Dark Energy and Dark Matter as Different Manifestations of Vacuum Energy

Kabir A. Umar

Centre for Satellite Technology Development, National Space Research and Development Agency, Obasanjo Space Centre, Km 17, Airport Road, PMB 437, Garki, Abuja, Nigeria

Abstract: Dark energy and dark matter are described as different manifestations of vacuum energy within the framework of Extra Dimensional Symmetry (EDS) that doubles large spatial dimensions with microscopic partners. In this framework, the bare vacuum energy component exists in a gravitationally inert state where actual gravitational constant $G_o = 0G$, while real particles oscillate between this inert state and the active state where $G_o = 2G$. The background effect of neutrino substrates in the inert state makes $G_o > 0G$, causing the gravitation of virtual particles with positive pressure appearing as dark matter. A small component of vacuum energy from the inert state also spills into the gravitationally active state as dark energy. This is due to an energy density constraint and speed limit asymmetry between the two gravitational states that limits the capacity of the inert state to contain all the vacuum energy component. This form of dark energy and dark matter, are parameterized by a common asymmetry parameter Γ which is suppressed in deep gravitational potential wells. The dynamics of this form of dark matter however, is further parametrized by the phase and kinetic energy dependent parameters of its neutrino substrate. This results in the existence of a dominant light form of dark matter and a detectable heavy form of dark matter. The model predicts a curvature suppressed Gravitational Wave Reheating (GWR) mechanism in which gravitational waves produce electromagnetic secondary in the presence of strong negative pressure.

Keywords: dark energy; dark matter; extra dimension; gravity; neutrino; vacuum energy

1. Introduction

Dark energy is a mysterious energy component that has been observed to be driving the accelerated expansion of the universe, and have defied several explanations since its discovery in supernova observations, first reported in 1998 [1]. Its existence has since been confirmed by several independent observations like the Planck measurements of the Cosmic Microwave Background (CMB), indicating that it accounts for about 68.3% [2] of the gravitating energy content of the universe. This is in addition to the older dark matter mystery of gravitationally attractive but invisible energy component constituting about 26.8% of the gravitating energy content of the universe. Only about 4.6% is in the form of visible baryonic matter.

The cosmological constant (Λ) earlier introduced into Einstein's Field Equations, while being the simplest solution, results in a conflict between measured density of dark energy and the 120 orders of magnitude larger value predicted from quantum field theory [3]. The Λ problem has defied logical solution from supersymmetric cancellation approach, relaxation of vacuum energy [4] and anthropic approaches [5]. It also defies an approach that simply makes the spacetime metric insensitive to Λ [6].

Slowly evolving scaler field models like Quintessence, is one of the prominent alternative approaches to solve the dark energy mystery without the Λ route. We also have modified gravity models and unification of dark energy and dark matter. See Ref. [7] for detailed review and Ref. [8, 9] for recent review.

The amount of theoretical and observational efforts that has been applied to understand dark energy and dark matter shows that they require new physics beyond the existing standard model of cosmology and particle physics.

Attempts to resolve the dark matter mystery can be mainly classified as either a modification of gravity or introduction of new particles beyond the standard model of particle physics. However, both approaches of modified gravity and particle dark matter have failed to provide consistent explanations to the dark matter mystery even though each approach tends to explain some observations and fail at some others.

There is an approach that explains dark matter as gravitational polarization of vacuum energy by baryonic matter without invoking new particle or modifying gravity in the traditional sense [10]. It is based on the idea that matter and antimatter have opposite gravitational charges. one fundamental problem with this approach is that it requires a violation of the Weak Equivalence Principle and preliminary findings from measurements of antiproton to proton charge to mass ratio implies that matter and antimatter gravitate the same way up to 97% accuracy [11]. The ongoing AEgIS experiment at CERN [12] should provide a definitive test for the Weak Equivalence Principle.

In this paper, the dark energy and dark matter puzzle are tackled using the framework of Extra Dimension Symmetry (EDS) that doubles the number of large extra dimensions with microscopic partners.

This paper is organized as follows. Section 2 discusses the key dimensional symmetry that doubles the number of large spatial dimensions with microscopic partners. It also discusses the speed constraint, the two on and off gravitational states, their speed limit asymmetry and density constraint, which is then applied in section 4 to solve the Λ problem of vacuum energy. Section 3 discusses General Relativity in extra dimension S_0 and explore its unique features of gravitational inversion as well as the chain of causality in gravitation. It is shown that the expansion of the time-like S_0 dimension is equivalent to the curvature of our visible spatial dimensions S_1. Section 4 discusses the emergence of dark energy due to a speed limit asymmetry and energy density constraint discussed in section 2, while in section 5, the key reheating prediction is discussed. Section 6 discusses the gravitation of virtual particles which appears as dark matter due to the background effect of neutrino substrates on the gravitational constant in the inert state. Summary and conclusion follows in Section 7.

2. Extra Dimensional Symmetry Framework

In this framework, the number of large spatial dimensions is described by the dimension number S_n such that,

$$S_n = [4n - 1]d \quad (1)$$

where $n = 0, 1, 2, 3, \dots$ $n = 0$, corresponds to $S_n = -1d$ which is a time like spatial dimension that is invisible due to speed constraint discussed in Section 2.1.

$n = 1$, corresponds to $S_1 = 3d$ which is our visible spatial dimensions.

The EDS framework doubles large spatial dimensions with microscopic dimensional partners with opposite dimension numbers such that the total dimension number of the universe is zero as illustrated in Figure 1.

While the dimensional partner of S_0, is a Planck size S_P dimension, the dimensional partner of S_1 is denoted S_α. If there is perfect symmetry, $S_\alpha = -3d$. It is assumed that the large spatial dimensions S_1 and S_0 where inflated in the early universe at the expense of their dimensional partners S_α and S_P which contracted to their microscopic sizes becoming invisible.

