MSLED : A Minimal Supersymmetric Large Extra Dimensions Scenario

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Abstract: We propose a framework for the low-energy realization of supersymmetry which is very predictive, but differs radically in its phenomenological implications from the supersymmetric Standard Model (minimal or otherwise). The proposal consists of a supersymmetric version of the Large-Extra-Dimensions scenario, with the Standard Model living on a 3-brane, coupled to a bulk sector consisting of six-dimensional supergravity. This picture is motivated by a promising recent attempt (\texttt{hep-th/0304256}) to naturally understand the observed dark energy density, and this connection with dark energy prevents making the extra dimensions smaller than of order 5 \(\mu\)m. The resulting inability to change this size makes the model very predictive, and easily falsifiable within the near future. Being supersymmetric, it may plausibly be embedded into a more fundamental theory such as string theory, in which case an additional 4 compact dimensions may also be present having inverse radii at the TeV scale or higher. The model is close to, but consistent with, current experimental constraints. We outline possible phenomenological implications for particle physics (both at accelerators and elsewhere), for precision tests of gravity, for astrophysics and for cosmology.

Keywords: Strings, Branes, Cosmology.
1. Introduction

If supersymmetry were unbroken it would solve both the hierarchy and the cosmological constant problems, in the sense that the bose-fermi cancellations implied by unbroken supersymmetry could keep ultra-violet effects from generating dangerous contributions to the Higgs boson mass and to the vacuum energy. Unfortunately, the failure to find super-partners for the observed elementary particles appears to imply that the effective supersymmetry breaking scale is at least of order 1 TeV. Consequently, in practice low-energy supersymmetry is used only to solve the hierarchy problem, sacrificing its potential for solving the cosmological constant problem. This is true for essentially all of the proposed supersymmetric extensions of the Standard Model — including the minimal (MSSM) version.
This line of thinking is reasonably compelling within the standard 4-dimensional setting, but more possibilities may exist within the framework of the brane-world scenario with large extra dimensions (LED). Indeed, recently there has been progress towards understanding how the small size of the observed Dark Energy \( \lambda_{\text{obs}} \approx (0.003 \text{ eV})^4 \) can naturally emerge from theories having supersymmetric large extra dimensions (SLED) \( \lambda_{\text{obs}} \approx (0.003 \text{ eV})^4 \). Because these theories invoke new physics at sub-eV energies, they are likely to have many striking implications for cosmology, particle physics (both at colliders and at lower energies) and precision tests of general relativity.

In this article we wish to begin the discussion of the main observational implications of these theories, specializing where necessary to a minimal version of the SLED proposal (which we call MSLED). Besides being well-motivated from the cosmological-constant point of view, this minimal version has the great virtue of being very predictive. In particular, its use to explain the size of the observed Dark Energy removes the freedom to ‘move the goalposts’ by significantly changing the number and size of the extra dimensions, and so is much more easily falsified than is often true for extra-dimensional proposals.

1.1 Why SLED?

The SLED proposal \( \lambda_{\text{obs}} \approx (0.003 \text{ eV})^4 \) — like the LED proposal before it \( \lambda_{\text{obs}} \approx (0.003 \text{ eV})^4 \) — posits that at present there are two extra dimensions whose circumference, \( r \), is of order \( r \sim 10 \mu\text{m} \sim (10^{-2} \text{ eV})^{-1} \). This is only possible if all of the known particles and interactions besides gravity are trapped on a 3-brane which sits at a point within these extra dimensions, and if the scale of gravitational physics in the extra dimensions is of order \( M_g \sim 10 \text{ TeV} \).

SLED also supposes these large extra dimensions arise within a supersymmetric field theory, such as might be expected to arise in the low-energy limit of string theory. This can only work if supersymmetry is badly broken on our 3-brane, since we know that there are no super-partners for the observed particles having masses which are much smaller than \( M_g \). Given this scale for supersymmetry breaking on the brane there is also a trickle-down of supersymmetry breaking to the ‘bulk’ between the branes, whose size is set by the bulk’s Kaluza-Klein scale and so which can be as low as \( m_{sb} \sim 10^{-2} \text{ eV}. \)

Within this framework gravitational physics is effectively 6-dimensional for any energies above the scale, \( 1/r \sim 10^{-2} \text{ eV} \), and so the cosmological constant problem must be posed within this 6-dimensional context. In 6 dimensions the vacuum energy due to all of the known particles is localized on our brane, and so is really a localized energy source in the extra dimensions rather than directly contributing a 4-dimensional cosmological constant. Einstein’s equations then dictate how the extra dimensions curve in response to this local

\[1\] The supersymmetry breaking scale would be larger if the extra dimensions should be warped.
energy distribution, with the result that the resulting curvature precisely cancels (at the classical level) the vacuum energy on the branes [4]. If the bulk is supersymmetric then a similar classical cancellation also occurs amongst the other bulk contributions to the effective 4D cosmological constant [2,3,7].

Quantum effects in the bulk ruin this perfect cancellation of the 4D vacuum energy, but by an amount which is controlled by the supersymmetry-breaking scale within the bulk (i.e. by \( m_{sb} \sim 10^{-2} \) eV). Although for some theories these corrections can be of order \( \lambda \sim m_{sb}^2 M_p^2 \), for others this leading contribution also cancels, leaving a residual result \( \lambda \sim m_{sb}^4 \), which is the right order of magnitude to describe the observed density of Dark Energy [2,4,8].

Some open issues remain about whether this proposal provides a completely satisfactory mechanism for naturally obtaining a sufficiently small cosmological constant. Most notable among these is the issue of whether the internal space should prefer to dynamically warp and so to raise the scale \( m_{sb} \) without changing \( M_p \) [4]. This is almost certain to happen given the comparatively large energies available in the earlier universe, making it an interesting dynamical question whether this warping should persist into the present epoch. Even should it do so, however, the SLED proposal provides a mechanism whereby the question of the smallness of \( \lambda \) becomes a dynamical issue, and represents a step forward relative to previous proposals. Furthermore, it provides a completely new way in which supersymmetry might be realized at low energies. For these reasons we believe it provides a very well-motivated framework whose phenomenological consequences are worth exploring in their own right.

1.2 What is MSLED?

Because the SLED proposal modifies physics at sub-eV scales, it has many other observational implications besides its explanation for the small size of the cosmological constant. These implications are most restrictive if they are cast in terms of a particularly simple variant of the SLED proposal which, following [4], we call ‘minimal’ SLED or MSLED.

The action for any SLED variant has the form

\[
S_{\text{tot}} = S_{SG} + S_3 + S_3' + S_{\text{int}},
\]

where \( S_{SG} \) describes the action of 6-dimensional supergravity, \( S_3 \) contains the physics of the 3-brane on which we find ourselves situated, \( S_3' \) describes the physics of any other parallel branes and \( S_{\text{int}} \) describes the interactions between our brane and the 6D supergravity fields in the bulk. MSLED makes the following particularly simple choices for \( S_{SG} \) and \( S_3 \).

**Our Brane:** We first choose the degrees of freedom on our brane to be given simply by the usual Standard Model particle content, including its elementary Higgs field. Since the
Standard Model can be defined as the most general renormalizable theory of this particle content, we are guaranteed that the most general renormalizable interactions which can be included in $S_3$ is simply the Standard Model itself. Furthermore, since we are dealing with a low-energy effective theory (as we must for any field theory of gravity) we also expect higher-dimensional, non-renormalizable interactions to arise in $S_3$ suppressed by powers of $M_g$. Since the gravitational scale of the 6D physics is $M_g \sim 10$ TeV in the SLED picture, with a few exceptions these higher-dimensional effective interactions are generically small enough to have escaped detection until now. Although the assumption of this minimal particle content is not required in order to have a small cosmological constant, it is by far the most conservative possibility whose restrictive predictions should first be explored.

The Bulk: The physics of the bulk, $S_{SG}$, is described by 6D supergravity. Since 6D supergravity comes in several varieties, this last choice contains several sub-options. As we shall see, observational constraints restrict the number of degrees of freedom which can live in the bulk, and so disfavor chiral supergravities like Nishino-Sezgin supergravity. They instead point towards the non-chiral, ungauged versions of 6D supergravity, for which the field content contains only a minimal particle content, such as consisting of a scalar dilaton ($\phi$), two symplectic majorana-weyl spin-1/2 dilatini ($\chi^r, r = 1, 2$), 2-form gauge potential ($B_{MN}$), two symplectic majorana-weyl gravitini ($\psi^r_M$) and metric ($g_{MN}$).

