Modern Perspectives on String Theory Compactification

Mirjam Cvetič

Outline:

Focus on D-branes & particle physics

I. Type II (D-branes at small string coupling)

→ emphasize Intersecting D-branes:

Standard Model & GUT's spectrum geometric

Highlight: nonperturbative effects D-instantons

(new geometric hierarchy)

Further progress: quiver constructions; global Type IIB models

II. F-theory (D-branes at finite coupling)

→Geometry of singular Calabi Yau manifolds

Focus on SU(5) GUT spectrum & couplings

Highlight: constructions with additional U(1)'s

instantons (time permitting)

III. Conclusions/Outlook

Perturbative String Theories → (finite) theory of quantum gravity

[Green,Schwarz'84]

Phenomenologically promising

Recent (MSSM): Bouchard,M.C.,Donagi'05 ...

Anderson,Gray,Lukas`09-'13...

Lebedev,Nilles,Raby,Ramos,Ratz Vaudrevange,Wingerter'07-'09...

Cleaver, Faraggi, Nanopoulos'01...

Heterotic E_8xE_8 string

Type IIA superstring

(closed)

Type IIB superstring

(closed)

Heterotic SO(32) string

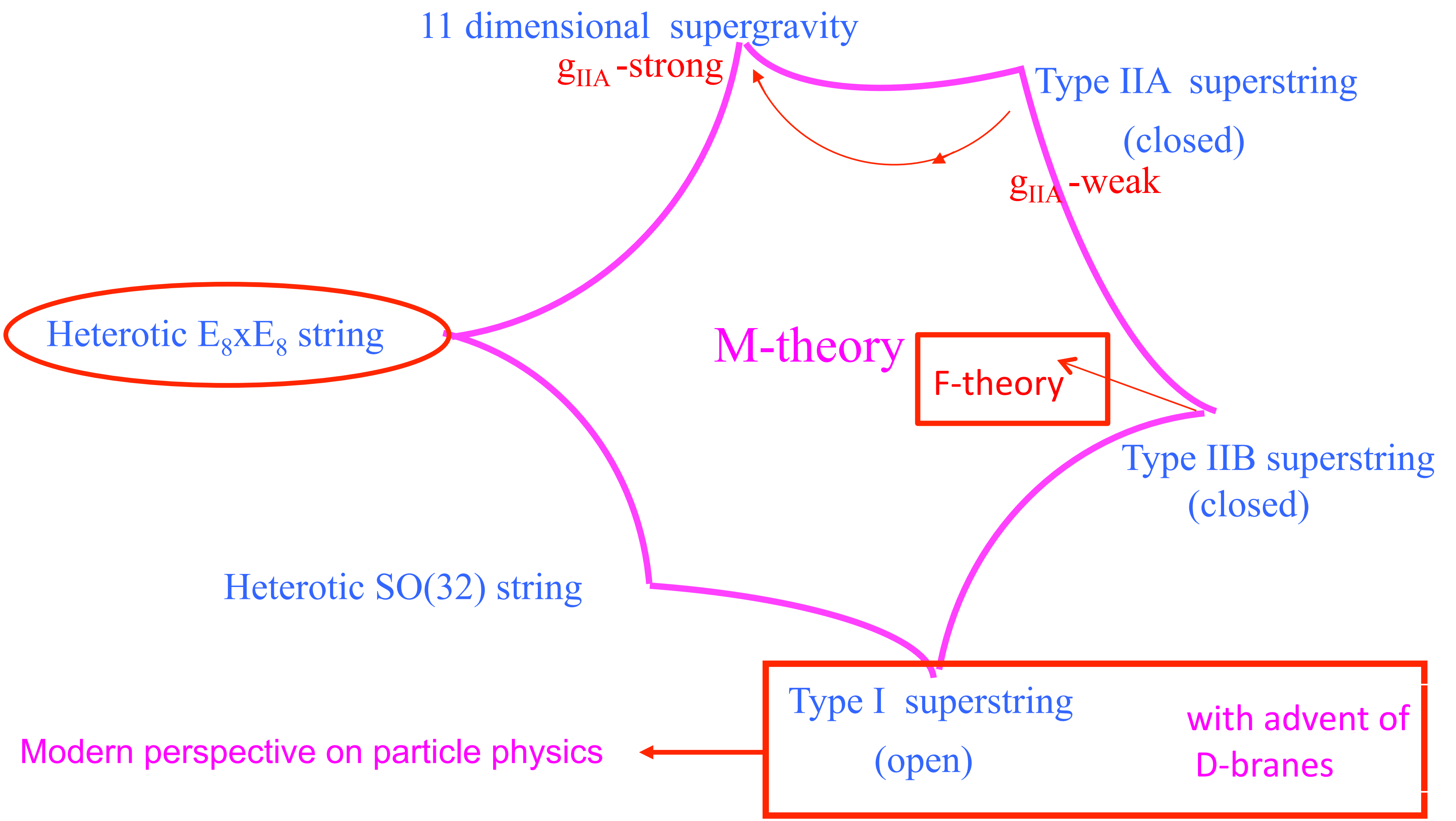
Type I superstring

(open)

Perturbative String Theories → (finite) theory of quantum gravity

[Hull,Townsend'94]
[Witten'95]

Non-perturbative Unification



Different String Theories related to each other by Weak-Strong Coupling DUALITY

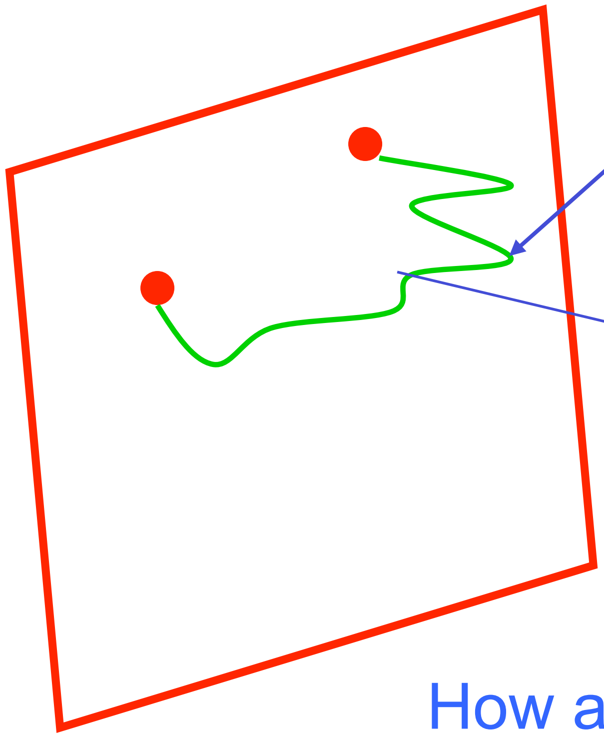
D-branes & Particle Physics →

Beautiful geometric relation to particles & forces of nature

Open strings w/ charges at the ends

Ends ``attached " to boundary of   Dp – branes [Polchinski'95]

