Splitting $SO(10)$ with a bulk flux

or "How to use one tool for four jobs".

www.hyperstake.com

Based on [1506.05771 & 1507.06819]

together with W. Buchmüller, M. Dierigl and F. Rühle

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HELMHOLTZ ASSOCIATION

DESY

> **Introduction**

> **Wavefunctions in a flux background**

> **An explicit $SO(10)$ model**

> **Phenomenology**

Puzzles and a solution?

Puzzles

- *Matter fields* come in *three complete GUT multiplets*, whereas *Gauge and Higgs* fields come in single incomplete representations.

  "Split" (GUT) **multiplets in only part of the theory**

- *No hints* for SUSY at the LHC or in flavor physics

  "Split" Supersymmetry (or rather a variant thereof)**?**
  i.e. heavy sfermions, light gauginos/higgsinos

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Is flux a solution?

> Introduce an additional $U(1)_A$ with bulk flux in extra dimensions.
>> **High scale susy breaking** in the charged sector.
>> Charged fields **circumvent gauge symmetry breaking** by orbifolding.

Outline

Equations of motion in a flux background on T^2

Scalars

$$\Delta_2 \phi = g^{mn} D_m D_n \phi = m^2 \phi, \quad m^2 = 4\pi N \left(n + \frac{1}{2} \right)$$

> Charged scalars **do not** have a zero mode.
> $\Rightarrow$ Obtain a mass $\mathcal{O}(1/R) \sim M_{\mathrm{GUT}}$.

Fermions

$$\left(\Gamma^m D_m \right)^2 \psi = m^2 \psi, \quad m^2 = 4\pi N \left(n + \frac{1}{2} \mp \frac{1}{2} \right)$$

> Charged fermions **can** have a zero mode, depending on their chirality.

[Bachas '95; Braun, Hebecker, Trapletti '07]

Zero-modes of the internal space Dirac equation

Fermion zero modes on T^2

- have a **non-trivial profile** across the internal space and are
- **M-fold degenerate**, if M is the number of (torus) flux quanta.

$$\psi = \mathcal{N} e^{iq\alpha_1(y_1+\tau y_2)-i\pi M\tau y_2^2}\ \theta\begin{bmatrix} j/M \\ -\frac{q}{2\pi}(\alpha_1\tau-\alpha_2)\end{bmatrix}(M(y_1+\tau y_2),-M\tau)$$

[Cremades, Ibanez, Marchesano '04]

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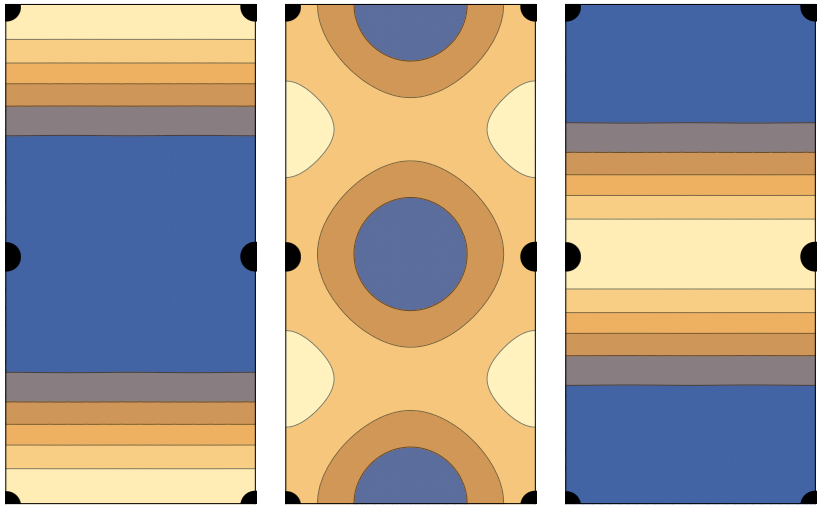
[Cremades, Ibanez, Marchesano '04]

Orbifold: assemble even/odd combinations from these wavefunctions

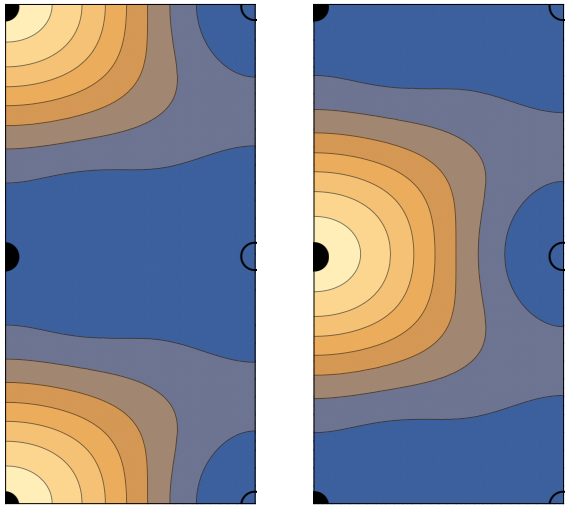
- Flux quantization changes $\Rightarrow$ # of "orbifold quanta" $N = M/2$
- Without Wilson lines: $N+1$ even, $N-1$ odd combinations
  With Wilson lines: N even, N odd
- **Vanish at some fixed points** as expected
  $\rightarrow$ localized flux picture for Wilson lines

