Nature of Dark Energy

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Abstract

A cosmological constant dark energy (Λ), capable of early universe inflation and sensitive to matter and radiation is described within the Rute framework. Rute is a spin model of discrete spacetime in which time is driven by spin along an extra dimension. In this scenario, matter and antimatter are opposite spin states and a key dimensional symmetry doubles the spatial dimensions with microscopic partners. Its Gravitational Wave Reheating (GWR) mechanism predicts that gravitational waves with strain above a threshold, should release electromagnetic secondaries during propagation. This feature, offers a tantalising opportunity for indirect gravitational wave observation. A number of other verifiable predictions are discussed.

Keywords: *Rute – Dark Energy – Gravitational Wave Reheating– Dimensional Symmetry – Inflation – Spin.*

I. Introduction

Dark energy has so far constituted an enigma since Riess *et al*.(1998) followed by Perlmutter *et al.* (1999) published their supernova observations of the accelerated expansion of our Universe. Since then, several independent lines of evidence have led to the conclusion that there is a mysterious negative pressure dark energy component driving the accelerated expansion of the universe. Results published by the Planck collaboration (Ade *et al*. 2013), show that dark energy density constitutes about 68.3% of the total energy density of our Universe, while ordinary baryonic matter constitutes 4.9%. The invisible dark matter component makes up 26.8%.

Dark Energy, according to the standard model of cosmology known as the Lambda Cold Dark Matter model (ΛCDM), is in the form of Einstein's cosmological constant (Λ). Λ in turn, is known to arise from vacuum energy, an intrinsic energy associated with empty space. But quantum field theory estimated a vacuum energy density 10^{120} times more than the observed dark energy density. This is the cosmological constant problem. The challenge here is to provide a satisfactory explanation to the nonzero and extremely small value of Λ without suffering the common finetuning problem. It is also not known what the connection of Λ, if any, is to inflation (a brief period of exponential expansion of the early universe) (Brandenberger 2001).

Supersymmetry (SUSY) provides an elegant framework for the cancellation of large Λ to a very small value. In unbroken SUSY, every bosonic particle has its own fermionic superpartner with same mass but with each contributing opposite signs thereby cancelling vacuum energy and resulting in zero Λ. Null search result for SUSY partners of the standard model particles shows that SUSY, if at all describes our universe, must be broken. Even with SUSY breaking around 10^3 GeV, it is still very far above the observed dark energy density.

There are a number of other cancellation models such as that from string theory which cancels the bare Λ down to a small effective value (Bousso and Polchinski 2000). There are also relaxation models where the value of the vacuum energy density is relaxed (Kachru *et al.* 2003) including anthropic considerations (Banks *et al.* 2001) and even an approach that makes the spacetime metric insensitive to the cosmological constant (Kachru *et al.* 2000; Arkani-Hamid *et al.* 2000).There are several other alternative approaches which avoid the thorny problem of Λ such as quintessence, unification of dark energy and dark matter (Sherrer 2004) and modification of gravity (Zhao and Li 2010). For detailed review see Copeland *et al.* (2006) and Kamionkowsky (2007).

On appreciating the seriousness of the Λ problem, it becomes more apparent that a satisfactory solution requires new Physics. Such a solution should also provide some clues to other problems like the Physics of inflation and the nature of time among others.

In this paper, we approach the Λ problem using the RUTE model we have developed. RUTE is not a cancellation model since vacuum energy here, is gravitationally inert. In this scenario, vacuum energy is gravitationally inert and unavailable for useful work in visible 3-D space because vacuum energy oscillations are restricted to a Planck size extra dimension. Here, dark energy is modeled as a spill component of vacuum energy with energy scale coupled to entropy and therefore had inflationary energy scale in the early universe before it asymptotically fell to its present energy scale. It is well known however, that a Λ driven inflation usually suffer from the graceful exit and reheating problems as attempted in Brandenberger and Mazumdar (2004). This can be resolved with an asymptotically falling Λ and the Gravitational Wave Reheating (GWR) mechanism provided by this framework for releasing some component of vacuum energy from a microscopic extra dimension into the visible spatial dimensions, first as Standard Model (SM) photons before pair creation and annihilation of other SM particles, obviating the need for a scalar field driven inflation.