Extends in p+1 dim. world-volume



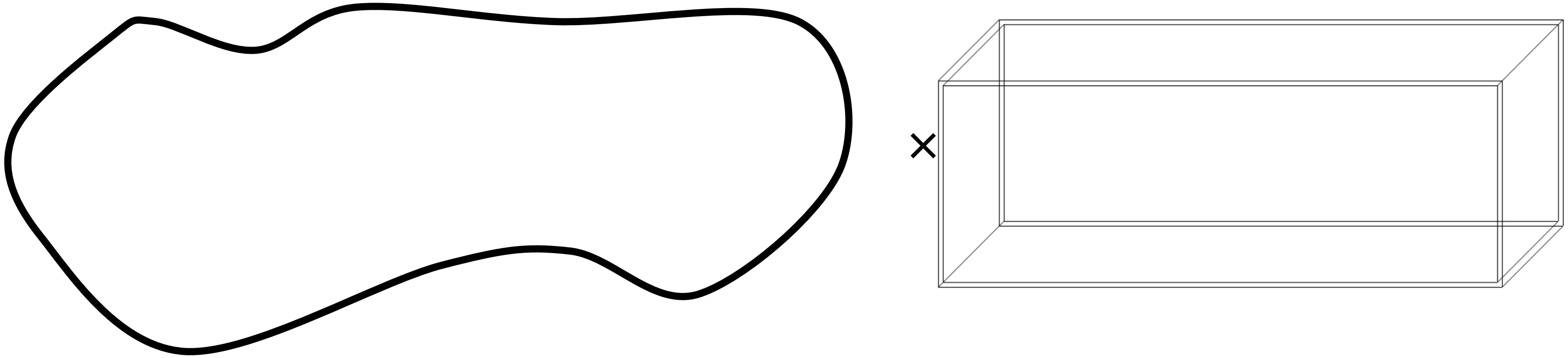
Quantum theory-string excitations
result in MASSLESS spin -1
Gauge bosons →
Photon, gluon, W,Z-bosons
live on D-branes

How about matter → compactification?

Compactification

$D=9+1 \longrightarrow D=3+1$

X_6-special space (Calabi-Yau) $\times$ $M_{(1,3)}$-flat



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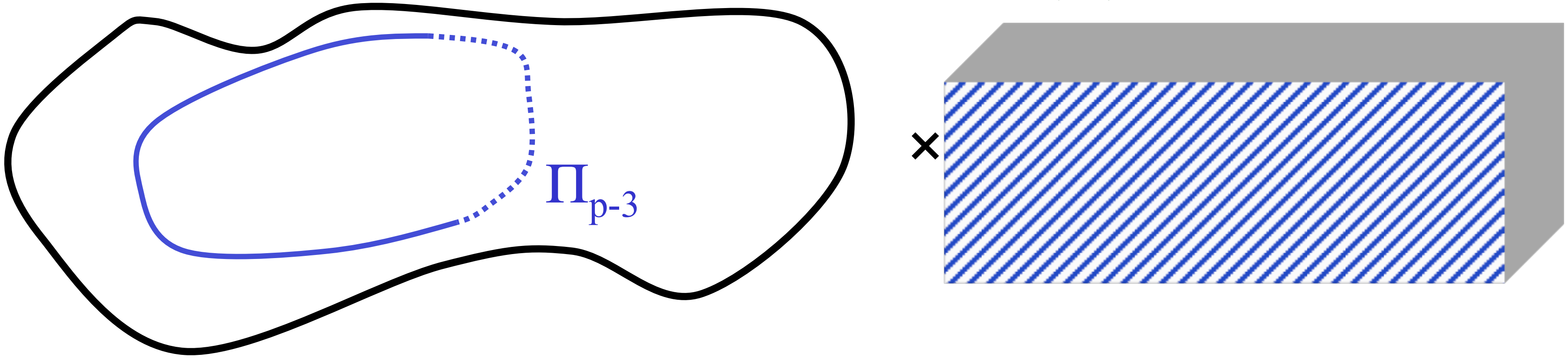

D p-branes – extend in p+1 dimensions:

3+1-our world $M_{(3,1)}$;(p-3)-wrap Π_{p-3} cycles of X_6

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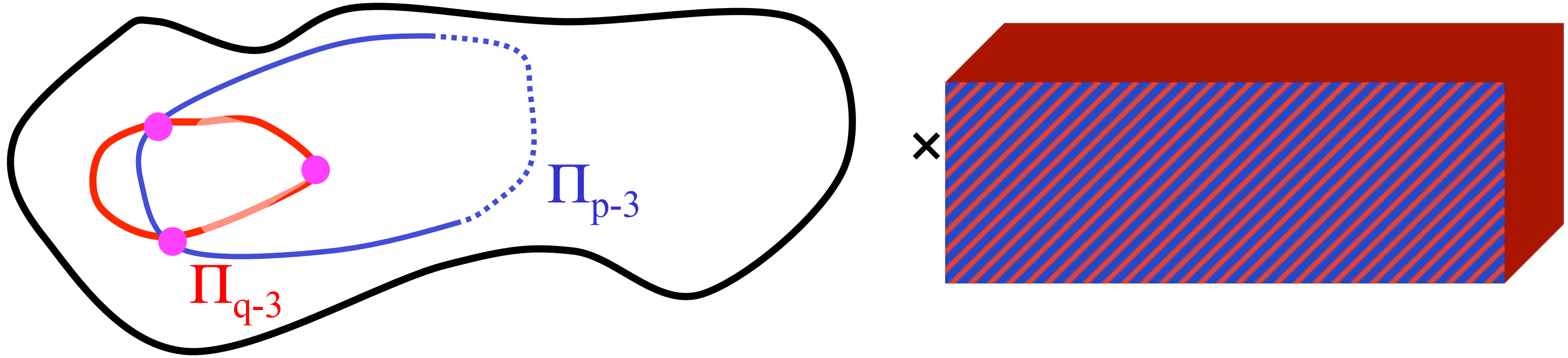

D p-branes – extend in p+1 dimensions:
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D q-branes – extend in q+1 dimensions:
3+1-our world $M_{(3,1)}$;(q-3)-wrap Π_{q-3} cycles of X_6

$\Pi_{q-3} \cap \Pi_{p-3}$
$\Pi_{q-3} \subset \Pi_{p-3}$

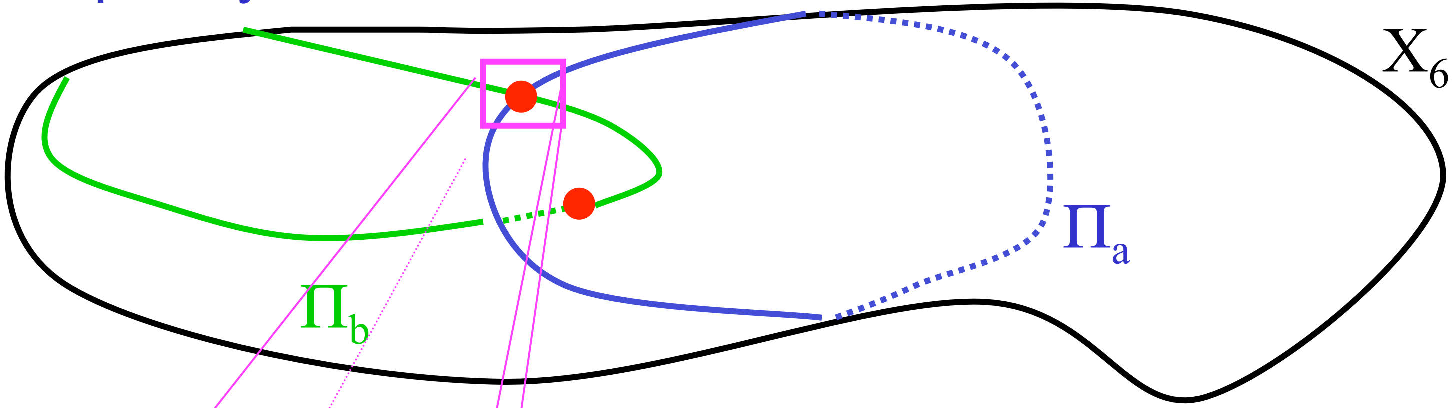
$\Downarrow$

Rich structure

D-branes at singularities & Wilson lines: Aldazabal,Font,Ibáñez,Violero’98....
M.C.,Wang,Plümacher’00;M.C.Wang,Uranga’01… (more later)

