Perturbative and Non-perturbative Effects In String Vacua

I. Modern String Theory & implications for particle physics –D-branes

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

III. New non-perturbative effects: D-instanons

Phenomenological implications: Majorana neutrino masses, μ-parameter, modified Yukawa couplings

R.Blumenhagen, M.C.,T.Weigand, hep-th/0609191 (initiated major activity);
M. C.,R.Richter,T.Weigand, hep-th/0703028;
R.Blumenhgen,M.C.,D.Lüst,R.Richter,T.Weigand, arXiv:0707.1871;
R.Blumenhagen,M.C.,R.Richter,T.Weigand,arXiv:0708.0403.

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

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

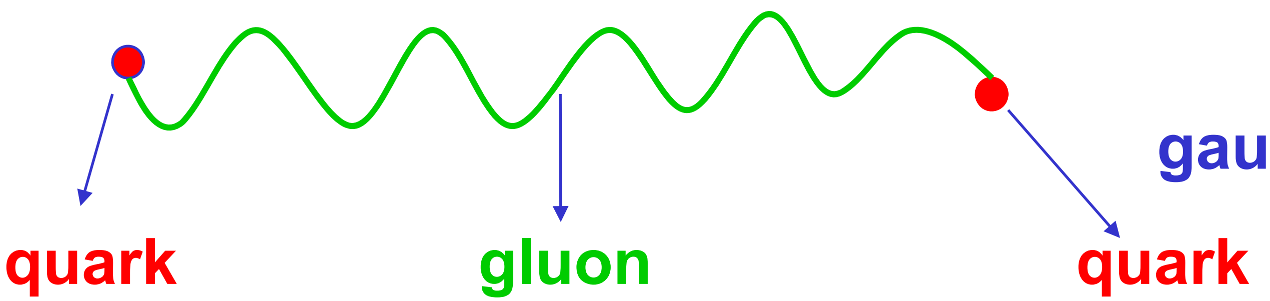
Force mediated via spin 1-particles: gluons,W-bosons&photon

3-families:

$Q_L \sim (\underline{3}, \quad \underline{2}, \quad {}^1/_6 \ )$ – quarks

$L \sim (\underline{1}, \quad \underline{2}, \quad -1 \ )$ – leptons, etc.

chiral matter



gauge interactions

& Supersymmetry

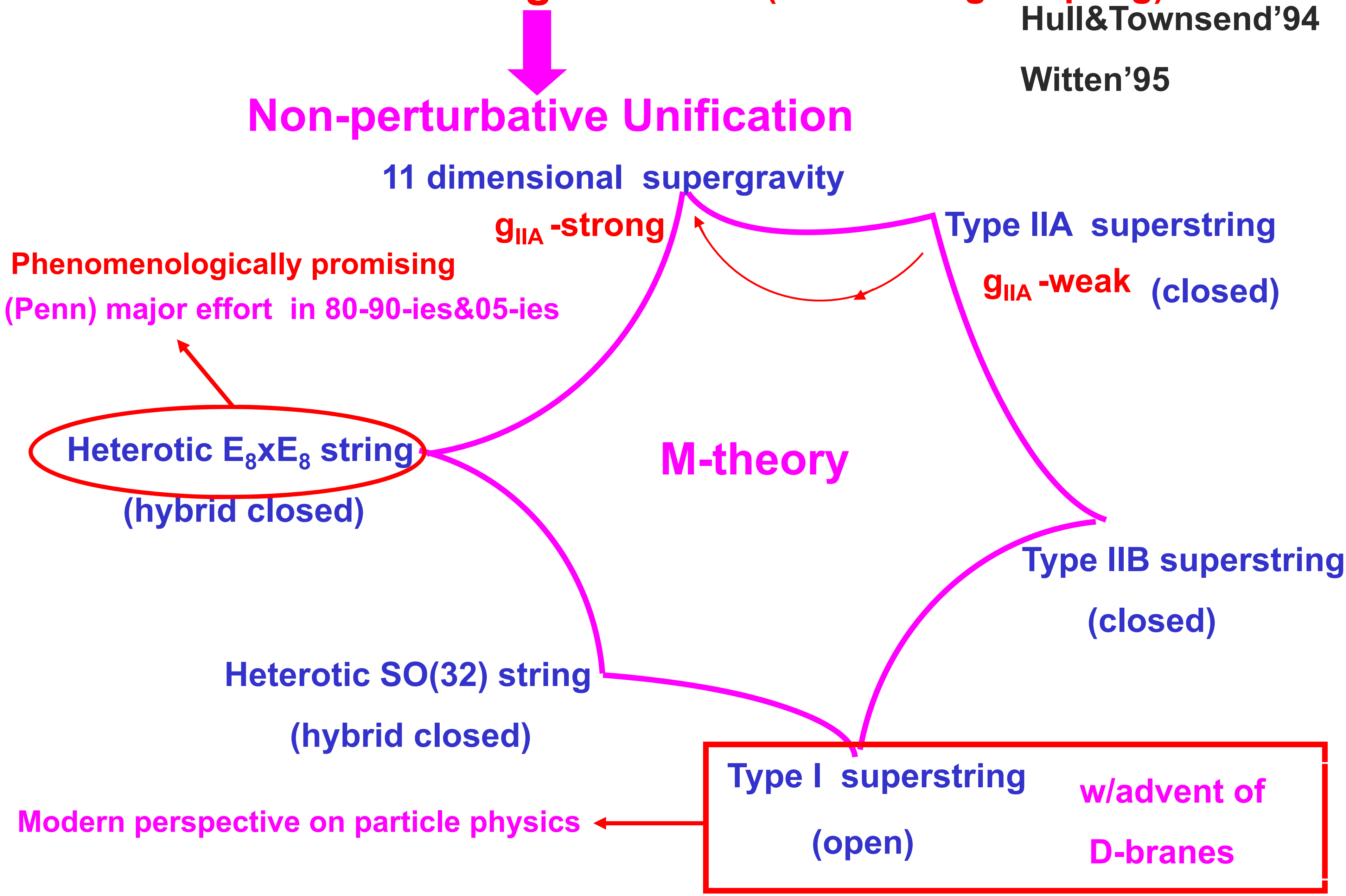
Modern String Theory (w/ D-branes) – geometric origin!

