GUTs in Type IIB String Compactifications

Thomas W. Grimm

Bethe Center for Theoretical Physics

based on work in progress

0906.0013 [hep-th] with R. Blumenhagen, B. Jurke, T. Weigand

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PASCOS, Hamburg, July 2009

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What is F-theory?

- F-theory is Type IIB string theory with varying dilaton-axion $\tau = C_0 + i/g_s$
  $\Rightarrow$ string coupling g_s space-time dependent $\Rightarrow$ 12-dim auxiliary theory Vafa

  Important case: four-dim compactifications with dilaton varying over compact space

Type IIB string theory with varying dilaton-axion τ over internal 6-dim manifold B_3	$\cong$	F-theory on elliptically fibered Calabi-Yau fourfold Y_4 (8-dim) with base B_3 τ is complex structure of 2-torus at each point in B_3

- F-theory provides a geometrical framework encoding non-perturbative physics in g_s:
  examples: 7-branes wrapping four-cycle in B_3 are encoded by fibration of Y_4

- Orientifold limit: Type IIB orientifold with D7-branes and O7-planes Sen
  - string coupling becomes small away from the 7-branes and peaks at the sources

GUT models and Compactification

- Recently, there has been much progress in realizing GUT models in local F-theory constructions on intersect. 7-branes   Beasley,Heckman,Vafa; Donagi,Wijnholt

  ⇒ various new insights for models for which gravity can be decoupled
  important example: new mechanism to break GUT group

  However:
  New GUT breaking in local F-theory models requires knowledge about global geometry.
  Cannot address global constraints. Restrictive?
  Cannot address moduli stabilization in local set-ups. Value of couplings?

- Construction of compact scenarios with all the desired properties is more challenging:
  ⇒ general F-theory background: construction of viable compact Calabi-Yau fourfolds
  ⇒ new consistency conditions (such as tadpole cancellation)

  recent works: Donagi,Wijnholt; Marsano,Saulina,Schäfer-Nameki
  Blumenhagen,TG,Jurke,Weigand; Collinucci

The Problem

Construct compact Calabi-Yau fourfold examples with fluxes which support a GUT model in a local region.

- shrinkable complex surface supports $SU(5)$ GUT 7-brane
  $\Rightarrow$ mathematical fact: 7-brane has to be on a del Pezzo surface
- study the full geometry of the Calabi-Yau fourfold, not just the base B_3
- compute and cancel all global tadpoles
- compute four-dimensional spectrum and couplings

Our Approach

[1.] construct GUT models in perturbative Type IIB orientifold compactifications which realize many interesting features of local F-theory GUTs Blumenhagen,Braun,TG,Weigand

- Advantage: conceptually very clear, rich classes of Calabi-Yau orientifold geometries
- Disadvantage: obstacle for fully realistic GUT models is the perturbative absence of certain couplings, e.g. the $10\,10\,5_H$-Yukawas

[2.] lifting orientifold GUTs to F-theory, in particular: constructing Calabi-Yau fourfold Blumenhagen,TG,Jurke,Weigand; Collinucci

[3.] identify a new large class of Calabi-Yau fourfold geometries which posses all the desired features work in progress

- Advantage: in the class of fourfolds also models with $10\,10\,5_H$-Yukawas and other non-perturbative couplings are permitted
- Advantage: full computational control using the powerful tools of toric geometry

Building Models in Type IIB orientifolds

➪ Calabi-Yau Orientifolds: Calabi-Yau space Y + orientifold involution

- orientifolds with $O3$ / $O7$ planes: $\Omega_p\,(-1)^{F_L}\,\sigma$

  (Ω_p world-sheet parity, σ is holomorphic isometry)

➪ D7 branes with gauge bundles: Calabi-Yau manifold Y + D-branes

- stack of N_a space-time filling D7 branes wrapped on susy four-cycle $\iota : D_a \hookrightarrow Y$

  $\Rightarrow U(N_a)$ gauge group, preserve $\mathcal{N} = 1$ susy on world-volume

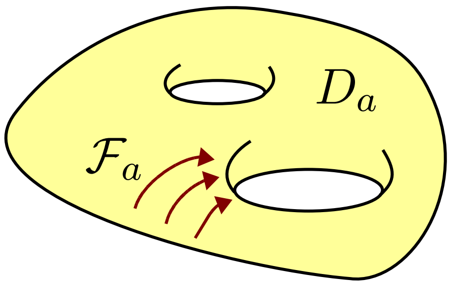
- D7-branes can carry a gauge flux bundle $\mathcal{F}_a$

