M-Theory and Particle Physics

I. Brief Developments in String Theory w/ implications for particle physics - D-branes

II. Supersymmetric Standard Model constructions w/ intersecting D-branes (particle spectrum & couplings) - geometric

III. D-branes and Fluxes (gravitational effects from D-branes) - moduli stabilization

⇓

Constructions of Standard Models w/ stabilized moduli

Quest to unify forces of nature ⇒

….Veneziano,….Di Vecchia,……

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

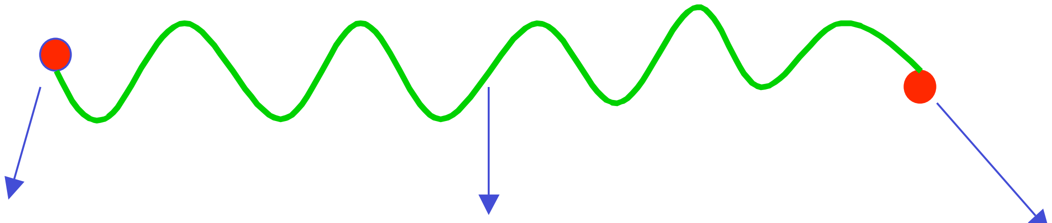
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

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



quark

gluon

quark

gauge interactions

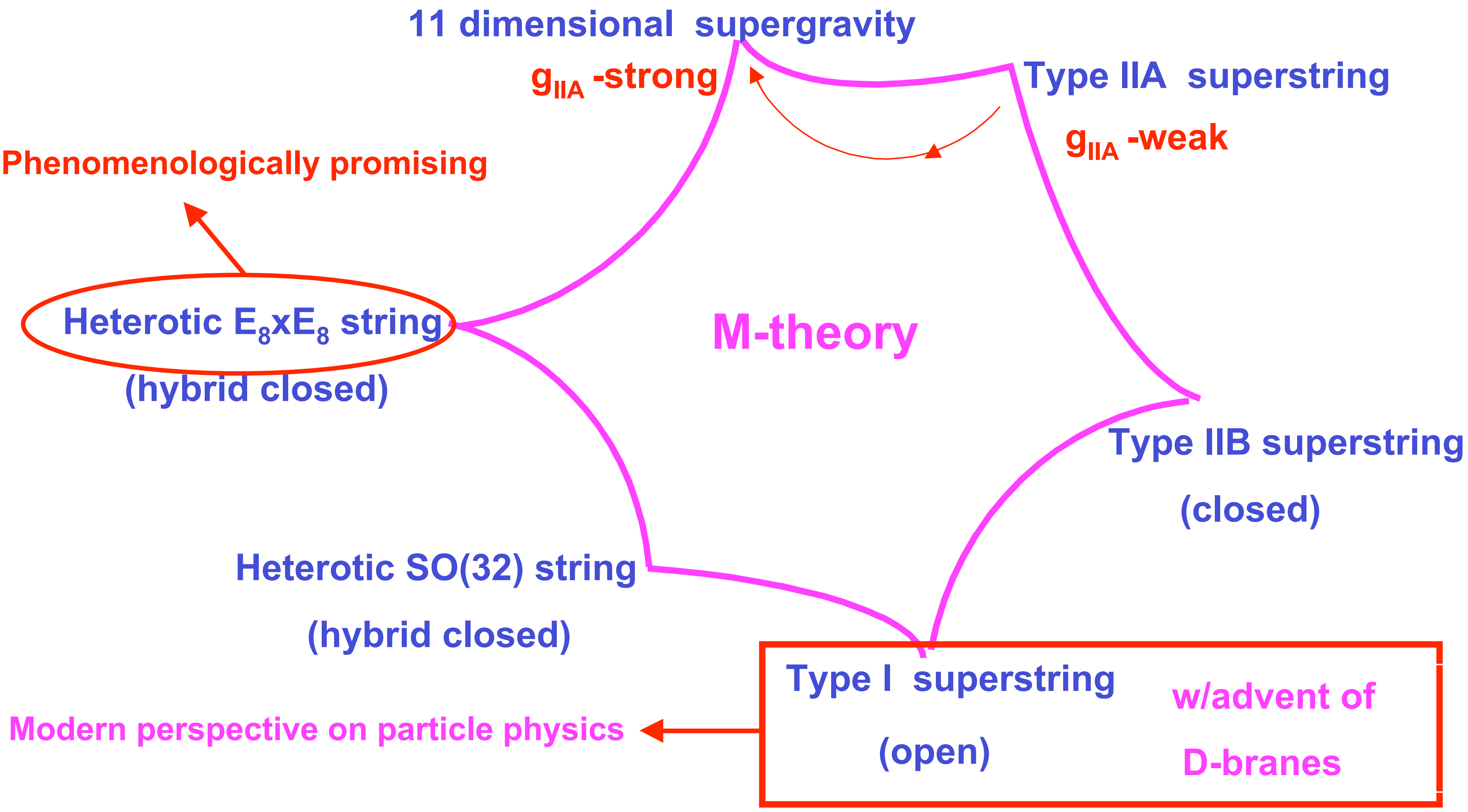
Modern String Theory (w/ D-branes) – geometric origin!

Perturbative String Theories

Non-perturbative Unification

Hull&Townsend'94

Witten'95



11 dimensional supergravity

g_{IIA} -strong

Type IIA superstring

g_{IIA} -weak

Phenomenologically promising

Heterotic $E_8 x E_8$ string

(hybrid closed)

M-theory

Type IIB superstring

(closed)

Heterotic SO(32) string

(hybrid closed)

Type I superstring

(open)