Chiral and non-chiral models differ in whether or not the two bulk dilatini, $\chi_r$, (or the two bulk gravitini, $\psi_M$) share the same 6D chirality: $\Gamma^7 \chi^r = \pm \chi^r$.

It must be emphasized that these choices differ considerably in their implications for upcoming experiments from the presently popular paradigm of the supersymmetric Standard Model, in its minimal (MSSM) and more complicated variants. In particular, the assumption that the physics of our brane is described by the Standard Model, brings back all of the virtues of this model which had to be sacrificed when the MSSM was adopted. This allows us to retain a natural understanding as to why the renormalizable couplings on our brane must be baryon- and lepton-number conserving.

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2The few exceptions are those interactions which violate symmetries like lepton number or baryon number, which we must envision as being forbidden by conservation laws. More about this later.

3There are also two kinds of non-standard brane fields which may also be required on our brane in addition to the Standard Model. These are the Goldstone modes associated with the position of our brane in the extra dimensions, and with the breaking of supersymmetry on our brane. We do not follow these modes explicitly here because they get eaten by bulk modes, and so are natural to include with the bulk-brane interactions, $S_{\text{int}}$.

4Strictly speaking, this multiplet is reducible, since a smaller gravity multiplet can be built using only the metric, gravitino and the self-dual piece of $B_{MN}$.
1.3 How Large Are the Extra Dimensions?

The predictiveness of the SLED proposal lies in the inability to make the extra dimensions smaller — and so easier to hide — without destroying the explanation of the observed Dark Energy. In this section we discuss the most restrictive observational limit on the possible size the extra dimensions can take, in order to show that this is (just) large enough to be consistent with the size of the Dark Energy density. Our purpose is to argue that this consistency does not allow much freedom to shrink the extra dimensions, and so fairly robustly sets the scale of the extra dimensions, as well as constraining the kind of 6D supergravities which can be entertained.

Supernova Bounds

The strongest limit on the size of two large extra dimensions comes from the constraint that energy loss into Kaluza Klein modes not provide too efficient an energy-loss mechanism for supernovae [10,11]. This process has been studied in detail for the special case of the radiation of gravitons into the bulk, with the recent study [11] showing that an acceptably small energy-loss rate requires the 6D gravitational scale, $M_g$, to satisfy $M_g > 8.9$ TeV.\(^5\)

For unwarped extra dimensions this requires the extra-dimensional size to be $r < 10 \mu m$.\(^6\)

This limit may be even stronger for SLED, because the theory in the bulk is supersymmetric and so can offer more modes into which energy may be lost. Although the precise loss rate is not yet computed for SLED, a simple estimate is obtained by scaling the graviton energy loss rate by the total number of degrees of freedom, $N$, in the extra dimensions whose couplings allow them to be emitted singly starting only from brane states. For instance if only gravitons could be emitted, this number would be $N_{LED} = 3$ for particle collisions in vacuo on flat 3-branes, since this corresponds to the 3 of the 9 6D graviton polarizations which can couple to purely 4D stress energy. We therefore estimate the loss rate into SLED bulk states to be

$$\Gamma_{SLED} \approx \Gamma_{LED} \left( \frac{N}{3} \right).$$

where $\Gamma_{LED} \propto M_{g}^{-4}$ is the standard result for graviton emission by flat branes. This leads the SLED bound on $M_{g}$ to become

$$M_{g} > \left( \frac{N}{3} \right)^{1/4} 8.9 \text{ TeV}.$$  \(^{(1.3)}\)

\(^5\)Our conventions define the 4D Planck scale by $M_{p}^{2} = (8\pi G_N)^{-1} = M_{g}^{4}r^{2}$ when the two extra dimensions have volume $V = r^{2}$.

\(^6\)Ref. [11] quotes $r < 1.6 \mu m$, but uses conventions where the extra-dimensional volume is given by $V = (2\pi r)^{2}$. 
The bound therefore depends on the number $\mathcal{N}$, although the $1/4$ power in the last expression shows that this dependence is not inordinately strong. This number is clearly model-dependent in two separate ways. First, it depends on the total number of states in the bulk which are massless in the 6D sense, and so which are potentially available channels for carrying off energy. This depends on the multiplet content of the supergravity under consideration, and can be quite large for the chiral theories. In the same counting that assigns 9 spin states to the 6D graviton, the (massless) 6D gravity, gauge and matter supermultiplets respectively have $32 = 16_F + 16_B$, $16 = 8_F + 8_B$ and $8 = 4_F + 4_B$ spin states, where $B$ and $F$ denote whether the states being counted are bosons or fermions. The number of massless 6D bulk states can therefore be as small as 32 for non-chiral 6D supergravities [12, 13], with no matter multiplets in the bulk. Alternatively, for chiral, gauged 6D supergravity in the bulk, anomaly cancellation requires the number of matter and gauge multiplets to satisfy the condition $N_m = N_g + 244$ [14], and so even choosing $N_g = 0$ in this case implies there must be 1952 massless 6D spin states in the bulk. If all of these contributed as strongly to the energy-loss as an allowed graviton mode, this would lead to the bound $M_g > 34$ TeV and so $r < 0.67 \mu$m. Fortunately, as we now argue, the real bound is likely to be less restrictive than this, even for the chiral theories.

The real bounds are likely to be weaker because the second source of model-dependence acts to reduce $\mathcal{N}$, and so to weaken the bounds on $M_g$ and $r$. This second model-dependence is to do with the size of the amplitude for emitting a single bulk particle given only brane-bound particles in the initial state. This amplitude depends on both the kind of bulk particle involved, and on the kinds of effective interactions with the bulk which arise on the branes. For instance, even for gravitons not all of the 9 possible 6D spin states are emitted from particles moving along a flat brane because not all of the graviton polarizations couple to the purely 4D components of the matter stress tensor. More graviton spins would couple if the brane were bent or moving in the transverse dimensions, or in the presence of more complicated internal initial states on the brane.

Similar statements apply for the other bulk fields, whose couplings also depend on the kinds of interactions which are present between brane and bulk particles. For example, the fact that supersymmetry is broken on our brane implies the existence of model-independent couplings between the brane-based Goldstone fermion and the bulk gravitino [13]. For other bulk particles, preliminary examination of the simplest kinds of brane couplings to

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7 More precisely, the anomaly-cancellation condition is $N_m - N_g = 273 - 29 N_t$, where $N_t$ is the number of tensor multiplets. Although the option $N_t = 1$ allows the writing of a Lorentz-invariant action, $N_t > 1$ could permit anomaly cancellation with fewer matter fields.

8 We thank the referee for stressing that not all bulk particles are likely to be emitted as strongly as are some graviton modes.
6D scalars and vectors is given in refs. [16] and [17], and similar estimates for the fermion couplings relevant to neutrino interactions are given below. From these it is clear that the strengths of these couplings — and so also the strengths of the resulting bounds — can vary considerably, depending on the brane details.

The weakest possible bound on $r$ occurs for models for which only the graviton and gravitino couple linearly to brane matter. Because of the weak dependence on $N$ in $\Gamma_{SLED}$ this leads to constraints which are essentially the same as for pure-graviton emission in the nonsupersymmetric case. Alternatively, if $N \sim 100$ then the LED constraint would be marginally strengthened to $M_g \gtrsim 12$ TeV and $r \lesssim 5.3$ $\mu$m. It is clear that these are only rough estimates and that an explicit calculation of the rate of energy lost is desirable for specific models (but lies beyond the scope of the present article).

There are also other, nominally stronger, bounds on extra-dimensional models which come from the non-observance of Kaluza-Klein modes decaying into photons after having been produced in supernovae or in the early universe. We ignore these bounds for the present purposes, since unlike the bound just discussed they can be completely evaded depending on the details of the model. For instance, they do not arise if KK modes can efficiently decay into invisible light modes on other branes. We regard the model building which such an evasion requires to be well worth the cost if the resulting theory can make progress on the much more difficult cosmological constant problem.

**The Dark Energy Constraint**

Balanced against these bounds is the requirement of a sufficiently small Dark Energy density. Within SLED models this energy arises as a Casimir energy, whose evaluation (including the back-reaction of the branes on the bulk geometry) has not yet been done, but is in progress. Perhaps the most interesting thing about the SLED proposal is that within it the success of the description of the size of the cosmological constant comes down to the discussion of the $O(1)$ factors, which we describe here.