In resolving the mysteries of dark energy and dark matter, this paper focuses on the S_0 dimension and its microscopic dimensional partner S_P as well as their interactions with the visible spatial dimension S_1.
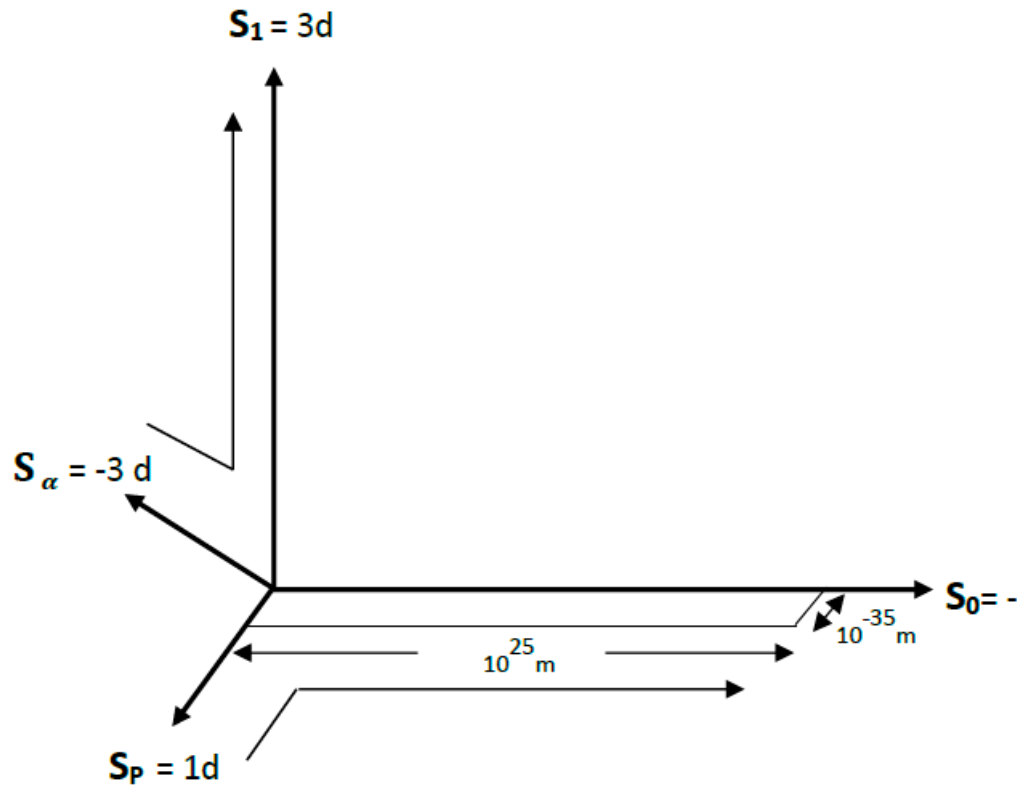
Figure 1. Large spatial dimensions S_1 and S_0 and their microscopic dimensional partners S_α and S_P. Gravitational inversion symmetry implies that S_P and S_α were contracted to their minimum microscopic sizes to inflate S_1 and S_0 in the early universe. Before then, it is assumed they were all comparable in size. The gravitational inversion interaction is now between S_1 and S_0 as illustrated in Figure 5 in section 3.1.

2.1. Speed constraint and invisibility of S_0

Despite its cosmic size, the S_0 dimension is invisible due to its time like behavior from the speed constraint illustrated in Equation (2) and Figure 2. The speed constraint requires that a particle's velocity must always equal the maximum speed limit c in the $S_1 - S_0$ dimension. Massless particles like photons have zero velocity component along S_0, while massive particles and antiparticles travel in opposite directions along S_0. This motion along S_0 is quantitatively equivalent to the passage of time such that,

$$c^2 = \mu^2 + v^2 \ (2)$$

where μ is particle velocity along S_0, and v is particle velocity along visible spatial dimension S_1.
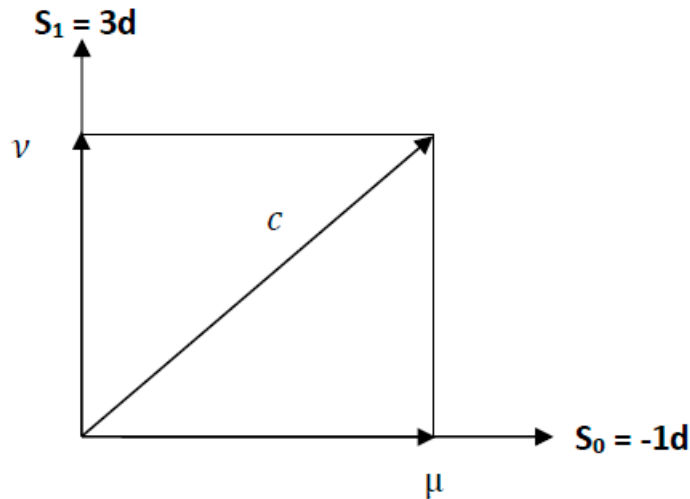
Figure 2. The speed constraint relationship between visible spatial dimensions S_1 and time like spatial dimension S_0.

When $v \to 0$, for massive particles, $\mu \to c$ and conversely, when $v = c$ for massless particles, $\mu = 0$ to satisfy the speed constraint.