  $\Rightarrow$ restrict to $\mathcal{F}_a$ of rank one: line bundles

  $$\mathcal{F}_a = \mathbf{1}_{N_a} F_a^{(0)} + \sum_i \mathbf{T}_i F_a^{(i)} \qquad (\mathrm{tr}(\mathbf{T}_i) = 0)$$

  – natural split $U(N_a) \to SU(N_a) \times U(1)_a$

  – $F_a^{(i)}$ can break $SU(N_a)$ further: split of $U(1)$ factors



➪ D- and F-terms form gauge bundles on D7 branes:

- gauge-flux $\mathcal{F}_a$ might induce a gauging + D-term: Jockers,Louis

Key point: since $\dim_{\mathbb{R}}(D_a) = 4$ there can be two-forms $F_a^{(i)}$ on which are non-trivial on D_a but non-trivial or trivial on Y

$\Rightarrow$ non-trivial parts of $\mathcal{F}_a \Rightarrow$ massive $U(1)$ via Green-Schwarz mechanism

$\Rightarrow$ trivial parts of $\mathcal{F}_a$ do not couple to bulk scalars $\Rightarrow$ massless $U(1)$

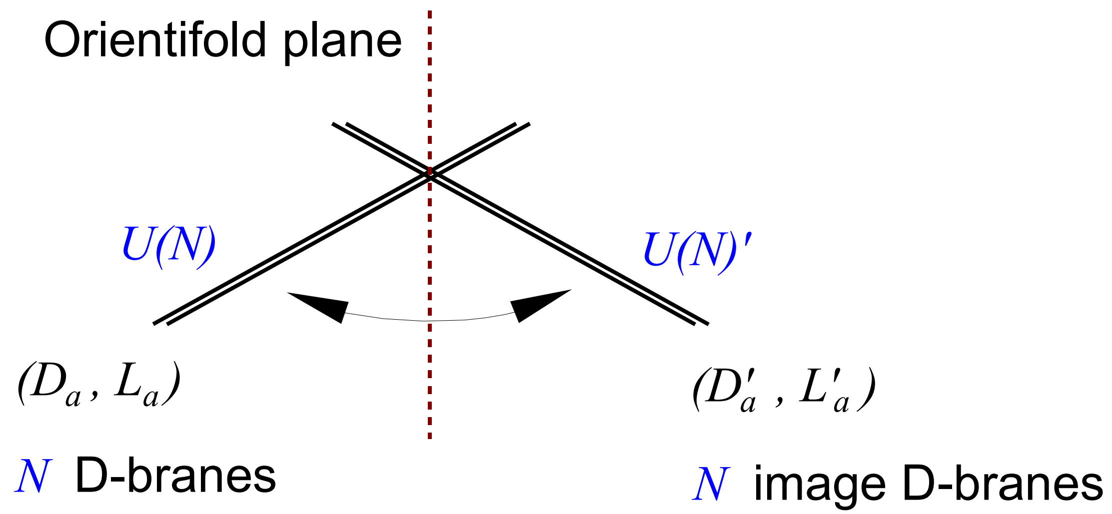
- D7-brane superpotential is function of D7-moduli and complex structure Witten

$$W = \int_{\mathcal{C}_5} \mathcal{F}_a \wedge \Omega \qquad\qquad D_a \subset \partial\mathcal{C}_5$$

- obtained e.g. from Witten's holomorphic Chern-Simons action
- dimensional reduction keeping non-dynamical three-forms TG,Ha,Klemm,Klevers
- can be computed explicitly in F-theory to appear: TG,Ha,Klemm,Klevers

➪ Orientifold planes and D-branes:

- orientifold involution σ maps D7-brane to image D7-brane:
  line bundles $\mathcal{F}'_a = -\sigma^* \mathcal{F}_a$



- D7-brane and image D7-branes might intersect in Riemann surfaces

- generically: two D7-branes in a threefold intersect in Riemann surfaces
  three D7-branes in a threefold intersect in points

➪ Tadpole cancellation: vanishing of all induced tadpoles in the compact Y/σ

- D7-tadpole:
$$\sum_a N_a \left([D_a] + [D'_a]\right) = 8\,[D_{O7}]$$

- induced D5-tadpole (from gauge-flux on D7-branes) and induced D3-charge (from essentially all sources) needs to be canceled