w/advent of

D-branes

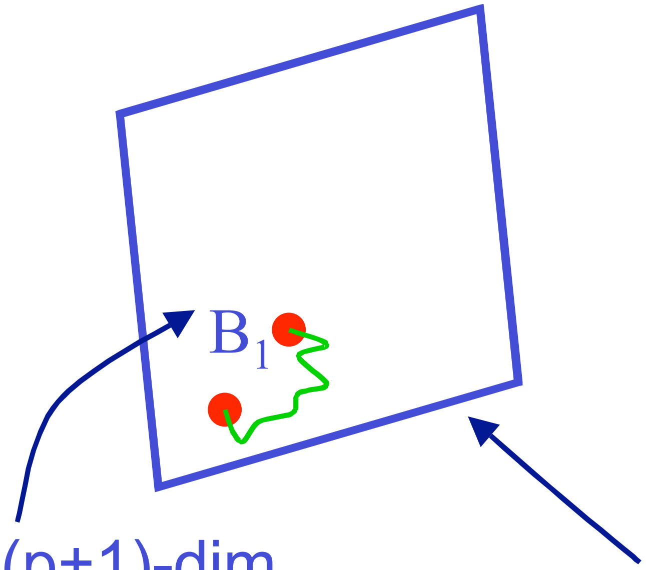
Modern perspective on particle physics

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

Polchinski'96

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

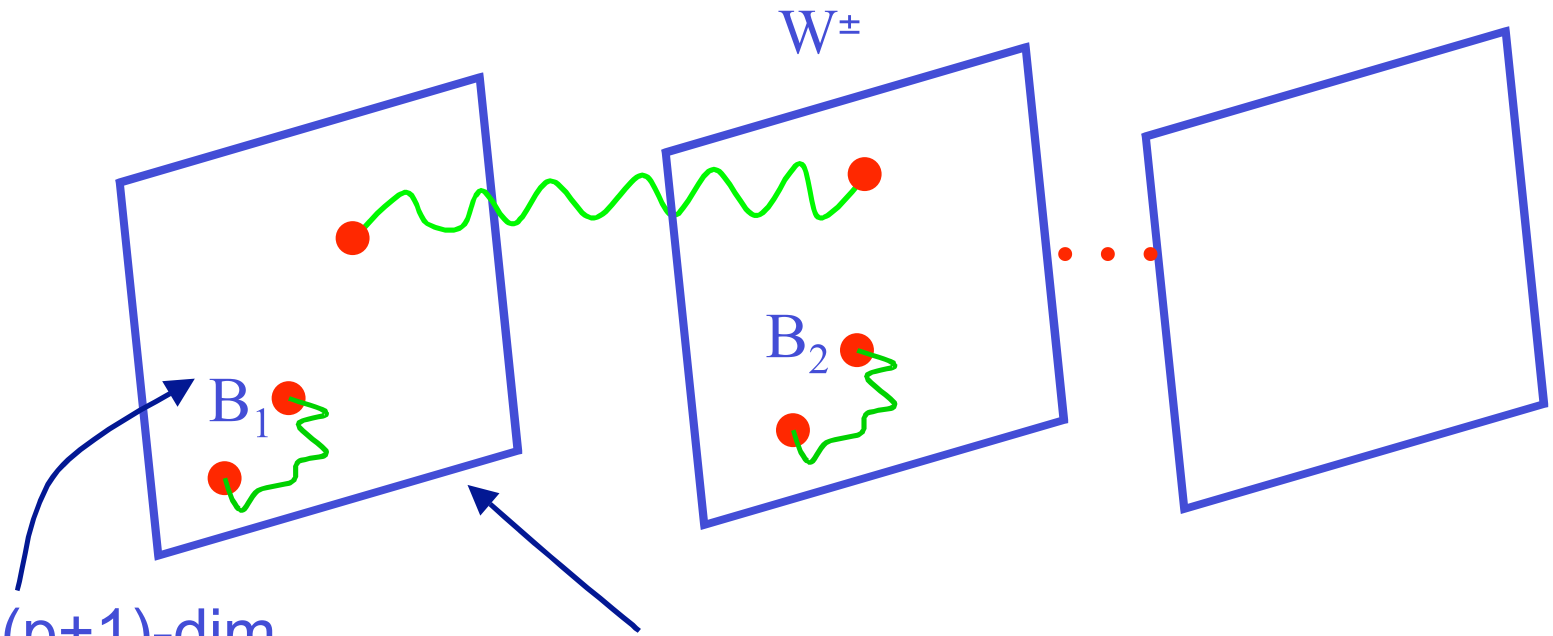
(9-p) – dim
transverse

U(1)

Polchinski’96

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

(9-p) – dim
transverse

$$U_1(1) \times U_2(1) \times \ldots U_N(1)$$
$$\downarrow$$
$$U(N)$$

N-coincident D-branes

↓

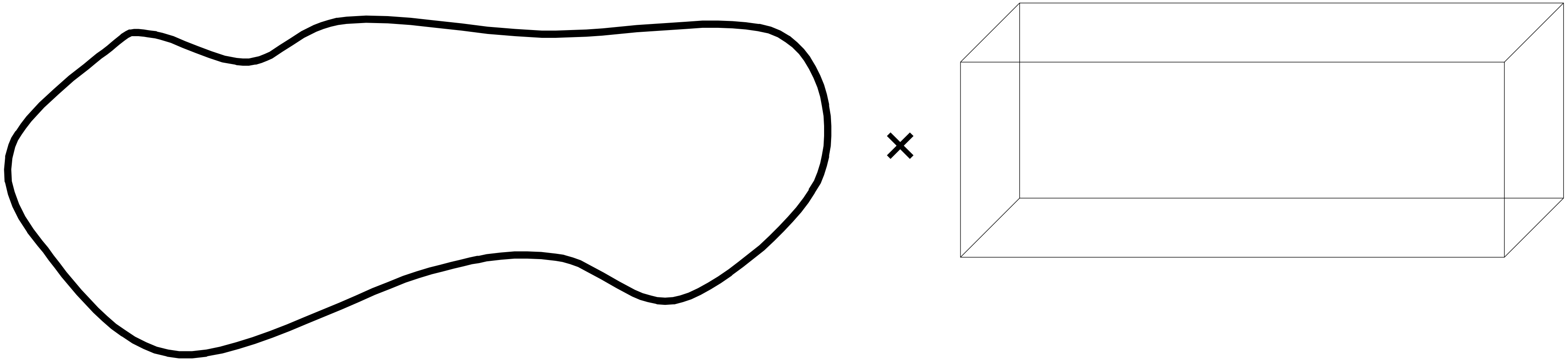
non-Abelian gauge symmetry

Compactification

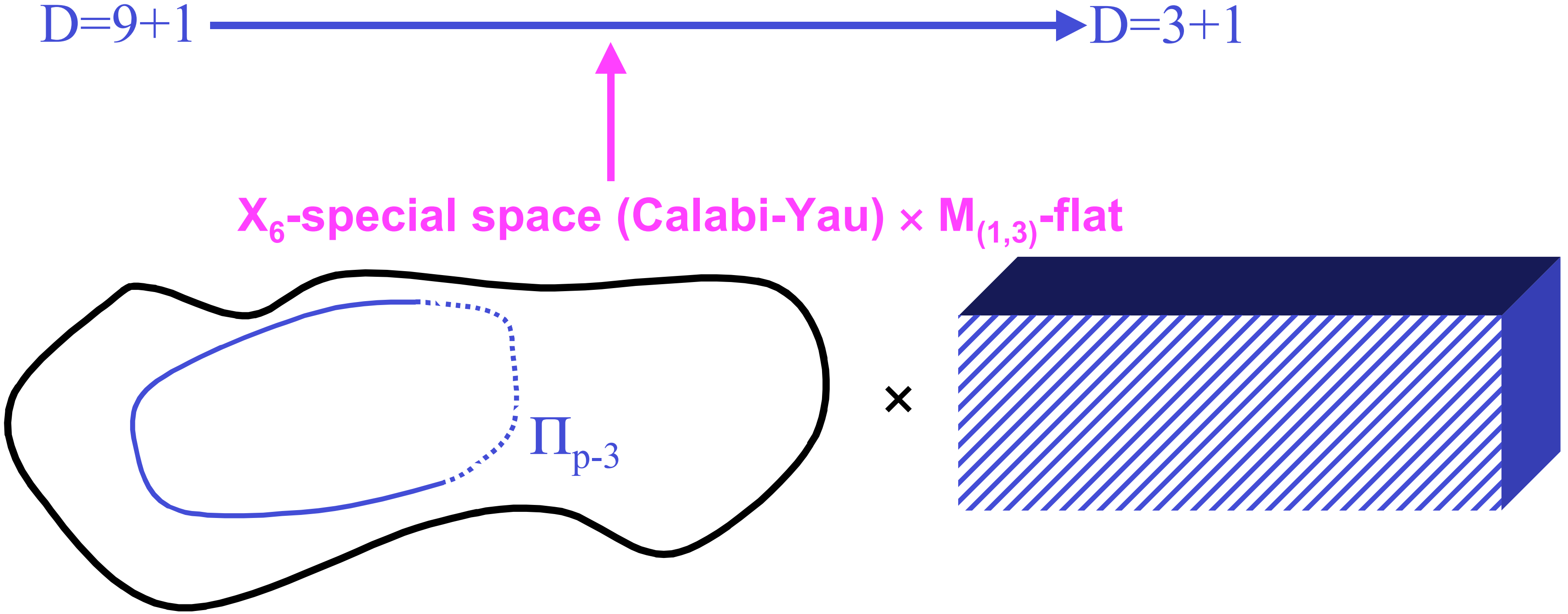
D=9space + 1 time → D=3space + 1 time

& supersymmetry

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



Compactification



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

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

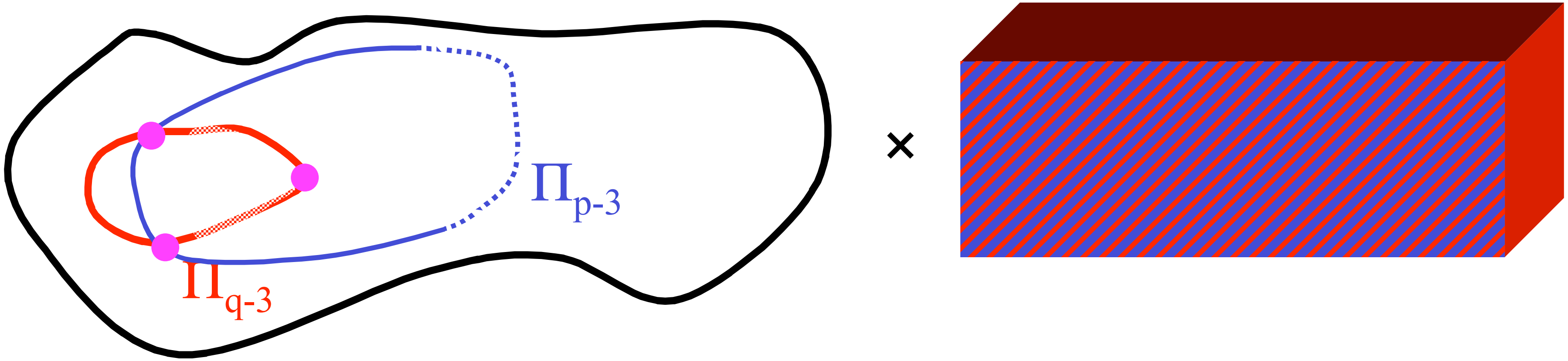
D p-branes – extend in p+1 dimensions:
3+1-our world $M_{(3,1);}$; (p-3)-wrap Π_{p-3} cycles of X_6

