Advances in String Phenomenology

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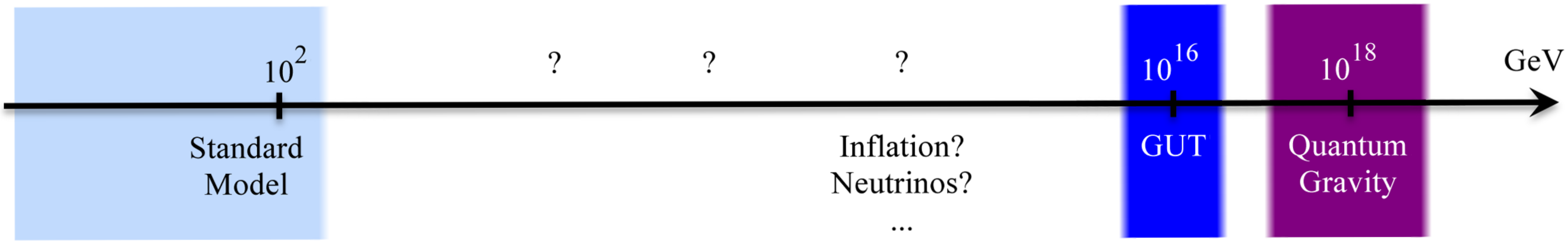
Frontiers in high-energy physics



Quantum Field Theory

- powerful universal framework
- quantitative description of particle physics interactions at the precision level

General Relativity

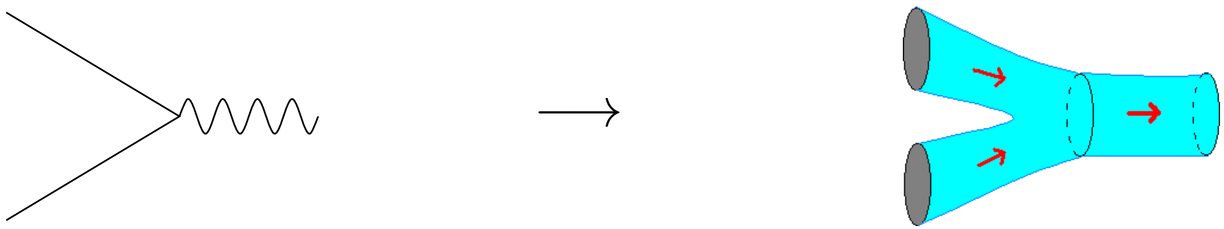
- classically very successful
- non-renormalisable as perturbative QFT (effective theory)

Approaches to fundamental Quantum Theory of Gravity:

- modify quantization procedure (e.g. Loop Quantum Gravity)
- modify dynamics in the UV, but not the 'kinematics': **String Theory**

String Theory

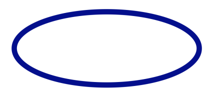
Particles are quantum excitations of 1-dimensional strings of length ℓ_s.



Resulting theory

- is ultra-violet finite in 10 spacetime dimensions

- flows at smaller energies to well-probed concepts of

Quantum Field Theory	$\leftrightarrow$	open strings	
General Relativity	$\leftrightarrow$	closed strings	

- is thus a candidate ultra-violet regulator of QFT and General Relativity.

String theory

Internal consistency comes with extra degrees of freedom:

- 10-dimensional theory
- Supersymmetric in the UV*   *(In absence of dilation tadpoles)
- Infinite tower of massive states, . . .

Two possible conclusions:

- Discard theory and look for alternatives
  - but the stakes are high
- Stick to string theory and investigate its consequences

S. Weinberg:

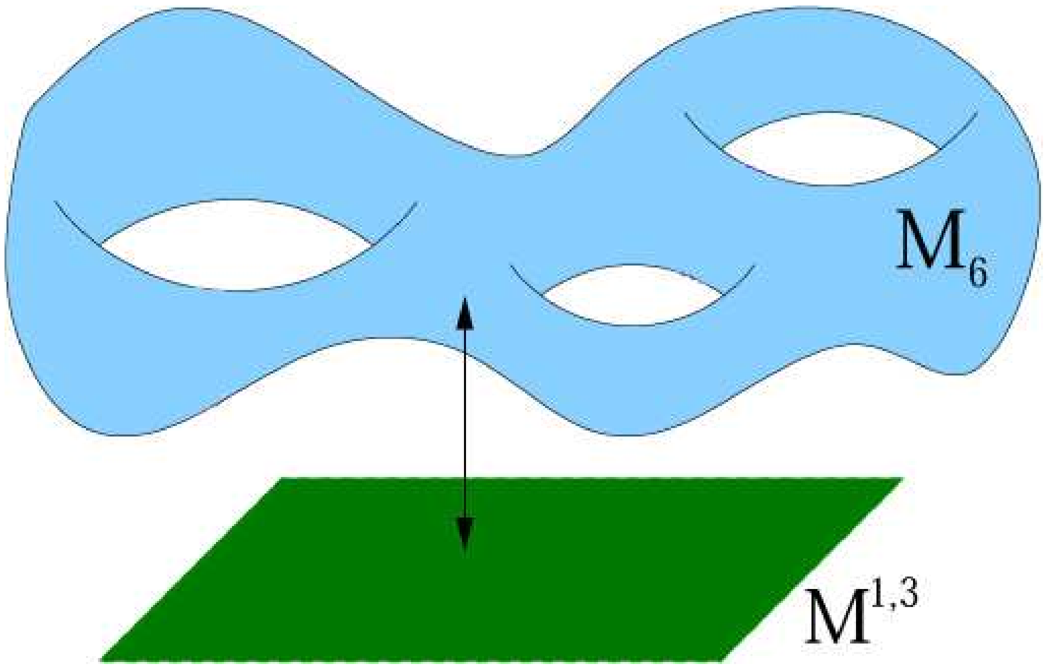
Our mistake is not that we take our theories too seriously, but that we do not take them seriously enough.

String compactification

To arrive at 4 large extra dimensions we need to compactify 6 dimensions.

Ansatz for spacetime: $\mathcal{M}^{1,9} = \mathcal{M}^{1,3} \times \mathcal{M}_6$

- $\mathcal{M}^{1,3}$: four extended spacetime dimensions (maximally symmetric)
- $\mathcal{M}_6$: compactification space
- in general warped product, unwarped also possible



String Landscape

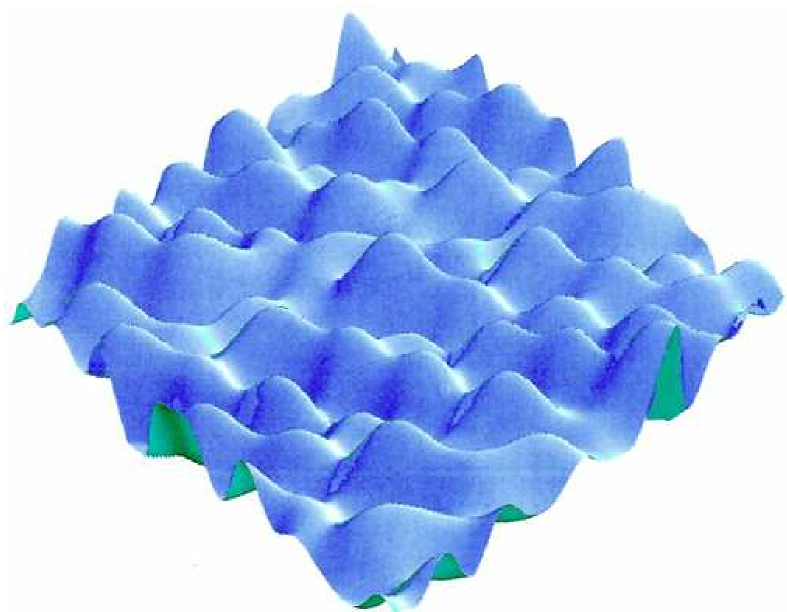
String vacuum = background value for string fields which constitute solution to string equations of motion

- Metric $\langle g_{ij} \rangle$: internal background geometry $\mathcal{M}_6$
- Generalized field strengths: $\langle F_{i_1 \ldots i_p} \rangle$: 'fluxes'

Each vacuum makes definite predictions for 4-dim. effective field theory, which are explicitly testable.

