Testing Anisotropic String Compactifications in the Lab

Strings at the LHC, micron-sized extra dimensions and hidden photons

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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
- Strings at LHC scales [`see Luest’s talk`]
- Two micron-sized extra dimensions and fifth-forces at the edge of detectability
- Dynamical solution of the hierarchy problem based on moduli stabilisation
- Stringy SLED scenarios promising for dark energy as the brane back-reaction might cancel the contribution to Λ from the SM brane [`see Burgess’s talk`]

$$\Lambda \sim M_{6D}^2/M_p \sim M_{KK}^{6D} \sim 10^{-3}\,\text{eV} \quad \text{for} \quad M_{6D} \sim 1\,\text{TeV}$$

- Rich spectrum of light states
- Very light hidden photons with kinetic mixing with the ordinary photon
- Good 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

$$L \sim 10\,\mu\text{m} \sim (0.01\,\text{eV})^{-1} \qquad l \sim \left(V_6/L^2\right)^{1/4} \sim 10^{-4}\,\text{fm} \sim (1\,\text{TeV})^{-1} \ll L$$

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

$$\mathcal{V} = \sqrt{\tau_1}\tau_2 - \tau_3^{3/2} = t_1\tau_1 - \tau_3^{3/2}$$

- 2D $\mathbb{C}P^1$ base: $t_1 := (LM_s)^2$
- 4D K3 fibre: $\tau_1 := (lM_s)^4$
- 4D blow-up mode (del Pezzo): $\tau_3 := (dM_s)^4$

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:

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

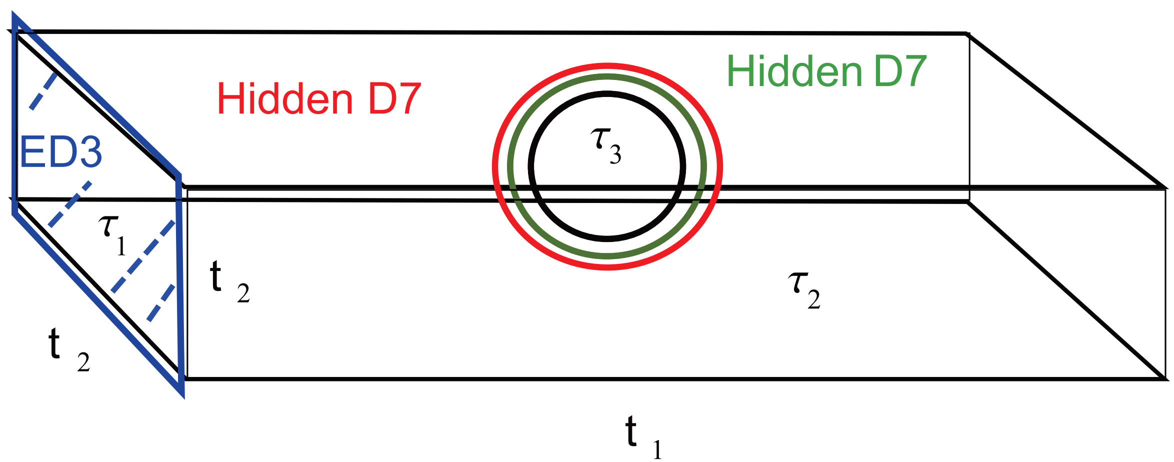
  $V_F = V_{\rm lead} + \delta V_{\rm poly}$, $V_{\rm lead} \sim \mathcal{V}^{-3}$ and $\delta V_{\rm poly} \sim \mathcal{V}^{-3-p}$ with $p \simeq 1$

  $\Rightarrow d \simeq \langle\tau_3\rangle^{1/4}\ell_s \gtrsim l \simeq \langle\tau_1\rangle^{1/4}\ell_s \sim 10^{-17}$ mm $\ll L \simeq \sqrt{\langle\mathcal{V}\rangle/\langle\tau_1\rangle}\,\ell_s \sim 0.01$ 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}
small hierarchy	1 TeV	2000 TeV	2 TeV	0.5 TeV	50 MeV	0.3 MeV
large hierarchy	3 TeV	10 TeV	4 TeV	1 TeV	1 TeV	0.01 eV

The moduli are lighter than KK masses (if not fixed by D-terms that give $m \sim M_s$)

- 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 $m_{\mathcal{V}} \simeq \frac{M_p}{\mathcal{V}^{3/2}} \sim 10^{-18}$ 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

Can evade strong astrophysical bounds 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:

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

Hidden photon 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*

  `[Jaeckel, Redondo and Ringwald]`

  Get $\Delta N_\nu^{\rm eff} = 1.3 \pm 0.9$ (WMAP7+BAO+H_0) if $\chi \sim 10^{-6}$ (PLANCK: $\Delta N_\nu^{\rm eff} \simeq 0.07$)