Compactification

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

$\uparrow$

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

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

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

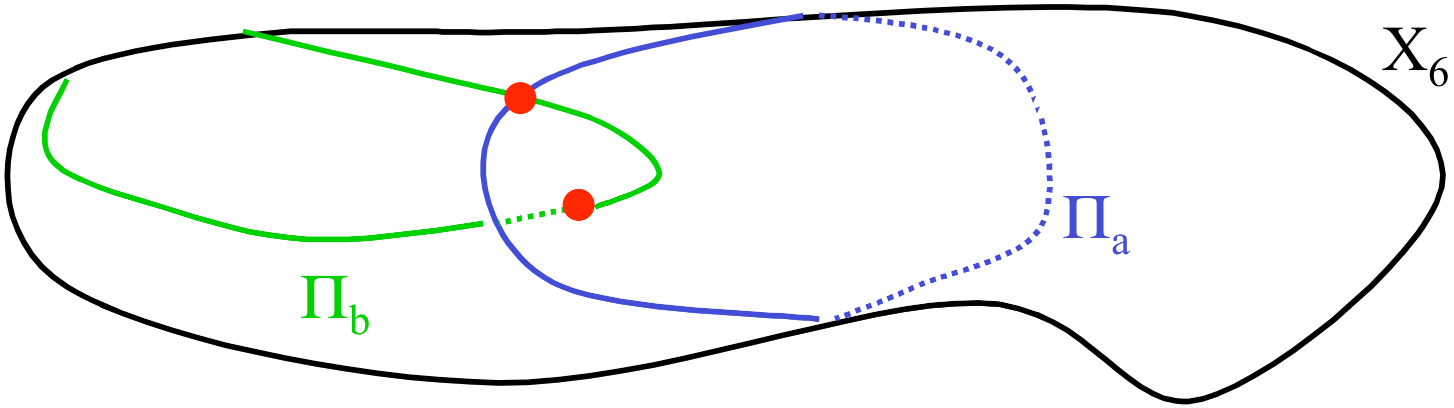
$\Downarrow$

Rich structure!

[D-branes at singularities& Wilson lines-failed at realistic constr.
e.g.,w/Wang&Plümacher'00; w/Wang&Uranga'01]

Focus on D6-branes – Realistic Particle Physics

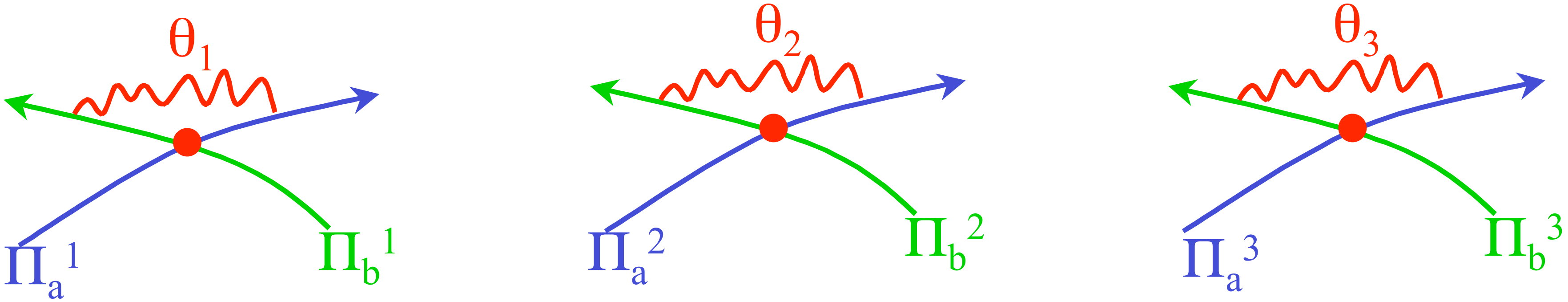
wrap 3-cycles Π



In internal space intersect at points:

$[\Pi_a] \circ [\Pi_b]$ - topological number

$\Pi_a = \Pi_a^1 \otimes \Pi_a^2 \otimes \Pi_a^3$ – Factorizable 3-cycles

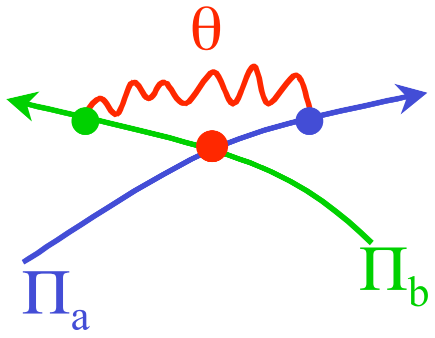


Berkooz, Douglas & Leigh '96

At each intersection-massless 4d fermion ψ

Geometric origin of chirality!

Engineering of Standard Model



N_a- D6-branes wrapping Π_a

N_b- D6-branes wrapping Π_b

$$U(N_a) \times U(N_b)$$

$\Psi \sim (N_a , \overline{N}_b)$ - $[\Pi_a]°[\Pi_b]$ – number of families

$N_a = 3$, $N_b = 2$, $[\Pi_a]°[\Pi_b] = 3$

$$U(3)_C \times U(2)_L$$

$\Psi \sim (3 , 2)$ - 3 copies of left-handed quarks

Global consistency conditions:

D6-brane charge conserv. in internal space - RR tadpole cancellation

Sagnotti et al. ’90s;Gimon&Polchinski’97….Blumenhagen,Görlich,Körs &Lüst’00…

& supersymmetry conditions (constraining!)

technical (no time!)

⇩

Building Blocks of Supersymmetric Standard Model

Angelantonj, Antoniadis,Dudas&Sagnotti'00

Non-Supersymmetric Standard-like Models (infinitely many)

Blumenhagen, Görlich, Körs & Lüst '00-01
Aldazabal, Franco, Ibanez, Rabadan & Uranga '00-'01
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.
.

$M_{string} \sim M_{planck}$ large NS-NS tadpole
large radiative corrections

↓

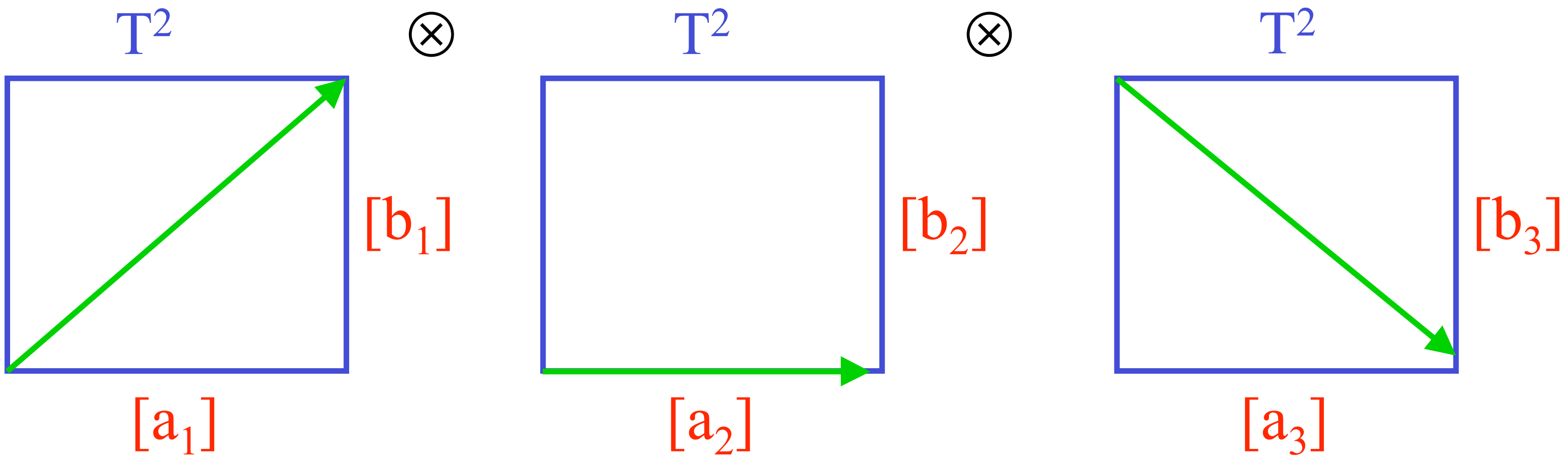
Supersymmetric Standard-like Models (constrained)