➪ Spectrum from intersecting D7-brane

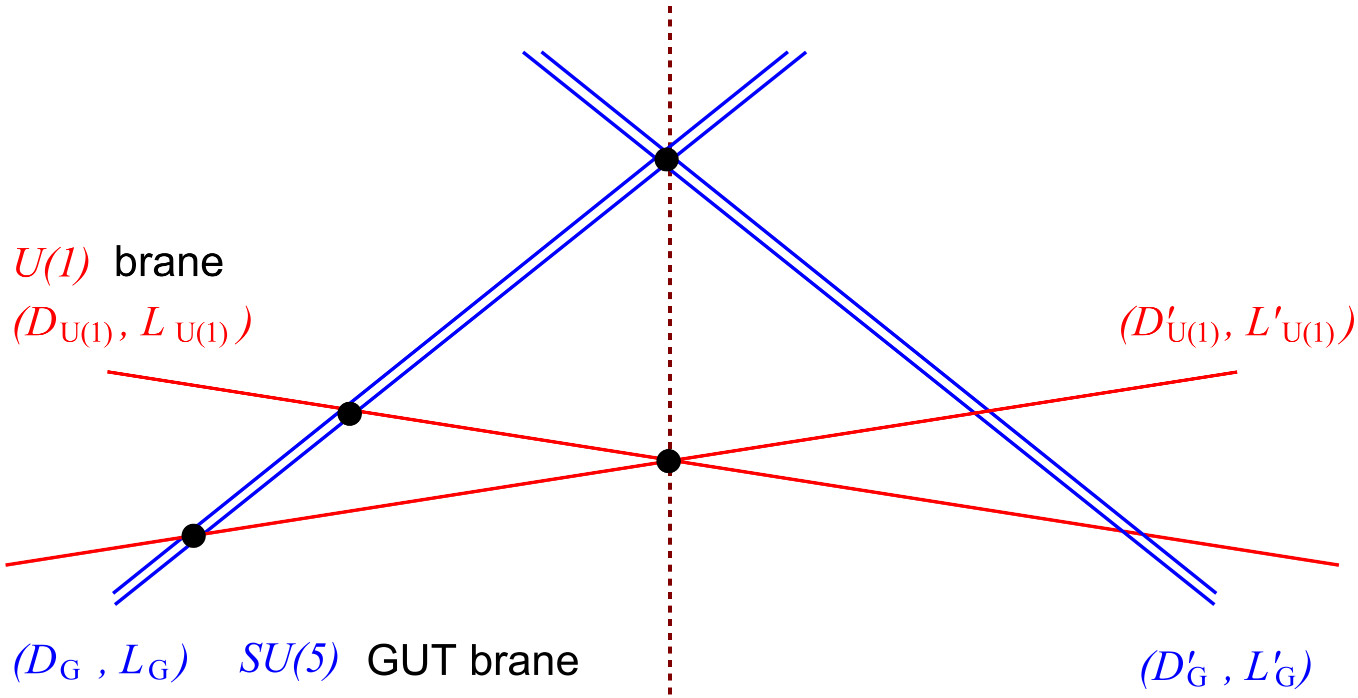
- adjoint matter from D7 branes: open strings ending on one D7-brane

$h^{2,0}(D_a)$ deformations of the brane
$h^{1,0}(D_a)$ Wilson line moduli

$\Rightarrow$ both absent for special four-cycles such as del Pezzo surfaces

- chiral matter from intersections: open strings ending on different D7-branes (bifundamental reps.,symmetric reps.,anti-symmetric reps.)

➪ Schematics of a GUT model from D7 branes:

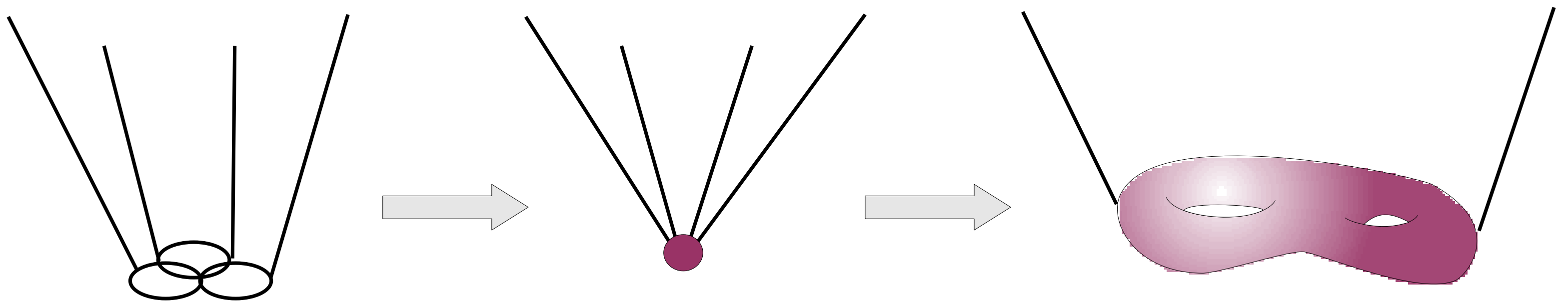


$\mathbf{10}$	3	$D_G \cap D'_G$
$\overline{\mathbf{5}}$	3	$D_G \cap D'_{U(1)}$
$\mathbf{1}_N$	3	$D_{U(1)} \cap D'_{U(1)}$
$\mathbf{5}_H + \overline{\mathbf{5}}_H$	$1+1$	$D_G \cap D_{U(1)}$

➪ Hypercharge GUT breaking: $SU(5) \times U(1) \to SU(3) \times SU(2) \times U(1)_Y \times U(1)$

Concrete compact GUT models

➪ Del Pezzo surfaces in a compact Calabi-Yau: del Pezzo transitions



Simple Examples:

- E_8 del Pezzo transition starting with $\mathbb{P}_{1,1,1,6,9}[18]$ Morrison, Vafa

  $h^{(1,1)} = 2,\ h^{(2,1)} = 272 \quad \longrightarrow \quad h^{(1,1)} = 3,\ h^{(2,1)} = 243$

- E_6 del Pezzo transition starting with quintic hypersurface

  $h^{(1,1)} = 1,\ h^{(2,1)} = 101 \quad \longrightarrow \quad h^{(1,1)} = 2,\ h^{(2,1)} = 90$

$\Rightarrow$ there exist whole chains of del Pezzo transitions realized in toric geometry

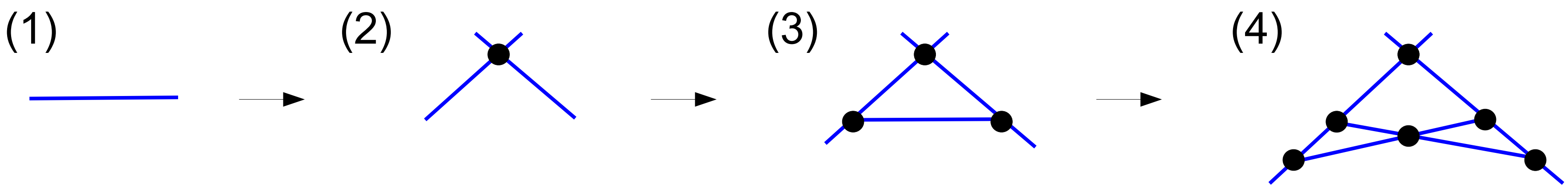
➪ continue to perform del Pezzo transitions torically (add further divisors)

Transition (1): generate one generic dP_6

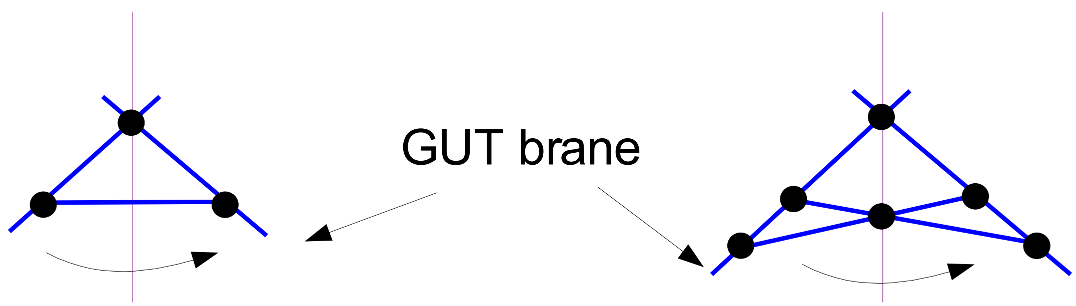
Transition (2): generate two intersecting dP_7 (intersecting in $\mathbb{P}^1$)

