

Title: The Potential Fate of Local Model Building

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Abstract: In recent years there has been a lot of interest in F-Theory GUTs, mostly considering local models. In this talk I first consider an $SU(5)$ GUT locally at the "point of E_8 ". The requirements of proton stability and reasonable flavour structure single out exactly two models. However, both models cannot be embedded in a semilocal construction (via the spectral cover approach). This casts doubts on the predictivity of local models.

Motivation and Outline

- F-Theory Model Building: Generalisation of type IIB intersecting branes
- Usually, consider local models: Focus on brane stack or points within the stack and decouple bulk of the compactification manifold
- Advantage: Simple, physics basically fixed by symmetry
- Obvious question: Existence of global completion

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- Advantage: Simple, physics basically fixed by symmetry
- Obvious question: Existence of global completion
- GUT models need to address proton stability
- Dimension-four proton decay: Forbidden by matter parity or variants – should be defined locally
- Dimension-five proton decay: Use zero mode assignment, i.e. additional $U(1)$ symmetries present in the setup

Contents

- 1 F-Theory GUT Model Building
- 2 Local $SU(5)$ GUTs in F-Theory
- 3 Matter Parity and Proton Stability in Local Models
- 4 Semilocal Embedding
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String Phenomenology

- ① Find realistic particle physics models in string theory:
 - Gauge group (standard model or GUT)
 - Matter content (chiral spectrum, doublet-triplet splitting, absence of light exotics)
 - Proton stability
 - Fermion masses and mixings
 - Spontaneously broken $\mathcal{N} = 1$ SUSY in four dimensions
- ② Look for imprints of string theory in low-energy physics:
 - Mediation schemes, patterns of soft masses
 - Exotics below GUT/Planck scale
 - Thresholds, gauge coupling unification

GUTs and Strings

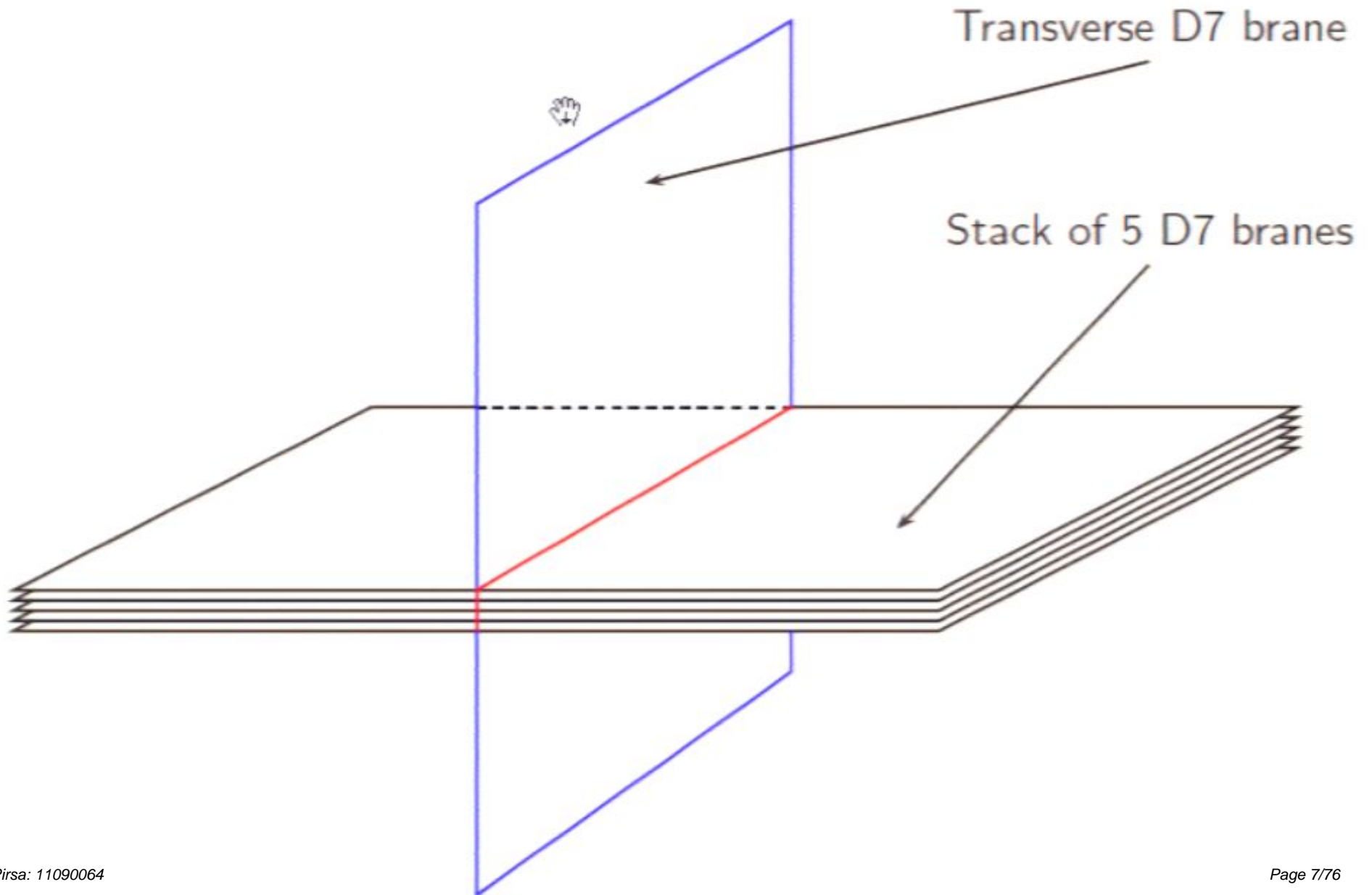
Promising paths:

- $E_8 \times E_8$ heterotic string on orbifolds or smooth Calabi–Yaus
 - Global models, i.e. full compactification space is specified
 - Gauge fields live in bulk, matter in bulk or on lower-dimensional subspaces
- Type II theories with intersecting branes \rightsquigarrow F-theory
 - Mostly local models, i.e. focus on branes and “decouple” bulk
 - Gauge fields on branes, matter on intersections of branes

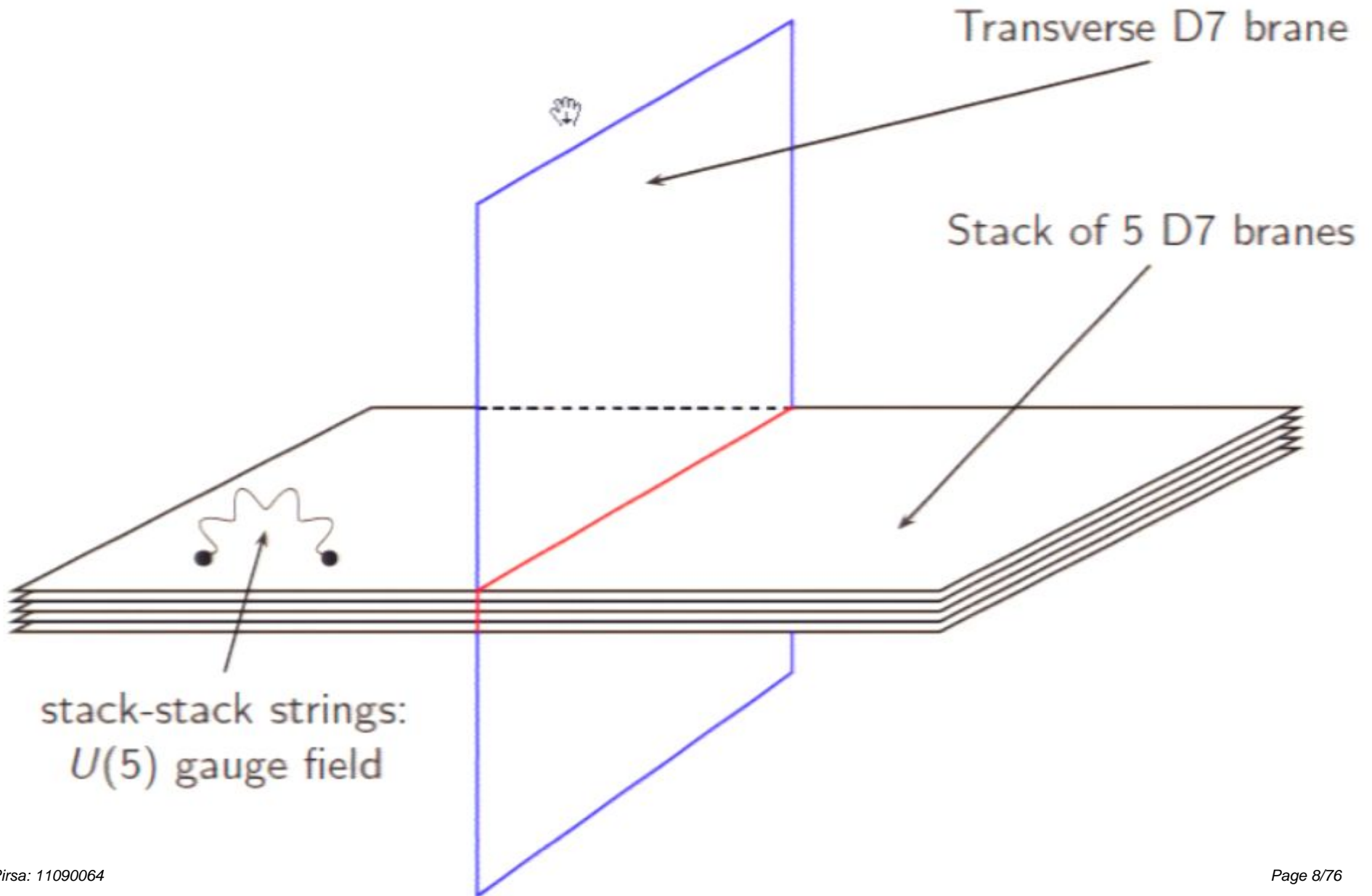
General features:

- Exceptional symmetry groups (though not as gauge groups in four dimensions)
- Nontrivial pattern of gauge and matter fields localised on different subspaces of compactification space

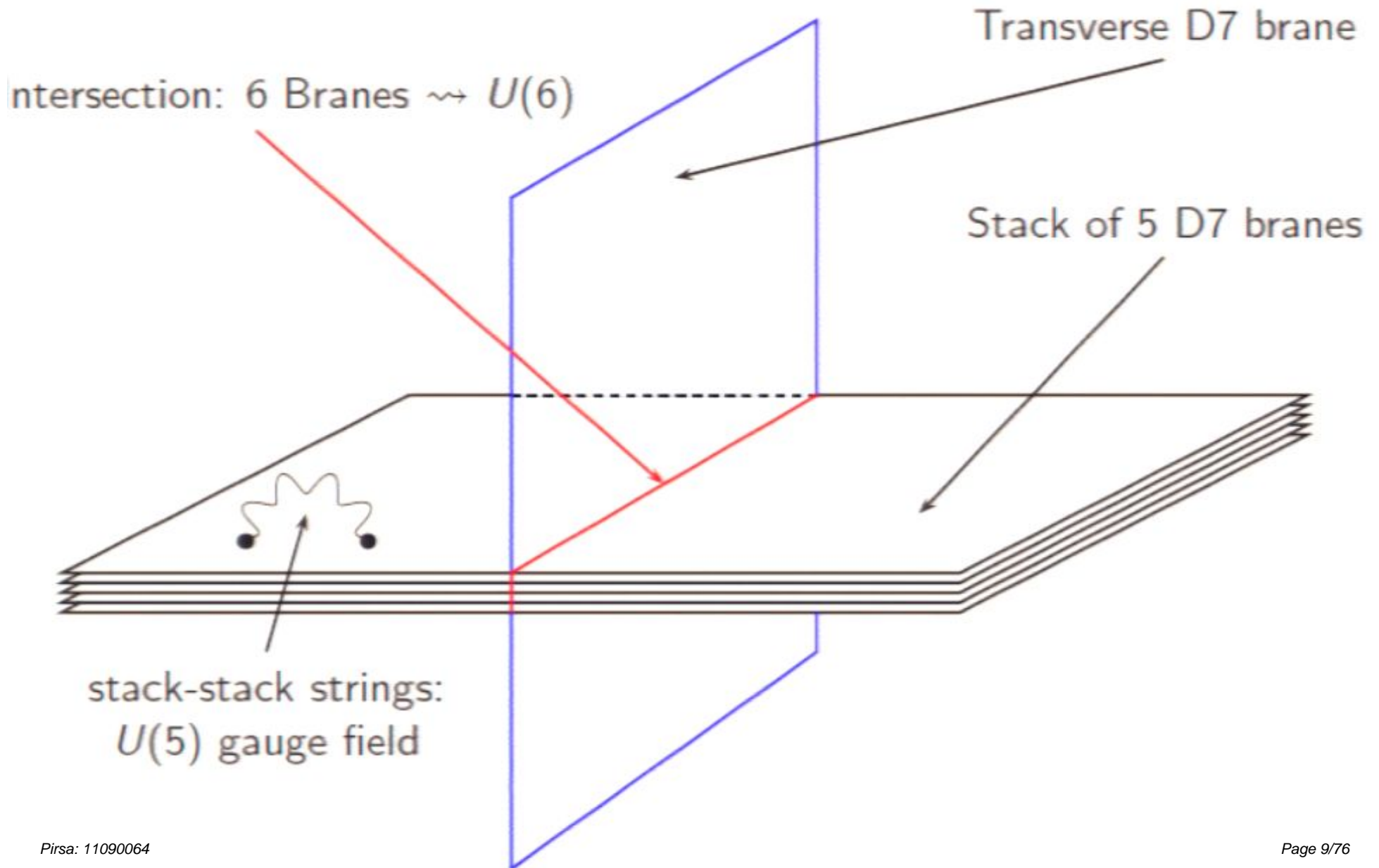
Cartoon: Intersecting Branes in Perturbative Type IIB



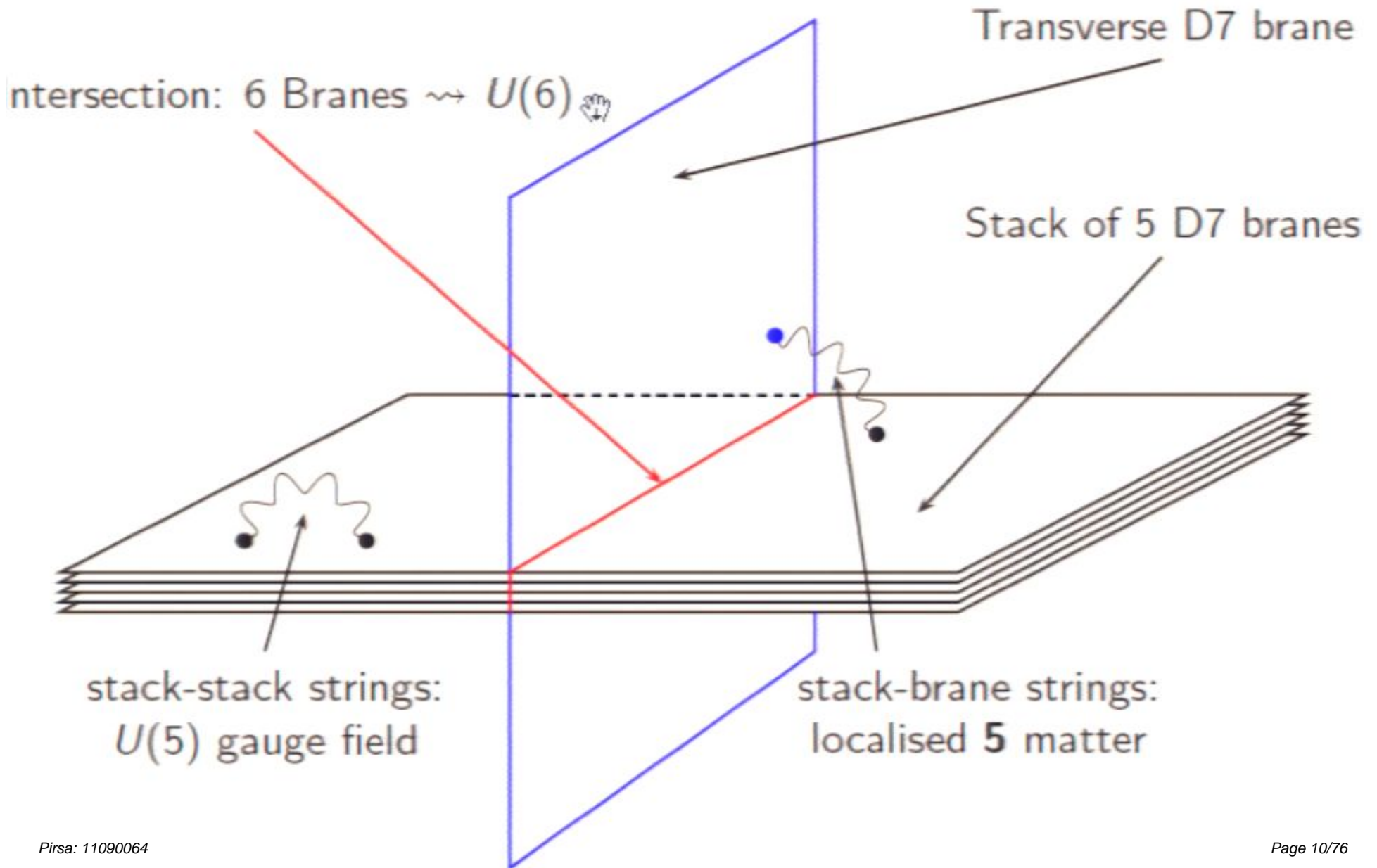
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Intersecting Branes