In the absence of a definitive calculation of the Casimir energy in the presence of branes within a compact two-dimensional solution to 6D supergravity, a reasonable picture of the $r$ dependence of the Casimir energy can be obtained by dimensional analysis supplemented by the tracking of the large logarithms which crop up due to the ultraviolet sensitivity of the result to large mass scales (like $M_g$) \[8\]. Taking care to write the result in the Einstein frame (for which Newton’s constant is not field dependent), the result is

$$V(r) = \frac{A}{r^4} \left[ 1 - a \log(M_pr) + \frac{b}{2} \log^2(M_pr) + \cdots \right] + \cdots,$$  \hspace{1cm} (1.4)

where $A$, $a$ and $b$ are dimensionless constants, the first ellipses represent possible terms involving higher powers of $\log r$, and the second ellipses indicate terms involving higher
powers of $1/r$. As written, $V$ is positive for all $r$ provided $A > 0$ and $2b > a^2$.

Besides being the likely result of explicit calculations, this potential is known to be able to describe a phenomenologically acceptable description of time-dependent Dark Energy \cite{18, 19}. If $a^2 + (b/4)^2 - 2b > 0$ the potential has a local minimum at $r_-$ and a maximum at $r_+$, where $4b\log(M_pr_\pm) = b + 4a \pm \Delta$, and $\Delta = 4[a^2 + (b/4)^2 - 2b]^{1/2}$. $r_+$ and $r_-$ are naturally of order 10 $\mu$m provided $a/b \approx 70$. It should be noticed that the success of the cosmologies of refs. \cite{18, 19} do not rely on the existence of a minimum or maximum, but in them the acceleration of the present-day Dark Energy is described by the epoch when $r$ is in the vicinity of $r_\pm$, at which point we have, for instance

$$\lambda \approx V(r_\pm) = \frac{A}{16r^4} \left[ b + \Delta \right].$$

Given estimates for $A$, $a$ and $b$ we may determine what the smallest value is that $r$ can take at present without having $\lambda$ be unacceptably large.

The constant $A$ is obtained from a Casimir energy calculation, and depends on details of the extra-dimensional geometry and the boundary conditions satisfied by the various bulk fields which are massless in 6 dimensions. For the present purposes we estimate the size of $A$ using calculations of the Casimir energy on a 2-torus, with supersymmetry broken by choosing different boundary conditions for bosons and fermions \cite{21}. Calculations such as these have been computed in many places for torii. For torii $A$ depends on the various toroidal shape moduli \cite{21} but for simplicity we ignore these moduli and estimate $A$ using the numerical results of ref. \cite{22} for a square torus. In this case $A = -0.15$ for a periodic massless scalar and $A = 0.23$ for a completely antiperiodic massless spin-half fermion. This leads to the estimate for $A$ for a supersymmetric theory, with supersymmetry broken by boundary conditions, of $A \approx (0.23 - 0.15)N = 0.08N$, where $N$ counts the number of bosonic degrees of freedom in the bulk (e.g. $N = 16 + 8N_g + 4N_m$). With $N = 16$ we have $A \approx 1.3$.

The constants $a$ and $b$ are likely to arise from logarithmic divergences in 6 dimensions, and although they are not yet calculated we expect $b \sim a^2$, with $a \sim N/(2\pi)^3$, for $N$ an indicator of the number of degrees of freedom in the bulk (and so $a/b \sim 70$ is possible if $N \sim 10$, as for the 6D supergravity multiplet). Taking $\Delta \approx O(a)$ we then find

$$\lambda \sim \frac{Aa}{16r^4} \sim \frac{1.3}{70 \times 16r^4} \sim \frac{1}{(6r)^4}.$$  

(1.6)

This estimate is this section’s main result. Given that $(10 \mu m)^{-1} = 0.020$ eV, we see that $\lambda$ takes the observed value $(0.003 \text{ eV})^4$ when $r$ is close to its current observational

\footnote{This roughly captures what is expected from the back reaction of the branes, since these introduce conical singularities into the geometry which affect the boundary conditions of different spins in different ways.}
upper limit, $r \sim 5 \mu m$ (up to within the uncertainties of the estimates given). Clearly these estimates strongly motivate a more detailed analysis of the Casimir energy within specific SLED vacua.

### 1.4 More Fundamental Origins?

One of the principal motivations for the supersymmetric Standard Model comes from the plausibility of its arising as the low-energy limit of a well-motivated, more fundamental, theory at higher energies. It is worth asking to what extent the same might also be true for the SLED proposal. Since it is difficult to say anything concrete about this without having some framework in mind for what the kind of fundamental physics might be, we choose to cast this question in terms of what is at present probably our best-motivated fundamental supersymmetric theory: string theory. Since SLED is a particular case of the brane-world scenario, it is plausible that it could be obtained from string theory since this naturally includes D-branes and similar objects onto which it is known that Standard Model particles can be trapped.

A successful embedding of SLED into string theory consists of identifying string vacua for which the low-energy excitations describe both the 6D supergravity of the bulk and the degrees of freedom trapped on the branes. Indeed, the non-chiral (gauged and ungauged) 6D supergravities have a known string provenance in this way as dimensional reductions of 10D string vacua, and although a complete string derivation of the chiral 6D theory is not yet known — see however [23] — it is plausibly derivable as the low-energy limit of 10D heterotic string theory compactified on $K_3$.

Knowing how the branes arise within string theory is also important, and this has three different aspects. It involves finding string vacua having 3-branes in the effective low-energy 6D supergravity; it involves finding the particles of the Standard Model living on one of them; and it involves obtaining the brane-bulk couplings which are required by the mechanism of making the observed dark energy small [2, 3].

A complete construction has not yet been accomplished, although branes having the required dimension and dilaton couplings may be obtainable either from D3 branes in 10D Type IIB string vacua, or from NS5-branes wrapped on 2-cycles in 10D heterotic (or 11D $M$-Theory) compactifications to 6 dimensions.

An important difficulty in obtaining MSLED models from string theory is also familiar from attempts to find the MSSM within string theory: there are typically too many degrees of freedom in the low-energy theory. This is a particularly pointed problem for MSLED given the strong constraints against the existence of too many light modes in the bulk.

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*The precise requirement is for the dilaton coupling to vanish in the 6D Einstein frame.*
Furthermore, because the supersymmetry-breaking scale in the bulk is so low, MSLED models cannot blindly appeal to supersymmetry breaking to give these moduli TeV-scale masses. What is required is a compactification to 6 dimensions for which the moduli for the internal dimensions (and any other light fields) are fixed at the string scale without breaking the bulk 6D supersymmetry. These conditions make a string theory derivation of the MSLED challenging, but perhaps not necessarily more so than a similar derivation of the MSSM.

It is this problem of ubiquitous light fields which argues against the simplest compactifications of 10D models to 6D. For example, for the perturbative heterotic string (or in the 11D Horava-Witten scenario) all of the gauge degrees of freedom coming from the $E_8 \times E_8$ or $SO(32)$ gauge sectors are expected to populate the bulk in a 6D compactification. Fewer such fields may arise if the low-energy gauge sector lives at the singularities of manifolds of $G_2$ holonomy, but these are not sufficiently well understood at the moment to allow the construction of explicit models.

Better prospects for finding SLED vacua with acceptably few light fields in the bulk may come from Type II theories (and their orientifolds — including Type I vacua) with the gauge sector localized on D-branes. In general, for the quasi-realistic examples found to date the Standard Model fields are localized on a D3 brane which is located at singularities in the bulk, or they are localized on the intersection of wrapped D6 or D5 branes (see for instance [24, 25]). Furthermore, for Type IIB theories it is known that compactifications with fluxes can fix many of the low-energy moduli which would have arisen without the fluxes [26, 27]. These kinds of models also have the advantage that quasi-realistic models have been constructed for which the Standard Model (or its supersymmetric extension) is known to live on a brane [28].

The 10D scenarios of interest here require a compactification for which 4 of the internal 6 dimensions are much smaller than the remaining 2. How much smaller they are is likely to depend on the details of the compactification, and in particular on whether any of the 4 smaller dimensions should be warped. For instance, the compactification might be envisioned to arise simply as an orientifold of the product space $K_3 \times T^2$ or in a more complicated way as an elliptically-fibred Calabi-Yau compactification — i.e. a compactification which is locally $T^2 \times B$ — for which the elliptic fiber is a $T^2$ whose size varies with position in $B$.

