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Primordial Wormholes and their Traversability Constraints: In the Context of the Presence and Absence of Exotic Matter

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Abstract: Wormholes, though never directly observed, arise as legitimate solutions to the field equations of general relativity. Early work by Patton and Wheeler introduced the concept of quantum foam, wherein the gravitational vacuum at the Planck scale consists of fluctuating microscopic geometries. Among these configurations, submicroscopic wormholes may naturally emerge, particularly in the extreme conditions of the early universe. Governed by the uncertainty principle, such wormholes are expected to be highly transient. However, it has been conjectured that quantum fluctuations could enable their gradual growth, allowing Planck-scale wormholes to expand to microscopic or even macroscopic sizes. During the inflationary epoch, this process might have produced an interconnected network of primordial wormholes. Classically, wormholes are unstable and rapidly collapse into singularities. To render them traversable, Kip Thorne and collaborators proposed the necessity of exotic matter, which counteracts gravitational collapse by violating the null energy condition through negative stress-energy density. While exotic matter is not observed macroscopically, quantum field theory permits negative energy densities and fluxes under strict constraints imposed by quantum inequalities. In this work, we present a comprehensive analysis of various theoretical models proposed to stabilize wormholes, assessing their consistency within the broader framework of quantum gravity and early-universe cosmology. We further investigate the potential role of antimatter and the implications of charge–parity–time (CPT) violation in both flat and curved spacetimes for wormhole dynamics. Additionally, alternative models of traversable wormholes that do not require exotic matter are discussed. Our aim is to evaluate the plausibility of traversable primordial wormholes and to elucidate their potential significance in shaping our understanding of the universe's earliest stages.

Keywords: primordial wormholes, quantum foam, quantum fluctuation, traversable wormholes.

INTRODUCTION

A wormhole is a theoretical spacetime construct that serves as a bridge connecting two distinct points either within the same universe or between different universes, providing a theoretical possibility for interuniversal travel. Conceptually, it can be understood as a conduit resembling tunnel with its end points located at separate regions in spacetime, allowing for potential shortcut through the fabric of cosmos. Historically, the first type of wormhole solution discovered was the Schwarzschild wormhole, which would be present in the Schwarzschild metric describing an eternal black hole. However, it was found that it would collapse too quickly for anything to cross from one end to the other. A wormhole hypothesis had been proposed by Hermann Weyl in 1928 in connection with mass analysis of electromagnetic field energy [1]. However, he used the term "one dimensional tube" instead of wormhole. In 1935, Einstein and physicist Nathan Rosen extended the implications of the theory of general relativity, introducing the concept of "bridge" within the fabric of spacetime. They postulated the existence of bridges, which could serve as cosmic connectors, linking separate points across the expanse of spacetime [2]. Subsequently, these theoretical shortcuts were coined as Einstein-Rosen bridges, solidifying their place in the annals of theoretical physics. These bridges can be modeled as vacuum solutions to the Einstein field equations, and form intrinsic parts of the maximally extended version of the Schwarzschild metric describing an eternal black hole devoid of charge and rotation. The term "maximally extended" refers to the concept that spacetime lacks discernible boundaries, indicating that a geodesic path within the fabric of spacetime should theoretically be extendable indefinitely into both the particle's past and future.

While wormholes are theoretically predicted by general theory of relativity, they have never been observed in nature. One significant query revolves around whether the laws of physics permit the topology change necessary for the creation of wormholes. This change, in fact, demands the formation of closed time-like loops, which presents a challenging proposition within the existing framework of theoretical physics. Moreover, certain topology changes may be intricately linked to energy conditions, a topic that will be thoroughly explored in a subsequent section. Another pivotal question pertains to whether the laws of physics permit the creation of submicroscopic Lorentzian wormholes. Even though wormhole formation is prohibited on the classical level, it might be allowed quantum-mechanically. One more raised issue is the existence of natural or artificial processes that could lead to their enlargement. This problem has been addressed by the present work and constitutes the core of the theoretical aspect presented in this work. The formation of submicroscopic wormholes at the early universe and their subsequent enlargement during the inflationary phase to the macroscopic size depends significantly on the nature and topology of spacetime at the Planck scale.

MATTER AT THE SUBQUANTUM LEVEL

The nature of space has been discussed by W. K. Clifford in 1870 [3] and influenced drastically by Einstein vision in 1915 in that space geometry is the magic building material out of which matter and everything else are made. However, exploration of Clifford – Einstein space theory of matter has been criticized by Andrei Sakhorov [4] who excluded geometry as a viable building material.

In depth of the universe, where reality blurs with the abstract, lies an intriguing concept known as quantum foam. This enigmatic term encapsulates the tumultuous and frothy nature of the fabric of spacetime at the tiniest scales, where the laws of physics as we conventionally understand them seem to dissipate into a realm of uncertainty and unpredictability. Quantum foam represents the volatile and dynamic nature of spacetime on the smallest scales, where the classical notion of space as a smooth and continuous entity crumbles, revealing a complex and intricate structure that flickers and fluctuates incessantly. The concept arises from quantum mechanics, suggesting that at the Planck scale (10^{-35} m), spacetime becomes inherently turbulent and unstable, akin to a churning sea of fluctuating and crumbling structures constantly popping in and out of existence.

