String Phenomenology

Angel M. Uranga
IFT UAM-CSIC

Asian Winter School
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Plan

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- Panorama A

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- Panorama A
- Non-perturbative aspects

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- Panorama A
- Non-perturbative aspects
- Panorama B

Plan

- Panorama A
- Non-perturbative aspects
- Panorama B
- Fluxes and applications

>Panorama A

"String Phenomenology"

- String theory describes gravitational and gauge interactions in a unified framework, consistent at the quantum level

- What about the Standard Model ? (or whatever extension)

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- Aim of String Phenomenology:

  - Understand basic mechanisms realizing interesting properties
    Chirality, susy, gauge symm, moduli stab, flat potentials, instantons...

  - Determine classes of constructions incorporating subsets of them
    Non abelian gauge interactions, replicated charged fermions, Higgs scalars, Yukawas, moduli stabilization, tuning of cc, ...

  - Within each class, obtain explicit models as close to SM as possible with the hope of learning more about the high energy regime of SM in string theory

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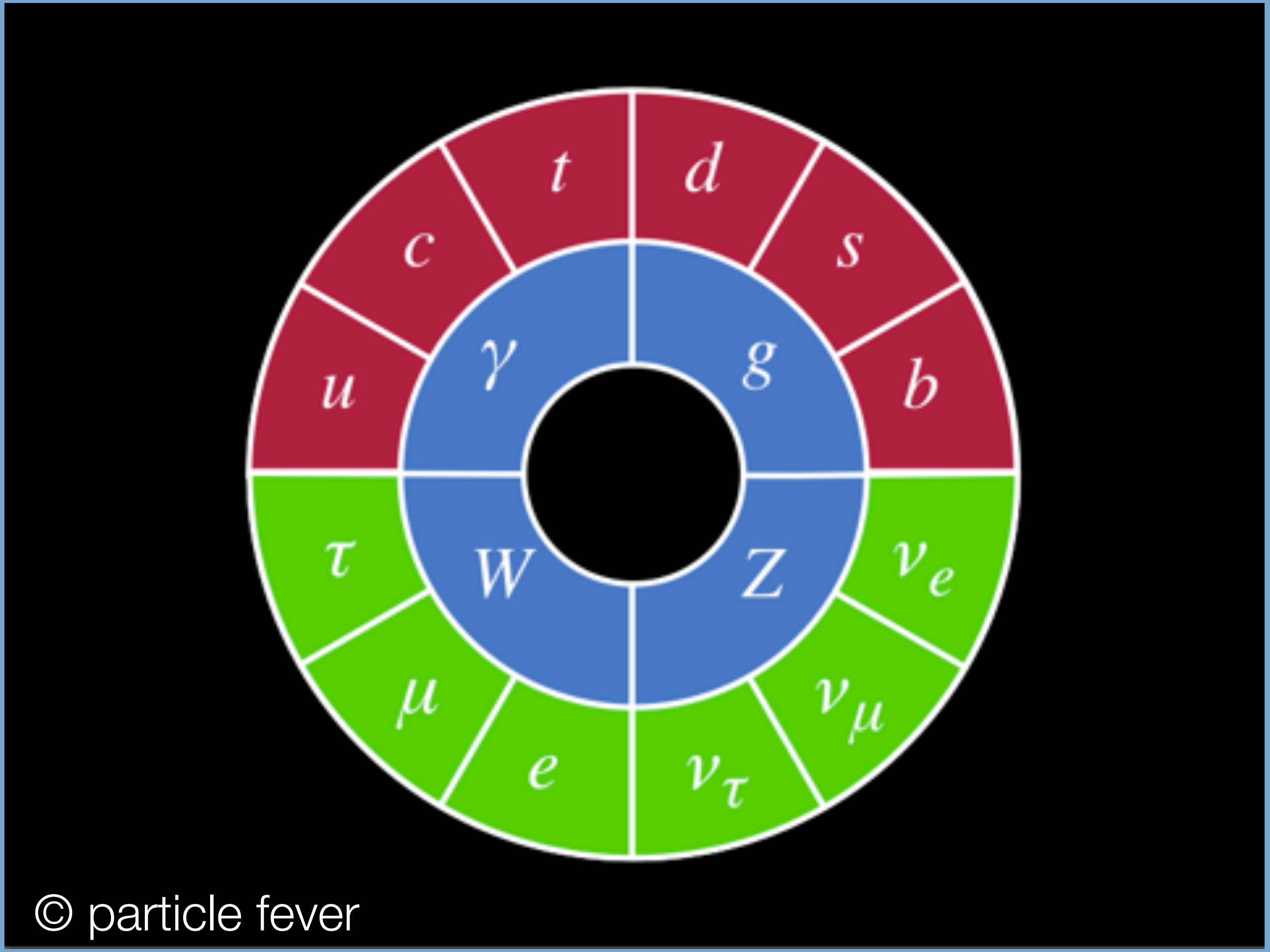
- Old program, yet sustained progress, following formal developments...