The key element of RUTE is the interpretation of time as progression of events in a spatial reference frame driven by the relative motion of that reference frame along either direction of a spatial component of time dimension. In this scenario, time as a temporal dimension, requires a designated spatial component apart from the 3 spatial dimensions to function .It differentiates between time as an entropic effect and time as a space-like dimension. Indeed such separate interpretations of time as a progressive effect and time as a spacelike dimension provides an extra degree of freedom in tackling the dark energy problem. A problem that still requires a Planck size spacelike partner of the known entropic time dimension. The idea of two time dimension had been suggested in Bars (2006) although in a different context of SM particles and forces.

II. The RUTE Framework.

RUTE is a model of spacetime structure. Its dimensional symmetry requires that for every macroscopic spatial dimension, there is a microscopic dimensional partner with a negative dimension number D_N. This is such that the total dimension number of the universe adds up to zero. In this case, the dimensional partner of the spatial component of time dimension T_1 is a Planck size T_2 dimension ($T_2 = -1$–D) whereas for the macroscopic set of visible spatial dimensions S_1, the microscopic counterpart is S_2 dimensions ($S_2 = -3$-D).

A. Entropic Gravity

While RUTE is in agreement with general relativity, it is also in agreement with recent developments in entropic gravity (Verlinde 2011). Here, attractive gravity is caused by any change in information encoded in visible 3-D space due to presence of mass/energy or changes in particle position or even changes in the curvature of spacetime (gravitational waves). Presence of negative pressure on the other hand does not constitute entropy change in 3-D space and therefore cannot be gravitationally attractive. It follows that it has to be repulsive according to general relativity.

B. Inert Vacuum Energy

Vacuum energy in this framework is gravitationally inert because it does not encode any information changes in visible 3-D space and its oscillations are restricted to a Planck size extra dimension. The spacetime metric is only sensitive to component of vacuum energy oscillation that gets directed along (spills into) the visible 3-D space as dark energy. This spill mechanism is discussed in section 5.

C. Volume constraint and entropic gravity

The volume constraint simply infers that the 8-D spatial volume of the universe is constant. That is, the contraction or expansion of any dimension must be balanced by a corresponding expansion or contraction of another dimension. This implies that, while the gravitational contraction of S_1 by positive pressure and energy drives the expansion of spacelike time dimension T_1 as shown in fig. 1, the expansion of S_1 driven by negative pressure is required to be fed by the contraction of its microscopic dimensional partner S_2.

In this scenario, any entropy change (change in encoded information) in the visible spatial dimension is required to be encoded on the ring-like surface of the spatial component of time dimension T_1-T_2 (see fig. 2 in section 3) . Interestingly, the length of T_1 dimension in Planck unit here, is equal to the entropy of the universe in an analogous way the surface area of a blackhole is known to be a measure of its entropy.

$$S = 2\pi r \quad (1)$$

where r is the radius of the spatial component of time dimension due to its ring-like structure. As it is shown in the coming sections (particularly in section 5), it is this measure of entropy that dark energy is coupled to, since it is also a function of radius r.

It follows that any change in entropy (or change in information in Planck unit) encoded in visible 3-D space, reduces its volume to increase the length of T_1 dimension by one Planck unit.

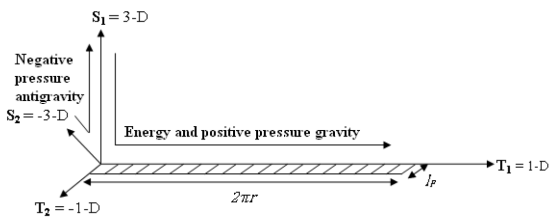

Fig. 1: Gravitational flow across the 7 spatial dimensions of $S_1 = 3$-D, $T_1 = 1$-D, and $S_2 = -3$-D. T_2 is constant in size.

