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Submillimeter Extra Dimensions and TeV-Scale Quantum Gravity

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We briefly review some phenomenological, astrophysical, and cosmological aspects of theories with large extra dimensions and low-scale quantum gravity.

The extraordinary weakness of gravity in comparison with all the other known subatomic forces is a great mystery in fundamental physics. For decades, the standard paradigm has been that there is a giant "desert" in energy scales over 17 orders of magnitude. This huge discrepancy in scales is the so-called hierarchy problem. This desert stretches from energies of order 100 GeV, currently probed with existing particle physics accelerators, all the way up to energies of order 10^{19} GeV (or length scales of order 10^{-33} cm) where, according to this view, gravity should "catch up" and unify with other interactions.

Recently this paradigm has been challenged [1, 2]. It was shown that the scale of quantum gravity can be 16 orders of magnitude smaller than what was expected, and thus be accessible with present and future high-energy accelerators. This is accomplished by postulating the existence of large extra dimensions of submillimeter size.

Of course, the idea that our world may have extra space dimensions in addition to the three "obvious" ones that we see is not new. Until very recently, however, these extra dimensions were assumed to be curled up into tiny circles about 10^{-33} cm in size, killing any hope for experimentally detecting them.

This size estimate comes from assuming the size is determined by the value of Newton's gravitational constant, $G_N \sim (10^{33}\ \text{cm})^2$. This sets the

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length scale at which, according to Newton's law, the gravitational force between elementary particles

$$F(r) \sim G_N \frac{m_1 m_2}{r^2} \tag{1}$$

becomes strong. In our framework, the extra dimensions, instead of being 10^{-33} cm, can be as large as 1 mm, and thus accessible not only with particle accelerators, but also in proposed table-top experiments measuring gravity at submillimeter distances.

To explain how this may be possible, let us ask what we know about the gravitational interaction experimentally. Due to its miniscule strength, we know surprisingly little: gravity has only been measured down to distances of about 1 mm. The old paradigm relies on the assumption that the Newtonian gravitational force (1) is not modified from centimeter distances (where it has been measured already) all the way down to 10^{-33} cm.

Our framework postulates that quantum gravity becomes strong at a scale $M_P f \sim$ TeV not much above the electroweak scale. The observed weakness of gravity at distances $\geq$1 mm is attributed in our scenario to the existence of new space dimensions of submillimeter size to which gravitational force lines can spread. There are several ways to see how the extra dimensions can "weaken" gravity at large distances. The simplest perhaps is the Gauss law. Imagine that there are N extra compact dimensions of size $\sim R$. We shall assume that roughly all of them have an equal size. The precise shape of the compact manifold is not important for our purposes. Now consider two pointlike test masses m_1 and m_2 in this universe. Obviously, if the distance between particles r is smaller than the size of extra dimensions R, these particles see the universe as being effectively $(4 + N)$-dimensional and the gravitational force between them will be governed by a $(4 + N)$-dimensional Gauss law:

$$F(r) \sim G_{Nf} \frac{m_1 m_2}{r^{2+N}} \tag{2}$$

where $G_{Nf} = M_{Pf}^{-(2+N)}$ is the fundamental Newton constant, and we can define M_{Pf} as the fundamental Planck scale. Solution of the hierarchy problem then sets $M_{Pf} \sim$ TeV.

Now, at distances $r \gg R$, gravitational flux cannot spread in extra dimensions and we should recover the usual four-dimensional Newton law (1). The relation between the observed G_N and the fundamental G_{Nf} Newtonian constants is given by [1]

$$G_N \sim \frac{G_{Nf}}{V_N} \tag{3}$$

where $V_N \sim R^N$ is the volume of the transverse high-dimensional space. For instance, in the case of two large dimensions, $V_2 \sim (1\ \text{mm})^2$ up to factors of the order of one, depending on the precise geometry of the extra space. In general, the shape of the extra space need not be isotropic and the size of compactification radii can be different. The upper bound on the largest of these radii comes from the gravitational force measurements and is $\sim$1 mm.