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

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

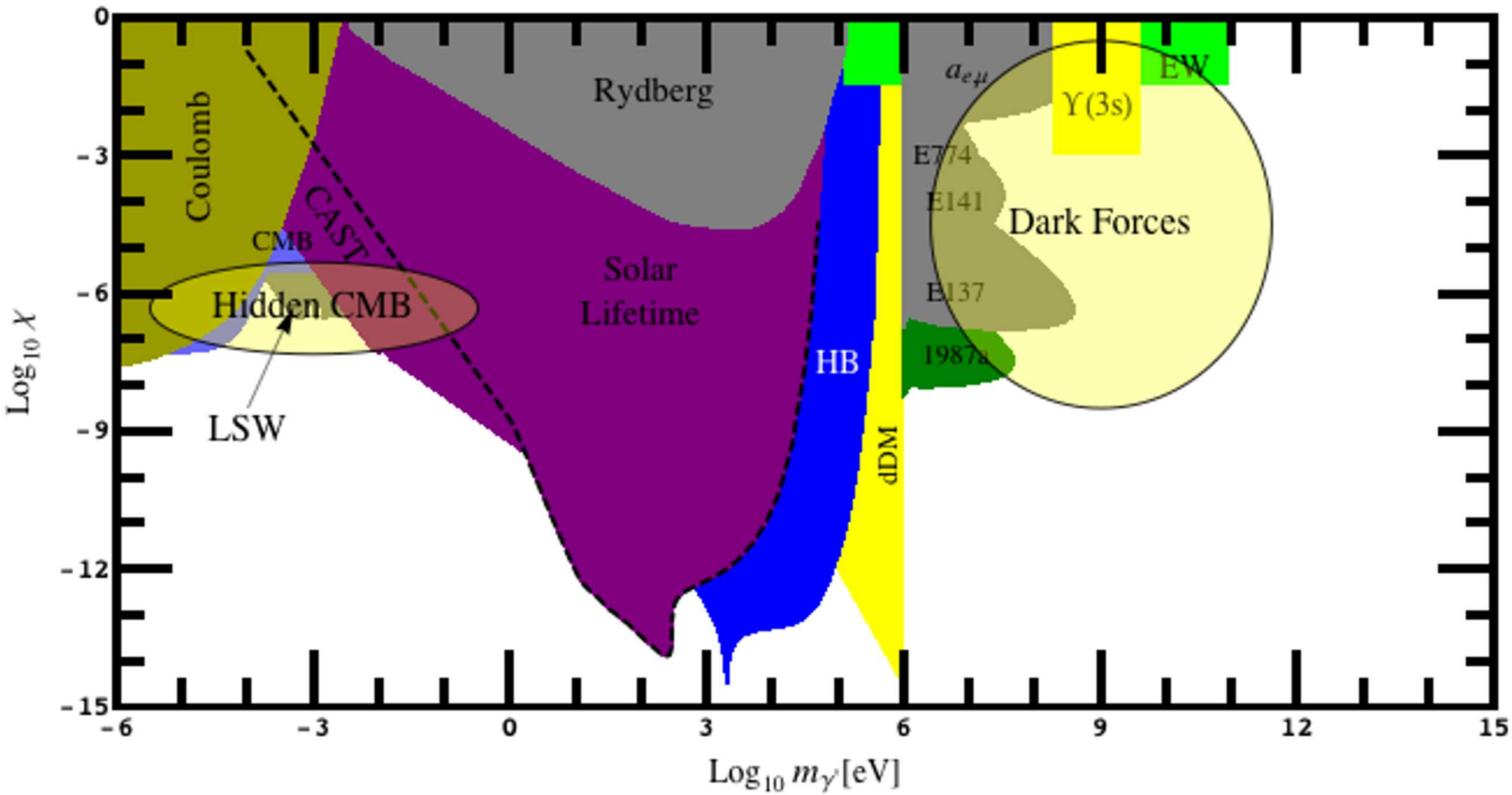
  For $m_{\gamma'} \sim 1$ GeV, interesting explanations of

