080 x 10^-11
P-Q	1.277927041424811 x 10^-10 - 1.181514887804750 x 10^-10	9.641215362006097 x 10^-12
Q-R	1.181514887804750 x 10^-10 - 1.095616433472236 x 10^-10	8.589845433251408 x 10^-12
R-S	1.095616433472236 x 10^-10 - 1.018755216926332 x 10^-10	7.686121654590390 x 10^-12
S-T	1.018755216926332 x 10^-10 - 9.497079927116147 x 10^-11	6.904722421471730 x 10^-12
T-U	9.497079927116147 x 10^-11 - 8.874488914958372 x 10^-11	6.225910121577758 x 10^-12
U-V	8.874488914958372 x 10^-11 - 4.991900847971677 x 10^-11	3.882588066986695 x 10^-12
V-W	4.991900847971677 x 10^-11 - 3.194816315548408 x 10^-11	1.797084532423269 x 10^-12
W-X	3.194816315548408 x 10^-11 - 2.218621897457171 x 10^-11	9.761944180912373 x 10^-12
X-Y	2.218621897457171 x 10^-11 - 1.630007399664216 x 10^-11	5.886144977929551 x 10^-12
Y-Z	1.630007399664216 x 10^-11 - 1.247975101837743 x 10^-11	3.820322978264729 x 10^-12

Z	1.247975101837743 x 10^-11 - 0 *(We have not calculated for larger UV limit wavelengths)*	1.247975101837743 x 10^-11

Calculation of the loss by intervals and calculation of the total loss.

Now, we calculate the loss by applying the percentages *(the loss percentages have been calculated for each specific wavelength, not for the interval between two values. Therefore, to define the range of total loss, we will first use the percentages starting from each UV limit and then up to that limit, which will give us a minimum and maximum estimate, ensuring that the actual loss lies between these two values)* In the last row, where it says "total," the sum of all losses will be displayed.

	Energy density difference *(J/M3)*	% loss *(max)*	Pérdida *(max)*	% pérdida *(min)*	Pérdida *(min)*
AA-AB	1.573629374605140 x 10^-11	0,99%	1.557893080859088 x 10^-12	0%	0
AB-AC	5.851837588806392 x 10^-11	4,76%	2.785474692271842 x 10^-12	0,99%	5.793319212918327
AC-BA	6.436246484247782 x 10^-11	9,09%	5.850548054181233 x 10^-12	4,76	3.063653326501944
BA-BB	5.615168422931481 x 10^-11	13,04%	7.322179623502650 x 10^-12	9,09%	5.104188096444716
BB-CA	4.927854207980365 x 10^-11	16,67%	8.214732964703270 x 10^-12	13,04 %	6.425921887206396
CA-CB	4.348575588587904 x 10^-11	20%	8.697151177175807 x 10^-12	16,67 %	7.249075506176036
CB-D	3.856434068286667 x 10^-11	23,08%	8.900649829605626 x 10^-12	20%	7.712868136573333
D-E	6.510347583942819 x 10^-11	28,57%	1.860006304732463 x 10^-11	23,08 %	1.502588222374003
E-F	5.252239672494590 x 10^-11	33,33%	1.750571482842447 x 10^-11	28,57 %	1.500564874431705
F-G	4.298594371434549 x	37,5%	1.61197288928795	33,33	1.432721503999

	10^-11		6 x 10^-11	%	135
G-H	3.562556762670661 x 10^-11	41,18%	1.467060874867778 x 10^-11	37,5%	1.335958786001498
H-I	2.985491021497748 x 10^-11	44,44%	1.326752209953599 x 10^-11	41,18%	1.229425202652773
I-J	2.526596783667591 x 10^-11	47,37%	1.196848896423338 x 10^-11	44,44%	1.122819610661877
J-K	2.157144462545529 x 10^-11	50%	1.078572231272765 x 10^-11	47,37%	1.021839331907817
K-L	1.856410085864861 x 10^-11	52,38%	9.723876029760141 x 10^-12	50%	9.282050429324303
L-M	1.609047739333721 x 10^-11	54,55%	8.777355418065446 x 10^-12	52,38%	8.428192058630029
M-N	1.403763787741238 x 10^-11	56,52%	7.934072928313477 x 10^-12	54,55%	7.657531462128453
N-O	1.231998022873881 x 10^-11	58,33%	7.186244467423348 x 10^-12	56,52%	6.963252825283177
O-P	1.087111579342080 x 10^-11	60%	6.522669476052480 x 10^-12	58,33%	6.341121842302352
P-Q	9.641215362006097 x 10^-12	61,54%	5.933203933778552 x 10^-12	60%	5.784729217203658
Q-R	8.589845433251408 x 10^-12	62,96%	5.408166684775087 x 10^-12	61,54%	5.286190879622916
R-S	7.686121654590390 x 10^-12	64,29%	4.941407611736162 x 10^-12	62,96%	4.839182193730110
S-T	6.904722421471730 x 10^-12	65,52%	4.523974130548278 x 10^-12	64,29%	4.439046044764176
T-U	6.225910121577758 x 10^-12	66,67%	4.150814278055892 x 10^-12	65,52%	4.079216311657747
U-V	3.882588066986695 x 10^-12	75%	2.911941050240021 x 10^-11	66,67%	2.588521464260030
V-W	1.797084532423269 x 10^-12	80%	1.437667625938615 x 10^-11	75%	1.347813399317451
W-X	9.761944180912373 x 10^-12	83,33%	8.134628085954279 x 10^-12	80%	7.809555344729898
X-Y	5.886144977929551 x	85,71%	5.04501486058341	83,33	4.904924610108

