Recent progress in String Phenomenology

I. Modern String Theory & particle physics ➔ D-branes

II. Supersymmetric Standard Model w/ (intersecting) D-branes

III. New non-perturbative effects: D-instanons
Phenomenological implications: Majorana neutrino masses, μ-parameter, modified Yukawa couplings…

IV. Conclusions/outlook

Quest to unify forces of nature ⇒

Green&Schwarz'84

String Theory – most promising candidate

as a consistent (finite) quantum theory of strings where elementary particles arise as massless excitations of strings.

In particular, gravitons - massless excitations of closed strings

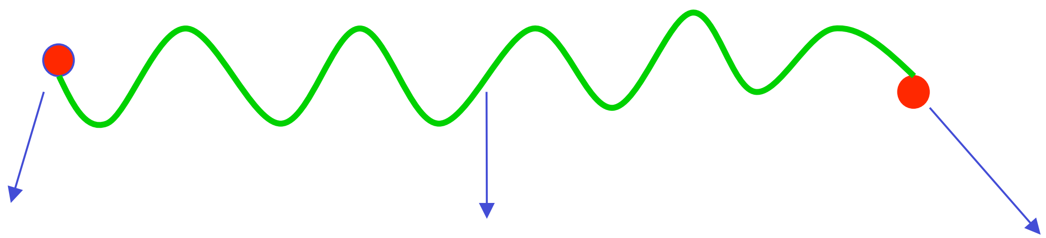
Quantum gravity for free!

Standard Model of elementary particle interactions (strong, weak & electromagnetic) based on Non-Abelian Gauge theory

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Force mediated via spin 1-particles: gluons,W-bosons&photon

3-families: $Q_L \sim (\underline{3}, \underline{2}, {}^1/_6)$ – quarks; $L \sim (\underline{1}, \underline{2}, -1)$ – leptons, etc. chiral matter



gauge interactions

quark gluon quark

Modern String Theory (w/ D-branes) – geometric origin!

Perturbative String Theories (small string coupling)

Hull&Townsend'94

Witten'95

Non-perturbative Unification

11 dimensional supergravity

Phenomenologically promising

g_{IIA} -strong

Type IIA superstring

g_{IIA} -weak (closed)

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

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

Heterotic E_8xE_8 string

(hybrid closed)

M-theory

Type IIB superstring

(closed)

Heterotic SO(32) string

(hybrid closed)

Modern perspective on particle physics

Type I superstring

(open)

w/advent of

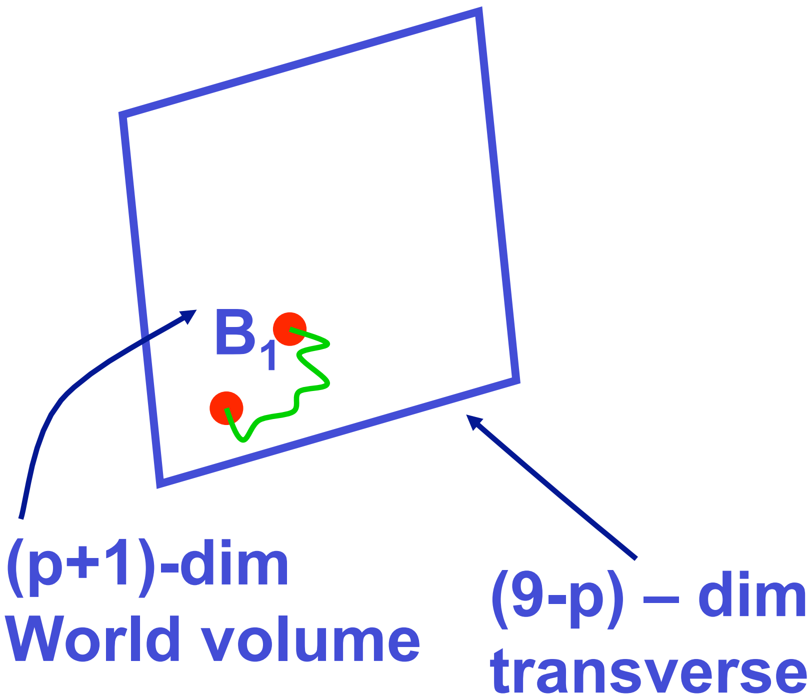
D-branes

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

Polchinski'96

D-branes & non-Abelian gauge theory

D p-branes (focus on field theory side; for AdS/CFT c.f., C. Herzog's talk)