If the small 4 dimensions are unwarped and have volume $V_4 = \ell^4$, then the effective 6D gravity scale is related to the string scale, $M_s$ and $\ell$ by $M_g = e^{-\Phi/2} M_s^2 \ell$, where $\Phi$ is the 10D dilaton and we assume a string-frame 10D Einstein action of the usual form $L_{10} \propto e^{-2\Phi} R$. Within a perturbative low-energy framework with no particularly small numbers put in by
hand (i.e., for which $e^\Phi < 1$ and $M_s\ell > 1$) we are led to a picture where both the string scale and the size of the 4 small dimensions are not so different from the 6D gravity scale $M_g$. In this unwarped scenario we therefore expect to find TeV-scale phenomena associated with the small 4 extra dimensions and with string physics itself. Notice also that the conditions for the validity of perturbation theory, $e^\Phi \ll 1$ and $M_s\ell \gg 1$, both imply $M_g > M_s$, and so within the unwarped picture string physics can be expected to appear at energies lower than $M_g \sim 10$ TeV.

Alternatively, if the small 4 dimensions are strongly warped we may have $\ell^{-1} \sim M_s \gg M_g$ with the hierarchy between these two scales arising from the warping within the four extra dimensions. Scenarios in which the string scale is still close to the Planck scale or the intermediate scale $M_s \sim 10^{11}$ GeV could be possible in this setting. Within this kind of hybrid Randall-Sundrum/ADD scenario we need not expect to find more string or extra-dimensional physics at the TeV scale beyond that expected purely from the 6D degrees of freedom, but it may instead have interesting cosmological implications.

An interesting remark in this regard for both of these kinds of pictures is that the desired string compactification need not stabilize the large two extra dimensions, since these can instead be still dynamically evolving at present along the lines described in previous sections. All that is required is that the loop-generated potential for the 2D moduli have a form similar to that described in earlier sections. In particular, it would be interesting to be able to predict the initial features of this late-time cosmology as the final state of an earlier inflationary period, given the recent progress towards finding inflation within string theory [27, 31, 32].

2. Implications for Particle Physics

In this section we briefly summarize the main implications which the MSLED proposal can be expected to have for current particle physics experiments. We expect these to come in two broad classes of phenomena: neutrino physics and collider experiments at TeV scales. These two kinds of observables differ in the extent to which they test the general SLED proposal or its more specific MSLED variant. In this section we argue that SLED models very generically predict new effects for TeV colliders. We also explore whether the MSLED proposal predicts new neutrino physics. In passing we remark that that the minimal MSLED predicts only unobservably small new phenomena for flavor-changing experiments such as those being done with $K$ and $B$ mesons.

2.1 Neutrino Physics

The SLED proposal relies on the numerical coincidence between the value of $1/r$ which is
required in 6 (unwarped) dimensions by the explanation of the Dark Energy density, and by the explanation of the size of the electro-weak/gravitational hierarchy, $M_g^2/M_p$. Since the value for $1/r$ which results is also close to the mass differences, $(\Delta m^2_{\text{atm}})^{1/2} = 0.05 \text{ eV}$, appearing in atmospheric neutrino oscillations \[^{[34]}\] — or $(\Delta m^2_{\odot})^{1/2} = 0.007 \text{ eV}$ for solar neutrinos \[^{[33]}\] — it is natural to ask whether there might be a physical reason for this.

Models Without Brane-Bulk Neutrino Mixing

It must be emphasized at the outset that in general there need not be a connection between neutrino masses and the extra-dimensional scales within SLED. For instance, we might imagine stepping outside of MSLED and accounting for neutrino oscillations by simply putting 3 light sterile neutrinos onto our brane along with the Standard Model, with their masses tuned to the appropriate values by hand. Alternatively, even within MSLED we could obtain neutrino masses without introducing new low-energy brane degrees of freedom by contemplating the usual dimension-5 interaction on our brane,

$$\mathcal{L}_5 \propto \frac{h^2}{M_g} (L^i \gamma_L L^j) H_i H_j + \text{c.c.},$$

where $L = (\nu_e)$ denotes the Standard Model leptons, and $H$ representing the Higgs doublet. The challenge in this kind of explanation of neutrino masses would be to understand why the dimensionless coupling $h$ should be so extremely small: $h^2 \sim 10^{-11}$. Such small couplings are natural in the sense that they are stable under renormalization, and their explanation would require an understanding of why the underlying higher-dimensional physics (such as the appropriate vacuum of string theory) preserves baryon and lepton number to high accuracy. In either of these two ways of understanding neutrino masses, it is difficult to make a definitive prediction for what to expect in neutrino experiments from SLED or MSLED.

Models With Brane-Bulk Neutrino Mixing

Things would be more interesting, however, if there should be a nontrivial mixing between brane-bound neutrinos and bulk fermions. This could arise through an interaction of the form

$$S_{\text{int}, N} = \int d^4x \, [g_{ai}(L^i_\alpha \gamma_L N^j) H_i + \text{c.c.}],$$

where $N^j$ denotes a collection of 6D bulk fermions and $g_{ai}$ are coupling constants having dimensions of inverse mass, which we expect to be roughly of order $M_g^{-1}$ in size. In this expression the index $i = 1, 2$ is an $SU_L(2)$ gauge index while the index $a = 1, 2, 3$ labels fermion generations.

Models of this class are studied in detail in ref. \[^{[36, 37, 38]}\]. What has poisoned attempts to build 6D neutrino phenomenology along these lines is the efficiency with which active-
sterile neutrino mixing can drain energy away from astrophysical sources like supernovae. This can happen in either of two separate ways: either from losses due to incoherent radiation of bulk neutrinos; or from losses due to resonant oscillations into bulk neutrinos. Because of these constraints previous workers typically choose their models to be effectively 5-dimensional — an option which seems unavailable to us in the SLED context.

It is the first of these which seems the most dangerous in the present instance, since the constraint relies simply on the emission rate into sterile modes being of order \( \Gamma_s \approx (m/E)^2 \Gamma_\nu \), where \( \Gamma_\nu \) is the rate for emitting the standard active neutrinos, \( E \sim 100 \) MeV is the typical neutrino energy, and \( m \sim g_a v / r \) is the mass term which is responsible for the brane-bulk neutrino mixing. Because of the enormous number of bulk states which can be radiated, the energy loss due to this emission channel is too large provided \( mr \sim g_a v < 2 \times 10^{-4} \). At face value such small values are incompatible with the regime \( g_a v \sim O(1) \) which are required by neutrino phenomenology.

For this reason we do not further pursue brane-bulk neutrino mixing within SLED, although one always wonders whether a constraint which relies in this way on supernova physics might have loopholes to do with our fairly poor understanding of neutrino physics within dense supernova cores. If ref. [37] is correct, this kind of worry actually may be justified for the bound on brane-bulk neutrino mixing which is derived from coherent bulk neutrino production within supernovae. At face value this bound can be even stronger than the one just discussed, and so potentially is even more dangerous. However, ref. [37] claims that this bound is weaker than had been previously thought, because of a feedback effect due to neutrinos modifying their own environment within supernovae in such a way that the beginnings of efficient oscillation into bulk modes acts automatically to switch off the bulk radiation. If so, then this second bound need not be a concern for MSLED models. We believe it to be worth exploring in more detail the extent to which these bounds rule out nontrivial bulk-brane neutrino mixing within the MSLED framework.

### 2.2 Signatures at Colliders

A robust consequence of the SLED proposal is the existence of many bulk Kaluza-Klein modes whose mass spacing is of order \( 2\pi/r \sim 0.3 \) eV. Although each of these modes is coupled to ordinary particles only with gravitational strength, their enormous phase space at TeV energies makes their collective effects enter into observables at collider experiments with rates of order

\[
\Gamma(E) \propto \left( \frac{1}{M_p^2} \right) (E r)^2 \sim \left( \frac{E^2}{M_g^4} \right),
\]

whose size is controlled by powers of \( M_g \) rather than \( M_p \). For this reason the production of missing energy at TeV scale colliders is a robust signal of the SLED proposal.
Of course, the same arguments apply equally well to the non-supersymmetric LED proposal, where they again argue for a robust collider signal, and this has led to extensive studies of the possible phenomenological signatures of graviton emission into the bulk \([39, 40]\). Since these studies typically show that observable effects require \(M_g \lesssim 1\) TeV, one might worry that the supernova constraint \(M_g \sim 10\) TeV must preclude the expected SLED collider signal from being observably large.

