Testing String Vacua in the Lab

Large extra dimensions and hidden photons

MICHELE CICOLI

DESY Theory Group

EPS HEP 2011, 23 Jul 2011

Based on:

1. MC, M. Goodsell, J. Jaeckel and A. Ringwald, arXiv:1103.3705 [hep-th]
2. MC, C. Burgess and F. Quevedo, arXiv:1105.2107 [hep-th]
3. MC, M. Kreuzer and C. Mayrhofer, arXiv:1107.0383 [hep-th]

Main results

- Type IIB flux compactifications on K3 fibrations
- Explicit compact examples from toric geometry with del Pezzo divisors
- Stabilisation of all closed string moduli
- Get a very large anisotropic volume of the compactification manifold
- Two micron-sized extra dimensions and fifth-forces at the edge of detectability
- Strings at LHC scales [`see Luest's talk`]
- Dynamical solution of the hierarchy problem based on moduli stabilisation
- The bulk is approximately supersymmetric: $m_{3/2} \sim 1$ meV
- SUSY is badly broken on the SM brane: NO superpartners!
- Stringy SLED scenarios promising for dark energy as the brane back-reaction might cancel the contribution to Λ from the SM brane $\Rightarrow \Lambda \sim M_{KK}^{6D} \sim 1$ meV for $M_{6D} \sim 1$ TeV
- Rich spectrum of light states
- Very light hidden photons with kinetic mixing with the ordinary photon
- Good predictions for *Hidden CMB* and *Dark Forces* – Detectable in the lab (DESY)!

Anisotropic compactifications

Type IIB LARGE Volume Scenarios can naturally give rise to TeV scale strings:

$$V_6 \sim e^{c/g_s} \gg 1 \qquad g_s \ll 1 \qquad \mathcal{V} := V_6 M_s^6 \sim M_p^2/M_s^2 \sim 10^{30} \;\Rightarrow\; M_s \sim 1\,\text{TeV}$$

BUT the CY has a symmetric shape: $L \sim V_6^{1/6} \sim (10\,\text{MeV})^{-1} \sim 10\,\text{fm}$

Need to find anisotropic solutions with $V_6 \sim L^2 l^4$ where

$$L \sim 10\,\mu\text{m} \sim (0.01\,\text{eV})^{-1} \qquad l \sim 10^{-4}\,\text{fm} \sim (1\,\text{TeV})^{-1} \ll L$$

Consider K3-fibred CY three-folds with del Pezzo divisors:

$$\mathcal{V} = t_1 \tau_1 - \tau_3^{3/2}$$

- 2D $\mathbb{P}^1$ base: $t_1 := (L M_s)^2$
- 4D K3 fibre: $\tau_1 := (l M_s)^4$
- 4D blow-up mode (del Pezzo): $\tau_3 := (d M_s)^4$

Large volume limit: $t_1 \tau_1 \gg \alpha \gamma \tau_3^{3/2} \;\Rightarrow\; \mathcal{V} \simeq t_1 \tau_1 = L^2 l^4 M_s^6 \sim e^{c/g_s} \sim 10^{30}$
Need to fix $\tau_1 \sim \mathcal{O}(10)$ 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

No-scale structure $\Rightarrow$ Kähler moduli τ_i fixed beyond the leading order in α' and g_s

- Leading α' correction to K depends only on $\mathcal{V}$
- Open string loop corrections to K depend on the brane set-up
  1. $D7$ wrapping $\tau_1 \Rightarrow \tau_1$-dependence due to locality $\Rightarrow \langle\tau_1\rangle \sim g_s^{4/3}\,\langle\mathcal{V}\rangle^{2/3} \gg 1$
  2. No $D7$ wrapping $\tau_1 \Rightarrow$ No τ_1-dependence since open strings are far away
- Non-perturbative racetrack on τ_3: $W = W_0 + A\,e^{-a_3 T_3} - B\,e^{-b_3 T_3}$