This suggests that time can be an emergent temporal dimension driven by the velocity of a particle along S_0 dimension. How fast time appears to pass for a massive particle can be equivalent to the ratio of its S_0 component of velocity μ to the speed limit c as,

$$\frac{1}{\gamma^*} = \frac{\mu}{c} \quad (3)$$

Where γ^* is the equivalent Lorentz factor for the S_0 dimension. Since

$$\mu^2 = c^2 - v^2 \quad (4)$$

$$\gamma^* = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \quad (5)$$

2.2. Speed limit asymmetry
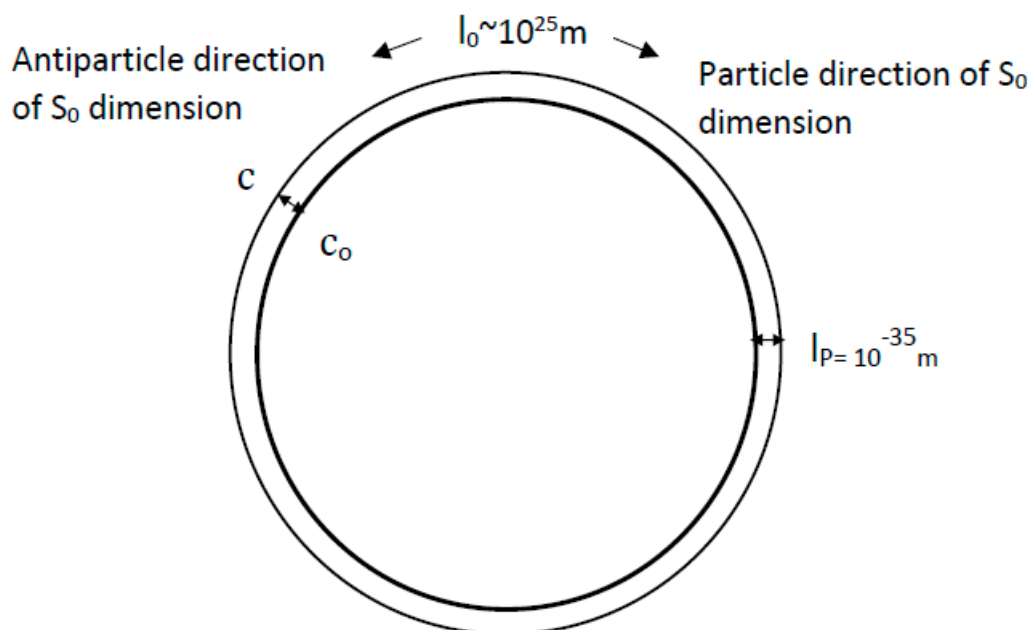
Figure 3. Ring structure of S_0 - S_P dimensions with two unequal speed limit states C and C_0, at the two ends of S_P dimension. Traveling in opposite directions of S_0 represents particle and antiparticle states. A net spin with respect to this time like dimension might cause baryon asymmetry.

The asymmetry in speed limits c and c_0 is described by the asymmetry parameter Γ which is the ratio of the Planck size of S_P to the size of S_0 dimension and $0 < \Gamma < 1$

$$\Gamma = \frac{2\pi}{l_o} \quad (6)$$

where l_o is the size of S_0 in Planck unit. And $l_o = \Delta l_o + l_f$. where $l_f \sim 10^{60}$, is the value of l_o in flat spacetime. The increase in size Δl_o is proportional to the absolute value of the gravitational potential $|\Phi|$ such that,

$$\Delta l_o = \varepsilon |\Phi| \quad (7)$$

where ε is a constant. We also have the following asymmetry relationship between the two speed limits which is also affected by the dynamics of Γ.

$$C_o = C[1 - \Gamma] \quad (8)$$

2.3. Gravitational state oscillation

Standard model particles, except neutrinos, oscillates between the two speed states which are also opposite gravitational on and off states. This is such that for a particle of energy E, the state life time t_s for such particle is

$$t_S = \frac{4\pi\hbar}{\sqrt{E_P^2 - E^2}} \quad (9)$$

Where $\hbar$ is the reduced Planck constant and E_P is the Planck energy.

The oscillation of most standard model particles between the two gravitational states $G_0 = 0G$ and $G_0 = 2G$, makes gravity discrete on microscopic spacetime scale. It however appears smooth on macroscopic spacetime scale with an average gravitational constant G.

2.4. Energy density constraint

The energy density constraint essentially constrains the total energy density in a given volume of spacetime to always equal the upper limit of the Planck density ρ_P. This is only obtainable in the gravitational active state where the speed limit is c while the bare vacuum energy component exists in the inert state with lower speed limit and hence lower Planck density ρ_{P0}.

$$\rho_P^2 = \rho_m^2 + \rho_{vac}^2 \quad (10)$$

where ρ_{vac} is the vacuum energy density, and ρ_m is the total baryonic matter density. The key significance of this, is in the emergence of non zero Λ dark energy in section 4. However, such energy density constraint implies a Planck density limit to the density of black holes like that suggested in [13], where Planck stars replaces black hole singularities.

3. General Relativity in S_0 dimension

Solution of Einstein's Field Equations in 1+1 dimensionality is being used as a pedagogical tool [14] and reveals some interesting properties of the equations in such dimensionality.

In this section, the focus is on General Relativity in -1+1 dimension which has some inverted features not seen 1+1 dimensionality because of the negative dimension number of S_0. The negative dimension number of the S_0 dimension gives it some time like features such as appearance of positive

energy density as negative energy density and the inversion of positive pressure to negative pressure. Eintein's Field Equations in S_0 can be expressed as

$$G^*_{\mu\nu} + \Lambda^* g_{\mu\nu} = \frac{8\pi G}{c^4} T^*_{\mu\nu} \quad (11)$$

Where $G^*_{\mu\nu}$ is the equivalent Einstein Tensor in S_0 dimension. Λ^* is the equivalent cosmological constant and $T^*_{\mu\nu}$ is the stress energy tensor as seen in S_0 dimension.