The concept of spacetime foam has been first introduced by A. Wheeler [5] in 1957. At the Planck scale, quantum fluctuations of spacetime exhibit an outstanding feature whereby spacetime takes all sorts of non-trivial topological structures such as microscopic wormholes. Spacetime acquires in the classical limit simply connected features observed at large scale.

Experimental physics provided the precision measurements of the effect of these fluctuations on the energy levels of the hydrogen atoms. In fact, the electron in the hydrogen atom is subject to the electric field of the nucleolus (Ze/r^2) and in addition to a quantum fluctuation field independent of the influence of the atom and being a property of space itself. The calculated fluctuation field in a region of observation of dimension *L* is of the order [6]

$$\Delta\xi = (\hbar c)^{1/2} / L^2 \tag{1}$$

where *ħ* is the reduced Planck constant, and *c* is the speed of light.

This field may cause a small displacement Δx of the electron from its orbit. Consequently, the electronic energy levels will be shifted by

$$\Delta E = (\Delta x^2)/2 \tag{2}$$

The left-hand side of this equation can be measured as the main part of the Lamb – Rutherford shift, and accordingly the mean square displacement Δx of the electron caused by the fluctuation field on the right-hand side can be determined, thus confirming the predicted magnitude of the fluctuation field itself.

In geometrodynamic, the quantum fluctuations in the normal metric coefficients -1, 1, 1, 1 are of the order $\Delta g = L^* / L$, [7] where L^* is the Planck length, namely

$$L^* = (\hbar G / c^3)^{1/2} = 1.6 \times 10^{-33} \text{ cm} \tag{3}$$

Therefore, the quantum fluctuations of the metric are negligible at the scale length *L* of atoms, nuclei, and elementary particles.

QUANTUM FLUCTUATION AND MICROSCOPIC WORMHOLES

We can envision quantum fluctuations by looking deep in successively smaller and tinier scales. At large scale, induced quantum fluctuations appear negligible (Fig 1a).

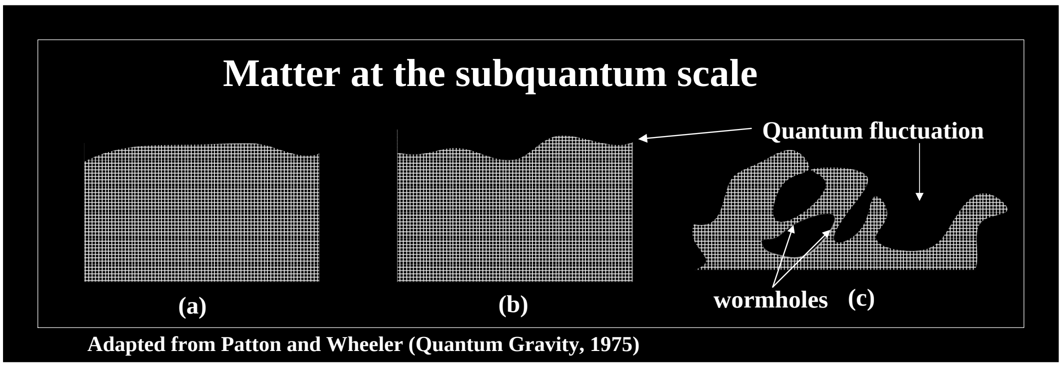

Figure 1: Matter as it appears at smaller and smaller scales.

As we come closer, or as *L* diminishes, the fluctuations become more pronounced (Fig 1-b), and when approaching the Planck scale (Fig. 1c), the predicted fluctuations become of the order $\Delta g \approx 1$. At this scale, spacetime appears to suffer from a change in connectivity, and its geometry exhibits various types of topological structures including microscopic "wormholes", continuously forming and disappearing.

ELECTRICITY AND QUANTUM FLUCTUATIONS

In 1924 Hermann Weyl proposed the concept that electricity is lines of force trapped in the topology of a multiply connected space [8]. Today, according to quantum theory, electric lines of force of fluctuation origin will thread through a typical wormhole of dimension *L*, and carry a flux of the order [6]

$$\int E \cdot ds = [(\hbar c)^{1/2} / L^2].L^2 \approx (\hbar c)^{1/2} \tag{4}$$

This picture led scientists to think of space as exhibiting a kind of fluctuating foam-like structure, with continuous creation and annihilation of positive and negative charges of order [6]

$$q \approx (\hbar c)^{1/2} = 10e \tag{5}$$

It is important to note that these fluctuation charges are not a property of elementary particles, since the relevant scale of distance is twenty orders of magnitude smaller than nuclear dimensions. These charges are exclusively electric, and are not quantized in magnitude, and occur everywhere. However, it is not clear, according to this model why fluctuation charges should assemble into elementary particles in a quantized form.

