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New Aspects of the Cosmology of Extra Dimensions

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The cosmology of higher dimensional spacetime models in which ordinary matter is confined to a hypersurface (brane) is discussed. The nonconventional aspects of the corresponding cosmological scenarios is emphasized. Some issues relevant to the primordial universe, such as inflation, are reviewed.

1. INTRODUCTION

Theories of fundamental interactions often require the introduction of new compact spatial dimensions. One may cite Kaluza–Klein theories, supergravity, and superstring theories. This leads to interesting cosmological scenarios which have been studied in the last 20 years (see, e.g., ref. 1). But this type of idea has received a new twist with the advent of strongly coupled string theories: gravitational interactions may not feel the same spatial dimensions as the gauge interactions of the Standard Model. In other words, our four-dimensional world would be confined to a hypersurface in a higher dimensional universe and only gravitational effects would allow us to probe the extra dimensions: photons being confined to the hypersurface, electromagnetic means—such as light—would not directly reach such dimensions. For example, in the supergravity theory of Hořava and Witten [2], spacetime is 11-dimensional, whereas the Yang–Mills gauge fields live on 9-branes, which are 10-dimensional hypersurfaces. After compactification on a 6-dimensional compact manifold, this leaves us with 5-dimensional supergravity coupled with 4-dimensional gauge and matter supermultiplets.

Once one realizes that the structure of matter has been tested at the microscopic scale only through the standard gauge interactions, for example, using electromagnetic probes, this leaves us with a new exciting possibility:

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new dimensions which are felt only by the gravitational interactions may open up at distance scales much larger than the ones already tested by the standard gauge interactions in modern-day accelerators [3].

It is well known in Kaluza–Klein theories that the Planck scale M_P is expressed in terms of the Planck scale M of the higher dimensional theory and of the radius of the compact dimensions. When this radius is large in terms of the former scale M, the Planck scale may be much larger than M. In other words, the fundamental scale M of the theory may be orders of magnitude smaller than the derived scale M_P. Indeed, M could be as low as the electroweak scale [3], thus leading to possibilities of exploring the effects of the new dimensions in the next generation of colliders.

Such possibilities obviously lead to unconventional scenarios for cosmology. If the scale M is much larger than the electroweak scale, cosmology might indeed be the privileged way of probing such theories.

In the following, we will start by describing an example of such a theory, the Hořava–Witten theory [2], where there is a single compact dimension of the type described above. We will then briefly review more general possibilities with a large number of extra dimensions. We then discuss the properties of inflation in this context and make some comments about the presence and role of topological defects.

2. EXAMPLES OF HIGHER DIMENSIONAL THEORIES

Let us start with an example which appears in the context of strongly coupled superstring theories. It is believed that the strongly coupled heterotic $E_8 \times E_8$ string theory is adequately described by an 11-dimensional theory. In the field theory limit, this so-called M-theory has been described by Hořava and Witten [2]. The gravity sector is described by the unique 11-dimensional supergravity action on $R^{10} \times S_1/Z_2$, which, restricted to boson fields, reads

$$\begin{aligned}\mathcal{S} = {} & \frac{1}{\kappa_{11}^2}\int d^{11}x \;\sqrt{g^{(11)}}\left(-\frac{1}{2}\,\mathcal{R}^{(11)} - \frac{1}{48}\,G_{IJKL}G^{IJKL}\right)\\ & - \frac{\sqrt{2}}{3456\kappa_{11}^2}\int d^{11}x\,\epsilon^{I_1\cdots I_{11}}C_{I_1I_2I_3}G_{I_4\cdots I_7}G_{I_8\cdots I_{11}}\\ & - \frac{1}{8\pi(4\pi\kappa_{11}^2)^{2/3}}\int d^{10}x\;\sqrt{g^{(10)}}\;\mathrm{tr}\,F_{AB}F^{AB}\end{aligned} \tag{1}$$

where $I, J, \ldots$ are 11-dimensional indices, $A, B, \ldots$ are 10-dimensional indices, and G is the field strength of a fundamental three-form C ($G = 6dC + \cdots$).

The compact dimension has an orbifold structure: the Z_2 projection corresponds to the reflection on the 11th coordinate ($x^{11} \to -x^{11}$) and acts as the chirality projector on the gravitino degrees of freedom. The 3-form C is odd under this projection, whereas the metric tensor is even. The 10-dimensional action is understood as an integral over the two boundaries associated with the orbifold endpoints (9-branes, that is, hypersurfaces with nine spatial dimensions), say at $x_{11} = 0$ and $x_{11} = 1/2$.