Transition (3): generate three intersecting dP_8

Transition (4): generate four intersecting dP_9



- always E_6 lattices trivial CY $\Rightarrow$ hypercharge flux
- simple quintic involutions extend to transitioned spaces



- able to completely analyze the compact CY (intersections, volumes etc.)
  $\Rightarrow$ realization of many of the desired GUT properties

F-theory up-lifts of orientifold GUTs

➪ main obstacle in orientifold GUTs: missing $\mathbf{10}^{(2,0)}\ \mathbf{10}^{(2,0)}\ \mathbf{5_H}^{(1,-1)}$ Yukawa

$\Rightarrow$ perturbative $U(1)$ symmetry can be brocken non-perturbatively

➪ F-theory provides a geometrical framework encoding non-perturbative physics in g_s

Recall: Vafa

Type IIB string theory with varying dilaton-axion $\tau = C_0 + i/g_s$ over internal threefold B_3	$\cong$	F-theory on elliptically fibered Calabi-Yau fourfold Y_4 with base B_3; τ is complex structure of elliptic fiber
7-branes on divisors in B_3 (e.g. D7-branes and O7-planes)	$\cong$	singularities of the elliptic fibration over divisors in B_3 with appropriate monodromies
two 7-branes inters. on curves in B_3; three 7-branes inters. on points in B_3	$\cong$	further singularity enhancement over curves/points in B_3

➪ $\mathbf{10}\,\mathbf{10}\,\mathbf{5_H}$ Yukawas are permitted in F-theory due to E_6 enhancements over points goal: lifting simple orientifold models to F-theory on Calabi-Yau fourfold

➪ first quintic transition with dP_6

- involution preserving del Pezzo divisor
- D7 tadpole $\Rightarrow$ $SO(8)$ gauge group: minimal gauge-group on dP_6
- D3 tadpole:

$$\frac{\chi_o(8H) + 8\chi_o(D_w)}{2} + 2\chi(O7) = 1224$$

➪ Constructing base B_3 for Calabi-Yau fourfold:

- non-Calabi-Yau 3-dim hypersurface in new toric ambient space
- note that B_3 is not Fano $\Rightarrow$ elliptic fibration over B_3 must degenerate to yield enhanced gauge groups
- $SO(8)$ singularities over dP_6 surface possible, but minimally G_2 enforced

  $\Rightarrow$ use Tate algorithm to determine gauge group

➪ D3-brane tadpole:

$SO(8)$ singularities must be blown up to determine Euler characteristic $\chi(Y_4)$

general result for G-degenerations over a divisor D Sethi,Vafa,Witten

Klemm,Lian,Roan,Yau; Andreas,Curio

$$\begin{aligned}\chi(Y_4) &= 12\int_{B_3} c_1(B_3)c_2(B_3) + 360\int_{B_3} c_1^3(B_3) - r_G c_G(c_G+1)\int_D c_1^2(D) \\ &= 1224 \qquad SO(8) \text{ in this example}\end{aligned}$$

➪ Exceptional gauge groups:

over B_3 can generate non-perturbative gauge enhancements:

$\Rightarrow$ obtain exceptional gauge groups:

example: E_6 gauge group on $dP_6 = \{\tilde{w} = 0\}$

$\Rightarrow$ enhancement to E_7 over Riemann surface

$\Rightarrow$ enhancement to E_8 over points: Yukawa couplings $\mathbf{27}^3$

$\Rightarrow$ no weak coupling orientifold limit

➪ $SO(10)$ couplings in the lifted B_3 the $\mathbf{10}\,\mathbf{10}\,\mathbf{5_H}$ is still absent

(O-planes do not intersect)

Conclusions

- Discussed constructions of GUTs in Type IIB orientifold compactifications
  - many of the local F-theory mechanisms can be realized (e.g. GUT breaking)
  - global consistency conditions
  - non-perturbative generations of the missing couplings needed $\Rightarrow$ F-theory

- Construction of promising class of compact CY orientifolds with intersecting del Pezzos

- Lift of orientifold models to F-theory:
  - elliptic fibrations over non-Fano bases which are hypersurfaces in toric space $\Rightarrow$ Calabi-Yau fourfolds as complete interesections
  - exceptional gauge enhancements are possible

- new class of Calabi-Yau fourfold geometries which can support GUT models
  $\Rightarrow$ full computational control using toric geometry (e.g. resolution of singular fibration)

- Not addressed: - four-form fluxes in F-theory
  - combination with moduli stabilization, susy breaking