First supersymmetric Standard Model

w/G. Shiu and & A. Uranga'01

Toroidal/Orbifold compactifications (conformal field theory techniques)

$T^6/(Z_N \times Z_M)$



$T^6 =$ $T^2 \otimes T^2 \otimes T^2$

$[b_1]$ $[b_2]$ $[b_3]$

$[a_1]$ $[a_2]$ $[a_3]$

$(n_a^i, m_a^i) =$ $(1,1)$ $(1,0)$ $(1,-1)$

$[\Pi_a] =$ $[\Pi_a^1] \otimes [\Pi_a^b] \otimes [\Pi_a^c]$

homology class of 3-cycles

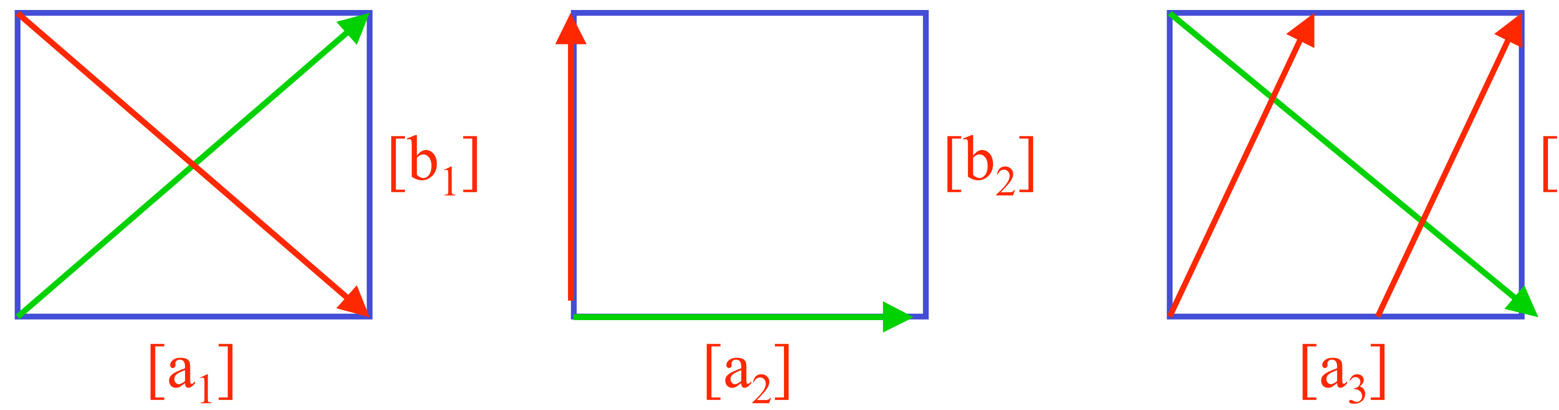
$[\Pi_a^i] = n_a^i [a_i] + m_a^i [b_i]$

$[N_a, n_a^i, m_a^i]$

Toroidal/Orbifold compactifications (conformal field theory techniques)

$T^6/(Z_N \times Z_M)$

$T^6 = T^2 \otimes T^2 \otimes T^2$



$(n_a^i, m_a^i) =$ (1,1) (1,0) (1,-1)

$[\Pi_a] = [\Pi_a^1] \otimes [\Pi_a^b] \otimes [\Pi_a^c]$

homology class of 3-cycles

$[\Pi_a^i] = n_a^i [a_i] + m_a^i [b_i]$

$[N_a, n_a^i, m_a^i] \quad [N_b, n_b^i, m_b^i]$

Intersection number: $I_{ab} = [\Pi_a] \circ [\Pi_b] = \Pi_{i=1}^{3} (n_a^i m_b^i - n_b^i m_a^i)$

Global Consistency Conditions

Gimon&Polchinski'98,Sagnotti et al. '90-ies
Blumenhagen, Görlich, Körs & Lüst '00

Cancellation of Ramond-Ramond (RR) Tadpoles

Gauss law for D6-charge conservation

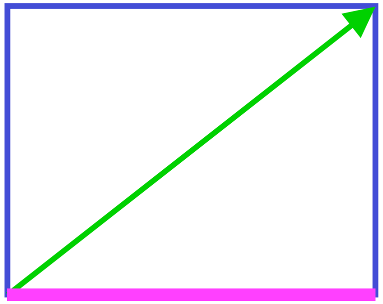
$$N_a \; (\, [\Pi_a] \; + \; [\Pi_{a'}] \,) \; = \; -4 \, [\Pi_{O6}]^{*}$$

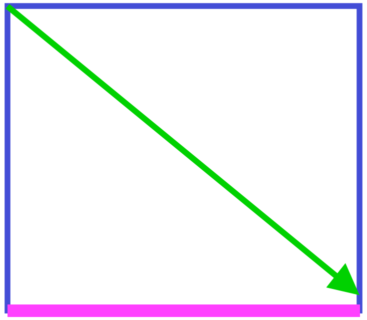
* **Constraints on wrapping numbers**

Not possible to satisfy of CY spaces (``total''tension = charge = 0)

Orientifold plane - fixed planes w/ negative D6- charge

..





Global consistency conditions
(D6-brane charge conservation in internal space)

for toroidal/orbifold compactifications

$$\sum_a N_a \; n_a^1 n_a^2 n_a^3 = 16$$

$$-\sum_a N_a \, n_a^1 m_a^2 m_a^3 = 16$$

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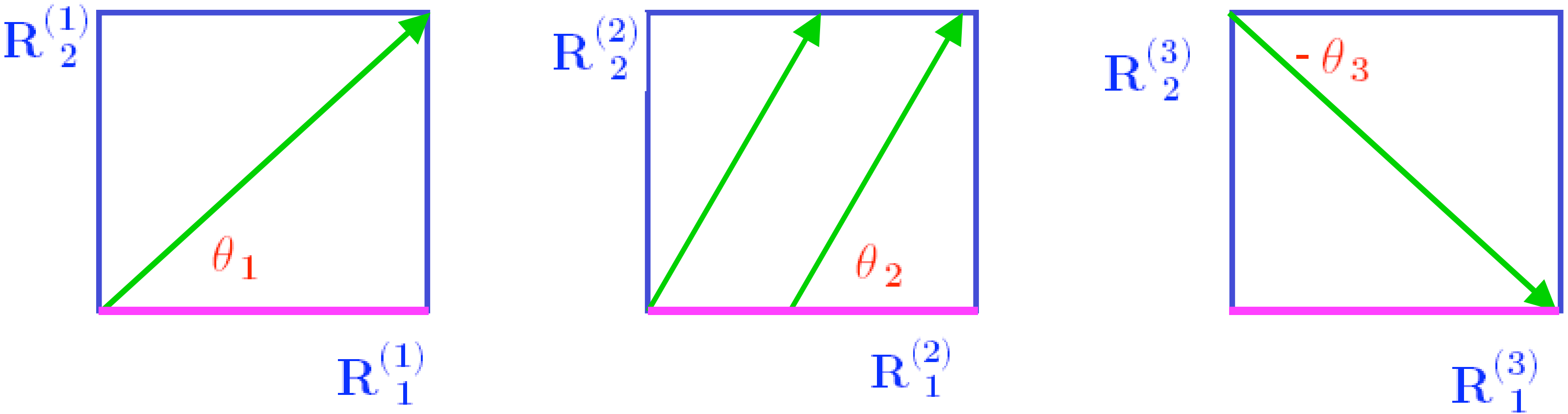
Supersymmetry (toroidal/orbifold example)



$$\theta_1 + \theta_2 + \theta_3 = 0$$

$$\arctan\left(\frac{m_1}{n_1}\chi_1\right) + \arctan\left(\frac{m_2}{n_2}\chi_2\right) + \arctan\left(\frac{m_3}{n_3}\chi_3\right) = 0$$