Standard Model of Particles

Standard Model of Particles



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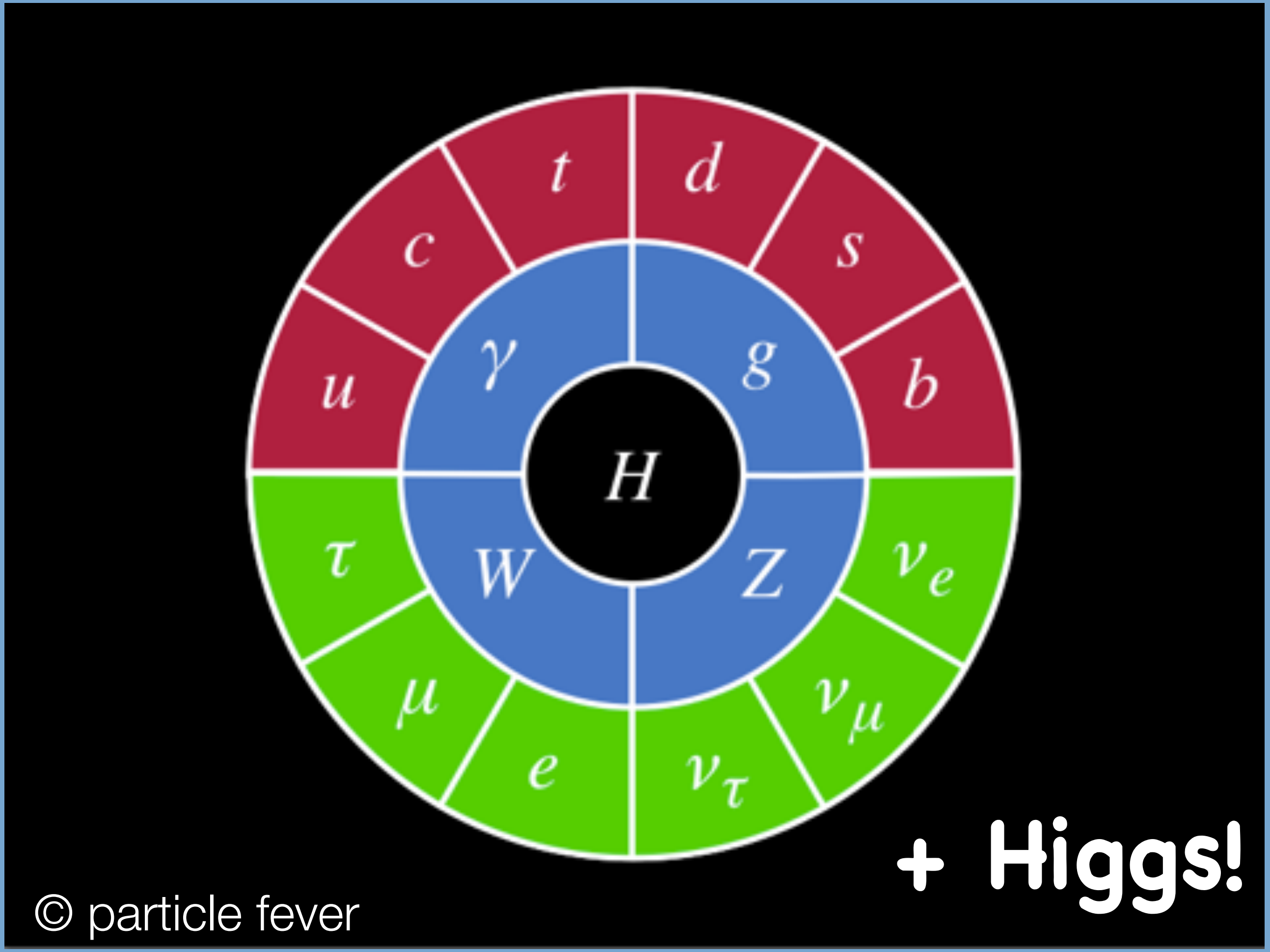


Standard Model of Particles

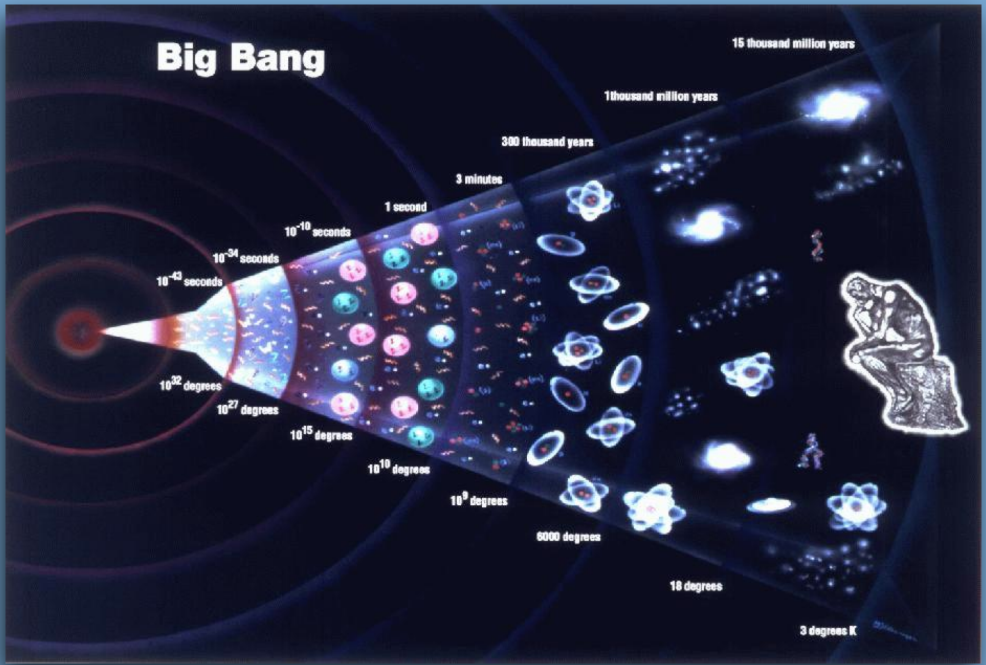
SU(3) x SU(2) x U(1)$_Y$

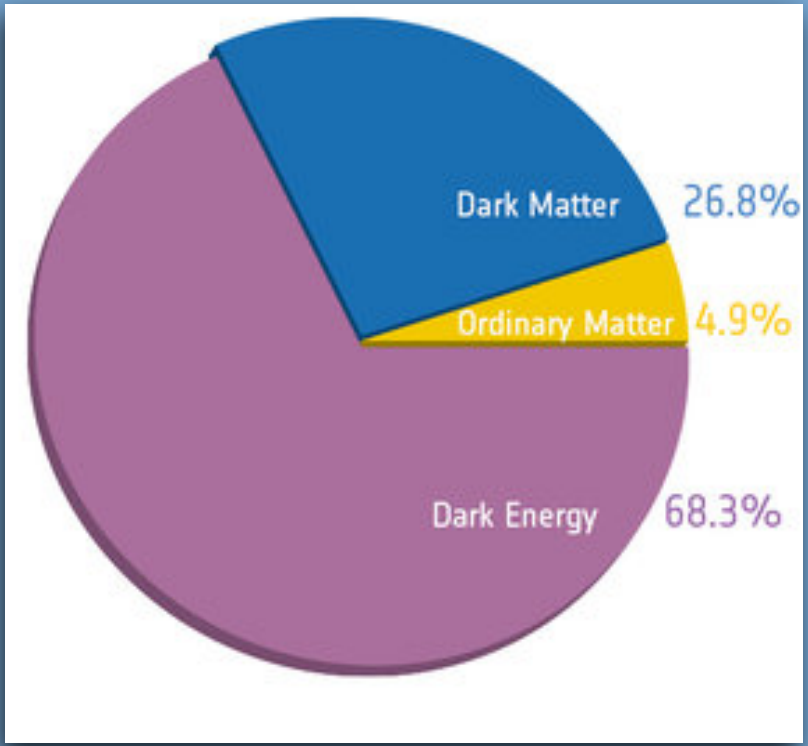
Matter fields		Y
Q_L	$3(3,2)$	$1/6$
U_R	$3(\bar{3},1)$	-$2/3$
D_R	$3(\bar{3},1)$	$1/3$
L	$3(1,2)$	-$1/2$
E_R	$3(1,1)$	1
ν_R	$3(1,1)$	0

