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Suppression of Quantum Vacuum Energy Modes by Cosmological Boundary Conditions: A Numerical Coincidence with Dark Energy Density and its evolution

Iker Padilla Muñoz

E-mail: padillamunoz.iker@gmail.com

Abstract. We show that when standard quantum vacuum fluctuations are subjected to boundary conditions imposed by a finite causal universe, specifically the region accessible since the time of recombination, bounded by the distance to the cosmic microwave background (CMB) at ∼45.7 billion light-years ($\sim 8.65 \times 10^{26}$ m) and assuming a discretized space structure at the Planck length scale ($\sim 1.616 \times 10^{-35}$ m), the resulting suppression of vacuum modes leads to an effective energy deficit. This deficit closely matches the observed dark energy density in the present ($\sim 5.3 \times 10^{-10}$ J/m^3) and the evolution in the past for different redshifts, without introducing any free parameters or exotic new physics. The calculation builds on established physical principles such as the Casimir effect and relativistic causality. Although this article does not aim to explain dark energy, the observed numerical coincidence suggests a possible connection between suppressed quantum vacuum fluctuations and dark-energy density.

Contents

1 Introduction

The cosmological constant problem represents a major inconsistency between quantum field theory (QFT) and observational cosmology. The vacuum energy density predicted by QFT per field is on the order of $\sim 10^{113}$ J/m^3, whereas the observed dark energy density is approximately $\sim 5.3 \times 10^{-10}$ J/m^3, differing by $\sim$120 orders of magnitude. In this work, we will calculate the deficit, compared to a spectrum without boundary conditions, of a spectrum discretized by the causal universe's boundary conditions. We will then compare this deficit with the currently observed dark-energy density and the calculated values from DESI+CMB for different redshifts when the universe was dominated by dark-energy.

2 Conceptual Basis

Quantum fluctuations of the electromagnetic field exist, are discretized by boundary conditions (only stationary waves can exist[1]), and interact with matter, as demonstrated in the Casimir effect. These fluctuations are subject to boundary conditions defined by the finite causal horizon since recombination (when electromagnetic waves began to propagate freely)—the observable universe in terms of the CMB radius. This restricts the number of permissible vacuum modes, producing a measurable energy deficit compared to an ideal (infinite) mode spectrum.
To calculate the energy deficit compared to a continuous unbounded spectrum, we need to discretize space in multiples of the Planck length. Therefore, if the difference between the wavelengths allowed by the boundary conditions is smaller than the Planck length, no loss is assumed. As the difference increases, intermediate modes get lost since there are no wavelengths corresponding to all different Planck lengths, and the loss becomes greater. It is important to note that Planck-scale space discretization enables the calculation of the loss, but the loss itself originates solely from the boundary conditions. Only quantum fluctuations of the electromagnetic field are computed, as massive fields cannot exceed wavelengths of 140 µm, and the gluon field is confined in glueballs that also do not exceed 140 µm in wavelength. In both cases, their bounded and unbounded spectra are identical.
Neutrinos, though massive, can exhibit nearly infinite wavelengths but interact negligibly with matter and thus were not constrained by the electrons in the opaque phase of the universe. The same applies to hypothetical fields such as the graviton, axion, and dark photon.

3 Methodology

The procedure consists of calculating, within the defined boundary, the points at which the spacing between consecutive wavelengths reaches a specific multiple of the Planck length. These wavelengths are then used as ultraviolet cutoffs to compute the corresponding energy density.

We will calculate the deficit for 4 different redshifts: z=0, z=0.1, z=0.2, z=0.3. For each redshift, we will have to multiply the CMB radius by the scale factor to obtain L. The CMB radius at z=0 is [2]:

$$8.6473 \times 10^{26} \text{ m} \tag{3.1}$$

The wavelength λ_n for which the difference between two consecutive modes $\lambda_{n+1} - \lambda_n$ equals a specified multiple $\Delta\lambda$ of the Planck length is given by:

$$n = \sqrt{\frac{2L}{\Delta\lambda \ell_P}} \tag{3.2}$$

$$\lambda_n = \frac{2L}{n} \tag{3.3}$$

where L is the radius of the CMB for each redshift and ℓ_P is the Planck length.

The percentage of modes suppressed for each difference between allowed wavelengths is:

$$\%_{\text{lost}} = \frac{\Delta\lambda - 1}{\Delta\lambda} \times 100 \tag{3.4}$$

The energy density for each UV cutoff is calculated as follows:

$$\omega = \frac{2\pi c}{\lambda}, \rho = \frac{\hbar\omega^4}{8\pi^2 c^3} \tag{3.5}$$

Then we calculate the energy density in each interval by calculating the difference between consecutive UV limits and applying the percentages calculated above for each UV limit. Since the percentage is calculated based on a specific difference between allowed wavelengths and not for a full interval, we calculate two versions: one applying the maximum percentage loss for the interval and another applying the minimum percentage loss. In this way, a possible range for the lost energy density is obtained (the actual value must lie between both). Finally, it is multiplied by two to account for the four components of the virtual photon (since the initial calculation is done for only 2).