  $\Rightarrow$ fix $\langle\tau_3\rangle \sim 1/g_s \sim \mathcal{O}(10)$ and $\langle\mathcal{V}\rangle \sim e^{c/g_s} \sim 10^{30}$

  Fix $\langle\tau_1\rangle \sim \langle\tau_3\rangle \sim \mathcal{O}(10)$ via poly-instanton corrections from an $ED3$ on τ_1:

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

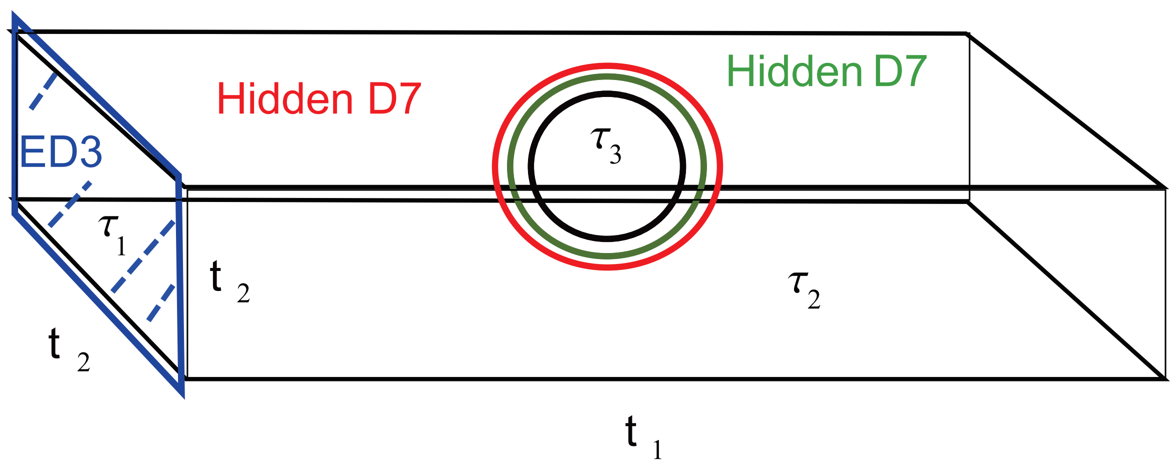
  $V_F = V_{\rm lead} + \delta V_{\rm poly}$, $V_{\rm lead} \sim \mathcal{V}^{-3}$ and $\delta V_{\rm poly} \sim \mathcal{V}^{-4}$

  $\Rightarrow d \simeq \langle\tau_3\rangle^{1/4}\ell_s \gtrsim l \simeq \langle\tau_1\rangle^{1/4}\ell_s \sim 10^{-17}$ mm $\ll L \simeq \sqrt{\langle t_1\rangle}\,\ell_s \sim 0.01$ mm

- Closed string loop corrections to K depend on τ_1 but do not beat the poly-instantons:

$$\delta V_{(g_s)} \sim \Lambda^2\ {\rm STr}(M^2) \sim (M_{KK}^{6D})^2 m_{3/2}^2 \sim \frac{\tau_1}{\mathcal{V}^4} \sim 10^{-120}\,M_p^4$$

Pictorial view



Mass scales

- Higher dim Planck scales: $M_{10D} = (4\pi)^{1/8}\, M_s \quad M_s := \ell_s^{-1} \quad M_{6D} = (4\pi\tau_1)^{1/4}\, M_s$
- 4D Planck scale: $M_p = \sqrt{4\pi\mathcal{V}}\, M_s$
- 6D KK scale: $M_{KK}^{6D} = M_s/t_1^{1/2} = 1/L$
- 10D KK scale: $M_{KK}^{10D} = M_s/\tau_1^{1/4} = 1/l$
- SM KK scale: $M_{KK}^{SM} = M_s/\tau_{SM}^{1/4} = 1/d$

	M_s	M_{6D}	M_{10D}	M_{KK}^{SM}	M_{KK}^{10D}	M_{KK}^{6D}
isotropic case	1 TeV	2000 TeV	2 TeV	0.5 TeV	50 MeV	0.3 MeV
anisotropic case	3 TeV	10 TeV	4 TeV	1 TeV	1 TeV	1 meV