The bosonic action (1) and the corresponding fermionic one constructed in ref. 2 do not form the complete quantum action, but they are rather an effective description including the lowest orders of an expansion in the parameter $\kappa_{11}^{2/3}$. Because of the presence of the boundary, the fermionic action includes divergent terms proportional to $\delta(0)$ (as well as its derivatives) possibly to some power: in a full quantum treatment, the boundary presumably acquires a nonzero thickness of order M^{-1} and the divergent $\delta(0)$ terms are smoothed out into terms of order M, where M is the fundamental mass scale:

$$\kappa_{11}^2 = M^{-9} \tag{2}$$

One may compactify the theory down to five dimensions [4–10]. We choose a simple ansatz for the metric

$$ds^2 = e^{-2\phi/3}(g_{\alpha\beta}\, dx^\alpha\, dx^\beta + e^\phi g_{ab}^{(0)}\, dx^a\, dx^b) \tag{3}$$

where α, β, ... are 5-dimensional indices and the 6-dimensional metric $g_{ab}^{(0)}$ is normalized ($\int d^6x \ \sqrt{g^{(0)}} = M^{-6}$) in such a way that the 6-dimensional volume V_6, as measured from 5 dimensions, is given by

$$V_6 = M^{-6} e^{3\phi} \tag{4}$$

The 5-dimensional bosonic action reads

$$\begin{aligned}\mathcal{S} = &-\frac{1}{2\kappa_5^2}\int d^5x\ \sqrt{g}\left(\mathcal{R}^{(5)} + \frac{1}{2}\,\partial^\alpha\phi\partial_\alpha\phi\right.\\ &\left.+ \frac{1}{24}\,e^{2\phi}G^{\alpha\beta\gamma\delta}G_{\alpha\beta\gamma\delta} + \cdots\right)\\ &- \frac{1}{16\pi\alpha}\int d^4x\ \sqrt{g^{(4)}}e^\phi \ \mathrm{tr}\ F^{\alpha\beta}F_{\alpha\beta}\end{aligned} \tag{5}$$

where $g^{(4)}$ is the determinant of the 4-dimensional metric $g_{\mu\nu}$ on the two 3-branes which form the boundary of spacetime (from now on, the indices μ, ν are are four-dimensional indices), $\alpha = (4\pi)^{2/3}/2$, and

$$\kappa_5^2 = M^{-3} \tag{6}$$

The scale where the theory becomes 11-dimensional corresponds to the unification of the gauge couplings. It is therefore the grand unification scale M_U. It can be computed from the mass of the Kaluza–Klein states and is therefore obtained from (4):

$$M_U \sim M e^{-\phi/2} \tag{7}$$

The corresponding common value α_U of the gauge couplings is read from (5):

$$\alpha_U \sim \alpha e^{-\phi} \tag{8}$$

If we denote by R the radius of the orbifold dimension, one also reads from (5) the value of the 4-dimensional (reduced) Planck scale:

$$m_P^2 = M^3 R \tag{9}$$

Putting back factors of π, one obtains (see, e.g., ref. 11)

$$\begin{aligned} M &= M_U (2\alpha_U)^{-1/2} \sim 3.4 M_U \\ R^{-1} &= \frac{1}{2\pi} \frac{M_U^3}{m_{Pl}^2} (2\alpha_U)^{-3/2} \sim 10^{-3}\, M_U \end{aligned} \tag{10}$$

where we used $M_U = 3 \times 10^{16}$ GeV and $\alpha_U^{-1} = 23.3$.

This shows that:

- Since R^{-1} is smaller than the unification scale M_U where the theory becomes 11-dimensional, there is a mass range where the theory is effectively 5-dimensional [12];
- The fundamental scale in the theory is the 5-dimensional Planck scale M, which is somewhat smaller than the Planck scale.[2]

It should be noted that, because the original theory is not fully determined by the action (1), its compactified version is valid only for a certain range of mass scales. In particular, we disregarded the nonzero thickness of the boundary, presumably associated with some nonperturbative effect in quantum M-theory. Had we restored a nonvanishing thickness, the gauge fields of the boundary would propagate in the corresponding layer (of width of order M^{-1}): this would generate in the 4-dimensional theory massive states of mass M. Since we consider on the other hand the Kaluza–Klein states of mass R^{-1}, our treatment is not consistent unless we impose the condition

$$M R \gg 1. \tag{11}$$

This is obviously satisfied if we plug in the data (10). Notice that, physically,

[2] Strictly speaking, it is the 11-dimensional Planck scale $M_{11} \sim M e^{-\phi/3}$. More precisely, $M_{11} = M_U (2\alpha_U)^{-1/6} \sim 1.5\ M_U$.