Challenges:

- There are many vacua - the 'string landscape'. What are their properties? Classification?
- Which vacuum is 'ours'? Is there a dynamical selection principle, or are all vacua realized in another universe ?



String Phenomenology

Aim: String solutions to 4d field theory challenges in phenomenology

Geometry/topology of compactification space $\leftrightarrow$ **4d effective physics**

- Production of hierarchies via interplay of higher-dimensional geometric scales or via other stringy effects (e.g. stringy instantons)
- Exploit higher-dimensional profile of particle fields in flavour sector or in (gauge) symmetry breaking
- Natural stringy origin to otherwise adhoc symmetries in particle physics and cosmology (inflation)

  $\leftrightarrow$ Consistent embedding of IR-global symmetries into framework of quantum gravity

String Pheno at work

1) Early-universe (string) cosmology

- Inflation requires explicit knowledge of higher dimensional operators in full quantum gravity
- Use UV completion of global symmetries within string theory to protect effective action
- Especially well-motivated in context of large-field inflation $\Delta\Phi \simeq M_{\mathrm{Pl.}}$ (sizable tensor-scalar ratio)

2) Cosmological constant problem

- Can sensibly be addressed only in UV finite theory
- Multitude of string vacua might help realize finite-tuning of CC

3) Particle physics

- Many approaches in various string corners
- This talk: **F-theory (GUT) model building**

Outline

I.) Invitation to String Phenomenology

II.) GUTs from F-theory - Generalities

III.) Basics of SU(5) GUT model building

GUT breaking - Doublet-Triplet Splitting - Proton decay

IV.) New F-theory Technology for model building

U(1) and discrete symmetries - Yukawas - Non-SUSY GUTs

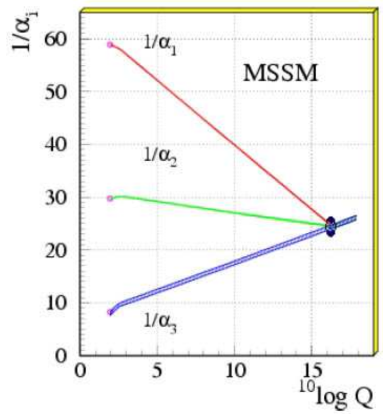
II.) GUTs from F-theory - Generalities

F-theory GUTs

Assumption:

Unification at $M_{\rm GUT} = 2 \times 10^{16}$ GeV is no coincidence. **F-theory GUTs** aim at

- addressing typical challenges of GUT models with stringy methods
- providing rationale for observed patterns



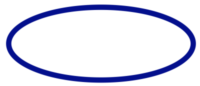
Two key ingredients from F-theory:

- Localisation of gauge d.o.f. $\leftrightarrow$ hierarchy $\frac{M_{\rm GUT}}{M_{\rm Pl}} \simeq 10^{-3}$
- exceptional symmetry groups $\leftrightarrow$ Yukawa couplings/flavour

F-GUT programme: initiated in [Donagi,Wijnholt][Beasley,Heckman,Vafa]'08

- Particle physics applications $\leftrightarrow$ 4-folds, G_4-fluxes, ...
- Exploring non-perturbative geometric corner of string landscape
  $\leftrightarrow$ more general than initial SUSY-GUT idea!

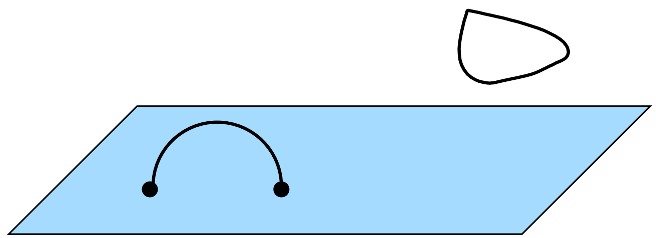
7-branes in string theory

closed strings  massless graviton

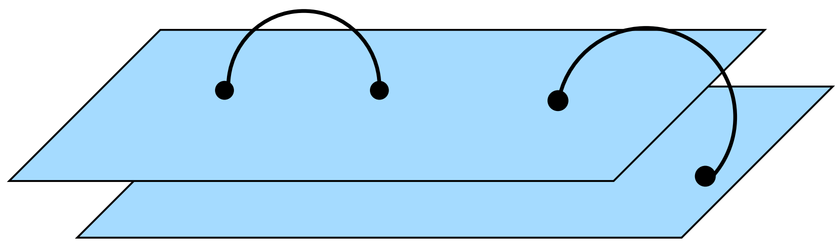
open strings  massless vector boson

7-brane = (7+1)-dim. subspace of in $\mathcal{M}^{1,9}$ on which open strings end

one single 7-brane
→ *single* gauge boson



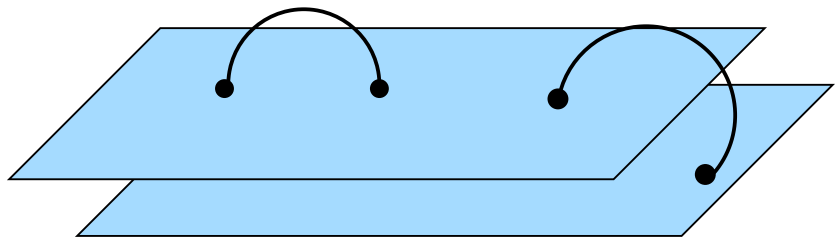
stacks of N coincident 7-branes
→ $U(N)$ gauge bosons



7-branes in string theory

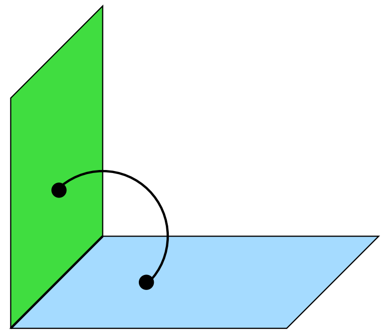
stacks of N coincident 7-branes

$\rightarrow U(N)$ gauge bosons



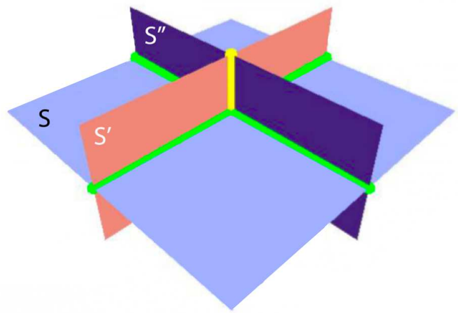
7-branes intersecting at an 'angle'

