

A Thermodynamic Nature of Vacuum Energy

Mohamed Mekouar

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Abstract

We propose a thermodynamic model of dark energy in which the observed accelerated expansion of the universe arises as a consequence of the underlying microscopic degrees of freedom within spacetime. In this framework, spacetime is not fundamental but emergent from discrete entangled nodes, and the cosmological volume grows as the number of entangled branches increases. Furthermore, we revisit black hole entropy via the ER=EPR conjecture, showing that the Bekenstein-Hawking entropy can be viewed as a collective contribution from Planck-scale entangled wormholes. This work suggests that dark energy is not a fundamental field but an emergent thermodynamic phenomenon rooted in the quantum structure of spacetime.

1 Introduction

The nature of dark energy is still one of the most profound unsolved problems in modern cosmology. Observations of the universe's accelerated expansion, first suggested by supernova data in the late 1990s and built on earlier work tracing back to Edwin Hubble's discovery of cosmic expansion, have led to the reintroduction of the cosmological constant, originally proposed by Albert Einstein in 1917 as a possible explanation. Over the decades, a variety of models have attempted to explain the origin of dark energy. However, a fundamental mechanism underlying its existence has not yet been established. In this work, we propose a new possible framework that seeks to explain the origin and nature of dark energy.

2 Philosophical Motives

It may seem irrelevant at first, yet, reality remains one of the most complex and sophisticated concepts which could solve a lot of mysteries. Despite centuries of research, our understanding of what constitutes reality is still far from complete. What does it truly mean for something to be real? Is reality itself fundamental? If not, how does it emerge? Does nature already impose intrinsic rules to follow? Could multiple versions of reality

coexist across possible universes? Does the objects exist in multiple forms hidden from us? What is time? Ultimately, can the universe, in any meaningful sense, understand itself?

Reality, a word derived from "real" and the suffix "ity", denotes a state or condition of being real. To be real often implies the ability to observe the environment. But what if the universe is, in some sense, conscious of itself through the interplay of its own components? For the universe to evolve coherently over time, it would need to track events and actions through some form of encoding mechanism. Without such mechanism, the physical laws would lack any reference to the past states, causing a break down. The universe would continuously reset, preventing any changes and evolution we observe today. What does the word *evolution* mean? Taking our species as an example, if humans had not evolved, we would not be in our current state. This is because all biological information is stored in our DNA, inherited from our ancestors. Evolution is an inherent process of change over time. Otherwise, individuals would differ completely in their biological properties. Evolution requires a memory to occur. And in living organisms, that memory is encoded in the DNA. This makes us ask a deeper question, what about the universe? Does it, as well, have a type of memory? Encoding past events and information, enabling it to evolve too? The answer is yes, the universe **must** remember. The universe must encode the past, and a pure evidence is the Cosmic Microwave Background and gravitational waves. Therefore, what is reality?

Reality might be the byproduct of the processing of thousands or even millions of interdependent probabilities, all originating from a single source, the Big Bang, where the tree of probabilities first began. In fact, the Big Bang might itself be one probability of other probabilities. One probability determines the next probabilities, the future. A causal chain of probabilities. The universe might be a medium of multiple interlinked entanglements. Objects exist in a superposition of states until observed, introducing an inherent uncertainty. Now, imagine an alternate world in which planets are flat. From the perspective of an intelligent being of that world, such reality would be obvious and normal. However, from our viewpoint governed by different physical laws, it would appear impossible and unrealistic. We would likely reject it, since it contradicts our physical laws. This suggests an emergent but probabilistic nature of reality. Each universe might yield different outcomes. The rules are inherent to nature and the universe itself, and we are bound to accept them, whether we like it or not, since we, ourselves, are part of these natural rules. Reality is shaped by these probabilistic rules, and thus, it is fundamentally relative. We are merely a part of it.

3 Probabilistic Spacetime

The universe may be probabilistic in nature, as explored. Accordingly, space and time can be understood as probabilistic aspects. Imagine nodes distributed throughout the universe, each representing a probability. The chance of an outcome depends on the previous network of probabilities. Through this web, both spatial structures and time flow

emerges. Effectively, distance, in this sense, is how closely the two nodes within spacetime are related. A measure of correlation between nodes, a relationship.