Here one may ask the following question. Although the gravitational force has not been directly measured at submillimeter distances, what about macroscopic systems (e.g., neutron stars) for which the gravitational self-energy is known to be very important, but the interparticle separation is much smaller than 1 mm? The brief answer why such systems do not put any significant restriction on submillimeter gravity is that the gravitational self-energy is a "bulk effect." Consider a body of size $L \gg R$. We can estimate the gravitational self-energy of this body by dividing the body into R-size balls. The total energy can be viewed as a sum of self-energies of individual balls, plus their interaction (bulk) energy. The crucial point is that the bulk energy dominates whenever $L \gg R$. So modification of the total energy that comes from changing gravity at $\ll R$ distances is very small. For instance, taking the body to be spherically symmetric, for two extra dimensions the relative change in gravitational energy is

$$\frac{\Delta E}{E} \sim \left(\frac{1\ \text{mm}}{L}\right)^2 \tag{4}$$

The smallest observed object for which one may expect this effect to play any role is a neutron star with size $L \sim 10$ km. We see that even in this case the relative change in energy is $\sim 10^{-12}$, which is negligible.

A similar argument applies to any large object, including the large-scale behavior of our present universe, which cannot be affected by changing gravity at $L \ll R$ distances.

This new framework leads to a variety of novel and striking phenomena including very exotic events. For instance, propagation of a signal over cosmic distances with a speed faster than the speed of light would be allowed, in principle, because of a "short-cut" though extra dimensions.

The second legitimate question is: What about other interactions? For instance, the Coulomb law has been measured at distances much smaller than 1 mm. This fact makes propagation of photons in extra dimensions impossible. This naturaly leads us to the idea of a so-called "brane universe." In this scenario, although gravitons can freely propogate in the extra dimensions, the particles of the standard model must be localized on a 3-dimensional subspace ("brane"). This is the three-dimensional world that we see around us, embedded in the higher dimensional space-time. The idea of the brane universe goes back to ref. 4, where it is was proposed in a different context. This authors suggested the mechanism of fermion localization in the form of the domain wall zero modes.

A field-theoretic mechanism for localization of the gauge fields on a brane was suggested in ref. 5. This analysis shows that if gauge fields are localized on a brane, the extra dimensional bulk should be confining. That is, no charged state (under the gauge field in question) can propagate in the bulk.

In string theory perhaps the the most natural way for localization of the standard model field on a brane is in the *D*-brane context [6]. In this picture the standard model particles can be identified with the excitations of the open strings stuck on the *D*-brane, whereas gravity comes from the closed string sector propagating in the bulk.

CONSTRAINTS

Now let me explain why this scenario is not ruled out. The reason for such a question is that in this picture we are introducing a new massless particle, the high-dimensional graviton, coupled via TeV-scale suppressed interaction with all the standard model particles. In the usual four-dimensional context the existence of such a particle would be incompatible with many experiments. As an example, one can think of light Goldstone bosons, such as axions, which like gravitons have derivative couplings to the standard model fermions. There are well-known astrophysical lower bounds on the suppression scale of such couplings, around $\sim 10^8$–10^{10} GeV. In this light it may look surprising that TeV-scale gravity can survive. Of course, for a complete answer there is a long list of all possible constraints that one has to study; for instance, macroscopic gravity (discussed above), mesoscopic gravity, electroweak observables, rare events such as ($K \to \pi$ + graviton), astrophysical and cosmological constraints, etc. Many of these have been studied in detail in ref. 2. Clearly it is impossible to discuss all of these here. I will rather try to give a general reason that saves TeV graviton. Consider a process that involves normal four-dimensional gravity. Every time a graviton is emitted we pay the price

$$\sim \frac{E}{M_P} \tag{5}$$

where E is a characteristic energy of the process. The crucial point is that the price that we would pay for emitting a high-dimensional graviton in a similar process would involve a higher power of the ratio:

$$\sim \left(\frac{E}{M_{Pf}} \right)^{1+N/2} \tag{6}$$

This allows us to satisfy experimental bounds with much smaller fundamental Planck scale if N is large. Already for $N = 3$ there is no experiment forbidding $M_{Pf} \sim$ TeV. For $N = 2$ the strongest constraint so far comes from SN 1987A, which gives a lower bound on M_{Pf} from 30 TeV [2] to 50 TeV [8]. This constraint comes from the graviton contribution to star cooling. In general the cooling rate into gravitons scales as

$$\sim \left(\frac{T}{M_{Pf}} \right)^{2+N} \tag{7}$$

where T is the star temperature.