$\rightarrow$ matter fields in bifundamental representation $(\overline{N}_a, N_b)$



triple intersection of 7-branes

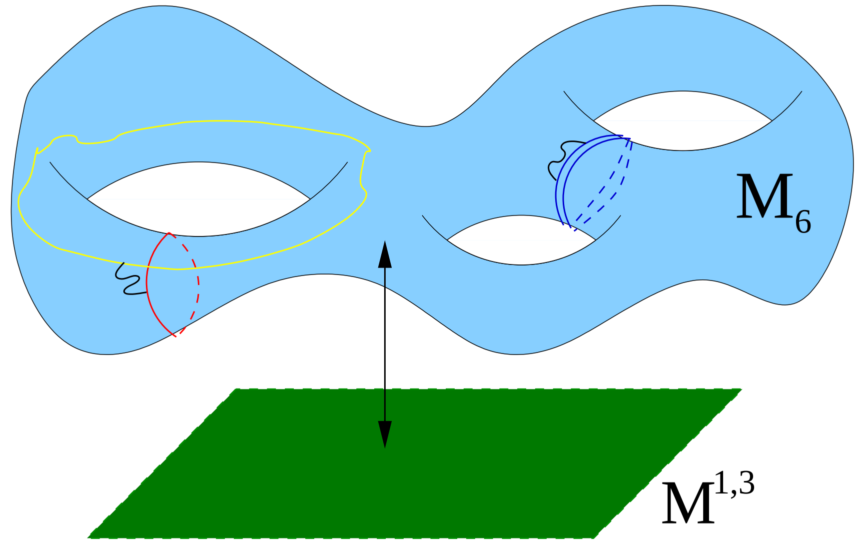
$\rightarrow$ Yukawa couplings $\phi_i \phi_j \phi_k$



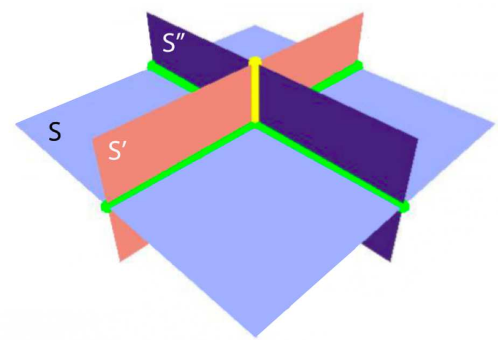
7-branes in string theory

Compactification:

- $\mathcal{M}^{1,9} = \mathcal{M}^{1,3} \times \mathcal{M}_6$
- 7-brane:
  - fills $\mathcal{M}^{1,3}$
  - wraps 4-dim. subspace (4-cycle) S_4 of $\mathcal{M}_6$

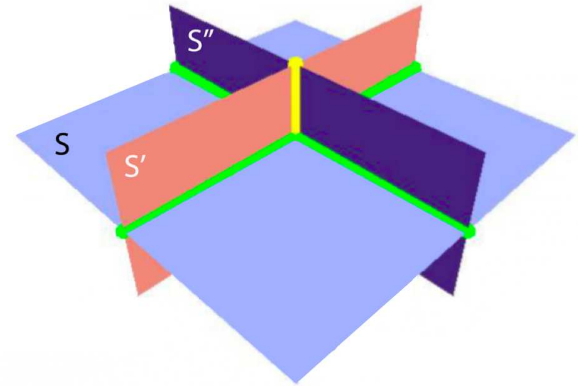


• gravity		bulk	$\mathcal{M}^{1,3} \times \mathcal{M}_6$
• gauge bosons	$\leftrightarrow$	7-brane	$\mathcal{M}^{1,3} \times S_4$
• charged matter		curves	$\mathcal{M}^{1,3} \times C_2$
• Yukawa couplings		points	$\mathcal{M}^{1,3} \times \text{pt.}$



Localisation with 7-branes

• gravity		bulk	$\mathbb{R}^{1,3} \times \mathcal{M}_6$
• gauge bosons	$\leftrightarrow$	7-brane	$\mathbb{R}^{1,3} \times S_4$
• charged matter		curves	$\mathbb{R}^{1,3} \times C_2$
• Yukawa couplings		points	$\mathbb{R}^{1,3} \times \mathrm{pt.}$



Exploit different scales to account for hierarchy $M_{\mathrm{GUT}} = 10^{-3} M_{\mathrm{Pl}}$

- $S_{10\mathrm{D}} = M_*^8 \int_{\mathbb{R}^{1,3}\times\mathcal{M}_6} \sqrt{-g}R$ — $M_{\mathrm{Pl.}}^2 \sim M_*^8 \,\mathrm{Vol}(\mathcal{M}_6)$
- $S_{\mathrm{YM}} = M_*^4 \int_{\mathbb{R}^{1,3}\times S_4} F^2$ $\leftrightarrow$ $\alpha_{\mathrm{GUT}}^{-1} \sim M_*^4 \,\mathrm{Vol}(S_4)$
- GUT breaking — $M_{\mathrm{GUT}}^4 \sim \mathrm{Vol}(S_4)^{-1}$

arrange $\mathrm{Vol}(S_4)$, $\mathrm{Vol}(\mathcal{M}_6)$, $M_* = \ell_s^{-1}$ in agreement with GUT physics:

$$\underbrace{\ell_s}_{0.2x} < \underbrace{R_{S_4}}_{2.2x} < \underbrace{R_{\mathcal{M}_6}}_{5.6x} \qquad x = 10^{-16}\mathrm{GeV}^{-1}$$

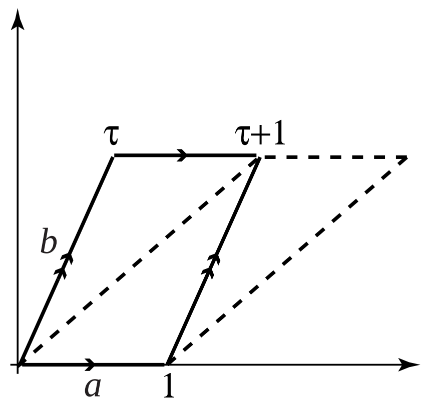
$\mathrm{Vol}(S_4) =: R_{S_4}^4$, $\quad \mathrm{Vol}(\mathcal{M}_6) =: R_{\mathcal{M}_6}^6$

The magic of F-theory

F-theory encodes 7-branes in elliptically fibered $4_{\mathbb{C}}$-fold Y_4.

- A 7-brane acts as a magnetic source for a complex scalar field τ.
  $\Longrightarrow$ τ varies holomorphically normal to the 7-branes.

- τ = complex structure of elliptic curve $\mathbb{E}_\tau$ [Vafa'96]
- information about 7-brane $\leftrightarrow$ varying complex structure τ of $\mathbb{E}_\tau$

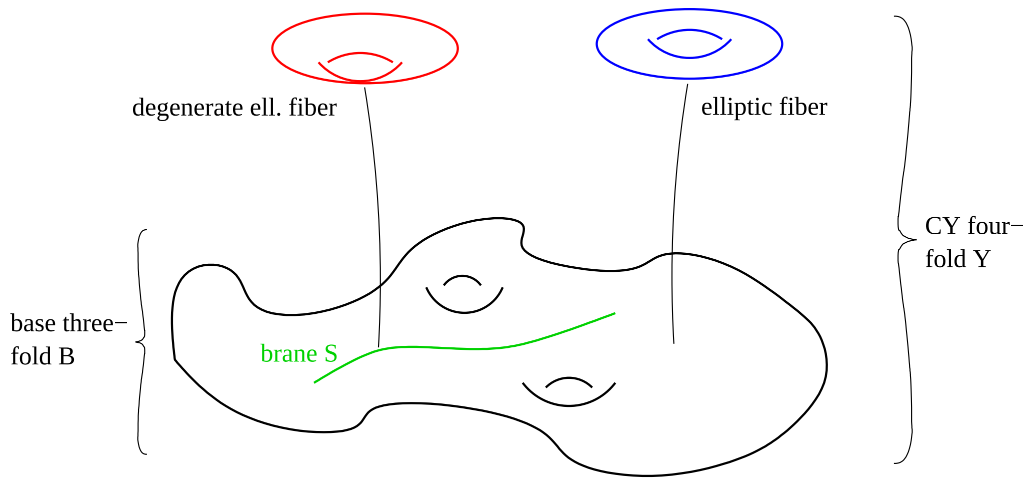


Brane language:

7-branes wrap 4-cycle $S \subset \mathcal{M}_6$

F-theory language:

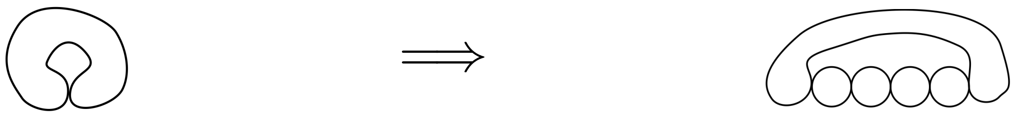
S = locus of fiber degeneration



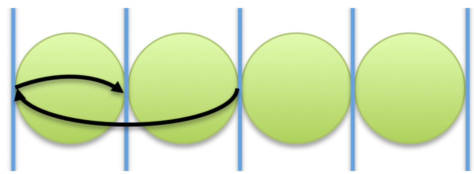
Non-abelian gauge symmetry

Singularity type in co-dim. $1_{\mathbb{C}} \leftrightarrow$ gauge group G along 7-brane

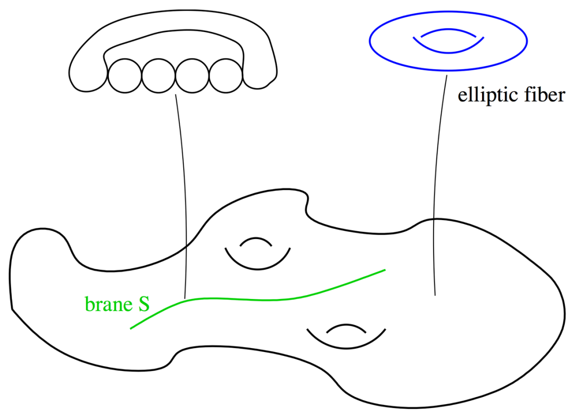
- replace singular point in fibre by tree of $\mathbb{P}^1_i$ $\quad i = 1, \ldots, \mathrm{rk}(G)$



- **Group theory of G $\Longleftrightarrow$ extended Dynkin diagram**
- Each node of Dynkin diagram
  $\leftrightarrow$ stretched open strings
  $\equiv$ G-gauge bosons

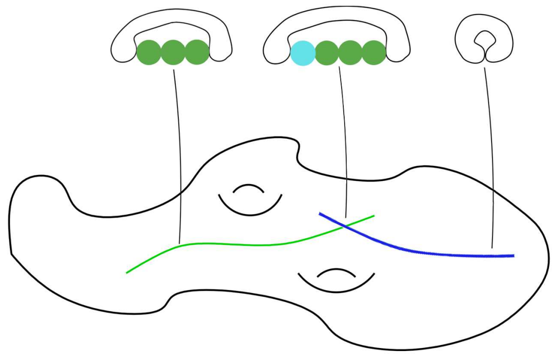


SU(5)-bosons over 4-cycle $S \subset B_3$:
$\Leftrightarrow$ SU(5)-GUT theory on 7-brane



SU(5) GUT models in F-theory

Further singularity enhancement at **intersection of S and single branes D**



a) matter: enhancement of singularity type on intersection $S \cap D$

- $SU(6) \to SU(5) \times U(1)$ [Katz,Vafa '96]
  $\mathbf{35} \to \mathbf{24} + 1 + \mathbf{5} + \overline{\mathbf{5}}$ $\Longrightarrow \overline{\mathbf{5}}_m = (d_R^c, L)$ or $\mathbf{5}_H + \overline{\mathbf{5}}_H$
- $SO(10) \to SU(5) \times U(1)$
  $\mathbf{45} \to \mathbf{24} + 1 + \mathbf{10} + \overline{\mathbf{10}}$ $\Longrightarrow \mathbf{10} = (Q_L, u_R^c, e_R^c)$

b) Yukawas: Intersection of curves at points [BHV; DW] '08

- $\langle \mathbf{10}\,\overline{\mathbf{5}}\,\overline{\mathbf{5}} \rangle \subset \langle (\mathbf{66})^3 \rangle$ of SO(12) as in perturbative Type IIB
- $\langle \mathbf{10}\,\mathbf{10}\,\mathbf{5} \rangle \subset \langle (\mathbf{78})^3 \rangle$ of $\mathbf{E_6}$ **(only) truly F-theoretic input**

Putting things in perspective

Strengths of this approach:

- Much of physics is geometrised

  even D(-1)-instantons: [Billo,Frau,Giacone,Lerda,Pesando,...]

- Complex geometry guarantees compatibility of non-perturbative branes
  $\rightarrow$ exceptional symmetry as required for GUT physics

Drawback:

- No direct worldsheet techniques available

Complementary type of constructions overcome this difficulty:

perturbative Type I/ Type II orientifolds/orbifolds

starting with [Bianchi,Sagnotti'89]/[Gimon-Polchinski'96];

chirality implemented in [Angelantonj,Bianchi,Pradisi,Sagnotti,Stanev'96]

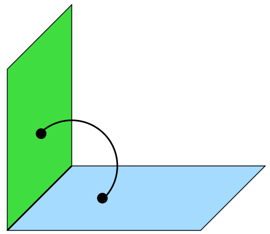
✓ explicit control over string tower

✓ direct evaluation of string amplitudes at high level of sophistication

Gauge backgrounds

Matter states in $\mathbb{R}^{1,3}$:

$\leftrightarrow$ wave functions on $2_\mathbb{R}$-dim.
matter curve C_R



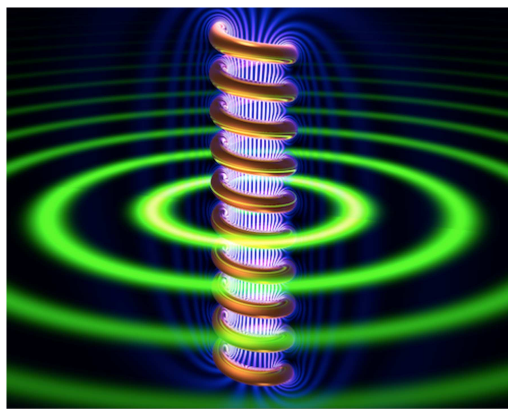
Inspiration from 2-dim. Euclidean QFT:

$\#$ of charged fermionic zero modes $\leftrightarrow$ background gauge field A

- chiral index: $\mathrm{ind}_{\not{D}} = \nu_+ - \nu_- = \frac{1}{2\pi} \int_{C_R} F$ $\qquad D = \partial - ieA$
  - known via anomalies (Fujikawa): $\mathrm{ind}_{\not{D}} = \frac{1}{2} \partial_\mu j_5^\mu$
  - Atiyah-Singer-index theorem

  $\leftrightarrow$ field strength F

- on top. non-trivial C_R:
  $\oint A$ affects non-chiral spectrum



Gauge background

$\leftrightarrow$ **massless spectrum**

III.) Specifics of SU(5) GUT model building

SU(5) GUT model building

Challenges of SU(5) GUT theory:

1. SU(5) GUT breaking
2. Doublet-Triplet splitting in Higgs sector
3. Proton Decay
4. Detailed Flavour structure, μ-term, . . .