What we observe as a stretching of spacetime may be due to the increasing number of probabilities, since the beginning of all probabilities.

$$V(t) \propto P(t) \propto e^{S(t)}$$

$$\log V(t) \propto S(t)$$

As entropy grows, the volume grows exponentially. Since the Big Bang, the probabilities range has been increasing as more and more possibilities are created, following a branching structure resembling a tree or chain. Spacetime emerges from the entanglement of these probabilistic nodes, forming a network of discrete units. As the number of possible states and nodes increases, spacetime expands accordingly, with the number of outcomes growing exponentially. At quantum scales, spacetime is but composed of discrete units. However, from our macroscopic perspective, it appears smooth. Denote N_P as the number of probabilistic nodes, each contributing to one unit of area.

$$A = 4l_p^2 N_P \ln d$$

Expressing the surface area A as discrete units, where: d is the dimension of internal Hilbert space associated with each node. It was derived from the total entropy and Bekenstein-Hawking entropy relation. Total entropy:

$$S = N_P \ln d$$

From Bekenstein-Hawking entropy:

$$S = \frac{A}{4l_p^2} \implies A = 4l_p^2 N_P \ln d$$

Spacetime is an emergent structure arising from a network of entanglements between quantum states. The "closeness", within this view, corresponds to the strength of entanglement between those states. The more strongly two quantum subsystems are entangled, the closer they appear in the emergent spacetime [13]. In regions of high density, quantum entanglements become disrupted due to the introduction of noise into the system. In black holes, the event horizon is a boundary where entanglement is maximally disrupted. Gravitational waves, in this context, can be viewed as ripples in the entanglement graph, propagating at the speed of causality. Effectively, entanglement strength is inversely proportional to the surrounding density.

4 ER=EPR View of Spacetime

If ER=EPR is correct in suggesting that spacetime emerges from quantum entanglement, thus, the Bekenstein-Hawking entropy of a black hole should emerge from the sum of the entropic contributions of all the wormholes (Einstein-Rosen bridges) on its horizon. Since ER=EPR expects the Einstein-Rosen bridges to be Planckian due to their nature with elementary entangled particles, therefore, each would have a Planckian area [11]. The black hole's horizon would therefore be $A = NA_P$ where N is the number of these tiny wormholes, $N = \frac{A}{A_P}$

$$S_{WH} = \alpha k_B$$

$$S_{BH} = NS_{WH}$$

$$S_{BH} = \frac{A}{A_P} \alpha k_B$$

$$S_{BH} = \frac{A}{\frac{G\hbar}{c^3}} \alpha k_B = \frac{\alpha A c^3 k_B}{G\hbar}$$

Thus, $\alpha = \frac{1}{4}$ to match the Bekenstein-Hawking entropy expectations. From the original paper of ER=EPR conjecture, it was proposed that these wormholes are Planckian.

"In fact we go even further and claim that even for an entangled pair of particles, in a quantum theory of gravity there must be a Planckian bridge between them, albeit a very quantum mechanical bridge which probably cannot be described by classical geometry." [11]

5 Vacuum Energy & ER=EPR Wormholes

The total number of ER=EPR wormholes in the observable universe is given by $N_{WH} = \frac{A_{obs}}{l_P^2} \approx 10^{123}$. However, these wormholes are subject to affect the universe's structure. Each would occupy a mass density of $p = \frac{m_P}{l_P^3}$ due to their geometric nature. Assuming this density is distributed over the entire observable universe and across the total number of ER = EPR wormholes, denoted by N, , the resulting total mass density becomes

$$p_{total} = \frac{m_P}{N l_P^3}$$

This value is extremely close to the observed density of dark energy [5]. This may not be a mere coincidence, but rather an indication of a deeper physical relation, possibly an emergent phenomenon. ER=EPR wormholes are but a possibility for explaining this behavior, wherein vacuum energy could arise from a network of fluctuating, entangled microscopic wormholes, contributing an effective cosmological constant. Alternatively, the origin of this density may lie in the fundamental degrees of freedom of spacetime itself. From our perspective, ER=EPR wormholes are able to connect the observable universe

to the exterior, rather than just an internal entanglement within our horizon. Thus, our observable universe might not be completely isolated but quantum effects happen to link the "outside" with ours, or parent universe. Such connections may allow quantum information to flow between our universe and the parent or exterior.

Since the total number of ER=EPR wormholes N scales roughly with the area of the observable universe horizon A_{obs} , and because the observable horizon size changes over cosmological time, as the universe expands, the effective dark energy density arising from these wormholes, is inversely proportional to the horizon area and thus will evolve with cosmic expansion. Instead, it would slowly weaken over extremely long timescales [4]. Estimating the timescale of this weakening is equivalent to estimating how long it takes for the area of the observable universe to increase, which is about a Hubble time, or, equivalently, observable universe's age.