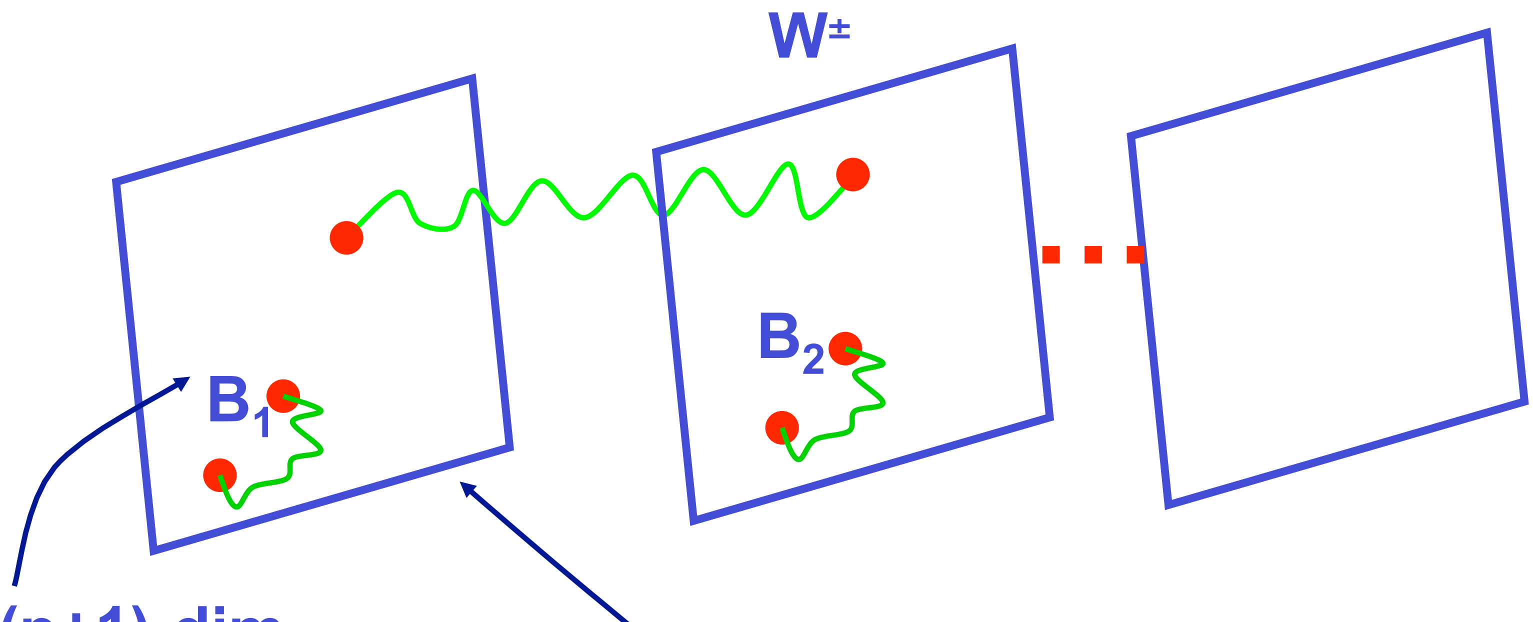


B_1=U(1) spin-one particles as massless excitations of open strings w/boundaries on a D-brane

Polchinski'96

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

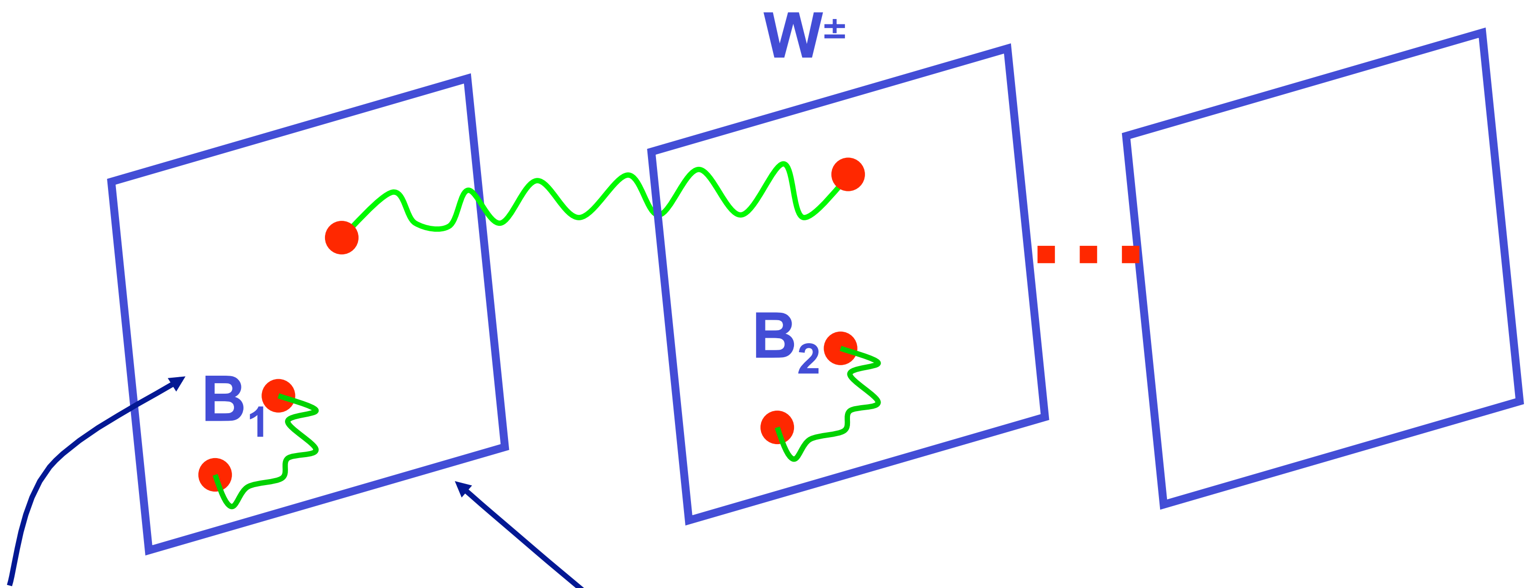
(9-p) – dim
transverse

$U_1(1) \times U_2(1) \times \ldots U_N(1)$ N D-branes

Polchinski'96

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

(9-p) – dim
transverse

$U_1(1) \times U_2(1) \times \ldots U_N(1)$ N-coincident D-branes

↓

$U(N)$ non-Abelian gauge symmetry

FIELD THEORY SIDE of D-branes

(as boundaries of open strings)