To compare with the values from DESI+CMB we use the ratio between the dark energy density at redshift z and its present value (ρ_{DE0}) is given by [3]:

$$\frac{\rho_{\text{DE}}(z)}{\rho_{\text{DE0}}} = (1+z)^{3(1+w_0+w_a)} \exp\left(-3w_a \frac{z}{1+z}\right). \tag{3.6}$$

Where [4]:

$$w_0 = -0.42 \pm 0.21$$

$$w_a = -1.75 \pm 0.58$$

The final result is multiplied by the central value of the density obtained for z=0 to compare the evolution.

4 Results

For z = 0:
The cumulative energy loss due to the results of the mode suppression:

$$\rho_{\text{lost}} = (5.3341 \pm 0.315) \times 10^{-10}\ \text{J/m}^3 \tag{4.1}$$

matching the observed dark-energy density:

$$\rho_{\Lambda} = 5.3 \times 10^{-10}\ \text{J/m}^3 \tag{4.2}$$

For z = 0.1:
The cumulative energy loss due to the results of the mode suppression:

$$\rho_{\text{lost}} = (6.45 \pm 0.362) \times 10^{-10}\ \text{J/m}^3 \tag{4.3}$$

within the estimation ranges reported by DESI+CMB:

$$\rho_{\text{lost}} = (6.16 \pm 0.417) \times 10^{-10}\ \text{J/m}^3 \tag{4.4}$$

For z = 0.2:
The cumulative energy loss due to the results of the mode suppression:

$$\rho_{\text{lost}} = (7.69 \pm 0.454) \times 10^{-10}\ \text{J/m}^3 \tag{4.5}$$

within the estimation ranges reported by DESI+CMB:

$$\rho_{\text{lost}} = (6.81 \pm 0.962) \times 10^{-10}\ \text{J/m}^3 \tag{4.6}$$

For z = 0.3:
The cumulative energy loss due to the results of the mode suppression:

$$\rho_{\text{lost}} = (9.019 \pm 0.532) \times 10^{-10}\ \text{J/m}^3 \tag{4.7}$$

within the estimation ranges reported by DESI+CMB:

$$\rho_{\text{lost}} = (7.31 \pm 1.584) \times 10^{-10}\ \text{J/m}^3 \tag{4.8}$$

The precision of the estimated energy loss due to mode suppression could be further enhanced. This would involve calculating with a greater number of intervals. It is anticipated that as the number of intervals increases, the calculated energy loss would tend to decrease. This is attributed to the fact that the energy density for each ultraviolet cutoff decreases with the fourth power of the wavelength ($\rho \propto \omega^4 \propto \lambda^{-4}$), whereas the percentage of lost modes does not increase at a commensurate rate.

5 Conclusion

The near-exact numerical match between the energy lost due to vacuum mode suppression and the observed value of dark energy density at $z = 0$ is striking, and suggests that cosmological boundary conditions could play a key role in both the magnitude and evolution of dark energy density. It could also suggest that, at least in this context, Planck-scale discretization might be possible, as it is the only assumption made and leads to an almost exact agreement with the observed result. Furthermore, the evolution of this suppressed energy density with redshift remains fully consistent with current observational constraints from DESI and CMB data in the range $z = 0.1$–0.3. This strengthens the idea that the match may not be a coincidence, as it reproduces not only present-day values but also those from the past, without introducing any arbitrary parameters. The model relies on well-established and experimentally tested principles such as the Casimir effect and includes only one unproven but plausible assumption: the quantization of spaceat the Planck length scale. Thus, it not only predicts the evolution of dark energy density, but also provides a direct link between quantum vacuum fluctuations and the nature and density of dark energy. According to these calculations, the dark energy density matches the energy density deficit resulting from the suppression of vacuum modes, compared to an infinite continuous spectrum with no boundary conditions.