Perturbative String Theories (small string coupling)

Hull&Townsend'94

Witten'95

Non-perturbative Unification

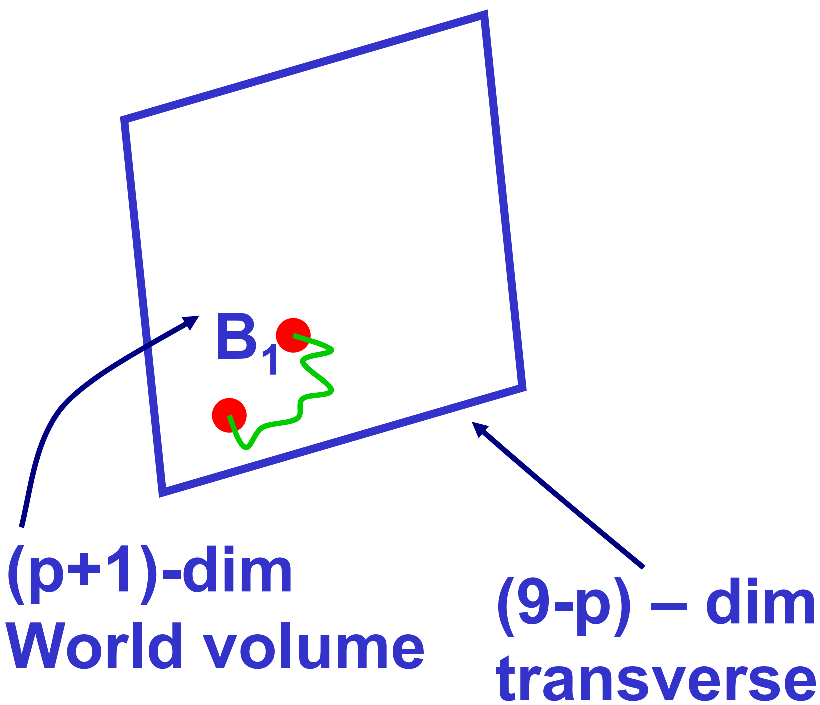


Different String Theories related to each other by Weak-Strong Coupling DUALITY

Polchinski'96

D-branes & non-Abelian gauge theory

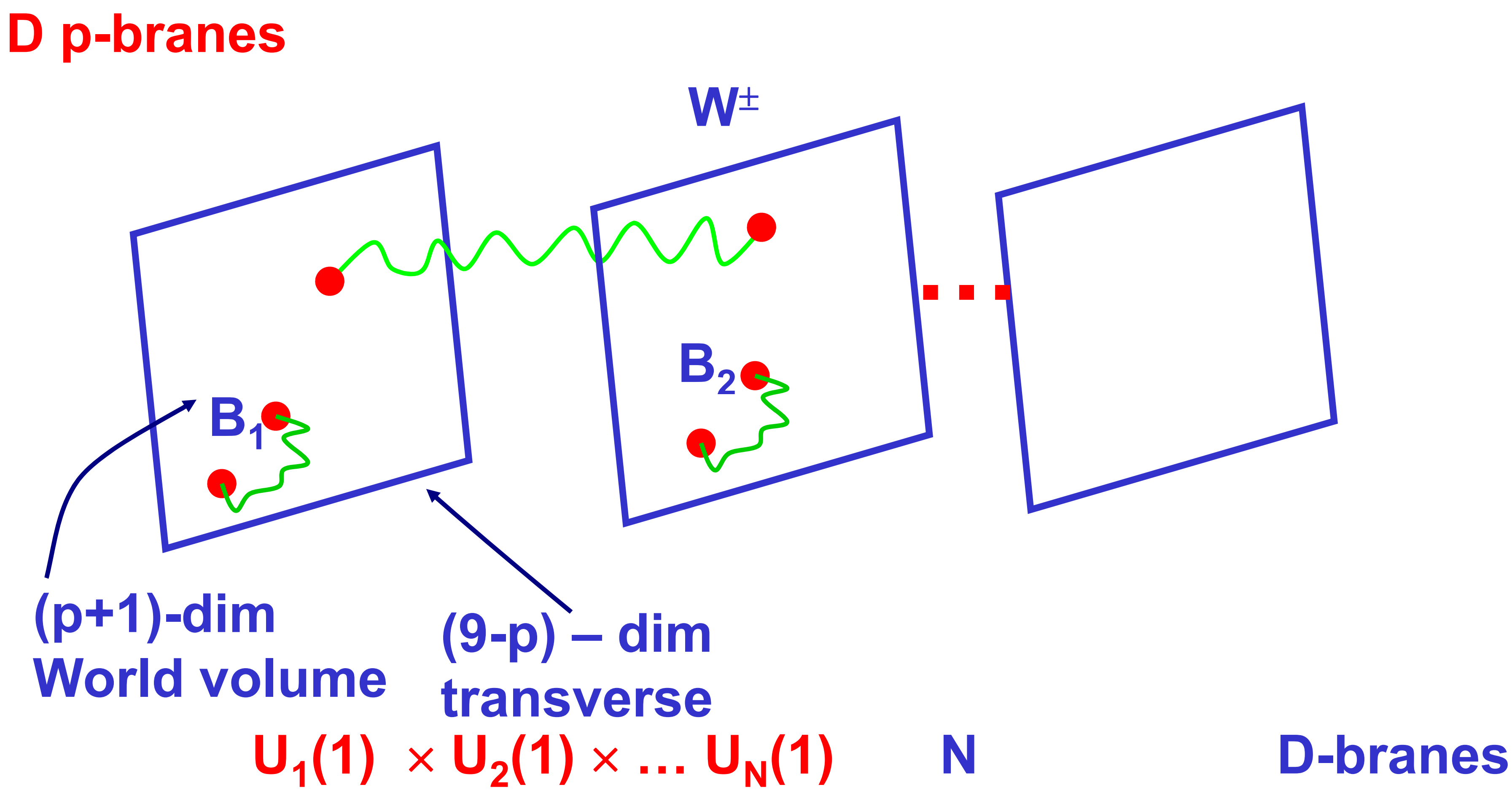
D p-branes



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

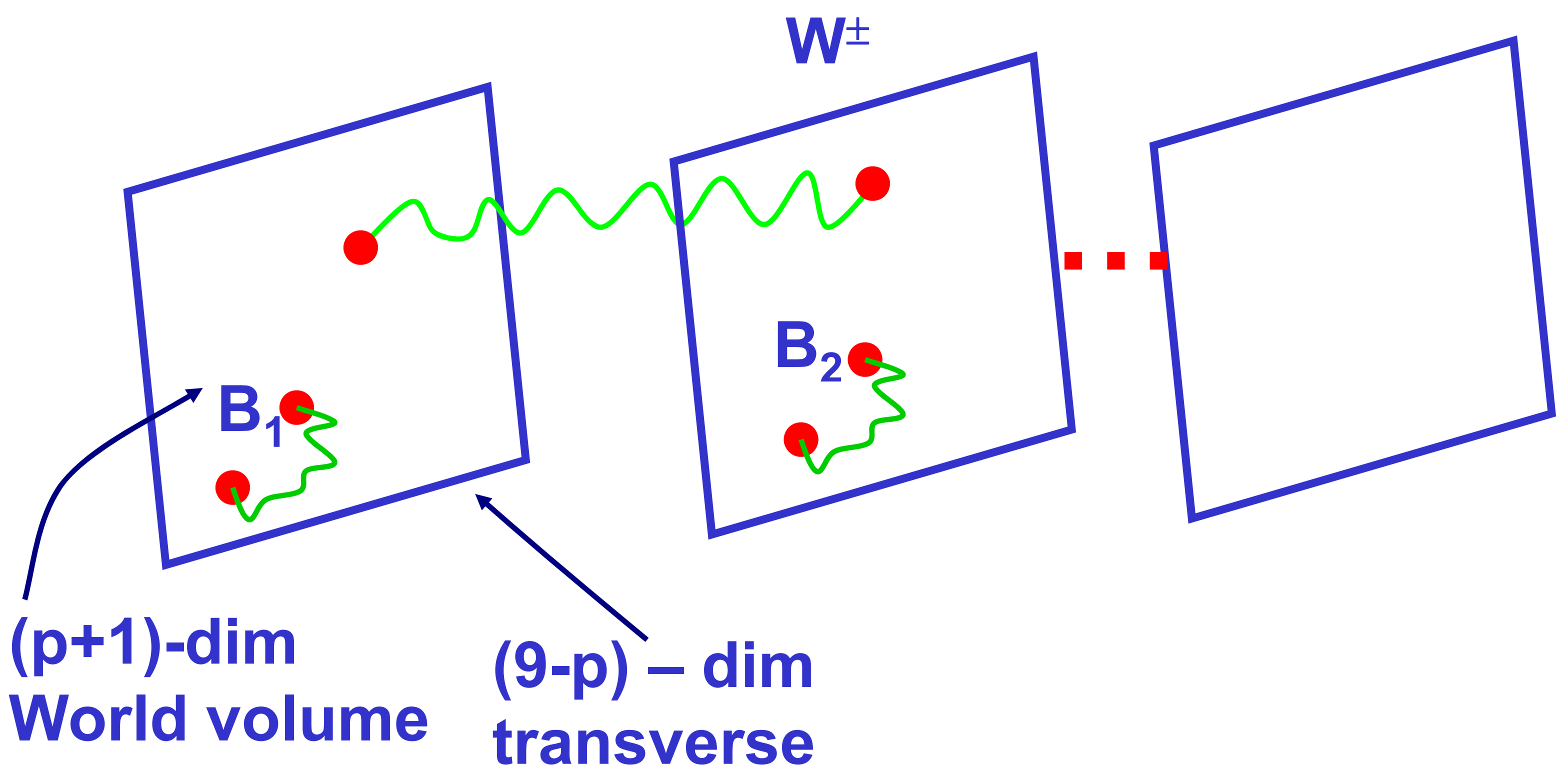


$U_1(1) \times U_2(1) \times \ldots U_N(1)$

Polchinski'96

D-branes & non-Abelian gauge theory

D p-branes



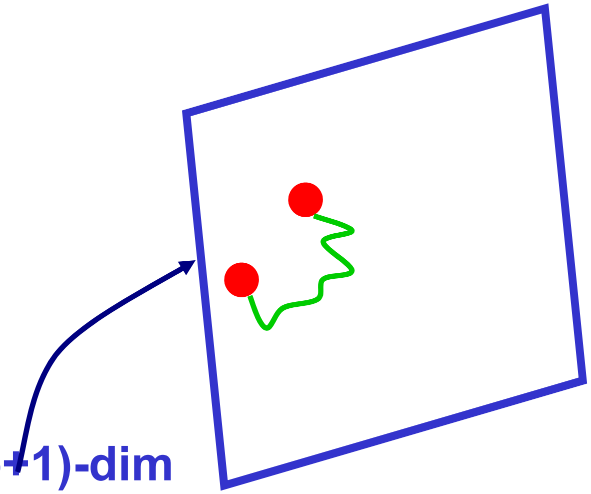
$U_1(1) \times U_2(1) \times \ldots U_N(1)$ N-coincident D-branes

↓

$U(N)$ non-Abelian gauge symmetry

DIGRESSION-Dual Nature of D-branes

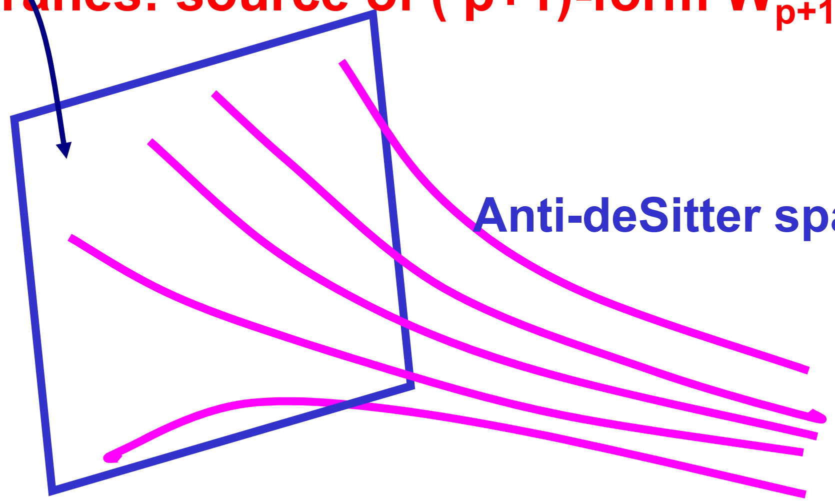
D p-branes:boundaries of open strings



(Conformal) Field Theory

(p+1)-dim
World volume

D p-branes: source of (p+1)-form W_{p+1}potential & curve space-time