(i) non-Abelian gauge symmetry

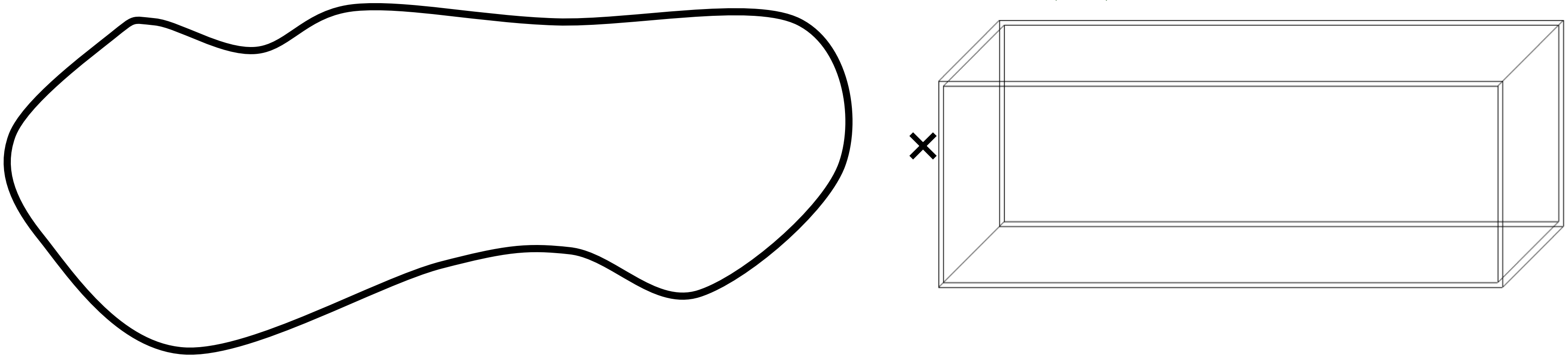
N-coincident D-branes ➡ U(N)

(ii) Appearance of matter ➡ turn to compactification

Compactification

D=9+1 → D=3+1

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

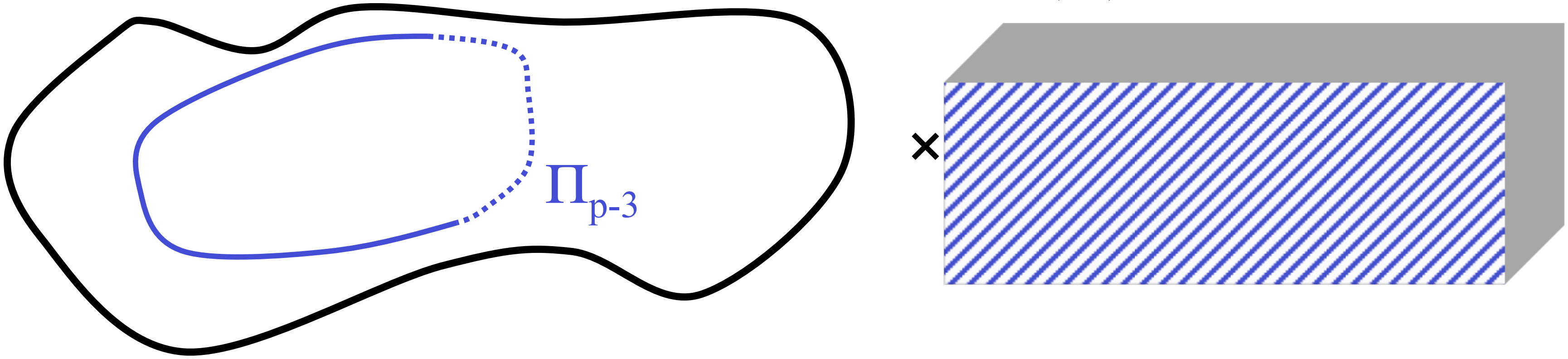


Compactification

D=9+1 ⟶ D=3+1

↑

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



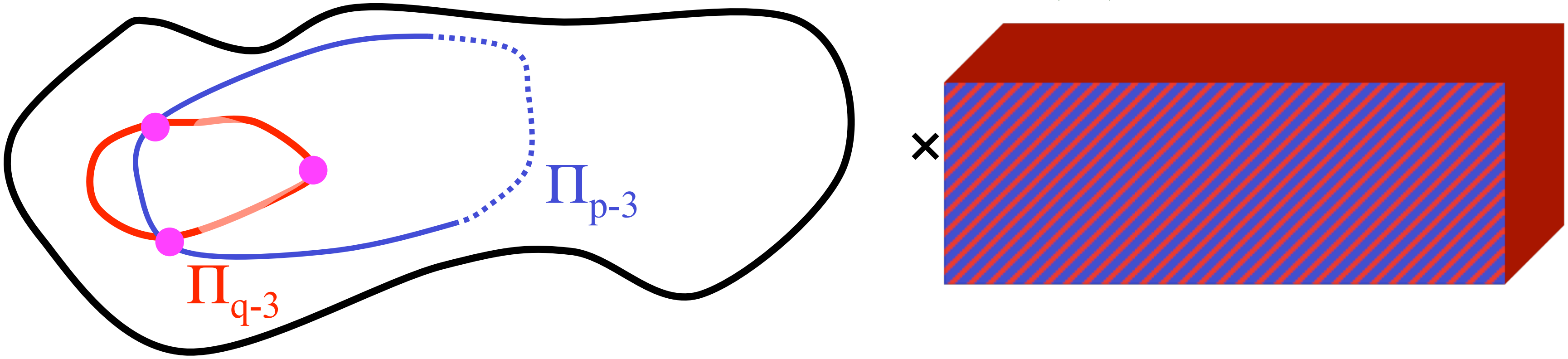
D p-branes – extend in p+1 dimensions:

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

Compactification

D=9+1 → D=3+1

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



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

⇓

Rich structure

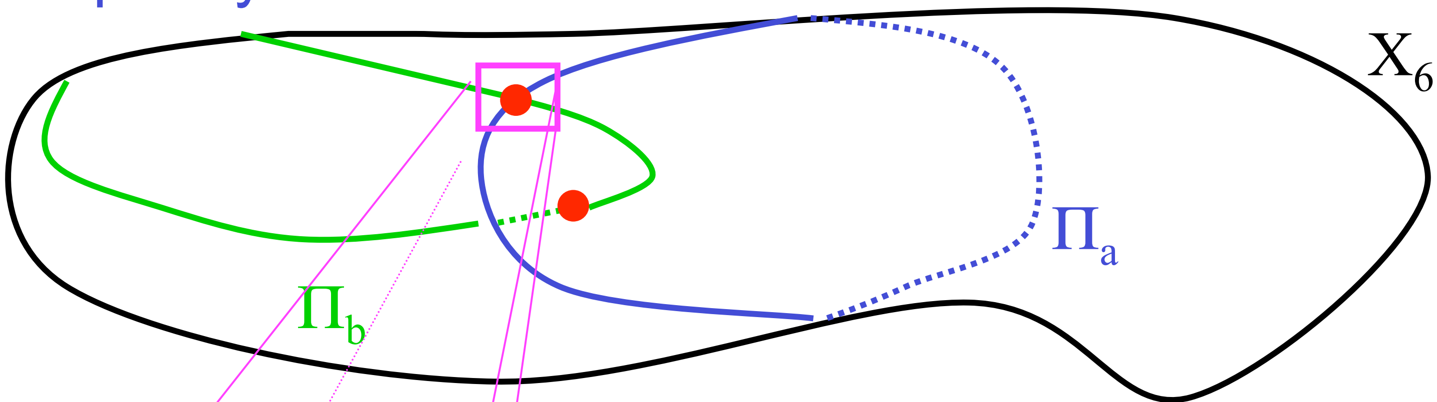
D p-branes – extend in p+1 dimensions:
3+1-our world $M_{(3,1)}$;(p-3)-wrap Π_{p-3} cycles of X_6

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

D-branes at singularities & Wilson lines: **Aldazabar et al. 98....**
M.C.,Wang&Plümacher'00;M.C.Wang&Uranga'01…

Intersecting D6-branes

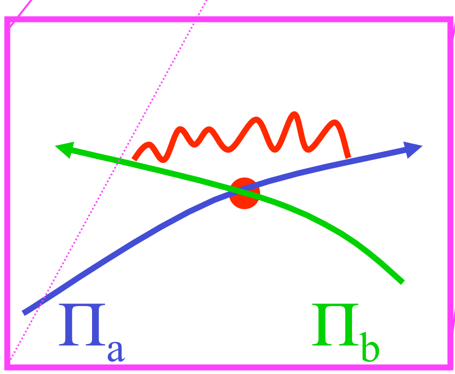
wrap 3-cycles Π



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!

Model Building with Intersecting D-branes

[Blumenhagen,Görlich,Körs,Lüst'00],[Aldazabal,Ibáñez,Rabadan,Uranga'00]...

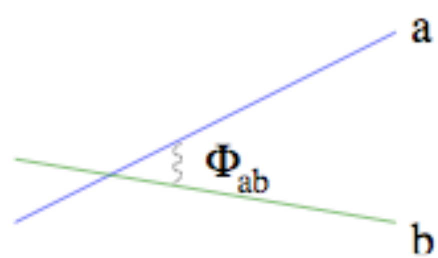
Engineering of semi-realistic constructions w/ Intersecting D6-branes wraping three-cycles Π – Standard Model:

– Non-Abelian gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$

$\longrightarrow$ U(N) as a stack of N-coincident D-branes

– Chiral matter quarks & leptons

$\longrightarrow$ at intersections of D-branes in internal space;bi-fund.



– Family replication 3-copies of fermion families

$\longrightarrow$ no. of D-brane intersections in internal space $\Pi_a \circ \Pi_b$

$\longrightarrow$ Origin of Standard Model Geometric!

Status

• $\mathcal{O}(100)$ inequivalent SUSY global toroidal orbifold SM & GUT models (geometric phase) with semi-realistic features

-typically suffer from chiral exotics - limitations of orbif. constr.

realistic (Yukawa) couplings? - focus in the rest

-moduli stabilization ? - separate topic

[M.C.,Uranga,Shiu, hep-th/0107143,017166]... Just MSSM [Gmeiner,Honecker, 0806.3039]

Rational Conformal Field Theory constructions-promising

[Dijkstra, Huiszoon,Schellekens, hep-th/0411129]...

-models without chiral exotics

-couplings in principle calculated, but hard & hierarchy?

-non-geometric phase–moduli stabilization?

• New Developments: (local) F-theory GUT's/SM's...

[Donagi,Wijnholt, 0802.2969],[Beasley,Heckman,Vafa, 0802.3391]...

