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Can We Understand de Sitter Spacetime with String Theory?

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Recent astronomical data point to the fact that the expanding universe is actually accelerating in expansion rate. This calls for formulating string theory in de Sitter space. There are difficulties, though, since it is very difficult to formulate quantum field theory, let alone string theory, in de Sitter space. Moreover, supersymmetry seems to be incompatible with the positive cosmological constant of de Sitter spacetime. In this paper we would like to present our work in formulating string theory in de Sitter space by utilizing bubbles of nothingness. These bubbles interpolate de Sitter space of near-bubble region and flat spacetime of asymptotic region. We also comment on the resolution of the cosmological constant problem in this context.

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I. DE SITTER SPACE AND QUANTUM FIELD THEORY

We now have much evidence that the universe is expanding with positive acceleration [1, 2]. This calls for many new ideas, since conventional gravity is an attractive force and cannot accelerate the expansion of the universe. A positive cosmological constant [3,4] is the oldest and simplest solution to this. (For more recent work on the cosmological constant see, for example, Ref. [5]. See also Ref. [6] for a mechanism generating the cosmological constant out of quantum fluctuations of unstable modes about gravitational instantons.) However, de Sitter (dS) space which is the cosmological solution with positive cosmological constant Λ, does not easily allow string theory within it. The problem is as follows. There is a deep rooted problem of formulating quantum field theory (QFT) in dS space, let alone string theory. The basic reason is that whereas dS space allows only finite degrees of freedom, QFT (or string theory) has infinite degrees of freedom. The finiteness of degrees of freedom in dS space is related to the fact that it has finite entropy and thus the degrees of freedom in it can only be finite [7–11].

In this section, we would like to briefly describe the salient features of dS space [12] and why we have difficulties in putting quantum field theories into it. Also, we would like to mention why supersymmetry seems to be in conflict with this spacetime. De Sitter space naturally describes an exponentially expanding universe. Unlike anti-de Sitter space, which has spatial asymptopia, dS space has asymptopia in the past and future infinities. Moreover dS space has a horizon which is observer dependent. So, an observer can only see part of the space, due to exponential expansion in the future. We can put one of the observers at the North or the South Pole. The Penrose diagram of dS space is identical to that of the anti de Sitter Schwarzschild black hole. So, although the two spacetimes have different geometry, the causal structure is the same. Another difference is that where the black hole singularities were, we now have the infinitely inflated past infinity I^- and future infinity I^+. One interesting thing is that in dS space there is no positive conserved energy. Any time-like Killing vector in some region is space-like in some region, so there cannot be unbroken SUSY. If there were Q^2, where Q is the supercharge, energy will be positive. Another thing is that there is a cosmological event horizon that has temperature and entropy as was first pointed out by Hawking and Gibbons [13]. The entropy is inversely proportional to the cosmological constant, *i.e.* $S = 3\pi/\Lambda$. Due to the presence of the horizon, quantum gravity in dS may not admit a single, objective and complete description of the universe.

There are troubles in quantizing dS space. To begin with, not many controllable time-dependent string backgrounds are known, let alone dS background. Next, one cannot make sense in a precise way of local particle physics quantities. Because of the horizon experienced by an observer, one cannot hope to witness the final state

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of the whole universe. What does it mean to quantize a spacetime then? In flat space we have the S-matrix which relates past and future infinities. In AdS space we have boundary correlators of bulk fields. However, in dS space we do not have analogs of these.

There have been some attempts to formulate quantum field theories in dS space. Common problem in formulating QFT on a curved background is ambiguity in the choice of vacuum. In dS space there is a one-parameter family of vacua invariant under the de Sitter group. A fixed observer sees the world as a closed finite system at a non-zero temperature. The degrees of freedom seen by any given observer are in some sense equivalent to the degrees of freedom seen by any other inertial observer. Banks and Fischler proposed that one can use this to define the analog of the S-matrix to describe observations made by an inertial observer in dS space. In any case, there is a serious problem in putting QFT which has infinite degrees of freedom into dS space which allows only finite degrees of freedom and thus allows finite dimensional Hilbert space. This is easy to see from the fact that entropy is the logarithm of the number of states and dS has finite entropy.