6 Dark Energy & Degrees of Freedom

In this view, dark energy might not be fundamental but rather an emergent, thermodynamic phenomenon. From the first law of thermodynamics, we have:

$$dE = TdS - PdV$$

We consider the volume scaling as $V = r^3$ since the region inside a spherical horizon with a (3+1)-dimensional spacetime has a volume scaling as r^3 , and the total energy inside this volume as $E = \rho V = r^3 \rho$. Differentiating with respect to r gives

$$\begin{aligned} \frac{dE}{dr} &= \frac{d\rho}{dr} r^3 = 3r^2 \rho + r^3 \frac{d\rho}{dr} \\ dE &\approx TdS \\ dS &= \frac{dS}{dr} dr \\ \frac{dE}{dr} &= T \frac{dS}{dr} \end{aligned} \tag{1}$$

Equating:

$$3r^2 \rho + r^3 \frac{d\rho}{dr} = T \frac{dS}{dr}$$

The entropy associated with the horizon of radius r is given by the Bekenstein-Hawking entropy formula [2, 8]:

$$S_{BH} = \frac{k_B c^3 A}{4 \hbar G}$$

$A = 4\pi r^2$:

$$\begin{aligned} S_{BH} &= \frac{\pi k_B c^3 r^2}{\hbar G} \\ \frac{dS}{dr} &= \frac{2\pi k_B c^3}{\hbar G} r \end{aligned}$$

$$3r^2\rho + r^3\frac{d\rho}{dr} = T\frac{dS}{dr}$$

The temperature corresponding to an acceleration $a = \frac{c^2}{r}$ (Unruh temperature) is

$$T = \frac{\hbar a}{2\pi c k_B} = \frac{\hbar c}{2\pi k_B r}$$

Where $a = \frac{c^2}{d}$

$$T = \frac{\hbar c}{2\pi k_B d}, S = \frac{\pi k_B c^3 d^2}{\hbar G}$$

The temperature is therefore related to the Gibbons-Hawking temperature. Applying the first law of thermodynamics,

$$\frac{dE}{dr} = T\frac{dS}{dr}$$

We substitute to get

$$r^3\frac{d\rho}{dr} + 3r^2\rho = \frac{\hbar c}{2\pi k_B r} \times \frac{2\pi k_B c^3 r}{\hbar G} = \frac{c^4}{G}$$

Dividing both sides of the equation by r^3 returns:

$$\frac{d\rho}{dr} + \frac{3}{r}\rho = \frac{c^4}{Gr^3}$$

Multiplying by r^3 , and integrating with respect to r :

$$\frac{d\rho}{dr} + \frac{3}{r}\rho = \frac{c^4}{Gr^3} \implies r^3\frac{d\rho}{dr} + 3r^2\rho = \frac{c^4}{G} \implies \frac{d}{dr}(r^3\rho) = \frac{c^4}{G}$$

We eliminated r^3 from the denominator to simplify the expression. Accordingly, integrate both sides to find the final energy density as a single expression, since we are dealing with the derivative $\frac{d\rho}{dr}$.

$$\int \frac{d}{dr}(r^3\rho)dr = \int \frac{c^4}{G}dr \implies r^3\rho = \frac{c^4}{G}r + C$$

$$\boxed{\rho_{DE} = \frac{c^4}{Gr^2} + \frac{C}{r^3}} \quad (2)$$

$$\rho_{DE} = \frac{c^4}{Gr^2} \quad \rho_2 = \frac{C}{r^3}$$

The results closely match the dark energy densities [5, 15] (with a 5σ level of confidence from SOES team) when considering the radius of the observable universe, yielding a remarkable agreement with a value of approximately $6.25 \times 10^{-10} J/m^3$ or equivalently $6.95 \times 10^{-27} kg/m^3$. According to the Planck 2018 observations, the dark energy density is about $7 \times 10^{-27} kg/m^3$, which, when converted to energy density in J/m^3 using the relation $\rho_E = \rho_m c^2$, corresponds to precisely $\rho_{DE} = 7 \times 10^{-27} \times c^2 = 6.3 \times 10^{-10} J/m^3$, both values showing a perfect match with our theoretical results. Notably, the acceleration scale $a = \frac{c^2}{d}$ is related to the surface gravity of a de Sitter horizon. This, again, predicts that dark energy may slowly change over time and decreasing as the cosmological area