Higgs in (1,2), Y=-1/2

Cosmological Standard Model

(ΛCDM, "concordance model")





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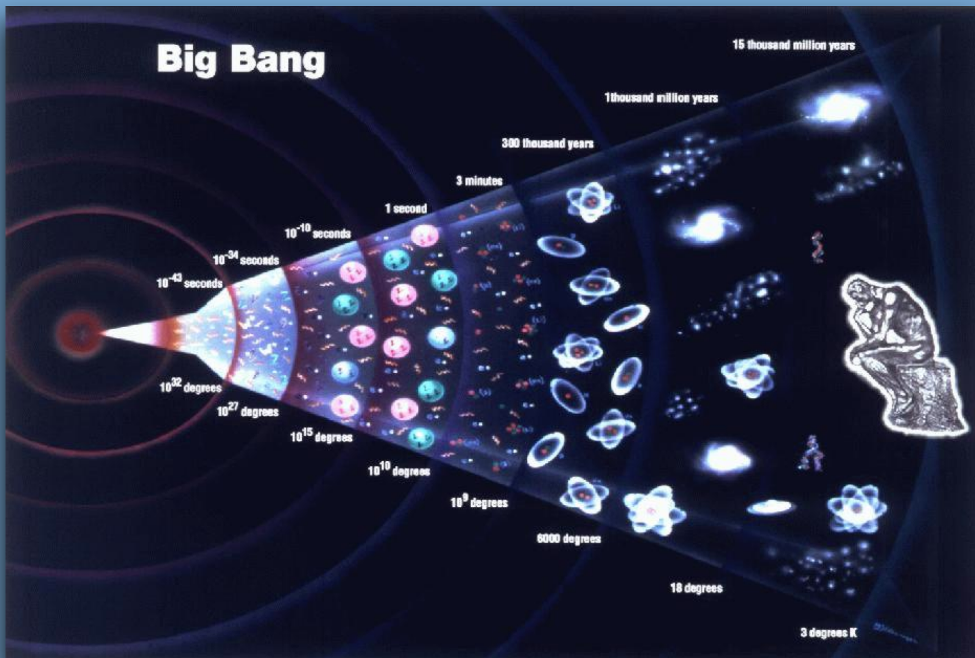