We argue that this conclusion may be too pessimistic for several reasons. First, these calculations were done only for the graviton and we have already seen that radiation rates into the bulk are more efficient in SLED because of the existence there of all of the graviton’s super-partners \([16]\). Furthermore, the pessimistic conclusion also relies too heavily on there being no new physics at energies which are lower than the scale \(M_g\), even though \(M_g\) is really only the scale of 6D gravity as measured by the higher-dimensional Newton constant. As such, it need not be the threshold at which new physics first emerges. (A similar error would be made for the weak interactions if the Fermi constant, \(G_F^{-1/2} \sim 300\) GeV, were used to infer where the scale where the physics of the electro-weak interactions first appears. In reality we know that this physics starts at \(M_w = 80\) GeV rather than 300 GeV, because of the appearance of small dimensionless couplings in the relation between \(G_F\) and \(M_w\).) In the same fashion, it is likely that within the SLED proposal the string scale is at or below the scale \(M_g\), making some states potentially available to experiment at scales of a few TeV.

Furthermore, depending on how it arises within a more microscopic theory like string theory, there is a possibility in the SLED picture that there are also Kaluza-Klein and winding states associated with the ‘other’ 4 compact dimensions obtained when compactifying from 10 to 6 dimensions. As we saw in earlier sections, these should also have masses in the TeV regime provided the 4 small internal dimensions are not strongly warped. In this regime collider reactions should resemble string collisions near Planckian energies \([41]\). A more precise study of the phenomenology of these modes requires the study of the string compactifications from 10 to 6 dimensions which lead to the kinds of 6D models of present interest.

The most likely collider signal (besides the direct production of new string or KK states) of SLED physics is therefore likely to be missing energy, which can be produced in association with an isolated jet or lepton. Such a signal is unlikely to be confused with the missing energy signals of alternative proposals, such as the Minimal Supersymmetric Standard Model (MSSM). There are also discussions in the literature \([42, 43]\) about the possibility of producing mini black holes when collider energies approach the 6D gravitational scale. However, these calculations are still subject to considerable theoretical uncertainty.
Among the open and speculative issues are: the mass at which the black hole description starts being valid [44]; the applicability of using Thorne’s hoop conjecture when computing the black hole production cross-section [45]; the use of the generalized uncertainty principle (which the authors of ref. [46] claim implies a large increase in the energy necessary to form a black hole, putting them beyond the reach of the LHC); and the validity of the description of black-hole creation in terms of the collision of Aichelburg-Sexl shock waves [47].

2.3 Flavour Physics

Another way to distinguish the predictions of MSLED from alternate proposals is in their implications for flavor-changing physics as seen in $B$ and $K$ factories. Unlike theories like the MSSM, MSLED does not predict new phenomena in these experiments because its flavor physics is essentially described by the Standard Model. Indeed, a virtue of the MSLED proposal is that it retains many of the Standard Model successes in this regard, such as the natural understanding — through the GIM mechanism — of why flavour-changing neutral currents are small, and of why CP violation is small for $K$ mesons physics even though the intrinsic CP-violating phase in the Cabbibo-Kobayashi-Maskawa matrix is not small. At present (with very few, controversial exceptions) the existing data on weak decays of hadrons, including rare decays ($B \rightarrow X_s \gamma$, ...) and CP violating observables (CP asymmetry of $B \rightarrow J/\Psi K_S$, ...) is described within theoretical and experimental uncertainties by the SM, and so MSLED inherits this success. The CKM mechanism has passed its first precision tests successfully and is very likely the dominant source of CP violation in flavour-changing processes.

The only hope to see new effects in flavour-changing meson experiments within the MSLED framework would be if flavor-diagonal new physics taken together with the ordinary weak interactions could be separated from penguin contributions to various meson decays. Unfortunately, any such an analysis is likely to require a much more accurate understanding of penguin processes and matrix elements than is currently feasible.

It must be emphasized that these statements hold only for the minimal MSLED proposal, and do not follow robustly for all models in the SLED class. This is because one may always use the freedom to introduce new flavour physics by complicating the physics of our brane, without ruining the success of the basic 6D SLED mechanism.

3. Cosmology

Since the main motivation of the SLED proposal comes from cosmology, it is not surprising that some of its observational implications are cosmological. In this section we briefly
summarize the opportunities for testing the proposal which can be explored over comparatively long distance scales. These come in three different types: implications for Dark Energy, implications for tests of General Relativity on large and small distance scales, and implications for Dark Matter. We close with some speculations about how inflation might be embedded into the SLED picture.

3.1 Dark Energy

Besides providing a natural size for the Dark Energy density, the SLED proposal makes many further predictions concerning the properties of Dark Energy. First and foremost, it predicts that the Dark Energy is dynamically evolving in time even now, and so is not simply a cosmological constant. Rather it is what has come to be known as a ‘quintessence’ model [50], involving a cosmologically evolving 4D scalar field (or fields) whose microscopic origin is the overall breathing mode of the 2 large extra dimensions, \( r \) (plus possibly various shape moduli for these same dimensions).

Besides predicting the Dark Energy to be cosmologically evolving, SLED also predicts a very specific form for the quintessence field’s scalar potential. Given that the Einstein-Hilbert action implies the radion kinetic energy has the form \( M_p^2(\partial_\mu r \partial^\mu r)/r^2 \), the canonically-normalized field is \( \varphi = M_p \log(M_p r) \), leading to an exponential potential with a power-law prefactor. This is a form originally proposed by ref. [18].

Because the radion’s scalar potential has a previously-discussed form, it follows that the SLED predictions for Dark Energy evolution are likely to resemble those of refs. [18, 19]. This shows that SLED can share the viable phenomenology of these models, as well as their theoretical puzzles. In particular, although these models have many tracker solutions [19], their successful description of present-day cosmology does not rely on them and instead depends on the initial conditions of the radion field in an important way. This in turn implies that a completely adequate description of the cosmology of Dark Energy is likely to require a better understanding of these initial conditions, possibly as a consequence of an earlier inflationary epoch [52]. (Of course, these conclusions must be re-examined to the extent that shape moduli are also cosmologically active — see for instance [21] for a preliminary examination of this issue for torii.)

It should be stressed that these predictions for the Dark Energy are robust consequences of the relaxation mechanism with which the SLED proposal cancels the contributions of the brane tensions to the Dark Energy, since this mechanism implies the existence of a very light scalar field, \( r \), whose mass is of order the present-day Hubble scale, \( m_\varphi \sim H_0 \sim 10^{-33} \text{ eV} \).

\[11\] The potential for any shape moduli depends on more detailed information about the geometry of the two large dimensions.
Quintessential Naturalness Issues

The existence of a scalar as light as \( m_\varphi \sim 10^{-33} \) eV brings with it a further naturalness issue, which asks how such a small scalar mass can be stable against radiative corrections as physics associated with energy scales larger than \( m_\varphi \) are integrated out \([51]\). Remarkably, this naturalness problem is automatically explained in the SLED proposal as a consequence of the natural explanation of the small size of the observed Dark Energy density. This SLED explanation proceeds essentially along the lines anticipated in refs. \([22, 19]\), and proceeds as follows.

The explanation has two parts, depending on the energies being integrated out. For particles with masses, \( m \), lying between \( m_\varphi \sim 10^{-33} \) eV and \( 1/r \sim 0.01 \) eV, the effective theory is 4-dimensional, and standard arguments apply. These state that the integration over modes having mass \( m \) which couple to the quintessence field with strength \( g \) should contribute (at one loop) an amount \( \delta m_\varphi \sim mg/(4\pi) \). Since in the present case the quintessence field couples with gravitational strength, the relevant coupling is of order \( g \sim m/M_\text{Pl} \), leading to the estimate

\[
\delta m_\varphi \sim \frac{1}{4\pi} \left( \frac{m^2}{M_\text{Pl}} \right),
\]

which is acceptably large because this calculation necessarily presupposed \( m \lesssim 1/r \sim 0.01 \) eV in order to be performed in 4 dimensions.

