Large extra dimensions and light hidden photons from anisotropic string vacua

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We derive type IIB vacua which are very promising to put string theory to experimental test. These are Calabi-Yau compactifications with a 4D fibration over a 2D base. The moduli are fixed in such a way to obtain a very anisotropic configuration where the size of the 2D base is exponentially larger than the size of the 4D fibre. These provide stringy realisations of the supersymmetric large extra dimensions scenario and extensions of the ADD scenario which are characterised by TeV-scale strings and two micron-sized extra dimensions. We also study the phenomenological properties of hidden Abelian gauge bosons which mix kinetically with the ordinary photon and get a mass via the Green-Schwarz mechanism. We show that anisotropic compactifications lead naturally to dark forces for an intermediate string scale or even to a hidden CMB for the extreme case of TeV-scale strings.

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1. Introduction

We focus on the study of the phenomenological implications of stabilised type IIB string compactifications where the extra dimensions are Calabi-Yau geometries with a 4D fibration over a 2D base [1]. Of particular interest are anisotropic vacua where the characteristic size of the 2D base is exponentially larger than the characteristic size of the 4D fibre [2].

These provide stringy realisations of scenarios with strings at LHC scales, micron-sized extra dimensions and Standard Model particles localised on branes, including the supersymmetric large extra dimensions scenario [3] and extensions of the ADD scenario [4] (see section 2).

These anisotropic compactifications turn out to be very promising to make contact with current experiments also because they give rise to interesting phenomenological properties of hidden Abelian gauge bosons with a kinetic mixing with the ordinary photon [5]. In fact, they lead naturally to a GeV-scale hidden photon (the so-called *dark forces*) for an intermediate string scale or to an meV-scale hidden photon (the so-called *hidden CMB*) allowing some fine-tuning of the underlying parameters in the case of TeV-scale strings (see section 3).

2. Micron-sized extra dimensions from anisotropic compactifications

Type IIB flux compactifications are very promising to test string vacua. In particular, LARGE Volume Scenarios (LVS) can naturally give rise to strings at LHC scales and two micron-sized extra dimensions (EDs) for compactifications on fibred Calabi-Yau (CY) three-folds [2]. The internal volume $\mathscr{V}$ is fixed exponentially large in string units: $\mathscr{V} \simeq e^{c/g_s} \gg 1$, where c is an $\mathscr{O}(1)$ parameter and the string coupling $g_s \ll 1$ is in the perturbative regime. $M_s \simeq 1$ TeV can be obtained for $\mathscr{V} \simeq 10^{30}$ since dimensional reduction gives $\mathscr{V} \simeq M_p^2/M_s^2$, providing a dynamical solution of the hierarchy problem based on moduli fixing. If all the EDs are of the same size $L \simeq \mathscr{V}^{1/6} M_s^{-1} \simeq (10\,\text{MeV})^{-1} \simeq 10\,\text{fm}$, L is much smaller than the current bounds from tests of Newton's law. Thus if we want to obtain a much larger L, we need to find anisotropic solutions with $\mathscr{V} \simeq L^2 l^4 M_s^6$ where $L \simeq 10\,\mu\text{m} \simeq (1\,\text{meV})^{-1}$ and $l \simeq 10^{-4}\,\text{fm} \simeq (1\,\text{TeV})^{-1} \ll L$, that would lead to a stringy derivation of ADD scenarios with two micron-sized EDs [4]. This is why we focus on CY three-folds with a 2D $\mathbb{P}^1$ base with volume $t_1 := (LM_s)^2$, a 4D K3 or T^4 fibre with size $\tau_1 := (lM_s)^4$ and a 4D del Pezzo with volume $\tau_3 := (dM_s)^4$. In fact, the CY volume $\mathscr{V} \simeq t_1\tau_1 - \tau_3^{3/2}$ [1], in the limit $t_1\tau_1 \gg \tau_3^{3/2}$, simplifies to the desired form $\mathscr{V} \simeq t_1\tau_1 \simeq L^2 l^4 M_s^6$. Given that in LVS the leading dynamics fixes only the combination of t_1 and τ_1 corresponding to $\mathscr{V} \simeq 10^{30}$, one flat direction is left over. Hence, if we parameterise it by τ_1, we need to fix $\tau_1 \simeq \mathscr{O}(10)$ so that $\langle t_1 \rangle \gg \sqrt{\langle \tau_1 \rangle} \simeq \sqrt{\langle \tau_3 \rangle} \Rightarrow L \gg l \simeq d$.