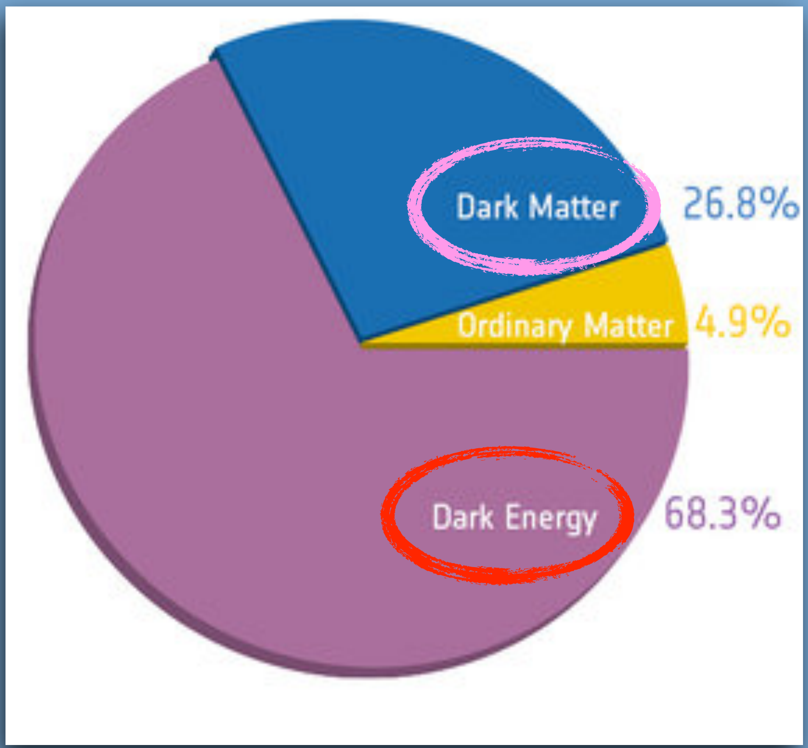

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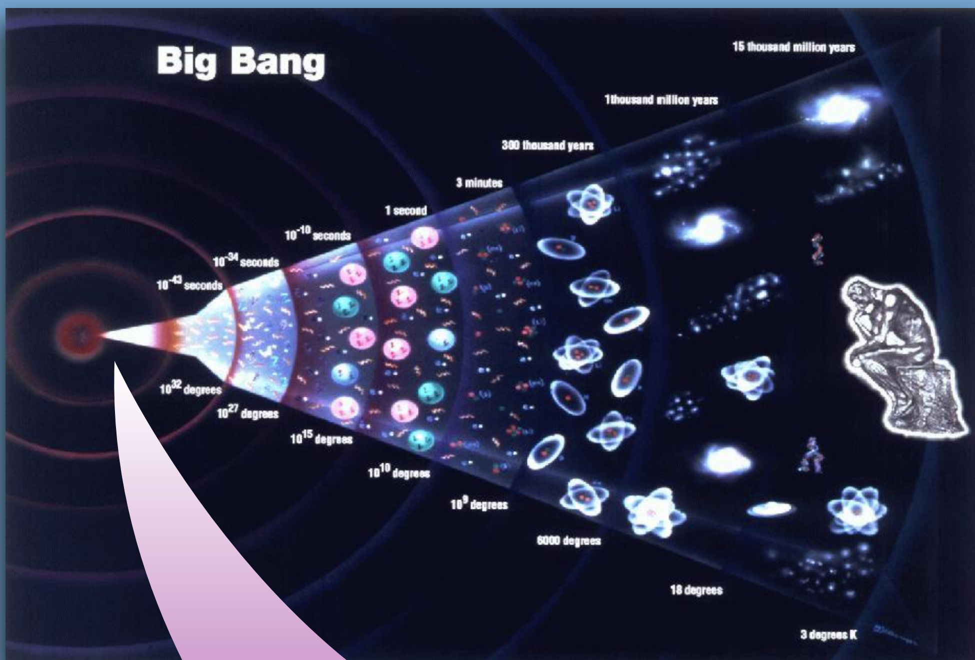
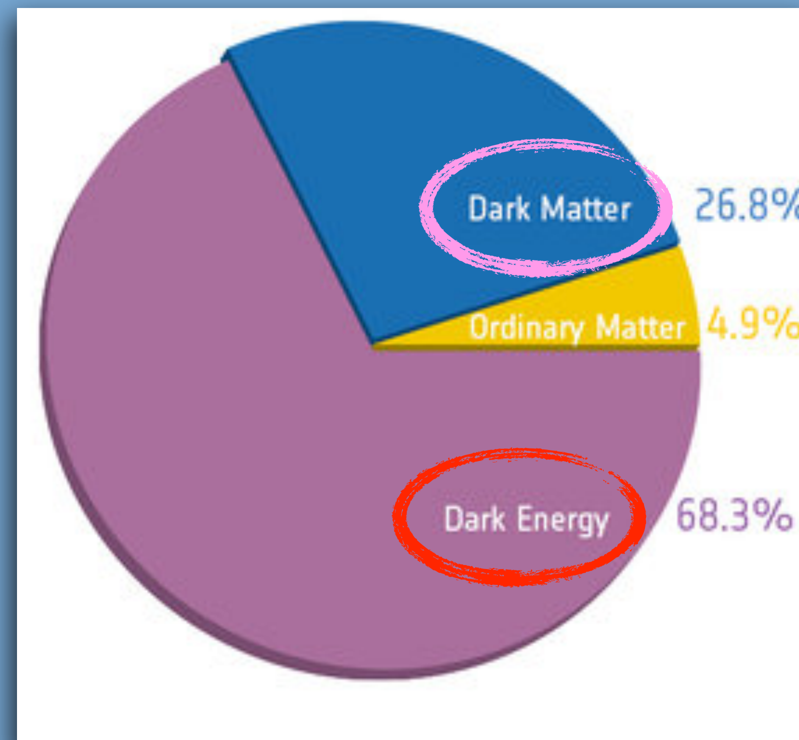
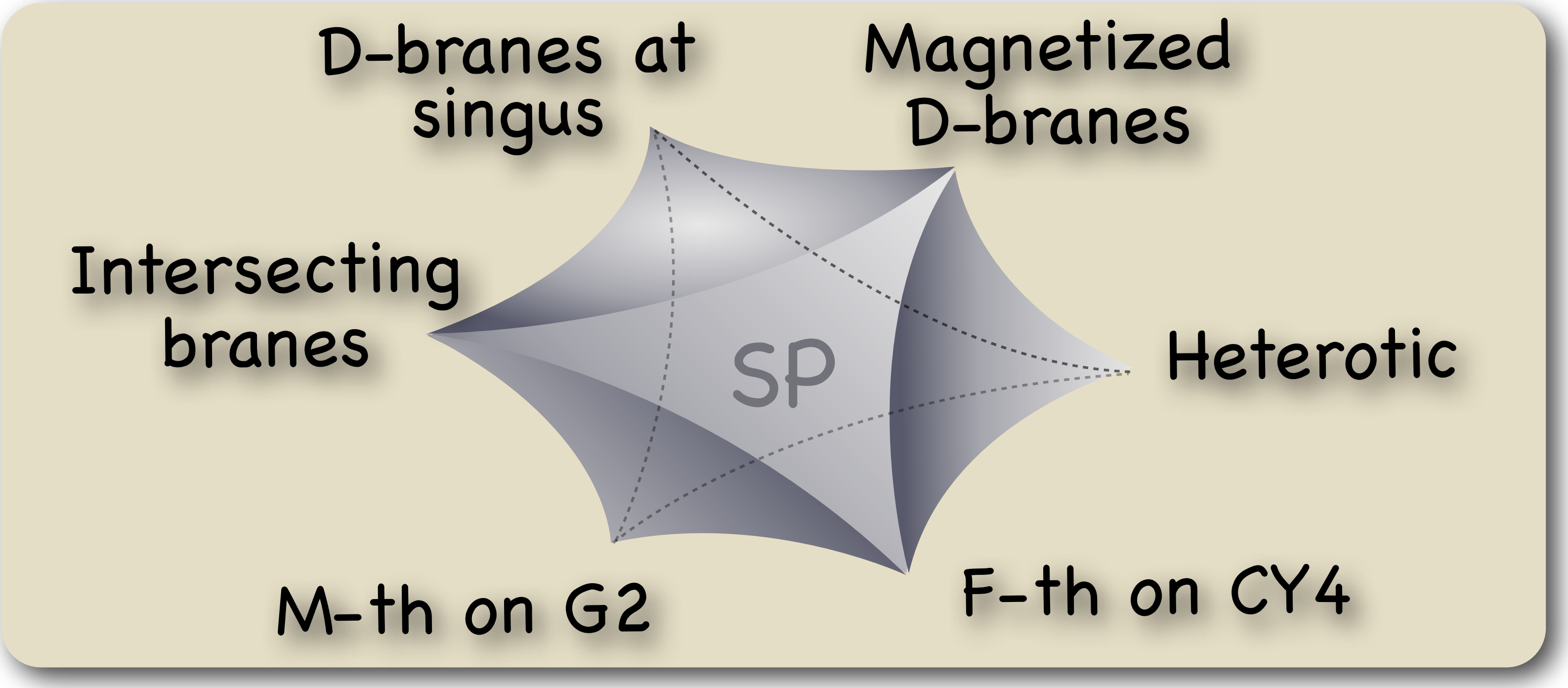




inflation
cf. Shiu's
lectures

“String Phenomenology”