Intersecting D6-branes

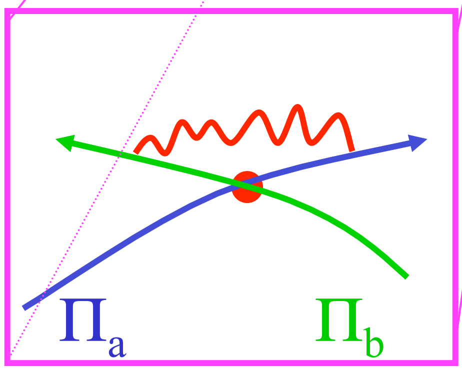
wrap 3-cycles Π



In internal space intersect at points:

Number of intersections $[\Pi_a] \circ [\Pi_b]$ - topological number

Geometric origin of family replications!



[Berkooz, Douglas & Leigh '96]

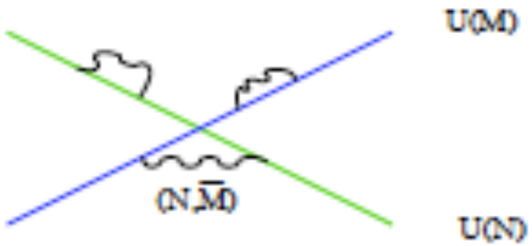
At each intersection-massless string excitation-

spin ½ field ψ - matter candidate

Geometric origin of matter!

Intersecting D-branes → fertile ground for particle physics model building
(Type IIA string theory) pedagogical review (TASI'10) [M.C., Halverson'11]

Reproduce key features of SM & SU(5) GUT spectrum:
non-Abelian gauge symmetry, chirality & family replication geometric



Representation	Multiplicity
$(\overline{a}, b)$	$\pi_a \circ \pi_b$
$(\overline{a}, \overline{b})$	$\pi_a \circ \pi'_b$
$\begin{smallmatrix}\Box\\ \Box\end{smallmatrix}_a$	$\frac{1}{2}\left(\pi'_a \circ \pi_a + \pi_{O6} \circ \pi_a\right)$
$\Box\!\Box_a$	$\frac{1}{2}\left(\pi'_a \circ \pi_a - \pi_{O6} \circ \pi_a\right)$

Global consistency: Gauss law for D-brane charge in internal space→ stringy
[Aldazabal,Franco,Ibáñez,Rábadan,Uranga'00-01][Blumenhagen,Görlich,Körs,Lüst'00-01]
[Angelantonj, Antoniadis,Dudas,Sagnotti'00]...

Large classes (order of 100's) of globally consistent
supersymmetric SM & GUT constructions; also couplings

[M.C.,Shiu,Uranga'01]
[Ibáñez,Marchsano,Rábadan'01]...
[Honecker et al.'03-'13]...

[M.C. Papadimitriou '03]
[Cremades,Ibáñez,Marchesano'03]...

Nonperturbative effects: D-instantons

i. Important role in moduli stabilization

[Strominger'86]...[Giddings,Kachru,Polchinski'01]...
[Kachru,Kallosh,Linde,Trivedi'03]...
[Balasubramanian, Berglund, Conlon, Quevedo'05]...

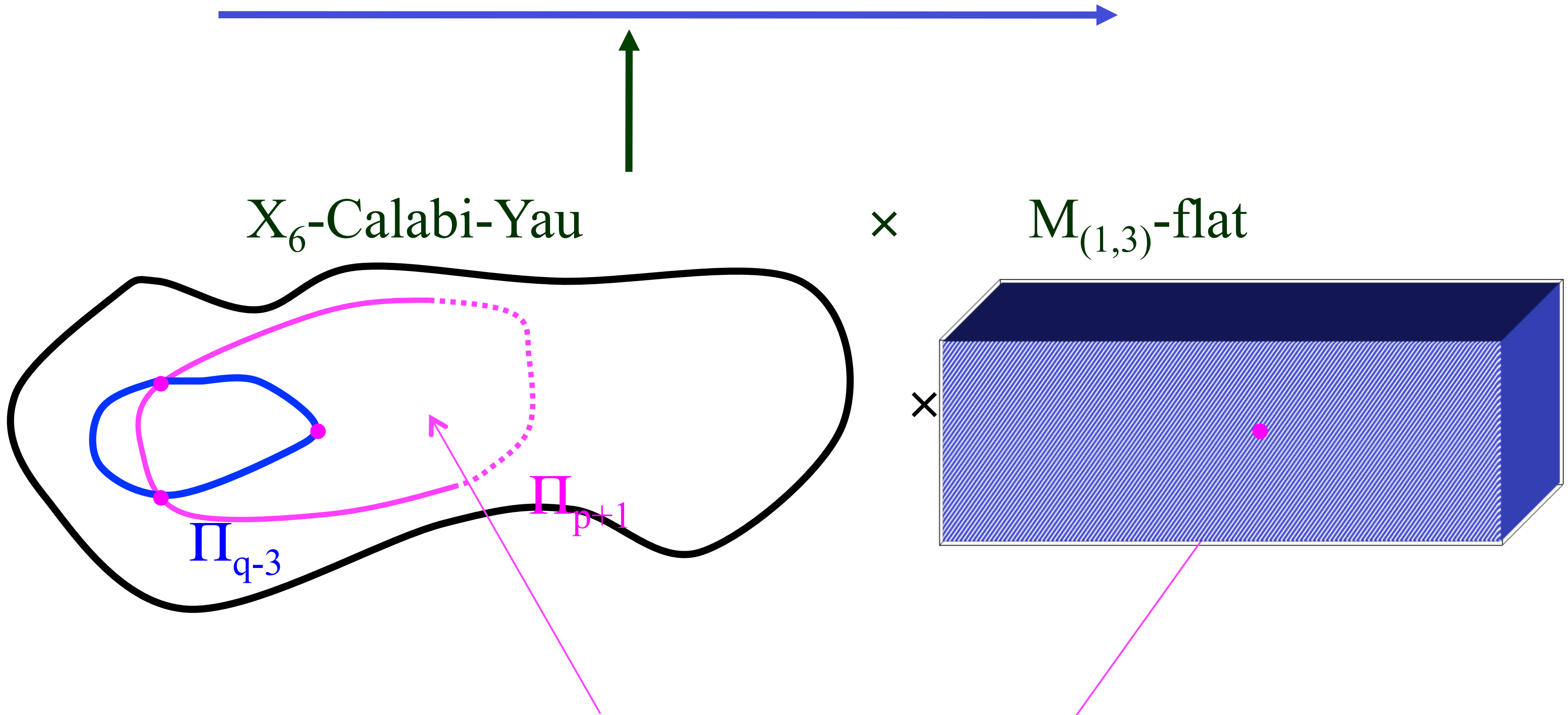
ii. New types of D-instantons: generate certain perturbatively absent couplings for charged sector matter

[Blumenhagen,M.C.,Weigand'06][Ibáñez,Uranga'06]
- charges matter coupling corrections
[Florea,Kachru,McGreevy,Saulina'06]
-supersymmetry breaking

Review: [Blumenhagen,M.C.,Kachru,Weigand '09]

Encoded in non-perturbative violation of ``anomalous'' U(1)'s

D-Instanton - Euclidean D-brane backgound



Wraps cycle Π_{p+1} cycles of X_6 point-in 3+1 space-time

New geometric hierarchies for couplings:

$$\mathcal{R}e\left(e^{-S_{E2}}\right) = e^{-\frac{2\pi}{\ell_s^3 g_s}\mathrm{Vol}_{E2}} = e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}}\frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{D6}}}$$

stringy!