  - 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

Hidden photon 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

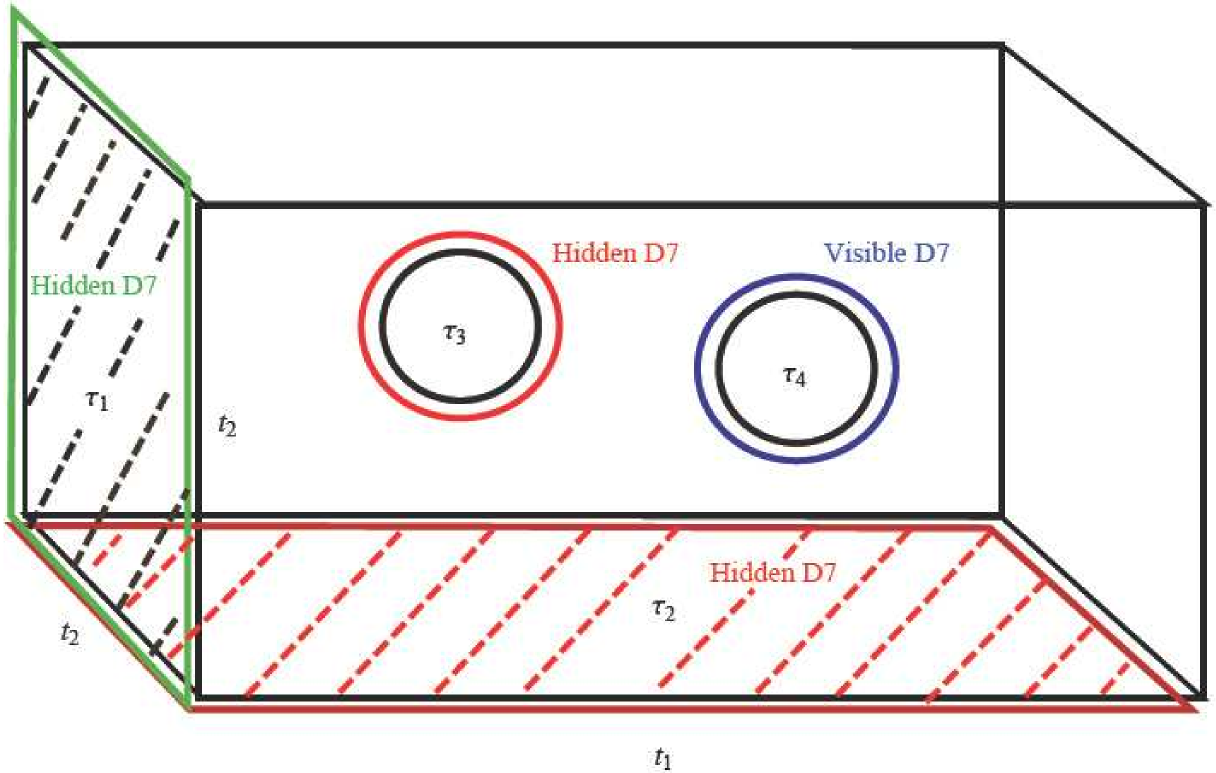
$$\chi \sim g_Y g_{\rm hid}/\left(16\pi^2\right) \sim 0.5 \times 10^{-2}/\sqrt{\tau_{\rm hid}}$$

- $m_{\gamma'} \neq 0$ 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!

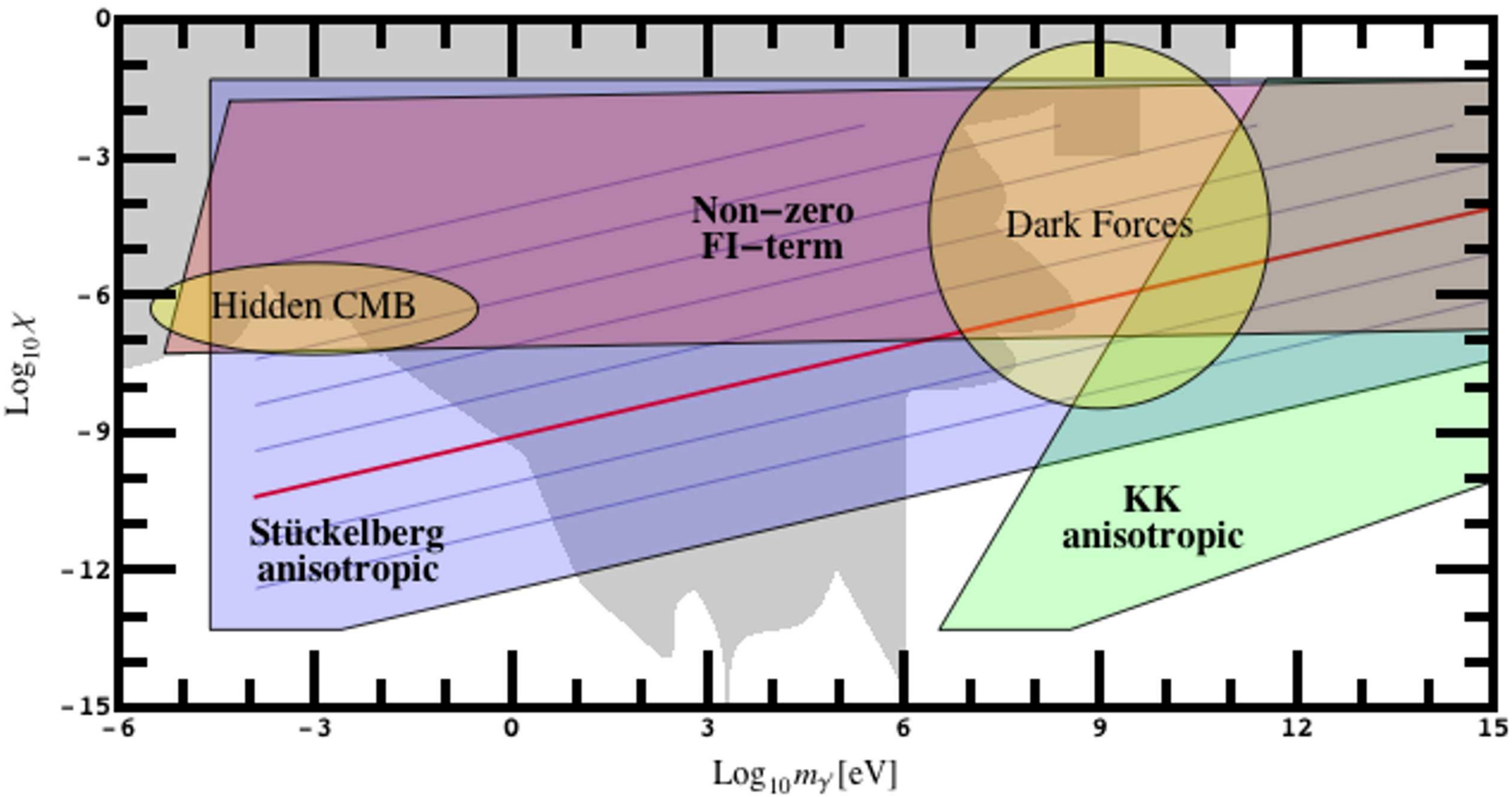
$$\langle\tau_3\rangle \simeq g_s^{-1} \qquad \langle\mathcal{V}\rangle \simeq e^{c\langle\tau_3\rangle} \qquad \langle\tau_1\rangle = \kappa\,\langle\tau_2\rangle \quad \text{with} \quad \kappa = \left(g_s c_1\right)^2/c_2$$