In -1+1 dimensionality, just as in 1+1, the curvature term $G^*_{\mu\nu}$ is zero, and Equation (11) becomes

$$\Lambda^* g_{\mu\nu} = \frac{8\pi G}{c^4} T^*_{\mu\nu} \quad (12)$$

3.1. Features of General Relativity in S_0 dimension

The negative one dimensionality of S_0 confers on it some unique features such as:

i.   Positive energy density in S_1 is equivalent to negative energy density everywhere in S_0.

An energy density associated with a given Planck volume of 3d space S_1 appears as an equivalent negative energy density everywhere along S_0 dimension associated with it as a positive cosmological constant as illustrated in Figure 4.

ii.   Positive pressure in S_1 is equivalent to negative pressure in S_0

Any form of positive pressure in S_1 appears as negative pressure in S_0 for the same reason of negative dimensionality. The result is a positive cosmological constant expansion of S_0.

iii.   Negative pressure in S_1 is equivalent to a positive pressure in S_0

The same negative dimensionality causes the inversion of negative pressure in S_1 appearing as positive pressure in S_0 driving its negative cosmological constant contraction.

The result is that the curvature of S_1 ($G_{\mu\nu}$) is equivalent to the cosmological constant expansion of S_0 as illustrated in Figure 5 such that,

$$G_{\mu\nu} + \Lambda^* g_{\mu\nu} = 0, \quad (13)$$

and a positive cosmological constant term ($\Lambda g_{\mu\nu}$) in S_1 is equivalent to a negative cosmological constant term ($-\Lambda^* g_{\mu\nu}$)   in S_0 such that,

$$\Lambda g_{\mu\nu} - \Lambda^* g_{\mu\nu} = 0 \quad (14)$$
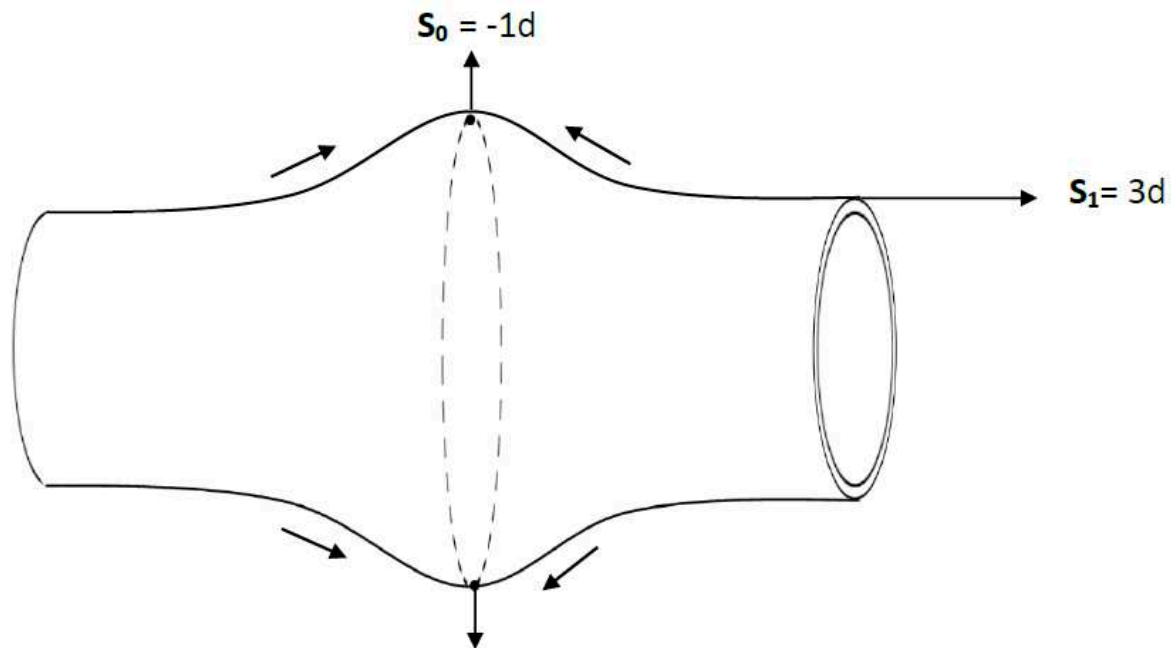
Figure 4. A gravitational well in S_1 is inverted into a gravitational hill with the expansion of S_0 by a test particle. The test particle is replicated over 10^{60} times everywhere along S_0 dimension.
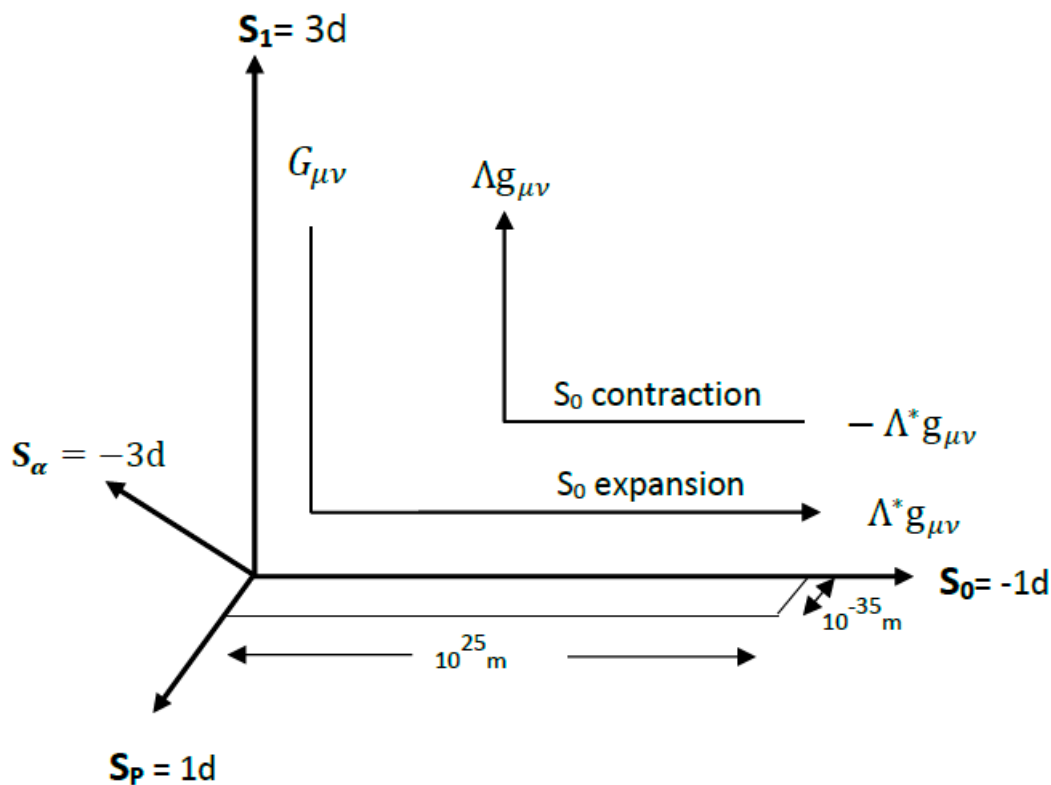
Figure 5. Gravitational inversion. A positive cosmological constant expansion of S_0 is equivalent to curvature of S_1. Also, a negative cosmological constant contraction of S_0 is equivalent to a positive cosmological constant expansion of S_1.