For particles more massive than \( 1/r \) the analysis must be done in 6 dimensions, and in this case the stability of \( m_\varphi \) is ensured by the same mechanism which keeps the Dark Energy density sufficiently small. That is, to the extent that the radion potential is of order \( V(r) \sim 1/r^4 \), the radion mass is naturally \( m_\varphi \sim 1/(M_\text{Pl}r^2) \) and so has the right size for \( r \sim 10 \) \( \mu \)m. The SLED proposal itself explains why particles on the brane do not contribute to \( V(r) \) at all regardless of their masses. On the other hand, for particles in the bulk the integration over modes of mass \( m \) can generate dangerous terms which are of order \( \delta V \sim m^2/r^2 \). If generated, these would both give too large a vacuum energy density, and contribute the too-large amount \( \delta m_\varphi \sim m/(M_\text{Pl}r) \).\(^{12}\) Notice that the result \( m_\varphi \sim 1/r \) obtained when \( m \sim M_\text{g} \) corresponds to the usual estimate for the loop-induced radion mass in non-supersymmetric LED models.

Typically, the absence of these dangerous \( m^2/r^2 \) terms need only be ensured at one loop in the bulk theory, and they are in particular absent in the 6D theories of most practical interest (such as those obtained by compactification from 10D supergravity) \([4, 8]\).

\(^{12}\)Although quoted above in Jordan-frame units, these expressions for \( m_\varphi \) are most easily understood in the 4D Einstein frame using the canonically-normalized field \( \varphi \), with \( M_\text{Pl}r \sim e^{\varphi/M_\text{Pl}} \). In terms of this we have \( V(r) \sim m^2/r^2 \) implying \( V(\varphi) \sim (m^2 M_\text{Pl}^4/M_\text{g}^2) e^{-2\varphi/M_\text{Pl}} \) while \( V(r) \sim 1/r^4 \) implies \( V(\varphi) \sim M_\text{Pl}^4 e^{-4\varphi/M_\text{Pl}} \).
3.2 Tests of Gravity

There are two types of changes to gravitational physics which must follow in any variant of
the SLED proposal (and not just for its MSLED version). These involve tests of Newton’s
inverse-square law on distances of order \( m_{KK}^{-1} \sim r/(2\pi) \), as well as very-long-distance
modifications to gravity over scales up to the present-day Hubble length, \( H_0^{-1} \).

Short-Distance Tests

The deviations from Newton’s inverse-square law for gravitation must break down
in SLED for the same reason as it does within the earlier LED proposal: the effects of
ordinary graviton exchange begin to compete at these distances with the exchange of
various Kaluza-Klein modes from the two large extra dimensions. The range over which
the deviations from the inverse-square law arise is set by the lightest of the nonzero masses
of the Kaluza-Klein modes. Although the precise value of this lightest mass depends on
the details of the precise shape of the extra dimensions, we have seen above that they are
of order \( m_{KK} \sim 2\pi c/r \) with \( c = 1 \) for a toroidal compactification. It would be worthwhile
computing the form of the predicted force law in more detail for representative geometries,
given the many bulk fields in SLED whose Kaluza Klein modes could be relevant.

The bad news here is that the requirement \( r \sim 5 \mu m \), which follows from the Dark
Energy density, implies \( r/(2\pi) \sim 0.8 \mu m \), which is some two orders of magnitude below
the 100 \( \mu m \) range to which the best present searches for these effects are sensitive [53, 54].
They might not be beyond the reach of future tests based on precision measurements of
the Casimir effect [54], however. The good news is that there absolutely must be an effect,
and that the \( O(1 \mu m) \) range cannot be moved to still smaller values to evade better tests,
once these become available.

Long-Distance Tests

SLED models must also predict very long-range forces of roughly gravitational strength,
of the general scalar-tensor form. This follows quite generally as a consequence of the relax-
atation mechanism it predicts for the Dark Energy density, which we have seen leads naturally
to one or more fields, \( \varphi \), whose mass is presently incredibly small, \( m_{\varphi} \sim H_0 \sim 10^{-33} \) eV.
Unlike almost all other quintessence proposals, we have seen how this small scalar mass
can be naturally stable against quantum effects within the SLED framework.

Such a light scalar is strongly constrained by searches for a very-long-range force which
competes with gravity [55]. At the classical level the theory is very predictive because the
breathing mode of an extra dimension is known to couple to ordinary matter on our brane
through their contributions to the trace of the stress tensor, \( T_{\mu\nu}^\mu \), and at first sight this seems
to be a fatal prediction since gravitational-strength couplings of this form can already be ruled out with some precision.

A more detailed look is again more interesting, and whether these tests falsify SLED cosmology relies on more detailed calculations of the $r$-field couplings than are presently available. That they do can be seen from models such as those of refs. [22, 19], for which the precise strength and coupling of the light field can actually depend on some of the details of its cosmological evolution, since they can evolve during the history of the universe. They can do so because in the models investigated these couplings are field-dependent. Since the measurements which constrain these models are performed only during the present epoch, they are satisfied provided the couplings happen to be small at present, and this is what happens in the cosmological models of [19]. (It has also been claimed that an evolution to small couplings is an attractor in the space of solutions of related scalar-tensor models [56].)

Similar effects can arise within SLED scenarios because loop effects can introduce an $r$-dependence into otherwise field-independent quantities. Clearly the question of how big these couplings now are (and whether their motion can be traced within the domain of perturbation theory) can be addressed in a more focussed way given a real calculation of the potential and interactions of the field $\varphi$ (and any other light fields) from a specific microscopic model for the extra-dimensional geometry. This provides yet more motivation for exploring the details of such compactifications, including loop effects, more closely.

The possibility that there can be very light scalar fields around providing us with interesting non-standard gravitational physics on the longest distance scales is particularly exciting given the recent opportunities for testing this kind of scenario. It motivates, in particular, a more careful exploration of the phenomenology of scalar tensor theories for solar-system tests, as well as for tests in more exotic settings (like the recently-discovered system consisting of two pulsars which orbit one another [57]). Given a theoretical framework for such forces, it becomes possible to make more specific statements about the nature of their expected couplings, which allows more focussed analyses of the constraints which can be expected from these systems.

### 3.3 Dark Matter

If the SLED picture does describe the nature of Dark Energy, then we must rethink what has become the standard particle-physics paradigm for the origin of Dark Matter. The standard (Weakly-Interacting Massive Particle — WIMP) paradigm involves the Dark Matter consisting of the relic abundance of a stable particle having a weak-scale mass and a weak-interaction annihilation cross section. This is attractive because any such particle would
naturally have the presently-observed abundance provided only that it were originally in thermal equilibrium with the other observed particles in the very early universe.

The standard paradigm can be even more ambitious if one assumes that physics at the TeV scale is governed by the MSSM or one of its less-minimal variants, since in this case there is a very natural candidate for such a stable and weakly-interacting particle having a weak-scale mass. This is because these are properties which are naturally true for the lightest supersymmetric particle (LSP). The LSP is expected to be stable on quite general grounds if the supersymmetric theory enjoys an exact or approximate $R$ parity, and such a parity seems to be required in these models in order to explain the non-observation of baryon- and lepton-number violating decays.

**SLED Dark Matter**

All of this seems to be lost in the MSLED scenario, since the brane sector is described purely by the Standard Model and has no superpartners in the usual sense. It is therefore necessary to think again of where the Dark Matter might arise in this picture. Although we do not yet know the answer, we wish to argue that it is again the WIMP proposal which is the most attractive. There are two reasons for thinking so. The first of these is the original WIMP motivation: a stable particle with a weak-scale mass and weak-interaction annihilation cross section can naturally have the right present-day abundance if it were originally in thermal equilibrium with ordinary matter at very high temperatures during the very early universe. (As we discuss below, this motivation can have additional complications within an LED framework because of problems which arise if the KK modes in the two large dimensions are themselves in equilibrium at these high scales.)

The second reason which points to WIMPs as being the simplest candidate is given by the ‘Why Now?’ problem of any quintessence cosmology. This question asks why it should be that the universal energy density in matter, radiation and Dark Energy should happen to have been so similar to one another during the very recent universe. This question is all the sharper given that these three forms of energy vary very differently as a function of the universal scale factor as the universe expands.

Although this problem is normally posed for models of Dark Energy given that the Dark Matter is assumed to be given by some kind of WIMP, we may ask it in reverse given the SLED picture of what the Dark Energy is. A clue as to how to do so fruitfully can be found in ref. [58], who argue that the Why Now? problem has a natural solution if two things are true. 1. The Dark Matter is a relic WIMP abundance, and 2. the Dark Energy is a cosmological constant which is parameterically of order $\lambda \sim (M_w^2/M_p)^4$. In this case this reference argues that their present day abundances would naturally be close to one another now, since they are both set by ratios of $M_w$ and $M_p$. For these authors this is true.
by assumption for the Dark Energy, but it is also true for WIMPs due to the competition between the weak-interactions (through their control of the WIMP annihilation rate) and gravity (through its control of the expansion rate of the universe).