- Matter localised at intersection (“matter curve”) where symmetry is enhanced – representations can be inferred from decomposition of adjoint of higher group: [Katz, Vafa]

$$G \longrightarrow G_1 \times G_2$$

$$\text{adj}(G) \longrightarrow \text{adj}(G_1) \oplus \text{adj}(G_2) \oplus \bigoplus \text{matter reps } R_i$$

- Stacks of D7 branes and their intersections: $U(N)$ gauge groups, bifundamental matter
- Include O7 planes: Realise $SO(2N)$ gauge groups and two-index antisymmetric representations, e.g. **10** of $SU(5)$
- Matter curves six-dimensional – matter still in hypermultiplets, 4D zero modes determined by fluxes
- Triple intersection of matter curves: Yukawa couplings via triple adjoint interaction

$$(\text{adj}(G))^3 \supset R_1 R_2 R_3 + \dots$$

Problems

- Possible symmetry groups: $U(N)$, $SO(2N)$ and $Sp(2N)$
- Matter representations: Bifundamental, two-index antisymmetric
- For $SU(5)$ GUTs: diagonal $U(1) \subset U(5)$ forbids top quark Yukawa coupling
- For $SO(10)$ GUTs: no spinors available

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- For $SO(10)$ GUTs: no spinors available
- Both require local E_6 enhancement:

$$SU(5) \text{ Yukawas: } (\mathbf{78})^3 \supset \mathbf{10} \cdot \mathbf{10} \cdot \mathbf{5}$$

$$SO(10) \text{ Spinors: } \mathbf{78} \longrightarrow \mathbf{45} + \mathbf{1} + \mathbf{16} + \overline{\mathbf{16}}$$

- Type IIB string theory has more general (p, q) branes – cannot be treated perturbatively
- Nicely realised in F-theory

F-Theory: Axiodilaton Monodromy

Type IIB contains complex scalar field: axiodilaton

$$\tau = C_0 + ie^{-\phi}$$

When encircling a 7-brane, τ undergoes $SL(2, \mathbb{Z})$ monodromy transformation

$$\tau \longrightarrow \frac{a\tau + b}{c\tau + d}$$

E.g. for a single D7 brane at $z = 0$,

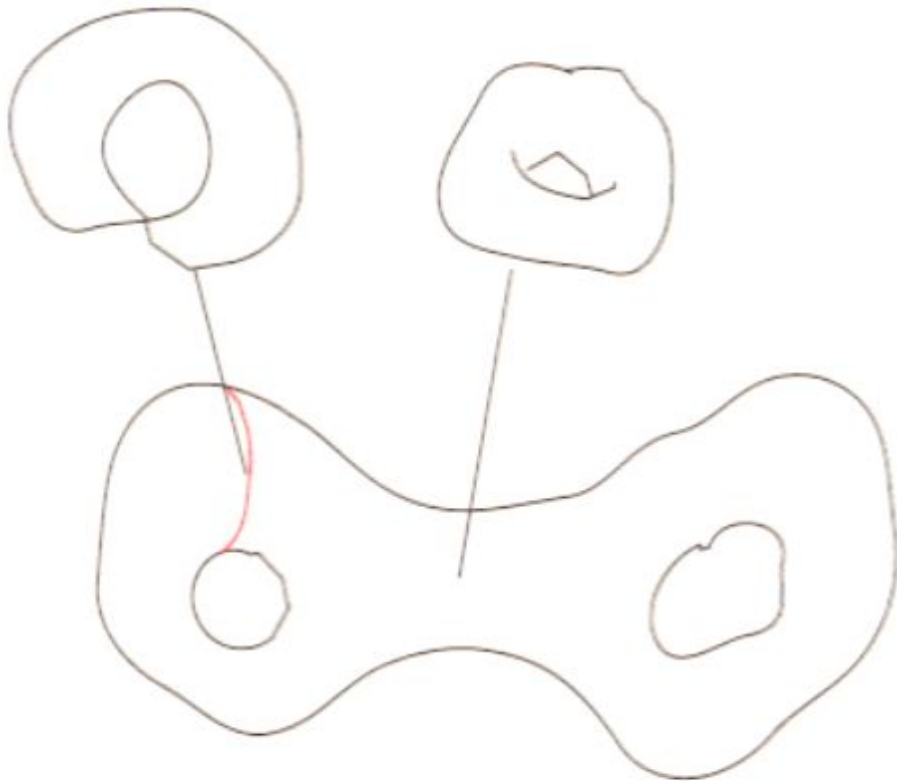
$$\tau \longrightarrow \tau + 1 \quad \Rightarrow \quad \tau \sim \ln z$$

\Rightarrow at brane positions, τ diverges

F-Theory: Extra Torus

[Vafa 96]

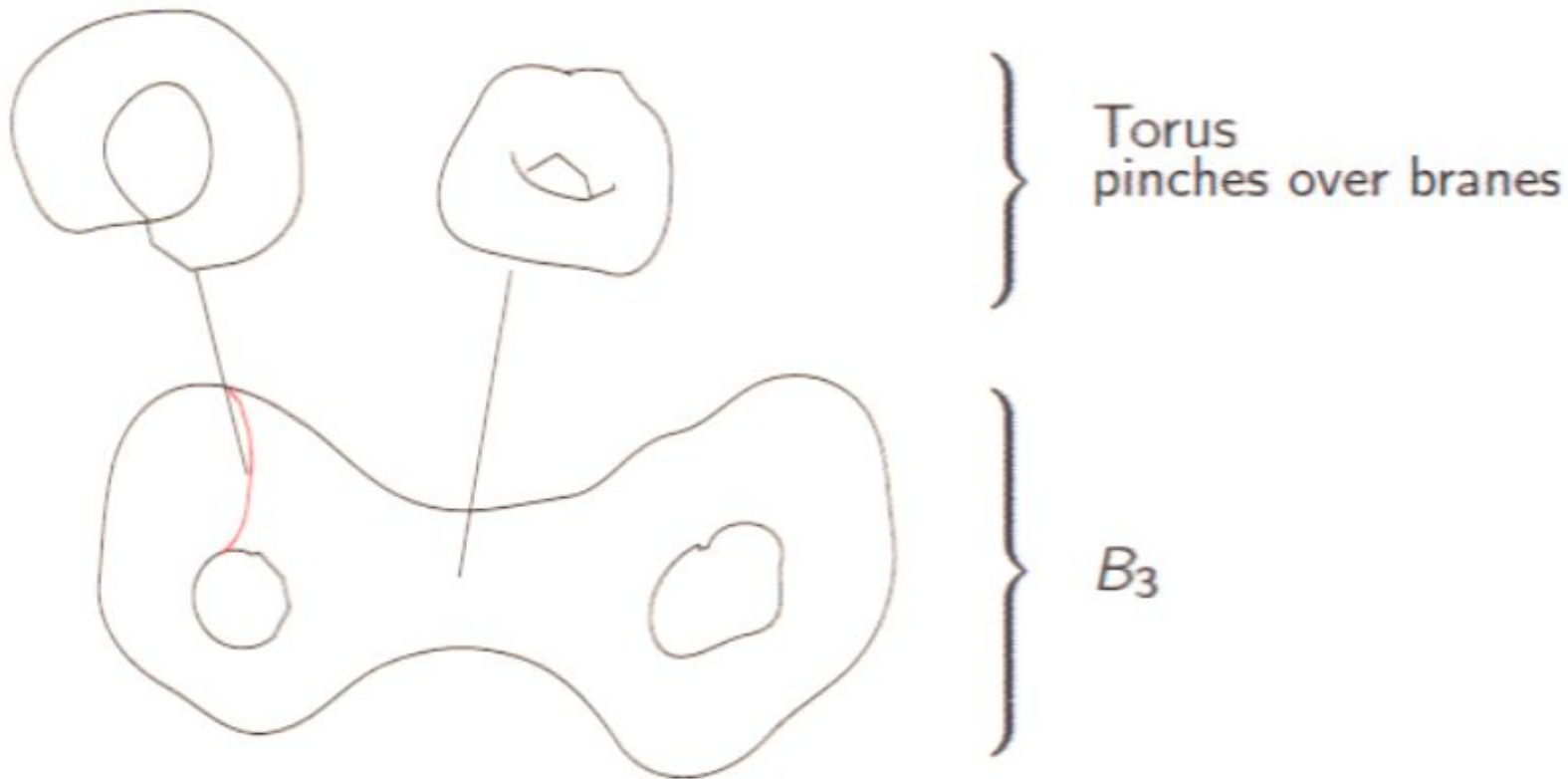
Key idea of F-Theory: $SL(2, \mathbb{Z})$ is also symmetry of torus complex structure \rightsquigarrow describe variation of τ by auxiliary torus over every point of compactification space B_3 : elliptic fibration