Two principal model building ideas in F-theory:

- **GUT breaking via Hypercharge flux** [BHV,DW '08]
- **Splitting of matter curves**

Status of these two ingredients:

- at first sight local ($\equiv$ depending only on GUT brane S)
- on closer inspection, they require understanding of global details
  $\Longrightarrow$ triggered a lot of formal progress
  with many important questions still open

Hypercharge flux GUT breaking

SU(5) field strength on 7-brane $\mathcal{F} = \underbrace{\mathbb{F}}_{\text{4 large dim.}} + \underbrace{F}_{\text{along } S}$

Decomposition:

$$F = \sum_a T^a_{SU(3)} F_a + \sum_i T^i_{SU(2)} F_i + T^Y F_Y$$

hypercharge generator $T_Y = \mathrm{diag}(-2,-2,-2,3,3) \subset SU(5)$

Vacuum expectation value $\langle F_Y \rangle = \langle dA_Y \rangle \neq 0$ on GUT brane S

- $SU(5) \longrightarrow SU(3) \times SU(2) \times U(1)_Y$

  $\mathbf{24} \to (\mathbf{8},\mathbf{1})_{0_Y} + (\mathbf{1},\mathbf{3})_{0_Y} + (\mathbf{1},\mathbf{1})_{0_Y} + \cancel{(\mathbf{3},\mathbf{2})_{5_Y}} + \cancel{(\overline{\mathbf{3}},\mathbf{2})_{-5_Y}}$
  $\overline{\mathbf{5}} \to (\overline{\mathbf{3}},\mathbf{1})_{2_Y} + (\mathbf{1},\mathbf{2})_{-3_Y}$
  $\mathbf{10} \to (\mathbf{3},\mathbf{2})_{1_Y} + (\overline{\mathbf{3}},\mathbf{1})_{-4_Y} + (\mathbf{1},\mathbf{1})_{6_Y}\,,$
  $\mathbf{5}_H \to (\mathbf{3},\mathbf{1})_{-2_Y} + (\mathbf{1},\mathbf{2})_{3_Y}\,, \quad \overline{\mathbf{5}}_H \to (\overline{\mathbf{3}},\mathbf{1})_{2_Y} + (\mathbf{1},\mathbf{2})_{-3_Y}$

- do not introduce exotic chiral multiplets in $(\mathbf{3},\mathbf{2})_{5_Y} + (\overline{\mathbf{3}},\mathbf{2})_{-5_Y}$ from $\mathbf{24}$ on bulk of S ✓

Doublet-Triplet Splitting

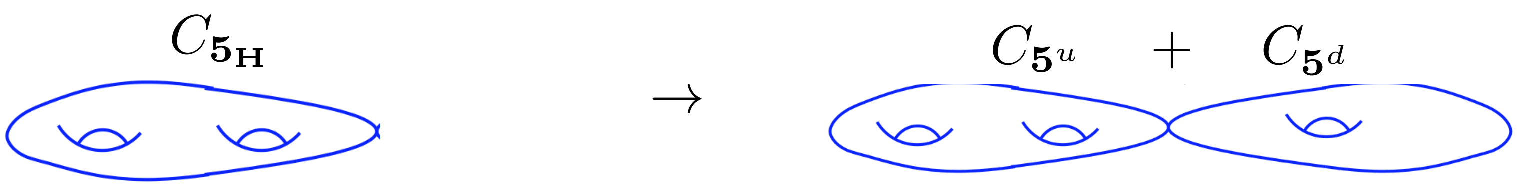
1) Matter from complete GUT multiplets on curves

e.g. $\mathbf{10} \rightarrow (\mathbf{3}, \mathbf{2})_{1_Y} + (\overline{\mathbf{3}}, \mathbf{1})_{-4_Y} + (\mathbf{1}, \mathbf{1})_{6_Y}$

$$\int_{C_{10}} F_Y \overset{!}{=} 0 \overset{!}{=} \int_{C_{\overline{\mathbf{5}}_\mathbf{m}}} F_Y$$

2) Higgs from incomplete GUT multiplets on split curves

$$\mathbf{5}_H \rightarrow \underbrace{\cancel{(\mathbf{3}, \mathbf{1})_{-2_Y}}}_{T^u} + \underbrace{(\mathbf{1}, \mathbf{2})_{3_Y}}_{H^u} \qquad \overline{\mathbf{5}}_H \rightarrow \underbrace{\cancel{(\overline{\mathbf{3}}, \mathbf{1})_{2_Y}}}_{T^d} + \underbrace{(\mathbf{1}, \mathbf{2})_{-3_Y}}_{H^d}$$



$$\int_{C_{10}} F_Y \overset{!}{=} 0 \overset{!}{=} \int_{C_{\overline{\mathbf{5}}_\mathbf{m}}} F_Y, \qquad \int_{C_{\mathbf{5^{u/d}}}} F_Y \overset{!}{\neq} 0$$

Crucial for success: **Hierarchies of localisation of states**

Proton Decay

Conventional SU(5) GUTs suffer from too large proton decay

Dimension 4: $W \subset \lambda\, \mathbf{10}\, \overline{\mathbf{5}}_{\mathbf{m}}\, \overline{\mathbf{5}}_{\mathbf{m}}$

- gives rise to R-parity violating $u^c_R\, d^c_R\, d^c_R$, $L\, L\, e^c_R$, $Q\, L\, d^c_R$
- Experimental bound: $\lambda \overset{!}{\leq} 10^{-12}$
- **Necessary condition**: $C_{\mathbf{5_m}}$, $C_{\mathbf{5_H}}$ are different curves [BHV '08]

  otherwise: $\mathbf{10}\, \overline{\mathbf{5}}_{\mathbf{m}}\, \overline{\mathbf{5}}_{\mathbf{H}}$ implies $\mathbf{10}\, \overline{\mathbf{5}}_{\mathbf{m}}\, \overline{\mathbf{5}}_{\mathbf{m}}$
- **Curve split is not sufficient** - see later [Watari et al.'09]

Dimension 6:

- From exchange of heavy gauge bosons in $(\mathbf{3}, \mathbf{2}) + (\overline{\mathbf{3}}, \mathbf{2})$
- decay rate is well within experimental bounds if $M_{\rm GUT} = 10^{16}$GeV

  $\rightarrow$ no problem in SUSY GUTs ✓

Proton decay

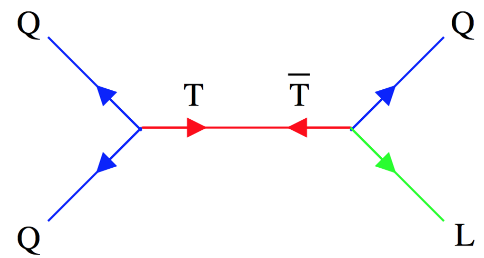
Dimension 5: focus on effective terms of type $W \supset \frac{c^2}{M_{\rm eff}} \mathbf{10\,10\,10\,\bar{5}_m}$

- effective terms of type $\frac{c^2}{M_{\rm eff}}(QQQL + u^c_R u^c_R d^c_R e^c_R)$
- via tripletino exchange, e.g.