The moduli are lighter than KK masses:

- S- and U-moduli: $m_{U,S} \sim m_{3/2} \sim M_s^2/M_p \sim 1$ meV Stable against loops!
- T-moduli can be even lighter due to no-scale structure
  $m_1 \simeq \frac{M_p}{\mathcal{V}^2} \sim 10^{-32}$ eV $\qquad m_{\mathcal{V}} \simeq \frac{M_p}{\mathcal{V}^{3/2}} \sim 10^{-18}$ eV
  BUT need still to take radiative corrections into account!

Supersymmetry breaking

- Need large SUSY breaking for TeV scale strings
  $\Rightarrow$ consider a non-SUSY brane construction with just the SM in the EFT
- The bulk is approximately supersymmetric: $m_{3/2} \sim M_s^2/M_p \sim 10^{-3}$ eV for $M_s \sim 1$ TeV
- Check fifth forces due to light moduli!
- SUSY is badly broken on the SM brane
  $\Rightarrow$ large radiative corrections to moduli masses from loops of massive open strings!

$$\delta m \simeq \frac{\zeta\, M_s^2}{M_p} \simeq \frac{\zeta\, M_p}{\mathcal{V}} \quad \text{where} \quad \mathcal{L}_{\rm int} = \frac{\zeta}{M_p}\, \delta\phi\, F_{\mu\nu} F^{\mu\nu}$$

  - $\zeta = 1/\mathcal{V}$ for $\tau_1 \Rightarrow$ Mass of the K3 fibre is unchanged: $m_1 \sim 10^{-32}$ eV
    BUT it is very weakly coupled: $g \sim 1/(M_p \mathcal{V}) \Rightarrow$ no bounds from 5-th forces
  - $\zeta = 1$ for $\mathcal{V} \Rightarrow$ Mass of the volume shifted from $m_2 \sim 10^{-18}$ eV to $m_2 \sim 10^{-3}$ eV
    at the edge of detectability in fifth force experiments for scalars with $g \sim 1/M_p$!

Phenomenology

UV completion gives more info on the EFT than simple low gravity models

Low-energy bulk SUSY and new states make the predictions differ from minimal ADD

Many exotic light states $\Rightarrow$ stringent constraints from colliders, astrophysics and cosmology

- Generic constraints of SLEDs
- Constraints related to the presence of specific types of new light fields

1. Tests of Newton's inverse square law
2. Energy loss into the EDs due to radiation of KK modes
3. Absence of MSSM superpartners for each of the known SM particles

   SUSY is non-linearly realised: $electron \to electron + Goldstino$

   The Goldstino is eaten up by the gravitino when the theory is coupled to the bulk

   $\Rightarrow$ The spectrum on the SM brane does not include the MSSM

   $\Rightarrow$ Prediction: LHC searches should find no superpartner — so far successful!
4. Can evade strong astrophysical bounds from neutron-star cooling ($M_{6D} > 700$ TeV) since the KK modes decay into invisible *dof*

Hidden photons

Hidden photon interacting with the visible sector via kinetic mixing with the hypercharge:

$$\mathcal{L} \supset -\frac{1}{4}F^{(\mathrm{vis})}_{\mu\nu}F^{\mu\nu}_{(\mathrm{vis})} - \frac{1}{4}F^{(\mathrm{hid})}_{\mu\nu}F^{\mu\nu}_{(\mathrm{hid})} + \frac{\chi}{2}F^{(\mathrm{vis})}_{\mu\nu}F^{(\mathrm{hid})\mu\nu}$$
$$+ m^2_{\gamma'}A^{(\mathrm{hid})}_{\mu}A^{(\mathrm{hid})\mu} + A^{(\mathrm{vis})}_{\mu}j^{\mu}$$

$m_{\gamma'}$ may arise via:

- Hidden Higgs (model-dependent)
- Stückelberg mechanism (typically stringy)

Focus on the Stückelberg mechanism to get robust predictions!