II. DE SITTER SPACE AND STRING THEORY

What are the attempts in string theory then? The problem worsens in string theory, since string theory contains an infinite collection of quantum field theories. An early attempt was made by Hull [14], who introduced Euclidean branes by introducing T-duality on a timelike circle. There were also considerations of dS/CFT correspondence by Strominger [15]. However, this attempt had difficulties since dS space has two boundaries of Past and Future spheres. Thus, a single observer cannot see both boundaries, due to the horizon, and description of the entire space is beyond what can be physically measured. Gutperle and Strominger [16] introduced spacelike branes, describing the process of creation and decay of branes. More recently, dS vacuum is regarded as one of many vacua allowed in the string theory landscape.

In this paper, we would like to have a different approach. We would like to view dS space as a part of a larger spacetime, which interpolates between dS and flat asymptotia. The larger spacetime definitely allows infinite degrees of freedom. A bubble solution forms such a background. Near the bubble the spacetime is dS space and asymptotically it is flat. Moreover, one can construct such a background starting from D3-branes and double Wick rotating them. The bubble solutions have a region, the near-bubble wall region, which is dS space, but is asymptotically flat Minkowski space. Therefore, it has plenty of room to allow the infinite degrees of freedom of string theory. Moreover, we will argue that most matter is accumulated near the bubble wall as it expands. Therefore most of the galaxies are formed near the bubble wall and it is natural that intelligent observers see dS space around them. These solutions are obtained by performing double Wick rotation (DWR) on well-known D/M-brane solutions, and we will call them D/M-bubbles [17]. First, we find that near the bubble wall, the geometry becomes 'de Sitter × non-compact internal space'. Second, we find that the case of the extremal D3-bubble corresponds to Hull's Euclidean brane (called E4-brane) [14]. However, other cases we have considered, such as M2- or M5-bubbles, are new and cannot be obtained by Hull's timelike T-duality of type II theories.

Extremal D3-bubbles preserve full 32 supersymmetries near the bubble wall and at the asymptotic infinity. In order to make sense of supersymmetry in this background, Ramond-Ramond (RR) should be imaginary, which is also a consequence of DWR. Imaginary valued fields, at least form free cases, can be regarded as fields with the wrong sign for the kinetic term. At first glance, this might sound pathological. However, there is a long history of fields with the wrong kinetic term [18], and recently such fields have been considered as candidates for dark energy [19], being the source for the acceleration of the expansion of the universe. The situation gets more complicated when we couple the imaginary field with real valued charges. The coupling gives rise to an imaginary term in the Lagrangian. Our proposal is that we should interpret such a term as a signature of the instability of the vacuum. This is in the spirit of Schwinger's original work [20] on pair creation in a strong electric field. Here, the imaginary value of the effective potential has a definite physical interpretation. This is the consequence of DWR from the real valued fields of $\mathrm{AdS}_p\times \mathrm{S}^q$ backgrounds.

There is a 'no-go theorem' in string theory (supergravity) which rules out dS space as a result of non-singular warped compactification [21]. The basic assumptions for this theorem are: (i) no higher curvature correction in the gravity action; (ii) non-positive potentials for the scalars; (iii) massless fields with positive kinetic terms; and (iv) a finite effective Newton's constant in lower dimensions. There are some ways to detour the no-go theorem, for example see [22, 23]. Alternatively, one can accept the vastness of the string landscape [24] and resort to the anthropic principle [25].