  $\mathbf{5_H} = (T_u, H_u), \mathbf{\bar{5}_H} = (T_d, H_d)$:

  $QQT_u + QLT_d + M_{KK} T_u T_d \rightarrow \frac{1}{M_{KK}} Q\,Q\,Q\,L$

  $\leftrightarrow$ present if T_u, T_d on same curve C_{5_H}



- Remedy: Missing partner mechanism

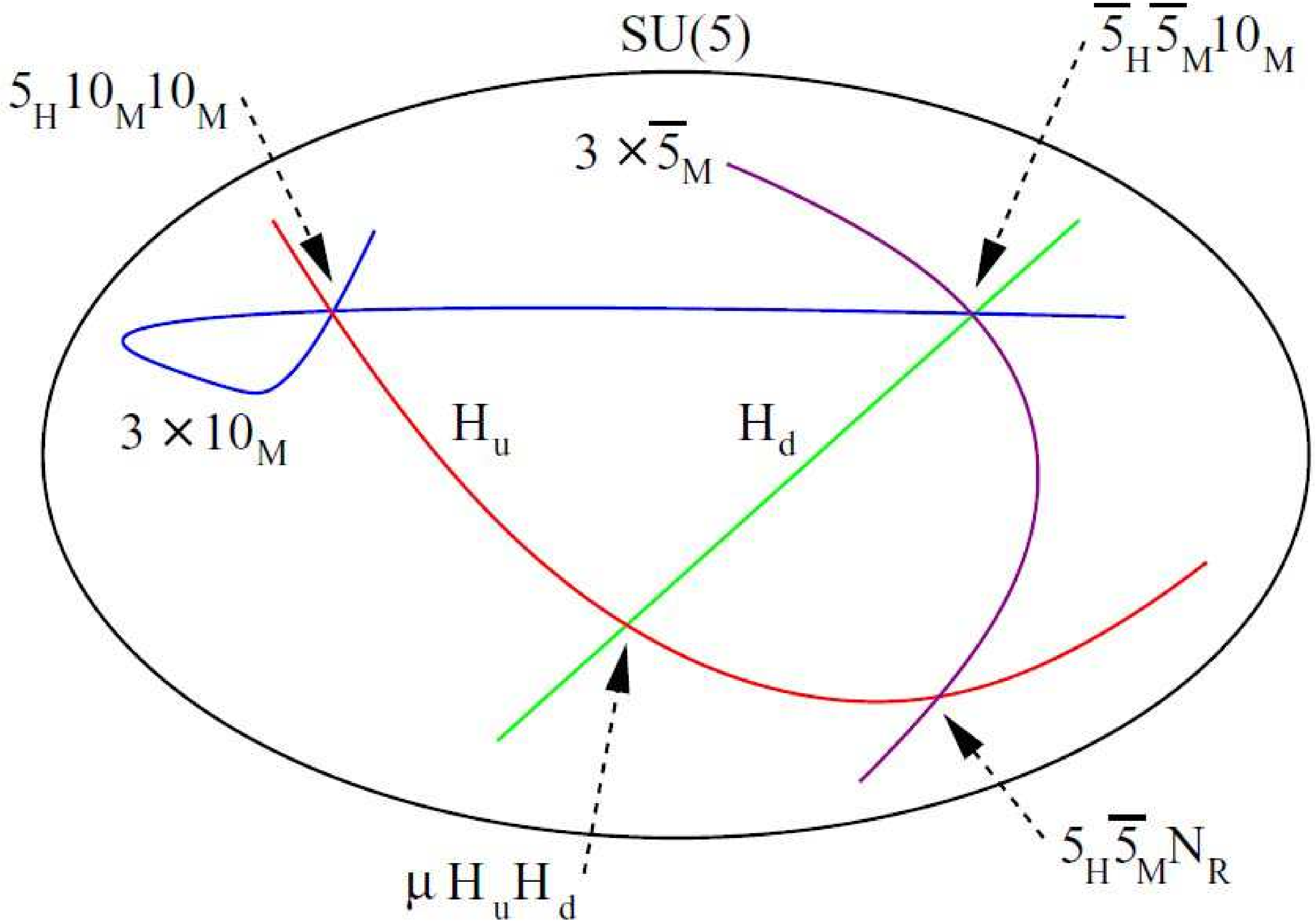
  $QQT_u + QLT_d + M_{KK} T_u \tilde{T}_d + M_{KK} \tilde{T}_u T_d$

  $\Longrightarrow$ no integration to $QQQL$ possible
- **need H_u and H_d on two separate curves** [BHV, DW '08]
- This also prevents an $\mathcal{O}(1)$ μ term $\mu H_u H_d$ ✓

  and realises doublet-triplet splitting ✓

SU(5) GUTs

Necessary conditions on **local** geometry of GUT brane:



Beasley,Heckman,Vafa, 0806.0102

IV.) New F-theory technology for model building

The need for U(1) symmetries

Problem: [Watari et al.'09]

- local split of matter curves on S insufficient for absence of couplings
- dangerous Yukawa points will in general still be present

Sufficient criterion: [Marsano,Saulina,Schäfer-Nameki '09]

- **Extra U(1) selection rules** must distinguish between matter curves
- Generically pattern of Yukawas agrees with allowed charges
- Example $SU(5) \times U(1)$: $\mathbf{10}_{q_1}$ $(\bar{\mathbf{5}}_{\mathbf{m}})_{q_2}$ $(\mathbf{5}_{\mathbf{H^u}})_{q_3}$ $(\bar{\mathbf{5}}_{\mathbf{H^d}})_{q_4}$

  $\mathbf{10}\,\bar{\mathbf{5}}_{\mathbf{m}}\,\bar{\mathbf{5}}_{\mathbf{H}} : q_1 + q_2 + q_4 \overset{!}{=} 0$ $\qquad$ $\mathbf{10}\,\mathbf{10}\,\mathbf{5}_{\mathbf{H}}: 2q_2 + q_3 \overset{!}{=} 0$

  $\cancel{\mathbf{10}\,\bar{\mathbf{5}}_{\mathbf{m}}\,\bar{\mathbf{5}}_{\mathbf{m}}}: q_1 + 2q_2 \overset{!}{\neq} 0$ $\qquad$ $\cancel{\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\bar{\mathbf{5}}_{\mathbf{m}}} : 3q_1 + q_2 \overset{!}{\neq} 0$

Technical Challenge:

- Understanding abelian gauge symmetries in F-theory
- U(1)s are beyond the local regime

U(1) groups in F-theory

General lore: [Morrison,Vafa'96]

- U(1) gauge potential from expansion of M-theory 3-form

$$C_3 = \underbrace{A}_{4\,\mathrm{dim.}} \wedge \underbrace{\mathsf{w}}_{\mathrm{on}\, Y_4} + \ldots \qquad\qquad \mathsf{w} \in H^{1,1}(Y_4)$$

- presence of such new 2-forms w

  $\leftrightarrow$ geometric constraint on complex structure of 4-fold geometry

  Y_4 must allow for **extra rational sections** $\leftrightarrow$ **Mordell-Weil group**