increases. There are various possible mechanisms by which this may occur. Dark energy might arise as the universe attempts to maximize entropy by expanding, or creating new space, generating an effective repulsive pressure. Alternatively, dark energy might be a collective phenomenon emerging from quantum gravitational degrees of freedom entangled across the horizon, potentially explained via ER=EPR wormholes or other frameworks, however, it is important to emphasize that this idea remain but a hypothesis rather than established fact. The units of energy density ρ_{DE} are $\frac{J}{m^3}$. Therefore, the constant C must have units of Joules to match the expected units of $\frac{J}{m^3}$. The second term should consequently correspond to a negligible energy density, over which the dark energy density dominates.

Since we are not yet in a pure de Sitter universe, we must use the current properties of our universe, which are associated with the radius of the observable universe. A de Sitter horizon, by contrast, is applicable only in a de Sitter universe containing exclusively vacuum energy. Our geometry and expansion states differ from a pure de Sitter spacetime. The expansion is significant and constant in a pure de Sitter universe unlike ours. Only recently, on cosmological timescales, has dark energy began to dominate, marking a transition toward accelerated expansion but not yet a true de Sitter state. Furthermore, the expression $\frac{c^4}{G}$ is known as the *Planck force* hinting towards a quantum regime of vacuum energy. The equation we derived is not specific but rather a general equation applicable in quantum mechanical regimes, which we will explore further in the next section. Therefore, the chosen distance d is not explicitly related to the de Sitter horizon or any other specific horizon. It must be noted that the choice of volume scaling in the form $V = r^3$ is not random, but reflects the observational evidence favoring a spatially flat universe with typically negligible curvature. According to the latest measurements, any significant deviation from flatness such as required by a spherical geometry with $V = \frac{4\pi}{3}r^3$ is not allowed. The Planck 2018 data limit the curvature parameter to be $\Omega_K = 0.0007 \pm 0.0019$, indicating a universe that is flat to within a fraction of a percent [5, 6]. Theoretically, using the flat volume form is essential for consistency with known physical principles. For instance, substituting the Planck length into the energy density derived from a spherical volume expression, does not yield the correct Planck energy density, whereas the choice $V = r^3$ reproduces the expected Planck energy density exactly. Finally, the use of $V = r^3$ is not only observationally motivated but also theoretically necessary for matching fundamental theories. Finally, the model produces results consistent with both the spatial geometry inferred from the latest observations and the measured dark energy density.

7 Cosmological Horizon Entropy from Vacuum Energy

In this section, we will derive the cosmological horizon's entropy uniquely from the vacuum energy. According to the Bekenstein–Hawking entropy formula,

$$S_{BH} = \frac{k_B c^3 A}{4\hbar G}$$

Choosing the area $A = 4\pi r^2$:

$$S_{BH} = \frac{k_B \pi c^3 r^2}{\hbar G}$$

As shown in Eq.(4), the dark energy density can be expressed as $\rho_{DE} = \frac{c^4}{Gr^2} + \frac{C}{r^3}$. The first term $\frac{c^4}{Gr^2}$ dominates in our recent universe, thus:

$$\rho_{DE} \approx \frac{c^4}{Gr^2}$$

We could substitute the following:

$$\rho_{DE} = \frac{c^4}{Gr^2} \implies r^2 = \frac{c^4}{G\rho_{DE}}$$

into the BH entropy formula:

$$S_{BH} = \frac{k_B \pi c^3 r^2}{\hbar G} \implies \boxed{S_{BH}(\rho_{DE}) = \frac{\pi k_B c^7}{\hbar G^2 \rho_{DE}}} \quad (3)$$

Where ρ_{DE} must be in units of J/m^3 . Otherwise, we could divide the formula by c^2 to use kg/m^3 as units of mass density of dark energy, leaving us with:

$$S_{BH}(\rho_{DE}) = \frac{\pi k_B c^5}{\hbar G^2 \rho_{DE}}$$

The derived formula represents the entropy of a de Sitter universe, dominated by dark energy. The cosmological horizon entropy S_{BH} decreases as the dark energy density ρ_{DE} increases, and vice versa. We could estimate the cosmological horizon entropy by substituting $r = 4.4 \times 10^{26}$ into the dark energy density equation, resulting in a consistent entropy of around $3.2145 \times 10^{100} J/K$ or 2.3282×10^{123} degrees of freedom. If the dark energy density is actually variable, it would imply that as the radius increases, the dark energy density decreases, and consequently, the entropy would increase. However, when considering gravitational collapse resulting from the reduction in dark energy density, entropy would likely be in a state of increasing and decreasing in the very distant future, which might possibly cause a time reversal.