EUCLIDIAN VERSUS LORENTZIAN MANIFOLDS

Quantum foam involves a topological change that necessarily entails complications of singularities or degeneracies of the geometry, or of closed time-like curves [9]. One way to overcome these problems is to consider Euclidian manifolds [10]. Indeed, on a quantum scale, spacetime may be fundamentally Euclidean, with Lorentzian spacetime attained in the classical limit far from the Planck regime. However, Euclidean quantum gravity has its own formidable problems [11], such as the failure of the Euclidean action to be positive definite, in addition to the problem of interpretation and to the process of recovering Lorentzian spacetime. The two versions of spacetime foam have been a great attraction to theoretical physicists. The Euclidean foam has been explored as having a possible role in determining the fundamental constants of nature [12]. There is also a suggestion that Lorentzian wormholes extracted from microscopic foam can be suitably enlarged. This same idea, but from a different perspective, constitutes one of the topics we are considering and developing in this paper.

In this work, we envision primordial spacetime foam filling all space at the Planck scale with all sorts of topological fluctuations including microscopic wormholes. These microscopic entities persist for a microscopic time-period, but can be appreciably enlarged by primordial inflation.

ENERGY CONDITIONS

It has been long believed that for the Einstein equations to describe a spacetime corresponding to reality, the stress energy tensor in the field equation has to be physically reasonable, and the state of reasonableness is referred to as the energy conditions. However, energy conditions are not part of general theory of relativity, but are external ideas pertaining to the nature of matter imported for the purpose of taming the stress-energy tensor to eliminate unphysical spacetime. The energy conditions are restricted to the values of pressure P and density ρ in each direction. There are two types of conditions, pointwise conditions that must hold at each point of spacetime, and averaged conditions that need only hold on average of an observer's path in spacetime. In theoretical study of wormholes, energy conditions play a critical role in understanding the plausibility and behavior of these hypothetical structures potentially found within the quantum foam. There are two types of conditions, pointwise conditions that must hold at each point of spacetime, and averaged conditions that need only hold on average of an observer's path in spacetime. Energy conditions, including null energy condition (NEC), weak energy condition (WEC), strong energy condition (SEC), and dominant energy condition (DEC), are fundamental principles derived from general theory of relativity that impose constraints on the distribution and flow of energy and matter in spacetime. These conditions serve as crucial guidelines for ensuring the stability and viability of wormholes, dictating the necessary energy requirements to uphold the integrity of the wormhole's throat and prevent its collapse [13]. Violation of these conditions, such as the creation of exotic matter with negative energy densities, have been proposed as potential mechanisms to stabilize traversable wormholes, allowing the formation of stable passages between distant regions of the universe. Despite the speculative nature of these energy conditions in the context of wormholes, their exploration remains vital in advancing our comprehension of the profound interplay between spacetime geometry and the laws of physics on both the macroscopic and quantum scale. Several notable works, including those by Morris and Thorne [14], Visser [15], and Hawking [16], have extensively discussed the implications of energy conditions on the theoretical framework of wormholes, shedding light on the intriguing possibilities and challenges associated with these fascinating cosmic phenomena.

ENLARGING LORENTZIAN WORMHOLES

Extensive research work has addressed the possible existence of submicroscopic wormholes [16-17]. It has been postulated that the existence of Lorentzian wormholes of the Morris-Thorne (MT) type is allowed by the laws of physics at the microscopic scale. T. Roman [18] considered the case of a microscopic Lorentzian wormhole embedded in a flat deSitter space and the possibility of enlarging it to a macroscopic size. In this section we shall follow T. Roman's model, and discuss in a following section the constraints of preventing the wormhole from eventual collapse.

T. Roman considered the model of (MT) traversable wormholes [18]. These wormholes are devoid from horizons, and thus are traversable in a two-way passage through them. For this type of wormholes, there is a violation of the weak energy condition (WEC) and the averaged weak (AWEC) energy condition at its throat. Another intriguing feature of these wormholes is the possibility to use them as time machine for backward time travel. However, Hawking [19] and others think that nature employs what they called "Chronology Protection Agency" which prevents the formation of a time-like closed type loops.

It is well established that quantum field theory allows local violations of the weak energy condition [13, 20]. This takes the form of locally negative energy and fluxes, as for the Casimir effect, as an example.

THE STATIC MORRIS-THORNE WORMHOLES

In this section we introduce Roman's approach [18] to show how submicroscopic wormholes can be enlarged by inflation to macroscopic size. For consistency, we will follow in this section the argument presented by Roman [18] to show how the wormhole is enlarged by inflation. Our starting point is the spherically symmetric and static metric of traversable wormhole in the Static Morris-Thorne (MT) model. The (MT) metric is given by [14]

$$ds^2 = -e^{2\Phi(r)}dt^2 + \frac{dr^2}{(1-b(r)/r)} + r^2(d\theta^2 + sin^2\theta\, d\phi^2) \quad (6)$$