Anti-deSitter space-time (negative cosmol. const.)

Related?

Yes!

Maldacena'97

Anti-deSitter/Conformal Field Theory Correspondence AdS/CFT

DIGRESSION: Gravitational role of branes

Black Holes in string theory

First constructions suitable for microscopic counting (w/Youm'95,w/Tseytlin'95,..Kallosh et al.'93-present…)

Microscopic properties Strominger&Vafa'96, …w/Tseytlin '95-'96, w/Larsen'97-'00….

Brane World Randall&Sundrum'99

[related -first supergarity domain walls w/Griffies&Rey'92,… w/Soleng'94-'96 (review)]

Source for ``Gravity Fluxes"

Can fix the shape of compactified space-

…Giddings,Kachru &Polchinski'01..,KKLT'03…w/Li&Liu'04…

Stabilization of Moduli (no time!)

FIELD THEORY SIDE of D-branes

(as boundaries of open strings)

(i) non-Abelian gauge symmetry

N-coincident D-branes ➡ U(N)

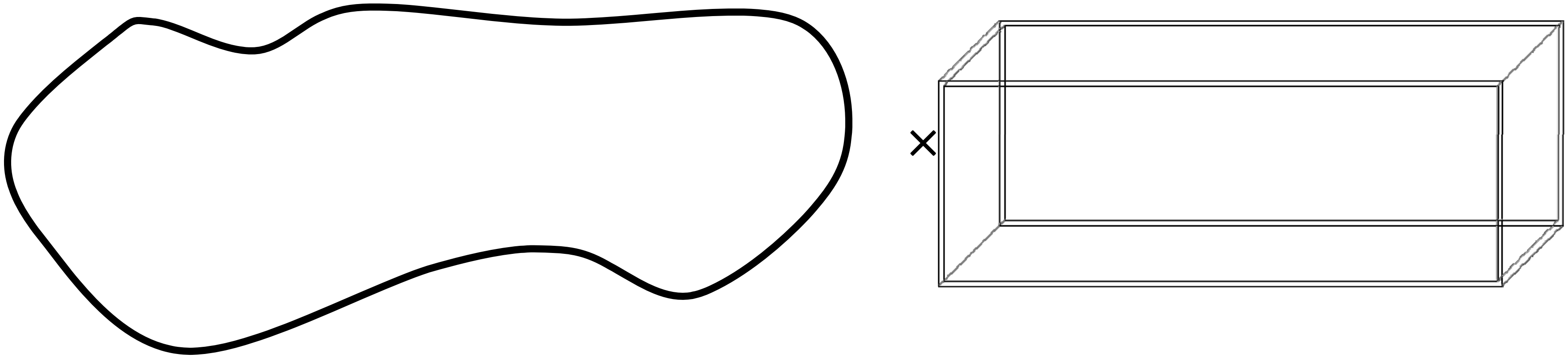
(ii) Appearance of matter ➡ turn to compactification