III. Nature of Time

The actual nature of time has been one of the unsolved problems in Physics (Lobo 2007; Barbour 2009). RUTE essentially interprets time as an irreversible progressive effect of motion of a spatial reference frame along either direction of a spatial component of time dimension. In this scenario, there is difference between time as an effect and time as a spacelike dimension. In essence, while a time dimension has a spatial component, it is the motion of a reference frame along either direction of such dimension that drives time. Specifically, as illustrated in fig 2, it is the rotation of every point in space (brane universe) along T_1 dimension that drives time as we know it and relativistic effects such as time dilation results from speed deficit along such dimension.

In line with the Feynman-Stueckelberge interpretation, particles and antiparticles travel in opposite directions along the spatial component of time dimension T_1, as illustrated in fig. 2. Massless particles with maximum spatial velocity c have zero orbital speed along T_1. Thus, the speed limit c, serves as a barrier between particle and antiparticle states.

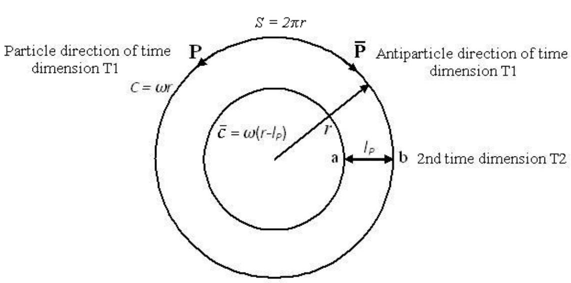

Fig. 2: The 2-D ring structure of the spatial component of time dimension in RUTE brane universe. The ring thickness (brane thickness) which is Planck length l_P in size, is the spatial component of a second time dimension T_2.

The entropy S of the universe as illustrated in fig. 2 above, is simply the surface area of the ring-like T_1-T_2 dimension in Planck unit. Since T_2 is Planck size, entropy simply equals $2\pi r$ which is the length T_1 dimension as expressed in eq. (1).

A. Speed Constraint

Given the speed of light constraint from special relativity and associated relativistic effects, the interpretation within the RUTE framework requires that all reference frames must always travel at speed of light c through combined spacetime dimensions. That is, the vector sum of its spatial velocity $\mathbf{V}$ along the 3 spatial dimensions S_1 and its velocity $\mathbf{V_T}$ along T_1 dimension must always equal $\mathbf{C}$.

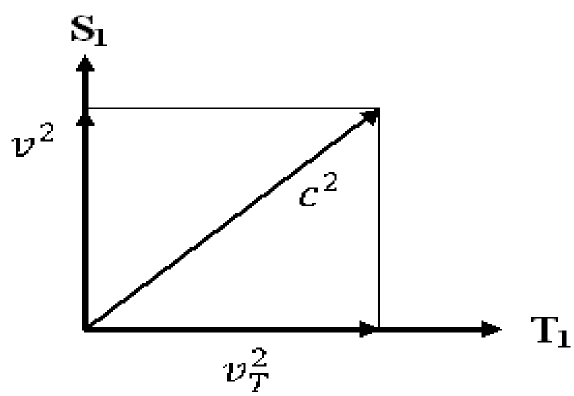

Fig. 3: The speed constraint. It is required that the magnitude of the vector sum of the spatial and time dimension components of velocity of any reference frame must always equal c.

$$c^2 = v^2 + v_T^2. \quad (2)$$

As illustrated in fig. 3, for a spatial reference frame or massive particle with spatial velocity v (relative to an observer), its velocity v_T component along T_1 dimension can be expressed as

$$v_T = \sqrt{c^2 - v^2}. \quad (3)$$

Its clock rate factor Γ can be expressed as the ratio of its speed along T_1 dimension to the speed of light

$$\Gamma = \frac{V_T}{c}\ . \quad (4)$$

That is,

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

The inverse of the clock rate factor gives the Lorentz factor,

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \quad (6)$$

IV. Second Time Dimension

As noted in the previous section, the speed constraint limits a reference frame to always move at resultant velocity, c, through 3-D space and T_1 dimension,. In what follows, we discuss T_2 dimension, which is the dimensional partner of T_1. In this scenario, T_2 is the brane thickness with which the speed constraint equally applies. Its Planck size and reflective boundary condition results in an oscillatory time dimension where every point in space oscillate between 2 vacuum states a and b (brane surfaces) along T_2 dimension as shown in fig. 4 below.