Here, $b(r)$ and $\Phi(r)$ are adjustable functions referred to as the "shape function" and the "redshift function", respectively. An important aspect of the coordinate r is that it is nonmonotonic in that it decreases from $+\infty$ to a minimum value b_0 representing the location of the throat of the wormhole, and then it increases from this value to $+\infty$ again. As evident from the metric, there is a coordinate singularity at the throat where $r = b$. At this point, the metric coefficient g_{rr} becomes divergent. However, the radial proper distance

$$l(r) = \pm \int_{b_0}^{r} \frac{dr}{(1-b(r)/r)^{1/2}} \quad (7)$$

must be finite everywhere. An important requirement for the wormhole to be transverable is that it has no horizon, which implies that $g_{tt} = -e^{2\Phi(r)}$ must be never allowed to vanish, and therefore, $\Phi(r)$ must be finite everywhere. Let us next consider an equatorial slice at t = constant, and where $\theta = \pi/2$. In this case, the metric in Eq. (6) becomes

$$ds^2 = \frac{dr^2}{(1-b(r)/r)} + r^2 d\phi^2 \quad (8)$$

On the other hand, the three-dimensional Euclidean embedding space metric can be written as

$$ds^2 = dz^2 + dr^2 + r^2 d\phi^2 \quad (9)$$

The metric on the embedded surface can then be written as

$$ds^2 = \left[1 + \left(\frac{dz}{dr}\right)^2\right]\ dr^2 + r^2 d\phi^2 \quad (10)$$

The embedded surface is axially symmetric, and therefore, it can be described by $z = z(r)$. From Eqs. (8) and (9), we have

$$\frac{dz}{dr} = \pm(r/(b(r)-1)^{-1/2} \tag{11}$$

It is required that space be asymptotically flat far from the throat. This condition can be satisfied if dz/dr approaches zero as l approaches $\pm\infty$, or equivalently b/r approaches zero as l approaches $\pm\infty$. For this condition to be realized, HT requires that the wormhole must flare outward near the throat, i.e.,

$$\frac{d^2r(z)}{dz^2} > 0 \tag{12}$$

Or, from Eq. (11) we have,

$$\frac{d^2r(z)}{dz^2} = \frac{b-b'r}{2b^2} > 0 \tag{13}$$

where the prime denotes differentiation with respect to *r*. HT considered a particularly simple solution whereby, they choose *b* = *b*(*r*), and Φ(*r*) = 0. This choice implies that the tidal force be zero as seen by stationary observers. For the case where $b(r) = {b_0}^2/r$, and Φ(*r*) = 0, a solution of Eq. (11) gives

$$z(r) = b_0 cosh^{-1}\left(\frac{r}{b_0}\right) \tag{14}$$

MT defined an "exoticity function" (ζ):

$$\zeta \equiv \frac{\tau-\rho}{|\rho|} \tag{15}$$

where *ρ* and τ are the energy density and radial tension, respectively. The wormhole material in the HT model is everywhere exotic, i.e., $\zeta = 0$. It extends outward from the throat, with *ρ*, τ, and the pressure *p* asymptoting to zero as $= \pm\infty$.

ROMAN'S INFLATING WORMHOLE

Roman [19] considered a simple generalization of the HT wormhole metric (Eq. 6) by simply multiplying the spatial part of the metric by a deSitter scale factor $e^{2\chi t}$.

$$ds^2 = -e^{2\Phi(r)}dt^2 + e^{2\chi t}\left[\frac{dr^2}{(1-b(r)/r)} + r^2(d\theta^2 + sin^2\theta\, d\phi^2\right] \tag{16}$$

Here, $\chi = (\Lambda/3)^{1/2}$, where Λ is the cosmological constant [18]. The geometry of the wormhole is such that circles of constant r are centered on the throat of the wormhole. The coordinate system is chosen by to be comoving whereby the throat of the wormhole is always located at *r* = *b* = b_0 for all *t*. For Φ(r) = *b*(*r*) = 0, Roman's metric reduces to a flat deSitter metric, whereas for x = 0, it reduces to the static wormhole metric of Eq. (6). The main objective of Roman's work is to investigate the possibility of enlarging an initially submicroscopic wormhole during the inflationary era. For this purpose, he found it rational to choose Φ(*r*) and *b*(*r*) that leads to the formation of a reasonable wormhole at *t* = 0, which is assumed to be the onset of inflation. The enlargement process can be visualized by considering the proper circumference *c* of the wormhole throat, where *r* = *b* = b_0 for θ = π/2, at any time *t* = const. The time-dependence of the conference is given by

$$c = \int_0^{2\pi} e^{\chi t}\, b_0 d\phi = e^{\chi t}(2\pi b_0) \tag{17}$$

This means that the initial value of the circumference is increased with time by a factor $e^{\chi t}$. The radial proper length through the wormhole between any two points *A* and *B* at any time *t* = const. is given by

$$l(t) = \pm e^{\chi t} \int_{r_A}^{r_B} \frac{dr}{(1-b(r)/r)^{1/2}} \tag{18}$$

Again, the initial radial proper separation is increased by a factor $e^{\chi t}$. Hence, the size of the throat and the radial proper distance between the wormhole mouths increase exponentially with time. Next, it is important to see that the wormhole form of the metric is preserved with time. Toward this end, a slice of spacetime characterized by *t* = const., *θ* = π/2 is chosen. Referring to Eq. (16) in a flat 3D Euclidean space with metric

$$ds^2 = d\bar{z}^2 + d\bar{r}^2 + \bar{r}^2 d\phi^2 \tag{19}$$

The metric (Eq. 16) on the slice (*t* = const., *θ* = π/2) becomes

$$ds^2 = \frac{e^{2\chi t} dr^2}{(1-b(r)/r)} + e^{2\chi t} r^2 d\phi^2 \tag{20}$$