Instanton can intersect with physical Dq-brane (charged zero modes)

→ non-perturbative charged matter couplings

Specific examples of instanton induced charged matter couplings:

i) Majorana neutrino masses original papers...

ii) Nonpert. Dirac neutrino masses [M.C., Langacker'08]

iii) 10 10 5 GUT coupling in SU(5) GUT's
[Blumenhagen, M.C., Lüst, Richter, Weigand'07]

iv) Polonyi-type couplings
[Aharony, Kachru,Silverstein'07] [M.C., Weigand'07,'08]
[Heckman,Marsano,Sauline,Schäfer-Nameki,Vafa'08]

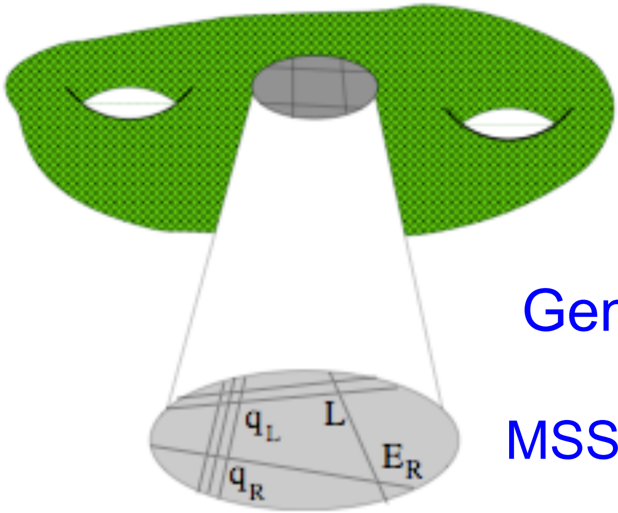
i) Local embeddings: Type II(A) original papers...
F-theory [Heckman,Marasno,Schäfer-Nameki,Saulina'08]

ii) Global embeddings: Type I [M.C.Weigand'07,'08]
Type IIB [Blumenhagen,Braun,Grimm,Weigand'08]
F-theory [M.C.,Garcia-Etxebarria,Halverson'10]
New algorithm ← [Blumenhagen,Jurke,Rahn,Roschy'10]

Standard Model Quiver Analysis of D-instanton effects

Initiated for the local Madrid quiver [Ibáñez,Richter'08]

Systematic Analysis for multi-stack SM quivers:
(compatible with global string constraints)



Landscape analysis of MSSM w/ realistic fermion (including neutrino) textures (order ten)
[M.C.,Halverson,Richter'09-11]

NMSSM [M.C.,Halverson,Langacker'10-11]

General SM quivers & string constraints on exotics
[M.C.,Halverson,Langacker'11]

MSSM& additional nodes:U(1)'s;SUSY breaking;dark matter
[M.C.,Halverson,Piragua'12]

Bottom-up (local) approach initiated by [Aldazabal,Ibáñnez,Quevedo,Uranga'00]...

Related works: [Antoniadis,Kiritsis,Rizos,Tomaras'02]...[Velinde,Wijholt'04]...
[Leontaris'09][Anastasopoulos,Kiritsis,Lionetto'09]...
[Kiritsis,Lennek,Schellekens'09]...

MSSM at toric singularities: [Krippendorf,Dolan,Maharana,Quevedo'10-'12]...

Further Developments in Compactifications w/D-branes:

Conformal Field Theory Global Constructions
(non-geometric Type II phase):
many three-family Supersymmetric Standard-like Models;
couplings?; fluxes? [Dijkstra,Huiszoon,Schellekens'04]...

Improvements on Global Construction Techniques (Type IIB):
D-branes at singularities; D7/D3-branes;
[Balasubramanian,Berglund,Braun,Garcia-Etxebarria'12]...
[Cicoli,Krippendorf,Mayrhofer,Quevedo'13]...

Discrete Gauge Symmetries in String Compactification
(persist non-perturbatively) & implications:
[Berasaluce-Gonzalez,Ibáñez,Uranga'11]...
[Ibáñez,Schellekens,Uranga'12][Anastasopoulos,M.C.,Richter,Vaudrevange'12]...

→ II. F-theory Compactification

Why F-theory Compactification?

Domain of string theory landscape with promising particle physics

- Potential for GUT models with couplings that are perturbatively absent in Type II compactifications, e.g., 10 10 5 in SU(5) GUT's

[Donagi,Wijnholt'08]
[Beasley,Heckman,Vafa'08]....

- Moduli stabilization (fluxes)

[Gukov,Vafa,Witten'99]...

Conceptual: geometric description at finite string coupling

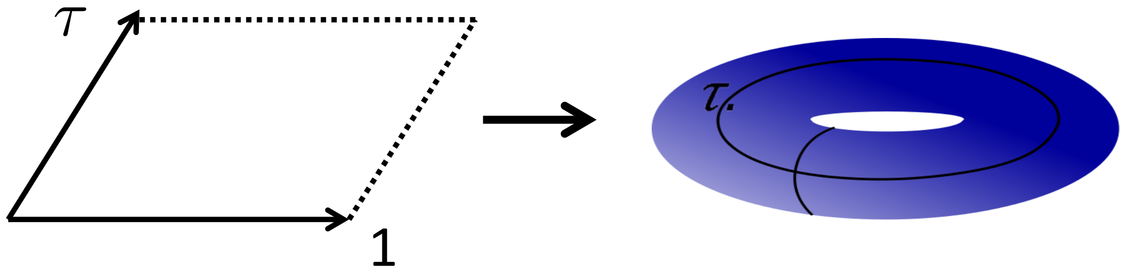
- F-theory via finite coupling Type IIB string theory:
  Consistent set-up of back-reacted seven-branes
  Nonperturbative coupling regions on non-Calabi-Yau geometry

[Vafa'96]...