In this paper, we introduce imaginary fields to detour the no go theorem. Consider the Einstein equation with some form field.

$$R_{ab} = \frac{1}{2}F_{ac}F_b{}^c - \frac{1}{8}\eta_{ab}F_{cd}F^{cd}, \qquad d * F^{(2)} = 0, \quad (1)$$

which has the well-known Freund-Rubin-type solution:

$$ds^2 = ds^2_{AdS} + ds^2_{sphere}, \qquad F^{(2)} = me^2 \wedge e^3, \qquad (2)$$

where $e^2 \wedge e^3$ is the volume of the unit sphere. From the observation that the nontrivial components of the Ricci tensor are $R_{00} = -R_{11} = R_{22} = R_{33} = m^2/4$, we are tempted to think of an imaginary valued field strength ($m^2 < 0$) so that the above solution is converted to the type $ds^2 = ds^2_{hyperbolic} + ds^2_{dS}$, that is, the geometry is factorized into two-dimensional hyperbolic space and two-dimensional dS space.

III. WITTEN'S BUBBLE SOLUTION

One typical example of a solution thus made is the original Witten's bubble solution [26], obtained by double Wick rotating the Schwarzschild black hole solution. With string/M theories in mind, let us consider a Schwarzschild black hole in general D-dimensions:

$$ds^2 = -\left(1 - \left(\frac{r_0}{r}\right)^{D-3}\right) dt^2 + \left(1 - \left(\frac{r_0}{r}\right)^{D-3}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\Omega^2_{D-3}\right). \tag{3}$$

Taking the following double Wick rotation, $t = -i\xi$, $\theta = \frac{\pi}{2} + i\psi$, we obtain a bubble solution

$$ds^2 = \left(1 - \left(\frac{r_0}{r}\right)^{D-3}\right) d\xi^2 + \left(1 - \left(\frac{r_0}{r}\right)^{D-3}\right)^{-1} dr^2 + r^2\left(-d\psi^2 + \cosh^2\psi\, d\Omega^2_{D-3}\right). \tag{4}$$

The radial coordinate should be restricted as $r \geq r_0$, to prevent three temporal coordinates appearing. Regularity at $r = r_0$ requires that the coordinate ξ be periodic; $\xi \sim \xi + \frac{4\pi r_0}{D-3}$. Asymptotically, the solution describes the standard Kaluza-Klein compactification. This is more transparent in Rindler coordinates,

$$\tau = r\sinh\psi, \qquad \rho = r\cosh\psi, \qquad (\tau^2 < \rho^2) \tag{5}$$

in which the asymptotic geometry becomes a circle times $(D-1)$-dimensional flat Minkowski spacetime:

$$\begin{aligned} ds^2 &\simeq d\xi^2 + dr^2 + r^2\left(-d\psi^2 + \cosh^2\psi\, d\Omega^2_{D-3}\right) \\ &= d\xi^2 - d\tau^2 + d\rho^2 + \rho^2\, d\Omega^2_{D-3}\,. \end{aligned} \tag{6}$$

The internal circle shrinks to zero size at $r = r_0$ and the geometry is not extended to the region $r < r_0$; thus, it is called a bubble of nothing. The whole nowhere-singular solution describes a bubble of nothing with its wall accelerating in time ($\rho^2 = \tau^2 + r_0^2$). In this sense, the solution is also called a Kaluza-Klein bubble. In the asymptotic region, the geometry represents a flat Minkowski spacetime Kaluza-Klein compactified on a circle of period $\Delta\xi$. The size of the compact direction becomes vanishing at $r = r_0$, and the geometry is defined only for $r \leq r_0$, thus, this is called the 'bubble of nothing'. The bubble wall is accelerating and follows $\rho^2 = \tau^2 + r_0^2$.