Comparing the coefficients of $d\phi^2$, we have

$$\bar{r} = e^{\chi t} r|_{t=const}. \tag{21}$$

Taking the differential of Eq. (21) and squaring, we obtain

$$d\bar{r}^2 = e^{2\chi t} dr^2|_{t=const.} \tag{22}$$

Preservation of the wormhole form of the metric with respect to $\bar{z}, \bar{r},$ and ϕ coordinates is achieved if the metric on the embedded slice has the form

$$ds^2 = \frac{d\bar{r}^2}{(1-\bar{b}(\bar{r})/\bar{r})} + \bar{r}^2 d\phi^2 \tag{23}$$

where $\bar{b}(\bar{r})$ reaches a minimum at some $\bar{b}(\bar{r}_0) = \bar{b}_0 = \bar{r}_0$. Eq. (20) can be rewritten in the form of Eq. (23) by using Eqs. (21) and (22)

$$\bar{b}(\bar{r}) = e^{\chi t} b(r) \tag{24}$$

In the following, we follow the Roman's model in which he shows that the inflated wormhole will have the same overall size and shape relative to the $\bar{z}, \bar{r}, \phi$ coordinate system, as the initial *z*, *r*, ϕ embedding space coordinate system. In fact, the embedding scheme adopted by the author corresponds to a series of embedding spaces, each corresponding to a particular value of *t* = const. Following the embedding procedure outlined in Eq. (9-11), and using Eqs. (21), (22) and (23), it is readily apparent

$$\frac{d\bar{z}}{d\bar{r}} = \pm \left(\frac{\bar{r}}{\bar{b}(\bar{r})} - 1 \right)^{-1/2} = \frac{dz}{dr} \tag{25}$$

Eq. (25) implies

$$\bar{z}(\bar{r}) = \pm \int \frac{d\bar{r}}{(\bar{r}/\bar{b}(\bar{r})-1)^{1/2}} = \pm e^{\chi t} \int \frac{dr}{(r/b(r)-1)^{1/2}} = \pm e^{\chi t} z(r) \tag{26}$$

From Eq. (22) and (26), it can be seen that the relation between the embedding space at any time *t* and the initial embedding space at *t* = 0 is

$$ds^2 = d\bar{z}^2 + d\bar{r}^2 + \bar{r}^2 d\phi^2 = e^{2\chi t}[dz^2 + dr^2 + r^2 d\phi^2] \tag{27}$$

Accordingly, relative to the $\bar{z}, \bar{r}, \phi$ coordinate system the wormhole will always remain the same size, but it will change size relative to the initial t = 0 embedding space.

An analogue to the "flare out condition", Eq. (12), can be written for the expanded wormhole at or near the throat

$$\frac{d^2\bar{r}(\bar{z})}{d\bar{z}^2} > 0 \tag{28}$$

Using Eq. (21), (22) and (24), the flare out condition at or near the throat reads

$$\frac{d^2\bar{r}(\bar{z})}{d\bar{z}^2} = e^{-\chi t}\left(\frac{b-b\prime r}{2b^2}\right) = e^{-\chi t}\left(\frac{d^2r(z)}{dz^2}\right) > 0 \tag{29}$$

Using Eq. (21) and (24), the right-hand side of Eq. (29) can be written in terms of the barred coordinates as

$$\frac{d^2\bar{r}(\bar{z})}{d\bar{z}^2} = \left(\frac{\bar{b}-\bar{b}\prime\bar{r}}{2\bar{b}^2}\right) > 0 \tag{30}$$

where

$$\bar{b}'(r) = \frac{d\bar{b}}{d\bar{r}} = b'(r) = \frac{db}{dr} \tag{31}$$

The flare out condition, Eq. (30), preserve the same form as that for the static wormhole.

INFLATION AND THE EXPANSION OF PRIMORDIAL WORMHOLES

In this section, we discuss the implication of inflation on the fate of wormholes. The rapid expansion of the surrounding space causes the two mouths of the wormhole to quickly lose causal contact with one another, and the presumably issues of traversability will arise only after inflation. If the mouths were to remain in causal contact throughout the duration of inflationary period, then there would be a constraint on the initial size of the wormhole [16]. The application of the present scenario to small Schwarzschild-Nordström wormholes might lead to the formation of larger wormholes, which can then be made traversable [18]. However, these wormholes are characterized by the absence of cosmological horizon, which tend to make them collapse very rapidly. This issue is presumably exacerbated by the positive energy released during the decay of the false vacuum. Circumventing this problem is only possible by the injection of flux of negative energy. However, the magnitude and duration of such fluxes is determined by the uncertainty principle, as in the case found to hold for negative fluxes injected in extreme Reissner-Nordstrom black hole [21]. During inflation the size of the wormhole throat is genuinely increased due to cosmological expansion. Investigation of the components of the stress-energy tensor reveals that the false vacuum terms remain constant with time while the exotic wormhole material terms decay exponentially with time [18]. For the case where the exotic energy density of the wormhole term is negative, then the total amount of positive energy density of the false vacuum remains constant as the volume increases, whereas the total amount of negative energy decreases because the negative energy density exponentially decreases. When the false vacuum decays, a huge amount of positive energy might flood the wormhole, triggering a gravitational collapse of the throat. This situation can be avoided if the two energy densities in the stress-energy tensor are roughly comparable in magnitude at the end of inflation.