Appendix: Calculations

For $z = 0$

$$\mathrm{L} = 8.6473 \times 10^{26}\ \mathrm{m} \tag{.1}$$

$\Delta\lambda$	**Interval** λ **[**μ**m]**	**% loss**	$\rho_1 - \rho_2$ **[J/m^3]**	$\Delta\rho$ **[J/m^3]**	$\rho_{\text{loss,max}}$	$\rho_{\text{loss,min}}$
1.00–1.01	167.19–168.02	0.00%–0.99%	$7.99\times10^{-10} - 7.83\times10^{-10}$	1.57×10^{-11}	1.56×10^{-13}	0
1.01–1.05	168.02–171.32	0.99%–4.76%	$7.83\times10^{-10} - 7.24\times10^{-10}$	5.85×10^{-11}	2.79×10^{-12}	5.79×10^{-13}
1.05–1.10	171.32–175.35	4.76%–9.09%	$7.24\times10^{-10} - 6.60\times10^{-10}$	6.44×10^{-11}	5.85×10^{-12}	3.06×10^{-12}
1.10–1.15	175.35–179.29	9.09%–13.04%	$6.60\times10^{-10} - 6.04\times10^{-10}$	5.61×10^{-11}	7.32×10^{-12}	5.10×10^{-12}
1.15–1.20	179.29–183.15	13.04%–16.67%	$6.04\times10^{-10} - 5.55\times10^{-10}$	4.93×10^{-11}	8.21×10^{-12}	6.43×10^{-12}
1.20–1.25	183.15–186.92	16.67%–20.00%	$5.55\times10^{-10} - 5.11\times10^{-10}$	4.35×10^{-11}	8.70×10^{-12}	7.25×10^{-12}
1.25–1.30	186.92–190.63	20.00%–23.08%	$5.11\times10^{-10} - 4.73\times10^{-10}$	3.86×10^{-11}	8.90×10^{-12}	7.71×10^{-12}
1.30–1.40	190.63–197.82	23.08%–28.57%	$4.73\times10^{-10} - 4.08\times10^{-10}$	6.51×10^{-11}	1.86×10^{-11}	1.50×10^{-11}
1.40–1.50	197.82–204.77	28.57%–33.33%	$4.08\times10^{-10} - 3.55\times10^{-10}$	5.25×10^{-11}	1.75×10^{-11}	1.50×10^{-11}
1.50–1.60	204.77–211.48	33.33%–37.50%	$3.55\times10^{-10} - 3.12\times10^{-10}$	4.30×10^{-11}	1.61×10^{-11}	1.43×10^{-11}
1.60–1.70	211.48–217.99	37.50%–41.18%	$3.12\times10^{-10} - 2.76\times10^{-10}$	3.56×10^{-11}	1.47×10^{-11}	1.34×10^{-11}
1.70–1.80	217.99–224.31	41.18%–44.44%	$2.76\times10^{-10} - 2.47\times10^{-10}$	2.99×10^{-11}	1.33×10^{-11}	1.23×10^{-11}
1.80–1.90	224.31–230.46	44.44%–47.37%	$2.47\times10^{-10} - 2.21\times10^{-10}$	2.53×10^{-11}	1.20×10^{-11}	1.12×10^{-11}
1.90–2.00	230.46–236.44	47.37%–50.00%	$2.21\times10^{-10} - 2.00\times10^{-10}$	2.16×10^{-11}	1.08×10^{-11}	1.02×10^{-11}
2.00–2.10	236.44–242.28	50.00%–52.38%	$2.00\times10^{-10} - 1.81\times10^{-10}$	1.86×10^{-11}	9.72×10^{-12}	9.28×10^{-12}
2.10–2.20	242.28–247.98	52.38%–54.55%	$1.81\times10^{-10} - 1.65\times10^{-10}$	1.61×10^{-11}	8.78×10^{-12}	8.43×10^{-12}
2.20–2.30	247.98–253.56	54.55%–56.52%	$1.65\times10^{-10} - 1.51\times10^{-10}$	1.40×10^{-11}	7.93×10^{-12}	7.66×10^{-12}
2.30–2.40	253.56–259.01	56.52%–58.33%	$1.51\times10^{-10} - 1.39\times10^{-10}$	1.23×10^{-11}	7.19×10^{-12}	6.96×10^{-12}
2.40–2.50	259.01–264.35	58.33%–60.00%	$1.39\times10^{-10} - 1.28\times10^{-10}$	1.09×10^{-11}	6.52×10^{-12}	6.34×10^{-12}
2.50–2.60	264.35–269.59	60.00%–61.54%	$1.28\times10^{-10} - 1.18\times10^{-10}$	9.64×10^{-12}	5.93×10^{-12}	5.78×10^{-12}
2.60–2.70	269.59–274.72	61.54%–62.96%	$1.18\times10^{-10} - 1.10\times10^{-10}$	8.59×10^{-12}	5.41×10^{-12}	5.29×10^{-12}
2.70–2.80	274.72–279.76	62.96%–64.29%	$1.10\times10^{-10} - 1.02\times10^{-10}$	7.69×10^{-12}	4.94×10^{-12}	4.84×10^{-12}
2.80–2.90	279.76–284.71	64.29%–65.52%	$1.02\times10^{-10} - 9.50\times10^{-11}$	6.90×10^{-12}	4.52×10^{-12}	4.44×10^{-12}
2.90–3.00	284.71–289.58	65.52%–66.67%	$9.50\times10^{-11} - 8.87\times10^{-11}$	6.23×10^{-12}	4.15×10^{-12}	4.08×10^{-12}
3.00–4.00	289.58–334.38	66.67%–75.00%	$8.87\times10^{-11} - 4.99\times10^{-11}$	3.88×10^{-11}	2.91×10^{-11}	2.59×10^{-11}
4.00–5.00	334.38–373.85	75.00%–80.00%	$4.99\times10^{-11} - 3.19\times10^{-11}$	1.80×10^{-11}	1.44×10^{-11}	1.35×10^{-11}
5.00–6.00	373.85–409.53	80.00%–83.33%	$3.19\times10^{-11} - 2.22\times10^{-11}$	9.76×10^{-12}	8.13×10^{-12}	7.81×10^{-12}
6.00–7.00	409.53–442.34	83.33%–85.71%	$2.22\times10^{-11} - 1.63\times10^{-11}$	5.89×10^{-12}	5.05×10^{-12}	4.90×10^{-12}
7.00–8.00	442.34–472.88	85.71%–87.50%	$1.63\times10^{-11} - 1.25\times10^{-11}$	3.82×10^{-12}	3.34×10^{-12}	3.27×10^{-12}
8.00–∞	472.88–∞	87.50%–100%	1.25×10^{-11} - 0	1.25×10^{-11}	1.25×10^{-11}	1.09×10^{-11}