The approximate geometry in the near-bubble region describes a disk and a $(D-2)$-dimensional dS space, when we use the near-bubble coordinate, $u^2 = r^{D-3} - r_0^{D-3}$:

$$ds^2 \simeq \frac{1}{r_0^{D-3}}\left(u^2 d\xi^2 + \frac{4r_0^2}{(D-3)^2} du^2\right) + r_0^2\left(-d\psi^2 + \cosh^2\psi\, d\Omega^2_{D-3}\right) + \mathcal{O}(u^2/r_0^{D-3}). \tag{7}$$

When we apply DWR to various D/M-brane solutions in string/M theories, we get their bubble cousins. The non-extremal bubbles exhibit similar features to Witten's bubble; the solutions are restricted to the outside of some fixed radial coordinate $r_0 > 0$, the asymptotic geometry describes Minkowski spacetime compactified on a circle, and the bubble wall is accelerating in the asymptotic coordinates. The extremal bubbles inherit most good features from their D/M-brane counterparts. The geometry near the bubble wall, sharply factorized as dS space and hyperbolic space, is not just an approximate solution but an exact solution. The wall of the extremal bubbles follows a null line; nevertheless, the near bubble solution preserves the full 32 supersymmetries. However, these solutions are plagued by various imaginary valued fields; therefore, they look 'pathological'. The option one can choose at this point is either to abandon those solutions or to interpret their physical meaning. The strategy we will follow in this paper is the latter: to interpret those solutions as some quantum process like instantons [27,28].

Recall that instanton solutions, giving valued finite actions in Euclidean space, become involved with the imaginary valued actions upon Wick rotation back to the Lorentzian spacetime. We interpret the dS part including imaginary gauge fields as the instanton obtained à la Coleman-de Luccia [29] or Hawking-Turok [30]. We would like to emphasize here that our solutions need not assume any false vacua as was done with the Coleman-de Luccia instanton and also contrast with the Hawking-Turok instanton in that they are geodesically complete without any singularity. The extremal near-bubble geometries discussed in this paper are classically stable in the sense that the factorization of dS space and the hyperbolic spatial section persists forever. However, we argue in a later section that they are unstable in the semi-classical sense. The imaginary fields (interpreted in this paper as the fields coming through the tunneling process from S^4 to dS_{3+1}) induce the creation of spherical branes much like Schwinger's process of pair creation [20]. The bubble solutions have a surprising cosmological application. The empirical evidence (the acceleration of the present universe and the dominant contribution from the matter component with the equation of state parameter $w \sim -1$ [2]) for the positive cosmological constant imposes on us the problem of explaining why the cosmological constant is so small, but is yet non-vanishing. We will find a possible solution to the cosmological constant problem in the context of string/M theories. This is achieved by utilizing the created branes as the factor which effectively lowers the cosmological constant of dS spacetime.

IV. D-BUBBLES

Most well-known brane configurations have their bubble cousins. In this section, we will study in detail the bubble solution obtained from the non-extremal D3-brane solution. We will call it the D3-bubble. Let us start with a non-extremal D3 solution:

$$\begin{aligned} ds^2 &= H_3^{-\frac{1}{2}}(r)\left(-f_3(r)dt^2 + d\vec{x}^2\right) \\ &\quad + H_3^{\frac{1}{2}}(r)\left(f_3^{-1}(r)dr^2 + r^2 d\Omega_5^2\right), \\ H_3(r) &= 1 + \frac{\mu_3^4 \sinh^2\alpha_3}{r^4}, \quad f_3(r) = 1 - \frac{\mu_3^4}{r^4} \end{aligned} \tag{8}$$

with the electric and the magnetic RR field strength as

$$\begin{aligned} \mathcal{F}_{(5)} &= -*dH_m \\ &\quad + d\left(H_e^{-1} - 1\right) \wedge dt \wedge dx_1 \wedge dx_2 \wedge dx_3 \\ H_m &= 1 + \frac{\mu_3^4 \sinh\alpha_3 \cosh\alpha_3}{r^4}, \\ H_e^{-1} &= 1 - \frac{\mu_3^4 \sinh\alpha_3 \cosh\alpha_3}{r^4 + \mu_3^4 \sinh^2\alpha_3}. \end{aligned} \tag{9}$$