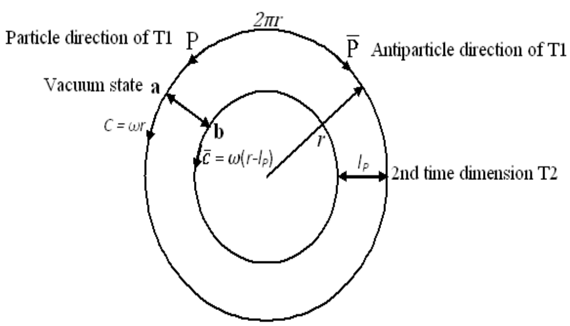

Fig. 4: A vacuum reference frame oscillates between the 2 vacuum states a and b with different speed limits c and $\bar{c}$ along T_2 dimension at the Planck frequency f_{Planck}

The 2 opposite vacuum states a and b for time dimension T_2 are analogous to the particle and antiparticles states for time dimension T_1 and there is a difference in speed limit c and $\bar{c}$ between the 2 states. This difference in speed $(c - \bar{c}\ )$ between the vacuum states can be described by the cosmological factor Γ.

$$\Gamma = \frac{(c-\bar{c}\ )}{c} \quad (7)$$

$$\Gamma = \frac{l_p}{r} \quad (8)$$

and $0 < \Gamma < 1$, asymptotically approaching zero with growth of entropy $2\pi r$.

The factor $\frac{\Gamma}{2\pi}$ gives the relative size of the two time dimensions T_1 and T_2.

A. Energy Density Constraint

If we apply the speed constraint to time dimension T_2, then a vacuum reference frame (empty space) must travel at c along T_2 dimension, but with the Planck size of T_2 and its reflective boundary condition; such a vacuum state must oscillate at $f_{\text{Planck}} = c/l_p$. The speed constraint in eq. (2) results in the frequency constraint,

$$f_{\text{Planck}}^2 = f^2 + f_{vac}^2. \quad (9)$$

where f_{vac} is the vacuum oscillation frequency along T_2 dimension and f is the oscillation frequency along the spatial dimensions S_1. These oscillations translate to energy as $E = \hbar f$. where $\hbar$ is the Planck constant, leading to the Planck energy and Planck energy density constraints.

$$E_{\text{Planck}}^2 = E^2 + E_{vac}^2 \quad (10)$$

$$\rho_{Planck}^2 = \rho^2 + \quad (11)$$

where E and E_{vac} are the energy of a particle and the associated vacuum energy along T_2 dimension. ρ and ρ_{vac} are the spatial component of energy density and component vaccum energy density along T_2 dimension respectively. In essence, the sum of spatially observable energy density ρ of a given reference frame and its component vacuum energy density ρ_{vac} along time dimension T_2 must always equal the upper limit of the Planck density ρ_{Planck}. The reference to upper limit here is due to an intrinsic asymmetry between the 2 vacuum states along T_2 dimension**.**

The energy density constraint forbids infinite energy densities such as black hole singularity and big bang singularity, while predicting the existence of Planck stars also described in Rovelli and Vidoto (2014).

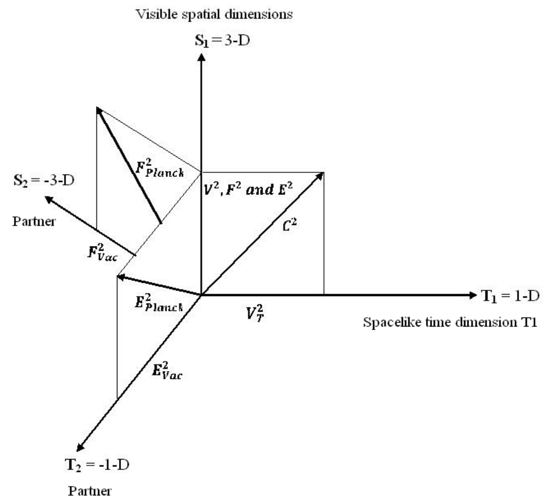

Fig. 5: The basic structure of 8 dimensional space showing the relative projections of Velocity, Energy and Force into the visible spatial dimensions S_1.