$$\left(\frac{\rho_{\text{ loss,max\_total}} + \rho_{\text{ loss,min\_total}}}{2}\right) \times 2 = (5.3341 \pm 0.315) \times 10^{-10}\ J/m^3$$

For $z = 0.1$

$$L = \frac{8.6473 \times 10^{26}}{1.1} \approx 7.86 \times 10^{26} \text{ m} \tag{.2}$$

$\Delta\lambda$	**Interval λ [μm]**	**% loss**	$\rho_1 - \rho_2$ **[J/m^3]**	$\Delta\rho$ **[J/m^3]**	$\rho_{\text{loss,max}}$	$\rho_{\text{loss,min}}$
1.00–1.01	159.40–160.19	0.00%–0.99%	$9.67\times10^{-10}-9.48\times10^{-10}$	1.90×10^{-11}	1.89×10^{-13}	0
1.01–1.05	160.19–163.33	0.99%–4.76%	$9.48\times10^{-10}-8.77\times10^{-10}$	7.08×10^{-11}	3.37×10^{-12}	7.01×10^{-13}
1.05–1.10	163.33–167.18	4.76%–9.09%	$8.77\times10^{-10}-7.99\times10^{-10}$	7.79×10^{-11}	7.08×10^{-12}	3.71×10^{-12}
1.10–1.15	167.18–170.93	9.09%–13.04%	$7.99\times10^{-10}-7.31\times10^{-10}$	6.80×10^{-11}	8.86×10^{-12}	6.18×10^{-12}
1.15–1.20	170.93–174.61	13.04%–16.67%	$7.31\times10^{-10}-6.71\times10^{-10}$	5.96×10^{-11}	9.94×10^{-12}	7.78×10^{-12}
1.20–1.25	174.61–178.21	16.67%–20.00%	$6.71\times10^{-10}-6.19\times10^{-10}$	5.26×10^{-11}	1.05×10^{-11}	8.77×10^{-12}
1.25–1.30	178.21–181.74	20.00%–23.08%	$6.19\times10^{-10}-5.72\times10^{-10}$	4.67×10^{-11}	1.08×10^{-11}	9.34×10^{-12}
1.30–1.40	181.74–188.60	23.08%–28.57%	$5.72\times10^{-10}-4.93\times10^{-10}$	7.88×10^{-11}	2.25×10^{-11}	1.82×10^{-11}
1.40–1.50	188.60–195.22	28.57%–33.33%	$4.93\times10^{-10}-4.30\times10^{-10}$	6.36×10^{-11}	2.12×10^{-11}	1.82×10^{-11}
1.50–1.60	195.22–201.62	33.33%–37.50%	$4.30\times10^{-10}-3.78\times10^{-10}$	5.20×10^{-11}	1.95×10^{-11}	1.73×10^{-11}
1.60–1.70	201.62–207.83	37.50%–41.18%	$3.78\times10^{-10}-3.35\times10^{-10}$	4.31×10^{-11}	1.78×10^{-11}	1.62×10^{-11}
1.70–1.80	207.83–213.85	41.18%–44.44%	$3.35\times10^{-10}-2.98\times10^{-10}$	3.61×10^{-11}	1.61×10^{-11}	1.49×10^{-11}
1.80–1.90	213.85–219.71	44.44%–47.37%	$2.98\times10^{-10}-2.68\times10^{-10}$	3.06×10^{-11}	1.45×10^{-11}	1.36×10^{-11}
1.90–2.00	219.71–225.42	47.37%–50.00%	$2.68\times10^{-10}-2.42\times10^{-10}$	2.61×10^{-11}	1.31×10^{-11}	1.24×10^{-11}
2.00–2.10	225.42–230.99	50.00%–52.38%	$2.42\times10^{-10}-2.19\times10^{-10}$	2.25×10^{-11}	1.18×10^{-11}	1.12×10^{-11}