Compactification

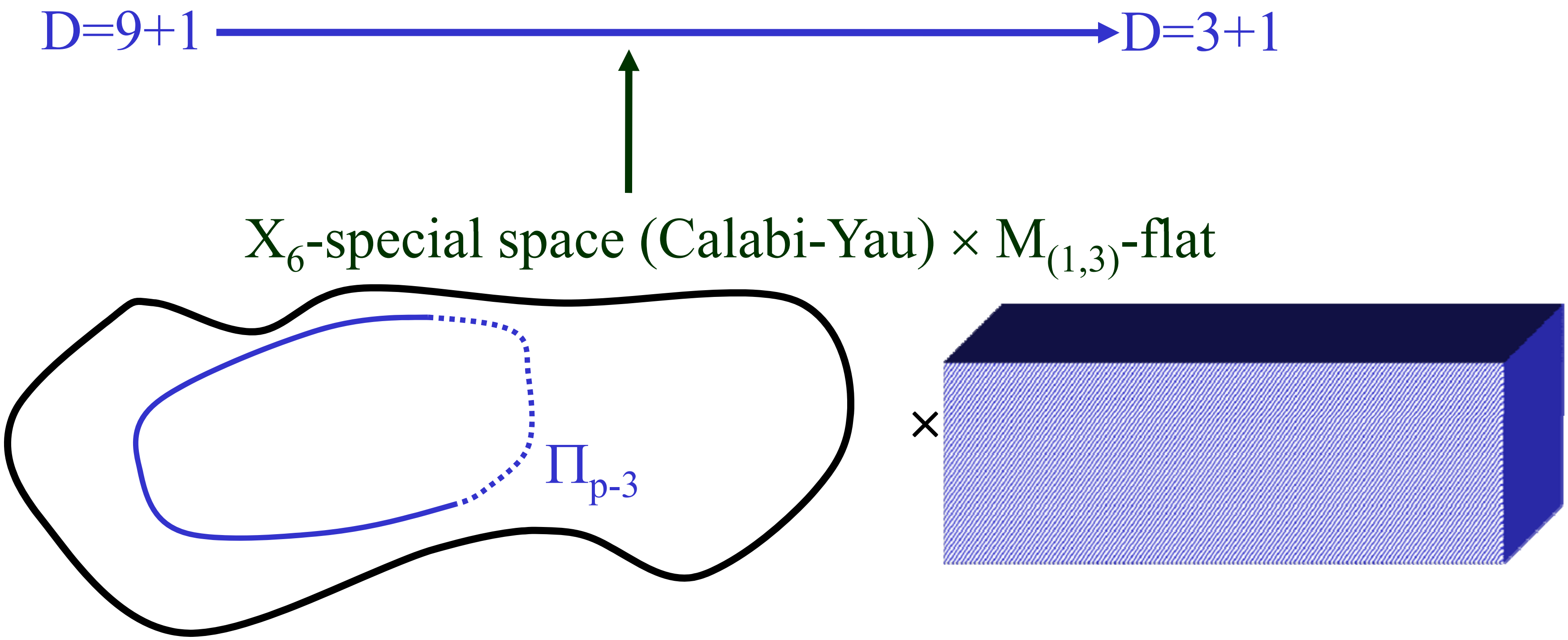
D=9+1 → D=3+1

↑

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

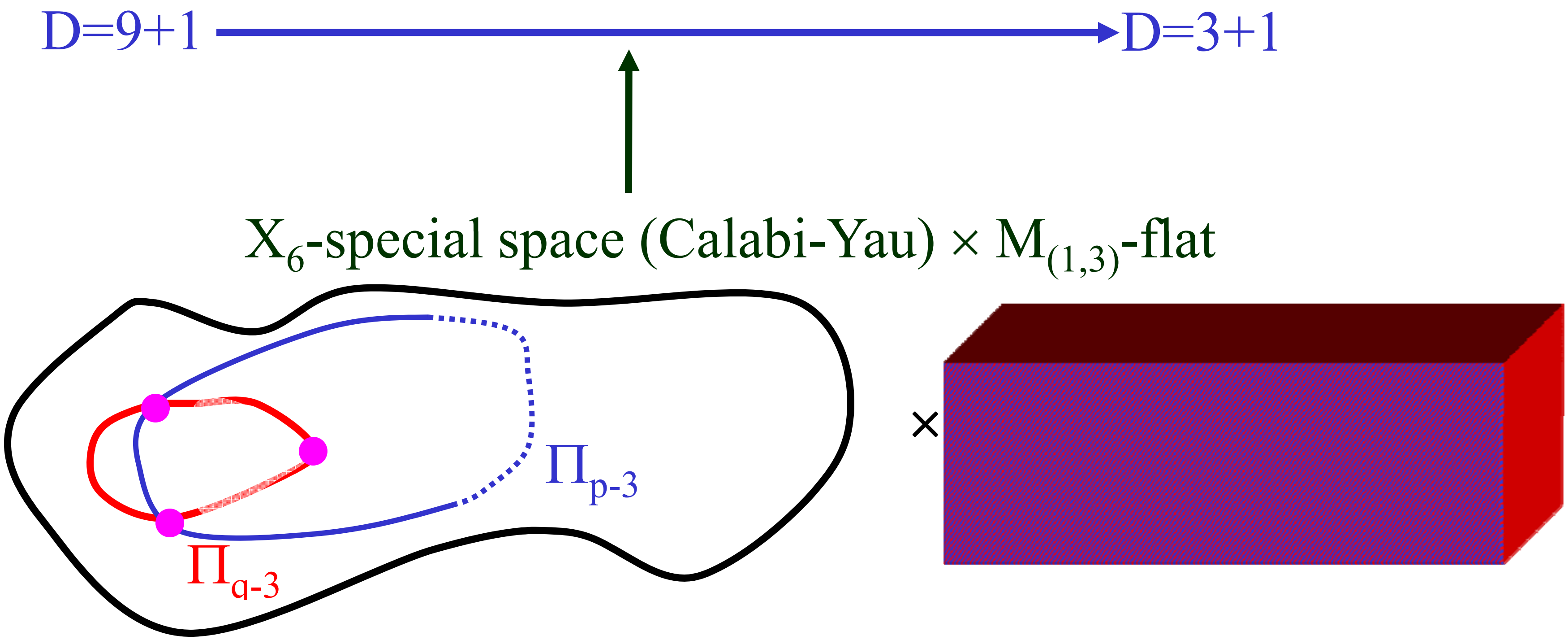


Compactification



D 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 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