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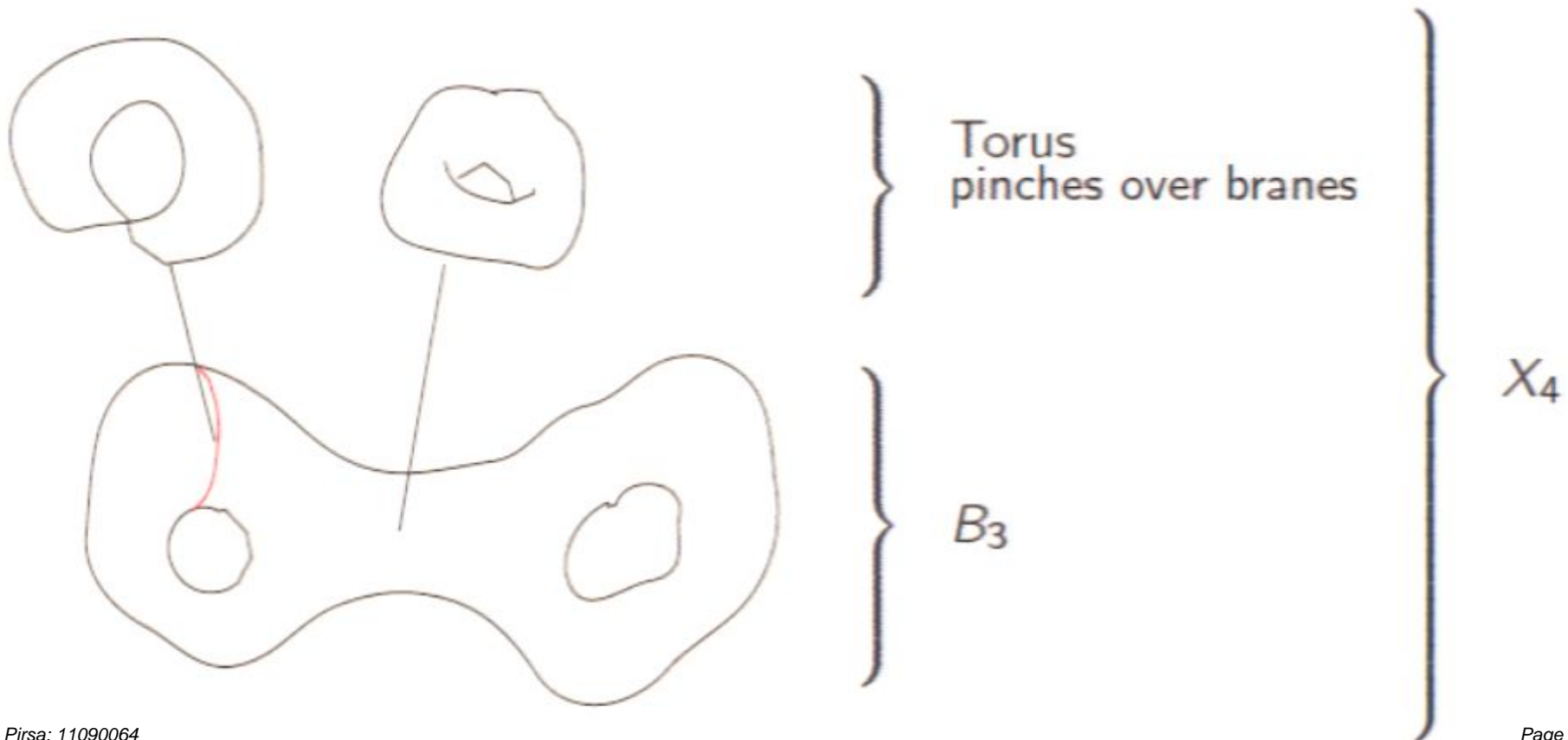
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F-Theory: Tate Model

[Bershadsky et al. 96]

Elliptic fibration: Torus over complex three-dimensional base, described by Weierstraß model in Tate form

$$y^2 = x^3 + a_5xy + a_4x^2 + a_3y + a_2x + a_0$$

$x, y \in \mathbb{C}$, a_k : functions on the base B_3

Brane positions \Leftrightarrow torus degenerates \Leftrightarrow Discriminant vanishes:

$$\Delta = \text{polynomial in the } a_k = 0$$

Type of brane (stack), i.e. gauge symmetry, determined by vanishing orders of the a_k and Δ (cf. ADE classification of singularities) [Kodaira '60s]


Intersections with other branes \Leftrightarrow Local symmetry enhancement \Leftrightarrow Locally Δ and a_k vanish to higher order: Matter curves, Yukawa points

Global, Semilocal, Local

For F-Theory GUTs, different degrees of locality:

- *Global* model: Specify full compactification space (CY fourfold): Includes all branes, fluxes, obeys consistency conditions, can stabilise moduli etc. [Blumenhagen et al.; Grimm et al.; Marsano et al.;...]
- *Semilocal* model: Focus on the GUT surface (brane stack) S and matter curves within S : Decouples bulk of compactification space, certain consistency conditions included [Hayashi et al.; Donagi, Wijnholt; Grimm, Weigand; Marsano et al.; Dudas, Palti; CL, Nilles, Stephan;...]
- *Local* model: Consider only points within S where matter curves intersect and interactions are localised: Simple, hope for predictivity. Certain questions cannot be answered, and actual existence of global completion is not guaranteed. [Donagi, Wijnholt; Heckman, Vafa et al.; Watari et al.;...]

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Local $SU(5)$ GUT

To engineer $SU(5)$ GUT, take brane position locally given by coordinate $w = 0$ and choose Tate model appropriately:

$$y^2 = x^3 + a_5 xy + a_4 x^2 + a_3 y + a_2 x + a_0$$

a_k : functions on base

Local $SU(5)$ GUT

To engineer $SU(5)$ GUT, take brane position locally given by coordinate $w = 0$ and choose Tate model appropriately:

$$y^2 = x^3 + b_5 xy + b_4 w x^2 + b_3 w^2 y + b_2 w^4 x + b_0 w^5$$

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b_k : functions on brane stack

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a_k : functions on base

b_k : functions on brane stack

Discriminant becomes

$$\Delta = w^5 (b_5^4 P + w b_5^2 (8b_4 P + b_5 R) + \mathcal{O}(w^2))$$

P, R : polynomials in the b_k

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P, R : polynomials in the b_k

Locally, $SU(5)$ is enhanced

to $SU(6)$: $P = 0 \Rightarrow$ localised **5**

to $SO(10)$: $b_5 = 0 \Rightarrow$ localised **10**

Yukawa Couplings

- Tate model for $SU(5)$ GUT localised at $w = 0$:

$$y^2 = x^3 + b_5 xy + b_4 w x^2 + b_3 w^2 y + b_2 w^4 x + b_0 w^5$$

- Yukawa couplings require $SO(12)$ and E_6 enhancements:

$$(66)^3 \supset \bar{5}_{H_d} \bar{5}_M 10_M \quad \Rightarrow b_5 = b_3 = 0$$

$$(78)^3 \supset 5_{H_u} 10_M 10_M \quad \Rightarrow b_5 = b_4 = 0$$

For both, Δ vanishes to order 8

- \curvearrowright Matter spectrum and Yukawa couplings can be engineered in F-theory

Point of E_8

[Heckman, Tavanfar, Vafa]



- Need E_6 and $SO(12)$ enhancements for up- and down-type Yukawas
 - CKM matrix: Favourably, these points coincide (no geometric suppression of quark mixing) $\rightsquigarrow E_7$
 - For PMNS matrix: Further enhancement to E_8 (but we do not consider neutrinos in the following)
 - Hence: One single Yukawa “point of E_8 ”, all interactions localised here
- ↪ Allows for higher interaction terms – Froggatt–Nielsen type masses using GUT singlets
- Simple and potentially predictive: All (superpotential) interactions determined by group theory, geometric data can be largely ignored