WORMHOLES TRAVERSABILITY CONSTRAINS

As discussed in the last section, wormholes flooded with positive energy produced by false vacuum decay may collapse gravitationally. One possible method to keep the wormhole traversable is to inject negative energy flux in the wormhole. Many proposals have been advanced to solve this problem. Morris and Thorne [14] suggest injecting exotic material providing negative energy density to keep the wormhole open and traversable. Extensive research work investigated various possibilities to identify the necessary mechanism and exotic material required for stabilizing wormholes against gravitational collapse. In the following, we will outline and discuss the most prominent methods proposed to address this issue.

Dark Energy

Utilizing dark energy to sustain a wormhole post-inflation remains a speculative yet tantalizing possibility in cosmological discourse. Dark energy, known for its repulsive gravitational effect, drives the accelerated expansion of the universe and could potentially counteract the gravitational collapse that might threaten the stability of a wormhole. While no empirical evidence currently supports this concept, theoretical studies have proposed the role of exotic matter, including negative energy densities, to stabilize wormholes. Further exploration is warranted to elucidate the intricate interplay between dark energy and exotic matter in maintaining the integrity of wormholes. Caldwell and Kamionkowski [22] delve into the dynamics of dark energy, offering insights into its potential implications for cosmic structures. Additionally, works by K. Zangeneh et. al. [23], and Pedro F. Gonzalez-Diaz [24] explore the feasibility of traversable wormholes in the context of exotic matter and dark energy, providing theoretical foundations for investigating the role of dark energy in stabilizing these intriguing cosmic passages.

Phantom energy is a hypothetical form of dark energy possessing negative kinetic energy and predicting expansion of the universe causing it to accelerate so quickly and leading to a scenario known as the Big Rip. In fact, the universe reaches an infinite degree in finite time, causing expansion to accelerate without bound. The concept is related to emerging theories of a continuously-created negative mass dark fluid characterized by a time dependent cosmological constant [25]. Sushkov [26] extend the notion of phantom energy on inhomogeneous spherically symmetric spacetime configuration and show that phantom energy is able to support the existence of static wormhole. He found an exact solution describing a static spherically symmetric wormhole with phantom energy and show that a spatial distribution of the phantom energy is mainly restricted by the vicinity of the wormhole's throat.

However, recent developments in cosmology suggest that data interpretations supporting the existence of dark matter may be inaccurate. A foundational premise of supernova (SN) cosmology is that the standardization of Type Ia supernova luminosities is independent of progenitor age. Observations of SN host galaxies challenge this assumption, revealing a strong (5.5σ) correlation between standardized SN magnitudes and progenitor age. Such dependence naturally induces a redshift-dependent systematic bias in SN-based cosmological measurements. Because progenitor age and host galaxy mass follow distinct evolutionary paths with redshift, this bias is largely uncorrected by the standard mass-step approach. Incorporating an explicit correction for age evolution leads to significantly improved agreement between SN data and the $w0w_aCDM$ model recently favored by DESI BAO analyses combining BAO and CMB data. Additional support comes from an evolution-insensitive test that relies exclusively on SNe hosted by young, coeval galaxies across all redshifts. When SNe are analyzed jointly with BAO and CMB probes, the resulting discrepancy with the ΛCDM model exceeds 9σ, substantially larger than previously reported, and points toward a time-varying dark energy equation of state in a universe that is no longer accelerating [27].

Gravitational Signature of Antimatter

Antimatter, characterized by its unique properties of possessing the opposite charge and quantum numbers to ordinary matter, has been postulated as a potential exotic material that could play a crucial role in maintaining the traversability of wormholes. The speculative utilization of antimatter stems from its capacity to generate negative energy densities, a requisite feature for counteracting the gravitational forces that may lead to the collapse of wormholes. Its role in the context of CPT (charge-parity-time) violation, a fundamental symmetry in particle physics, has garned attention in both flat and curved spacetime scenarios. The violation of CPT symmetry, if substantiated, could lead to the emergence of exotic properties such as negative energy densities crucial for preventing the collapse of wormholes. Theoretical studies, including those by Kostelecký and Mews [28], A. Angelopoulos et al. [29], and S. Al Dallal et al. [30], have explored the implication of CPT violation in diverse physical phenomena, emphasizing its potential significance in the utilization of antimatter as a stabilizing agent for these cosmic conduits. However, many arguments have been advanced either emphasizing or refuting the idea of antimatter possessing anti-gravitational signature. The most important argument against antimatter as having anti-gravitational properties have been advanced by P. Morrison [31] based on energy conservation of a matter-antimatter pair created at the Earth's surface. A second argument against antigravity was presented by L. I. Schiff [32]. Schiff argument stems from the principle of equivalence and quantum field theory. A third argument was proposed by Myron L. Good [33], where he argued that antigravity would lead to unacceptable level of CP violation in the anomalous regeneration of Kaons. On the other hand, several theories were advanced predicting the antigravity nature of antimatter. Santilli [34-35] showed that the isodual theory predicts that antimatter in the field of matter experience antigravity. M. J. T. F. Cabbolet [36] published the first non-classical principles governing matter-antimatter gravitational repulsion. Their approach was formulated in framework of Elementary Process Theory (EPT), supporting the idea of gravitational repulsion between matter and antimatter. M. Villata [37] argues that antigravity appears as a prediction of general relativity when CPT theory is applied. Villata constructed a new equation by applying discrete operators for charge (C), parity (P), and time (T) to the equation of motion of general relativity for a particle in a gravitational field. M. J. T. F. Cabbolet [38] criticized the approach of Villata on the ground that quantum physics from which the CPT symmetry is taken and general relativity theory are two distinct paradigms in physics that are proven to be incompatible. However, in general theory of relativity, the weak equivalence principle (WEP) requires that all masses react identically to gravity irrespective of their internal structure. The discrepancies in identifying the signature of the gravitational field of antimatter have prompted scientists to adopt the realm of experimental physics to solve this issue. Witteborn and Fairbank [39] set up an experiment to compare the gravitational acceleration of electrons and positrons by analyzing the time of flight. However, the Schiff and Barnhill effect [40] caused electrons inside the metal of the drift tube to sag under gravity, until the gravitational force was balanced by the electrostatic force of compression. Subsequently, the production of antihydrogen was proposed to overcome the above difficulties.