Here, Hodge star $*$ is with respect to the 6-dimensional *flat* space transverse to the brane world-volume. We followed the notations for the harmonica functions from the bubble geometry obtained à la Witten [26]. Double Wick rotations along the temporal direction and one of the spherical directions lead us to

$$\begin{aligned} ds^2 &= H_3^{-\frac{1}{2}}(r)\left(f_3(r)d\xi^2 + d\vec{x}^2\right) \\ &\quad + H_3^{\frac{1}{2}}(r)\left(f_3^{-1}(r)dr^2 + r^2\left(\cosh^2\psi d\Omega_4^2 - d\psi^2\right)\right). \end{aligned} \tag{10}$$

The fact that RR field strength is involved in the solution basically contrasts with Witten's bubble (4). It results in the 'unwanted' imaginary value of the field:

$$\begin{aligned} \mathcal{F}_{(5)} &= 4i\mu_3^4 \sinh\alpha_3 \cosh\alpha_3 \left(\cosh^4\psi\, d\Omega_4 \wedge d\psi\right. \\ &\quad \left. - r^{-5} H_3^{-2} d\xi \wedge dx_1 \wedge dx_2 \wedge dx_3 \wedge dr\right). \end{aligned} \tag{11}$$

However, as was mentioned earlier, we will interpret this imaginary value of the solution as some quantum process like the instanton.

In the near-bubble coordinate ($u^2 = r^4 - \mu_3^4$, $u^2 \ll \mu_3^4$), the metric is factorized into $D_2 \times \mathbf{R}^3 \times dS_{4+1}$, where 5-dimensional dS spacetime has the cosmological constant $\Lambda_{4+1} = 6/(\mu_3^2 \cosh\alpha_3)$.

Integrating the 5-form field strength over the hyperbolic space that is transverse to dS space, we obtain the electric and magnetic fluxes $\int_{\mathrm{H}_5} *\mathcal{F}_{(5)} = i\mathrm{Vol}_4$, $\int_{\mathrm{H}_5} \mathcal{F}_{(5)} = -i\mathrm{Vol}_4$, where Vol_4 is the coordinate volume of the anti-selfdual 'instanton'. It is very interesting to see that both the electric and the magnetic flux density are independent of the number Q_3 of D3-brane cousins. This is a universal feature common to most D/M-bubble configurations. In the next section, we use this feature as one important clue to give the answer to the cosmological constant problem. One can take DWR on other D/M-brane configurations to get their corresponding D/M-bubble solutions. Details can be found in Ref. [17].

D3-bubble solutions correspond to E4-brane solutions in type IIB theory. One can see this explicitly by adopting Rindler coordinates: $\tau = r\sinh\psi$, $\rho = r\cosh\psi$. Hence, the total results suggest equivalence between DWR and Hull's time-like T-duality.

In a realistic cosmological situation, we can expect that actually there are multiple bubbles [31]. In the case of two bubbles, both of which are expanding, the collision of bubbles leads to the formation of a singularity. This might sound as if the inhabitants of the bubble wall are destined to have a doomsday. However, if you live near the bubble wall, you will never witness the singularity formation. This means that we cannot see the bubbles swallow us up. The bubbles are expanding at the speed of light, but no observer can see them swallow up the whole spacetime completely because all the observers will be left, being squeezed by the expanding bubbles to the near-bubble region. Depending on the position in $\vec{\rho} \in \mathbf{R}^4$, the effective cosmological constant varies. Notice that there is a universe' corresponding to each bubble and the multi-bubble background gives rise to the multiverse picture. The form of the multiverse thus obtained is reminiscent of a Swiss cheese [17]. Some of the earlier ideas of multiverse can be found, for example in Refs. [32,33]. A varying cosmological constant in the multiverse is reminiscent of more recent ideas of the landscape [25].