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

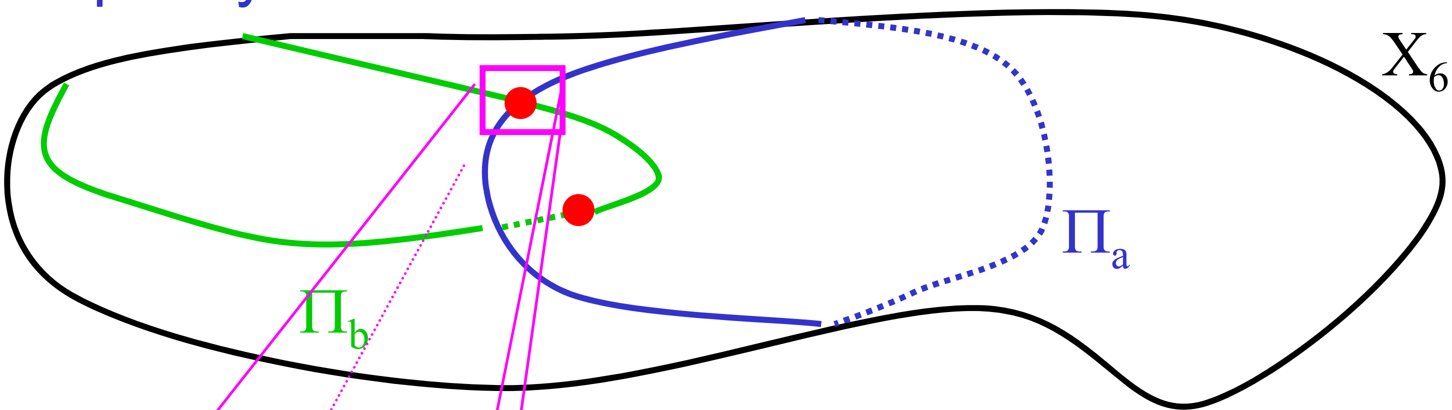
⇓

Rich structure

Penn efforts, early ‘00: D-branes at singularities& Wilson lines
…w/Wang&Plümacher’00; w/Wang&Uranga’01…

Intersecting D6-branes

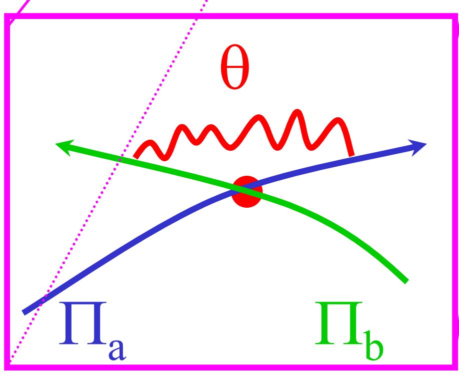
wrap 3-cycles Π



In internal space intersect at points:

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

Geometric origin of family replications!



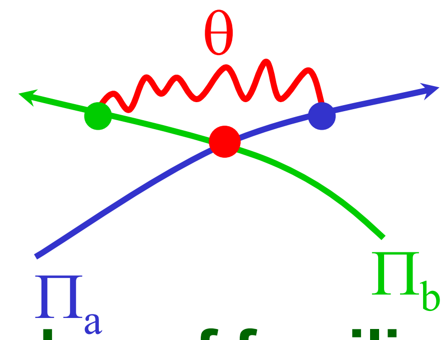
Berkooz, Douglas & Leigh '96

At each intersection-massless string excitation-

spin ½ field ψ - matter candidate

Geometric origin of matter!

Engineering of Standard Model



N_a- D6-branes wrapping Π_a

N_b- D6-branes wrapping Π_b

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

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

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

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

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

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

& supersymmetry conditions (constraining!) - technical (no time!)

⬇

Building Blocks of Supersymmetric Standard Model

Explicit Constructions

Special six-dimensional internal space (special Calabi-Yau) :

compact flat   w/isolated singularities

↓ ↓

Torus T^6 modded out by discrete symmetry $(Z_N \times Z_M)$ ⇒

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

[Toy example T^2/Z_2]

String theory can be quantized exactly employing

conformal field theory techniques   Dixon et al'85; M.C.,Dixon'85; M.C.'86-'87

Explicit constructions(CFT-techniques):

Toroidal Orbifolds: $T^6/\mathbb{Z}_N \times \mathbb{Z}_M$ geometric phase

- Large (infinite) classes of non-supersymmetric Standard Models [Berlin/Munich group'00-'01],[Madrid group'00-'01]

- First three-family supersymmetric Standard Model on $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold [M.C.,Shiu,Uranga '01]

- Majority of supersymmetric models on $\mathbb{Z}_2 \times \mathbb{Z}_2$

i. Semi-realistic constructions (including $SU(5)$ GUT's)

Systematic searches [Penn group'03-'05]...

Rigid cycles [Blumenhagen,M.C.,Marchesano,Shiu'05]... Coisotropic D8-branes [Font,Marchesano,Ibáñez'06], Further models [Texas A&M group'05-'07], etc.

ii. Coupling calculations

Yukawa couplings [Cremades,Ibàñez,Marchesano'03],[M.C.,Papadimitriou'03 (full CFT calculation)]...

Kähler potential [Lüst,Mayr,Richter,Stieberger'04]...

One-loop corrections [Lüst,Stieberger'03],[Abel,Owen'03]...

iii. Counting (landscape) [Munich group'05],[Douglas,Taylor'06],...

- Other Orbifolds:

[Blumenhagen et al.'03],[Honecker'03]...brane recombination [Honecker,Ott'05],[Bailin,Love,arXiv:0705.0646 [hep-th]] MSSM, but Yukawas?

- RCFT models (non-geometric phase)–large classes of semi-realistic models

[Dijkstra,Huiszoon,Schellekens'04] [Anastasopoulos,Dijkstra,Kiritsis,Schellekens'05]

Three-family SM model w/$SU(2)_L$ x $SU(2)_R$ directly (Z_2 x Z_2 orbifold)

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

III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)$* $\times Sp(8)]_{hidden}$									
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\boxminus}$	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,Ibáñez&Marchesano'02

Embedding in Z_2 x Z_2 orbifold-allows for consistent construction

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

***"hidden sector" (unitary) branes - necessary for global consistency**

(D-brane charge conservation)

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

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	$(n^1, l^1) \times (n^2, l^2) \times (n^3, l^3)$	$n_{\square\square}$	$n_{\substack{\square \\ \square}}$	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 sector

no chiral exotics!