- F-theory via Geometry:
  Globally defined elliptically fibered Calabi-Yau manifold

F-theory via Type IIB: basic ingredients

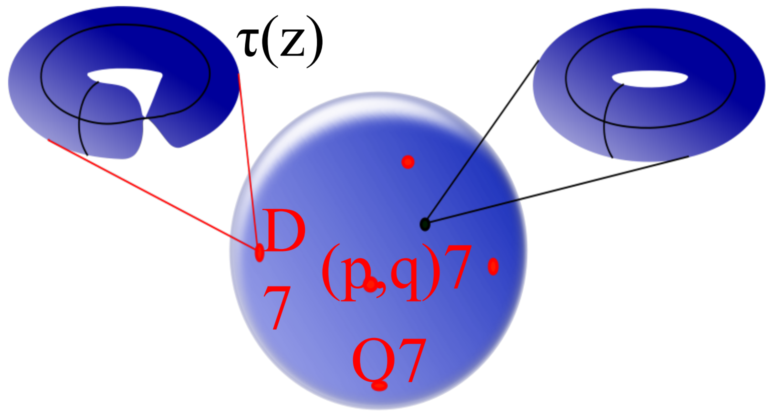
- F-theory is a geometric, duality invariant formulation of Type IIB string theory: invariant geometric object is two-torus $T^2(\tau)$



- Modular parameter τ of $T^2(\tau)$: $\tau \equiv C_0 + i g_s^{-1}$ Type IIB axion-dilaton

  (duality= S-duality)

- $T^2(\tau)$-fibration over a base space B:



Weierstrass parameterization:

$$y^2 = x^3 + fxz^4 + gz^6$$

f, g- function fields on B

[z:x:y] homog. coords on $\mathbf{P}^2(1,2,3)$

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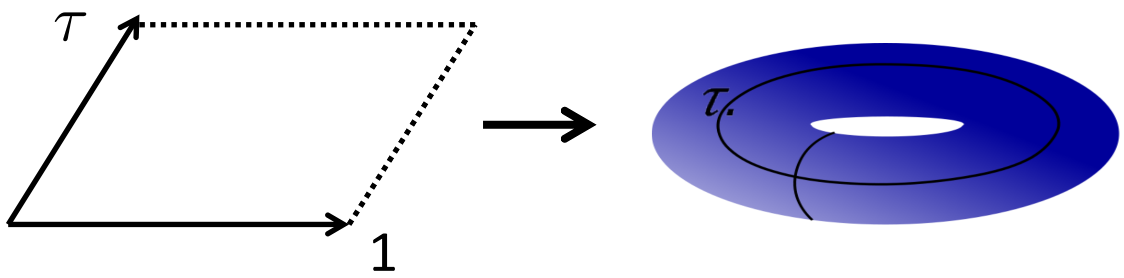

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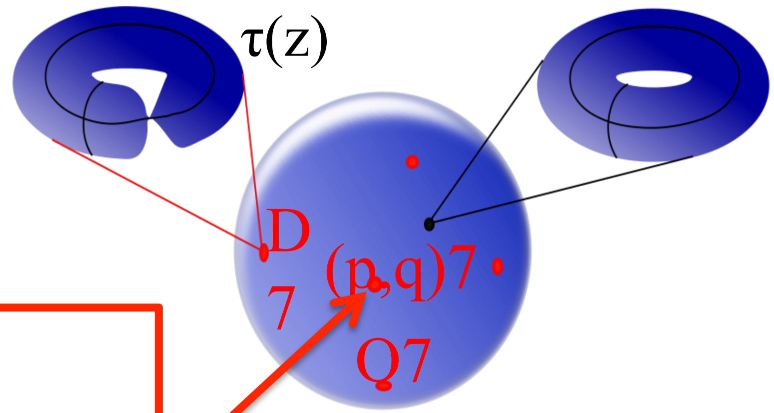

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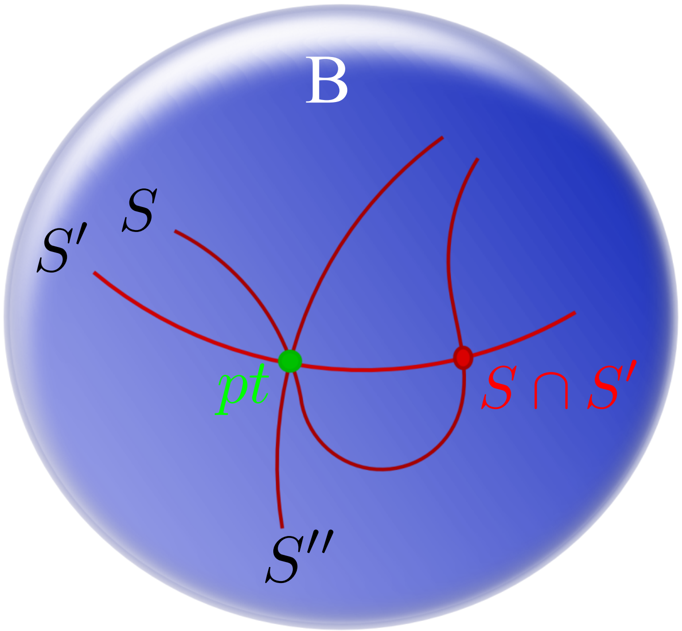
7-branes
non-perturbative regime:
$g_s \rightarrow \infty$ ⟺ singular

F-theory: basic ingredients

- Total space of $T^2(\tau)$-fibration: singular elliptic Calabi-Yau manifold X

  D=4, N=1 vacua: fourfold X_4 [all dimensions complex]

- X-singularities encode complicated set-up of intersecting 7-branes:



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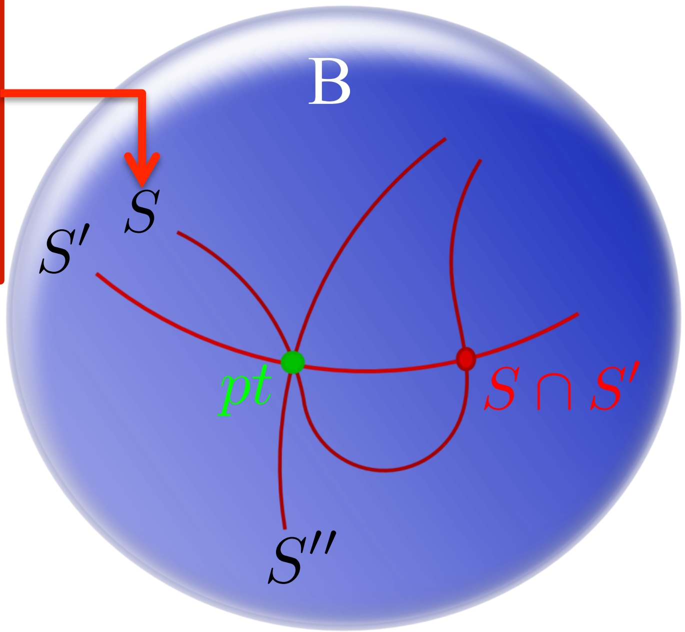
Non-Abelian gauge theory (ADE sing.) in codimension one in B S (7-branes)