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



Small hierarchy

Neglecting subleading loop corrections

$$V_F = \mu_1 \frac{\sqrt{\tau_3}}{\mathcal{V}} e^{-4\pi\tau_3} - \mu_2 W_0 \frac{\tau_3}{\mathcal{V}^2} e^{-2\pi\tau_3} + \mu_3 \frac{W_0^2}{\mathcal{V}^3}$$

Only τ_3 and the volume $\mathcal{V} \simeq \alpha\sqrt{\tau_1}\tau_2$ fixed at $\langle\tau_3\rangle \sim \mathcal{O}\left(1/g_s\right)$ and $\langle\mathcal{V}\rangle \sim e^{2\pi/g_s}$

Get $M_s \sim M_p/\mathcal{V}^{1/2} \sim 1$ TeV without fine-tuning ($W_0 \sim \mathcal{O}(1)$) for $\langle\tau_3\rangle \sim 10$ and $\langle\mathcal{V}\rangle \sim 10^{30}$

Direction in the (τ_1, τ_2)-plane orthogonal to $\mathcal{V}$ is still flat. Include g_s corrections to K

$$\delta V_{(g_s)} = \left(\frac{\mathcal{A}}{\tau_1^2} - \frac{\mathcal{B}}{\mathcal{V}\sqrt{\tau_1}} + \frac{\mathcal{C}\tau_1}{\mathcal{V}^2}\right)\frac{W_0^2}{\mathcal{V}^2}$$

Fix the remaining flat direction: $\langle\tau_1\rangle \simeq c\,\mathcal{V}^{2/3}$ where $c = \frac{\left(g_s \mathcal{C}_1^{KK}\right)^{4/3}}{\left(\mathcal{C}_{12}^{W}\right)^{2/3}}$

Small hierarchy ($\tau_2 > \tau_1 \gg \tau_3$) without fine-tuning:

$$\mathcal{C}_1^{KK} = \mathcal{C}_2^{KK} = 0.1,\ \mathcal{C}_{12}^{W} = 5 \quad \Rightarrow \quad \langle\tau_1\rangle = 1.3\cdot 10^{17} \quad \text{and} \quad \langle\tau_2\rangle = 3.2\cdot 10^{21}$$

$$L \simeq \sqrt{t_1} M_s^{-1} \simeq \left(\tau_2^{1/2}/\tau_1^{1/4}\right) M_s^{-1} \sim 3\times 10^6\ \ell_s > l \simeq \tau_1^{1/4} M_s^{-1} \sim 2\times 10^4\ \ell_s$$

Large hierarchy

Large volume expansion: $V_F = V_{\rm lead} + \delta V$, $V_{\rm lead} \sim \mathcal{V}^{-3}$ and $\delta V \sim \mathcal{V}^{-3-p}$ with $p > 0$

After T_3-axion minimisation

$$V_{\rm lead} = \frac{8\sqrt{\tau_3}\left(A^2 a_3^2 e^{-2a_3\tau_3} - 2ABa_3b_3e^{-(a_3+b_3)\tau_3} + B^2 b_3^2 e^{-2b_3\tau_3}\right)}{3\mathcal{V}} + \frac{4W_0\tau_3\left(Aa_3e^{-a_3\tau_3} - Bb_3e^{-b_3\tau_3}\right)}{\mathcal{V}^2} + \frac{W_0^2\hat{\xi}}{\mathcal{V}^3}$$

$$\delta V = \left\{\frac{-16\sqrt{\tau_3}}{3\mathcal{V}}\left[A^2a_3^3C_1e^{-2a_3\tau_3} + B^2b_3^3C_2e^{-2b_3\tau_3} - ABa_3b_3e^{-(a_3+b_3)\tau_3}\left(a_3C_1 + b_3C_2\right)\right] + \frac{4W_0}{\mathcal{V}^2}\left[Bb_3C_2\left(b_3\tau_3 + c\tau_1\right)e^{-b_3\tau_3} - Aa_3C_1\left(a_3\tau_3 + c\tau_1\right)e^{-a_3\tau_3}\right]\right\} e^{-c\tau_1}\cos(c\psi_1)$$