Antihydrogen atoms were first brought into existence in CERN in 1995. The first experiment was performed using the Low Energy Antiproton Ring (LEAR). It turns out that these antihydrogen atoms are too "hot" to be used for gravitational studies. In the late 1990s, two collaborations were formed, namely, ATHENA and ATRAP. The ATHENA collaboration disbanded in 2005, and a new collaboration ALPHA was formed. The ALPHA collaboration announced in 2010 the trapping of 38 antihydrogen atom for 0.167 of a second [41], and in April 2011 they announced the trapping of 309 antihydrogen atoms for about 1000 seconds [42]. Other experiments (AEGIS) and collaborations such as GBAR failed at having a definite answer to solve this issue. Lately, a group at CERN conducted anihydrogen experiment on antihydrogen atoms released from magnetic confinement in the ALPHA-g apparatus, and found that they behave in a way consistent with gravitational attraction to the Earth [43]. However, the question arising from this experimental approach needs to be replicated by other groups using more precise experiments. It is also important to consider a more fundamental approach using antineutrons instead of antihydrogen atoms, as the screening of charges from the immediate environment could pose an issue.

TRAVERSABLE WORMHOLES WITHOUT EXOTIC MATTER

Traversable wormholes, without the reliance on exotic matter, have emerged as a compelling area of exploration in theoretical physics. The concept of exotic matter has captivated many groups of scientists. However, the existence of such matter in nature remains one of the unresolved questions in physics. Consequently, scientists have been inclined to seek solutions to the field equations of general relativity that don't require exotic matter. Various studies have proposed alternative mechanisms that circumvent the need for exotic matter, thereby offering the possibility of realizing these hypothetical structures within the framework of known physical principles. Einstein- Dirac-Maxwell (EDM) theory holds significant relevance in the context of wormholes, providing a comprehensive framework for understanding the intricate interplay between gravity, electromagnetism, and quantum mechanics within these hypothetical structures. J. L. Blázquez-Salcedo et al. [44] (BSKR wormhole) constructed a specific example of a class of traversable wormholes in Einstein-Dirac-Maxell theory in four spacetime dimensions, without the need of any form of exotic matter. They restrict their work to a model with two massive fermions in a singlet spinor state, and show the existence of spherically symmetric asymptotically flat configurations which are free of singularities, representing localized states. They claim that these solutions satisfy a generalized Smarr relation, being connected with the external Reissner-Nordstrom black hole. They also reported an exact wormhole solution with ungauged massless fermions. The BSKR wormholes are obtained by joining a classical solution to the Einstein-Dirac-Maxwell equations on the "up" side of the wormhole ($r \geq 0$) to a corresponding solution on the "down" side of the wormhole ($r \leq 0$). Nevertheless, the solution to the Einstein-Dirac-Maxwell theory for traversable wormhole was criticized by D. L. Danielson et al. [45] on the basis that the metric fails on the wormhole throat at $r = 0$.

Furthermore, the matching were done in such a way that the resulting spacetime metric, Dirac field, and Maxwell field composed solution to the EDM equations in a neighborhood of $r = 0$, then all the fields would be smooth at $r = 0$ in a suitable gauge. They concluded that the BSKR wormholes cannot be solutions to the EDM equations, attributing the failure of this type of wormhole to the inability of the Maxwell field to satisfy the necessary matching conditions, and more significantly, from the failure of the Dirac field to satisfy the required matching conditions.