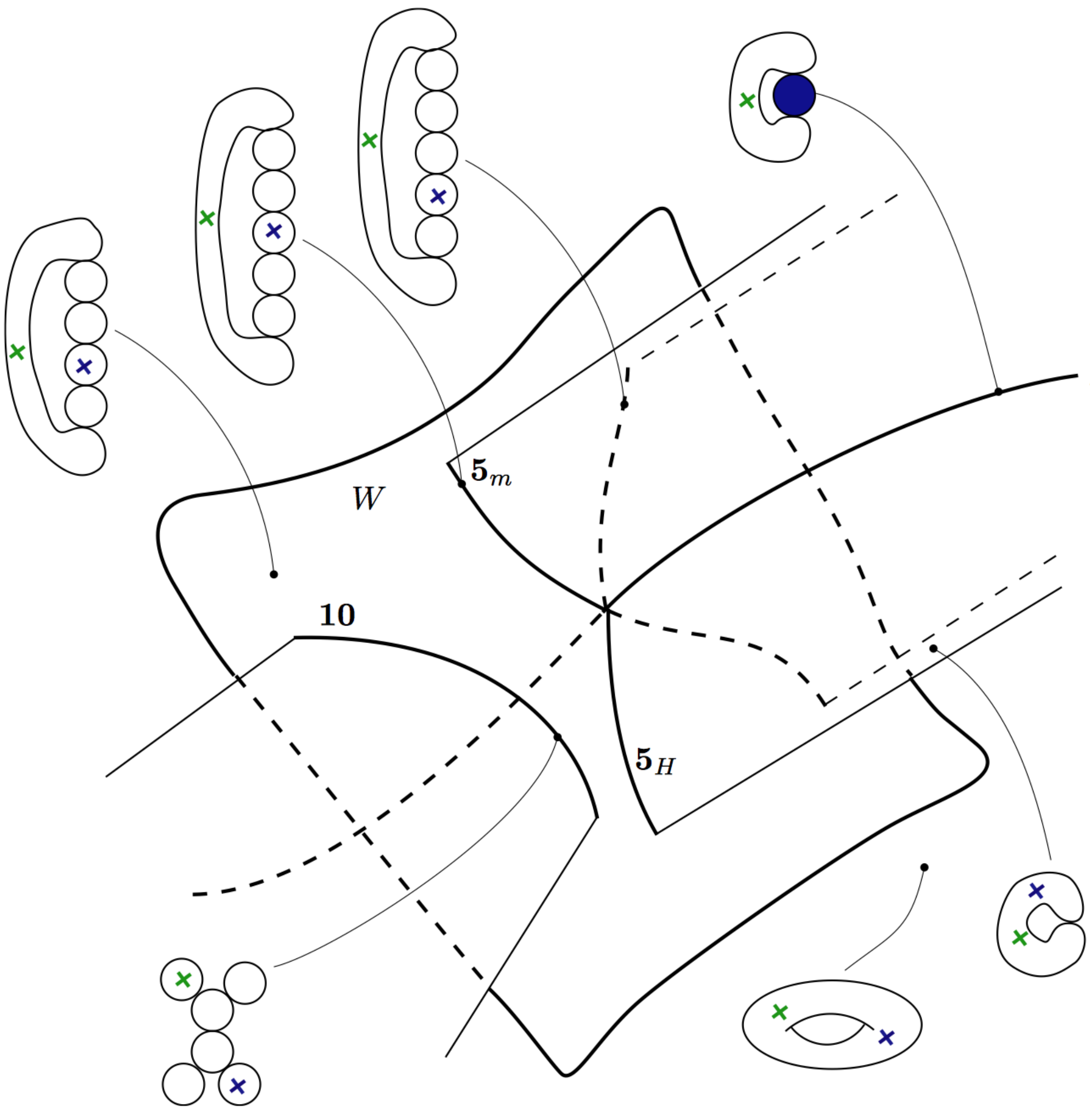
Implementation in full 4-fold Y_4: [Grimm,TW' 10], ...

- Matter curves on S automatically split in agreement with their charges
- New matter curves arise away from S $\Rightarrow$ **charged SU(5)-singlets**

  $\leftrightarrow$ unHiggsing of U(1)

  $\leftrightarrow$ candidate for N_R^c

U(1) groups in F-theory



Mayrhofer,Krause,TW 1109.3454

SU(5) × U(1) × U(1)

[Borchmann,Mayrhofer,Palti,TW] [Cvetič,Klevers,Grassi,Piragua]'13

Explicit description of Y_4 as hypersurface in $\mathbb{P}^2[3]$:

5 inequivalent toric $SU(5) \times U(1) \times U(1)$ realisations

Example:

$$0 = b_{0,2} w^2 s_0^2 \mathsf{v}^2 \mathsf{u} + c_{2,1} w s_0 \mathsf{w} \mathsf{v}^2 + d_{0,2} w^2 \mathsf{v} s_0^2 s_1 \mathsf{u}^2 + + b_1 s_0 s_1 \mathsf{w} \mathsf{v} \mathsf{u} + c_1 \mathsf{w}^2 \mathsf{v} s_1 + d_{2,2} w^2 s_0^2 s_1^2 \mathsf{u}^3 + d_1 s_0 s_1^2 \mathsf{w} \mathsf{u}^2 + b_2 s_1^2 \mathsf{w}^2 \mathsf{u}$$

Curve on $\{w = 0\}$	Matter representation	
$\{b_1 = 0\}$	$\mathbf{10}_{\mathbf{-1,2}}$	$\mathbf{10}$
$\{b_{0,2} = 0\}$	$\mathbf{5}_{\mathbf{-3,1}}$	–
$\{c_{2,1} = 0\}$	$\mathbf{5}_{\mathbf{2,-4}}$	$\mathbf{5}_{\mathbf{H^u}}$
$\{c_1 = 0\}$	$\mathbf{5}_{\mathbf{2,6}}$	$\mathbf{5}_{\mathbf{m}}$
$\{b_1 b_2 - d_1 c_1 = 0\}$	$\mathbf{5}_{\mathbf{-3,-4}}$	$\mathbf{5}_{\mathbf{H^d}}$
$\{d_{2,2} b_1^2 + d_1 (b_{0,2} d_1 - d_{0,2} b_1 = 0\}$	$\mathbf{5}_{\mathbf{2,1}}$	–

In addition: 6 charged singlet curves, including $\mathbf{1}_{\mathbf{5,10}} \equiv N_R^c$

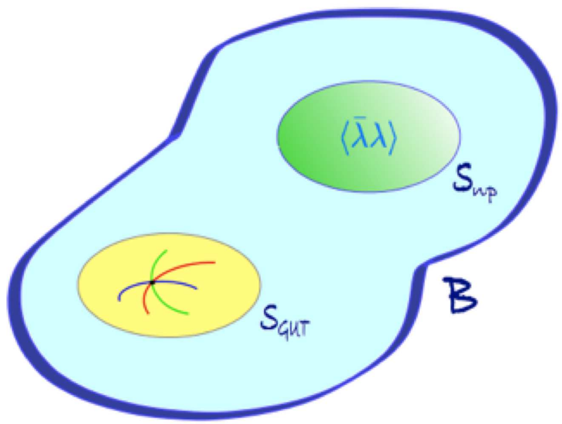
Yukawa textures

Yukawas $\leftrightarrow$ overlap of matter wavefunction at curve intersection point

$\rightarrow$ at first sight 'ultra-local'

Approach 1: All families from the same curve

- For single Yukawa point, mass matrix of rank 1 [BHV'08]
- Subleading non-pert corrections from D3/M5-instantons [Marchesano,Martucci'09] [Font,Ibanez,Marchesano13]
  $M_i \simeq (1, \epsilon, \epsilon^2)$ with $\epsilon \simeq e^{-S_{\rm inst}}$
- instantons are global data!



Font et al.,1307.8089

Approach 2: Different families from different curves

- U(1) selection rule allows for top coupling, but forbids others
- subleading correction either from instantons or due to Froggatt-Nielson mechanism after giving VEV to singlets [Palti'09], ...
- Both depends on global data.