3.2. Gravitational chain of causality

The inversion of gravitation discussed in the previous section suggests that at a more fundamental level, gravity is the expansion or contraction of S_0 dimension. This then manifests in an inverted form as curvature or expansion of S_1 dimension as illustrated in Figures 5 and 6. The existence of gravitational on and off states acts as a filter in this gravitational chain of causality enabling real particles to gravitate while virtual particles remain inert.
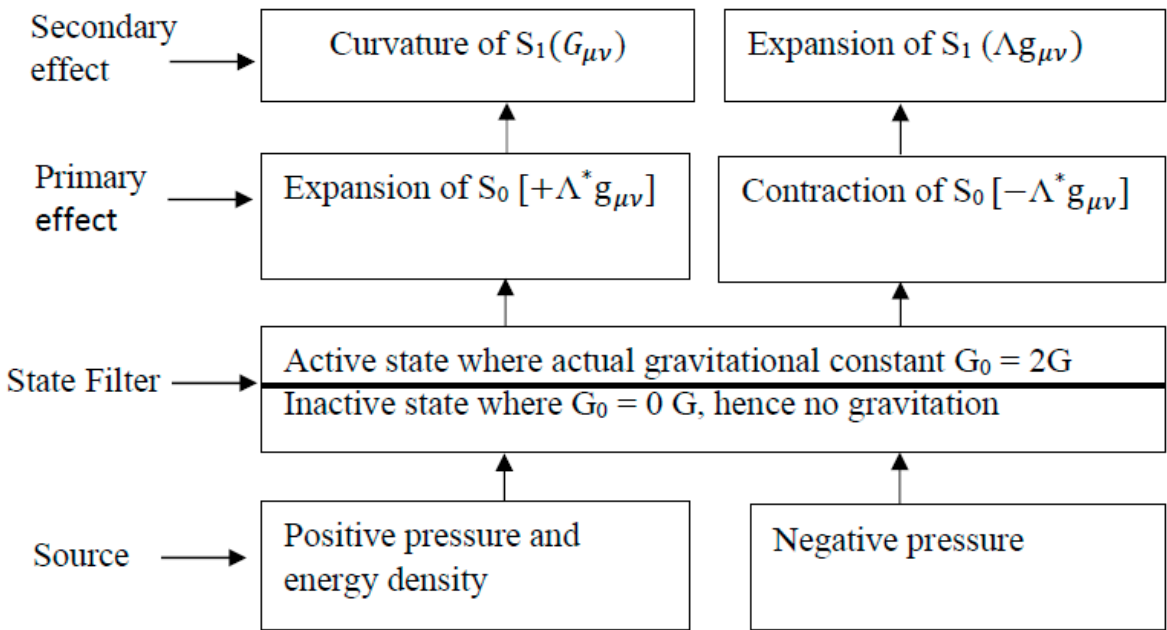
Figure 6. Gravitational chain of causality. Gravity at a more fundamental level is about expansion or contraction of S_0 which manifests invertedly in S_1 as curvature or expansion respectively. Also gravitation of particles depends on if they are in a gravitationally active or inert state.

The relatively permanent existence of the bare vacuum energy component in the gravitationally inert state ensures that it does not gravitate. This partly solves the cosmological constant problem. The second part of the problem about the non zero value is addressed in the next section.

4. Emergence of non zero Cosmological Constant

The asymmetry in speed limit described in Equation (8) between the two gravitational states also reflects in the values of their Planck densities such that

$$\rho_{P0}^2 = \rho_P^2[1 - \Gamma^4] \quad (5)$$

Where ρ_{P0} is the lower Planck density in C_0 state and ρ_P is the Planck density in the C state.

The existence of the bare vacuum energy component ρ_{vac} in the lower C_0 state implies that

$$\rho_{vac} = \rho_{P0} \quad (16)$$

Which is less than the Planck density and the energy density constraint requires that the total vacuum energy density should be equal to the Planck density in the absence of matter.