Write $a_3 = b_3 + m$ and then integrate out τ_3 ($Z \sim \mathcal{O}(1)$)

$$e^{-b_3\tau_3} = \frac{3W_0\sqrt{\tau_3}}{4Z\mathcal{V}} f_{\rm corr}$$

$$f_{\rm corr} \equiv 1 - \frac{3\epsilon}{1 + m\left(\frac{1}{b_3} - \frac{B_3}{Z}\right)} \qquad \epsilon \equiv \frac{1}{4b_3\tau_3} \ll 1 \quad \text{for} \quad b_3\tau_3 \gg 1$$

NB: single exponential case for $m = 0$: $f_{\rm corr} = 1 - 3\epsilon$

Large hierarchy

Subleading potential for τ_1 ($\beta \sim \mathcal{O}(1)$)

$$\delta V = \frac{\beta}{\mathcal{V}^3} \, (c\tau_1 - p \, b_3 \tau_3) \, e^{-c\tau_1} \cos{(c\psi_1)}$$

Global minimum at

$$c\langle\psi_1\rangle = \pi \text{ and } c\langle\tau_1\rangle = p \, b_3 \langle\tau_3\rangle + 1 \simeq p \, b_3 \langle\tau_3\rangle$$

$$p \equiv -\frac{r_3}{r_1} = \left[\frac{mB(C_1+n)}{r_1} - \frac{(b_3+m)}{b_3}\right](1 - f_{\rm corr})$$

NB: single exponential case for $m = 0$: $|p| = 3\epsilon = 3/(4b_3\tau_3) \ll 1 \quad \Rightarrow \quad c\langle\tau_1\rangle = -3/4 < 0$

BUT p can be positive and large enough in the race-track case:

$$W_0 = B = N_b = 10, \; A = 0.02, \; N_a = 11, \; C_1 = 1, \; n = -0.4506, \; c = 2\pi, \; \xi = 0.7, \; g_s = 0.01$$

$$\Rightarrow \langle\tau_3\rangle \simeq \frac{1}{g_s} = 100, \quad p \simeq 1, \quad \langle\tau_1\rangle \simeq \frac{\langle\tau_3\rangle}{10} = 10, \quad \mathcal{V} \simeq 5.2 \times 10^{28}, \quad M_s \simeq 3 \text{ TeV}$$

Huge anisotropy

$$d \simeq \langle\tau_3\rangle^{1/4}\ell_s \gtrsim l \simeq \langle\tau_1\rangle^{1/4}\ell_s \sim 10^{-17} \text{ mm} \ll L \simeq \langle t_1\rangle^{1/2}\ell_s = \sqrt{\langle\mathcal{V}\rangle/\langle\tau_1\rangle}\,\ell_s \sim 0.01 \text{ mm}$$

Poly-instanton corrections

The action of an $ED3$ can get NP corrections from another $ED3$ wrapping a different 4-cycle [Blumenhagen and Schmidt-Sommerfeld]

$ED3_i$ wrapping Σ_i and $ED3_j$ wrapping Σ_j

The action S_i is given by the gauge kinetic function f_i on fictitious $D7$ wrapping S_i

f_i can get NP corrections from $ED3_j$

$$f_i = \text{Vol}(\Sigma_i) + h(F_i)S + f_i^{1-loop}(U) + A_j(U)\, e^{-2\pi \text{Vol}(\Sigma_j)}$$

$$\Rightarrow S_i \to S_i + e^{-S_j}$$

If both Σ_i and Σ_j are rigid

$$W = W_0 + A_i\, e^{-2\pi\left(T_i + C_j\, e^{-2\pi T_j}\right)} + A_j\, e^{-2\pi\left(T_j + C_i\, e^{-2\pi T_i}\right)}$$

If Σ_j is non-rigid with $h_{2,0}(\Sigma_j) = 1$ and $h_{1,0}(\Sigma_j) = 0 \Rightarrow \Sigma_j = K3$

$$W = W_0 + A_i\, e^{-2\pi\left(T_i + C_j\, e^{-2\pi T_j}\right)}$$

No single instanton contribution to W!