Kinetic mixing at 1-loop:

$$\chi \sim \frac{g_Y\, g_{\mathrm{hid}}}{16\pi^2}$$

Phenomenology

Similar to neutrino mixing, kinetic mixing induces photon $\leftrightarrow$ hidden photon oscillations

- Thermal photons get a plasma mass of the order $\omega_P \sim 1$ meV

  $\Rightarrow$ resonant conversion into γ' with $m_{\gamma'} \sim 1$ meV after BBN but before CMB decoupling

  $\Rightarrow$ increase in the effective number of relativistic *dof*: *Hidden CMB*

  Get $\Delta N_\nu^{\rm eff} = 1.3 \pm 0.9$ (WMAP7+BAO+H_0) if $\chi \sim 10^{-6}$

  Experiments in Hamburg: ALPS (DESY) and SHIPS (Observatory)

- SM particles get a small charge under the hidden $U(1)$ leading to *Dark Forces*

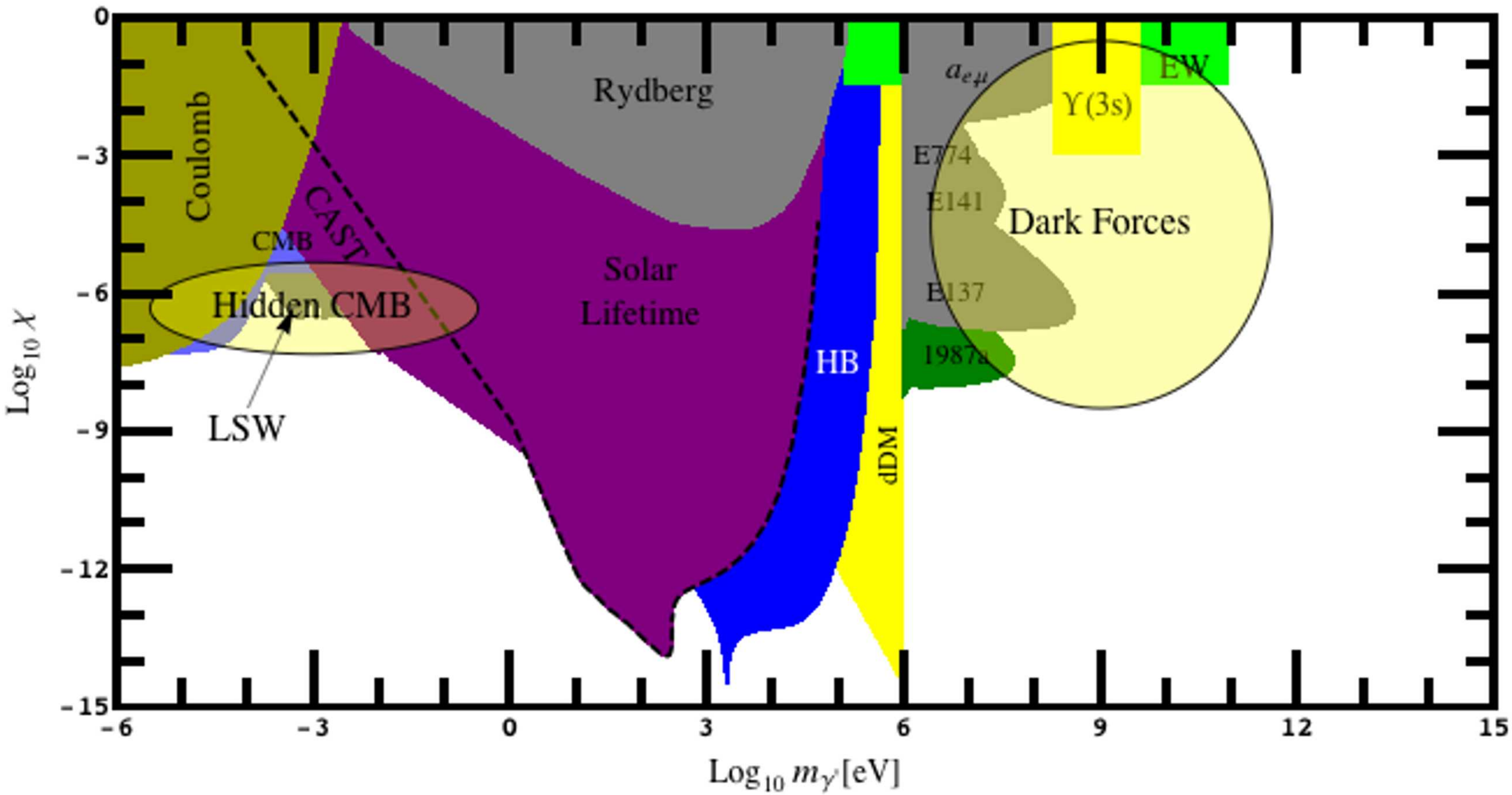
  For $m_{\gamma'} \sim 1$ GeV, interesting explanations of:

  - deviation of $(g-2)_\mu$ from the SM prediction if $\chi \sim 10^{-3} \div 10^{-2}$
  - puzzling observations connected to DM and astrophysics (DAMA, CoGeNT and PAMELA) if $\chi \gtrsim 10^{-6}$

  New fixed-target experiments at DESY (HIPS), MAMI and Jefferson Lab

Parameter space

Constraints on the $(\chi, m_{\gamma'})$ parameter space from astrophysics, cosmology and laboratory experiments



Hidden photons as open strings

- In type IIB vacua, γ' is an excitation of a $D7$ wrapping a 4-cycle τ_{hid} far from the SM
- For large τ_{hid}, $g_{hid}^{-2} = \tau_{hid}/(4\pi) \ll 1 \Rightarrow \chi$ significantly suppressed

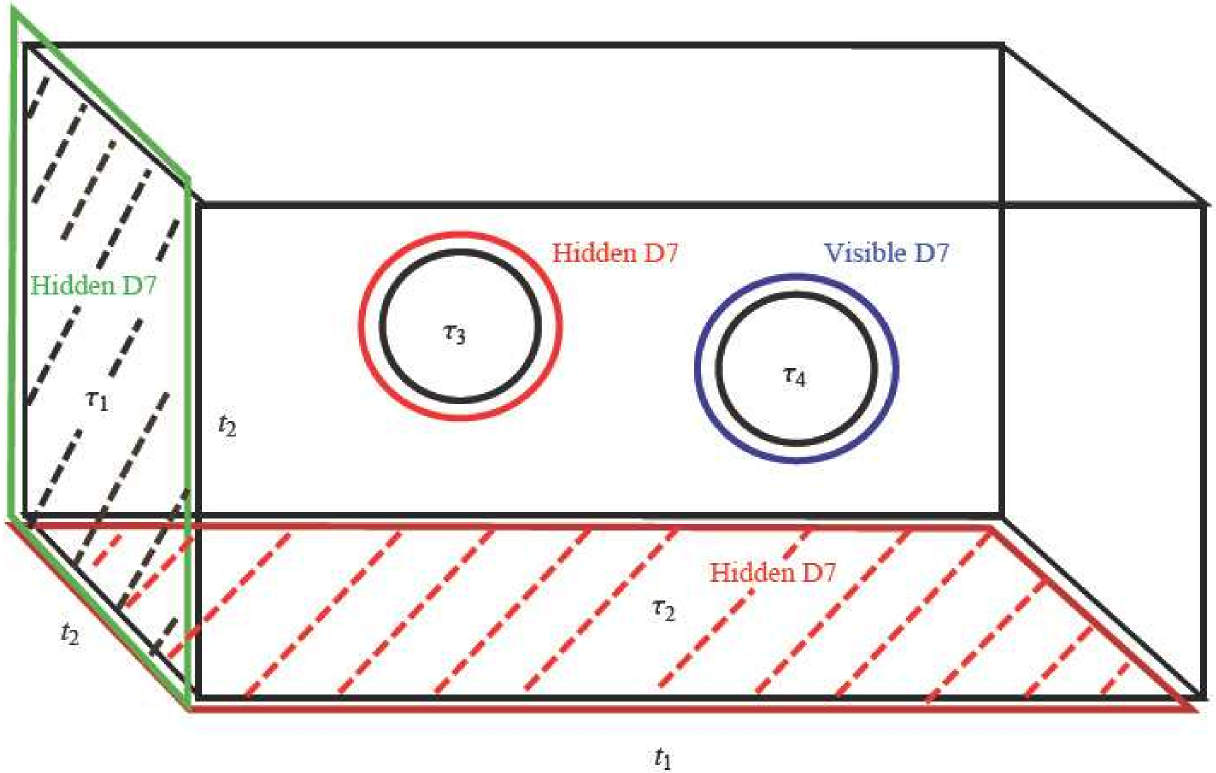
$$\chi \sim g_Y g_{\rm hid}/\left(16\pi^2\right) \sim 0.5 \times 10^{-2}/\sqrt{\tau_{\rm hid}}$$