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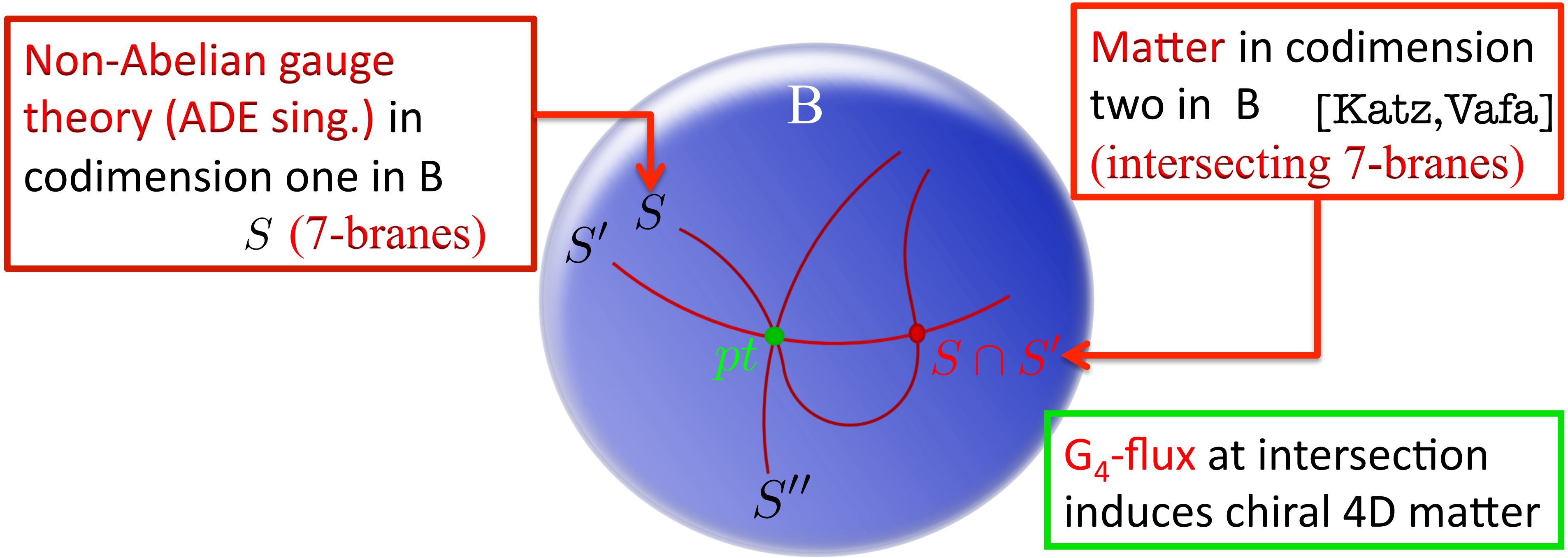

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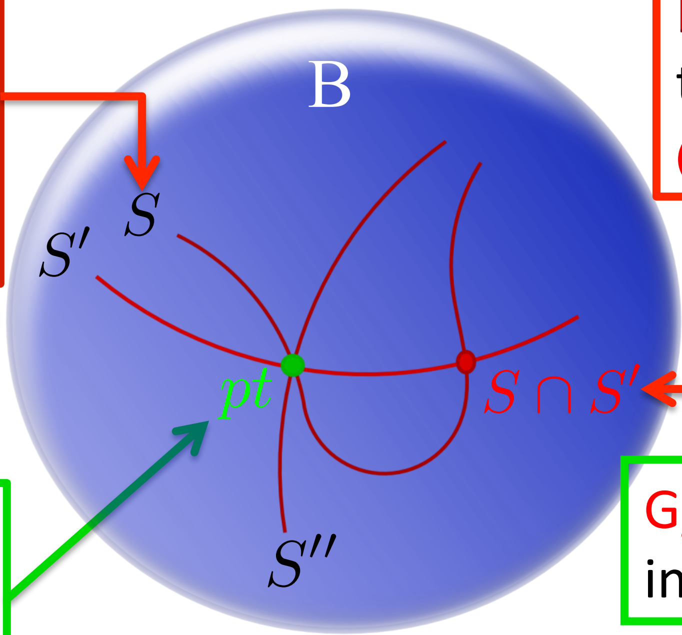

Matter in codimension two in B [Katz,Vafa] (intersecting 7-branes)

Yukawa couplings in codimension three at $pt = S \cap S' \cap S''$

G_4-flux at intersection induces chiral 4D matter

Focus on F-theory SU(5) GUT's

[Donagi,Wijnholt'08][Beasley,Heckman,Vafa'08]...

(Semi) local constructions:

[Donagi,Wijnholt'09-10]...[Marsano,Schäfer-Nameki,Saulina'09-11]...

Review: [Heckman]

Global constructions:

[Blumehagen,Grimm,Jurke,Weigand'09][M.C., Garcia-Etxebarria,Halverson'10]...
[Marsano,Schäfer-Nameki'11-12]...[Clemens,Marsano,Pantev,Raby,Tseng '12]...

Technical progress G_4 fluxes (chirality):

[Cecotti,Cordova,Heckman,Vafa'10]...[Grimm,Weigand'10][Grimm,Hayashi'11]...
[Krause,Mayrhofer,Weigand'11-12]...[Braun,Collinucci,Valandro'12]...
[Kuntzler,Schäfer-Nameki'12]...[M.C.,Grassi,Klevers,Piragua'13]...

Flavor (Yukawa Couplings): wave function profiles, G_4,fluxes, instantons, …

[Cecotti, Cheng, Heckman, Vafa'09][Marchesano,Martucci'11]
[Aparicio,Font,Ibáñez,Marchesano'11][Cámara,Dudas,Palti '11]...

⇒ Most recent efforts: focus on GUT's with U(1)'s

Why U(1) Symmetries in F-theory?

Particle physics: important ingredient of Beyond Standard Model Physics

- Light U(1) gauge bosons: Z'-physics, NMSSM, $U(1)_{PQ}$, …
- Massive (Stückelberg) U(1) gauge bosons: low energy global symmetry

→ selection rules (proton decay; R-parity violation; neutrino masses…)

Multiple U(1)'s desirable

Conceptual: new types of elliptic fibrations (new Calabi-Yau manifolds)

- U(1)'s related to Abelian Mordell-Weil group of elliptic fibrations (rational points of elliptic curves)

→ less understood (global issues)

- Few systematic studies in contrast to non-Abelian groups

U(1)'s & Mordell-Weil Group

4D Abelian gauge fields arise from classical Kaluza-Klein reduction of C_3

(C_3-potential for G_4)

$$C_3 = A^B \omega_B \supset A^i \omega_i + A^m \omega_m$$

(1,1)-forms on X

Cartans of non-Abelian group

U(1)-gauge fields

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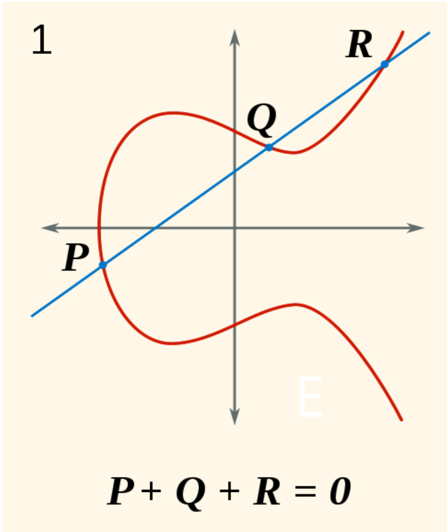
Construction of (1,1)-form ω_m via rational sections

1. Rational point Q on elliptic curve E with zero point P
   - is solution $[z_Q : x_Q : y_Q]$ in field K of Weierstrass form

$$y^2 = x^3 + f x z^4 + g z^6$$

   - Rational points form group (addition) on E

Mordell-Weil group of rational points



[wikipedia.org]

2. In fibration Q induces rational section $\hat{s}_Q : B \to X$

and existence (1,1)-form ω_m [Dual to divisor class S_Q, related to $\hat{s}_Q$]