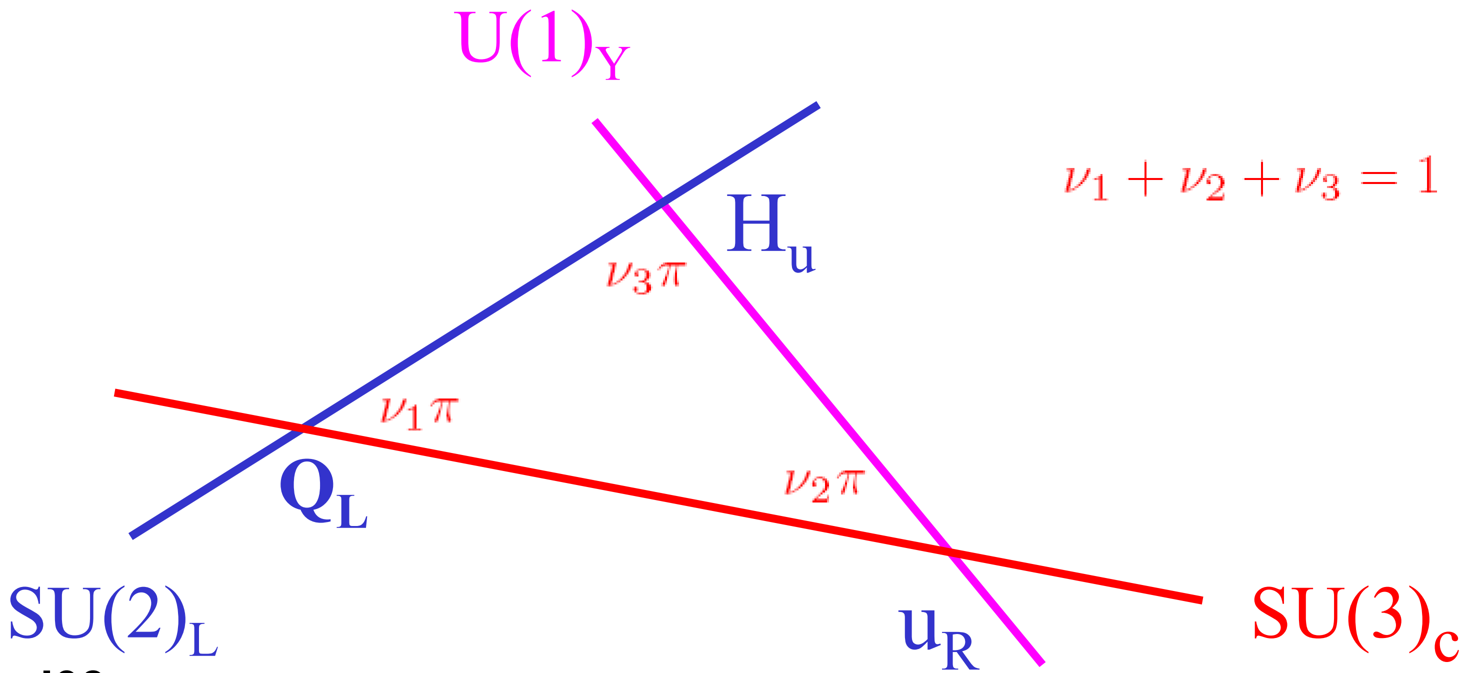
$Sp(8)_L \times Sp(8)_R$ 1-Higgs (8,8), one-family confining hidden sector

brane splitting ↓ brane splitting

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

Yukawa Couplings

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



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

Status

• $\mathcal{O}(100)$ toroidal orbifold models (geometric phase) with semi-realistic features
-typically suffer from chiral exotics
-problems with realistic Yukawa couplings
-moduli stabilization issues

$\longrightarrow$ "The devil is in the details"
though further progress and more promising models are being constructed

• Rational Conformal Field Theory constructions-promising:
-models without chiral exotics
-couplings can in principle be calculated, but hard & hierarchy?
-non-geometric phase–modul stabilization?

Specific coupling issues

- Neutrino masses – Dirac and of order of charged sector masses

Majorana neutrino masses – absent

- μ-parameter – typically absent

- SU(5) GUT models – absent $10\,10\,5_H$-couplings

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))

Anomalous U(1) & Anomaly Cancellation

gauge group $\prod_a U(N_a) = \prod_a SU(N_a) \times U(1)_a$

in general: $U(1)_a$ is anomalous

anomaly cancelled by 4D Green-Schwarz mechanism,

mediated by Chern-Simons couplings,

arising from Wess-Zumino D-brane action:

$$S_{\mathrm{WZ}} = \sum_a N_a \mu_6 \int_{\mathbb{R}^{1,3} \times \Pi_a} e^{trF_a} \sum_p C_{2p+1}$$

abelian gauge potential becomes massive and anomalous $U(1)_a$ survives as a global perturbative symmetry

In addition, RR C_{2p+1} forms

transform under anomalous U(1)

More later

Prior work… New focus on new D-instanton corrections to charged matter:

Related work (contemporary with hep-th/0609191)

[Haack,Krefl,Lüst,VanProeyen,Zagermann, hep-th/0609211] **Field theory instantons**

[Ibáñez,Uranga, hep-th/0609213] - also emphasis on charged (open sector) superpotential coupling corrections **Type IIA stringy instantons**

[Florea,Kachru,McGreevy,Saulina, hep-th/0610003] **Type IIB stringy instantons**

"New generation" of papers (contemporary with hep-th/07003028)

[Abel,Goodsell,hep-th/0612110]

[Akerblom,Blumenhagen,Lüst,Plauschinn,Schmidt-Sommerfield,hep-th/0612132]

[Bianchi,Kiritsis, hep-th/0702015],

[Bianchi,Fucito,Morales arXiv:0704.0784[hep-th]]

[Argurio,Bertolini,Ferretti,Lerda,Petersson aeXiv:0704.0262[hep-th]]

[Ibáñez,Schellekens,Uranga,arXiv:0704.1079[hep-th]] extensive RCFT search for global models

[Akerblom,Blumenhagen, Lüst,Schmidt-Sommerfeld, arXiv:0705.2366[hep-th]] one-loop & holomorphic coupling corrections

[Antusch, Ibáñez,T.Macri, arXiv:0706.2132 [hep-ph]] phenomenological study of neutrino masses

⋮

w/ Ralph Blumenhagen & Timo Weigand, hep-th/0609191
w/Robert Richter & Timo Weigand, hep-th/0603191

Why non-perturbative (D-INSTANTON) effects?

[affect open string sector-charged matter]

a) Stability of models - drastic

b) May **generate perturbatively absent** couplings w/hierarchy, exponentially suppressed by $1/g_{string}$

:

Phenomenological implications:

a) May generate **Majorana neutrino masses** in the scale range 10^{11} GeV< M_m < 10^{15}GeV → Realization of seesaw mechanism

b) May generate hierarchically small O(1TeV) μ-parameter

c) May generate the desired Yukawa couplings in SU(5) GUT's

:

Instantons–Heuristics

Probe for non-pert. terms by computing suitable amplitudes in D-instanton background.