This picture makes WIMPs attractive within any kind of SLED proposal, because the Dark Energy density is necessarily predicted to be of order \( \lambda \sim 1/r^4 \sim (M_w^2/M_p)^4 \), and so depends parameterically on \( M_w \) and \( M_p \) in precisely the desired way. The question in SLED and MSLED models then becomes how to identify a promising stable candidate WIMP. This is as yet unsolved in these models, although it is promising that there can be an enormous number of weakly-interacting states available having masses at the weak scale. We have seen that for compactifications from 10 dimensions, string modes, winding modes and Kaluza-Klein modes for the ‘other’ 4 dimensions can all have masses in the TeV region.

Two things are required in order to make one of these candidates into a Dark Matter WIMP. First one needs a good reason why the state of interest should be stable. This could be done, for example, for the KK modes of the ‘other’ 4 dimensions if these dimensions should have isometries giving rise to conserved charges. For instance, compactification on a 4 torus would provide the simplest such example, with the Dark Matter being the lightest KK mode carrying momentum in these weak-scale extra dimensions. Refs. 59 consider in detail the relic abundance for related proposals wherein the lightest KK mode is the Dark Matter candidate, and find that an acceptable abundance would arise if the Kaluza-Klein scale were \( M_{KK} \sim 2\pi/\ell \approx 1 \text{ TeV} \). This fits well into a picture for which \( 1/\ell \sim 0.1 \text{ TeV} \), and \( M_s \sim (M_g/\ell)^{1/2} \sim 1 \text{ TeV} \). In view of the obvious implications for colliders of these scales, it would be well worth constructing the simplest possible compactification along these lines in order to investigate its implications in more detail.13

Over-Closing the Universe

It happens that in LED and SLED models the real problem with Dark Matter is not why there is so much of it, but why there is so little. This is because LED and SLED models can become dangerous if KK modes in the large 2 extra dimensions (as opposed to the smaller 4 weak-scale dimensions) should be stable and be in equilibrium at the weak scale. If so, and if some of the massive KK modes are stable, then these modes become too abundant and their energy density comes to dominate the universe much too early in its history.

This problem need not be generic because it depends on more model-dependent details of the geometry of the extra dimensions and of the universe’s history. When considering LED models it is normally assumed that these modes were not in equilibrium when ordinary

\[13\text{For toroidal compactifications within string theory the possibility also arises of using the lightest winding mode as the Dark Matter particle, and this scenario is } T\text{-dual to the situation where the Dark Matter is made up of the lightest KK mode.}\]
matter had temperatures above a ‘normalcy’ temperature, $T_\ast$, which must be higher than the scale of nucleosynthesis but cannot be as high as the weak scale. It is more difficult to avail ourselves of this way out if we wish to explain the Dark Matter abundance in terms of a thermally generated WIMP, as in the previous section.

It can also happen that Kaluza-Klein modes do not carry a conserved charge if the 2 large dimensions are not very symmetric, since it is the conserved charges associated with extra-dimensional isometries which the KK modes carry. In this case KK modes could quickly decay into massless states which would not dominate the universal energy density. Indeed, it should be emphasized that it is sufficient to have these extra dimensions not be symmetric at very early epochs, when the universe’s temperature is above $T_\ast$, which could be true even if they are very symmetric right now.

We regard this kind of evolution of the extra dimensions to be quite likely to occur within the SLED proposal because its energy cost is not high when temperatures are as large as $T_\ast$. This is particularly true, given the propensity of the extra dimensions to warp in response to changes in tension on the various branes. (Indeed the possibility that this warping is not small now is the biggest hurdle which the SLED models must clear in order to definitively explain the present-day observed Dark Energy density.) If so, a realistic calculation of the residual energy tied up in KK modes for the ‘large’ 2 dimensions must await a more detailed calculation of the cosmological evolution of the 2D geometry. Such a calculation is not beyond our powers, and is in progress. It is one more motivation for better understanding the energetics and dynamics of brane world configurations within the SLED and LED scenario.

3.4 Inflation

Since SLED models require the 6D gravity scale, $M_g$, to be in the 10 TeV region, it is interesting to speculate whether and how inflation can arise. We see two main possibilities, depending on whether or not the fundamental scale $M_g$ itself changes during the hypothetical inflationary epoch.

**Weak Scale Inflation:** It is possible that $M_g$ remains in the TeV range throughout inflation and its aftermath. If so, then the successful description of CMB temperature fluctuations would require an extremely flat inflaton potential. Since $\delta T/T$ is related to the inflaton potential $V$ and slow-roll parameter $\epsilon$ by $\delta T/T \propto (V/\epsilon)^{1/2}$, and the observed fluctuation amplitude requires $(V/\epsilon)^{1/4} \sim 10^{16}$ GeV [60], it is clear that if $V^{1/4} \sim M_g \sim 10$ TeV then we require $\epsilon \sim 10^{-48}$.

**Dimensional Evolution:** A more attractive possibility arises if the sizes of the extra dimensions and the effective 6D gravity scale, $M_g$, themselves also change during the inflationary
epoch, along the lines of what occurs in the scenarios of ref. [33]. In these models the internal dimensions evolve like a power of time, $t$, while the observed 4 dimensions inflate exponentially with $t$. Such an evolution might ultimately provide an explanation for why there should be such a large hierarchy amongst the sizes of the various extra dimensions, as well as potentially providing a theory of the initial conditions for the moduli of the large 2 internal dimensions.

4. Have We Been MSLED?

A great deal of effort has been devoted to exploring the observable implications of supersymmetry over the last few years. The combination of good theoretical motivation and distinctive experimental signatures has attracted the interest of theorists, phenomenologists, cosmologists and experimentalists alike. The supersymmetric extension of the Standard Model has emerged from this study as the conservative choice for the most likely replacement of the Standard Model itself.

Implicit in this choice is the belief that the supersymmetric Standard Model is an inevitable consequence of TeV-scale supersymmetry breaking within a microscopic theory which is supersymmetric. Although originally motivated by solving the cosmological constant problem, what is intriguing about the SLED proposal is that it provides a radically different way in which supersymmetry could be realized at low energies. As such it provides a counterexample to the statement that the supersymmetric Standard Model is the sole low-energy manifestation of TeV-scale supersymmetry breaking.

Equally important, the connection with the cosmological constant makes the SLED proposal unique in several ways. First, if proven to be successful, it would be the only extant proposal which can provide a natural explanation for the observed size of the dark energy. Second, since it involves modifying physics at extremely low energies, it has very many observational consequences for particle physics and astrophysics, apart from its predictions for the dark energy. Finally, by relating the size of the extra dimensions to the observed dark energy, it is very predictive because it removes the freedom to shrink these dimensions to evade their experimental consequences.

In this article we provide a first step towards exploring the phenomenology of SLED models. We do so by identifying several robust consequences of the SLED proposal, as well as proposing a naturally minimal special case, MSLED, for which even more specific predictions may be made. The model which results encompasses many of the main properties of the large extra dimensions scenarios, but with a more focussed set of predictions because of the inability to tweak the model by choosing more large dimensions, or to arrange the
dimensions to be smaller or to significantly change the field content and interactions in the 6-dimensional bulk.

Among the observable consequences which follow quite robustly for the SLED proposal are:

- Deviations from Newton’s inverse-square law must occur at μm scales.
- The Dark Energy should be capable of dynamically evolving even during the present epoch, due to the presence of at least one very light scalar corresponding to changes in the size of the extra large dimensions.
- The existence of the cosmologically light scalar(s) predicts that gravity is described by a scalar-tensor model over astrophysical distance scales.
- Astrophysical systems (like supernovae) and experiments at TeV scales should see (or be close to seeing) significant missing energy processes corresponding to emission of Kaluza Klein modes in the large two dimensions. Because the extra dimensions are supersymmetric, in SLED there are significantly more such states than there are gravitons.

The minimal MSLED version of the model also predicts:

- Particles on our brane consist purely of those of the Standard Model itself. In particular the Standard Model particles have no superpartners in the effective theory below the TeV scale where the scale of 6D gravity becomes important. They do not because supersymmetry is badly broken (at the TeV scale) on our brane.
- Low-energy particle physics should be well-described by the Standard Model, with suppressed flavour-changing interactions. Since the influence of extra-dimensional physics is suppressed at lower energies, it is unlikely that new effects should emerge in experiments involving low-energy $K$ and $B$ mesons.