EXPERIMENTAL SIGNATURES

I now discuss some of the experimental signatures. This picture leads to a number of striking signatures for laboratory and accelerator experiments. For the case of two extra dimensions, planned submillimeter measurements [7] of gravity may observe the transition from a $1/r^2$ to a $1/r^4$ force law. For any number of new dimensions, the Large Hadron Collider (LHC) under construction at CERN and the proposed Next Linear Collider (NLC) should be able to observe strong quantum gravitational interactions. Furthermore, some particles can be kicked off our 3-dimensional world into the new dimensions, carrying away energy and other quantum numbers to other parallel brane universes. For more detailed discussion of collider signatures see, e.g., ref. 9.

The theory should drastically change above the TeV threshold in order to account for quantum gravity effects. At the present time the only candidate for a theory of quantum gravity is superstring theory. Embedding in the string framework [3] predicts strong gravity effects such as the production of black holes with the colliders.

NEUTRINO PHYSICS

Large extra dimensions offer an alternative explanation of the smallness of some parameters in the standard model, e.g., the neutrino mass [10, 11]. This is based on the simple fact that the right-handed neutrino ν_c is the only particle neutral under the standard model gauge group. Thus, unlike other leptons, it may freely propagate in extra dimensions. In such a case, its possible interaction with all the standard model states will be *automatically* suppressed by the large volume factor $\sim M_{Pf}^N V_N$ of the extra space. Here M_{Pf} stands for the fundamental Planck scale, of order TeV.

Using Eq. (3), we can express this factor as the ratio of the fundamental and observable Planck scales M_{Pf}/M_P and is roughly 10^{-14}–10^{-16}. Thus the standard Yukawa coupling between Higgs (H) and left- (ν) and right-handed neutrino will be suppressed by the same factor,

$$\sim\frac{M_{Pf}}{M_P} H\nu\nu_c \qquad (8)$$

and will generate a tiny Dirac mass for the neutrino,

$$m_\nu \sim 10^{-13}\ \text{eV} \qquad (9)$$

This mass is in the right ballpark in the light of Super-Kamiokande results [12].

The present mechanism predicts a peculiar mixing pattern between the neutrino and a tower of its Kaluza–Klein partners. Application of this picture to the solution of the solar neutrino problem through the MSW mechanism predicts the size of at least one extra dimension to be roughly 0.1 mm [11].

FLAVOR PHYSICS

Large extra dimensions may have implications for flavor physics. Traditionally, flavor physics is the most sensitive indicator of any new physics beyond the standard model. Many existing limits on new interactions come from flavor-changing transitions. The low-scale quantum gravity theories are no exception in this respect. In particular, one may expect all possible flavor-violating operators to be scaled by the fundamental scale of quantum gravity. For instance, operators like

$$\frac{(\bar{s}d)^2}{M_{Pf}^2},\quad \frac{(\bar{u}c)^2}{M_{Pf}^2},\quad \frac{(\bar{\mu}\sigma_{\mu\nu}e)F_{\mu\nu}}{M_{Pf}} \qquad (10)$$

with unsuppressed coefficients would induce K^0–$\bar{K}^0$, D^0–$\bar{D}^0$, and $\bar{\mu} \to e\gamma$ transitions to an unacceptable level. This puts severe restrictions on the flavor structure of the theory [13]. Due to the lack of complete understanding of the fundamental theory of quantum gravity, it is hard to estimate the actual strength of these couplings. In such a situation, at best we can put phenomenological bounds and restrict these operators by the gauge flavor symmetries of the low-energy theory. At first glance the latter sounds impossible since the corresponding gauge symmetries must be broken below TeV scale in order to allow for the masses and mixings of the ordinary fermions, quarks, and leptons. In the conventional setting this would be impossible since there are well-known lower bounds on the masses of flavor gauge (and scalar) fields around $\sim 10^6$ GeV or so. However, the high-dimensional nature of our picture makes these bounds compatible. The crucial aspect is that the flavor gauge fields can be high-dimensional bulk fields (much like the right-handed neutrino in the above example) and thus very weakly coupled to the standard model particles! The flavor violation from such fields can be reduced to an acceptable level. However, the suppression of the flavor-changing processes are at the borderline of experimental limits and deserve more detailed study.