Phenomenological issues

UV completion gives more info about the EFT than in simple models with low gravity scale

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

hierarchy	small			large		
regime	geo	sing (w mix)	sing	geo	sing (w mix)	sing
M_s	1 TeV	1 TeV	1 TeV	3 TeV	3 TeV	3 TeV
M_{6D}	2000 TeV	2000 TeV	2000 TeV	10 TeV	10 TeV	10 TeV
M_{10D}	2 TeV	2 TeV	2 TeV	4 TeV	4 TeV	4 TeV
M_{KK}^{c}	0.5 TeV	0.5 TeV	0.5 TeV	1 TeV	1 TeV	1 TeV
M_{KK}^{10D}	50 MeV	50 MeV	50 MeV	1 TeV	1 TeV	1 TeV
M_{KK}^{6D}	0.3 MeV	0.3 MeV	0.3 MeV	0.01 eV	0.01 eV	0.01 eV
$m_{3/2}$	0.01 eV	0.01 eV	0.01 eV	0.01 eV	0.01 eV	0.01 eV
m_{moduli}	0.01 eV	0.01 eV	0.01 eV	0.01 eV	0.01 eV	0.01 eV
m_2	0.01 eV	0.01 eV	10^{-17} eV	0.01 eV	0.01 eV	10^{-17} eV
m_1	10^{-12} eV	10^{-12} eV	10^{-22} eV	10^{-32} eV	10^{-32} eV	10^{-32} eV

Different KK scale of LH and SH $\leftrightarrow$ difference between models with 2 or more large EDs

SLED-related constraints

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 gravitons

   If $D = 4 + d$, $\sigma \sim \sum_n \sigma_n \propto (V_d E^d)/M_p^2 \propto E^d / M_D^{2+d}$

   For $M_D \sim 1$ TeV $\Rightarrow$ weak-interaction production rates

   Tevatron: $M_D > 1$ TeV for $d = 2$ and $M_D > 0.8$ TeV for $d = 6$

   SLEDs yield more bulk states $\Rightarrow$ more channels for energy loss: $\sigma_{SLED} \sim N \sigma_{LED}$

   When $d = 2$, $\sigma \propto M_{6D}^{-4} \Rightarrow$ constrain $M_{6D}/N^{1/4} \sim 0.3\, M_{6D}$ even if $N \sim 100$
3. Absence of MSSM superpartners for each of the known SM particles

   SUSY is nonlinearly 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!

Astrophysical bounds

Stronger constraints due to new energy-loss channels for stellar systems and supernovae

Typical ambient temperatures: $E \sim T \sim 10$ MeV

- Supernova energy loss: $M_{6D} > 10$ TeV for 2 EDs and $M_{10D} > 10$ GeV for 6 EDs
- Neutron-star cooling: $M_{6D} > 700$ TeV and $M_{10D} > 200$ GeV

  BUT model-dependent: evaded if the KK modes decay mainly into invisible *dof*

  $\Rightarrow$ It is crucial to know precisely how KK modes decay

  NB: Compact CYs have no continuous isometries $\Rightarrow$ KK modes can decay

  1. KK decays into SM fields: $\Gamma_{SM} \sim M_{KK}^3/M_p^2$,
  2. KK decays into effective 6D states: $\Gamma_{6D} \sim M_{KK}^5/M_{6D}^4$
  3. KK decays into 10D states: $\Gamma_{10D} \sim M_{KK}^9/M_{10D}^8$

  $\Rightarrow$ Relative rates: $\Gamma_{SM} : \Gamma_{6D} : \Gamma_{10D} \sim \frac{M_{KK}^3}{L^2 l^4} : \frac{M_{KK}^5}{l^4} : M_{KK}^9$

  $\Rightarrow$ Decays into 6D and 10D states dominate by a factor of $l^2/L^2 \ll 1$ if $M_{KK} \sim 1/l$

  For $M_{KK} \sim 10$ MeV, $L^{-1} \sim 0.01$ eV and $l^{-1} \sim 1$ TeV

  $\Rightarrow \Gamma_{SM} : \Gamma_{6D} \sim 10^{-16} : 100$ decays to 10D states are not energetically allowed!

Cosmology

Non-standard cosmology if the SM brane cools too quickly through evaporation into the bulk

LH with $M_{6D} \sim 10$ TeV: this occurs for $T > 100$ MeV (SH with $M_{10D} \sim 1$ TeV: it happens for $T > 10$ GeV) $\Rightarrow$ No problem since $T > T_{BBN} \sim 1$ MeV

Relics of bulk KK states are dangerous since they behave as matter: $\rho \propto a^{-3}$

- They can overclose the Universe if T is just a few MeV for LH or $T > 300$ MeV for SH
- They can create distortions of the MeV diffuse γ-ray background if they decay into γ's

$\Rightarrow$ Need to suppress the abundance of KK modes

- Decay to hidden *dof* as is required from the neutron star bounds
- Reheating temperatures not too far above T_{BBN}

NB: Good dark-matter candidates: lightest moduli like volume mode and K3 fibre

Cosmological constant

The LARGE Volume potential scales as

$$V_{LVS} \sim V(\mathcal{V}, \tau_3) + V(\tau_1) \sim \frac{M_p^4}{\mathcal{V}^3} + \frac{M_p^4}{\mathcal{V}^4}$$

If the AdS minimum is lifted to Minkowski via a natural cancellation at $\mathcal{O}(\mathcal{V}^{-3})$ [for example via NP effects at the quiver locus – `work in progress`]

$$\Rightarrow \qquad V \sim \frac{M_p^4}{\mathcal{V}^4} \sim \Lambda_{cc}^4$$

Perfect numerology for TeV-scale strings and right order of magnitude of the CC!