Gauge Theory Description

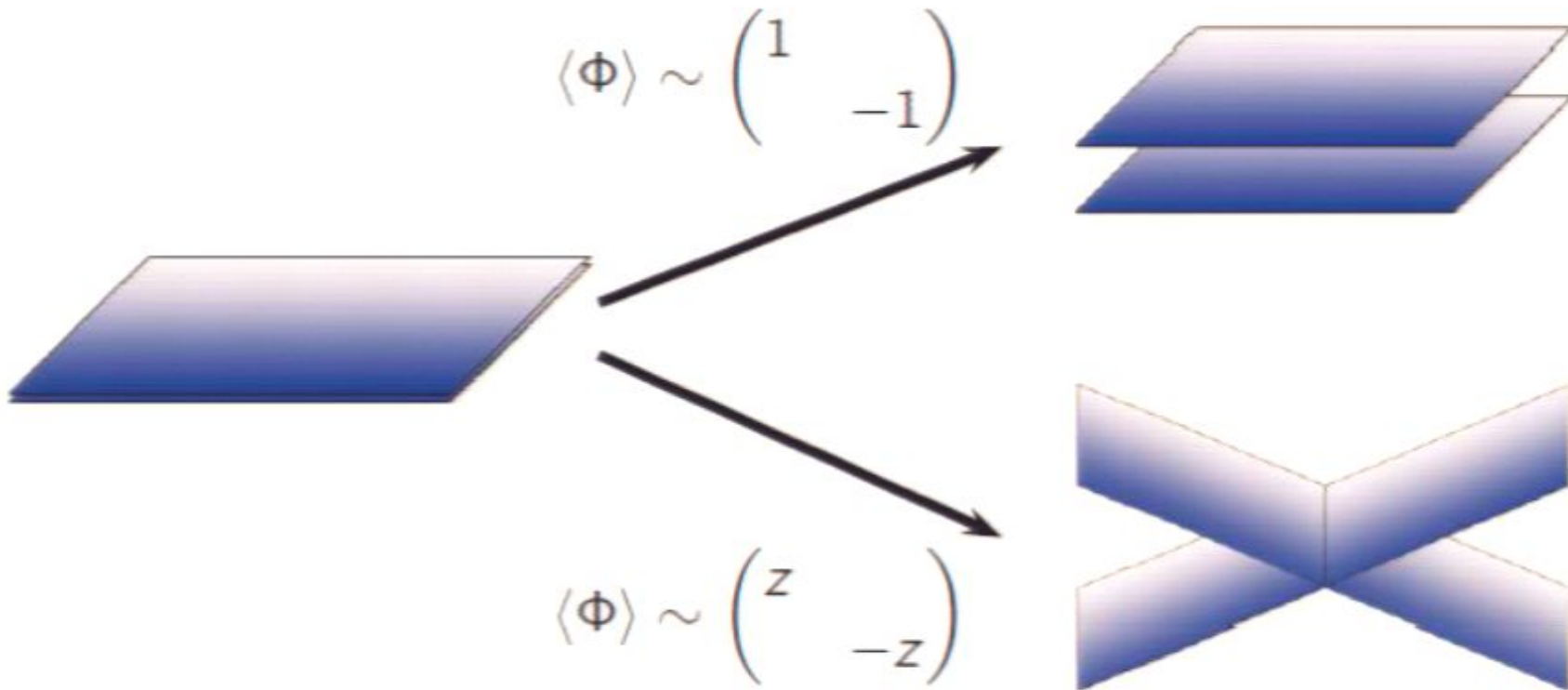
- $SU(5)$ GUT, variously enhanced (potentially) up to E_8
 $\leftrightarrow E_8$ gauge theory variously broken, generically to $SU(5)$
- 8D super-Yang–Mills theory contains adjoint scalar field
 $\rightsquigarrow E_8$ -breaking Higgs
- Actually: rank-preserving breaking

$$E_8 \longrightarrow (SU(5) \times SU(5)_\perp) \longrightarrow SU(5) \times U(1)^4$$

- Extra $U(1)$'s generically massive in F-Theory by geometric Stueckelberg effect, but this cannot be analysed in local model –
 $U(1)$'s remain as *global selection rules* [Grimm, Weigand]
- Higgs field varies over S – matter curves now visible as vanishing loci of Higgs eigenvalues

Type IIB interpretation: Higgs as Brane Splitter

Adjoint Higgs field – parameterises brane motion:



$\langle \Phi \rangle \neq 0$: Masses for W bosons – correspond to strings between the branes.

Symmetry is (partially) restored locally where (parts of) $\langle \Phi \rangle = 0$

E_8 Higgs

$$E_8 \longrightarrow SU(5) \times SU(5)_\perp$$
$$248 \longrightarrow (24, \mathbf{1}) \oplus (\mathbf{1}, 24) \oplus [(10, 5) \oplus (5, \bar{10}) \oplus \text{c.c.}]$$

$$\text{Higgs } \Phi \sim \begin{pmatrix} t_1 & & & & \\ & t_2 & & & \\ & & t_3 & & \\ & & & t_4 & \\ & & & & t_5 \end{pmatrix} \in (\mathbf{1}, 24), \quad \sum_i t_i = 0$$

Connection to Tate model: Deformed E_8 singularity,

$$y^2 = x^3 + b_0 w^5 \quad \longrightarrow \quad y^2 = x^2 + b_0 \prod (w - t_i)$$

\curvearrowright the b_k are symmetric polynomials in the t_i of order k , no b_1 because of tracelessness

Matter Curves

t_i are eigenvalues in the **5** of $SU(5)_\perp$, i.e.

$$\Phi e_i = t_i e_i$$

\curvearrowright **10** of $SU(5)_\perp$ spanned by $e_i \wedge e_j$, $i \neq j$, with eigenvalue $t_i + t_j$

Representations of $SU(5) \times SU(5)_\perp$ appear as $(\mathbf{10}, \mathbf{5}) \oplus (\mathbf{5}, \overline{\mathbf{10}})$

\curvearrowright in terms of $SU(5)$ reps, matter curves are given by

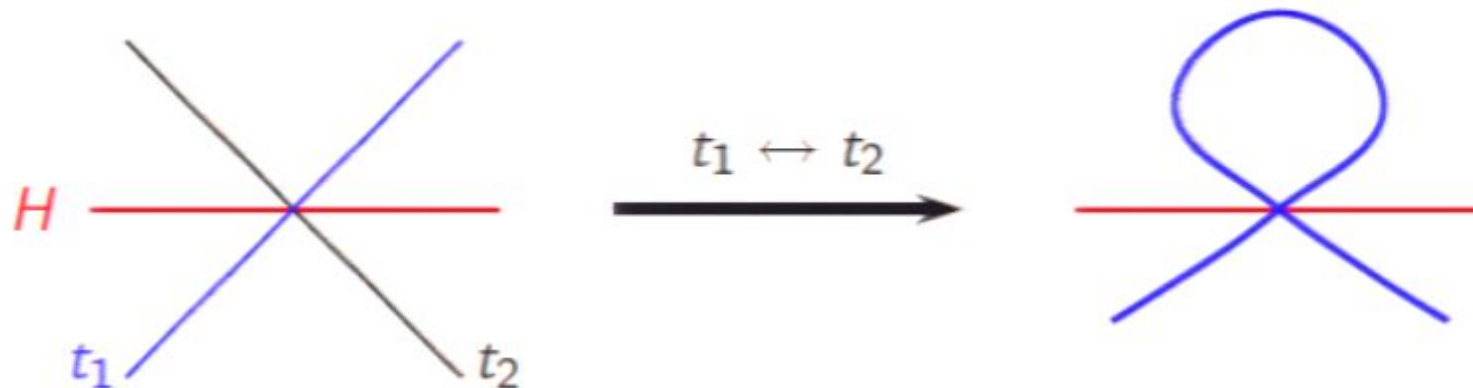
$t_i = 0$	localised 10
$-t_i - t_j = 0$	localised 5
$t_i - t_j = 0$	localised 1

t_i double as charges: For gauge-invariant terms, t_i must sum to zero (possibly using $\sum_i t_i = 0$) – realises $U(1)^4 \subset SU(5)_\perp$ selection rules

Monodromy

[Bershadsky et al.]