[M.C., Klevers,Piragua'13]
More details: M.C., Strings'13 talk

Example with two U(1)'s:

Construction of elliptic curve E with two rational points Q, R

Natural representation as hypersurface p=0 in del Pezzo dP_2

$$p = u(s_1 u^2 e_1^2 e_2^2 + s_2 u v e_1 e_2^2 + s_3 v^2 e_2^2 + s_5 u w e_1^2 e_2 + s_6 v w e_1 e_2 + s_8 w^2 e_1^2) + s_7 v^2 w e_2 + s_9 v w^2 e_1$$

$[u:v:w:e_1:e_2]$ –homogeneous coordinates of dP_2

(blow-up of $\mathbf{P}^2$ w/ [u':v':w'] at 2 points: $u'=ue_1e_2$, $v'=ve_2$, $w'=we_1$)

related work: [Borchman,Mayrhofer,Weigand'13]

Rk[MW]=1: [Morrison,Park'12; Mayrhofer,Palti,Weigand'12]

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$$\boxed{\begin{aligned} P:&\quad E_2 \cap p = [-s_9 : s_8 : 1 : 1 : 0]\,,\\ Q:&\quad E_1 \cap p = [-s_7 : 1 : s_3 : 0 : 1]\,,\\ R:&\quad D_u \cap p = [0 : 1 : 1 : -s_7 : s_9]\,. \end{aligned}}$$

Points represented by intersections of different divisors in dP_2 with p

[M.C., Klevers,Piragua'13]
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Promote the elliptic curve to the fibration over a base B
[s_i-become sections (functions of B coordinates), etc.]
→ New Calabi-Yau manifolds w/ two U(1)'s

Method general → can be applied to specific toric constructions w/two U(1)'s
[Bonetti,Braun,Grimm,Hohenegger'12][Borchmann,Mayrhofer,Palti,Weigand'13]
[Braun,Grimm,Keitel'13]

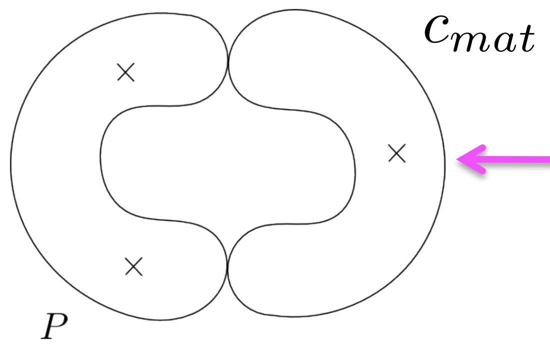
Matter representations

[M.C.,Klevers,Piragua'13]
related work:[Borchman, Mayrhofer,Weigand'13]

- Matter in F-theory arises from a co-dimension two singularities in B
- Singular fiber resolved into reducible curve $E=c_1+c_{mat}$

(M2-branes wrapping c_{mat})

Original singular fiber



Isolated matter curve

Advances in higher co-dimension singularities
...[Esole,Yau'11]...[Lawrie,Schäfer-Namek'12]

Complementary: deformations of singularities [Halverson,Grassi,Shaneson'13]

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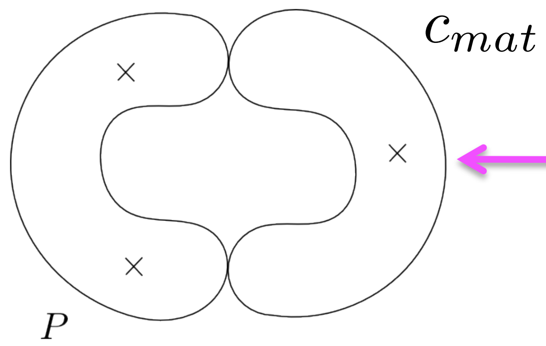

Isolated matter curve

Strategy: look for collisions of rational sections with singularities (Type I matter)

& loci in B where the sections are ill-defined (Type II matter)

Representations: via intersections of rational section divisors w/ c_{mat}

Summary of Matter Representations

	$U(1) \times U(1)$
Type I	$(1,0)$ $(0,1)$ $(1,-1)$
Type II	$(-1,1)$ $(0,2)$ $(-1,-2)$

X non-generic → realize SU(5) x U(1) x U(1)

Apply analogous techniques to determine matter representation

Summary of Matter Representations

	$U(1) \times U(1)$	$SU(5) \times U(1) \times U(1)$
Type I	$(1,0)\ (0,1)\ (1,-1)$	$(\mathbf{5}, -\frac{2}{5}, 0)\ (\mathbf{5}, \frac{3}{5}, 0)\ (\mathbf{5}, -\frac{2}{5}, -1)$
Type II	$(-1,1)\ (0,2)\ (-1,-2)$	$(\mathbf{5}, -\frac{2}{5}, 1)\ (\mathbf{5}, \frac{3}{5}, 1)\ (\overline{\mathbf{10}}, -\frac{1}{5}, 0)$

X non-generic → realize SU(5) x U(1) x U(1)

Apply analogous techniques to determine matter representations

Specific example

$$\boxed{\begin{aligned} s_1 &= t^3 s_1' \\ s_2 &= t^2 s_2' \\ s_3 &= t^2 s_3' \\ s_5 &= t s_5' \end{aligned}}$$

w/ SU(5) at t=0

Chirality & G_4 flux

[M.C.,Grassi,Klevers,Piragua'13]

4D matter chiralities = codimension two in B + G_4 flux

$$\boxed{\chi(\mathbf{R}) = -\frac{1}{4}\int_{\mathcal{C}_{\mathbf{R}}} G_4}$$

Geometry

i. Matter surfaces: C_R (associated with the fibration over matter curve in B)

Evaluate integrals

Chiral index

ii. G_4 flux: First construction of G_4 flux with rational sections

(construction of cohomology elements $H_V^{(2,2)}(\hat{X})$)

F-/M-theory duality

iii. Constraints on G_4 : by comparing origin of 3D Chern-Simons terms Θ_{AB} in F-& M-th.

→ determine non-zero Θ_{AB} in F-theory: fix chiralities & anomaly cancellation

...[Grimm,Hayashi'11]..[M.C.,Grassi,Klevers,Piragua'13] & [M.C.,Grimm,Klevers'12]

& compare to geometric calculations above

The full 4D spectrum

Example B=P^3 w/ U(1) x U(1): most general solution for G_4-flux

$$G_4 = a_5 n_9 \left(4 - n_7 + n_9\right) H_B^2 + 4 a_5 H_B S_P + a_3 H_B \sigma(\hat{s}_Q) + a_4 H_B \sigma(\hat{s}_R) + a_5 S_P^2$$

(q_1, q_2)	
$(1,0)$	$\frac{1}{4}\left[a_5 n_7 n_9 \left(4 - n_7 + n_9\right) + a_3 \left(2n_7^2 - \left(12 - n_9\right)\left(8 - n_9\right) - n_7 \left(16 + n_9\right)\right)\right]$
$(0,1)$	$\frac{1}{2}\left[a_5 n_9 \left(4 - n_7 + n_9\right)\left(12 - n_9\right) - a_4 \left(n_7 \left(8 - n_7\right) + \left(12 - n_9\right)\left(4 + n_9\right)\right)\right]$
$(1,1)$	$\frac{1}{4}\left[2 a_5 n_9 (4 - n_7 + n_9)(12 - n_9) - (a_3 + a_4)(n_7^2 + n_7(n_9 - 20) + 2(12 - n_9)(4 + n_9))\right]$
$(-1,1)$	$\frac{1}{4}\left(a_3 - a_4\right) n_7 \left(4 + n_7 - n_9\right)$
$(0,2)$	$\frac{1}{4} n_7 n_9 (-2 a_4 + a_5 (4 - n_7 + n_9))$
$(-1,-2)$	$-\frac{1}{4} n_9 (n_7 - n_9 - 4)(a_3 + 2 a_4 + a_5 (n_7 - 2 n_9))$