Constraints on complex structure moduli- Ui ~ $\chi_i = \frac{R_2^{(i)}}{R_1^{(i)}}$

$$\{\theta_i^a\} \neq 0 \quad U(N_a)$$

$$\{\theta_i^a\} = 0 \quad Sp(N_a)$$

i) Supersymmetric Standard Model Constructions- Penn leading the effort
primarily on Z_2xZ_2 orbifolds

a) FIRST STANDARD MODEL (1) **w/G. Shiu & A. Uranga'01**
branes wrap special cycles

b) MORE STANDARD MODELS (4)
branes wrap more general cycles (better models) **w/I. Papadimitriou'03**

c) SYSTEMATIC SEARCH FOR STANDARD MODELS (11)
based on left-right symmetric models-2 models very close to minimal SM
w/T. Li and T. Liu hep-th/0403061

d) NEW TECHNICAL DEVELOPMENTS-MORE MODELS (3)
Analysis of brane splittings/electroweak branes || w/ orientifold planes
w/P. Langacker, T. Li & T.Liu hep-th/0407178

e) NEW TECHNICAL DEVELOPMENS (rigid cycles) - MORE MODELS (5)
Branes on rigid cycles**w/R.Blumenhagen, F.Marchesano and G.Shiu, hep-th/0502095**
w/T. Liu,work in progress

ii) Calculation of couplings

Yukawa couplings – fermion masses **w/I. Papadimitriou'03**

iii) Phenomenological implications **w/P. Langacker and G. Shiu'02**

Pedagogical review **w/R.Blumenhagen,P.Langacker&G.Shiu, hep-th/0502005**

i) Supersymmetric Standard Models:

primarily on $Z_2 x Z_2$ orbifolds

a) FIRST STANDARD MODEL (1) w/G. Shiu & A. Uranga'01
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e) $U(1)_{B-L}$ from a more general D-brane conf. (1) Chen, Li &Nanopoulos hep-th/0509118
f) NEW TECHNICAL DEVELOPMENS (rigid cycles) – MORE (four-family) MODELS (5)
Branes on rigid cycles w/R.Blumenhagen, F.Marchesano and G.Shiu, hep-th/0502095
w/T. Liu,work in progress

Other orbifolds
(a) Z4-orientifold (1) - brane recombination Blumenhagen, Görlich & Ott'03
(b) Z4 x Z2-orientifold (1) - brane recombination Honecker'03
(c) Z6-orientifold - just SM (1)-Yukawa couplings (?) Honecker & Ott '04

ii) Calculation of couplings among matter particles

Yukawa couplings – fermion masses w/I.Papadimitriou'03
Four-point and higher-point functions Abel&Owen'03,Klebanov-Witten03…

Threshold corrections to gauge couplings Stieberger&Lüst'03

Pedagogical review w/R.Blumenhagen,P.Langacker&G.Shiu, hep-th/0502005

Four-family Standard Model

Table 2: D6-brane configurations and intersection numbers for the four-family Standard-like model. In the table, χ_i is the complex modulus for the $i-$th torus, and β_i^g is the beta function for the $i-$th Sp group from the $i-$th stack of branes.

$\ell^i \equiv m^i$

I	$[U(4)_C \times Sp(8)_L \times Sp(8)_R]_{observed} \times [U(4) \times Sp(8) \times Sp(8)]_{hidden}$										
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	c	d	d'	1	2
a	8	$(1,0)\times(1,1)\times(1,-1)$	0	0	1	-1	0	0	0	0
b	8	$(0,1)\times(1,0)\times(0,-1)$	0	0	-	0	0	0	0	0
c	8	$(0,1)\times(0,-1)\times(1,0)$	0	0	-	-	0	0	0	0
d	8	$(0,1)\times(1,-1)\times(1,-1)$	0	0	-	-	-	0	-1	1
1	8	$(1,0)\times(1,0)\times(1,0)$	$\chi_2 = \chi_3 = 1$							
2	8	$(1,0)\times(0,-1)\times(0,1)$	$\beta_1^g = \beta_2^g = -4$							

no inter-section w/ hidden secto

no chiral exotics!

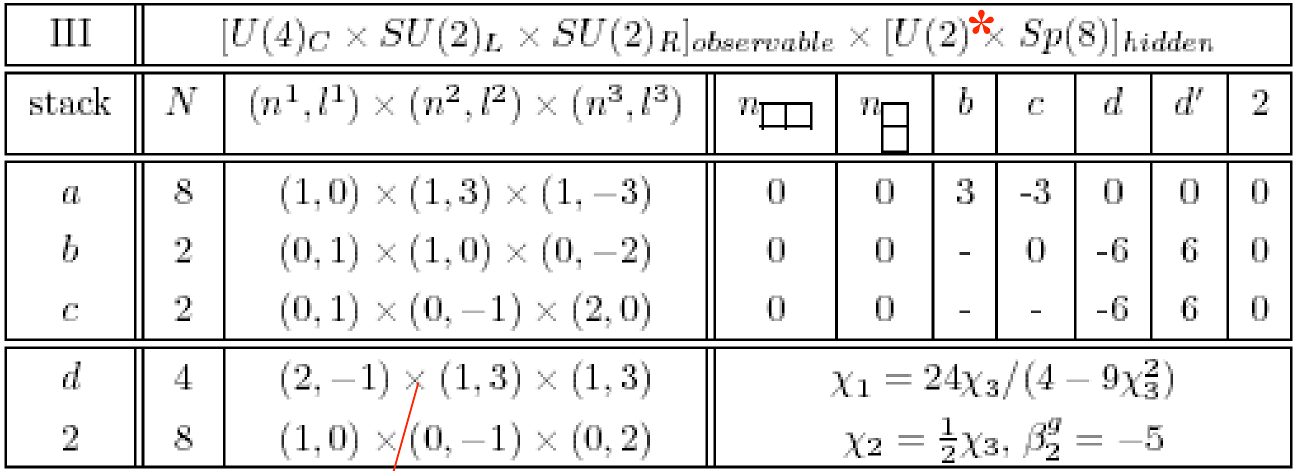
$Sp(8)_L$ x $Sp(8)_R$ 1-Higgs (8,8), one-family confining ``hidden sector

↓ brane splitting ↓ brane splitting ↓

$U(2)_L$ x $U(2)_R$ 16- Higgs (2,2), four-families

Three-family SM model w/Sp $(2)_L$ x Sp$(2)_R$ directly (Z$_2$ x Z$_2$ orientifold)

$$\ell^i \equiv 2\, m^i$$



III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)$*$\times Sp(8)]_{hidden}$								
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\Box\Box}$	$n_{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	b	c	d	d'	2
a	8	$(1,0)\times(1,3)\times(1,-3)$	0	0	3	-3	0	0	0
b	2	$(0,1)\times(1,0)\times(0,-2)$	0	0	-	0	-6	6	0
c	2	$(0,1)\times(0,-1)\times(2,0)$	0	0	-	-	-6	6	0
d	4	$(2,-1)\times(1,3)\times(1,3)$	$\chi_1 = 24\chi_3/(4-9\chi_3^2)$						
2	8	$(1,0)\times(0,-1)\times(0,2)$	$\chi_2 = \frac{1}{2}\chi_3,\ \beta_2^g = -5$						