2.10–2.20	230.99–236.42	52.38%–54.55%	$2.19\times10^{-10}-2.00\times10^{-10}$	1.95×10^{-11}	1.06×10^{-11}	1.02×10^{-11}
2.20–2.30	236.42–241.74	54.55%–56.52%	$2.00\times10^{-10}-1.83\times10^{-10}$	1.70×10^{-11}	9.60×10^{-12}	9.27×10^{-12}
2.30–2.40	241.74–246.94	56.52%–58.33%	$1.83\times10^{-10}-1.68\times10^{-10}$	1.49×10^{-11}	8.70×10^{-12}	8.43×10^{-12}
2.40–2.50	246.94–252.03	58.33%–60.00%	$1.68\times10^{-10}-1.55\times10^{-10}$	1.32×10^{-11}	7.89×10^{-12}	7.68×10^{-12}
2.50–2.60	252.03–257.02	60.00%–61.54%	$1.55\times10^{-10}-1.43\times10^{-10}$	1.17×10^{-11}	7.18×10^{-12}	7.00×10^{-12}
2.60–2.70	257.02–261.92	61.54%–62.96%	$1.43\times10^{-10}-1.33\times10^{-10}$	1.04×10^{-11}	6.55×10^{-12}	6.40×10^{-12}
2.70–2.80	261.92–266.72	62.96%–64.29%	$1.33\times10^{-10}-1.23\times10^{-10}$	9.30×10^{-12}	5.98×10^{-12}	5.86×10^{-12}
2.80–2.90	266.72–271.44	64.29%–65.52%	$1.23\times10^{-10}-1.15\times10^{-10}$	8.36×10^{-12}	5.48×10^{-12}	5.37×10^{-12}
2.90–3.00	271.44–276.08	65.52%–66.67%	$1.15\times10^{-10}-1.07\times10^{-10}$	7.54×10^{-12}	5.02×10^{-12}	4.94×10^{-12}
3.00–4.00	276.08–318.79	66.67%–75.00%	$1.07\times10^{-10}-6.04\times10^{-11}$	4.70×10^{-11}	3.52×10^{-11}	3.13×10^{-11}
4.00–5.00	318.79–356.42	75.00%–80.00%	$6.04\times10^{-11}-3.87\times10^{-11}$	2.18×10^{-11}	1.74×10^{-11}	1.63×10^{-11}
5.00–6.00	356.42–390.44	80.00%–83.33%	$3.87\times10^{-11}-2.69\times10^{-11}$	1.18×10^{-11}	9.85×10^{-12}	9.45×10^{-12}
6.00–7.00	390.44–421.73	83.33%–85.71%	$2.69\times10^{-11}-1.97\times10^{-11}$	7.12×10^{-12}	6.11×10^{-12}	5.94×10^{-12}
7.00–8.00	421.73–450.84	85.71%–87.50%	$1.97\times10^{-11}-1.51\times10^{-11}$	4.62×10^{-12}	4.05×10^{-12}	3.96×10^{-12}
8.00–∞	450.84–∞	87.50%–100%	1.51×10^{-11} - 0	1.51×10^{-11}	1.51×10^{-11}	1.32×10^{-11}

$$\left(\frac{\rho_{\text{ loss,max\_total}} + \rho_{\text{ loss,min\_total}}}{2}\right) \times 2 = (6.45 \pm 0.362) \times 10^{-10}\ J/m^3$$

$$\rho_{\text{DE}}(0.1) = (5.3341 \times 10^{-10}) \cdot (1+0.1)^{3(1+(-0.42\pm0.21)+(-1.75\pm0.58))} \exp\left(-3(-1.75 \pm 0.58)\frac{0.1}{1+0.1}\right) = (6.16 \pm 0.417) \times 10^{-10} \text{ J/m}^3 \tag{.3}$$

For $z = 0.2$

$$L = \frac{8.6473 \times 10^{26}}{1.2} \approx 7.20 \times 10^{26} \text{ m} \tag{.4}$$