Fancy pictures (of Wavefunctions on T^2/Z_2)

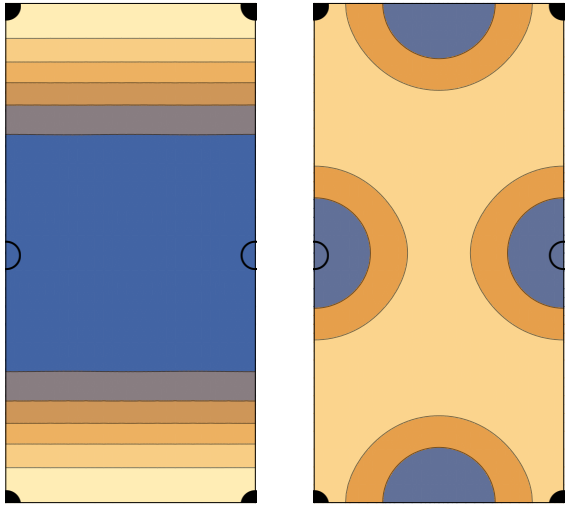
$N = 2$, $(\alpha_1, \alpha_2) = (0, 0)$



$(\alpha_1, \alpha_2) = (1, 0)$



$(\alpha_1, \alpha_2) = (0, 1)$



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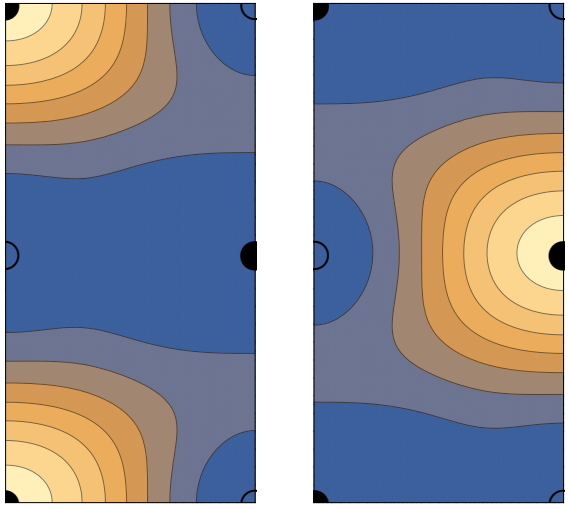

Evading GUT breaking with a flux

Wilson lines make wavefunctions vanish at some fixed points

- uncharged field: zero mode **constant** across internal space
  $\Rightarrow$ projected out
- charged field: zero mode **profile adapts** to Wilson line configuration
  $\Rightarrow$ **not** projected out

In addition, charged fields exhibit

- GUT-scale susy breaking and
- N-fold degeneracy

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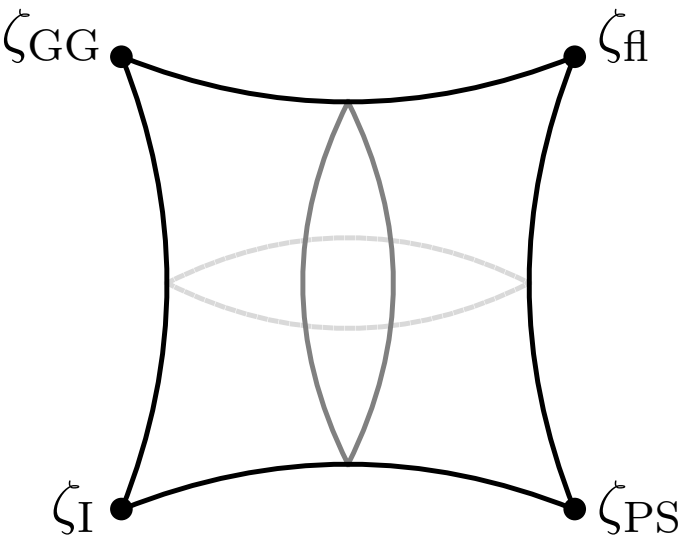
Charged fields are interesting candidates for matter fields in orbifold GUTs!

Outline

Ingredients

Our model contains

- 6d gauge group $SO(10) \times U(1)_A$,
- Wilson line breaking of $SO(10)$,
- $U(1)_A$ flux f with **3 flux quanta** and
- the $\mathbf{SO(10)}$ **anomaly-free** bulk fields $6 \times \mathbf{10}$, $2 \times \mathbf{16}$ and $2 \times \overline{\mathbf{16}}$, only one $\mathbf{16}$-plet ψ charged under $U(1)_A$.