non-zero Intersections w/hidden sector chiral exotics

wrapping nos. of SM - for toroidal orientifold does not cancel RR-tadpoles

Cremades, Ibanez & Marchesano'03

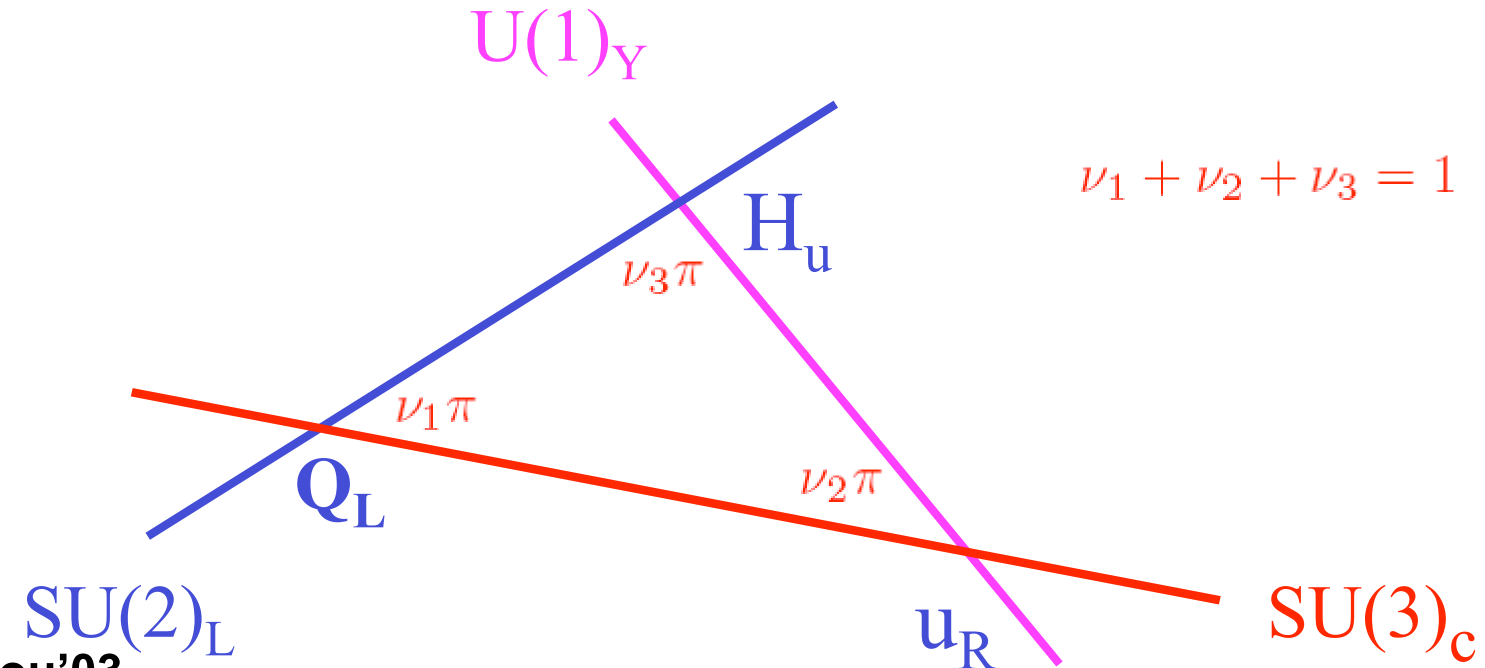
Embedding in Z$_2$ x Z$_2$ orientifold-allows for cancellation of RR-tadpoles

w/ Langacker, Li &Liu, hep-th/0407178

*"hidden sector" (unitary) branes - necessary for RR-tadpole cancellation

Yukawa Couplings

Intersections in internal space (schematic on ith-two-torus)



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

w/Papadimitriou'03

(Conformal Field Theory Techniques)

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

quantum part

classical part A_I^i -triangle areas on ith two-torus lattice

(c.f., Cremades, Ibanez & Marchesano'03 for detailed study)

Moduli Stabilization & Chiral Models

I. ``Hidden sector'' strong dynamics (ß < 0)- gaugino condensation

$$f_a = n_a^1 n_a^2 n_a^3 S - m_a^1 n_a^2 n_a^3 U_1 - n_a^1 m_a^2 n_a^3 U_2 - n_a^1 n_a^2 m_a^3 U_3$$

gauge coupling dilaton complex structure moduli

Nonperturbative potential depends exponentially on f_a- example of S, U_i-moduli fixed & SUSY broken

w/Langacker&Wang'03

II. Supergravity Fluxes:

Type IIA – program to classify N=1 supergravity vacua

(nearly Kähler internal space & chiral non-Abelian D-brane sector)

w/K. Behrndt, hep-th/0308045, 0403049, 0407163

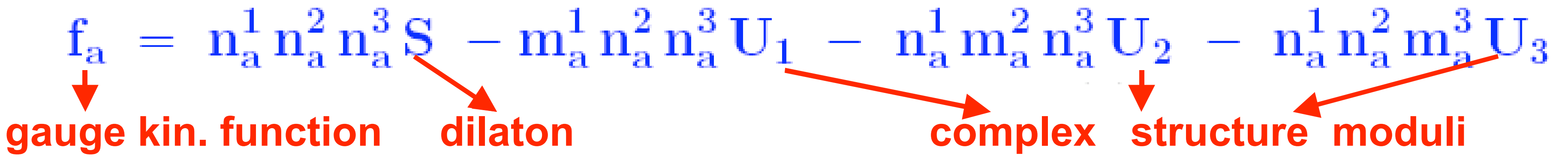
[also &w/P.Gao, hep-th/0502154 &w/T. Liu, work in progress]

Type IIB - first classes of 3&4 family SM's with fluxes turned on

w/T.Liu/hep-th/0409032, w/T.Li&T.Liu, hep-th/0501041

Moduli Stabilization & Chiral Models

I. ``Hidden sector'' strong dynamics (ß < 0)- gaugino condensation



$$f_a = n_a^1 n_a^2 n_a^3 S - m_a^1 n_a^2 n_a^3 U_1 - n_a^1 m_a^2 n_a^3 U_2 - n_a^1 n_a^2 m_a^3 U_3$$

gauge kin. function dilaton complex structure moduli

Example of S, U_i-fixed, SUSY broken

w/Langacker&Wang'03

II. Supergravity Fluxes:

Type IIA – nearly Kähler internal space & chiral non-Abelian D-brane sector

w/K. Behrndt, hepth/0308045, 0403049, 0407163

superpotential calculation

Derendinger,Kounnas,Petropoulos&Zwirner,hep-th/0411276,0503229; Cremades,Font&Ibanez,hepth/0506055

Type IIB - examples of SM with fluxes **Marchesano&Shiu hep-th/0408058,04091**

w/T.Liu/hep-th/0409032, w/T.Li&T.Liu, hep-th/0501041

Chen,Li&Nanopoulos, hep-th/0509118

Type IIB theory & Fluxes

[D1,D3,D5,D7- branes] [C(2n) – RR potentials]

Fluxes better understood: supersymmetry conditions, back-reaction, **potential** for moduli, etc.

Rich framework: cosmology, landscape, etc.

Focus on sta bilization of all moduli:

Giddings, Kachru&Polchinski ’01

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Kachru, Kallosh, Linde & Trivedi ’03

.

Denef, Douglas,Florea,Grassi&Kachru, hep-th/0503124

Aspinwall & Kallosh, hep-th/0506014

.

However, these efforts do not focus on realistic particle physics !

FOCUS: REALISTIC CHIRAL FLUX COMPACTIFICATIONS

[Standard Model and (some) moduli fixed due to fluxes]

Specific flux (w/ mild back-reaction; internal space conformal to Calabi Yau):

$$G_3 = F_3 - \tau H_3$$

RR-3form dilaton/axion NS-NS-3form

Supersymmetry: self-dual, primitive (2,1) form **Grana&Polchinski'00**

[Four-dim **superpotential:**
Gukov,Vafa&Witten'99

$$\mathbf{W} \sim \int \boldsymbol{\Omega} \wedge \mathbf{G}_{(3)} = \mathrm{f}^{\mathrm{I}}\, \mathrm{p}_{\mathrm{I}}$$

complex structure moduli]

Through Chern Simons term, G_3 (quantized) flux contributes to Q_{D3} charge:

$$N_{\rm flux} = \frac{1}{(4\pi^2\alpha')^2}\,\frac{i}{2\tau_I}\int_{X_6} G_3 \wedge \overline{G}_3$$

**STRONG CONSTRAINS ON GLOBAL CONSISTENCY CONDITION,
THUS CONSTRAINING ALLOWED D-BRANE SECTOR**

D-Brane Sector:

Type IIA: Intersecting D6-branes

↓ T-duality ($R_1^{(i)} \to \frac{\alpha'}{R_1^{(i)}}$)

Type IIB: Magnetized D9-branes

w/ induced D3 and D7 charges

(analogous global consistency conditions as for D6-branes)

Cascales&Uranga'03;Blumenhagen,Lüst&Taylor'03'

Antoniadis&Maillard'04 …

D-Brane Sector:

Type IIA: **Intersecting D6-branes**

$\downarrow$ **T-duality (** $\mathrm{R}_1^{(\mathrm{i})} \rightarrow \dfrac{\alpha'}{\mathrm{R}_1^{(\mathrm{i})}}$ **)**

Type IIB: **Magnetized D9-branes**

Cascales&Uranga'03;Blumenhagen,Lüst&Taylor'03

$\{\mathrm{N_a}\ ,\ (\mathrm{n_a^i}\ ,\ \mathrm{m_a^i}\ )\ \}$

$$m_a^i \frac{1}{2\pi} \int_{\mathbf{T}_\mathrm{i}^2} F_a^i = n_a^i$$

U(1)-D-brane magnetic field

Induced D3 and D7 charges

$$Q3_a = N_a n_a^1 n_a^2 n_a^3,$$

$$(Q7_i)_a = N_a n_a^i m_a^j m_a^k, \qquad \mathrm{i} \neq \mathrm{j} \neq \mathrm{k}$$