NONCONSERVATION OF GLOBAL CHARGES

An interesting prediction of our framework is the new potential source of nonconservation of global quantum numbers, such as baryon and lepton numbers [15]. Global charges are not conserved in the Brane universe. The nonconservation of global charges is due to quantum fluctuations of the brane on which the standard model lives. These fluctuations can produce baby branes which can capture global charges and carry them away from the brane. At high enough temperatures or energies comparable with the brane tension the process of baby brane creation becomes significant. This leads to global-charge transport from our brane. The corresponding process will look like nonconservation of global charges for a four-dimensional observer living on the brane. These processes somewhat resemble the loss of quantum coherence in quantum gravity [16–18]. The nonconservation rate is exponentially suppressed at present energies,

$$\sim \exp(-E/T) \tag{11}$$

where E is the energy of the baby brane. However, it may be significant in the cosmological context and can lead to new sources of baryogenesis.

STABILIZATION OF LARGE EXTRA DIMENSIONS

A very important, yet unresolved issue in this new class of theories is the question of radius stabilization. Perhaps the most natural explanation of this large size would be to generate the radius by dimensional transmutation [1]. Assume that effective potential has a logarithmic dependence on the radius. For example,

$$V = R^n f[\log(RM_{Pf})] \tag{12}$$

where f is a polynomial function of $\log(RM_{Pf})$. Then the minimum is determined by the value of $\log(RM_{Pf})$, which can be easily of order 10–30 without having very small coefficients in the polynomial f. This would stabilize the size of extra dimensions at values exponentially bigger than the fundamental length scale (M_{Pf}^{-1}) of the theory.

The question is, what physics can generate such a logarithmic dependence?

Witten suggested a way for generating a large mass scale from a small one via dimensional transmutation [21]. Witten considered a theory in which the vacuum expectation value (VEV) of a certain scalar Higgs field was undetermined at the tree level, and demonstrated that the quantum corrections due to supersymmetry breaking can generate a potential of the form (12) (where instead of radius R, the VEV of the scalar field must be understood).

At first glance the issue is not quite the same, since we are willing to generate a small mass scale (large radius) instead of large one. However, these issues are not completely unrelated. The point is that the high-dimensional theories often exhibit what is called infrared–ultraviolet "duality." That is, the infrared bulk of the present framework in some sense can be "mapped" to the ultraviolet "desert" of the old paradigm. To be more precise, the large distance in one theory is equivalent to the high energy scale in the other. For instance, in the gauge theory description the brane separation is a vacuum expectation value of the Higgs field that gives masses to the open string modes. Thus, in this picture generation of large interbrane distance is equivalent to the generation of the large mass scale. This duality between infrared gravity and ultraviolet gauge dynamics suggests that the solution also may work here [20].

In particular, potentials with a logarithmic dependence are quite common for codimension-two cases since the Green's functions in two transverse dimensions are logarithmic. As a simple illustrative example, let us imagine a model with two dimensions compactified on a sphere S_2. Let Φ be a complex scalar field defined on the sphere and assume that Φ has a nonzero expectation value $\Phi = v$ due to some dynamics. Assume that Φ transforms under a global $U(1)$ symmetry $\Phi \to e^{i\alpha}\Phi$. Then, its expectation value breaks $U(1)$, but (in general) leaves supersymmetry unbroken. Supersymmetry can be maximally broken if we discuss a topologically nontrivial winding configuration (vortex) which (in the flat-space limit) asymptotically looks like

$$\Phi(\infty) \sim ve^{i\theta} \tag{13}$$

where ρ is the distance from the core, and θ is the polar angle. Consider a vortex–antivortex pair "stuck" at the opposite poles of S_2. The bulk vacuum energy of the system coming from the gradient term diverges logarithmically with vortex–antivortex distance r, which in our case sets the size of extra dimensions:

$$V(r) \sim v^2 \log(rM) \tag{14}$$

where δ is the size of the core. Thus, we recover the $\log(R)$ behavior. Note that if it was only the potential energy of the vortex core, the supersymmetry would be unbroken at the tree level in the bulk. The logarithmic behavior of the bulk energy can be understood as a result of a *tree-level* transmission of the supersymmetry breaking from the brane to the bulk by the derivatively coupled massless Nambu–Goldstone field. The "local strength" of this breaking (Λ_{bulk}) scales as $\sim 1/\rho^2$ as a function of the distance from the brane, so that integrated vacuum energy is $\sim \ln(r)$. In this example, the Goldstone expectation value is part of the winding configuration; however, in the more generic case it may just play the role of a messenger at the loop level. The above example demonstrates that the role of two extra dimensions can be crucial. Note that for the three transverse dimensions with pointlike branes the scaling could be different. For instance, for the global monopoles stuck on S_3 the scaling would be linear in r.