Moduli stabilisation: Due to the no-scale structure, the Kähler moduli are fixed beyond leading order in α' and g_s. The α' corrections to the Kähler potential K do not develop any potential for τ_1 since they depend only on $\mathscr{V}$. Open string loop corrections to K depend on τ_1 if there is a D7-stack wrapping the fibre. In this case, they would fix τ_1 too large at $\langle \tau_1 \rangle \simeq g_s^{4/3} \langle \mathscr{V} \rangle^{2/3} \gg 1$. If there are instead no D7-branes wrapping τ_1, we expect no τ_1-dependent g_s correction to K since open strings are localised far away from the fibre. In this case, τ_1 can be fixed only by non-perturbative corrections to the superpotential W. In the presence of a racetrack superpotential on τ_3, $W = W_0 + A e^{-a_3 T_3} - B e^{-b_3 T_3}$, the del Pezzo divisor can be fixed at $\langle \tau_3 \rangle \simeq 1/g_s \simeq \mathscr{O}(10)$ and

the volume at $\langle \mathcal{V} \rangle \simeq e^{c/g_s} \simeq 10^{30}$. The fibre is then fixed at $\langle \tau_1 \rangle \simeq \langle \tau_3 \rangle \simeq \mathcal{O}(10)$ via poly-instanton corrections to W generated by a string instanton on τ_1:

$$W = W_0 + A e^{-a_3 \left(T_3 + C_1 e^{-2\pi T_1} \right)} - B e^{-b_3 \left(T_3 + C_2 e^{-2\pi T_1} \right)}. \tag{2.1}$$

The poly-instanton potential for τ_1, $V_{\text{poly}} \simeq \mathcal{O}(\mathcal{V}^{-4})$, is suppressed since the leading potential scales as $V_{\text{lead}} \simeq \mathcal{O}(\mathcal{V}^{-3})$. Closed string loops are τ_1-dependent but they can be shown to be negligible.

Mass scales: The higher dimensional Planck scales are $M_{10D} \simeq M_s$ and $M_{6D} = (4\pi\tau_1)^{1/4} M_s$, while the 4D Planck scale is $M_p = \sqrt{4\pi\mathcal{V}} M_s$. There are also different Kaluza-Klein (KK) scales: the theory becomes 6D above $M_{\text{KK}}^{6D} \simeq M_s/t_1^{1/2} \simeq 1/L$ and 10D above $M_{\text{KK}}^{10D} \simeq M_s/\tau_1^{1/4} \simeq 1/l$ while KK replicas of Standard Model (SM) particles show up at $M_{\text{KK}}^{\text{SM}} \simeq M_s/\tau_{\text{SM}}^{1/4} \simeq 1/d$, where τ_{SM} is an additional del Pezzo supporting the SM brane stack. For $M_s \simeq 3$ TeV, we would have $M_{6D} \simeq 10$ TeV, $M_{10D} \simeq 4$ TeV, $M_{\text{KK}}^{\text{SM}} \simeq M_{\text{KK}}^{10D} \simeq 1$ TeV and $M_{\text{KK}}^{6D} \simeq 1$ meV. The dilaton and the complex structure moduli are almost degenerate with the gravitino which has a mass $m_{3/2} \simeq M_s^2/M_p \simeq 1$ meV. The Kähler moduli can be even lighter due to no-scale structure. In fact, τ_3 has a mass of order $m_{3/2}$ but τ_1 and $\mathcal{V}$ are much lighter since $m_1 \simeq M_p/\mathcal{V}^2 \simeq 10^{-32}$ eV and $m_{\mathcal{V}} \simeq M_p/\mathcal{V}^{3/2} \simeq 10^{-18}$ eV. These moduli would mediate unobserved fifth forces but we still need to study radiative corrections.