$\Delta\lambda$	**Interval λ [μm]**	**% loss**	$\rho_1 - \rho_2$ **[J/m^3]**	$\Delta\rho$ **[J/m^3]**	$\rho_{\text{loss,max}}$	$\rho_{\text{loss,min}}$
1.00–1.01	152.56–153.32	0.00%–0.99%	$1.15 \times 10^{-9} - 1.13 \times 10^{-9}$	2.27×10^{-11}	2.25×10^{-13}	0
1.01–1.05	153.32–156.33	0.99%–4.76%	$1.13 \times 10^{-9} - 1.04 \times 10^{-9}$	8.44×10^{-11}	4.02×10^{-12}	8.36×10^{-13}
1.05–1.10	156.33–160.00	4.76%–9.09%	$1.04 \times 10^{-9} - 9.52 \times 10^{-10}$	9.28×10^{-11}	8.44×10^{-12}	4.42×10^{-12}
1.10–1.15	160.00–163.60	9.09%–13.04%	$9.52\times10^{-10} - 8.71\times10^{-10}$	8.10×10^{-11}	1.06×10^{-11}	7.36×10^{-12}
1.15–1.20	163.60–167.12	13.04%–16.67%	$8.71\times10^{-10} - 8.00\times10^{-10}$	7.11×10^{-11}	1.18×10^{-11}	9.27×10^{-12}
1.20–1.25	167.12–170.57	16.67%–20.00%	$8.00\times10^{-10} - 7.37\times10^{-10}$	6.27×10^{-11}	1.25×10^{-11}	1.05×10^{-11}
1.25–1.30	170.57–173.94	20.00%–23.08%	$7.37\times10^{-10} - 6.82\times10^{-10}$	5.56×10^{-11}	1.28×10^{-11}	1.11×10^{-11}
1.30–1.40	173.94–180.51	23.08%–28.57%	$6.82\times10^{-10} - 5.88\times10^{-10}$	9.39×10^{-11}	2.68×10^{-11}	2.17×10^{-11}
1.40–1.50	180.51–186.85	28.57%–33.33%	$5.88\times10^{-10} - 5.12\times10^{-10}$	7.58×10^{-11}	2.53×10^{-11}	2.16×10^{-11}
1.50–1.60	186.85–192.97	33.33%–37.50%	$5.12\times10^{-10} - 4.50\times10^{-10}$	6.20×10^{-11}	2.33×10^{-11}	2.07×10^{-11}
1.60–1.70	192.97–198.91	37.50%–41.18%	$4.50\times10^{-10} - 3.99\times10^{-10}$	5.14×10^{-11}	2.12×10^{-11}	1.93×10^{-11}
1.70–1.80	198.91–204.68	41.18%–44.44%	$3.99\times10^{-10} - 3.56\times10^{-10}$	4.31×10^{-11}	1.91×10^{-11}	1.77×10^{-11}
1.80–1.90	204.68–210.29	44.44%–47.37%	$3.56\times10^{-10} - 3.19\times10^{-10}$	3.64×10^{-11}	1.73×10^{-11}	1.62×10^{-11}
1.90–2.00	210.29–215.75	47.37%–50.00%	$3.19\times10^{-10} - 2.88\times10^{-10}$	3.11×10^{-11}	1.56×10^{-11}	1.47×10^{-11}
2.00–2.10	215.75–221.08	50.00%–52.38%	$2.88\times10^{-10} - 2.61\times10^{-10}$	2.68×10^{-11}	1.40×10^{-11}	1.34×10^{-11}
2.10–2.20	221.08–226.28	52.38%–54.55%	$2.61\times10^{-10} - 2.38\times10^{-10}$	2.32×10^{-11}	1.27×10^{-11}	1.22×10^{-11}
2.20–2.30	226.28–231.37	54.55%–56.52%	$2.38\times10^{-10} - 2.18\times10^{-10}$	2.02×10^{-11}	1.14×10^{-11}	1.10×10^{-11}
2.30–2.40	231.37–236.34	56.52%–58.33%	$2.18\times10^{-10} - 2.00\times10^{-10}$	1.78×10^{-11}	1.04×10^{-11}	1.00×10^{-11}
2.40–2.50	236.34–241.22	58.33%–60.00%	$2.00\times10^{-10} - 1.84\times10^{-10}$	1.57×10^{-11}	9.41×10^{-12}	9.15×10^{-12}
2.50–2.60	241.22–245.99	60.00%–61.54%	$1.84\times10^{-10} - 1.70\times10^{-10}$	1.39×10^{-11}	8.56×10^{-12}	8.34×10^{-12}
2.60–2.70	245.99–250.68	61.54%–62.96%	$1.70\times10^{-10} - 1.58\times10^{-10}$	1.24×10^{-11}	7.80×10^{-12}	7.63×10^{-12}
2.70–2.80	250.68–255.28	62.96%–64.29%	$1.58\times10^{-10} - 1.47\times10^{-10}$	1.11×10^{-11}	7.13×10^{-12}	6.98×10^{-12}
2.80–2.90	255.28–259.80	64.29%–65.52%	$1.47\times10^{-10} - 1.37\times10^{-10}$	9.96×10^{-12}	6.53×10^{-12}	6.40×10^{-12}
2.90–3.00	259.80–264.24	65.52%–66.67%	$1.37\times10^{-10} - 1.28\times10^{-10}$	8.98×10^{-12}	5.99×10^{-12}	5.88×10^{-12}
3.00–4.00	264.24–305.12	66.67%–75.00%	$1.28\times10^{-10} - 7.20\times10^{-11}$	5.60×10^{-11}	4.20×10^{-11}	3.73×10^{-11}
4.00–5.00	305.12–341.13	75.00%–80.00%	$7.20\times10^{-11} - 4.61\times10^{-11}$	2.59×10^{-11}	2.07×10^{-11}	1.94×10^{-11}
5.00–6.00	341.13–373.69	80.00%–83.33%	$4.61\times10^{-11} - 3.20\times10^{-11}$	1.41×10^{-11}	1.17×10^{-11}	1.13×10^{-11}
6.00–7.00	373.69–403.63	83.33%–85.71%	$3.20\times10^{-11} - 2.35\times10^{-11}$	8.49×10^{-12}	7.28×10^{-12}	7.08×10^{-12}
7.00–8.00	403.63–431.50	85.71%–87.50%	$2.35\times10^{-11} - 1.80\times10^{-11}$	5.51×10^{-12}	4.82×10^{-12}	4.72×10^{-12}
8.00–∞	431.50–∞	87.50%–100%	1.80×10^{-11} - 0	1.80×10^{-11}	1.80×10^{-11}	1.57×10^{-11}