Global consistency conditions
for toroidal/orbifold compactifications

$$\begin{aligned}
\sum_a N_a \, n_a^1 n_a^2 n_a^3 &= 16 \\
-\sum_a N_a \, n_a^1 m_a^2 m_a^3 &= 16 \\
-\sum_a N_a \, m_a^1 n_a^2 m_a^3 &= 16 \\
-\sum_a N_a \, m_a^1 m_a^2 n_a^3 &= 16
\end{aligned}$$

D-branes & Fluxes (Type IIB)

Global consistency conditions
for toroidal/orbifold compactifications

$$Q_{D3} \qquad \sum_a N_a \; n_a^1 n_a^2 n_a^3 = 16 - N_{flux}/2$$

$$Q_{D7_1} \qquad -\sum_a N_a \, n_a^1 m_a^2 m_a^3 = 16$$

$$Q_{D7_2} \qquad -\sum_a N_a \, m_a^1 n_a^2 m_a^3 = 16$$

$$Q_{D7_3} \qquad -\sum_a N_a \, m_a^1 m_a^2 n_a^3 = 16$$

$$N_{flux} = n_f N_0$$

Need negative D3-brane contributions - constrained !

Three-family SM model w/$Sp(2)_L$ x $Sp(2)_R$ electro-weak sector (Z_2 x Z_2 orientifold)

III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^{*} \times Sp(8)]_{hidden}$									
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\Box\Box}$	$n_{\boxminus}$	b	c	d	d'	2	
a	8	$(1,0)\times(1,3)\times(1,-3)$	0	0	3	-3	0	0	0	
b	2	$(0,1)\times(1,0)\times(0,-2)$	0	0	-	0	-6	6	0	
c	2	$(0,1)\times(0,-1)\times(2,0)$	0	0	-	-	-6	6	0	
d	4	$(2,-1)\times(1,3)\times(1,3)$	$\chi_1 = 24\chi_3/(4-9\chi_3^2)$							
2	8	$(1,0)\times(0,-1)\times(0,2)$	$\chi_2 = \frac{1}{2}\chi_3$, $\beta_2^g = -5$							

Non-zero Intersections w/hidden sector-chiral exotics

wrapping nos. of SM

Cremades, Ibanez & Marchesano'03

Z2 x Z2 orientifold embedding-cancellation of RR-tadpoles

*~~U(2)~~-D9-brane w/ negative D3-charge contribution

w/ Langacker, Li & Liu, hep-th/0407178

3-family SM Chiral Flux Vacuum:

U(1) x U(1) & nf=1 flux units **Marchesano & Shiu, hep-th/0408058,0409132**

f-family Standard Model w/Sp(2f)L xSp(2f)R & nf-units of flux

w/T. Liu hep-th/0409032

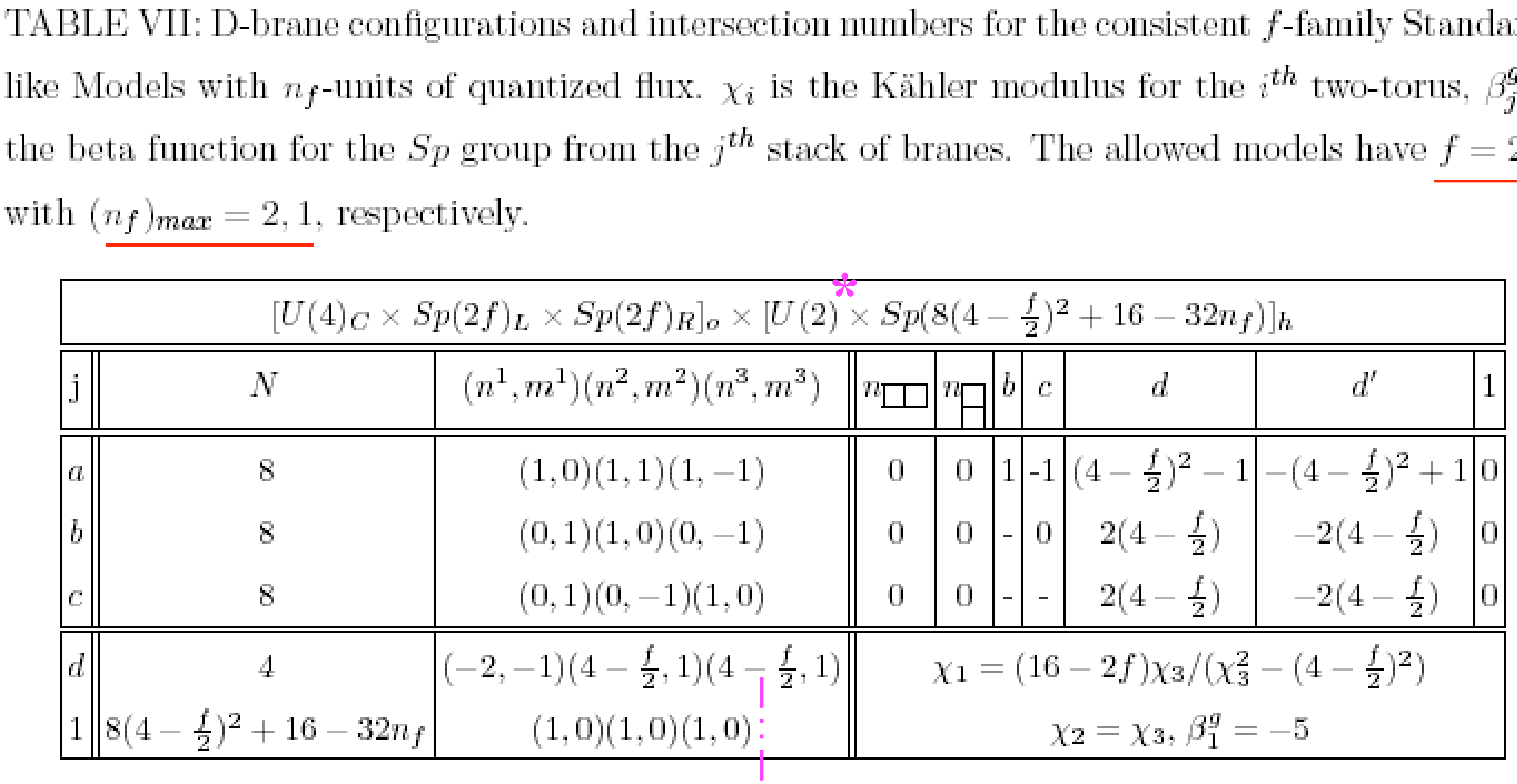

TABLE VII: D-brane configurations and intersection numbers for the consistent f-family Standard-like Models with n_f-units of quantized flux. χ_i is the Kähler modulus for the i^{th} two-torus, β^g_j is the beta function for the Sp group from the j^{th} stack of branes. The allowed models have $f=2,4$ with $(n_f)_{max}=2,1$, respectively.

$[U(4)_C \times Sp(2f)_L \times Sp(2f)_R]_o \times [U(2)^{*} \times Sp(8(4-\frac{f}{2})^2+16-32n_f)]_h$

j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	c	d	d'	1
a	8	$(1,0)(1,1)(1,-1)$	0	0	1	-1	$(4-\frac{f}{2})^2-1$	$-(4-\frac{f}{2})^2+1$	0
b	8	$(0,1)(1,0)(0,-1)$	0	0	-	0	$2(4-\frac{f}{2})$	$-2(4-\frac{f}{2})$	0
c	8	$(0,1)(0,-1)(1,0)$	0	0	-	-	$2(4-\frac{f}{2})$	$-2(4-\frac{f}{2})$	0
d	4	$(-2,-1)(4-\frac{f}{2},1)(4-\frac{f}{2},1)$	$\chi_1=(16-2f)\chi_3/(\chi_3^2-(4-\frac{f}{2})^2)$						
1	$8(4-\frac{f}{2})^2+16-32n_f$	$(1,0)(1,0)(1,0)$	$\chi_2=\chi_3,\ \beta^g_1=-5$						

intersections
w/hidden sector
chiral exotics

n_f=1, f=4: Sp(8)L x Sp(8)R $\xrightarrow{\text{brane splitting}}$ U(2)L x U(2)R

n_f=2, f=2: Sp(4)L x Sp(4)R $\xrightarrow{\text{brane splitting}}$ Sp(2)L x Sp(2)R

* **U(2)** w/specific wrapping nos (negative D3-brane charge) to cancel flux contrib

w/T. Li &T. Liu hep-th/0501041

New Sets of Flux Models

Gauge symmetry: $U(4)_C \times U(2)_L \times U(2)_R \times \underbrace{Sp(2N_1) \times Sp(2N_2)\ldots}_{\text{``Hidden sector''}}$

or $(Sp(2)_L)$ or $(Sp(2)_R)$

SM-sector contains branes w/ NEGATIVE D3 - brane charge
[Fluxes contribute to global consistency conditions in the D-brane Standard Model sector]

New representative models (of order 20) of 3- and 4-family Standard Models with up to 3-units of quantized flux.