- The b_k in the Tate mode^{mf} are symmetric polynomials in the t_i
 \Rightarrow Invariant under permutations of the t_i
- Interpretation: Self-intersection, locally distinct-looking branes are the same



- Heavy top requires coupling $\mathbf{5}_{H_u} \mathbf{10}_{\text{top}} \mathbf{10}_{\text{top}}$
 \rightsquigarrow (at least) \mathbb{Z}_2 monodromy $t_1 \leftrightarrow t_2$
- Fixes top and up-type Higgs curve: $\mathbf{10}_{\text{top}} \sim \{t_1, t_2\}$, $\mathbf{5}_{H_u} \sim -t_1 - t_2$
- Reduces $SU(5)_{\perp}$ to lower rank

$SU(5)$ Breaking

Need to break $SU(5) \rightarrow G_{\text{SM}}$ and remove X, Y bosons and Higgs triplets from spectrum

Discrete Wilson lines and adjoint Higgses not available for S a del Pezzo surface!

↪ Break $SU(5)$ by hypercharge flux

$$F_Y \sim \begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

F_Y must be globally trivial to preserve hypercharge – mechanism not available in heterotic models!

Superpotential Couplings

Good couplings: Quark and lepton masses, weak-scale μ term

$$W_{\text{good}} = \mu \mathbf{5}_{H_u} \bar{\mathbf{5}}_{H_d} + Y_u \mathbf{5}_{H_u} \mathbf{10}_M \mathbf{10}_M + Y_d \bar{\mathbf{5}}_{H_d} \bar{\mathbf{5}}_M \mathbf{10}_M$$

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Bad couplings: Baryon and lepton number violating operators

$$\begin{aligned}
 W_{\text{bad}} = & \beta \mathbf{5}_{H_u} \bar{\mathbf{5}}_M + \lambda \bar{\mathbf{5}}_M \bar{\mathbf{5}}_M \mathbf{10}_M & \text{dim-3/4} \\
 & + W^1 \mathbf{10}_M \mathbf{10}_M \mathbf{10}_M \bar{\mathbf{5}}_M + W^2 \mathbf{10}_M \mathbf{10}_M \mathbf{10}_M \bar{\mathbf{5}}_{H_d} \\
 & + W^3 \bar{\mathbf{5}}_M \bar{\mathbf{5}}_M \mathbf{5}_{H_u} \mathbf{5}_{H_u} + W^4 \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{H_d} \mathbf{5}_{H_u} \mathbf{5}_{H_u} \\
 K_{\text{bad}} = & K^1 \mathbf{10}_M \mathbf{10}_M \mathbf{5}_M + K^2 \bar{\mathbf{5}}_{H_u} \bar{\mathbf{5}}_{H_u} \mathbf{10}_M & \text{dim-5}
 \end{aligned}$$

Coefficients can contain singlet VEVs, suppressed by M_{GUT} [Conlon, Palti]

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$$+ W^3 \bar{\mathbf{5}}_M \bar{\mathbf{5}}_M \mathbf{5}_{H_u} \mathbf{5}_{H_u} + W^4 \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{H_d} \mathbf{5}_{H_u} \mathbf{5}_{H_u}$$

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dim-3/4

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Some terms related by interchange $\bar{\mathbf{5}}_{H_d} \leftrightarrow \bar{\mathbf{5}}_M$

Matter Parity

[Dimopoulos, Raby, Wilczek; Ibanez, Ross; Dreiner, Luhn, Thormeier]

Various discrete symmetries for proton stability – compatibility with $SU(5)$ singles out \mathbb{Z}_2 “matter parity”:

	$5_{H_u}, \bar{5}_{H_d}$	$10_M, \bar{5}_M$
P_M	+1	-1

Forbids all baryon and lepton number violating operators except

$$W^1 10_M 10_M 10_M \bar{5}_M \quad \text{and} \quad W^3 \bar{5}_M \bar{5}_M 5_{H_u} 5_{H_u}$$

W^3 (Weinberg operator), can be tolerated if suppression scale high enough (but will not be generated, so ignore from now on)

$W^1 \supset QQQL, \bar{u}\bar{u}\bar{d}\bar{e}$ extremely constrained – forbid this by clever choice of matter curves (i.e. $U(1)$ s)

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Model Requirements

For the local model we require

- P_M defined locally
- heavy top quark (i.e. rank-one up-type Yukawa matrix at tree level)
- No dim-5 proton decay (the W^1 operator forbidden at all orders)
- Masses for all quarks and leptons after switching on VEVs (down-type Yukawa matrix can be rank-zero or one, but not rank-two)

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Local model building freedom: Freely choose

- Monodromy (at least \mathbb{Z}_2)
- Assignment of matter and Higgs zero modes to curves
- Singlet VEVs (for matter parity even singlets)
- Assume: Allowed terms generated with order-one coefficients

Matter Parity

Define \mathbb{Z}_2 matter parity in terms of the t_i (i.e. as subgroup of $SU(5)_\perp$):

$$P_M = (-1)^{c_i t_i}, \quad c_i = 0, 1 \quad (\text{defined mod 2})$$

- Monodromy $t_1 \leftrightarrow t_2$ requires $c_1 = c_2 = 1$ so $\mathbf{10}_{\text{top}}$ is odd
- Up-type masses always allowed once gauge invariant
- Down-type masses give constraint:

	$\bar{\mathbf{5}}_{H_d}$	$\bar{\mathbf{5}}_M$	$\mathbf{10}_M$
charge	$t_i + t_j$	$t_k + t_l$	t_m

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$c_i t_i$	0/2	1	1

Gauge invariant iff all t_i distinct – can only be matter parity even if even number of $c_i = 1$ (singlets have charge $t_i - t_j$, so don't change the argument)

- Note: W^1 operator has same charge structure

Two Possibilities



Hence, two possible definitions of matter parity:

$$\text{Case I: } P_M = (-1)^{t_1+t_2+t_3+t_4}$$

$$\text{Case II: } P_M = (-1)^{t_1+t_2}$$

Now analyse matter, Higgs and VEV assignment for both cases: $\mathbf{10}_{\text{top}}$ and $\mathbf{5}_{H_u}$ already fixed, need to distribute remaining matter and $\bar{\mathbf{5}}_{H_d}$ according to their matter parity

Main restriction: Forbid W^1 , but allow down-type Yukawas

Case I: Matter and VEV Assignment

Matter **10** Curves

10₁	$t_{1,2}$	—	top
10₂	t_3	—	
10₃	t_4	—	

Matter **5** Curves

5₃	$-t_{1,2} - t_5$	—
5₅	$-t_3 - t_5$	—
5₆	$-t_4 - t_5$	—

Even Singlet Curves

1₁	$\pm(t_{1,2} - t_3)$	+
1₂	$\pm(t_{1,2} - t_4)$	+
1₄	$\pm(t_3 - t_4)$	+
1₇	$t_1 - t_2$	+

Case I: Matter and VEV Assignment

Matter **10** Curves

10₁	$t_{1,2}$	—	top
10₂	t_3	—	
10₃	t_4	—	

Matter **5** Curves

5₃	$-t_{1,2} - t_5$	—
5₅	$-t_3 - t_5$	—
5₆	$-t_4 - t_5$	—

Even Singlet Curves

1₁	$\pm(t_{1,2} - t_3)$	+
1₂	$\pm(t_{1,2} - t_4)$	+
1₄	$\pm(t_3 - t_4)$	+
1₇	$t_1 - t_2$	+

- W^1 without singlets:

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_2 \bar{\mathbf{5}}_6,$$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_5,$$

$$\mathbf{10}_1 \mathbf{10}_2 \mathbf{10}_3 \bar{\mathbf{5}}_3$$

Case I: Matter and VEV Assignment

Matter $\mathbf{10}$ Curves

$\mathbf{10}_1$	$t_{1,2}$	—	top
$\mathbf{10}_2$	t_3	—	no matter
$\mathbf{10}_3$	t_4	—	matter

Matter $\mathbf{5}$ Curves

$\mathbf{5}_3$	$-t_{1,2} - t_5$	—	matter
$\mathbf{5}_5$	$-t_3 - t_5$	—	no matter
$\mathbf{5}_6$	$-t_4 - t_5$	—	matter

Even Singlet Curves

$\mathbf{1}_1$	$\pm(t_{1,2} - t_3)$	+
$\mathbf{1}_2$	$\pm(t_{1,2} - t_4)$	+
$\mathbf{1}_4$	$\pm(t_3 - t_4)$	+
$\mathbf{1}_7$	$t_1 - t_2$	+

- W^1 without singlets:

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_2 \bar{\mathbf{5}}_6,$$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_5,$$

$$\mathbf{10}_1 \mathbf{10}_2 \mathbf{10}_3 \bar{\mathbf{5}}_3$$

\rightsquigarrow no matter on $\mathbf{10}_2, \mathbf{5}_5$

Case I: Matter and VEV Assignment

Matter **10** Curves

10₁	$t_{1,2}$	—	top
10₂	t_3	—	no matter
10₃	t_4	—	matter

Matter **5** Curves

5₃	$-t_{1,2} - t_5$	—	matter
5₅	$-t_3 - t_5$	—	no matter
5₆	$-t_4 - t_5$	—	matter

Even Singlet Curves

1₁	$\pm(t_{1,2} - t_3)$	+
1₂	$\pm(t_{1,2} - t_4)$	+
1₄	$\pm(t_3 - t_4)$	+
1₇	$t_1 - t_2$	+

- W^1 without singlets:

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_2 \bar{\mathbf{5}}_6,$$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_5,$$

$$\mathbf{10}_1 \mathbf{10}_2 \mathbf{10}_3 \bar{\mathbf{5}}_3$$

\rightsquigarrow no matter on **10₂**, **5₅**

- W^1 with singlets:

e.g. $\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_6 \mathbf{1}_4,$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_3 \mathbf{1}_1$$

Case I: Matter and VEV Assignment

Matter **10** Curves

10₁	$t_{1,2}$	—	top
10₂	t_3	—	no matter
10₃	t_4	—	matter

Matter **5** Curves

5₃	$-t_{1,2} - t_5$	—	matter
5₅	$-t_3 - t_5$	—	no matter
5₆	$-t_4 - t_5$	—	matter

Even Singlet Curves

1₁	$\pm(t_{1,2} - t_3)$	+	no VEV
1₂	$\pm(t_{1,2} - t_4)$	+	VEV
1₄	$\pm(t_3 - t_4)$	+	no VEV
1₇	$t_1 - t_2$	+	VEV

- W^1 without singlets:

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_2 \bar{\mathbf{5}}_6,$$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_5,$$

$$\mathbf{10}_1 \mathbf{10}_2 \mathbf{10}_3 \bar{\mathbf{5}}_3$$

\rightsquigarrow no matter on **10₂**, **5₅**

- W^1 with singlets:

e.g. $\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_6 \mathbf{1}_4,$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_3 \mathbf{1}_1$$

\rightsquigarrow no VEVs for **1₁**, **1₄**
(because of t_3)

Case I: Down-Type Higgs

Higgs-like 5 Curves	Down-type Yukawas
$\bar{5}_{H_u}$ $-t_1 - t_2$	
$\bar{5}_1$ $-t_{1,2} - t_3$	
$\bar{5}_2$ $-t_{1,2} - t_4$	
$\bar{5}_4$ $-t_3 - t_4$	

Case I: Matter and VEV Assignment

Matter $\mathbf{10}$ Curves

$\mathbf{10}_1$	$t_{1,2}$	—	top
$\mathbf{10}_2$	t_3	—	no matter
$\mathbf{10}_3$	t_4	—	matter

Matter $\mathbf{5}$ Curves

$\mathbf{5}_3$	$-t_{1,2} - t_5$	—	matter
$\mathbf{5}_5$	$-t_3 - t_5$	—	no matter
$\mathbf{5}_6$	$-t_4 - t_5$	—	matter

Even Singlet Curves

$\mathbf{1}_1$	$\pm(t_{1,2} - t_3)$	+	no VEV
$\mathbf{1}_2$	$\pm(t_{1,2} - t_4)$	+	VEV
$\mathbf{1}_4$	$\pm(t_3 - t_4)$	+	no VEV
$\mathbf{1}_7$	$t_1 - t_2$	+	VEV

- W^1 without singlets:

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_2 \bar{\mathbf{5}}_6,$$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_5,$$

$$\mathbf{10}_1 \mathbf{10}_2 \mathbf{10}_3 \bar{\mathbf{5}}_3$$

\rightsquigarrow no matter on $\mathbf{10}_2, \mathbf{5}_5$

- W^1 with singlets:

e.g. $\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_6 \mathbf{1}_4,$

$$\mathbf{10}_1 \mathbf{10}_1 \mathbf{10}_3 \bar{\mathbf{5}}_3 \mathbf{1}_1$$

\rightsquigarrow no VEVs for $\mathbf{1}_1, \mathbf{1}_4$
(because of t_3)

Case I: Down-Type Higgs

Higgs-like 5 Curves	Down-type Yukawas
$\bar{5}_{H_u}$ $-t_1 - t_2$	
$\bar{5}_1$ $-t_{1,2} - t_3$	
$\bar{5}_2$ $-t_{1,2} - t_4$	
$\bar{5}_4$ $-t_3 - t_4$	

Case I: Down-Type Higgs

Higgs-like 5 Curves	Down-type Yukawas
$\bar{5}_{H_u}$ ⚡ $-t_1 - t_2$	No masses at tree level or with singlets
$\bar{5}_1$ $-t_{1,2} - t_3$	
$\bar{5}_2$ ⚡ $-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{5}_4$ $-t_3 - t_4$	

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)

Case I: Down-Type Higgs

Higgs-like 5 Curves	Down-type Yukawas
$\bar{5}_{H_u}$ ⚡ $-t_1 - t_2$	No masses at tree level or with singlets
$\bar{5}_1$ ⚡ $-t_{1,2} - t_3$	either rank-two Yukawa matrix, or no up-type masses with singlets
$\bar{5}_2$ ⚡ $-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{5}_4$ $-t_3 - t_4$	

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)
- Down-type Yukawa should not be rank-two

Case I: Down-Type Higgs

Higgs-like 5 Curves	Down-type Yukawas
$\bar{5}_{H_u}$ ⚡ $-t_1 - t_2$	No masses at tree level or with singlets μ term
$\bar{5}_1$ ⚡ $-t_{1,2} - t_3$	either rank-two Yukawa matrix, or no up-type masses with singlets
$\bar{5}_2$ ⚡ $-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{5}_4$ $-t_3 - t_4$	

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)
- Down-type Yukawa should not be rank-two
- String-scale μ term for both Higgses on one curve

Case I: Down-Type Higgs

Higgs-like 5 Curves	Down-type Yukawas
$\bar{5}_{H_u}$ ⚡ $-t_1 - t_2$	No masses at tree level or with singlets μ term
$\bar{5}_1$ ⚡ $-t_{1,2} - t_3$	either rank-two Yukawa matrix, or no up-type masses with singlets
$\bar{5}_2$ ⚡ $-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{5}_4$ ✓ $-t_3 - t_4$	Rank-one Yukawa matrix, bottom quark heavy

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)
- Down-type Yukawa should not be rank-two
- String-scale μ term for both Higgses on one curve
- $\bar{5}_4 = \bar{5}_{H_d}$ is unique choice, tree-level coupling $\bar{5}_{H_d} \mathbf{10}_{\text{top}} \bar{5}_3$

Case I: Yukawas and CKM

- Example Assignment: Third generation on $\mathbf{10}_1$ and $\bar{\mathbf{5}}_3$, light generations on $\mathbf{10}_3$ and $\bar{\mathbf{5}}_3$
- Higgses: $\bar{\mathbf{5}}_{H_u}$ and $\bar{\mathbf{5}}_4$, only $\langle \mathbf{1}_2 \rangle \sim \epsilon$ required at first order
- Ignore $\mathbf{1}_7$ and $\mathcal{O}(1)$ coefficients
- Yukawa matrices (schematically):

$$Y^u \sim Y^d \sim \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

- CKM matrix:

$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

- Masses and mixings possible though not a great fit
- Degeneracy because three generations come from two curves

Case II

$$P_M = (-1)^{t_1+t_2}$$

↪ split t 's into $t_{\text{odd}} = \{t_1, t_2\}$ and $t_{\text{even}} = \{t_3, t_4, t_5\}$

- Symmetric setup, possible monodromy acting on t_{even}
- $\mathbf{10}_{\text{top}}$ is the unique matter $\mathbf{10}$ curve
- Down-type Higgs unique (up to relabeling)
- Matter-parity even singlets do not mix t_{odd} and t_{even}
- W^1 operator cannot be generated: Charge $4t_{\text{odd}} + t_{\text{even}}$ cannot be compensated by matter-parity even singlets
- Three possible matter $\bar{\mathbf{5}}$ curves (charges $t_{\text{odd}} - t_{\text{even}}$): model building choice
- Different choices of singlet VEVs possible, achieve masses and mixing

Local Model Summary

- Already locally, rather constrained model: Only two possible definitions of matter parity
- In both cases, assignments of matter and Higgses is unique or strongly constrained
- Restrictions mainly from forbidding W^1 while allowing for down-type masses
- W^3 operator (neutrino masses) is not generated in any case
- Masses for all matter fields and CKM mixing possible
- Involves choices of zero modes and VEVs by hand – these cannot be calculated in the local framework

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Semilocal Approach

[Friedman, Morgan, Witten; Donagi, Wijnholt; Marsano et al.]