8 Vacuum Energy Density Must Only Decrease

In the previous section, it was explored that the cosmological horizon entropy scales as $S_{BH} = \frac{\pi k_B c^7}{\hbar G^2 \rho_{DE}}$. In this perspective, following the 2nd law of thermodynamics, the entropy must either be in a state of increase or remain constant within a maximal value. Therefore, dark energy density must only either decrease or stay constant as well. However, a constant dark energy density implies a maximal entropy value which is not the case with our universe. Thus, the dark energy density must be decreasing to match the observations of an increasing entropy in the current state of the universe, it should diminish over time.

Finally, a strictly constant density would imply no change at all, which conflicts with the observed evolution of the universe. Furthermore, this implies that when the universe reaches maximal value of entropy, the dark energy density would approach a constant value. However, the mechanism will depend on how fast would dark energy decay.

9 A Solution to the Cosmological Constant Problem

Quantum field theory (QFT) predicts an incredibly high vacuum energy density due to the quantum cutoff, however, this predicted vacuum energy is relevant primarily in the very early universe or in regions of extreme spacetime curvature.

$$\rho_{DE} = \frac{c^4}{Gr^2} + \frac{C}{r^3} \approx \frac{c^4}{Gr^2}$$

The yielded equation is a general equation to vacuum energy, using $r = l_P = \sqrt{\frac{\hbar G}{c^3}}$:

$$\rho_P = \frac{c^4}{Gr^2} = \frac{c^4}{G(l_P)^2} = \frac{c^4}{G\left(\frac{\hbar G}{c^3}\right)} = \boxed{\frac{c^7}{\hbar G^2}} \approx 4.6 \times 10^{113} J/m^3$$

This corresponds to the Planck energy density in units of J/m^3 which is $\rho_P = \frac{c^5}{G^2 \hbar}$, as predicted by quantum field theory (QFT). Essentially, QFT accurately predicts this value at quantum cutoffs. However, it does not account for the size of the observable universe, which may lead to a much lower effective vacuum energy density. Therefore, vacuum energy is not a fixed constant, but rather a quantity that varies with the radius. Around Planck time, the universe was so dense and curved, and quantum gravity effects, therefore, dominated. The enormous vacuum energy $\sim 10^{123}$, may possibly account for the inflationary field that dominated the early universe right after the Big Bang, at Planck length. The vacuum catastrophe may be resolved by acknowledging that energy density arises thermodynamically and varies with the geometric horizon scale. From a degrees of freedom perspective, this naturally resolves the problem by positing the number of degrees of freedom contained within the vacuum energy density ρ_{vacuum} where $r^2 = Nl_P^2$. We have:

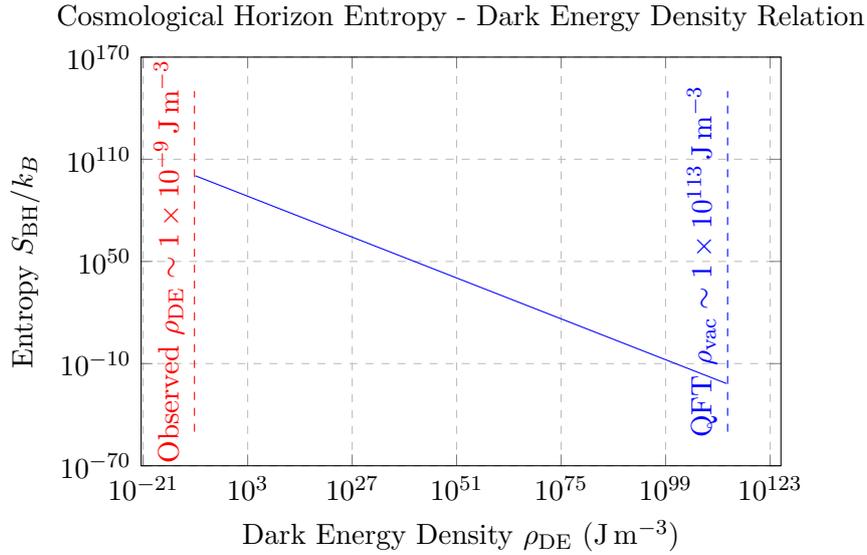
$$\rho_{DE} = \frac{c^4}{Gr^2} = \frac{c^4}{GNl_P^2}$$