Three -family SM with 3- units of flux (supersymmetric)

Table 5: D-brane configurations and intersection numbers for $Model - T_3 - 1$.

$Model - T_3 - 1$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable}$									
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	b	b'	c	c'	Kähler moduli
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	12	-10	$\chi_3=\chi_2=2\chi_1$
b	4	$(1,1)(2,-1)(1,0)$	-2	2	-	-	6	6	$\chi_3=2\sqrt{10}$
c	4	$(-2,-1)(4,1)(3,1)$	-6	-106	-	-	-	-	

Three -family SM with 2- units of flux

Table 6: D-brane configurations and intersection numbers for $Model - T_2 - 1$.

$Model - T_2 - 1$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(12-4n_f)]_{Hidden}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	b	b'	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	8	-8
b	4	$(2,1)(2,-1)(1,0)$	0	0	-	-	0	4
c	4	$(-2,-1)(3,1)(3,1)$	-44	-64	-	-	-	-
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\chi_3=\chi_2=\chi_1=\sqrt{21}$					

Three -family SM with 1- units of flux

Table 7: D-brane configurations and intersection numbers for $Model - T_1 - 1$.

$Model - T_1 - 1$	$[U(4)_C \times Sp(2)_L \times U(2)_R]_{Observable} \times [Sp(8)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	b	c	c'
a	8	$(1,0)(3,1)(3,-1)$	0	0	-3	3	0
b	2	$(0,1)(0,-1)(2,0)$	0	0	-	16	-
c	4	$(-2,-1)(4,1)(3,1)$	-6	-106	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$\chi_2=\chi_3, \frac{12}{\chi_2^2}+\frac{14}{\chi_1\chi_2}$				

More three-family SM’s with 1-unit of flux

Table 8: D-brane configurations and intersection numbers for $Model - T_1 - 2$.

$Model - T_1 - 2$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(8) \times Sp(4)]_{Hidden}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	b	b'	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	4	-6
b	4	$(2,1)(2,-1)(1,0)$	0	0	-	-	0	0
c	4	$(-2,-1)(2,1)(3,1)$	-18	-78	-	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$\chi_3 = \chi_2 = \chi_1 = 4$					
$(D7)_2$	8	$(0,1)(1,0)(0,-1)$						

Table 9: D-brane configurations and intersection numbers for $Model - T_1 - 3$.

$Model - T_1 - 3$	$[U(4)_C \times U(2)_L \times Sp(4)_R]_{Observable} \times [Sp(4)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	b	b'	c
a	8	$(-1,-1)(2,1)(2,1)$	-2	-30	3	-5	-4
b	4	$(1,0)(3,1)(1,-1)$	4	-4	-	-	0
c	4	$(1,0)(0,1)(0,-1)$	0	0	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$3\chi_3 = \chi_2,\ \frac{12}{\chi_2^2} + \frac{8}{\chi_1\chi_2} = 1$				

Phenomenology:

w/P. Langacker, T. Li & T. Liu, to appear

(models descendants of Pati-Salam Models)

(a) Yukawa Couplings:

-Pati-Salam model w/ minimal (MSSM) Higgs sector not viable;
For the specific construction-mass only for the 3rd family.

-Models w/ non-minimal Higgs sector better. However, Yukawa couplings symmetric-a handful of models w/ masses and mixings for 2nd and 3rd family.

-Modification of Yukawa couplings due to fluxes (backreaction)

w/S. Abel, work in progress

(b) Exotics:

-models possess chiral exotics due to SM branes intersecting w/ ``hidden'' sector ones - problem

-new chiral flux constructions w/ mainly right chiral exotics & Yukawa couplings to SM Higgs sector (M~ TeV) –but SM precision constraints

(c) $U(1)_{B-L}$ breaking:

-VEV of right sneutrino-problematic because of R-parity breaking

-$U(1)_{B-L}$ breaking by exotic sneutrinos- but SM precision constraints

I. Moduli Stabilization:

(a) Toroidal **complex structure moduli U_i** - fixed by fluxes.
(b) In some cases all toroidal **Kähler moduli T_i** - fixed by SUSY

OR

Examples of Kähler moduli fixed by SUSY & a hidden sector, w/ negative **ß function,** resulting in gaugino condensation w/ non-perturbative superpotential:

$$\mathbf{W_{eff}} = \frac{\beta \mathbf{\Lambda}^3}{\mathbf{32}\mathrm{e}\pi^2} \exp\left(\frac{\mathbf{8}\pi^2}{\beta} \mathbf{f}(\mathbf{T_i})\right) + \mathbf{W_o}$$

function of Kähler moduli flux contrib.(fixed complex structure moduli)

All toroidal Kähler moduli stabilized & SUSY restored (à la KKLT)

(c) D-brane splitting moduli-massive due to flux backreaction ("curse" lifted)

[However, twisted closed sector moduli not stabilised;
D-brane recombination moduli-could form flat directions w/Kähler moduli - problem!]

Flux SM's with Confining Hidden Sector that stabilizes the left-over Kähler modulus

$Model - F_1 - 5$		$[U(4)_C \times Sp(8)_L \times U(2)_R]_{Observable} \times [Sp(4) \times Sp(4)]_{Hidden}$					
j	N	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\square\square}$	$n_{\overset{\square}{\square}}$	b	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-1	6	-4
b	8	$(0,1)(0,-1)(1,0)$	0	0	-	3	-
c	4	$(-1,-1)(3,1)(2,1)$	-4	-44	-	-	-
$(D7)_1$	4	$(1,0)(0,1)(0,-1)$	$\chi_2 = \chi_3,\ \frac{6}{\chi_3^2} + \frac{5}{\chi_1 \chi_3} = 1$				
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\beta^g_{(D7)_1} = -3(0),\ \beta^g_{(D7)_2} = -5(-2)$				

Sector w/negative beta functions & Kähler moduli dependent gauge functions

Analysis of soft SUSY breaking mass terms

(a) Fluxes (and/or hidden sector strong dynamics) **break supersymmetry**.
Employing full Yukawa Coupling/Kähler potential calculations
w/Papadimitiriou'03,Lust,Mayr,Richter&Stieberger'04;Cremades,Ibanez&Marchesano'04

(b) Determine **soft supesymmetry breaking mass parameters** in terms of F- (and D-) supersymmetry breaking parameters in the closed moduli sector
Camara,Ibanez&Uranga, hep-th/0408064; Lust, Reffert&Stieberger, hep-th/0410074; Kane,Kumar,Lykken&Wang, hep-th/0411125; Ibanez&Font, hep-th/0412150 . . . .

(i) For all specific constructions (descendants of Pati-Salam models) & **SUSY breaking due to fluxes** **soft mass terms- degenerate among different family species** in the right and left sector & among Leptons and Quarks.
(The soft mass terms are governed by the intersection angles, and are the same for different family species in the right and left sector.)

Problematic for generating fermion masses and mixings at the loop level

(ii) SUSY breaking due to hidden sector strong dynamics-gaugino condens.

Can lift soft mass degeneracy/implications for fermion masses

work in progress w/S. Abel

Summary/Outlook

(a) Major progress: techniques for consistent SM constructions on orientifolds w/intersecting D6-branes&fluxes

(b) Sizable number of semi-realistic models (on the order of 20 classes) w/moduli stabilised; systematic searches

(c) Models not fully realistic:
typically some exotic matter, couplings not fully realistic,
toroidal moduli stabilized

FULLY REALISTIC CONSTRUCTIONS
particle spectrum, interactions & all moduli stabilized ?

NOT THERE YET, BUT GETTING BETTER AT IT