V. COSMOLOGICAL CONSTANT PROBLEM

The price we have to pay for a dS solution in string/M theories is to allow imaginary field strengths. In this section, we interpret this disturbing situation as one mechanism to temper the acceleration of the universe so that it leads to dS space with an almost, but not exactly, vanishing cosmological constant, like our present universe.

Note that the imaginary-valued term in the quantum effective action indicates the instability of the vacuum [20]. This statement is valid even in the classical action. Therefore, the imaginary potential term in the classical action indicates the violation of the unitarity, *i.e.*, the creation of probability. Utilizing this for the imaginary RR form field, we obtain spherical brane production. The imaginary RR form field can couple to spherical branes and this imaginary interaction term represents the instability of pure dS vacuum against the creation of spherical branes over its spherical space. This is similar to the Schwinger pair production procedure of charged particles in a strong electric field. Recall that the one-loop diagram of charged particles in the background of strong electric field results in the pure imaginary term in the effective action, which implies the instability of the corresponding vacuum and signals the pair creation of the charged particles. In the above, we get a pure imaginary term in the interaction of a spherical brane (the composite of a D3-brane and an anti-D3-brane) with dS background. One can interpret this term in the semi-classical sense as the instability of the dS vacuum, signaling the creation of spherical branes. The spherical symmetry of the spatial sphere of dS and the fact that the above result does not depend on the latitudinal position of the branes imply random creation of the spherical branes of random sizes over the spatial sphere. In this sense, D3-bubble dS vacua are unstable against the creation of spherical branes. One can show that the creation rate is the same over all the latitudes [17]. The spherical branes of random sizes condense in a spherically symmetric manner. These spherical branes wrapping sphere squeeze the expansion of dS, resulting in a lower effective cosmological constant. The condensation of the spherical branes provides us with a natural mechanism to explain the cosmological constant problem. The tension of the created spherical branes will squeeze the accelerating spatial sphere of dS space à la Brandenberger-Vafa mechanism [34], which results in the reduction of the cosmological constant. This procedure cannot exhaust the cosmological constant completely. Recall that the Schwinger pair creation process does not violate charge conservation. Despite the condensation of the spherical branes (with vanishing net brane charge), the electric flux density 'i' over the spatial hyperboloid should be invariant. This implies that the resultant geometry of the condensation of the spherical branes cannot be completely flat Minkowski spacetime where the imaginary electric flux is absent. Though the cosmological constant approaches '0' from above, it cannot vanish completely. This could be one explanation of the cosmological constant problem.

VI. CONCLUSION

In this paper, we show that the D3 brane configuration has its bubble cousin. It has a universal feature of having dS space as near-bubble geometry. The near-bubble geometry preserves 32 supersymmetries. The imaginary higher-form fields guarantee Killing spinors even in dS backgrounds. Therefore, the bubble solution is the domain wall solution interpolating two maximally supersymmetric regions, *i.e.*, the asymptotic flat Minkowski region and the near-bubble de Sitter $\times$ hyperbolic region. Especially supersymmetry makes sense of multi-bubble solutions obtained from multi-brane solutions *via* double Wick rotation. Though the observer can see the bubbles start inflating, once they invade the region near to the observer, each bubble will remain just as a deep throat of dS space and it will take infinite coordinate time for the bubbles to swallow up the whole spacetime. At the final stage, the observer will find himself in a grand Swiss cheese universe, where the effective cosmological constant varies from point to point near the cheese holes. This is a new stringy realization of the multiverse idea. The imaginary field strength triggers the creation of spherical D3-branes over the spatial section of dS space near D3-bubbles. The tensions of the spherical branes decelerate the expansion of dS space. Though the effective cosmological constant decreases with the condensation of the spherical branes, the conservation of the fluxes '$\pm i$' of higher-form fields prevents it from completely vanishing.

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