Fig. 5 shows the relative projection of velocity and energy into the visible spatial dimensions by the speed and energy constraints. If such constraint can be analogously applied to force in relation to the extra spatial dimensions S_2, then we should have the force constraint associated with the electromagnetic, the strong and weak nuclear forces. This is however beyond the scope of this work.

V. Cosmological Constant Dark Energy

The speed limit asymmetry discussed in section 4 results in the following relationship between the 2 vacuum states.

$$\rho_{Planck} - \bar{\rho}_{Planck} = \Gamma^2 \qquad (12)$$

where ρ_{Planck} is the maximum vacuum energy of vacuum state a with a maximum speed limit c as illustrated in fig.6 below. $\bar{\rho}_{Planck}$ is the deficit vacuum energy density of vacuum state b with deficit speed limit $\bar{c}$. $\Gamma \sim 10^{-60}$ is the cosmological factor, now asymptotically approaching zero as a function of radius r.

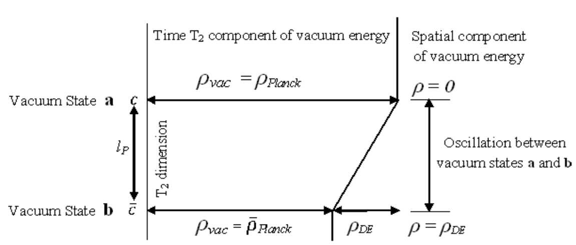

Fig. 6: Asymmetry between vacuum states a and b with densities $\rho_{Planc\,k} > \bar{\rho}_{Planck}$. The vacuum oscillates between states a and b. At vacuum state, vacuum energy is at its maximum value such that $\rho_{vac} = \rho_{planck}$ and spatial component therefore is zero$(\rho = 0)$. At vacuum state b, vacuum energy density has a deficit value of $\rho_{vac} = \bar{\rho}_{planck}$ and therefore, the spatial component of vacuum energy $\rho = \rho_{DE} \neq 0$ to satisfy the energy density constraint $\rho_{Planck}^2 = \rho^2 + \rho_{vac}^2$.

Given the energy density constraint where the energy density in spacetime must always equal the upper limit of the Planck density ρ_{planck} . Any deficite in vacuum energy density along T_2 dimension must be compensated for with a corresponding amount of vacuum energy oscillation being projected along the spatial dimension S_1. Therefore, as the vacuum oscillates, changing from state a to state b as shown in fig. 6, the resulting deficit along T_2 as the vacuum energy density changes from ρ_{Planck} to $\bar{\rho}_{Planck}$ has to be compensated for with the emergence of dark energy ρ_{DE} along the spatial dimensions where

$$\rho_{DE} = \Gamma^2 \rho_{planck} \, . \qquad (13)$$

The energy release is simply reversed with the reverse oscillation from state b to a, since T_2 is not an entropic dimension unlike T_1. This spill-clean up mechanism still produces the effect of a cosmological constant, preventing a catastrophic continuous vacuum energy release of about one solar mass per cm^3 per second, even with the presently small value of $\Gamma \sim 10^{-60}$.

With equation of state $\omega = -1$, it results as a negative pressure cosmological constant

$$\Lambda = \frac{8\pi G}{c^4}(\rho_{DE} + 3P). \qquad (14)$$

As shown in section 4, Γ asymptotically approaches zero as a function of radius r and entropy is also a function of r. With Γ evolving asymptotically with the growth of entropy, Λ runs in a step wise manner. In the early universe with $r \sim l_P$ and $\Gamma \sim 1$, $\Lambda \sim M_{\text{Planck}}^4$ enough to power inflation. The energy scale of Λ here asymptotically falls from the Planck scale with increasing entropy of the universe and with reheating effectively ending inflation, leaving a residual asymptotically vanishing cosmological constant now driving the late time acceleration of the universe. Thus Λ is naturally fine-tuned by the entropic growth of time, thereby avoiding the fine-tuning problem faced by most models of cosmological constant dark energy.