- Plenty of (related) constructions to ‘engineer’ SM in string theory



Remarkably, generic 4d compactifications are chiral

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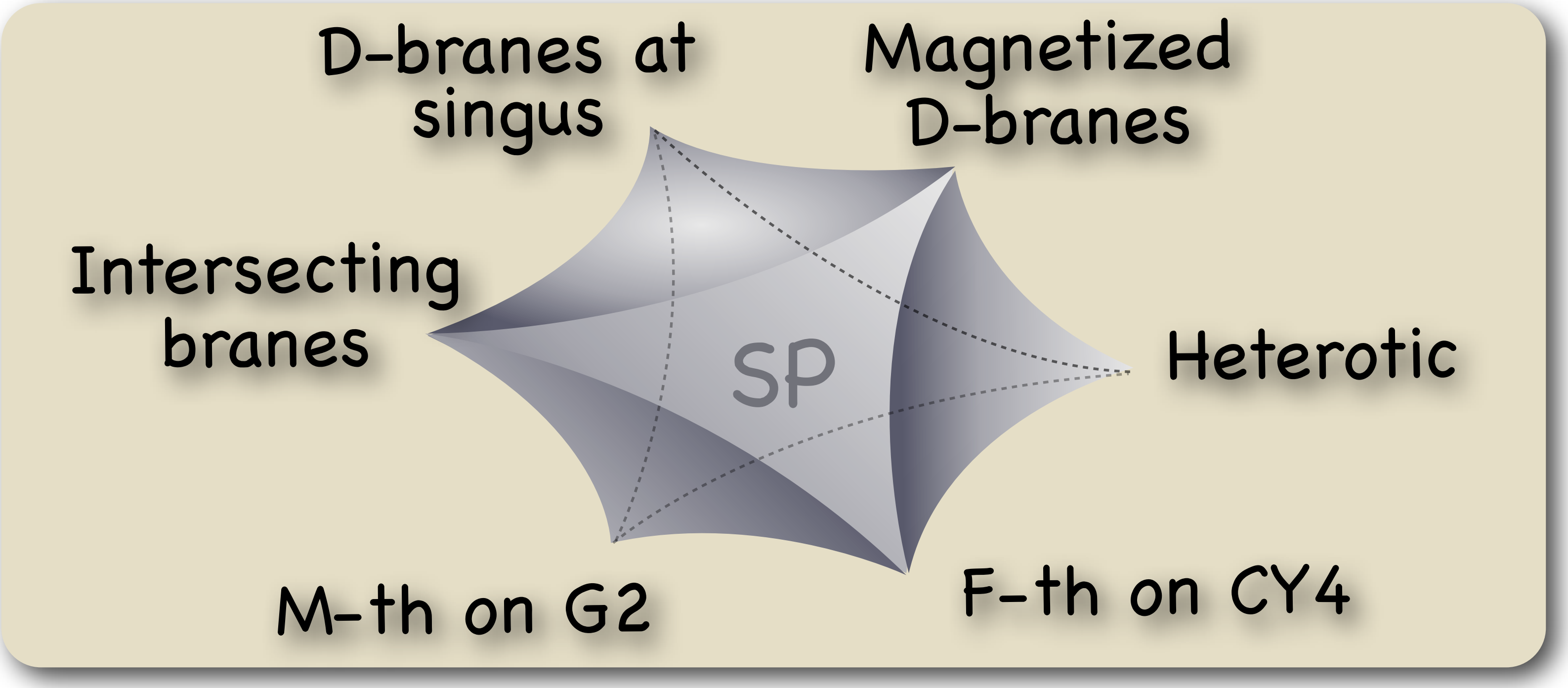

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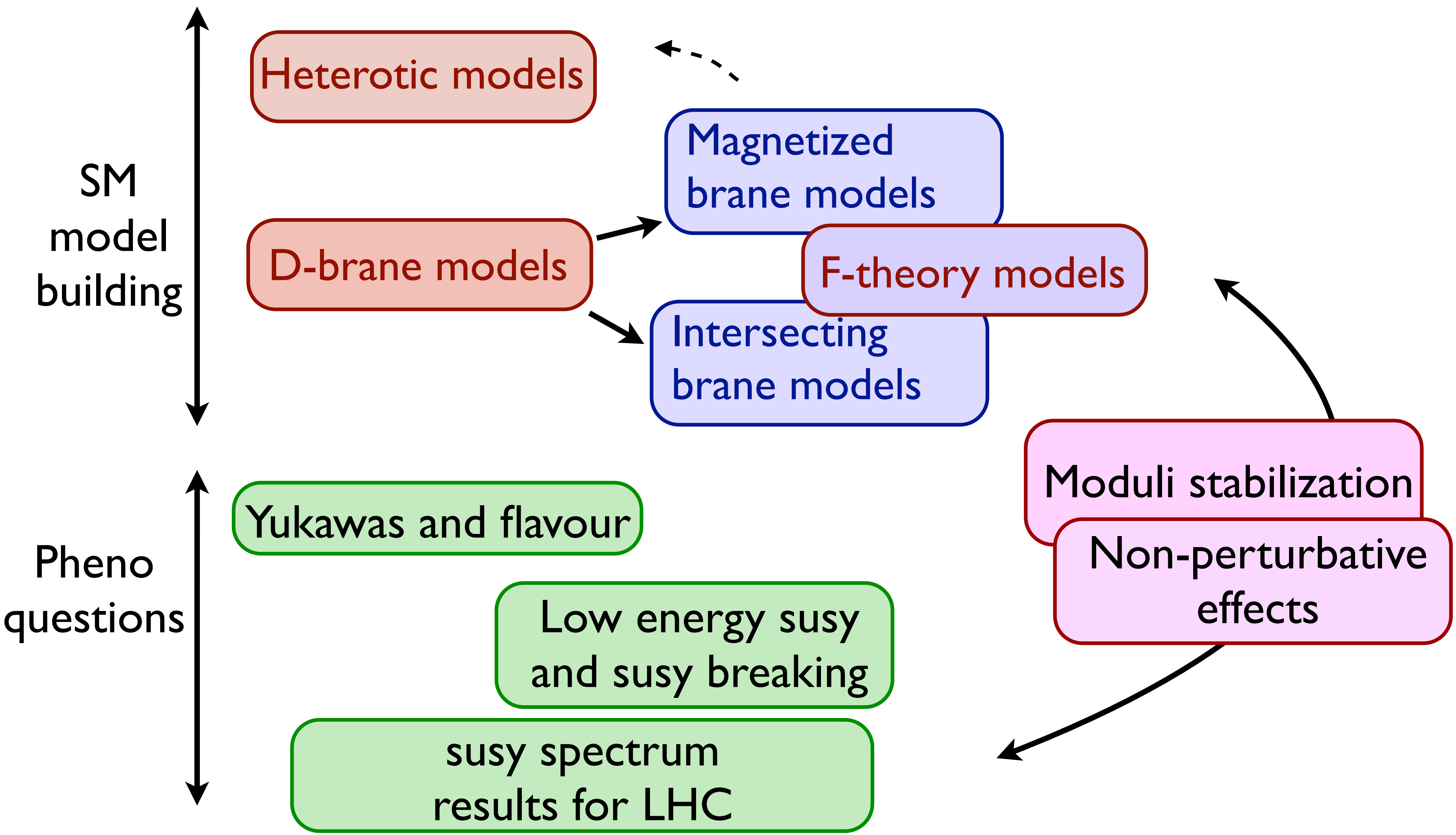
- Overview with an eye on recent developments