Many of these implications are at the edge of being tested experimentally, both from accelerator and table-top experiments, so if the SLED picture is right we are likely to know within the comparatively near future.

4.1 MSLED vs the MSSM

Since MSLED is being proposed as a low-energy realization of supersymmetry which is a well-motivated and concrete alternative to the standard MSSM picture, it is perhaps worth comparing their relative merits and liabilities given our present state of knowledge.
Theoretical Motivation: One of the main practical benefits of the supersymmetric Standard Model has been that it is both theoretically well-motivated, and yet is also concrete and broadly predictive, particularly in its MSSM form. This makes it possible to test in detail, and compare with the predictions of the Standard Model itself. MSLED is also very predictive, and has two strong theoretical motivations. Its main motivation comes from the SLED description of the cosmological constant, but it also shares the theoretical motivation of describing a class of weak-scale supersymmetry breaking which can plausibly arise from a more fundamental microscopic theory like string theory.

Hierarchy Problem: The MSSM and MSLED both address the hierarchy problem, although in different ways. The MSSM provides a way to understand the natural stability of the hierarchy against loop corrections, but does not in itself provide an explanation of why the force of gravity should be weak compared with the electro-weak force in the first place. (The explanation of this requires a theory of how supersymmetry breaks in a more microscopic context, which is not yet available.) In MSLED the TeV scale is fundamental and the weak strength of gravity relies on the size of the 2 large extra dimensions being so large, and the explanation of why this is true becomes a dynamical question. Given that this size is large, MSLED’s key claim is that it can preserve the resulting hierarchy against the influence of loops. The main issue to be addressed in showing this to be true also involves dynamics: do the extra dimensions warp as higher-energy scales are integrated out?

In both cases the explanation for the difference between the electro-weak and Planck scales could be dynamical. In the MSSM it depends on the way supersymmetry is broken, possibly by non-perturbative effects that lead naturally to a large hierarchy of scales. In the MSLED case it depends on the mechanism that fixes the size and shape of the extra dimensions, such as in the scalar potential discussed in section 2. An important point for the MSLED is that the same scale that is needed to understand the electro-weak hierarchy problem, also provides the natural scale for dark energy.

Low-Energy Supersymmetry: Both MSSM and MSLED involve supersymmetry broken at the electro-weak scale, although the way supersymmetry is realized in the low-energy theory is very different. The field content of the MSSM fills out complete 4D supermultiplets, and so supersymmetry is realized linearly. This happens because the typical splittings of masses in supermultiplets is smaller than the cutoff at the TeV scale. By contrast, in MSLED since supersymmetry is broken on the brane at the TeV scale, there are no super-partners for ordinary particles in the low-energy theory. Supersymmetry is therefore only realized

\footnote{Indeed, if naturality issues are taken seriously the MSSM is so predictive as to be close to being ruled out.}
nonlinearly there \[15\]. The bulk physics, however, has a small supersymmetry-breaking scale, and so particles fall into 6D supermultiplets which linearly realize 6D supersymmetry.

**Dark Energy:** The MSSM does not explain the small observed size of the cosmological constant within the low-energy effective theory, and so does not protect its value to be smaller than of order \((1\text{TeV})^4\). One of the main motivations for the MSLED proposal is its potential to explain this major problem in a natural way. Being a much more recent proposal, it is not completely clear as yet whether the MSLED proposal will provide the definitive solution (with the main obstacle likely to be the possibility of the large 2 dimensions warping too much in response to the various internal brane tensions). Nevertheless we believe it goes further in this regard than does the MSSM, inasmuch as it provides a mechanism for understanding why ordinary particles like the electron do not in themselves provide too large a cosmological constant.

**Gauge Coupling Unification:** The measured strengths of the electro-weak and strong interactions at the weak scale appear to be consistent with the unification of these three gauge coupling constants, once they are run up to much higher energy scales — subject to the assumption of a plausible spectrum of super-partners at the TeV scale. The ability to understand this running is often considered as a triumph of the MSSM. The MSLED scenario does not offer a similarly natural explanation for this apparent coupling unification at the GUT scale, since it is the TeV scale rather than a larger scale which is fundamental within this model. One attitude to take within MSLED is that the evidence for unification is not that compelling, and so to simply put it aside.

An alternative approach is also possible, however \[61, 62, 63\]. For instance in \[62\], it is argued that precisely in the case of two large extra dimensions, there is a natural logarithmic ‘running’ of the gauge couplings coming from the logarithmic dependence on position of the massless propagator in two dimensions. This assumes that gauge couplings are position dependent because they are given by expectation values of bulk fields (such as happens in string theory) that vary logarithmically with position in the extra dimensions. In this picture, some bulk fields (like twisted moduli) couple differently to different gauge groups, and the place in the bulk where they vanish would correspond to the unification point. (The large energy desert over which couplings run is replaced in this picture by the large distance between our brane and this unification point within the bulk.) Although it is far from clear that such a picture can be consistent with the SLED proposal, it is a logical possibility which can be explored.

**Proton Stability:** The Standard Model beautifully explains the baryon and lepton number conservation of the renormalizable interactions as being an accidental consequence of the
model’s particle content and gauge symmetries. Proton stability is then naturally assured if the scale which suppresses any higher-dimension non-renormalizable effective interactions is of order the GUT scale, since the first baryon-number violating interactions arise at dimension 6. This property is lost in the MSSM, for which gauge invariance permits many baryon and lepton-number violating renormalizable interactions. These must be forbidden using extra symmetries like $R$-parity, and even then care must be taken to avoid having dangerous dimension-5 interactions contribute to proton decay. MSLED inherits the natural explanation for lepton- and baryon-number conservation for all renormalizable interactions since it is simply given on our brane by the Standard Model itself. Just as for the Standard Model, baryon-number violating interactions first arise at dimension 6, but for MSLED the natural scale which suppresses these interactions is only $M_g \sim 10$ TeV. Consequently, the existence of a symmetry (like baryon-number itself) must also be invoked to adequately suppress those non-renormalizable interactions which could mediate proton decay. Indeed, gauged baryon-number symmetries frequently arise within explicit quasi-realistic brane-world string compactifications [64, 25].

**Flavour Problems:** The MSSM has many soft supersymmetry-breaking parameters, which potentially include many arbitrary phases and flavour-changing interactions. The current lack of experimental evidence for these interactions introduces a new naturalness problem whose resolution is not provided within the model. New problems of this sort do not arise for MSLED to the extent that it is only the Standard Model which appears on our brane. (Of course, MSLED does not in itself shed any light on why the known fermions have the particular masses and mixing angles they are observed to have.)

**Falsifiability:** Both the MSSM and MSLED are likely to be decisively tested (and possibly ruled out) in the next few years. Their experimental signatures are quite different, with the MSSM predicting a rich spectroscopy of supersymmetric particles, and MSLED predicting very finely-spaced Kaluza-Klein states and missing energy at accelerators, as well as deviations of gravity in table-top experiments. Depending on how it is embedded into a more fundamental theory it may also predict that TeV-scale KK modes and string states are also present to be seen in colliders.

**Plan B:** Both models have simple extensions that share their main attractive features and predictions but which can provide some (but not all) experimental signatures, should these be required (such as by experiments searching for flavour changes in meson physics). In the MSSM new gauge and matter supersymmetric multiplets could be considered as well as more general soft supersymmetry breaking couplings. In the MSLED case, various extensions of the standard model could be considered on our brane rather than just the Standard
Model. These extensions could eventually be explored if required either on experimental or theoretical grounds.

Dark Matter: Both models favour a WIMP candidate for dark matter, although the MSSM has in the lightest super-partner a very generic candidate, due to the assumed conservation of $R$-parity. MSLED may also have many possible candidates, such as higher-dimensional KK modes, although further studies are required in order to better identify the alternatives.

Fundamentalism: Neither the MSSM nor MSLED have been derived from a more fundamental theory such as string theory, but both have reasonable prospects for being found near already known string vacua.

There are clearly more open questions than answers regarding the possible experimental tests of the SLED and MSLED scenarios, but we regard the exploration of these issues to be worth pursuing given the exciting connections which may emerge between particle physics, gravitation, astrophysics and cosmology.

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