Now *semilocal* picture: Consider GUT surface S and fluxes, using spectral cover approach

Two types of fluxes (actually, both merge to G_4 flux in F-theory):

- $U(1) \subset SU(5)_\perp$ fluxes on matter curves (from the transverse branes): Determines (chiral) 4D zero modes for full GUT multiplets, free parameters up to anomaly cancellation requirements
- Hypercharge flux on S (globally trivial so hypercharge stays unbroken): Breaks $SU(5)$, restrictions to matter curves splits $SU(5)$

Aim: Find relations between homology classes of matter curves \rightsquigarrow relation between flux restrictions and multiplet splittings

Spectral Cover

Spectral cover: Five-fold cover of S in projective threefold

$$\mathbb{P}(K_S \oplus \mathcal{O}_S)$$

with homogeneous coordinates $U : V$ given by spectral equation for Φ .
Because of \mathbb{Z}_2 monodromy, spectral equation must factorise:

$$\begin{aligned} 0 &= b_0 U^5 + b_2 U^3 V^2 + b_3 U^2 V^3 + b_4 UV^4 + b_5 V^5 \\ &= (a_1 V^2 + a_2 UV + a_3 U^2) (a_4 V + a_7 U) (a_5 V + a_8 U) (a_6 V + a_9 U) \end{aligned}$$

b_k are sections in certain line bundles on $S \Rightarrow$ line bundles for the a_i
 \Rightarrow homology classes of matter curves

Impose triviality of hypercharge flux \rightsquigarrow solution contains three arbitrary line bundles

Involves particular solution of $b_1 = 0$ constraint – might not be most general one?

Fluxes and Zero Modes

$U(1)$ fluxes M_5, M_{10} : Free up to consistency conditions [Dudas, Palti]

Hypercharge flux on matter curves: $N_Y = F_Y \cdot (\text{homology class})$.

For curve with flux numbers M and N_Y , zero modes given by

$$\begin{array}{l} \mathbf{10} \begin{cases} \rightarrow (\mathbf{3}, \mathbf{2}) : M_{10} \\ \rightarrow (\bar{\mathbf{3}}, \mathbf{1}) : M_{10} - N_Y \\ \rightarrow (\mathbf{1}, \mathbf{1}) : M_{10} + N_Y \end{cases} \end{array} \quad \begin{array}{l} \mathbf{5} \begin{cases} \rightarrow (\mathbf{3}, \mathbf{1}) : M_5 \\ \rightarrow (\mathbf{1}, \mathbf{2}) : M_5 + N_Y \end{cases} \end{array}$$

Hypercharge flux must be globally trivial, hence no net “ $SU(5)$ breaking chirality”:

$$0 = F_Y \cdot c_1 = F_Y \cdot \eta \quad \rightsquigarrow \quad \sum_5 N_Y = \sum_{10} N_Y = 0$$

10 Curves

	M	N_Y
10_1	$-(M_{5_1} + M_{5_2} + M_{5_3})$	$-\tilde{N}$
10_2	M_{10_2}	N_7
10_3	M_{10_3}	N_8
10_4	M_{10_4}	N_9

5 Curves

	M	N_Y
5_{H_u}	$M_{5_{H_u}}$	\tilde{N}
5_1	M_{5_1}	$-\tilde{N}$
5_2	M_{5_2}	$-\tilde{N}$
5_3	M_{5_3}	$-\tilde{N}$
5_4	M_{5_4}	$N_7 + N_8$
5_5	M_{5_5}	$N_7 + N_9$
5_6	M_{5_6}	$N_8 + N_9$

- Three free parameters $N_{7,8,9}$ for the hypercharge flux, corresponding to three unspecified line bundles
- $\tilde{N} = N_7 + N_8 + N_9$
- Split some **5** curves \Rightarrow split some **10** curves
[Marsano et al.; Dudas, Palti]

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Case I: Matter Sector is Fine

- Doublet-triplet splitting for Higgses ($\tilde{N} \neq 0$) inevitably splits $\mathbf{10}_{\text{top}}$ and at least one more $\mathbf{10}$ curve (and at least one matter $\mathbf{5}$ curve)
- However, splitting of matter multiplets is OK as long as there are three generations of zero modes in the end, i.e. other $\mathbf{10}$ curve must have “opposite” split (hence cannot have three generations from one matter curve)
- Matter on $\mathbf{10}_1$, $\mathbf{10}_3$, $\mathbf{5}_3$ and $\mathbf{5}_6$, so to have full net generations, we require

$$N_7 = N_9 = 0 \quad \Rightarrow \quad \text{only } N_8 \text{ left free}$$

- No exotics from $\mathbf{10}$'s and remaining matter-like $\mathbf{5}$ curve can be satisfied by choosing appropriate M 's
- ↪ Satisfactory matter sector can be engineered easily

Case I: Higgs Sector is not Fine

- Higgs sector:

	$(3, 1)$	$(1, 2)$
5_{H_u}	$M_{5_{H_u}}$	$M_{5_{H_u}} + N_8$
5_1	M_{5_1}	$M_{5_1} - N_8$
5_2	M_{5_2}	$M_{5_2} - N_8$
5_4	M_{5_4}	$M_{5_4} + N_8$

- We can pairwise decouple unwanted triplets from 5_{H_u} and 5_2 , and from 5_1 and 5_4 by coupling to VEV for 1_2
- However:

$$\#(\text{doublets from } 5_{H_u}, 5_2) = \#(\text{triplets from } 5_{H_u}, 5_2)$$

- Problem persists even when allowing exotics from the matter sector
- Separately, down-type Higgs on 5_4 cannot be realised

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$\mathbf{5}_2$	$M_{\mathbf{5}_2}$	$M_{\mathbf{5}_2} - N_8$
$\mathbf{5}_4$	$M_{\mathbf{5}_4}$	$M_{\mathbf{5}_4} + N_8$

- We can pairwise decouple unwanted triplets from $\mathbf{5}_{H_u}$ and $\mathbf{5}_2$, and from $\mathbf{5}_1$ and $\mathbf{5}_4$ by coupling to VEV for $\mathbf{1}_2$
- However:

$$\#(\text{doublets from } \mathbf{5}_{H_u}, \mathbf{5}_2) = \#(\text{triplets from } \mathbf{5}_{H_u}, \mathbf{5}_2)$$

- Problem persists even when allowing exotics from the matter sector
- Separately, down-type Higgs on $\mathbf{5}_4$ cannot be realised

Case II: Again not Fine

- Only one matter **10** curve, split with same parameter as up-type Higgs
- Higgs triplets cannot be decoupled by even matter parity singlets
- No exotic matter \Rightarrow no doublet-triplet splitting
- Ignoring matter sector: Still cannot achieve pair of Higgs doublets

Case II: Again not Fine



- Only one matter **10** curve, split with same parameter as up-type Higgs
- Higgs triplets cannot be decoupled by even matter parity singlets
- No exotic matter \Rightarrow no doublet-triplet splitting
- Ignoring matter sector: Still cannot achieve pair of Higgs doublets

Upshot: In both cases, proper doublet-triplet splitting in Higgs sector does not work, even when allowing for exotics from the matter sector – both models cannot be realised already in semilocal setup!

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Conclusions

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 - Goal: Use locally defined matter parity and additional $U(1)$ s to ensure proton stability
 - Local model is already very constrained: Two cases only
 - In semilocal embedding, doublet-triplet splitting cannot be realised in either case
- ~→ Models fail first step towards realisation

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- ~→ Models fail first step towards realisation
- Predictivity of local point in question – Crucial model features required to have nonlocal origin?
 - GUT breaking by hypercharge flux seems too restrictive, also problems with exotics
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Conclusions

- Analysed F-Theory GUT in local and semilocal approach
- Goal: Use locally defined matter parity and additional $U(1)$ s to ensure proton stability
- Local model is already very constrained: Two cases only
- In semilocal embedding, doublet-triplet splitting cannot be realised in either case

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- Predictivity of local point in question – Crucial model features required to have nonlocal origin?
- GUT breaking by hypercharge flux seems too restrictive, also problems with exotics [Marsano et al.; Dudas, Palti]
- Possible loopholes: Localised matter might be more subtle
 - Non-diagonal Higgs fields (“T-Branes”, “Gluing Morphisms”) [Cecotti et al.; Donagi, Wijnholt]
 - Relation to higher symmetry groups [Esole, Yau; Marsano, Schäfer-Nameki]