Taking the area as that of our observable universe, the number of degrees of freedom is around $N \approx 7.5 \times 10^{122}$. As the universe expands, the vacuum energy effectively dilutes. Furthermore, according to Eq.(5) in section 9, S_{BH} depends inversely on ρ_{DE} , an extremely small vacuum energy density would result on a very large horizon entropy, and vice versa. The QFT vacuum energy overestimation and the total observable entropy of the universe coincide numerically, indicating a deeper relation between thermodynamic principles and

the vacuum energy. According to the relation (5):

$$S_{BH} = \frac{\pi k_B c^7}{\hbar G^2 \rho_{DE}}$$

It does result a consistent maximum entropy state due to the present vacuum energy density.



10 A Physical Interpretation of C

We could potentially find a physical meaning of the constant C from the following derived relation (see Section 8):

$$\rho_{DE} = \frac{c^2}{Gr^2} + \frac{C}{r^3} \implies C = r^3 \left(\rho_{DE} - \frac{c^2}{Gr^2} \right)$$

. Since $\rho_{DE} = \frac{c^2}{Gr^2}$, we may neglect the first term, yielding:

$$C = -\frac{c^2}{Gr^2}$$

Therefore, C has units of mass, consistent with the interpretation of ρ_{DE} as mass density. To find the physical meaning of it, we would put $r = r_{obs} = 4.4 \times 10^{26} m$ returning around $-5.92 \times 10^{53} kg$, which represents roughly the total mass of the observable universe in current epoch.

$$C \approx -M_{obs}$$

The negative sign is not supposed to yield a negative mass since the constant mainly arises as an integration constant due to the chosen reference frame.

11 Cosmic Inflation & Dark Energy Unification

Cosmic inflation is, in this model, the same as dark energy, both driven by vacuum energy. Therefore, the equation $\rho_{DE} = \frac{c^2}{Gr^2}$ unifies dark energy and inflation into a single framework. In this case, we further predict a precise value for when the radius was around 10^{-28} and 10^{-29} meters, during inflation. The energy density due to the inflation field is reported to be around $V(\phi) \approx (10^{16} GeV)^4 \approx 10^{64} GeV^4$ [10]. To convert it to the SI unit of J/m^3 , we can follow these steps: Given that $q = e = 1.60217 \times 10^{-19} C$, we have:

$$1eV = qV$$

Therefore, converting GeV to Joules is essentially:

$$1GeV = 10^9 \times 1eV = 10^9 \times qV \implies 1GeV \approx 1.6022 \times 10^{-10} J$$

To get meters, we would have to find the expression leading us to Jm by utilizing dimensional analysis, such that A has units of Jm : $A = \hbar c$. Finally, we could find J/m^3 from: The conversion of $(10^{64} GeV^4)^{1/4}$ to Joules. And we know that $1GeV = 1.6022 \times 10^{-10} J$. Therefore:

$$10^{16} GeV = 10^{16} \times 1.6022 \times 10^{-10} J \approx 1602.63 J$$

We could find the desired length by dividing the expression A by the conversion.

$$l = \frac{A}{1602.63} = \frac{\hbar c}{1602.63} \approx 1.973 \times 10^{-32} m$$

Finally, the energy density due to the inflationary field is around:

$$\rho_i = \frac{1602.63}{(1.973 \times 10^{-32})^3} \approx 2.085 \times 10^{101} J/m^3$$

However, our model tends to use fewer parameters while accurately returning more observational data, consistent with the principle of parsimony (Occam's Razor).

$$\rho_{DE} = \frac{c^4}{Gr^2}$$

Using $r \approx 10^{-29}$:

$$\rho_{DE} = \frac{c^4}{Gr^2} \approx 1.210 \times 10^{102} J/m^3$$

Using $r \approx 10^{-28}$:

$$\rho_{DE} = \frac{c^4}{Gr^2} \approx 1.210 \times 10^{100} J/m^3$$

Both values are remarkably close to the estimated energy density of the inflation field. In

this view, we unify dark energy and cosmic inflation within a single framework, driven by the same underlying principles.