intersecting D7- branes wrapping four-cycles in CY

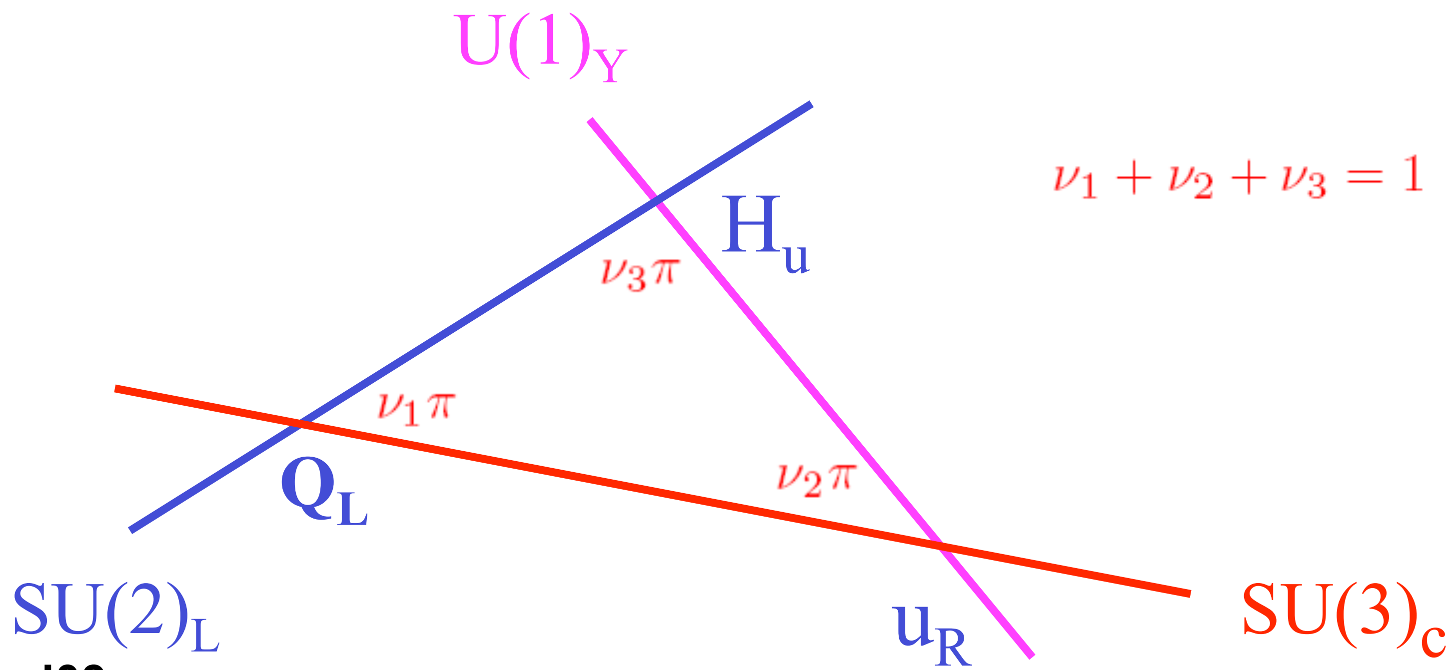
[in F-theory part of geometry of singular 8-dim. CY]

promising local MSSM (E8-symmetric intersection point) [Vafa et al'09]

global models? - work in progress [Marsano, Saulina, Schaefer-Nemeki '09],…

Yukawa Couplings

Intersections in internal space (schematic on i^{th}-two-torus)



$$\nu_1 + \nu_2 + \nu_3 = 1$$

w/Papadimitriou'03

(Conformal Field Theory Techniques)

$$Y = (2\pi)^{\frac{3}{2}} g_{st} \prod_{i=1}^{3} \left[\frac{\Gamma(1-\nu_1^i)\Gamma(1-\nu_2^i)\Gamma(1-\nu_3^i)}{\Gamma(\nu_1^i)\Gamma(\nu_2^i)\Gamma(\nu_3^I)} \right]^{\frac{1}{4}} \sum_I \exp\left(-\frac{A_I^1 + A_I^2 + A_I^3}{2\pi\alpha'}\right)$$

Geometric!

quantum part

classical part $A_I^{\,i}$ -triangle areas on i^{th} two-torus lattice

Cremades, Ibáñez, Marchesano'03

Specific coupling issues

- Neutrino masses (if there) -Dirac & of order of charged sector masses

Majorana neutrino masses – absent

- μ-parameter – typically absent
- SU(5) GUT models – absent $10\,10\,5_H$ couplings
- Hierarchical supersymmetry breaking, e.g., à la Polonyi

Perturbative absence of all such couplings due to violation of "anomalous" U(1)

→non-pertubative effects due to D-instantons

(non-perturbative violation of ``anomalous" U(1))

Extensive past literature on instantons in string theory ...

New stringy instanton effects in (open string) charged sector:

[Blumenhagen,M.C.,Weigand, hep-th/0609191]
[Ibañez,Uranga, hep-th/0609213]

- charged matter coupling corrections

[Florea,Kachru,McGreevy,Saulina, 0610003]

- supersymmetry breaking

Further developments: many papers...

Turin/Rome group, Munich group, Madrid/CERN group, Penn Group, Stanford group, etc.

D-Instantons–Heuristics

Relevant objects in Type IIA : Euclidean $D2$-branes (E2-branes), wrapping three-cycles Ξ

Rules: quantize (open) strings – zero modes

determine effective instanton action

Key features:

- Integrate over zero modes localized on $E2$

$\longrightarrow$ In path integral each fermionic zero mode has to appear for relevant instanton induced couplings exactly once

D-instantons – Heuristics

Euclidean E2-brane on internal three-cycle Ξ:

$$W_{np} \propto e^{-S_{E2}} = \exp\left[\frac{2\pi}{\ell_s^3}\left(-\frac{1}{g_s}\int_\Xi \mathrm{Vol}_\Xi + i\int_\Xi C_3\right)\right]$$

C_3 Ramond-Ramond three-form transforms under $U(1)_a$ of D_a-brane

(due to Chern-Simons terms in D-brane Wess-Zumino action expansion) $\longrightarrow$

Exponential not gauge invariant under $U(1)_a$!

$$e^{-S_{E2}} \to e^{i\,Q_a(E2)\,\Lambda_a}\; e^{-S_{E2}}$$

$$Q_a(E2) = N_a \int \delta(\Xi) \wedge \delta(\Pi^a_{q-3}) \wedge e^{F_a} = N_a\, \Xi \circ (\Pi_a - \Pi'_a)$$

Consequence:

If $Q_a(E2) \neq 0$ for some a, superpotential for charged fields:

$W = \prod_i \Phi_i\, e^{-S_{E2}}$ w/ $\sum_i Q_a(\Phi_i) + Q_a(E2) = 0$ for every a.