Since the gravitationally inert lower speed state lack the capacity to contain all the vacuum energy components, a small component spills into the gravitationally active state as dark energy.

$$\rho_{DE} = \rho_P\Gamma^2 \quad (17)$$
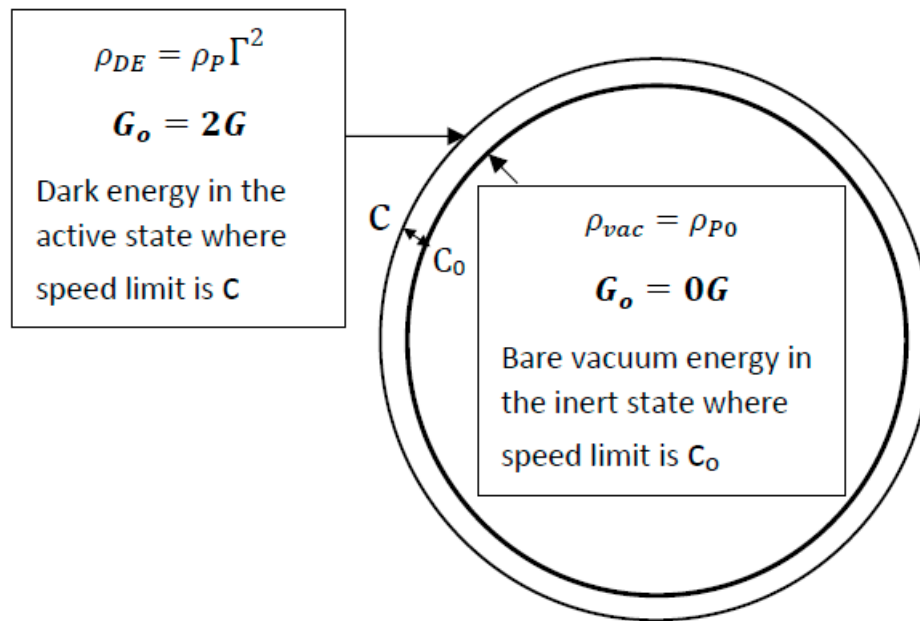
Figure 7. While the bare vacuum energy component occupy the gravitationally inert state C_0 to its limit, there has to be a component ρ_{DE} in the gravitationally active state C to satisfy the energy density constraint so that the total vacuum energy density equals the Planck density ρ_P. The lower Planck density ρ_{P0} is associated with speed state C_0.

Since Γ is suppressed with the expansion of S_0 in the gravitational well of massive objects (Equation (6) and Figure 4), the density of this form of dark energy varies spatially according to this suppression by gravitational potential wells. The deeper the gravitational well the more the suppression. And substituting the value of Γ from Equation (6),

$$\rho_{DE} = \frac{4\pi^2\rho_P}{l_0^2} \quad (18)$$

Where l_0 is the size of S_0 dimension in Planck unit, which increases with the absolute value of the gravitational potential Φ according to Equation (7).

5. Gravitational Wave Reheating (GWR) Prediction

The propagation of gravitational waves along the visible 3d space S_1 should naturally vibrate any extra spatial dimension such as the S_P and S_0 dimensions. Such stretching of S_P dimension during such vibration can cause the creation of real photons out of vacuum energy. This is the Gravitational Wave Reheating (GWR) mechanism of EDS.

However as illustrated in Figure 8, the expansion of S_0 dimension in gravitational potential wells suppresses the possible stretching of S_P dimension resulting in a threshold value of strain h below which reheating cannot occure.
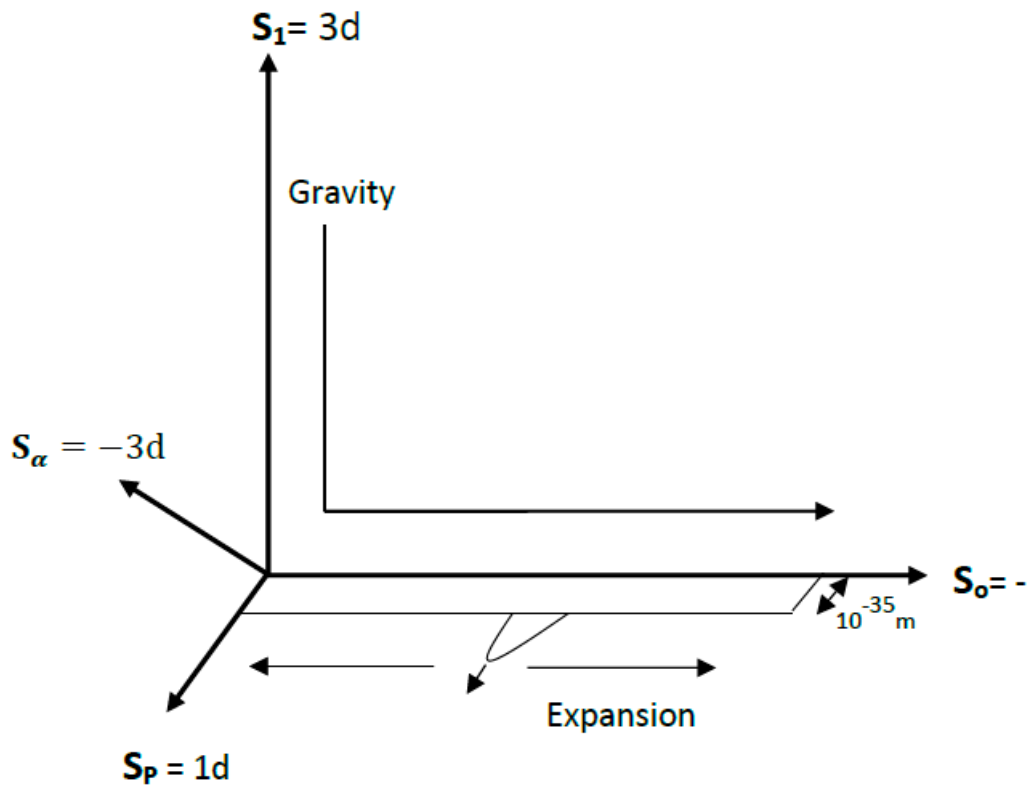
Figure 8. The expansion of the S_0 dimension in gravitational potential wells, suppresses the possible stretching of S_P dimension by gravitational waves oscillations.