Due to the energy density constraint, the presence of an energy scale (such as matter and radiation presence) above ρ_{DE} at any given moment prevents a spill making the density of dark energy zero at that point in space. In this case eq. (13) becomes

$$\rho_{DE} = \Gamma^2 \rho_{Planck} - \rho_T \tag{15}$$

where ρ_T is the local matter and radiation density and $\rho_{DE} = 0$ when $\rho_T \geq \Gamma^2 \rho_{Planck}$.

Given a volume of space, the average density of dark energy ρ_{DE} can then be expressed

$$\rho_{DE} = \int \left(\Gamma^2 \rho_{Planck} - \rho_T\right) dv \tag{16}$$

VI. Gravitational Wave Reheating (GWR) Mechanism

In RUTE with two time dimensions, where gravity drives the expansion of the spatial component of time dimension T_1, a Gravitational Wave (GW) oscillation along the spatial dimensions S_1 can be mirrored by a corresponding GW oscillation along the T_1-T_2 time dimensions. In what follows, we examine how a T_1-T_2 component of the GW oscillation produces heating effect on empty space releasing some vacuum energy as standard model photons. GW oscillation as seen at the fundamental Planck scale in this frame work is essentially an oscillation of the Planck length l_P, while the Planck area A_P remains constant as illustrated in fig. 7 below.

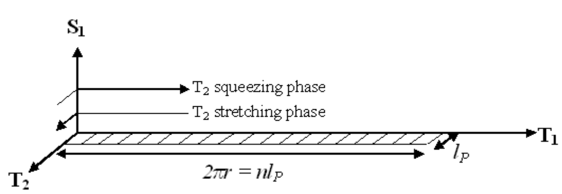

Fig. 7: T_1-T_2 dimension component of gravitational wave oscillation where one time dimension is stretched at the expense of the other and vice-versa while keeping area constant.

At the Planck scale, GWs simply increase Planck length in one dimension while decreasing it in another, keeping the Planck area and volume constant. During GW oscillation of T_1-T_2 dimension, an expansion or contraction of T_2 is balanced by a corresponding contraction or expansion of T_1, respectively.

During T_2 stretching phase of GW oscillation, vacuum oscillation frequency and hence vacuum energy density reduces by the same factor as the gravitational wave strain $\hbar$. Due to the energy density constraint, this results in the release of a corresponding amount of energy E into the visible spatial dimensions as photons with energy E. It is not reversed during the contraction phase,

$$E = \hbar E_P \tag{17}$$

Where E_P is the Planck energy.
However, due to the hardness of T_2 dimension against gravitational vibration, the actual strain A of T_1-T_2 oscillation can be expressed as

$$A = \hbar - \hbar_0 \tag{18}$$

where h_0 is the threshold strain above which T_2 can undergo gravitational oscillation such that reheating occurs and $A \geq 0$.
Eq. (17) becomes

$$E = (\hbar - \hbar_0)E_P,$$
(19)

or simply

$$E = AE_P. \tag{20}$$

The hardness of T_2 as presently understood in RUTE, is caused by the radiation pressure of neutrinos on T_2. It follows that $\hbar_0$ is proportional to neutrino density. As such, a neutrinoless region of space should be soft with zero threshold strain $\hbar_0$.

As the GW oscillation continues, it should continuously create standard model photons from the vacuum in its wake until its strain falls below the threshold. Thus, RUTE provides an ideal reheating mechanism for a Λ driven inflation. In this case, inflationary gravitational waves can readily reheated the universe with high energy gamma radiation during and immediately after inflation until the amplitude fall below the threshold. This implies that powerful astrophysical sources of gravitational waves should have Gamma Ray Bursts (GRB) secondaries. Therefore GRBs need to be investigated in the light of RUTE's Gravitational Wave Reheating mechanism.

The detection of Gravitational wave event designated GW150914 (Abbot *et al.* 2016) has opened an observational window. The detection of Gamma Ray Burst counterpart GW150914-GBM (Connaughton *et al*. 2016) 0.4 seconds later corresponding to 66% of the peak strain indicates that there is a threshold strain h_0 for Gravitational Wave Reheating. Future joint Gravitational Wave and GRB or even Fast Radio Burst (FRB) counterpart observations should provide further observational evidence and constraint for Gravitational Wave Reheating and associated parameters.