Non-perturbative breakdown of $U(1)_a$

D-instantons introduce a new hierarchy

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

Use $\frac{1}{\alpha_{\mathrm{GUT}}} = \frac{1}{\ell_s^3\, g_s}\mathrm{Vol}_{D6} \longrightarrow \mathcal{R}e\left(e^{-S_{E2}}\right) = e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}}\frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{D6}}}$

Stringy!

In general no field theory analog à la gauge instantons

Constraints on Zero Fermionic Modes:

I. 3-cycle wrapped by instanton: RIGID & invariant under orientifold projection

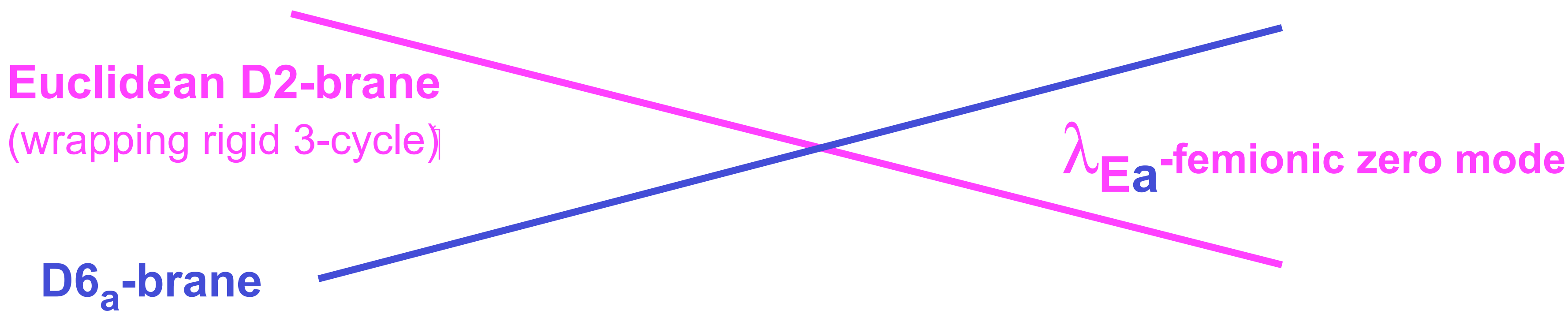
`` O(1) ''-instantons $\longrightarrow$ 4 bosonic modes x_E^μ & only 2 fermionic modes θ_α

yield directly superpotential measure: $\int d^4 x_E \, d^2\theta$

II. Zero modes (strings between $E2$ and $D6_a$):

$\longrightarrow$ Localized at the each intersection of $E2$ and $D6_a$ branes:

One single fermionic zero mode λ_a



Geometric!

$$Q_a(E2) = N_a \, \Xi \circ (\Pi_a - \Pi'_a)$$

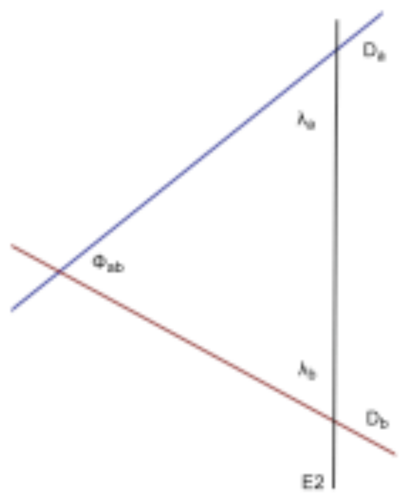
in agreement with $e^{-S_{E2}} \longrightarrow e^{i\, Q_a(E2)\, \Lambda_a} \; e^{-S_{E2}}$

Ralph Blumenhagen, M. C., Timo Weigand, hep-th/0609191

Develop conformal field theory instanton calculus to determine non-perturbatively induced superpotential couplings quantitatively

No time!

Building blocks: disc-level couplings of two λ modes to matter Φ_{ab}: $S = \int_{\Xi} \lambda_a \Phi_{ab} \overline{\lambda}_b$



In instanton effective action

$$\int d^4x d^2\theta d\lambda_a d\overline{\lambda}_b e^{-S_{E2} + \int_{\Xi} \lambda_a \Phi_{ab} \overline{\lambda}_b} \rightsquigarrow \phi_{ab} e^{-S_{E2}}$$

Superpotential due to O(1) instantons:

Specific coupling w/ each $U(1)_a$ charge violated by $\sum_i Q_a^i$

- Engineer intersections of O(1) instantons with D_a-branes

w/ total charges of λ_a's: $Q_a(E2) = -\sum_i Q_a^i$

- Identify disc diagrams that soak up each λ precisely ones

Specific Examples:

i Majorana neutrino masses original papers,...

ii Nonpert. Dirac neutrino masses [M.C.,Langacker, 0803.2876]

iii 10 10 5 GUT couplings

[Blumenhagen,M.C.,Lüst,Richter,Weigand,0707.1871]