$$\left(\frac{\rho_{\text{ loss,max\_total}} + \rho_{\text{ loss,min\_total}}}{2}\right) \times 2 = (7.69 \pm 0.454) \times 10^{-10}\ J/m^3$$

$$\rho_{\text{DE}}(0.2) = (5.3341 \times 10^{-10}) \cdot (1+0.2)^{3(1+(-0.42\pm0.21)+(-1.75\pm0.58))} \exp\left(-3(-1.75 \pm 0.58)\frac{0.2}{1+0.2}\right) = (6.81 \pm 0.962) \times 10^{-10} \text{ J/m}^3 \tag{.5}$$

For $z = 0.3$

$$L = \frac{8.6473 \times 10^{26}}{1.3} \approx 6.65 \times 10^{26} \text{ m} \tag{.6}$$

$\Delta\lambda$	**Interval** λ **[μm]**	**% loss**	$\rho_1 - \rho_2$ **[J/m^3]**	$\Delta\rho$ **[J/m^3]**	$\rho_{\text{loss,max}}$	$\rho_{\text{loss,min}}$
1.00–1.01	146.62–147.35	0.00%–0.99%	$1.35\times10^{-9} - 1.32\times10^{-9}$	2.66×10^{-11}	2.63×10^{-13}	0
1.01–1.05	147.35–150.24	0.99%–4.76%	$1.32\times10^{-9} - 1.22\times10^{-9}$	9.89×10^{-11}	4.71×10^{-12}	9.80×10^{-13}
1.05–1.10	150.24–153.77	4.76%–9.09%	$1.22\times10^{-9} - 1.12\times10^{-9}$	1.09×10^{-10}	9.89×10^{-12}	5.18×10^{-12}
1.10–1.15	153.77–157.23	9.09%–13.04%	$1.12\times10^{-9} - 1.02\times10^{-9}$	9.49×10^{-11}	1.24×10^{-11}	8.63×10^{-12}
1.15–1.20	157.23–160.61	13.04%–16.67%	$1.02\times10^{-9} - 9.38\times10^{-10}$	8.33×10^{-11}	1.39×10^{-11}	1.09×10^{-11}
1.20–1.25	160.61–163.92	16.67%–20.00%	$9.38\times10^{-10} - 8.64\times10^{-10}$	7.35×10^{-11}	1.47×10^{-11}	1.23×10^{-11}
1.25–1.30	163.92–167.17	20.00%–23.08%	$8.64\times10^{-10} - 7.99\times10^{-10}$	6.52×10^{-11}	1.51×10^{-11}	1.30×10^{-11}
1.30–1.40	167.17–173.48	23.08%–28.57%	$7.99\times10^{-10} - 6.89\times10^{-10}$	1.10×10^{-10}	3.15×10^{-11}	2.54×10^{-11}
1.40–1.50	173.48–179.57	28.57%–33.33%	$6.89\times10^{-10} - 6.00\times10^{-10}$	8.88×10^{-11}	2.96×10^{-11}	2.54×10^{-11}
1.50–1.60	179.57–185.46	33.33%–37.50%	$6.00\times10^{-10} - 5.28\times10^{-10}$	7.27×10^{-11}	2.73×10^{-11}	2.42×10^{-11}
1.60–1.70	185.46–191.16	37.50%–41.18%	$5.28\times10^{-10} - 4.67\times10^{-10}$	6.02×10^{-11}	2.48×10^{-11}	2.26×10^{-11}
1.70–1.80	191.16–196.71	41.18%–44.44%	$4.67\times10^{-10} - 4.17\times10^{-10}$	5.05×10^{-11}	2.24×10^{-11}	2.08×10^{-11}
1.80–1.90	196.71–202.10	44.44%–47.37%	$4.17\times10^{-10} - 3.74\times10^{-10}$	4.27×10^{-11}	2.02×10^{-11}	1.90×10^{-11}
1.90–2.00	202.10–207.35	47.37%–50.00%	$3.74\times10^{-10} - 3.38\times10^{-10}$	3.65×10^{-11}	1.82×10^{-11}	1.73×10^{-11}