Euclidean Dp-brane wrapping internal $(p+1)$-cycle

$\longrightarrow$ for Type IIA relevant objects are Euclidean $D2$-branes (E2-branes), wrapping three-cycles Ξ

Rules:

- Instanton sector corresponds to local minimum of (full) string action

$\longrightarrow$ $E2$-brane volume minimizing

- Integrate over zero modes localized on $E2$

$\longrightarrow$ All fermionic zero modes have to appear for relevant instanton induced couplings exactly once

Focus: induced superpotential terms involving charged matter fields Φ_i

$$W_{np} \propto e^{-S_{E2}} = \exp\left[\frac{2\pi}{\ell_s^3}\left(-\frac{1}{g_s}\int_\Xi \Re(\Omega_3) + i\int_\Xi C_3\right)\right]$$

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

$$e^{-S_{E2}} \longrightarrow e^{i\,Q_a(E2)\,\Lambda_a}\; e^{-S_{E2}}:\; Q_a(E2) = \frac{\ell_s^3}{2\pi} N_a\; \Xi \circ (\Pi_a - \Pi'_a)$$

CS-coupling induces gauging of global axionic shift symmetry

under $U(1)_a$ gauge transformation the RR-form C_3,
KK-reduced on 3-cycle $\widetilde{\Pi}$, transforms as

$$\begin{aligned} A_a &\longrightarrow A_a + d\Lambda_a \\ \int_{\widetilde{\Pi}} C^{(3)} &\longrightarrow \int_{\widetilde{\Pi}} C^{(3)} + Q_a(\widetilde{\Pi})\Lambda_a \end{aligned}$$

Consequence:
If $Q_a(E2) \neq 0$ for some a, no terms $W = e^{-S_{E2}}$ possible but:

$$W = \prod_i \Phi_i \; e^{-S_{E2}} \quad \text{with} \quad \sum_i Q(\Phi_i) + Q_a(E2) = 0 \;\; \forall a$$

is possible!
[non-perturbative breakdown of global $U(1)$ symmetry]

$\longrightarrow$ This selection rule explained in terms of fermionic zero modes:

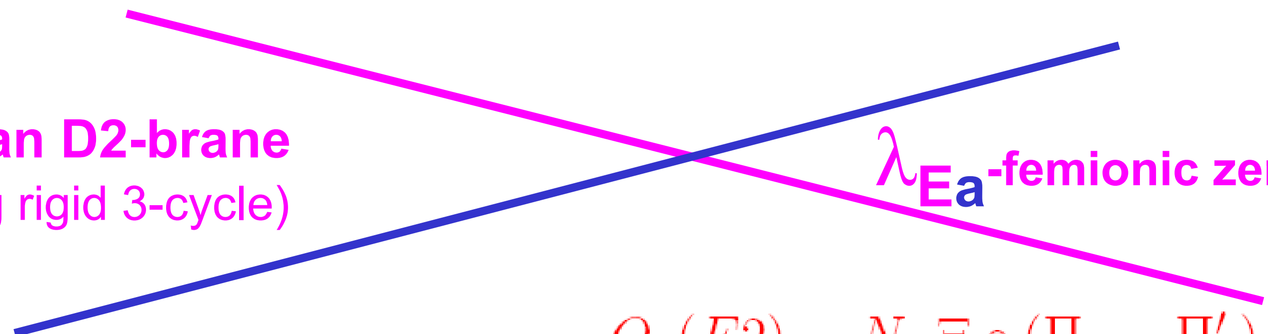
Constraints on Zero Fermionic Modes:

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

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



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

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

zero modes	Reps.	number
$\lambda_{a,I}$	$(-1_E, \Box_a)$	$I = 1, \ldots, [\Xi \cap \Pi_a]^+$
$\overline{\lambda}_{a,I}$	$(1_E, \overline{\Box}_a)$	$I = 1, \ldots, [\Xi \cap \Pi_a]^-$
$\lambda_{a',I}$	$(-1_E, \overline{\Box}_a)$	$I = 1, \ldots, [\Xi \cap \Pi'_a]^+$
$\overline{\lambda}_{a',I}$	$(1_E, \Box_a)$	$I = 1, \ldots, [\Xi \cap \Pi'_a]^-$

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

Develop CFT INSTANTON CALCULUS to determine non-perturbatively induced superpotential couplings quantitatively

no time, but c.f. R. Blumenhagen's talk

Phenomenological Implications:

Effects on Superpotential Matter Couplings

One can generate perturbatively forbidden matter couplings:

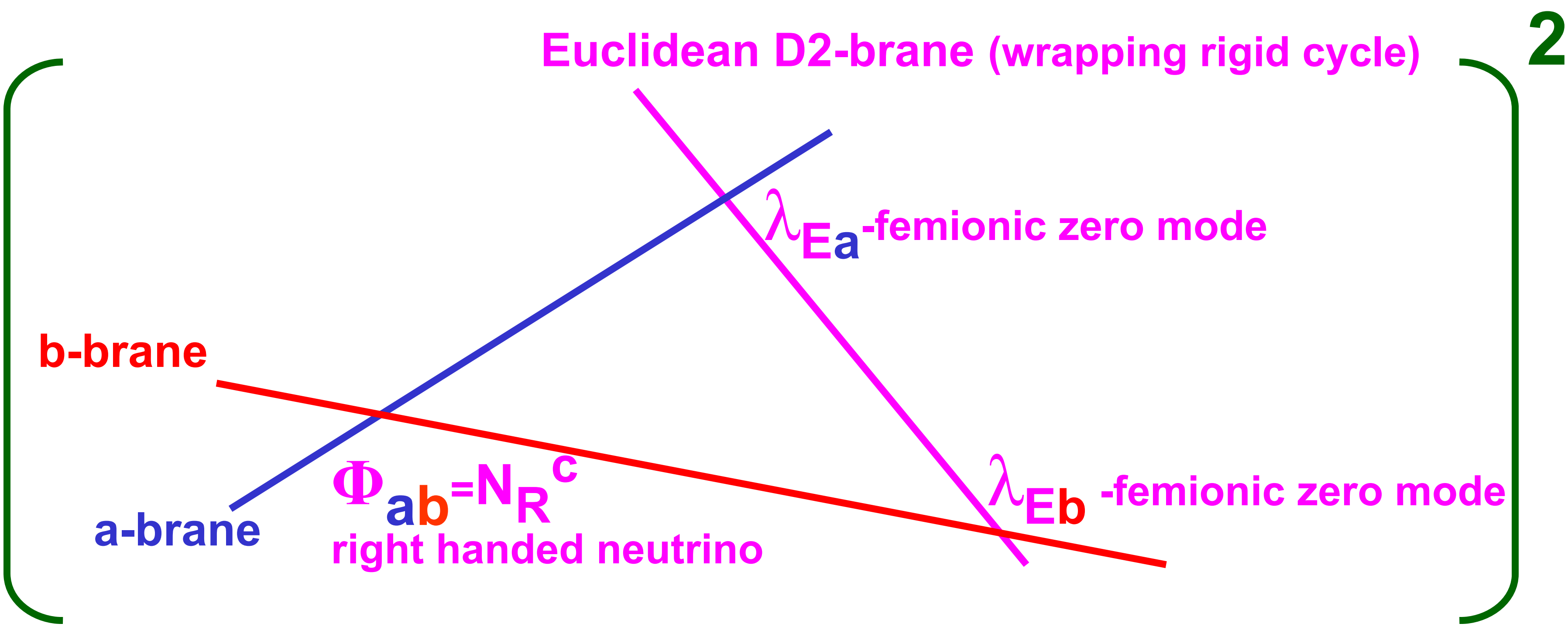
I. Majorana masses for right-handed neutrinos
$\longrightarrow$ Neutrino Dirac masses $W_H = H^+ \, L_L \, (N_R)^c$ typically present, and of order of charged sector masses

Majorana mass $W_m = M_m \, (N_R)^c \, (N_R)^c$ perturbatively forbidden

Note, N_R^c -Standard Model singlets, typically charged under additional anomalous $U(1)_a \times U(1)_b$, say as $(1, -1)$.

