Infinite number of MSSMs from heterotic line bundles?

Patrick K. S. Vaudrevange

TUM Institute for Advanced Study Garching
and
Universe Cluster Munich

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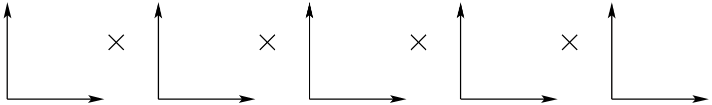
String Phenomenology 2015 Madrid

Based on:

- Stefan Groot Nibbelink, Orestis Loukas, Fabian Ruehle, P.V.: arXiv:1506.00879



- Heterotic string theory: $\mathrm{E}_8 \times \mathrm{E}_8$ gauge group in 10D
- Aim: connection to observable world
- Compactify six spatial dimensions on a compact space (e.g. 6-torus)
- Orbifolds: CFT & computability
- Calabi-Yaus with line bundle gauge background

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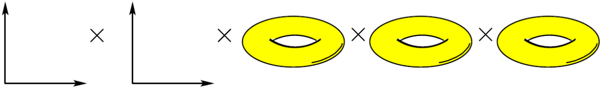

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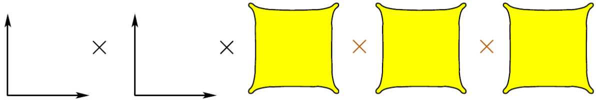

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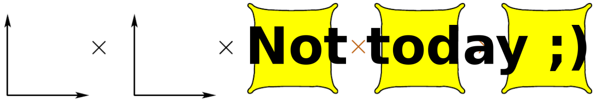

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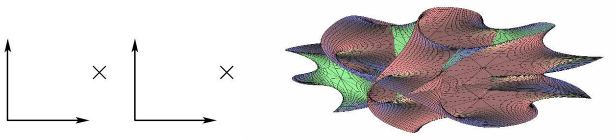

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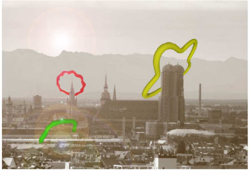
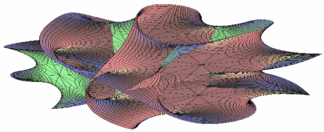
 $\times$ 

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Take home messages of this talk

- Starting point: CY with line bundle gauge background
- Find solutions to: flux quantization and Bianchi identity
  $\Rightarrow$ infinite sets of solutions
  $\Rightarrow$ infinite sets of inequivalent matter spectra
- However: 4D EFT critical
  - Gauge couplings stay perturbative (OK)
  - VEVs are needed to cancel D-terms inside the Kähler cone (problematic?)
    $\Rightarrow$ non-Abelian vector bundle (OK?)
  - F-terms cancel (OK)
- To do: construct non-Abelian vector bundle explicitly
  $\Rightarrow$ Stable?

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Complete Intersection Calabi-Yau: CICY 7862

Candelas, Dale, Lutken, Schimmrigk - 1987

- CY X described as hypersurface in product of projective spaces
- Hodge numbers $h_{11} = 4$ and $h_{21} = 68$
  $\Rightarrow$ four divisors: D_i, $i = 1, \ldots, h_{11} = 4$
- Non-vanishing triple intersection numbers and second Chern classes:

$$\kappa_{ijk} = \int_X D_i D_j D_k = 2 \quad \text{and} \quad c_{2i} = \int_{D_i} c_2 = 24$$

for $i \neq j \neq k \neq i$ from 1 to $h_{11} = 4$

Line bundle gauge background

- CICY 7862 X with $\mathrm{S}(\mathrm{U}(1)^5) = \mathrm{U}(1)^4$ gauge background.
- Specified by five vectors $k_{(a)} = (k^1_{(a)}, \ldots, k^4_{(a)}) \in \mathbb{Z}^4$, $a = 1, \ldots, 5$:

$$\mathcal{V} = \bigoplus_{a=1}^{5} \mathcal{O}_X\left(k^1_{(a)}, \ldots, k^4_{(a)}\right) \quad \text{with} \quad \sum_{a=1}^{5} k_{(a)} = 0$$

- Alternative description:

$$\frac{\mathcal{F}}{2\pi} = D_i\, H_i \ , \quad H_i = V_i^I\, H_I \quad \text{where}$$

  - D_i with $i = 1, \ldots, h_{11} = 4$: two-forms, Poincaré-dual to the divisors
  - H_I with $I = 1, \ldots, 16$: Cartan generators of $\mathrm{E}_8 \times \mathrm{E}_8$
  - V_i with $i = 1, \ldots, h_{11} = 4$: 16-component line bundle vectors

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Line bundle gauge background

- Write line bundle vector $V_i = (V_i', V_i'')$ for observable and hidden E_8
- Given the five vectors $k_{(a)}$ the corresponding line bundle vectors in the observable E_8 are

$$V_i' = (a_i^5, b_i, c_i, d_i)$$

(Exponent 5 indicates 5-times repetition)

- Using

$$\begin{pmatrix} a_i \\ b_i \\ c_i \\ d_i \end{pmatrix} = -\frac{1}{2} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & 1 \\ -1 & 1 & -1 & 1 \\ -1 & -1 & 1 & 1 \end{pmatrix} \begin{pmatrix} k^i_{(1)} \\ k^i_{(2)} \\ k^i_{(3)} \\ k^i_{(4)} \end{pmatrix}$$

for $i = 1, \ldots, h_{11}$

Line bundle gauge background

- Choose Model number 2, identifier $\{7862, 4, 5\}$

$$\left(k^i{}_{(a)}\right) = \begin{pmatrix} 1 & 1 & 0 & -1 & -1 \\ -1 & -2 & 0 & 2 & 1 \\ -1 & 0 & -1 & 2 & 0 \\ 1 & 1 & 1 & -3 & 0 \end{pmatrix}$$