Discrete symmetries

Studied in in various types of string constructions

[Camara,Marchesano,Ibanez][Uranga,Berasaluce et al.][Honecker,Staessens] '11-'15

One way to obtain discrete $\mathbb{Z}_k$ gauge symmetry is by Higgsing $U(1)$ with particle of charge k

- Higgs $\Phi = \varphi\, e^{ic}$: $\quad A \to A - d\chi, \quad c \to c + k\,\chi$
- After integrating out φ: $\quad S \simeq \int (dc + kA)^2 + \ldots$

Expectation in F/M-theory: [Camara,Marchesano,Ibanez][Grimm,Kerstan,Palti,TW]'11

- massive $\mathbb{Z}_k$ gauge field and Stuckelberg axion c from expansion

$$C_3 = c \wedge \alpha_3 + A \wedge \mathrm{w}_2, \qquad \mathbf{d\mathrm{w}_2 = k\,\alpha_3}$$

- $\int_{11D} (dC_3)^2 \simeq \int_{11D} (dc \wedge \alpha_3 + A \wedge d\mathrm{w}_2)^2 + \ldots \Longrightarrow \int (dc + kA)^2 + \ldots$

Thus **smoking gun for $\mathbb{Z}_k$ symmetry** should be $\mathrm{Tor} H^3(Y, \mathbb{Z}) = \mathbb{Z}_k$

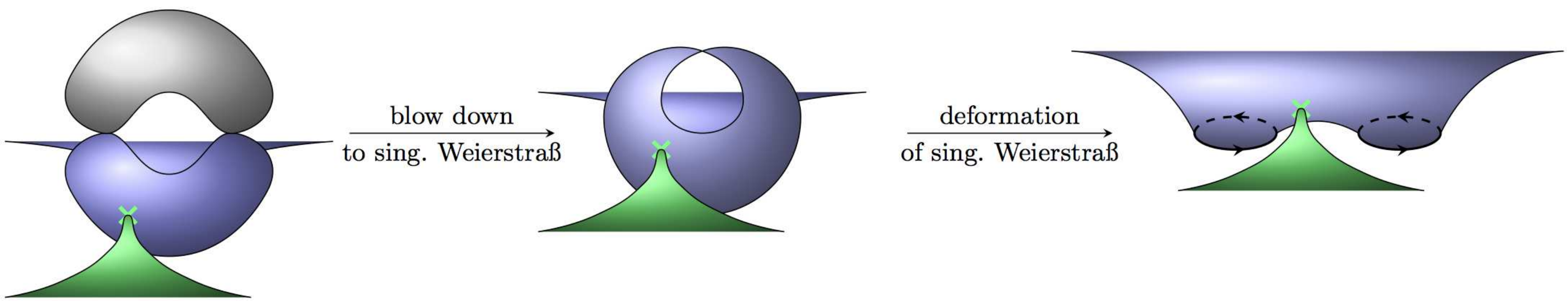
Discrete symmetries in F-theory

Recent activities have studied implementation in F-theory

[Morrison,Braun][Morrison,Taylor][(Anderson),Grimm,Keitel,Garcia-Etxebarria]

[Klevers,Mayorga,Oehlmann,Piragua,Reuter] [Mayrhofer,Palti,Till,TW]’14

- Higgsing described as topology changing process



- Explicit verification of conjecture that full lattice of magnetic and electric line operators physically realized in quantum gravity
- Phenomenological payoff:
  $SU(5) \times \mathbb{Z}_2$ R-parity model

The F-theory dictionary

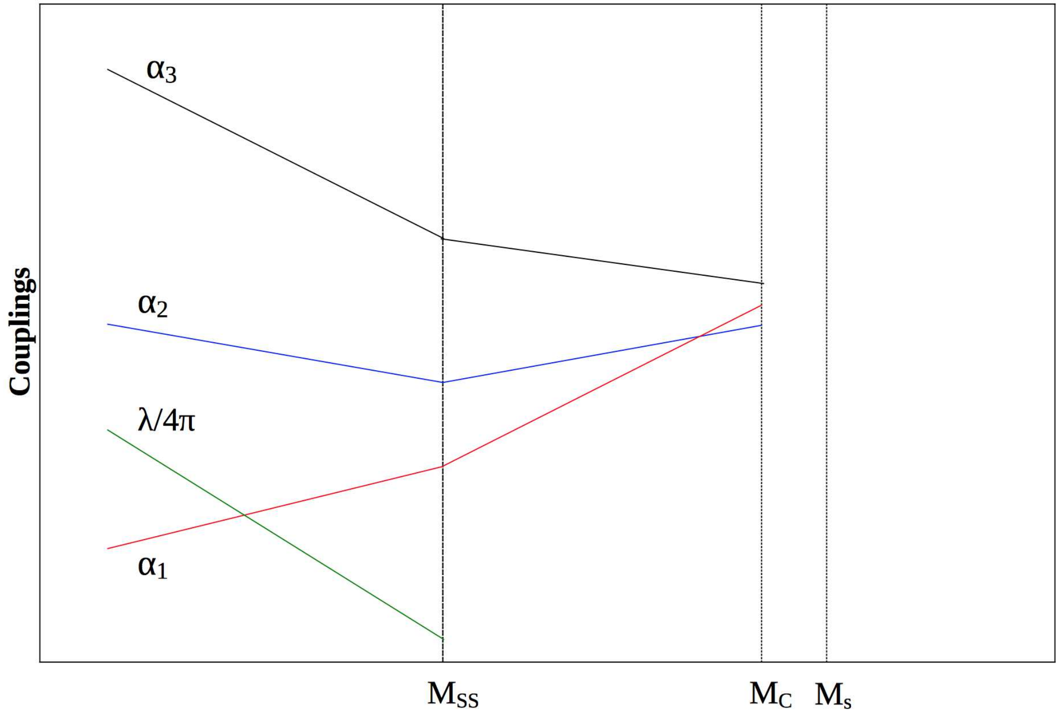
gauge theory data	geometric data
non-abelian gauge algebra $\mathfrak{g}$	singularities in codim. 1
gauge group G	torsional Mordell-Weil group *
abelian gauge groups	free Mordell-Weil group *
discrete gauge group factor	Tate-Shafarevich group *
matter representations	singularities in codim. 2
Yukawas	singularities in codim. 3*

$*$: systematic understanding beginning in 2010

Intermediate-SUSY GUTs

[Ibanez,Marchesano,Regalado,Valenzuela'12]

- Push $M_{\rm SUSY}$ up to 10^{11} GeV, where quartic Higgs coupling $\lambda = 0$.
- Standard gauge coupling unification is destroyed.
- Effect can be cancelled in principle against hypercharge-flux correction of [Blumenhagen'08]



Scenario:

$M_{\rm SUSY} = 10^{11}$GeV $\qquad M_{\rm GUT} = 10^{14}$GeV

Claim:

Dimension 6 proton decay from $X - Y$ boson exchange might be suppressed due to wavefunction distortion via hypercharge flux

(See however [Hebecker,Unwin'14])

Summary

String theory is a well-founded conceptual framework that can serve as top-down guidance for model building

F-theory GUTs as one example for fruitful interplay
internal geometry $\leftrightarrow$ field theory

Key question for phenomenology: Status of TeV-scale supersymmetry?

- many realizations of low-energy SUSY in string compactifications (e.g. via large volume compactifications of Type IIB with fluxes)
- But string theory does not require low-energy SUSY to work - not even in GUT context!
- Intermediate SUSY with interesting implications for Higgs mass
  Status of high-scale SUSY breaking? stability?

We have only started to explore the string solution space!