This is such that for reheating to occur, the gravitational wave strain h must be greater than the gravitational strain h_0 of S_0 expansion.

$$h > h_0 \quad (19)$$

and

$$h_0 = \frac{\Delta l_0}{l_f} = \frac{\varepsilon |\Phi|}{l_f} \quad (20)$$

Where Δl_0 is the increase in the size of S_0 dimension and it is proportional to the absolute value of the gravitational potential Φ from Equation (7). l_f is the size of S_0 in flat spacetime. h_0 hardens the S_P dimension against gravitational wave oscillation.

5.1. Energy scale of reheat photons

The maximum energy E_{max} of the reheat photons that can be emitted in the resulting spectrum can be described by

$$E_{max} = E_P h_P \quad (21)$$

Where E_P is the Planck energy and h_P is the effective stretching strain of the resulting S_P oscillation once the threshold gravitational wave strain is exceeded such that $h_P = h - h_0$.

5.2. Magnetic softening of the S_P dimension

Magnetic fields produce negative pressure that can flatten curvature and even dampen gravitational waves [15]. Within the EDS framework, the gravitational strain of expansion (h_0) of the S_0 dimension is a measure of spatial curvature. Therefore, the flattening of spacetime curvature softens the S_P dimension which becomes more sensitive to gravitational wave oscillation.

In essence, a strong magnetic field like that obtainable around magnetars, softens the S_P dimension by lowering the threshold strain required for reheating to occur with incident gravitational waves.

From energy conservation perspective, the energy lost by gravitational waves passing through a strongly magnetized region has to be released in some form and GWR provides the mechanism for converting the gravitational wave energy into electromagnetic one. It is expected that the brief burst of electromagnetic waves radiated while the gravitational waves passes through a strongly magnetized region such as magnetars, should be in the form of radio waves.

6. Dark Matter from Vacuum Energy

The bare vacuum energy component should always be gravitationally inert with its existence in the $G_0 = 0G$ state where the gravitational field is effectively swiched off. However, in this framework, neutrinos affects their background in the inert state such that $G_0 > 0G$. Within such background in the inert state, neutrinos provide some gravitational illumination described by Equation (22) that enables virtual particles to gravitate with positive pressure appearing as dark matter.

$$G_v = (\Gamma^2 + \beta\phi)G \quad (22)$$

Where G_v is the neutrino induced gravitational constant in the inert state. ϕ is a dimensionless phase parameter that is either zero or one, with zero being a ground state and one, the excited state. Γ is the same asymmetry parameter involved in the emergence of dark energy. β is a dimesionless parameter that varies with neutrino kinetic energy. $0 \leq \beta \leq 1$ and it is described by,

$$\beta = \frac{E_v}{E_P} \quad (23)$$

Where E_v is the neutrino kinetic energy and E_P is the Planck energy. Substituting Γ from Equation (6), Equation (22) becomes,

$$G_v = \left(\frac{4\pi^2}{l_0^2} + \beta\phi\right)G \quad (24)$$

Where l_0 is the size of the S_0 dimension (in Planck unit) which increases with the absolute value of the gravitational potential Φ in Equation(7), hence the suppression of dark matter effect in deep gravitational potential wells.

While hot dark matter is the form of dark matter that can be produced by relativistic neutrinos, cosmic neutrinos are nonrelativistic. Such non relativistic cosmic neutrino substrates should be further slowed down by the Higgs like drag from its self induced gravitational interaction with virtual particles within its background. This enhances the clustering of cosmic neutrino substrates and the gravitating virtual particles in their background appear as cold dark matter.

The gravitational potential suppression of G_v enables this substrate dependent form of dark matter to have hybrid behaviour by mimicking modified gravity form of dark matter such as Modified Newtonian Dynamics (MOND) while also exhibiting some particle behavior of its neutrino substrates like the gravitational polarization of vacuum energy approach [13] and superfluid dark matter described in [16].

Categories of neutrino substrate dependent dark matter

Heavy and light dark matter are two categories of neutrino substrate dependent dark matter that exists within the EDS frame work depending on the neutrino energy scale and phase parameter. Equation (22) consist of a rest term $\Gamma^2 G$ and a kinetic term $\beta\phi G$. The kinetic term can be active or inert depending on the phase parameter ϕ which can either be zero or one. ϕ is switched to one by a threshold negative pressure that depends on the gravitational potential and falls back to its ground state within a life time t_ϕ.

i.   Heavy dark matter

From Equation (22), an Ultra High Energy neutrino with a kinetic energy of 10^{15} eV and a phase parameter $\phi = 1$, will have an active kinetic term. It can induce a gravitational constant G_ν close to 10^{-13} G in the gravitationally inert state where the bare vacuum energy exists. With the gravitation of vacuum energy of the order the Planck density, it can manifest as detectable heavy dark matter with an equivalent gravitational parameter μ of a microscopic black hole with mass of a small asteroid outside the deep gravitational potential wells of planets and stars. As the high energy neutrino substrate falls back to the ground phase with $\phi = 0,$ or falls into the gravitational potential well of a planet like Earth, this effect is suppressed to making it become a lighter form of dark matter. A micro-resolution digital scale should have the sensitivity to detect the gravitational effect of such heavy dark matter outside the deep gravitational well of the planet.

ii.   Light dark matter

Neutrinos in the $\phi = 0$ phase, particularly cosmic neutrinos can induce G_ν close to 10^{-120} G in the gravitationally inert state, resulting in light and cold dark matter with an effective density close to dark energy clustered within and around galaxies. Such light form of dark matter which dominates the total dark matter density in this framework, can only be detected through the CMB, gravitational lensing and the dynamics of wide stellar binaries, galactic and extra galactic structures.