$$\mathcal{V} \sim 10^{30} \quad \Rightarrow \quad M_s \sim \frac{M_p}{\mathcal{V}^{1/2}} \sim 1\,\text{TeV} \quad \text{and} \quad V \sim \frac{M_p^4}{\mathcal{V}^4} \sim 10^{-120} M_p^4$$

$$\Lambda_{cc} \sim \frac{M_s^2}{M_p} \quad \text{just a coincidence?}$$

D-terms: isotropic case

Total potential

$$V = V_F + V_D = \frac{p_1}{\mathcal{V}^{2/3}}\left(\sum_j c_{bj}\frac{|\phi_j|^2}{\mathcal{V}^{4/9}} - \frac{p_2}{\mathcal{V}^{2/3}}\right)^2 + \sum_j k_j \frac{|\phi_j|^2}{\mathcal{V}^{22/9}} + V_F(T)$$

- If all the $U(1)$-charges have an opposite sign w.r.t. ξ

$$V = \frac{p}{\mathcal{V}^2} + V_F(T), \quad \text{with} \quad p = p_1 p_2^2 = \frac{9 f_b^2}{2\pi}$$

  Volume run-away since $V_F(T) \simeq \mathcal{O}(\mathcal{V}^{-3})$

- If one $U(1)$-charge has the same sign as ξ

$$V = V_F + V_D = \frac{p_1}{\mathcal{V}^{2/3}}\left(c_b|\phi_c|^2 - \xi\right)^2 + k\frac{|\phi_c|^2}{\mathcal{V}^2} + V_F(T), \quad \text{with} \quad \xi = \frac{p_2}{\mathcal{V}^{2/3}}$$

  The minimum for the matter field is at $\langle|\phi_c|^2\rangle = \frac{\xi}{c_b} - \frac{k}{2c_b^2 p_1 \mathcal{V}} \simeq \frac{\xi}{c_b}$

  Integrate out $\phi_c \rightarrow$ Still a run-away for $\mathcal{V}$!

$$V \simeq \frac{k}{c_b}\frac{\xi}{\mathcal{V}^2} + V_F(T) = \frac{p}{\mathcal{V}^{8/3}} + V_F(T), \quad \text{with} \quad p = \frac{9 k f_b}{6^{1/3}\pi c_b}$$

D-terms: anisotropic case

Total potential for a $D7$-brane wrapping D_1 with a non-zero gauge flux on t_2

$$V = V_F + V_D = \frac{\pi}{\tau_1}\left(\sum_j c_{1j}\tau_1^{1/3}\frac{|\phi_j|^2}{\mathcal{V}^{2/3}} - p\frac{\sqrt{\tau_1}}{\mathcal{V}}\right)^2 + \sum_j k_j \tau_1^{1/3}\frac{|\phi_j|^2}{\mathcal{V}^{8/3}} + V_F(T)$$

- If the $U(1)$-charges have all an opposite sign w.r.t. ξ

  $V = \pi p^2 \mathcal{V}^{-2} + V_F(T) \Rightarrow$ Run-away for $\mathcal{V}$

- If one $U(1)$-charge has the same sign as ξ

$$V = V_F + V_D = \frac{\pi}{\tau_1}\left(c_1|\phi_c|^2 - \xi_1\right)^2 + k\frac{|\phi_c|^2}{\mathcal{V}^2} + V_F(T), \quad \text{with} \quad \xi_1 = p\frac{\sqrt{\tau_1}}{\mathcal{V}}$$

Minimum for the matter field: $\langle|\phi_c|^2\rangle = \frac{\xi_1}{c_1} - \frac{k\,\tau_1}{2\pi c_1^2\mathcal{V}^2} \simeq \frac{\xi_1}{c_1} \rightarrow$ integrate out ϕ_c

$$V \simeq \frac{k}{c_1}\frac{\xi_1}{\mathcal{V}^2} + V_F(T) = \lambda\frac{\sqrt{\tau_1}}{\mathcal{V}^3} + V_F(T), \quad \text{with} \quad \lambda = \frac{k f_2}{2\pi c_1}$$

Fix τ_1 via loops and get $V = \delta\frac{W_0^2}{\mathcal{V}^{14/5}}$: good up-lifting if $\delta \sim \mathcal{V}^{-1/5}$ by fine-tuning loops

Model-dependent assumptions: no large Higgs mass of order $\langle\varphi_c\rangle \sim \sqrt{\xi_1} \sim M_s$

Yukawa couplings for fermions to evade the bounds on millicharged particles

Vanishing FI-terms with finite volume

Relation between $U(1)$-charges and chiral intersections

$$I_{D7i-D7j} = \int_{CY} \hat{D}_i \wedge \hat{D}_j \wedge (F_i - F_j)$$
$$= \left(f_{(i)}^k - f_{(j)}^k \right) k_{ijk} = q_{ij} - q_{ji}$$

Rewrite the FI terms as

$$\xi_i = \frac{1}{\mathcal{V}} \left[\sum_{j=1}^{n} \left(\frac{I_{D7i-D7j} + I_{D7i-D7j'}}{2} \right) t_j + \sum_{j=n+1}^{h_{1,1}} q_{ij} t_j \right]$$

First sum over the 2-cycles dual to the wrapped 4-cycles; last over the unwrapped ones

Require no chiral intersections between the $D7$-branes and their orientifold images

$$\Rightarrow \qquad \xi_i = \frac{1}{\mathcal{V}} \sum_{j=n+1}^{h_{1,1}} q_{ij} t_j$$

Can set $\xi = 0$ and have still massive $\gamma' \Rightarrow t_j \to 0$

More complicated CYs dynamically reduced to our previous cases!