Disclaimer: Necessarily incomplete

Follow particular path: not and ordered set

Road map

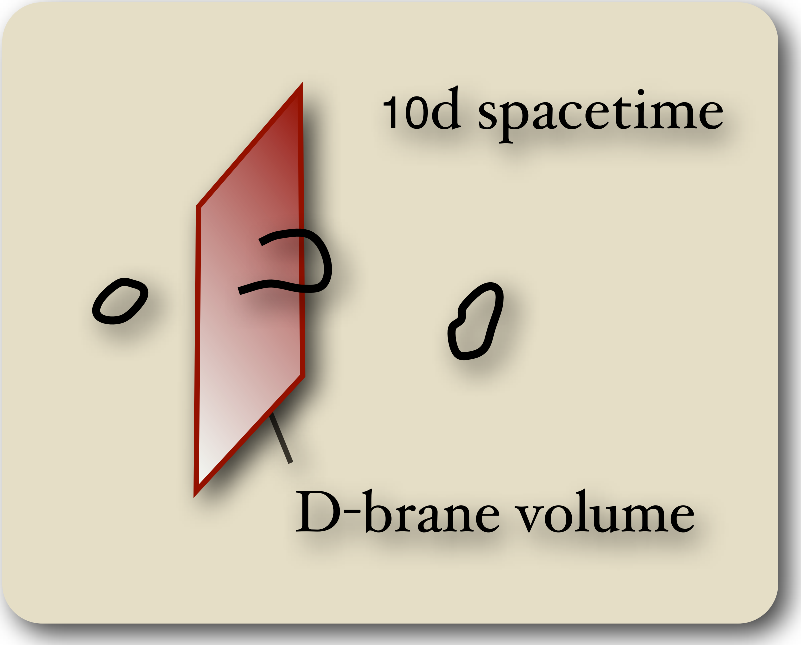


SM model building
Heterotic models
Magnetized brane models
D-brane models
F-theory models
Intersecting brane models
Moduli stabilization
Non-perturbative effects
Pheno questions
Yukawas and flavour
Low energy susy and susy breaking
susy spectrum results for LHC

D-branes

Some of most successful applications are based on D-branes

High-dim. planes on which open strings end



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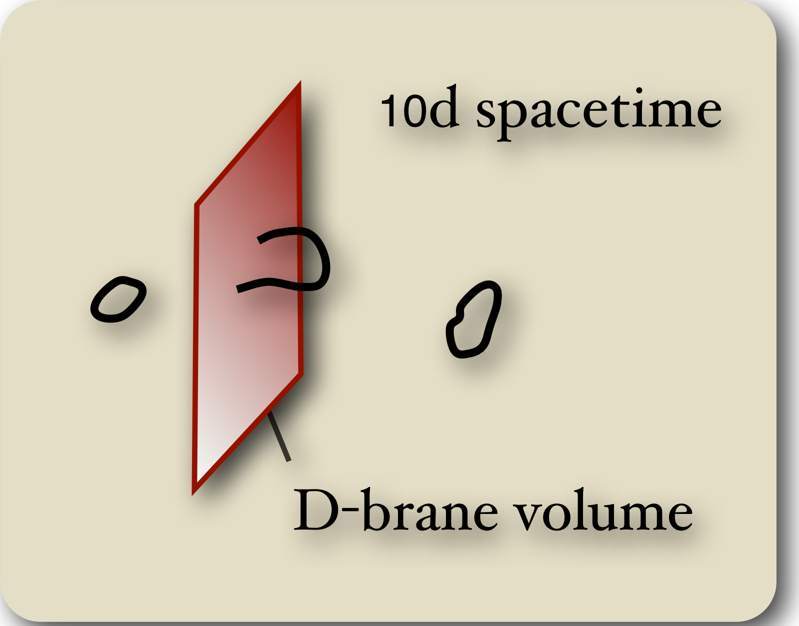

- Brane world:
  - Closed strings: gravity in 10d
  - Open strings: gauge+matter on brane

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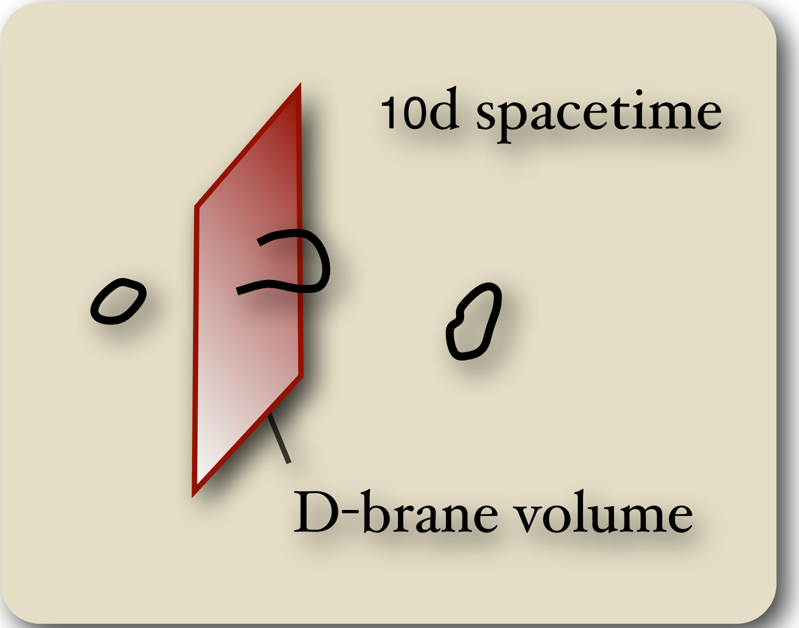

- Brane world:
  - Closed strings: gravity in 10d
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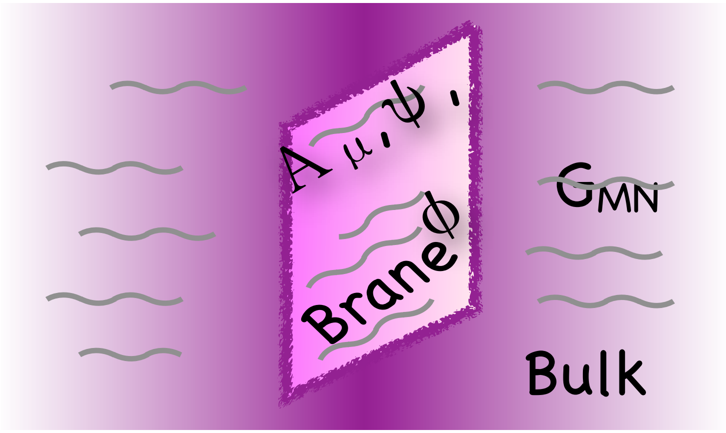
- Allows large extra dimensions

$$M_P^2\, g_{SM}^2 = \frac{M_s^{11-p}\, V_\perp}{g_s}$$



D-branes

- Geometrization of physical properties

  E.g. Non-abelian gauge interactions on volume of coincident D-branes

Piling them up...