Majorana Neutrino Masses:

D2-instanton wraps [2+1 (Euclidean time)]=3-cycle $[\Pi_{E2}]$



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

D2-instanton w/ $[\Pi_{SM}]^\circ[\Pi_{E2}]=0$, $[\Pi_a]^\circ[\Pi_{E2}] = 2$ & $[\Pi_b]^\circ[\Pi_{E2}] = -2$

→ **fermionic zero modes appear precisely ONCE and thus M_m non-zero**

Geometric!

$\longrightarrow$ Non-pert. Majorana coupling:

$W_m = M_m \, (N_R)^c \, (N_R)^c$ with $M_m = x \, M_s \, e^{-\frac{2\pi}{\ell_s^3 \, g_s} \mathrm{Vol}_{E2}}$

Use $\frac{1}{\alpha_{\mathrm{GUT}}} = \frac{1}{\ell_s^3 \, g_s} \mathrm{Vol}_{D6} \longrightarrow M_m = x \, M_s \, e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}} \frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{D6}}}$

For seesaw mechanism need $10^{11}\mathrm{GeV} < M_m < 10^{15}\mathrm{GeV}$

Possible within natural regime for

$0.4 \cdot R_{D6} > R_{E2} > 0.2 \cdot R_{D6}$ (assume x=$\mathcal{O}$ (1)).

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

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

Aim:

- Provide example of model with rigid $E2$-brane and suitable zero mode structure $\longrightarrow$ highly constraining
- Realize correct suppression scale for Majorana masses
- Exemplify CFT computation $\longrightarrow$ determine x exactly

Construct supersymmetric 3-stack GUT model:

$N_c = 5$: SU(5)-GUT stack $\qquad$ $N_a = N_b = 1$

sector	representation	matter
(c, c')	Antisym	$\mathbf{10}$
(c, a)	$(\overline{c}, a)$	$\overline{\mathbf{5}}$
(c, b)	$(c, \overline{b})$	$\mathbf{5}_H$
(a, b)	$(\overline{a}, b)$	N_R^c

with correct zero mode structure

$$[\Pi_{E2} \cap \Pi_a]^+ = 2, \quad [\Pi_{E2} \cap \Pi_b]^- = 2, \quad [\Pi_{E2} \cap \Pi_c]^\pm = 0$$

Constraining!

Extensive search merely leads to local set-up with 4 families of $\mathbf{10}$ and $32\ N_R^c$

Result: $< \nu^A \nu^B >_{E2_i} = \frac{2\pi}{g_s} \mathcal{V}_{E2} \overrightarrow{v}^T \mathcal{M} \overrightarrow{v} \; (2\pi)^4 \delta^4(k^A + k^B)$

$$\mathcal{M} = x \, M_s \, e^{-\frac{2\pi}{\alpha_{\rm GUT}} \frac{8}{57}} \begin{pmatrix} A_i & 0 & B_i & 0 \\ 0 & C_i & 0 & D_i \\ B_i & 0 & E_i & 0 \\ 0 & D_i & 0 & F_i \end{pmatrix}$$

$A_i, B_i \ldots \sim exp(-A/\alpha')$

$$x = \frac{(4\pi)^{3/2}\pi^2}{16} \left[\Gamma_{1-\theta^1_{ab}, 1-\theta^1_{E2a}, 1+\theta^1_{E2b}} \prod_{I=2}^3 \Gamma_{-\theta^I_{ab}, -\theta^I_{E2a}, 1+\theta^I_{E2b}} \right]^{\frac{1}{2}} \; e^{Z'}$$

$e^{Z'}$–one-loop contribution [Akerblom et al. arXiv:0705.236[he-th]]

Overall exponential suppression scale fixed by SUSY:

$$\frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{\Pi_c}} = \left(\prod_I \frac{(n^I_{E2})^2 + (\widetilde{m}^I_{E2})^2 U_I^2}{(n^I_c)^2 + (\widetilde{m}^I_c)^2 U_I^2} \right)^{1/2} = \frac{8}{57}$$

• Sum up contributions from all 64 factorizable E2-instantons, taking leading contribution (smallest triangle)
$\longrightarrow M_M \simeq 10^{10} GeV$
for triangles of order string scale (as required)

• Together with perturbative Dirac masses of $\mathcal{O}$(TeV) (due to Yukawa couplings of the type $\overline{\mathbf{5}}\,\mathbf{5}_H\,\mathbf{1}$)

$\longrightarrow$ Can engineer small neutrino masses of $\mathcal{O}$(1eV) via see-saw mechanism.

II. Further applications:

- μ -term $\mu H^+ H^-$ forbidden perturbatively

$\longrightarrow$ can well be generated by $E2$-instantons!

$\longrightarrow$ appropriate volume ratio may yield $\mu \simeq \mathcal{O}(\text{TeV})$

- R-parity violating couplings in the MSSM can be induced
  (constrains!)
- GUT $SU(5)$ suffer from absence of pert. Yukawa couplings

$\mathbf{10}\,\mathbf{10}\,\mathbf{5}_H$, where $\mathbf{10}$ from (a,a')-intersection

Can be generated by $E2$-instantons!

R. Blumenhagen, M.C., D.Lüst, R. Richter,T. Weigand, arXiv:0707.1871

→ Opens doors for phenomenological studies of (flipped) SU(5)

no more time, but c.f. R. Blumenhagen's talk

Summary/Outlook

(a) Major progress: development of techniques **for consistent constructions on orbifolds w/intersecting D-branes** (primarily on toroidal orbifolds)

(b) Sizable number of semi-realistic models**; systematic searches** (not-fully realistic-typically some chiral exotic matter)

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

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

New hierarchical couplings:

Majorana neutrino masses → seesaw mechanism realized within a local model

μ-parameter, SU(5) GUT Yukawa couplings,…

Challenge: search for global models with realistic features realizing D-instanton effects!

Foresee further progress:

(a) DEVELOPMENT of TECHNIQUES! →generalize constructions to general Calabi Yau spaces

(b) Further study of non-perturbative effects:
Vacuum de-/re-stabilization:SUSY breaking/open-string moduli stabilization
Effects of additional zero modes: non-rigid cycles, instanton cycle recombination, flux effects, etc.

R.Blumenhagen,M.C. R.Richter,T. Weigand, arXiv:0708.0403

[flux effects, c.f., also Tripathi,Trivedi '05, Kallosh, Kashani-Poor,Tomasiello'05]

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

FULLY REALISTIC CONSTRUCTIONS
particle spectrum & interactions?

NOT THERE YET, BUT GETTING BETTER AT IT

EFFORTS PRESENTED PLAYING KEY ROLE