The above toy example illustrates the simplest possibility of logarithmic dependence of the potential on the volume of extra space. Construction of realistic theories along these lines is an important issue.

COSMOLOGY

One of the least-studied and most fascinating aspects of this new class of models concerns early cosmology. One of the necessary consequences is that the universe at the beginning of the hot Big Bang was much colder (by a factor $\sim 10^{-15}$ or so) than has previously been thought. There are many new, intrinsically high-dimensional phenomena which could shed new light on the origin of inflation. As an example, consider "brane inflation" which could result from the interaction of our brane universe with a similar parallel brane world [19].

The traditional question in inflationary theories is the origin of the inflation, a weakly coupled scalar field with an extremely flat potential. Although technically possible, the flatness of this potential is hard to understand in conventional four-dimensional theories. In general, it is expected that quantum gravity corrections (which are uncontrollable in the region of large expectation values) will spoil this flatness. If the Hubble parameter during the would-be inflation is H, it is believed normally that the quantum gravity correction can generate (at least) curvature $\sim H^2$ of the inflaton potential and thus breakdown the slow-roll conditions necessary for the inflation. To clarify the origin of this correction, let the potential that can lead to the successful slow-roll condition be $V(\phi)$, where ϕ is an inflaton field. A necessary condition is that curvature of the potential, at least in some region, is smaller than the Hubble parameter

$$H^2 \sim V/3M_P^2 \tag{15}$$

Suppose this is the case for a given V. However, it is hard to understand what forbids in the low-energy effective theory terms like

$$\overline{\phi}\phi V/M_P^2 \tag{16}$$

(the overbar stands for Hermitian conjugation). These are not forbidden by any symmetries of the effective field theory. If present, they would break condition (15) unless various parts of the potential are carefully adjusted. Thus the only way to avoid such terms is to rely on the fundamental theory and assume that the fundamental theory is not generating them.

Within the "brane inflation" scenario this issue is resolved. In this picture, the inflaton is a field (ϕ) that parametrizes the distance (r) between two brane worlds embedded in the extra space. The typical distance between these two branes is much bigger than the string scale. So the potential between them is governed essentially by the infrared bulk (super)gravity. All the effects of higher string excitations are decoupled. Thus the potential is well known and at large distances has an inverse power-low dependence on the interbrane distance,

$$V(r) = M^4\left(a + b_i r^l e^{-m_i r} - \frac{1}{(Mr)^{N-2}}\right) \tag{17}$$

where M is the string scale, a and b_i are constants, and m_i are masses of the heavy modes (their contributions to the potential become unimportant at large distances). In the effective four-dimensional field theory picture this potential translates as the potential for the inflaton field $\phi = M^2 r$ and is automatically flat enough. Thus in this picture the inflation in four dimensions in nothing but the brane motion in the extra space. Branes falling on top of each other drive inflation in our space.

Cosmology based on brane dynamics may offer a new explanation for the observed baryon abundance in the universe. In particular, the collision between two parallel brane universes in early cosmological history could be responsible for the creation of the matter/antimatter asymmetry in our visible three-dimensional world [15]. In this picture our brane world collided with the other one (presumably) at the end of the brane inflation. During the collision the two worlds exchanged baryon number. Since the collision process is highly out of equilibrium, one expects that in the presence of *CP* violation an equal (in magnitude) and opposite net baryon number is left on each of the branes. Thus, the excess of the baryons in our world is exactly equal to the deficit of the hidden baryons in the hidden world.

There are new sources for the dark matter in the universe. One possible candidate is a gas of fundamental superstrings of submillimeter length [20]. For us, they would look like heavy stable particles that can account for some of the missing mass in the visible universe. These strings could have been produced at a relatively late stage of universe evolution (at temperatures around 1 MeV or so) and weigh $\sim 10^{10}$ GeV or larger. Note that in the conventional cosmological scenario, production of such heavy objects at low temperatures is impossible due to usual thermal suppression. Our picture avoids this difficulty due to the high-dimensional nature of the brane universe. Due to this nature, the strings are produced thermally, while they are still short (inverse-MeV long) and thus light enough to be created in the thermal bath. These strings connect two brane worlds which at high temperature "sit" on top of each other. Only later, when the universe cools to sufficiently low temperatures, do branes get separated and strings become very heavy.