	10^-12		8 x 10^-12	%	695
Y-Z	3.820322978264729 x 10^-12	87,5%	3.342782605981638 x 10^-12	85,71 %	3.274398824670699
Z	1.247975101837743 x 10^-11	90% *1	1.0849147109328618 x 10^-11	90% *1	1.0849147109328618 x 10^-11
TOTAL	—---------------------------	—--------	2.8081 x 10^-10	—--------	2.5090 x 10^-10

Since the loss is between the minimum and maximum values calculated, we take their average as a reasonable estimate of the total real loss.

$$\frac{2.8081\, x\, 10\text{^}{-10} + 2.5090\, x\, 10\text{^}{-10}}{2} = 2.65855\ *\ 10^{-10}$$

Since the electromagnetic field consists of two independent fields — the electric field and the magnetic field — and both exhibit quantum fluctuations of the same nature and behavior with respect to the contour, the total energy loss must consider the contribution of each separately. Therefore, the estimated loss obtained is multiplied by 2 to reflect the combined loss of the complete electromagnetic field.

$$(2.65855\ *\ 10^{-10})\ *\ 2\ =\ 5.3171\ *\ 10^{-10}10$$

A result very similar to the dark energy density estimation.

**1 It has been approximated with a 90%. From the UV limit wavelength corresponding to that density, 87.5% is lost, and with each step, there is an increasing percentage of loss. It could be calculated with another value between 87.5% and 100% of loss, but the difference would not be significant.*

7. Conclusions and Predictions

The Contour Theory solves the problem of the cosmological constant by proposing that observable dark energy is the net energy residual resulting from the difference between two opposing fields of equal energy magnitude: the dark energy field with negative pressure, and the quantum fluctuations field with positive pressure. Both fields have an energy density in ideal conditions on the order of 10^113 J/m3.

Only one untested assumption has been made, the quantization of spacetime in Planck lengths, but the fact that its inclusion produces an exact result consistent with observations cannot be attributed to chance. Therefore, this result can be considered an indirect proof that space is indeed quantized in Planck lengths.

The difference between both fields arises because the quantum fluctuations field is restricted by boundary conditions, imposed by the finite size of the observable universe and causality limited by the speed of light. This boundary defines which quantum modes are physically realizable, while the dark energy field is unaffected by these restrictions. The resulting difference coincides with the observed dark energy density:

Net dark energy =brute dark energy - quantum fluctuation of electromagnetic fields = 5,3 x 10^-10 J/m3

Although this difference is extremely precise and stable on a cosmic scale, it is proposed that boundary conditions may also be locally affected by matter clusters, which act as cavities that further restrict quantum modes. While the global effect of matter is negligible compared to the volume of the universe, on local scales, it could introduce minute fluctuations in the effective energy density, generating slight variations in the local expansion of space.

This phenomenon could be linked to the Hubble tension, i.e., the discrepancy observed between different measurements of the Hubble constant. The existence of regions where boundary conditions vary due to matter density could partially explain why different values of expansion are obtained depending on the scale or the observed environment.

A natural prediction derived from this theory is that the net dark energy density could slightly decrease over time. As the causal horizon grows, it allows quantum fluctuations to access an increasing number of modes. This implies that its effective energy will progressively increase, approaching the value of the dark energy field, which remains constant. Although this variation would be extremely slow and small due to the cosmic scale of the process, it could, in principle, be detected with sufficiently precise observations over cosmological time scales.

In conclusion, the Boundary Theory not only provides a natural and parameter-free solution to the fine-tuning of the cosmological constant but also offers a unifying framework to interpret current observational phenomena such as the Hubble tension, a prediction, and reinforces the evidence for a discrete structure of spacetime.

References and Python Calculation Notebook

https://en.wikipedia.org/wiki/Observable_universe

https://www.youtube.com/watch?v=Cu5LUAhzmNM&ab_channel=QuantumFracture

https://colab.research.google.com/drive/1wYHLN0UzEZYhFB2wp3Q6iVTDGaxhXIrY?usp=sharing Calculation of the energy density for each UV limit (including both intervals).

https://colab.research.google.com/drive/1W5K-MhTtZ1WqDR5otDu1Ns1PrN3nVHf1?usp=sharing Calculation of the wavelengths (including both intervals)

https://colab.research.google.com/drive/11hZFx6yA3MV9yMYQkimqDaelRA-qMCO-?usp=sharing Remaining calculation for the intervals represented in the document.

https://colab.research.google.com/drive/19emrN0wiP0avahHhLLCQAq2VAXQik5Mw?usp=sharing Remaining calculation for the intervals not represented in the document.