The concept of utilizing modified form of gravity, such as higher-dimensional theories of specific modifications of general relativity, has been proposed as a potential avenue to engineer stable and traversable wormholes [46]. Additionally, the incorporation of quantum effects and the manipulation of quantum fields have been theorized to create traversable wormholes without resorting to exotic matter. M. Hohman [47] proposed a static, spherically symmetric, traversable wormhole solution to multimetric gravity sustained solely by only non-exotic matter, i.e., matter that satisfies all energy conditions. He has shown that this solution is possible under specific conditions where the multimetric gravitational field equations reduce to the Einstein equations, albeit with a negative effective gravitational constants. N. Geodani and G. C. Samanta [48] proposed a traversable wormhole supported by non-exotic matter in general relativity. F. S. N. Lobo and M. A. Oliveira [49] constructed traversable wormhole geometries in the context of f(R) modified theories of gravity. They stipulate that the matter threading the wormhole satisfies the energy conditions, meaning that it is the effective stress-energy tensor containing higher order curvature derivative that is responsible for the violation of the null energy condition. Saiedi and Esfahani [50] determined exact wormhole solutions in the context of f(R) theory of relativity using power low expansion and a specific shape function. M. S. Churilova et al. [51] found an analytic solution representing traversable asymptotically flat and symmetric wormholes without the addition of exotic matter in two different theories independently: in the Einstein-Maxwell-Dirac theory and in the second Randall-Sundrum brane-world model. R. Sengupta et al. [52] explored the possibility of the construction of a traversable wormhole on the Randall-Sundrum braneworld with no exotic matter, utilizing the Kuchowicz potential. F. R. Klinkhamer [53] presented a traversable–wormhole solution of the gravitational field equation of general relativity without the need for exotic matter. Instead of exotic matter, the solution relies on a 3-dimensional "spacetime defect". Furthermore, M. Zubair et al. [54] developed a wormhole solution with non-exotic matter. Hence, the literature is rich with proposed solutions of traversable wormholes without exotic matter. While these theoretical frameworks present intriguing possibilities, the practical realization and empirical validation of traversable wormholes without exotic matter remain subjects of ongoing research and theoretical investigation in the field of theoretical physics. However, all this research work remains within the realm of theoretical physics, and what is required for the future is a unifying model. We believe that such model should emerge from a quantum theory of gravity to enhance our understanding of the evolution of wormholes from the microscopic to the macroscopic scale. Indeed, a quantum theory is necessary to describe wormholes at the submicroscopic scale, while general relativity is essential for finding solutions for traversable wormholes at the macroscopic scale.

More recently, a significant body of work has focused on modified theories of gravity. These theories have been tested in light of cosmological and observational data. Among these models is the $f(R,T)$ extended theory of gravity, where R refers to an arbitrary function of the Ricci tensor, and T denotes the trace of the energy tensor. Exploring of energy conditions for static wormholes models within the $f(R,T)$ extended theory reveals the physical nature and characteristics of the constructed wormhole. Energy conditions play a pivotal role in these models.

One of the models under consideration is the family represented by $f(R,T) = R + \lambda T$, where $T = \rho + P_r + 2P_l$ denotes the trace of the energy- momentum tensor, with P_r and P_l denoting the radial and lateral pressure, respectively [55]. Notably, it was observed that the parameter space can be partitioned into distinct regions, each yielding exact wormhole solution satisfying both the null energy condition (NEC) and the weak energy condition (WEC) with regard to lateral pressure. Employing this methodology, the authors constructed three distinct wormhole models, all of which adhere to the energy conditions

Other works have investigated the development of particular static wormhole under the assumption of an $f(R, T) = R + 2\lambda T$ extended theory of gravity [56]. A wormhole solution is derived by stipulating that the radial pressure follows an equation of state corresponding to a varying Chaplygin gas. Additionally, a wormhole model is formulated assuming that the radial pressure can be characterized by a varying barotropic fluid [56]. They have demonstrated that exact wormhole models can be constructed. Potentially entailing a violation of the null energy condition (NEC) and the dominant energy condition (DEC) at the throat of the wormhole.

Static wormholes models have also been explored within the framework of f(R, T) gravity, aiming to correlate the energy density of the matter component with the Ricci scalar [57]. The authors derived exact solutions for three specific cases of the Ricci scalar, two of which describe traversabe wormholes.

CONCLUSION

The notion of quantum foam, encapsulating the inherently fluctuating and dynamic character of spacetime at the Planck scale, has been advanced as a plausible origin of primordial topological structures that may have harbored wormholes in the early universe. In this framework, the Roman model has been employed to demonstrate the potential inflation-driven expansion of microscopic wormholes to macroscopic scales during the earliest cosmological epochs. Assuming that a finite fraction of these enlarged wormholes persisted beyond the inflationary phase, their subsequent stability against gravitational collapse has been examined.

The findings indicate that employing dark energy as a sustaining mechanism for post-inflationary wormholes remains a speculative yet conceptually compelling possibility in contemporary cosmology. Antimatter, distinguished by its opposite electric charge and quantum numbers relative to ordinary matter, has been proposed as a potential exotic constituent capable of maintaining wormhole traversability. Nonetheless, the gravitational properties of antimatter remain insufficiently constrained, and experimental claims suggesting gravitational equivalence between matter and antimatter warrant further independent verification.

Moreover, the Einstein–Maxwell–Dirac framework has been considered as a theoretical basis for exploring the intricate interactions underlying wormhole dynamics; however, this proposition has been critically challenged by alternative analyses. In parallel, several models have been proposed that enable traversable wormholes without recourse to exotic matter, each adopting distinct theoretical strategies to address the associated stability conditions.

Future investigations may profitably aim toward the development of a unified quantum-gravitational framework for traversable wormholes, thereby advancing our understanding of their evolution from microscopic fluctuations within the quantum foam to potential macroscopic manifestations in the early universe.

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