MR is the number of Kaluza–Klein states of mass less than M, which contributes to computations involving Kaluza–Klein states running in loops.

The two points noted just above may be pushed to their extreme:

- The theory looks 4-dimensional only up to the scale R^{-1}; it has been stressed for some time [13] that experimental data only constrain compactification scales to be larger than the presently available energy, say 1 TeV. But the present compact dimension is only felt by gravitational interactions, which have been tested only to the millimeter range, which corresponds to $R^{-1} \sim 10^{-4}$ eV.
- If we want to keep fixed the 4-dimensional Planck scale m_P, we see from (9) that the larger R is, the smaller the fundamental scale M is; following the previous remark, M could be as small as $(m_P^2 \times 10^{-4}\ \text{eV})^{1/3} \sim 10^8$ GeV. This is of course not compatible with (7) if one considers M_U to be of the order of 10^{16} GeV. But it has been noted [14] that the presence of extra spacetime dimensions, which amounts to the presence of Kaluza–Klein states in the effective lower dimensional theory, may significantly lower the unification scale to a value larger than the compactification scale by only one order of magnitude. Of course, the Kaluza–Klein states that one needs must be charged under the gauge symmetry: they are necessarily those associated to the 6-dimensional compact manifold of volume V_6.

The previous discussion rests on the hypothesis that there is a single compact dimension which is felt solely by the gravitational interactions. In the case of n such compact dimensions caracterized by the same radius R, (9) is modified to

$$m_P^2 = M^{2+n} R^n \tag{12}$$

where M is now the $(4 + n)$-dimensional Planck scale. This can be easily derived [3] by considering two test masses m_1 and m_2 placed within a distance r; they are subject to a gravitational potential:

$$\begin{aligned} V(r) &\sim \frac{m_1 m_2}{M^{n+2}} \frac{1}{r^{n+1}} \qquad \text{for} \quad r \ll R \\ V(r) &\sim \frac{m_1 m_2}{M^{n+2} R^n} \frac{1}{r} \qquad \text{for} \quad r \gg R \end{aligned} \tag{13}$$

where, in the latter case, the potential may be seen as due to a n-dimensional line with uniform mass density.

It has been stressed recently that in this case the higher dimensional Planck scale might be as low as the electroweak scale. For example, with $n = 2$, this would correspond to $R \sim (10^{-4}\ \text{eV})^{-1}$, that is, R in the millimeter range. Interestingly, this represents the limit of present experimental tests of gravity. In such an instance, the electroweak scale would be the fundamental scale of the theory, the Planck scale m_P being relegated to a derived scale. It requires, however, to explain the large hierarchy between R^{-1} and the electroweak scale. It is fair to say at this point that, however exciting this possibility is, there is no convincing theoretical argument to choose such a low value of the fundamental scale M, which may take any value between the electroweak and the 4-dimensional Planck scale m_P.

String models with two or more dimensions have also been constructed, based on the type I theory of open and closed strings [15]. Other examples have been considered where our 4-dimensional world was imbedded in a topological defect [16, 17, 3].

3. NONCONVENTIONAL COSMOLOGY

One may think that, if our 4-dimensional world is a slice (a 3-brane) within a higher dimensional spacetime, its evolution might be considered for the most part independently of what happens in the outer dimensions. This is not so. It is, for example, well known in general relativity that if we consider a slice in an enveloping spacetime, physics within the slice will be sensitive not only to the intrinsic curvature of the slice, but also to the curvature of the slice relative to the enveloping geometry. This is described by the notion of extrinsic curvature.