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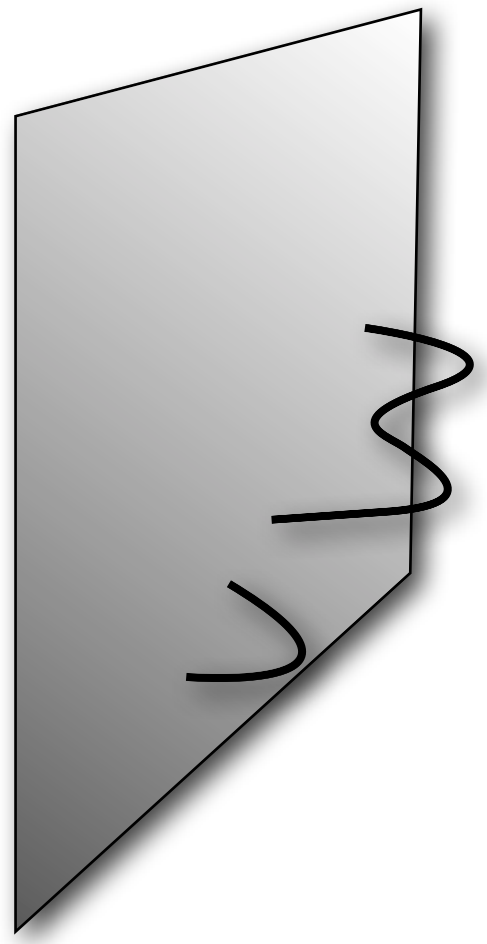
Piling them up...

... we engineer non-abelian gauge interactions!

D-branes

U(1) gauge field on the worldvolume of a single D-brane



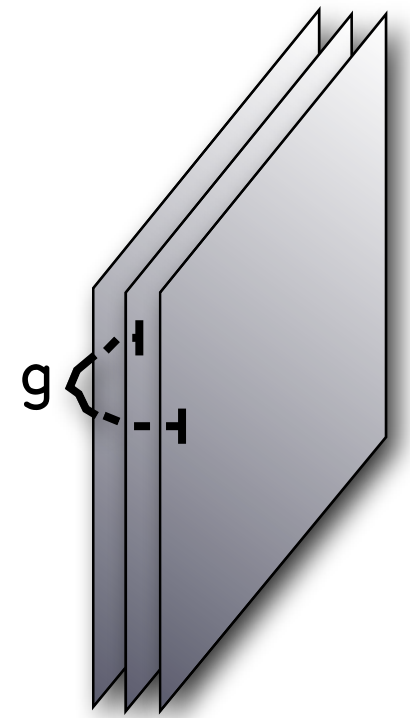
D-branes

U(1) gauge field on the worldvolume of a single D-brane

Electromagnetism

D-branes

Piling up e.g. 3 D-branes, we get 9 open string sectors



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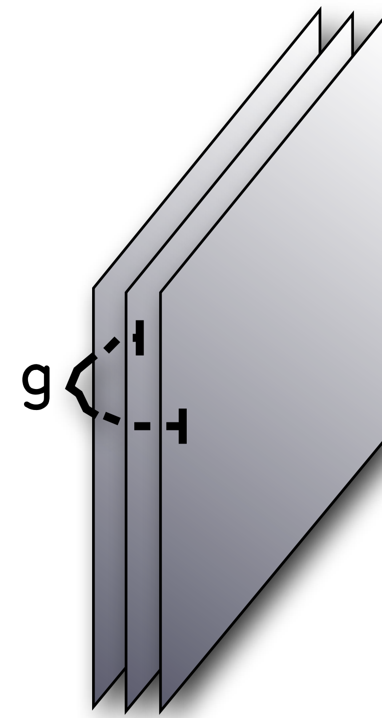
Piling up e.g. 3 D-branes, we get 9 open string sectors

"color-anticolor"

$$\begin{bmatrix} r\,\bar{r} & r\,\bar{g} & r\,\bar{b} \\ g\,\bar{r} & g\,\bar{g} & g\,\bar{b} \\ b\,\bar{r} & b\,\bar{g} & b\,\bar{b} \end{bmatrix}$$



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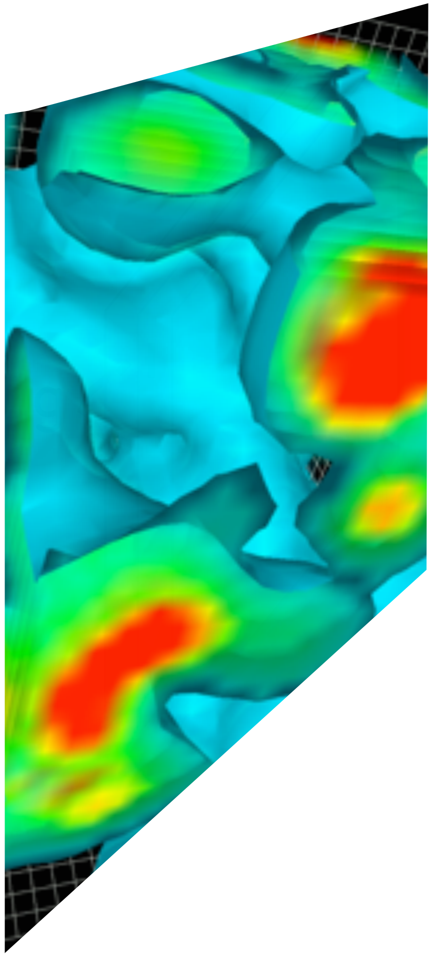