Supersymmetry breaking: Compactifications with TeV-scale strings need large supersymmetry (SUSY) breaking effects since gravity mediation would yield soft terms of order $M_{\text{soft}} \simeq m_{3/2} \simeq 1$ meV. Hence we consider a brane set-up that breaks SUSY explicitly, so that the low-energy theory contains just the SM. The bulk is instead approximately supersymmetric since $m_{3/2} \simeq 1$ meV, providing a stringy realisation of supersymmetric large EDs scenarios which are promising for explaining dark energy [3]. Given that SUSY is badly broken on the SM brane, we expect large radiative corrections to moduli masses from loops of massive open strings:

$$\delta m \simeq \zeta M_s^2/M_p \simeq \zeta M_p/\mathcal{V} \quad \text{where} \quad \mathcal{L}_{\text{int}} = (\zeta/M_p) \, \phi \, F_{\mu\nu} F^{\mu\nu}, \tag{2.2}$$

for a canonically normalised modulus ϕ. In the case of τ_1, $\zeta \simeq 1/\mathcal{V}$, as this is a flat direction at leading order. Hence the mass of the fibre is unchanged. However, since this modulus is very weakly coupled, $g \simeq 1/(M_p\mathcal{V})$, there are no bounds from fifth forces. For the volume mode, $\zeta \simeq 1$, and so its mass gets lifted to $m_{\mathcal{V}} \simeq 1$ meV, just at the edge of detectability in fifth force experiments.

Phenomenology: The phenomenology of these models differs from ADD scenarios due to the presence of new states and low-energy bulk SUSY. There are many implications for colliders, astrophysics and cosmology: (*i*) deviations from Newton's law; (*ii*) energy loss into the EDs due to radiation of KK modes; (*iii*) absence of superpartners of SM particles since SUSY is non-linearly realised; (*iv*) strong bounds from neutron-star cooling ($M_{6D} > 700$ TeV) and distortions of the MeV diffuse γ-ray background can be evaded since KK modes decay into invisible degrees of freedom (*dof*); (*v*) problems with BBN, if the SM brane cools too quickly through evaporation into the bulk, require a very low reheat temperature $T_{\text{RH}} \lesssim 100$ MeV; (*vi*) no over-closure of the Universe since the lightest KK mode cannot be stable due to the absence of continuous isometries in a compact CY; (*vii*) the lightest moduli and KK modes are good dark matter candidates.

3. Light hidden photons from anisotropic compactifications

Hidden photons γ' interact with the visible sector *only* via kinetic mixing with the hypercharge:

$$\mathscr{L} \supset -\frac{1}{4}F^{(\text{vis})}_{\mu\nu}F^{\mu\nu}_{(\text{vis})} - \frac{1}{4}F^{(\text{hid})}_{\mu\nu}F^{\mu\nu}_{(\text{hid})} + \frac{\chi}{2}F^{(\text{vis})}_{\mu\nu}F^{(\text{hid})\mu\nu} + m^2_{\gamma'}A^{(\text{hid})}_\mu A^{(\text{hid})\mu} + A^{(\text{vis})}_\mu j^\mu \,. \tag{3.1}$$

The hidden photon can get a mass $m_{\gamma'}$ either via a model-dependent Higgs mechanism in the hidden sector or via a Stückelberg mechanism which is typically stringy since it corresponds to the Green-Schwarz cancellation of the anomalies. Here we shall focus on the Stückelberg mechanism. The kinetic mixing takes place at one-loop and the corresponding parameter scales as $\chi \simeq g_Y g_{\text{hid}}/\left(16\pi^2\right)$.