A. Prospect of vacuum energy extraction.

In RUTE, gravitational waves are required for the extraction of vacuum energy but the conventional way of generating them requires astronomical amount of mass-energy. This is worsened by the high threshold strain required before reheating can occur. Therefore, any effort to extract vacuum energy for energy generation purpose will have to rely on the astrophysical gravitational wave background and a way to lower the threshold strain. With present understanding of RUTE, this will involve shielding neutrinos which is not feasible. More research effort is required in this regard as this is potentially an effective window for detecting gravitational waves through electromagnetic secondaries.

VII. Discussion

RUTE, with its key dimensional symmetry and interpretation of time, has provided an elegant solution to dark energy's cosmological constant problem. In this scenario, Λ is naturally fine-tuned by the entropic growth of time dimension as defined, thereby avoiding the fine-tuning problem faced by most Λ dark energy models. Specifically, it is a spill model of Λ. It relies on the nonentropic and therefore gravitationally inert nature of vacuum energy oscillations directed along a Planck size extra dimension, and an energy density constraint.

The energy density constraint ensures that the total energy density available in the visible spatial dimension and vacuum energy must always equal the Planck density. Vacuum energy oscillation between two unequal vacuum energy states ensures spill of vacuum energy into the visible spatial dimensions as dark energy as described by the asymptotically evolving cosmological factor Γ. Γ ~1 in the early universe provided a Planck scale Λ that can automatically power inflation before falling asymptotically to its present small value of $\Gamma \sim 10^{-60}$, coupled with reheating effectively ending inflation. Moreover spatial variation of such dark energy is predicted as it is sensitive to presence of matter and radiation. As a direct consequence of energy constraint, any energy scale higher than that of dark energy tends to suppress it by preventing a spill. Such spatial variation should be measurable with precision measurement.

The energy density constraint also forbids all forms of infinite energy densities like black hole and big bang singularities. Just like the speed constraint it was derived from, exceeding the Planck density is equivalent to exceeding the speed limit c. Instead, black holes are replaced with Planck stars like in Rovelli and Vidoto (2014). Moreover, the vacuum energy density in such a Planck star must be zero, since the spatial component is already at the maximum Planck value.

RUTE's Gravitational Wave Reheating mechanism is also an interesting outcome of the energy constraint where gravitational waves release vacuum energy as electromagnetic secondary. This conveniently provides a reheating mechanism for Λ driven inflation obviating the need for scalar field inflation. Powerful astrophysical gravitational waves even from black holes should have electromagnetic secondaries once their strain exceeds a threshold. Therefore Gamma Ray Bursts needs to be investigated in association with astrophysical sources of gravitational waves.

It is also interesting, how the length of the spatial component of time dimension T_1 describes the entropy S of our Universe (with $S = 2\pi r$) in an analogous way the surface area A of the event horizon of a black hole describes its entropy S. This agreement with entropic gravity, raises the question: Is our universe a holographic one in a much bigger and older Universe as also suggested in Pourhasan *et al.* (2013)?

If spacetime is quantized according to loop quantum gravity (Smolin 2004), then as the contracting extra spatial dimension S_2 reaches the minimum Planck scale, the expansion of the 3 macroscopic spatial dimensions S_1 stops, leading to the contraction of our universe as gravity reigns. As the universe reaches the Planck density during the contraction phase, the density constraint (or Planck degeneracy pressure) stops the contraction, effectively preventing a singularity. What happens from this point apart from a likely bounce, depends precisely on the nature of quantum gravity.

Conclusion

In conclusion, RUTE has provided a viable resolution of the cosmological constant problem of dark energy avoiding the fine-tuning problem that plagues most solutions to the cosmological constant problem. Beyond its testability, it tends to provide solution to other unsolved problems in Physics like the nature of time and Physics of inflation. The commencement of gravitational wave astronomy provides an observational tool to test some of its predictions. Interestingly the first signal detected was accompanied by a gamma ray burst which is consistent with the reheating prediction and can have far reaching implications on gravitational wave observation through electromagnetic secondaries and even the prospect of vacuum energy extraction if confirmed with more data.

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