Anisotropic compactifications

- **D7 wrapping** τ_2
  - Turn on a gauge flux only on t_1 (with $\chi \simeq 0.5 \cdot 10^{-2} \tau_2^{-1/2}$)

    $$m_{\gamma'} \simeq f_1 \, 10^{26} \chi^3 \text{ GeV} \qquad \text{like the isotropic case!}$$

  - Turn on a generic flux: get an additional parameter

    $$m_{\gamma'} \simeq 1.5 \cdot 10^{21} f_2 \frac{\chi}{\tau_1} \text{ GeV}$$

    χ and τ_1 not independent: anisotropic limit in terms of χ gives

    $$m_{\gamma'} \gg 6 \cdot 10^{25} f_2 \chi^3 \text{ GeV} \qquad \text{Not phenomenologically interesting!}$$

- **D7 wrapping** τ_1: Turn on a gauge flux on t_2 (with $\chi \simeq 0.5 \cdot 10^{-2} \tau_1^{-1/2}$)

  $$m_{\gamma'} \simeq 2.2 \cdot 10^{21} f_2 \frac{\chi}{\tau_2} \text{ GeV}$$

  Decouple χ from $m_{\gamma'}$ since the anisotropic limit gives just a upper bound

  $$m_{\gamma'} \ll 9 \cdot 10^{25} f_2 \chi^3 \text{ GeV} \qquad \text{Most promising example!}$$

Stabilisation of the extra dimensions

Fix the moduli as in the SH case: τ_1 fixed via g_s corrections to K

$$\langle\tau_3\rangle \simeq g_s^{-1} \qquad \langle\mathcal{V}\rangle \simeq e^{-a_3\langle\tau_3\rangle} \qquad \langle\tau_1\rangle = \kappa\,\langle\tau_2\rangle$$

with

$$\kappa = \frac{\left(g_s \mathcal{C}_1^{KK}\right)^2}{\mathcal{C}_{12}^W}$$

BUT need now to consider D-terms

$$V_D = \frac{g_i^2}{2}\left(\sum_j c_{ij}\varphi_j \frac{\partial K}{\partial \varphi_j} - \xi_i\right)^2 = \frac{\pi}{(\tau_i - g_s f^j q_{ij}/2)}\left(\sum_j c_{ij}\varphi_j \frac{\partial K}{\partial \varphi_j} + \frac{q_{ij}}{4\pi}\frac{\partial K}{\partial \tau_j}\right)^2$$

Total potential

$$V = V_D + V_F(\mathrm{matter}) + V_F(T)$$

where

$$V_F(\mathrm{matter}) \sim m_0^2(T)\varphi^2$$

D-term potential

- $D = 0$
  - No matter charged under the hidden $U(1)$
    - Isotropic case: $\xi \sim \mathcal{V}^{-2/3} = 0 \Leftrightarrow \mathcal{V} \to \infty$
    - Anisotropic case: $\xi \sim \sqrt{\tau_1}/\mathcal{V} = 0 \Leftrightarrow \mathcal{V} \to \infty$ or $\tau_1 \to 0$
  - With charged matter
    - If all $U(1)$-charges have an opposite sign w.r.t. $\xi \Rightarrow \langle|\varphi_i|\rangle = 0 \; \forall i$
    - If one $U(1)$-charge has the same sign as $\xi \Rightarrow \xi \sim \langle|\varphi|\rangle^2 = 0$ due to $V_F(\mathrm{matter})$
- $D \neq 0$
  - No matter charged under the hidden $U(1)$

    Both cases: $V_D \sim \mathcal{V}^{-2}$ while $V_F(T) \sim \mathcal{V}^{-3} \Rightarrow \mathcal{V} \to \infty$ no viable tuning
  - With charged matter
    - If all $U(1)$-charges have an opposite sign w.r.t. $\xi \Rightarrow \langle|\varphi_i|\rangle = 0 \; \forall i$
    - If one $U(1)$-charge has the same sign as $\xi \Rightarrow \xi \sim \langle|\varphi|\rangle^2 \neq 0$

      Partial cancellation of D-terms – Leading potential given by $V_F(\mathrm{matter})$
      - Isotropic case: $V \sim \mathcal{V}^{-8/3} \Rightarrow \mathcal{V} \to \infty$ no viable tuning
      - Anisotropic case: $V \sim \sqrt{\tau_1}/\mathcal{V}^3 \Rightarrow$ viable up-lifting term balancing against loops

NB: Solution for $\xi = 0$: dynamically reduce more complicated topologies to both our cases