12 Hubble Parameter in the Present and Inflationary Eras

The given model also estimates accurate Hubble parameter values. From the known Friedmann equation [7]:

$$H^2 = \frac{8\pi G}{3}\rho_\Lambda - \frac{k}{a^2} + \frac{\Lambda}{3}$$

And critical density is

$$\rho_c = \frac{3H^2}{8\pi G} \implies \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c} = \frac{8\pi G}{3H^2}\rho_\Lambda$$

Solving for H^2 :

$$\Omega_\Lambda = \frac{8\pi G}{3H^2}\rho_\Lambda \implies H^2 = \frac{8\pi G}{3} \frac{\rho_\Lambda}{\Omega_\Lambda} \implies H = \sqrt{\frac{8\pi G}{3\Omega_\Lambda}\rho_\Lambda}$$

For dimensional consistency, ρ_Λ must be in kg/m^3 . Substituting $\rho_\Lambda = \frac{c^2}{Gr^2}$ into the equation:

$$H = \sqrt{\frac{8\pi c^2}{3\Omega_\Lambda r^2}}$$

Using the present era radius $r = 4.4 \times 10^{26}$ and $\Omega_\Lambda \approx 0.6847 \pm 0.0073$:

$$H \approx 73.17 - 73.56 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

The results vary significantly depending on the chosen density parameter; however, they mostly align with those of the SH0ES team [15, 14], further validating their achievements. Furthermore, the presented formula predicts precise values based on various epochs. However, during CMB era, using the following scaling relation:

$$R_{CMB} = \frac{R_0}{1 + z_{CMB}}$$

Since $z_{CMB} = 1100$, therefore, $R_{CMB} \approx 4 \times 10^{23}$, plugging it in the formula using $\Omega_\Lambda \approx 1.3 \times 10^{-9}$ for consistency with the dark energy density parameter during the CMB era:

$$H = \sqrt{\frac{8\pi c^2}{3\Omega_\Lambda r^2}} \approx 8.09 \times 10^9 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

A higher Ω_Λ yields a lower Hubble parameter but never approaches the Planck 2018 estimate of $H \approx 67.9 \pm 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The estimated value from this model matches an era between inflationary and post-inflationary periods. To achieve such measured value by Planck 2018, either the radius would need to be larger than the current observable universe radius or a significantly high dark energy density parameter, higher than one, which is impossible under current physical models. In conclusion, the Planck 2018 result

might be due to an unaccounting for external effects or hidden systematic biases in the measurement process, which could influence the inferred value of the Hubble constant. During the inflationary era with a radius $r \approx 10^{-28} - 10^{-29}$ with $\Omega_\Lambda \approx 1$:

$$H \approx 2.67 \times 10^{56} - 10^{57} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Converting the results to inverse seconds yields:

$$H \approx \frac{2.67 \times 10^{56} - 10^{57}}{3.0865 \times 10^{19}} \approx 8.67 \times 10^{36} - 10^{37} \text{ s}^{-1}$$

We use a single density parameter because, according to our model, both dark energy and cosmic inflation originate for the same underlying reason. . The value well matches with the inflationary era time range which is thought to have occurred approximately 10^{-36} s to 10^{-32} s [1]. There is a tension present between the inflationary and the dark energy dominated epochs when calculating the Hubble parameter at the reduced observable universe radius corresponding to the redshift $z_{CMB} = 1100$, which Planck satellite might not detect, possibly filtering out inflationary residual effects.

13 Asymmetric Cyclic Universe

The model posits that our universe is not singular but part of an eternal cyclic of universes. If entropy were to decrease, the direction of time would appear reversed. However, this is not allowed in an isolated system, on cosmological scales, the dynamics might differ, allowing for a time-reversal phase. We propose a universe that begins with a traditional Big Bang or Big Bounce, evolving and expanding, and entropy increasing normally. As the universe expands further, entropy reaches its maximum value where "heat death" might be possible. However, rather than ending indefinitely, the universe enters a collapse phase due to a deceleration and decreasing value of dark energy density (Section 12). Essentially, during collapse, entropy starts decreasing (Section 7), causing a reversal in the arrow of time. From the universe's perspective, it would evolve forward and normally, but observers in other universes might perceive this as a reversing time, which it would be called "anti-universe" in this case. At the point of a required minimal radius during collapse, the universe undergoes a Big Bounce (Section 6) as dark energy starts increasing again within the same universe. Simultaneously, this bounce births a new universe, whose time arrow points in the opposite direction to the collapsing parent universe's reversal time. The new universe's entropy starts low again and time flows forward for an observer within this new universe. This model is not a simple loop in time rather a creation of two opposite universes from the same bounce, one expanding in a backward direction of time and the other forward relatively. The Big Bang of the parent universe already happened where it goes backward in time once it reaches a minimal radius and would undergo a continued cycle of expansion and collapse forever, essentially, the universe reaches not an "end" but its own rebirth. This is interestingly similar to an existing model called "Janus cosmological