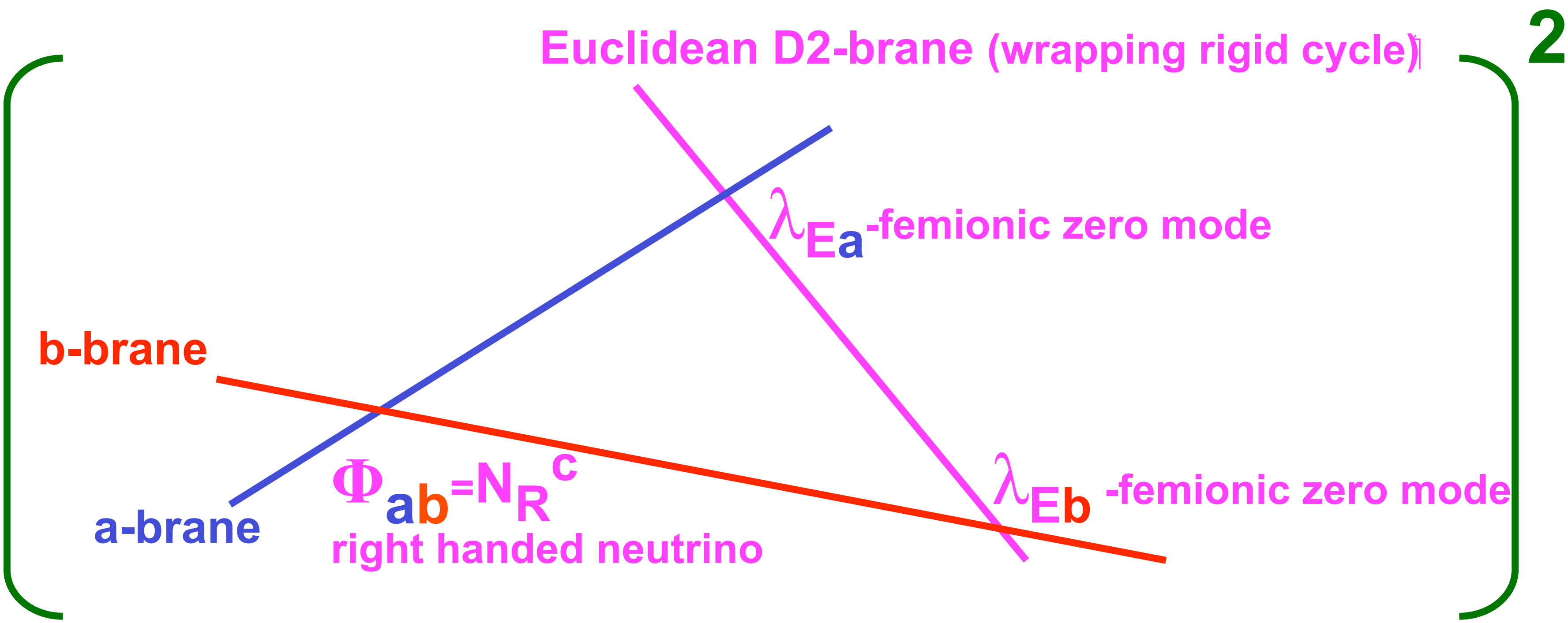
one-instanton effect $\longrightarrow g_s \rightarrow 1$ (M-theory on G_2)

iv Polonyi-type couplings

[Aharony,Kachru,Silverstein 0708.0493] [MC,Weigand 0711.0209,0807.3953]

[Heckman,Marsano,Saulina,Schafer-Nameki,Vafa 0808.1286]

Majorana Neutrino Masses:



E2-instanton w/ $[\Pi_{SM}]°[\Pi_{E2}] = 0$, $[\Pi_a]°[\Pi_{E2}] = 2$ & $[\Pi_b]°[\Pi_{E2}] = -2$

Fermionic zero modes appear precisely ONCE

→ **Non-zero non-pertubative coupling:** $M_m N_R^c N_R$

Geometric!

Concrete realisations on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$

[M. C., Robert Richter, Timo Weigand, hep-th/0703028]

→ Engineered to yield Majorana Mass $M_m \sim 10^{10}$ GeV

Together w/ Dirac Masses (Yukawa couplings à la before) $M_D \sim$ TeV

→ $M_\nu \sim M_D/M_m{}^2 \sim$ eV

→**Stringy Realization of**

Seesaw mechanism for neutrino masses!

Hierarchical superpotential couplings (neutrino masses, Yukawa couplings...)

Typically demonstrated within local orbifold Type IIA chiral SU(5) GUT's

Challenge: global models

Type I theory with magnetized D9-branes $\longrightarrow$

First chiral GUT's on globally defined Calabi-Yau spaces (algebraic geometry) [M.C.,T.Weigand, 0711.0209,0807.3953]

$\longrightarrow$ four-family SU(5) GUT's with Majorana masses or Polonyi term in the desirable regime

Most examples w/ O(1)-instantons based on SU(5) GUT's

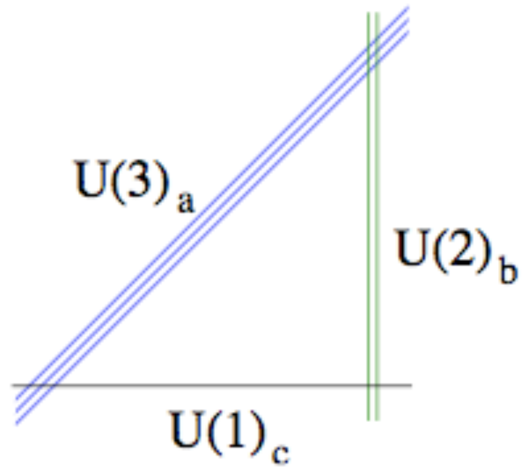
How about Multi-stack (local) Standard Models?

Addressed for Madrid Quiver [Ibáñez,Richter,08111583]

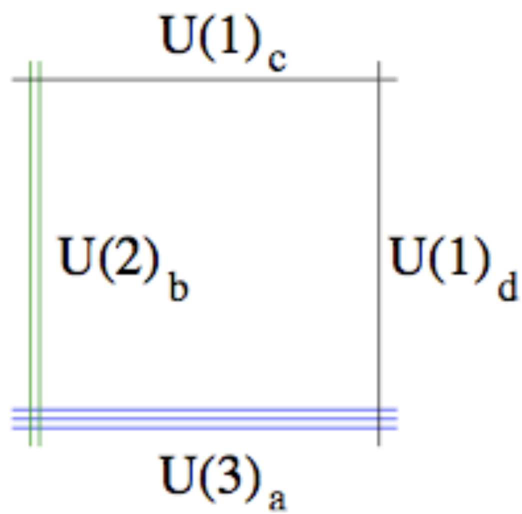
$\longrightarrow$ Systematic Analysis of Instanton Effects for MSSM