Anderson, Gray, Lukas, Palti - 2011

- Corresponding line bundle vectors:

$$\begin{aligned} V_1 &= \left(-\frac{1}{2}^5, \frac{1}{2}, \frac{1}{2}, \frac{3}{2}\right)(0^8) \\ V_2 &= \left(\frac{1}{2}^5, -\frac{3}{2}, -\frac{1}{2}, -\frac{5}{2}\right)(0^8) \\ V_3 &= \left(\,0^5, -1, -2, -1\,\right)(0^8) \\ V_4 &= \left(\,0^5,\ 2,\ 2,\ 2\,\right)(0^8) \end{aligned}$$

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Line bundle gauge background

- Integrated BIs of the Kalb-Ramond field in the presence of NS5 branes:

$$\begin{aligned} N_i &= N_i' + N_i'' \\ N_i' &= c_{2i} + \kappa_{ijk}\, V_j' \cdot V_k' \\ N_i'' &= c_{2i} + \kappa_{ijk}\, V_j'' \cdot V_k'' \end{aligned}$$

  for all divisors D_i , $i = 1, \ldots, h_{11} = 4$.
- BIs $\Rightarrow$ anomaly cancellation in the 4D EFT
- Unbroken SUSY requires $N_i \geq 0$
- We will choose V_i'' such that $N_i = 0$, i.e. $N_i'' = -N_i'$
- Chiral part of the 4D matter spectrum: multiplicity operator:

$$\mathcal{N} = \frac{1}{6}\,\kappa_{ijk}\, H_i H_j H_k + \frac{1}{12} c_{2i}\, H_i$$

  evaluated on each root p of $\mathrm{E}_8 \times \mathrm{E}_8$ using $H_i(p) = V_i \cdot p$ (and checked with cohomCalg) Blumenhagen, Jurke, Rahn, Roschy - 2010

Infinite set of MSSM-like models?

- BIs with $N_i = 0$ for CICY 7862:

$$24 + \sum_{i \neq j = 1}^{4} V_i \cdot V_j = 0$$

- Allows for infinite number of solutions, e.g.

$$\begin{aligned}
V_1 &= \left(-\frac{1}{2}^5, \ \frac{1}{2}, \ \frac{1}{2}, \ \frac{3}{2}\right)\left(\ 1^4, \ 0, -2, \ 0, \ 0\right) \\
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Infinite set of MSSM-like models?

- Gauge group $SU(5) \times SU(4) \times U(1)^9$
- Chiral spectrum (omitting U(1) charges):

Observable E_8		Hidden E_8	
Mult.	Rep.	Mult.	Rep.
12	$(\overline{\mathbf{5}}, \mathbf{1})$	$12k + 8$	$(\mathbf{1}, \mathbf{4})$
12	$(\mathbf{10}, \mathbf{1})$	$12k + 8$	$(\mathbf{1}, \overline{\mathbf{4}})$
		$4k$	$(\mathbf{1}, \mathbf{6})$
60	$(\mathbf{1}, \mathbf{1})$	$80k + 8$	$(\mathbf{1}, \mathbf{1})$

- Pure, mixed (non-)Abelian gauge and gravitational anomalies cancel for all k via generalized Green-Schwarz mechanism

Blumenhagen, Honecker, Weigand - 2005

- Order 4 symmetry of $X \Rightarrow$ 3 generation MSSM

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Infinite set of MSSM-like models?

- One-loop corrected DUY equations with VEVs: $D_{(x)} = 0$

$$\frac{1}{\ell_s^6}\sum_i V_i'\cdot t_{(x)}'\left(\mathrm{Vol}(D_i) - \frac{N_i'}{4}\,\frac{e^{2\varphi}}{8\pi^2\ell_s^2}\,\mathrm{Vol}(X)\right) + \sum q_x'\left|\langle s'\rangle\right|^2 = 0$$

for x-th U(1) such that $q_x' = t_{(x)}' \cdot p'$ for state with weight p' (for the hidden sector: interchange $'$ and $''$)

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- When $\langle s'\rangle = \langle s''\rangle = 0$ only solution:

$$V_D = g_{(x)}^2 D_{(x)}^2 \quad\Rightarrow\quad g_{(x)} \to 0 \quad \text{inside the Kähler cone}$$

$\Rightarrow$ solution: $g_{(x)} \neq 0$ and VEVs, i.e.

1. Choose $\mathrm{Vol}(D_i) = 6\,a^2 + \frac{N_i''}{4}\,\frac{e^{2\varphi}}{8\pi^2\ell_s^2}\,\mathrm{Vol}(X)$ $\quad (N_i'' = -N_i')$
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Infinite set of MSSM-like models?

- One-loop corrected DUY equations with VEVs: $D_{(x)} = 0$

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for x-th U(1) such that $q_x' = t_{(x)}' \cdot p'$ for state with weight p' (for the hidden sector: interchange $'$ and $''$)

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- When $\langle s' \rangle = \langle s'' \rangle = 0$ only solution:

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- Find solutions to: flux quantization and Bianchi identity
  $\Rightarrow$ infinite sets of solutions
  $\Rightarrow$ infinite sets of inequivalent matter spectra
- However: 4D EFT critical
  - Gauge couplings stay perturbative (OK)
  - VEVs are needed to cancel D-terms inside the Kähler cone (problematic?)
    $\Rightarrow$ non-Abelian vector bundle (OK?)
  - F-terms cancel (OK)
- To do: construct non-Abelian vector bundle explicitly
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