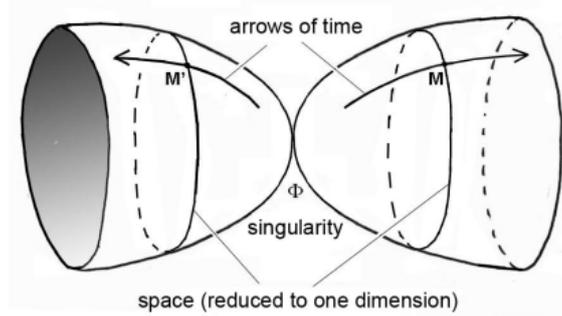


Figure 1: Original diagram of the Janus Cosmological Model by Petit & d'Agostini (2014), used here to illustrate similarities with the proposed Asymmetric Cyclic Universe.

model" [12]. This solution doesn't completely challenge Λ CDM since it actually exactly matches measured values as expected. The Janus model proposes a dual metric structure involving negative and positive mass. The two share conceptual similarities that requires analysis.

The time reversed mechanism of the two universes may lead to fundamentally opposite initial conditions, such as inverted CP (Charge-Parity) states and reversed baryon asymmetries [3]. Hypothetically, what we observe as dark matter may actually be ordinary matter from the collapsing parent universe, in a time-reversed orientation relative to ours. Possibly, the bounce caused one of particles of the parent universe to leak into our own universe shortly after the bounce (coinciding with our Big Bang). Essentially, dark matter could be "leaked" matter from the collapsing parent universe, evolving backward in time relative to us, so it is present in our universe's spacetime which evolves forward in time. Dark matter might seem to attract only gravitationally since there is no twin pair present to interact with as they are both opposite in the direction of time and gravity is time-symmetric, appearing as cold and invisible matter.

14 Conclusion

The vacuum energy, as discovered, naturally arises from thermodynamic principles combined with Bekenstein-Hawking entropy and Gibbons-Hawking temperature. Accordingly, it reflects a thermal or entropic origin of the vacuum. The cosmological constant can be understood as an equilibrium state of spacetime, arising from its underlying microscopic degrees of freedom. Additionally, spacetime itself may be interpreted as a thermal system, as originally considered by Ted Jacobson in his derivation of Einstein's field equations [9]. Spacetime might be an emergent thermodynamic system where quantum gravity might be encoded in the statistical mechanics of a horizon. Instead of thinking about dark energy as a fundamental constant, this model sees it as a natural consequence of the way spacetime itself behaves at a quantum level by involving thermodynamic principles. The cosmic horizon acts like a thermodynamic system. This horizon has an entropy, known as the Bekenstein-Hawking entropy, which essentially counts the microscopic quantum states

associated with the fabric of spacetime. This entropy reflects the quantum degrees of freedom of spacetime geometry itself. Additionally, the horizon has a temperature, which I relate to the Gibbons-Hawking temperature, arising due to quantum fluctuations near the horizon. These fluctuations produce an effect similar to the thermal radiation observed from black holes or the Casimir effect. The change in the total energy inside the observable universe is related to the changes in the horizon's entropy and temperature. This means the energy within this cosmic volume isn't just from ordinary matter or radiation, it also includes an energy contributions of these quantum microstates of the horizon. This energy density naturally scales with the size of the cosmic horizon, as the inverse square of the horizon radius. This explains why the dark energy density is so small but close to the critical energy density we observe today. The value of dark energy is, therefore, not a mere coincidence, it emerges directly from the thermodynamic and quantum properties of our universe's horizon. From this perspective, dark energy is not fundamental rather emergent and collective phenomenon. Both Gibbons-Hawking temperature and Bekenstein-Hawking entropy properties work together to contribute to this small dark energy density where the temperature encodes the way quantum fields fluctuate near the horizon and the entropy counts the number of ways spacetime can be configured microscopically. Finally, dark energy is, therefore, an effect of the finite information capacity of the cosmological causal horizon, encoded through a holographic entropy bound, or possibly, through a complex network of entangled quantum states (ER=EPR wormholes) that holds spacetime and causality together. In short, it represents the geometrical manifestation of spacetime's intrinsic tendency to reach a maximal state of entropy in the future whereas accelerated expansion is a thermodynamic response.

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