We will show how this modifies the evolution of the 4-dimensional universe on a simple example: a 5-dimensional spacetime $R^4 \times S_1/Z_2$ with matter confined to the world volume of a 3-brane. The metric is chosen to be

$$ds^2 = -n^2(\tau, y)\, d\tau^2 + a^2(\tau, y)\, dx^i\, dx^i + b^2(\tau, y)\, dy^2 \tag{14}$$

where x^i are the 3-dimensional spatial coordinates and y is the compact orbifold coordinate ($-1/2 \leq y \leq +1/2$, the Z_2 symmetry corresponding to the reflection $y \to -y$). Assuming isotropy and homogeneity in the brane, placed at $y = 0$, we choose an energy-momentum tensor

$$T^{\alpha}_{\beta} = \frac{\delta(y)}{b}\, \mathrm{diag}(-\rho, p, p, p, 0) \tag{15}$$

The metric is continuous at the brane and satisfies the Einstein equations

$$G_{\alpha\beta} = \kappa_5^2 T_{\alpha\beta} \tag{16}$$

where $G_{\alpha\beta}$ is the Einstein tensor. A local study of how discontinuities of the derivatives of the metric on the brane are constrained by the Einstein equations (in particular for $\alpha = \beta = 5$) yields [18]

$$\frac{\dot{a}_0^2}{a_0^2} + \frac{\ddot{a}_0}{a_0} = -\frac{\kappa_5^2}{36}\rho(\rho + 3p) \tag{17}$$

where $a_0(\tau) = a(\tau, y = 0)$ and we chose $n(\tau, y = 0)$. In terms of the Hubble parameter of our 4-dimensional world

$$H = \frac{\dot{a}_0}{a_0} \tag{18}$$

this equation reads

$$\dot{H} + 2H^2 = -\frac{\kappa_5^4}{36}\rho(\rho + 3p) \tag{19}$$

This should be compared with the more standard equation

$$\dot{H} + 2H^2 = \frac{\kappa_4^2}{6}(\rho - 3p) \tag{20}$$

with $\kappa_4^2 \equiv m_P^{-2}$, which is obtained in the standard 4-dimensional cosmology. This difference of behavior can be related to the extrinsic curvature of the 4-dimensional slice [18]. On the other hand, the equation of conservation of energy remains unchanged:

$$\dot{\rho} + 3(p + \rho)\frac{\dot{a}_0}{a_0} = 0 \tag{21}$$

The new equation obviously generates some definite departure from the standard behavior. For example, if we consider matter with an equation of state $p = w\rho$, in both cases (21) imposes that

$$\rho \propto a_0^{-3(1+w)} \tag{22}$$

but our new equation (19) yields

$$a_0(t) \propto t^{1/[3(1+w)]} \tag{23}$$

whereas the standard behavior from (20) is

$$a_0(t) \propto t^{2/[3(1+w)]} \tag{24}$$

A physical way to picture this striking difference of behavior is through "graviton evaporation." It has been noted that the presence of the wall breaks translational invariance in the compact dimensions and allows momentum nonconservation: the massive modes of the graviton on the wall may evaporate into the bulk and once in the bulk they have a small probability of returning since the phase space associated with the wall is so much smaller than the phase space associated with the bulk. Thus some energy will be seeping into the bulk [3]. In the general case of n compact dimensions, the rate for graviton production is proportional to $1/M^{n+2}$ (as can be seen by writing the metric $g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}/M^{(n+2)/2}$, which ensures that $h_{\alpha\beta}$ is canonically normalized). Restricting our attention to a single compact dimension ($n = 1$) and to radiation ($w = 1/3$), the rate of evaporation is, on dimensional grounds,

$$\dot{\rho} = -M^{-3}T^8 = -M^{-3}a_0^{-8} \tag{25}$$

which, using (22), yields $a_0 \propto t^{1/4}$ in agreement with (23).

Moreover, once in the bulk, the gravitons are standard gravitons of a 5-dimensional theory and are therefore stable. The most natural way to condense these gravitons is to interpose a second wall with energy density $\rho^* \sim -\rho$. This is exactly what happens in the model which we consider: the two walls are the boundaries of the orbifold direction, i.e., the 3-branes at $y = 0$ and $y = 1/2$. More precisely [18], since we allow for a y-dependent metric (14),

$$\rho^* n(1/2) = -\rho n(0) \tag{26}$$

Another possibility is to introduce a diffuse source of gravitons throughout the bulk. This could be provided by a field related with the fundamental 3-form C_{IJK} of 11-dimensional supergravity introduced in (1): the so-called Ramond–Ramond scalar ξ ($C_{abc} \equiv \xi\epsilon_{abc}$).

4. INFLATION

One may now consider the problem of inflation from the point of view of this nonconventional cosmology. The first question is whether one should envisage inflationary scenarios in the bulk or in the brine. Bulk inflation has the potential danger of expanding exponentially the compact dimensions, leading to very large radii (possibly a welcome feature if we are to consider theories with a low M scale). On the other hand, it might lead to a sharp decrease of the bulk energy density, a necessary condition for a scenario of brane inflation.