7. Summary and Conclusion

EDS provides an elegant framework for the resolution of the cosmological constant problem of dark energy and the nature of dark matter. In doing so it provides deeper insights into the dimensional structure of spacetime and chain of causality involved in gravitation. Specifically, it places the bare vacuum energy component in a state where the gravitational field is switched off with actual gravitational constant $G_0 = 0G$, while real standard model particles apart from neutrinos, oscillate between this gravitationally inert state and the active state.

Due to an energy density constraint and a speed limit asymmetry that limits the capacity of the inert state to contain all the vacuum energy component, a small component spills into the active state as dark energy. The asymmetry parameter is the ratio of the size of the spatial equivalent of time S_0 and its microscopic partner S_P.

The illuminating effect of neutrino substrates particularly cosmic neutrinos, induces non zero gravitational constant in the inert state, providing gravitation for virtual particles which appears as dark matter. This neutrino substrate dependent form of dark matter can exhibit a hybrid behaviour of particle dark matter and modified gravity form of dark matter like the gravitational polarization of vacuum energy approach [13] and superfluid dark matter [16].

The reheating prediction in which gravitational waves produce electromagnetic secondary with negative pressure from strong magnetic fields of magnetars and dark energy might be the sources of Fast Radio Bursts (FRBs) [17] and Excess Radio Background (ERB) [18].

Expected results from the trio of the JWST, Euclid and upcoming Nancy Grace Roman Telescope and Vera Rubin Observatory, are expected to provide precision measurements of dark energy density as well as the dynamics of dark matter. Such precision measurements should glean out the predicted suppression of dark energy density in the deep gravitational potential wells of baryonic matter like it apparently does to dark matter.

There are a number of potential insights that are beyond the scope of this paper. For instance it is possible that the fine structure constant just like Γ, is simply the ratio of the Planck scale to the size of the S_α dimension. This possibility as well as others like baryon asymmetry from net spin with respect to the S_0 dimension (Figure 3), shall be investigated in future work.

In conclusion, the EDS framework offers new physics explanations for dark energy and dark matter as different manifestations of vacuum energy that can be tested and provides potential insights into the dimensional structure of spacetime and gravity.

Author Contributions: Kabir Adinoyi Umar: Conceptualization, Investigation, Writing-original draft, Writing-review and editing, Resources. Benjamin Gbenga Ayatunji: Supervision.

Data availability: No data was used for the research described in the article

Acknowledgments: The author gratefully acknowledge Benjamin G. Ayatunji for his criticisms, encouragement and mentorship and S. X. K. Howusu for his inspiring advice and initial motivation for this work. This work was funded by the author.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Riess, A. G. *et al*., Observational evidence from supernovae for an accelerating universe and a cosmological constant, Astron. J. **116** (1998) 1009-1038, arXiv: astro-ph/9805201
2. Ade P. A. R. *et al*., Planck 2013 results. XVI. cosmological parameters, (2013), arXiv:1303.5076[astro-ph.CO].
3. Carroll, S. M., The cosmological constant, Living Rev. Rel. 4:1, (2001), arXiv:astro-ph/0004075
4. Kachru, S. *et al*., de Sitter vacua in string theory, Phys. Rev. **D68** (2003) 046005, arXiv:hep-th/0301240.
5. Banks, T. *et al*., On anthropic solutions of the cosmological constant problem, JHEP **0101** (2001) 031, arXiv:hep-th/0007206.
6. Arkani-Hamid, N., A small cosmological constant from a large extra dimension, Phys. Lett. **B480** (2000) 193-199, arXiv:hep-th/000197.
7. Copeland, E. J. *et al*., Dynamics of dark energy, Int. J. Mod. Phys. **D15** (2006) 1753-1936, arXiv:hep-th/0603057.
8. Oks E., Brief review of recent advances in understanding dark matter and dark energy, New Astron. Rev. **93** (2021) 101632, arXiv:2111.00363[astro-ph.CO].
9. Arun K. et al., Dark matter, dark energy and alternate models: a review, Advances in Space Research, **60**, (2017) 166-186, arXiv: 1704.06155[physics.gen-ph]
10. Hajdukovic D. S., Quantum vacuum and dark matter, Astrophysics and Space Science **337** (2012) 9-14
11. Borchert M. J., Devlin J. A., Ulmer S., et al., A 16 parts per trillion measurement of the antiproton to proton charge-mass ratio, Nature **601** (2022) 53-57
12. Huck S. et al., Toward a pulsed antihydrogen beam for WEP test in AEgIS, EPJ Web of Conf. **282** (2023) 01005
13. Rovelli, C., Vidoto, F., Planck Stars, Int. J. Mod. Phys. **D23** (2014) 1442026, arXiv:1401.6562
14. Boozer A. D., General relativity in (1+1) dimension, Eur. J. Phys. **29** (2008) 319-333
15. Tsagas C. G., Magnetic tension and the geometry of the universe, Phys. Rev. Lett. **86** (2001) 5421
16. Hossenfelder S., Mistele T., The Milky Way's rotation curve with superfluid dark matter, MNRAS **498** (2020) 3484-349, arXiv:2003.07324[astro-ph.GA]
17. Zhang B., The Physics of Fast Radio Bursts, (2022), arXiv:2212.03972[astro-ph.HE]
18. Fialkov A., Barkana R., Signature of Excess Radio Background in the 21-cm global signal and power spectrum, (2019), arXiv: 1902.02438[astro-ph.CO]