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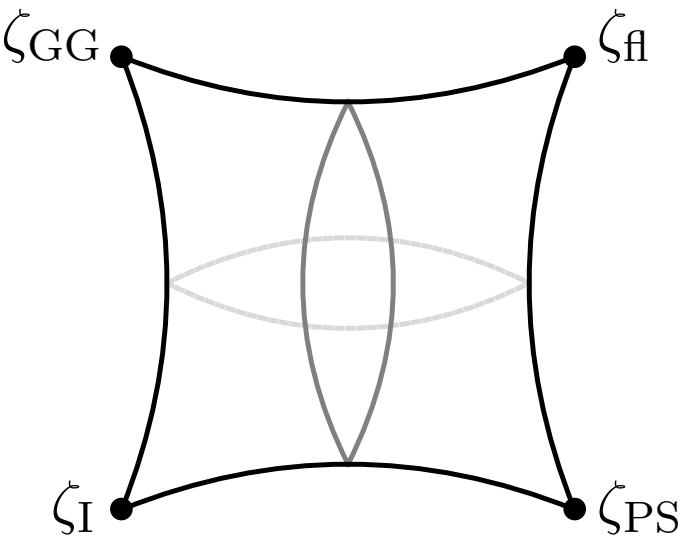

This gives

- 4d gauge group $\mathcal{G}_{\mathrm{SM}} \times U(1)_X$,
- **3 full generations** of chiral matter with
- large susy breaking in the matter sector at tree-level.
- Mixed anomalies can be cancelled with a Green-Schwarz mechanism.

Yukawa couplings

Fermion zero modes

	W_{GG}	W_{PS}
q_i	0	1
u_i^c	1	1
d_i^c	1	0
l_i	0	0
e_i^c	1	1
ν_i^c	1	0

- Fields feel different Wilson lines
- Uncharged bulk field:
  only component with $W_{\mathrm{GG}} = W_{\mathrm{PS}} = 0$ in 4d
- Charged bulk field:
  all fields 3 times + additional mode ($W_i = 0$)

$\Rightarrow$ **3 generations** of SM matter + vector-like exotics

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Yukawa couplings

- Yukawa couplings from fixed point superpotential
  $\Rightarrow$ proportional to field values at fixed points
- Higgs doublets $H_u \subset H_1$, $H_d \subset H_2$
- Mixing with vector-like 4th gen. possible for field with $W_i = 0$

Outline

Low-energy effective theory

Disclaimer: Work in progress; sketchy results / conjectures ahead!

Low-energy limit

We recover the Standard Model with 2 Higgs doublets.

- This is different from vanilla Split SUSY.
- Gauginos and/or Higgsinos can be light.
- Additional $U(1)_X$ broken by VEV of neutrino-like states from $\mathbf{16}, \overline{\mathbf{16}}$.
- Further: axion-like particle from 6d 2-form / GS mechanism

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Supersymmetry breaking

- Large masses $\mathcal{O}(M_{\mathrm{GUT}})$ for sfermions from flux
- Gravitino mass expected to be $\mathcal{O}(10^{12}\,\mathrm{GeV})$
- Gauginos/Higgsinos massless at tree level
  $\Rightarrow$ Gravity/Anomaly mediation; dependence on technical details

Masses and scales

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Fermion masses

- Yukawa couplings from $SO(10)$-brane
  $\Rightarrow$ extremely hierarchical Yukawas at the GUT scale
  $\Rightarrow$ RGE evolution / higher-order corrections
- Neutrino-like fields from uncharged $\mathbf{16}$ break $B - L$
  $\Rightarrow$ See-saw mechanism for neutrino masses possible
- Vector-like exotics can be given a large mass

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Moduli stabilization

- Volume and Dilaton can be stabilized using the flux
  (+ hidden sector gaugino condensation) [Braun, Hebecker, Trapletti '07]
- Spectra of uncharged fields depend on shape modulus
  $\Rightarrow$ Casimir energy stabilization [Buchmüller, Catena, Schmidt-Hoberg '09]

Wrap-up

We have...

- paired $SO(10)$ with a bulk flux to give an interesting model.
- cancelled all Anomalies.
- created 3 generations (I) and (high-scale) susy breaking (II).
- explained why a full matter $\mathbf{16}$ is present at low energies (III).
- moduli stabilization (IV).

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We plan to...

- implement ~~SUSY~~ mediation. $\Rightarrow$ Gauginos/Higgsinos at the LHC?
- work out the weak-scale Yukawa couplings.
- expand this setup to more general internal spaces.
- find an embedding into String Theory.