On the other hand, brane inflation might be sufficient to solve the standard problems of our 4-dimensional world. It has been stressed that it can only be realized in the case of a single compact dimension of the type discussed earlier [19, 20]. Let us then see in more detail under what conditions brane inflation is possible in the context of the simple model studied in the previous section. If we allow for a nonvanishing energy-momentum tensor in the bulk

$$(T_B)^\alpha_\beta = \mathrm{diag}(-\rho_B, p_B, p_B, p_B, p_B) \tag{27}$$

with the usual assumption of isotropy and inhomogeneity, then (19) reads

$$\dot{H} + 2H^2 = -\frac{\kappa_5^4}{36}\rho(\rho + 3p) - \frac{1}{3}\kappa_5^2 p_B \tag{28}$$

Assuming for simplicity vacuum solutions in the bulk and in the brane, i.e., $p_B = -\rho_B$ and $p = -\rho$, we see that, in order to have the brane vacuum energy dominate the bulk vacuum energy, we must require

$$\rho_B \ll \rho^2/M^3 \tag{29}$$

This requires specific initial conditions, but is not incompatible with the obvious conditions: $\rho_B < M^5$ and $\rho < M^4$.

Under this requirement, vacuum energy dominance yields a Hubble parameter

$$H = \frac{\rho}{6M^3} \tag{30}$$

which is linear in ρ, as observed already above and stressed by several authors [21, 19, 20].

With such a dependence of the Hubble parameter on ρ, a problem often discussed in connection of brane inflation—the problem of the mass of the inflaton field [22, 23]—is not present. Indeed, since $\rho < M^4$, we have $H < M$ and the fact that the mass of the inflaton is smaller than H is not a stringent constraint, as it would be if we were to apply the standard formulas valid in conventional scenarios of inflation.

An explicit example of such an inflationary solution has been given by Kaloper and Linde [19]. The metric is given by (14) with

$$\begin{aligned} b &= \text{const} \\ n &= 1 - \frac{b\rho}{6}|y| \\ a &= e^{Ht}\left(1 - \frac{b\rho}{6}|y|\right) \end{aligned} \tag{31}$$

with $H = \rho/6$. As explained earlier and in ref. 18, this local solution of the Einstein equations is promoted to a global one if we introduce a second brane at $y = 1/2$ with an energy density ρ^* satisfying (26).

5. CONCLUSIONS

There are many more aspects besides inflation that may be envisaged from the point of view of this nonconventional cosmology.

First, the bulk energy density may dominate over the energy density of the brane. The matter in the bulk would then behave as some hidden matter, but, being 5-dimensional, it would lead to a nonstandard evolution as well.

Topological defects are another interesting issue and the structure of space-time may lead to interesting new structures [11, 24, 25].

Of course, a central question is whether such an unconventional cosmological scenario might still be at work presently. It can easily be shown [18] that the presently allowed values for the energy density, the Hubble constant, and the acceleration parameter do not allow for such a possibility. Moreover, it is difficult to reconcile such a scenario with nucleosynthesis. This tends to show that the universe has undergone a transition to a standard evolution at a time prior to nucleosynthesis. Obviously, such a transition occurs concurrently with the stabilization of the compact dimension. Typically, a potential is generated for the radius of the compact dimension and from then on, one loses the 5-dimensional character (i.e., the reparametrization invariance of the 5-dimensional spacetime) of the Einstein equations, which is the basis of the nonconventional scenario discussed above. The stabilization of the compact dimension(s) is, however, a difficult problem, which leaves little hope at this point to be able to study the transition to a standard 4-dimensional scenario.

Finally, it should be stressed that, in the case where the fundamental scale M is pushed toward the electroweak scale (and $n = 2$), the radius of the compact dimension provides an interesting microscopic scale: $R \sim (10^{-4}\ \mathrm{eV})^{-1}$. Such a mass scale corresponds indeed to the vacuum energy that would be required in order to explain a nonvanishing cosmological constant at present times. Pseudo-Goldstone bosons with a mass of the order of the Hubble constant H_0 have been proposed [26] as viable candidates. It was recently noted [27] that the modulus field whose value fixes the radius R has precisely this property if the Casimir energy dominates the universe. This would, however, imply undesirable time variation of the Newton constant. An alternate possibility lies in the presence of Goldstone bosons associated with the position of the branes. It turns out [3] that these Goldstone bosons are eaten by the gauge fields $g_{\mu a}$ ($a = 4, \ldots, n+3$) to give a mass precisely in the range advocated.

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