[M.C., Halverson & Richter, 0905.3379]

Employ three-stack MSSM $U(3)_a \times U(2)_b \times U(1)_c$



& four-stack MSSM $U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$



Perturbative Analysis of three- and four-stack MSSM Spectra

`à la [Anastasopoulos,Dijkstra,Kiritsis,Schellekens,hep-th/0605226]`

⟶ of order 10000 quivers

Analysis at non-perturbative level:

MSSM models with potentially desirable Yukawa textures

[• absence of R-parity violating couplings also at non-perturbative level

• presence of top perturbative Yukawa couplings

• O(1) instanton induces a desired Yukawa coupling which do not simultaneously generate μ term

• neutrino masses via seesaw or non-perturbative Dirac masses]

⟶ on the order of 50 models w/ potentially desirable textures

⟶ further work

Solution #	q_L		d_R			u_R		L			E_R			N_R				H_u				H_d
	(a,b)	$(a,\bar{b})$	$(\bar{a},c)$	$(\bar{a},\bar{d})$	Γ_a	$(\bar{a},\bar{c})$	$(\bar{a},d)$	$(b,\bar{c})$	(b,d)	$(\bar{b},d)$	$(c,\bar{d})$	$\perp\!\perp_c$	$\sqcup\!\sqcup_d$	$\urcorner_b$	$\sqcap_b$	(c,d)	$(\bar{c},\bar{d})$	(b,c)	$(\bar{b},c)$	$(b,\bar{d})$	$(\bar{b},\bar{d})$	$(\bar{b},\bar{c})$
1	3	0	3	0	0	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
2	3	0	2	0	1	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
3	3	0	1	0	2	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
4	3	0	0	0	3	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
5	3	0	0	0	3	0	3	0	0	3	0	0	3	3	0	0	0	1	0	0	0	1
6	3	0	3	0	0	2	1	0	0	3	0	2	1	2	0	1	0	0	0	0	1	1
7	3	0	3	0	0	3	0	0	0	3	2	1	0	2	0	0	1	0	1	0	0	1
8	3	0	3	0	0	3	0	0	0	3	0	2	1	2	0	0	1	0	1	0	0	1
9	3	0	3	0	0	3	0	0	0	3	1	2	0	2	0	1	0	0	1	0	0	1
10	2	1	3	0	0	1	2	0	0	3	0	0	3	0	0	0	3	1	0	0	0	1
11	2	1	3	0	0	1	2	0	0	3	3	0	0	0	0	3	0	1	0	0	0	1
12	2	1	3	0	0	3	0	0	0	3	3	0	0	0	0	0	3	1	0	0	0	1
13	2	1	3	0	0	3	0	0	1	2	3	0	0	0	0	0	3	0	1	0	0	1
14	1	2	3	0	0	3	0	0	3	0	3	0	0	0	0	0	3	1	0	0	0	1
15	0	3	0	3	0	0	3	3	0	0	0	1	2	0	3	0	0	0	0	1	0	1
16	0	3	0	0	3	0	3	0	3	0	0	0	3	0	3	0	0	1	0	0	0	1
17	0	3	0	0	3	0	3	1	2	0	1	0	2	0	3	0	0	0	0	1	0	1
18	0	3	0	0	3	0	3	3	0	0	2	0	1	0	3	0	0	0	0	1	0	1
19	0	3	0	0	3	0	3	3	0	0	0	1	2	0	3	0	0	0	0	1	0	1
20	0	3	0	0	3	1	2	1	2	0	2	0	1	0	3	0	0	1	0	0	0	1
21	0	3	0	0	3	1	2	1	2	0	0	1	2	0	3	0	0	1	0	0	0	1
22	0	3	0	0	3	1	2	3	0	0	3	0	0	0	3	0	0	1	0	0	0	1
23	0	3	0	0	3	1	2	3	0	0	1	1	1	0	3	0	0	1	0	0	0	1
24	0	3	0	0	3	2	1	0	3	0	3	0	0	0	3	0	0	1	0	0	0	1
25	0	3	0	0	3	2	1	0	3	0	1	1	1	0	3	0	0	1	0	0	0	1
26	0	3	0	0	3	2	1	2	1	0	2	1	0	0	3	0	0	1	0	0	0	1
27	0	3	0	0	3	2	1	2	1	0	0	2	1	0	3	0	0	1	0	0	0	1
28	0	3	0	3	0	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
29	0	3	0	2	1	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
30	0	3	0	1	2	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
31	0	3	0	0	3	3	0	1	2	0	1	2	0	0	3	0	0	1	0	0	0	1

Solutions for hypercharge $U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c - \frac{1}{2}U(1)_d$

Summary/Outlook

(a) Development of techniques **for consistent constructions w/ D-branes (primarily focus on Type I/II)**

(b) Sizable number of semi-realistic models:
systematic searches

(c) Coupling calculation developed –Yukawa couplings, etc.

(d) Non-perturbative (D-instanton) effects:

New hierarchical couplings

$\longrightarrow$ within local (Type IIA)& global (Type I) chiral GUT's

$\longrightarrow$ classification of (local) MSSM multi-stack models

w/potential for realistic textures – constrained

Foresee further progress:

DEVELOPMENT of TECHNIQUES! →
constructions on general Calabi Yau spaces

Quantitatively improve realistic model constructions,
including further progress on globally consistent models
with desired non-perturbative effects

F-theory (D-branes part of singular 8-dim Calabi Yau)
promising ➔

at early stages of globally consistent constructions

FULLY REALISTIC CONSTRUCTIONS
particle spectrum & interactions?

NOT THERE YET, BUT GETTING BETTER AT IT

(efforts presented here will play a role)