All 4D anomalies cancelled;

Chiralities checked against Type II matter geometric chirality calculations

The full 4D spectrum

Example B=P^3 w/ U(1) x U(1): most general solution for G_4-flux

$$G_4 = a_5 n_9 (4 - n_7 + n_9) H_B^2 + 4 a_5 H_B S_P + a_3 H_B \sigma(\hat{s}_Q) + a_4 H_B \sigma(\hat{s}_R) + a_5 S_P^2$$

(q_1, q_2)	
$(1,0)$	$\frac{1}{4}\left[a_5 n_7 n_9 (4 - n_7 + n_9) + a_3\left(2n_7^2 - (12 - n_9)(8 - n_9) - n_7(16 + n_9)\right)\right]$
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$(-1,-2)$	$-\frac{1}{4} n_9 (n_7 - n_9 - 4)(a_3 + 2a_4 + a_5(n_7 - 2n_9))$

Same methods for SU(5)xU(1)xU(1) applied:

G_4-flux has 7 parameter; all 4D chiralities determined; anomalies checked;

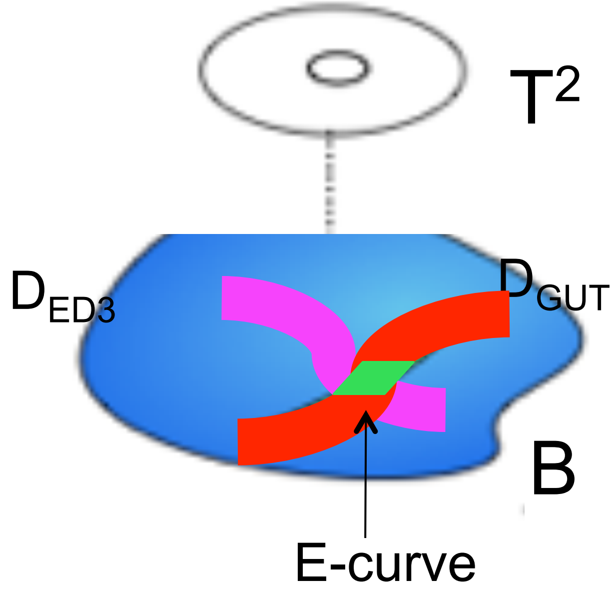
Chirality checked against Type II matter geometric calculations

Instantons in F-theory: Euclidean D3-brane (ED3)

Nonperturbative Superpotential

$$W \sim A e^{-T}$$

ED3 (wrapping divisor D_{ED3}) in the base B,
Intersecting GUT 7-brane (wrapping D_{GUT}) at a curve E



Correct number of zero modes for non-zero superpotential

Instantons in F-theory: Euclidean D3-brane (ED3)

Nonperturbative Superpotential $$W \sim Ae^{-T}$$

Past Work:

[Witten'96],[Donagi,Grassi,Witten'96],[Katz,Vafa'96],[Ganor'96]...
[Diaconescu,Gukov'98]...

Recent Work (string junctions; anomaly inflow; heterotic/F-theory duality…)

[Blumenhagen Collinucci,Jurke'10]
[M.C.,García-Etxebarria,Halverson'10-11][Donagi,Wijnholt'11]
[Grimm,Kerstan,Palti,Weigand'11][Marsano,Saulina,Schäfer-Nameki'11]
[Bianchi,Collinucci,Martucci'11][Grimm,Weigand,Kerstan,Palti '11]
[Kerstan,Weigand'12]...

↑

focus on G_4-fluxes on world-volume ED3

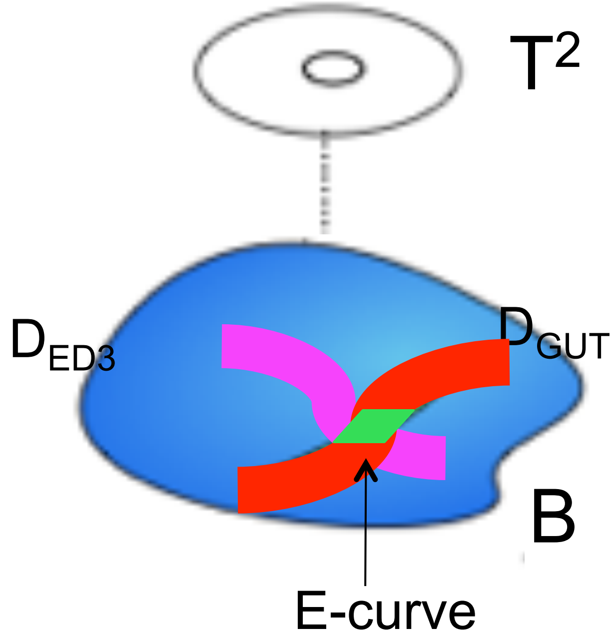
Superpotential

$$W \sim Ae^{-T}$$

due to ED3 (wrapping divisor D_{ED3}) In the base B,

Intersecting GUT 7-brane (wrapping D_{GUT})

Local structure captured by intersection curve E& flux G_4



[M.C.,Donagi,Halverson,Marsano'12]

Conjecture to compute (moduli dependent) Pfaffian A

via line bundle cohomology on the spectral cover curve over the intersection

[Checks: when heterotic dual exists & Type IIB limit (M –theory→further study)]

Comments:

- Pfaffian A has a rich structure: typically factorizes into non-trivial powers of 7-brane moduli polynomials w/intriguing substructure (geomeric)

- Points of E_8 enhancement can cause Pffafian to vanish (too many zero modes): E_8 enhanced point in instanton world-volume

- Phenomenological implications: in SU(5) GUTs, points of E_8 enhancement can give natural flavor structure, minimal gauge mediated supersymmetry breaking… [Heckman,Tavanfar,Vafa'10]

Summary

String Theory Compactification:

Focus on D-branes & particle physics (SM & GUT’s)

I. D-branes at small string coupling (Type II string theory)

- w/ intersecting D-branes: spectrum geometric
- Highlight: nonperturbative effects (D-instantons)
- Progress on landscape analysis of quiver constructions;
  global Type IIB models; discrete symmetries

II. D-branes at finite coupling (F-theory)

- singular elliptically fibered Calabi-Yau fourfolds
- Focus on SU(5) GUT’s w/ desirable couplings (geometry&flux)
- Highlight: constructions with additional U(1)’s
  (spectrum via geometry & F/M-theory duality)
  instantons

Outlook:

Foresee further progress:

I. Conceptual and technical developments:

i. Geometric approaches (advanced algebraic geometry techniques)
new features of Calabi Yau spaces
(singularities,resolutions,deformations)

ii. Power of dualities (M/F-theory) → fluxes in F-theory

II. Quantitatively improve realistic model constructions,
including further progress on non-perturbative effects