In the thermal bath coincident *D*-branes in general get stabilized by temperature effects. This can be understood both from string theory as well as effective four-dimensional field theory. From the effective gauge theory point of view, coincident *D*-branes correspond to restored gauge symmetry points. On the other hand, it is well known that high-temperature softly broken supersymmetric gauge theories, the points of restored gauge symmetries are always the local minima of the free energy. Thus, it is expected that branes get stabilized on top of each other at sufficiently high temperatures.

From the string theory picture, when branes are close to each other the strings that connect them are shorter and thus lighter and can be produced by thermal effects. The number density of the lowest modes is given by the usual equilibrium distribution and is $\sim T^3$. These strings, then, resist brane separation and create a binding potential.

This potential stabilizes branes on top of each other even if the zero-temperature potential is repulsive. The stabilization takes place only for temperatures higher than the curvature (or the repulsive strength) of the zero-temperature potential (m^2). Thus, branes will get separated once the temperature drops below a certain critical value $T_c \sim m$. Before this, however, branes drive a brief period of inflation, necessary to solve the cosmological problems associated with unwanted relic particles, such as moduli, or bulk gravitons. Again, such a late inflation is intrinsic to the brane picture and large extra dimensions, and would be difficult to get in the conventional scenario.

The inflation and subsequent dark matter production works roughly in the following way (see ref. 20 for more details).

As said above, when branes sit on top of each other, the lowest modes from the strings that stretch between them are effectively massless and are in thermal equilibrium. Their starting number density is given by an initial temperature $N_{\text{string}} \sim T_{\text{in}}^3$. We will take $T_{\text{in}} \sim M_{Pf}$. As soon as temperature drops below T_{in} the potential energy takes over and branes inflate. The string number density then drops exponentially fast, $\sim e^{-3n_e}$, and is $N_{\text{string}} \sim T_c^3$ right at the end of inflation. After this point the brane bound state gets destabilized and branes move away, stretching the strings between them. In field theory language this means that excited string modes are getting masses from the ϕ VEV. These modes become nonrelativistic and their number density freezes out within the time $\sim m^{-1}$. Let us take as an example the potential (17) with a single repulsive mode of mass m. Then, right after the end of inflation, the universe is left with strings of mass $\phi_0 \sim M^2 r_0 \sim M^2/m$ and initial number density $N_{\text{in}} \sim T_c^3$. The energy stored in this dark matter is $\rho_{\text{in}} \sim T_c^3 M^2/m$, which is a tiny fraction of the initial energy density of the oscillating branes $\rho_{\text{osc}} \sim M^4$. The brane oscillations reheat the universe to the temperature[2]

$$T_R \sim \sqrt{(m_\phi^3/\phi_0^2) M_P} \tag{18}$$

where $m_\phi \sim M(m/M)^{N/2}$ is the oscillation frequency, the mass of the oscillating inflaton field ϕ. After this point the string energy density scales as T^3, so that the present-day abundance can be estimated as

$$\Omega_{\text{string}} = \rho_{\text{string}}/\rho_c \sim 10^9\ \text{GeV} \cdot (T_c^3/mM^2) T_R \tag{19}$$

From graviton overclosure there is a strong bound on T_R [2], which in the case of two extra dimensions gives $T_R \sim$ MeV, even for $M \sim 10$ TeV. From (18) this gives $m \sim 10$ MeV or so. With these numbers, the right abundance $\Omega_{\text{string}} \sim 0.3$ could have resulted if $T_c \sim 1$ GeV.

In this way, strings produced thermally become superheavy later due to relative displacement of the branes in the extra space. In most cases these strings are long-lived enough to account for part of the dark matter. A very interesting issue which is the part of the present project is to study what happens if some of these strings break releasing their energy into ordinary particles. Such particles would be seen as very high energy cosmic rays. It is important to understand whether the observed high-energy cosmic rays can be explained by such a source.

In summary, I have given a very brief discussion of some of the aspects of theories with large extra dimensions and TeV-scale quantum gravity. These may shed new light on longstanding problems such as the hierarchy of scales, the nature of extra dimensions, and the cosmological history of our universe.

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