Similar to neutrinos, the kinetic mixing induces photon $\leftrightarrow$ hidden photon oscillations. Given that thermal photons get a plasma mass $\omega_P \simeq 1$ meV, a resonant conversion of photons into γ' with $m_{\gamma'} \simeq 1$ meV can occur after BBN but before CMB decoupling. This results in a *hidden CMB* which increases the effective number of relativistic *dof*. The current observational value $\Delta N^{\text{eff}}_\nu = 1.3 \pm 0.9$ can be obtained for $\chi \simeq 10^{-6}$ in a region that is tested experimentally. Moreover, due to the kinetic mixing, SM particles get a small charge under the hidden $U(1)$ leading to *dark forces*. A mass of the order $m_{\gamma'} \simeq 1$ GeV can explain either the deviation of $(g-2)_\mu$ from the SM prediction if $\chi \simeq 10^{-3} \div 10^{-2}$, or several puzzling observations connected to dark matter and astrophysics if $\chi \gtrsim 10^{-6}$, again in a region tested by experiments. For a review on these issues see [6].

Hidden photons as open strings: Hidden photons arise naturally in string compactifications. In type IIB vacua, the γ' is an excitation of a D7-brane wrapping a four-cycle τ_{hid} far from the SM. For large τ_{hid}, the hidden gauge coupling becomes very small since $g^{-2}_{\text{hid}} = \tau_{\text{hid}}/(4\pi) \ll 1$ resulting in a significantly suppressed χ which can naturally be of order 10^{-6}. By turning on a world-volume flux on the hidden D7-stack, a Kähler modulus τ_j gets a charge $q \neq 0$ under $U(1)_{\text{hid}}$ and the corresponding axion gets eaten up by the γ' which acquires a Stückelberg mass $m^2_{\gamma'} \simeq q^2 g^2_{\text{hid}}(K_0)_{jj}M^2_p$, where $(K_0)_{jj}$ is the jj element of the tree-level Kähler metric. Moreover, a moduli-dependent Fayet-Iliopoulos term gets generated. As can be seen from the expression for $m_{\gamma'}$, if the EDs are exponentially large, hidden photons can naturally be very light [7]. In the case of isotropic compactifications, no prediction can be obtained in the interesting regions of the $(\chi, m_{\gamma'})$ parameter space [7]. However anisotropic compactifications with hidden photons living on D7-branes wrapping the fibre divisor, predict a *hidden CMB* and *dark forces* which can be detectable in the lab [5]. Furthermore, all the moduli can be successfully fixed with the D-terms under control [5].

Phenomenological implications: Let us focus on LVS anisotropic compactifications with γ' living on the fibre divisor. τ_1 is fixed via g_s corrections to K at $\langle\tau_1\rangle = \kappa\langle\tau_2\rangle$ where $\kappa \simeq (g_s c_1)^2/c_2$ with c_1 and c_2 unknown coefficients of the loop corrections. The relation between $m_{\gamma'}$ and χ can be written as $m_{\gamma'} \simeq \kappa \, 10^{24} \chi^3$ GeV, leading to two interesting scenarios:

1. **Natural dark forces for intermediate scale strings**: $m_{\gamma'} \simeq 1$ GeV and $\chi \simeq 10^{-6}$ for $\kappa \simeq 10^{-6}$ which can be achieved without fine-tuning the underlying parameters. The string scale is $M_s \simeq 10^{11}$ GeV and the CY is slightly anisotropic: $L \simeq 10^4 M_s^{-1} > l \simeq 10^2 M_s^{-1}$.

2. **Hidden CMB with KK dark forces and strings at the LHC**: $m_{\gamma'} \simeq 1$ meV and $\chi \simeq 10^{-6}$ for $\kappa \simeq 10^{-18}$ which requires a severe fine-tuning and gives TeV-scale strings. KK hidden photons with $M^{\gamma'}_{\text{KK}} \simeq M_s \tau_1^{-1/4} \simeq 1$ GeV might behave as dark forces and the CY is very anisotropic: $L \simeq 10^{11} M_s^{-1} \gg l \simeq 10^2 M_s^{-1}$.

4. Conclusions

We showed why stabilised type IIB string compactifications with an anisotropic shape of the extra dimensions can be very interesting for putting string theory to experimental test. In fact, the anisotropy of the Calabi-Yau is a crucial feature to give rise to exponentially large extra dimensions at the edge of detectability, strings at LHC scales, and very light hidden photons which can have many interesting cosmological and phenomenological implications due to their kinetic mixing with the ordinary photon.

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