2.00–2.10	207.35–212.47	50.00%–52.38%	$3.38\times10^{-10} - 3.06\times10^{-10}$	3.14×10^{-11}	1.64×10^{-11}	1.57×10^{-11}
2.10–2.20	212.47–217.47	52.38%–54.55%	$3.06\times10^{-10} - 2.79\times10^{-10}$	2.72×10^{-11}	1.48×10^{-11}	1.43×10^{-11}
2.20–2.30	217.47–222.35	54.55%–56.52%	$2.79\times10^{-10} - 2.55\times10^{-10}$	2.37×10^{-11}	1.34×10^{-11}	1.29×10^{-11}
2.30–2.40	222.35–227.14	56.52%–58.33%	$2.55\times10^{-10} - 2.34\times10^{-10}$	2.08×10^{-11}	1.22×10^{-11}	1.18×10^{-11}
2.40–2.50	227.14–231.82	58.33%–60.00%	$2.34\times10^{-10} - 2.16\times10^{-10}$	1.84×10^{-11}	1.10×10^{-11}	1.07×10^{-11}
2.50–2.60	231.82–236.41	60.00%–61.54%	$2.16\times10^{-10} - 2.00\times10^{-10}$	1.63×10^{-11}	1.00×10^{-11}	9.78×10^{-12}
2.60–2.70	236.41–240.91	61.54%–62.96%	$2.00\times10^{-10} - 1.85\times10^{-10}$	1.45×10^{-11}	9.14×10^{-12}	8.94×10^{-12}
2.70–2.80	240.91–245.34	62.96%–64.29%	$1.85\times10^{-10} - 1.72\times10^{-10}$	1.30×10^{-11}	8.36×10^{-12}	8.18×10^{-12}
2.80–2.90	245.34–249.68	64.29%–65.52%	$1.72\times10^{-10} - 1.61\times10^{-10}$	1.17×10^{-11}	7.65×10^{-12}	7.51×10^{-12}
2.90–3.00	249.68–253.95	65.52%–66.67%	$1.61\times10^{-10} - 1.50\times10^{-10}$	1.05×10^{-11}	7.02×10^{-12}	6.90×10^{-12}
3.00–4.00	253.95–293.23	66.67%–75.00%	$1.50\times10^{-10} - 8.44\times10^{-11}$	6.57×10^{-11}	4.92×10^{-11}	4.38×10^{-11}
4.00–5.00	293.23–327.84	75.00%–80.00%	$8.44\times10^{-11} - 5.40\times10^{-11}$	3.04×10^{-11}	2.43×10^{-11}	2.28×10^{-11}
5.00–6.00	327.84–359.13	80.00%–83.33%	$5.40\times10^{-11} - 3.75\times10^{-11}$	1.65×10^{-11}	1.38×10^{-11}	1.32×10^{-11}
6.00–7.00	359.13–387.91	83.33%–85.71%	$3.75\times10^{-11} - 2.76\times10^{-11}$	9.95×10^{-12}	8.53×10^{-12}	8.29×10^{-12}
7.00–8.00	387.91–414.69	85.71%–87.50%	$2.76\times10^{-11} - 2.11\times10^{-11}$	6.46×10^{-12}	5.65×10^{-12}	5.54×10^{-12}
8.00–∞	414.69–∞	87.50%–100%	2.11×10^{-11} - 0	2.11×10^{-11}	2.11×10^{-11}	1.85×10^{-11}

$$\left(\frac{\rho_{\text{ loss,max\_total}} + \rho_{\text{ loss,min\_total}}}{2}\right) \times 2 = (9.02 \pm 0.532) \times 10^{-10}\ J/m^3$$

$$\rho_{\text{DE}}(0.3) = (5.3341 \times 10^{-10}) \cdot (1+0.3)^{3(1+(-0.42\pm0.21)+(-1.75\pm0.58))} \exp\left(-3(-1.75\pm0.58)\frac{0.3}{1+0.3}\right) = (7.31 \pm 1.584) \times 10^{-10}\ \text{J/m}^3 \tag{.7}$$

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