- $m_{\gamma'} \neq 0$ is due to the Green-Schwarz mechanism by turning on a world-volume flux

$$m^2_{{\rm St}\,ij} = \left(\frac{4 g_i g_j}{3\pi}\right) q_{ip} (\mathcal{K}_0)_{pm} q_{mj} M_p^2$$

- Kähler moduli get charged under $U(1)_{hid}$ and a comb. of axions gets eaten up by the γ'
- A moduli-dependent FI term gets generated $\Rightarrow$ take it into account for moduli fixing
- Promising study of γ' in the LARGE Volume Scenario for isotropic compactifications [Goodsell, Jaeckel, Redondo and Ringwald]
- BUT no prediction in the interesting regions and no full study of D-terms and moduli stabilisation (D-terms are dangerous since they give rise to a run-away for $\mathcal{V}$) $\Rightarrow$
  - Consider anisotropic compactifications and get good predictions
  - D-term problem solved by complicated CYs which dynamically reduce to the old ones

Pictorial view



Phenomenological implications

Focus on the most promising scenario (γ' on τ_1) and take moduli stabilisation into account

Fix τ_1 via g_s corrections to K and not via poly-instantons!

$$\langle\tau_3\rangle \simeq g_s^{-1} \qquad \langle\mathcal{V}\rangle \simeq e^{c\langle\tau_3\rangle} \qquad \langle\tau_1\rangle = \kappa\,\langle\tau_2\rangle \quad \text{with} \quad \kappa = (g_s c_1)^2/c_2$$

The relation between $m_{\gamma'}$ and χ can be written as $m_{\gamma'} \sim \kappa\, 10^{24}\chi^3$ GeV

1. **Natural Dark Forces for intermediate scale strings**
   - $m_{\gamma'} \simeq 1$ GeV and $\chi \simeq 10^{-6}$ for $\kappa \sim 10^{-6}$
   - No fine-tuning and $M_s \sim 10^{11}$ GeV
   - Slightly anisotropic CY: $L \sim t_1^{1/2}\,\ell_s \sim 10^4\,\ell_s > l \sim \tau_1^{1/4}\,\ell_s \sim 10^2\,\ell_s$
2. **Hidden CMB with KK Dark Forces and strings at the LHC**
   - $m_{\gamma'} \simeq 1$ meV and $\chi \simeq 10^{-6}$ for $\kappa \sim 10^{-18}$
   - Fine-tuning needed and $M_s \sim 1$ TeV
   - KK hidden photons with $M_{\gamma'}^{KK} \sim M_s \tau_1^{-1/4} \sim 1$ GeV might be Dark Forces
   - Very anisotropic CY: $L \sim t_1^{1/2}\,\ell_s \sim 10^{11}\,\ell_s \gg l \sim \tau_1^{1/4}\,\ell_s \sim 10^2\,\ell_s$

Predictions

Kinetic mixing vs γ' mass for anisotropic compactifications