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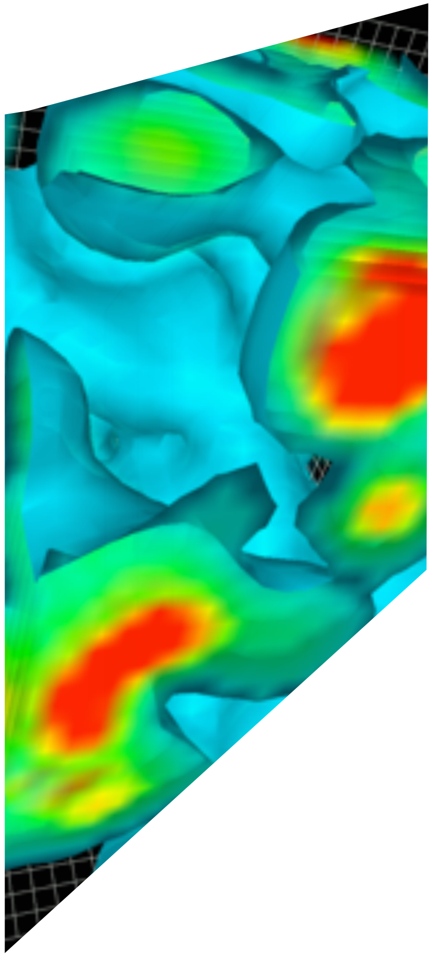
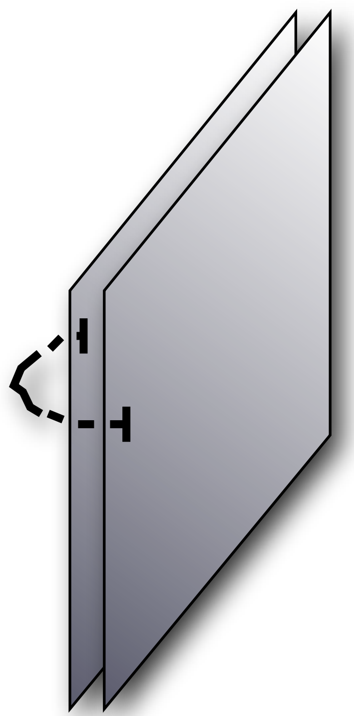


U(3): 8 "gluons" plus a U(1)

D-branes

Similarly, two extra D-branes



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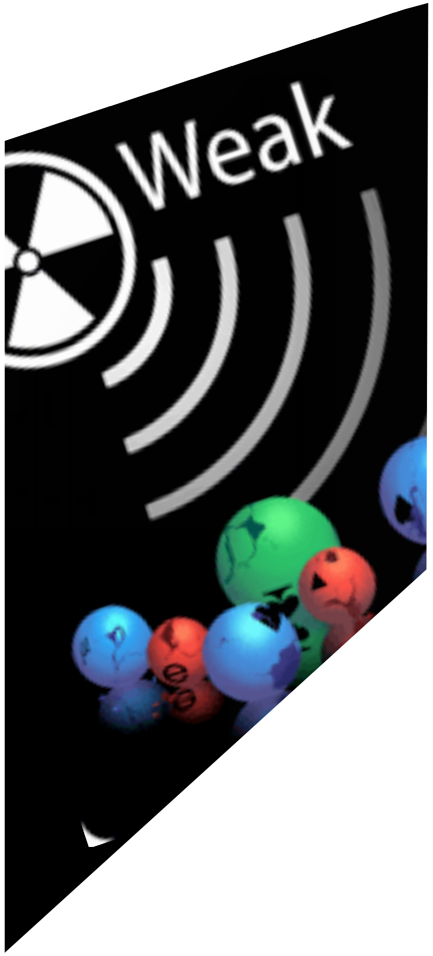

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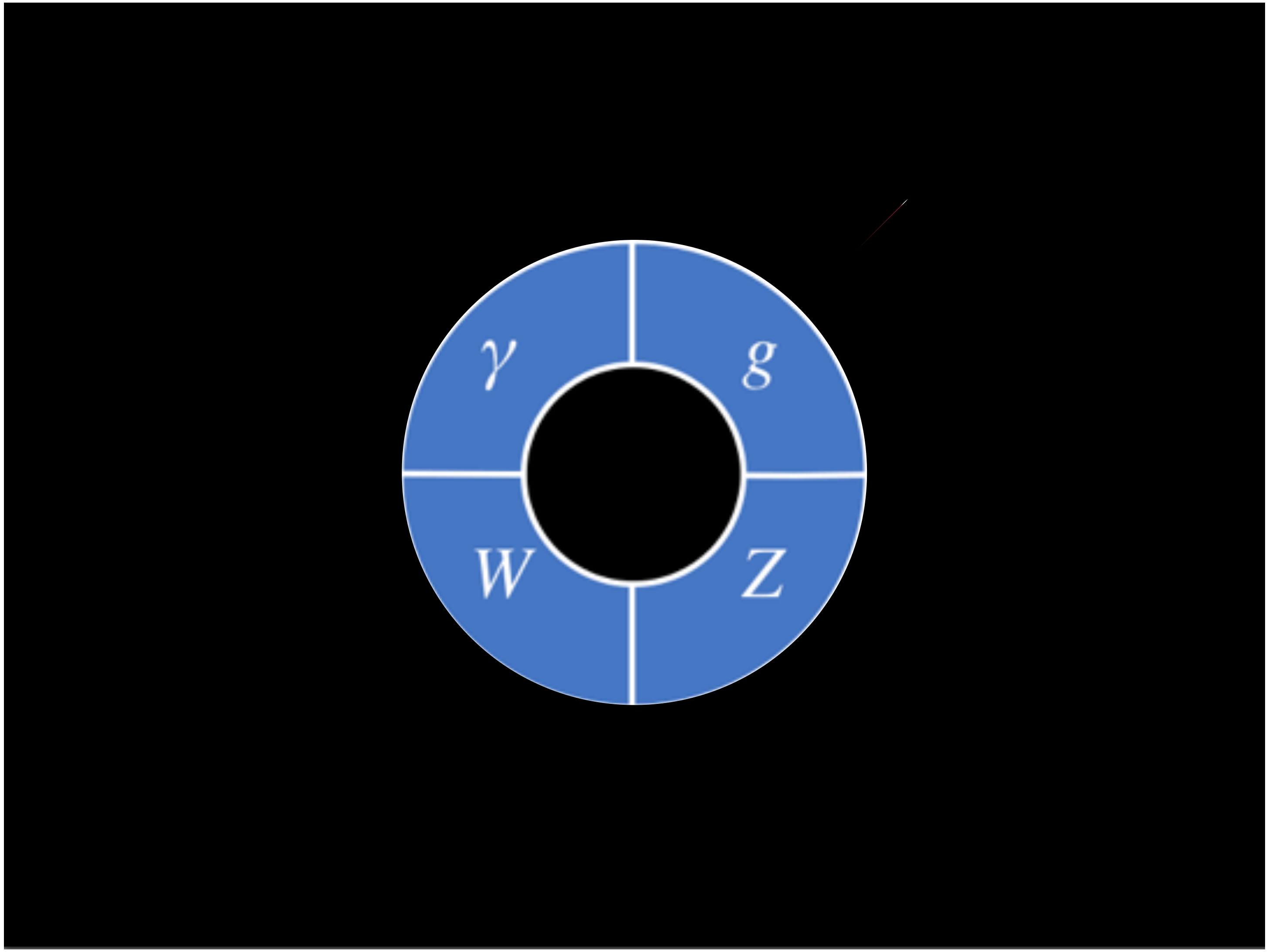
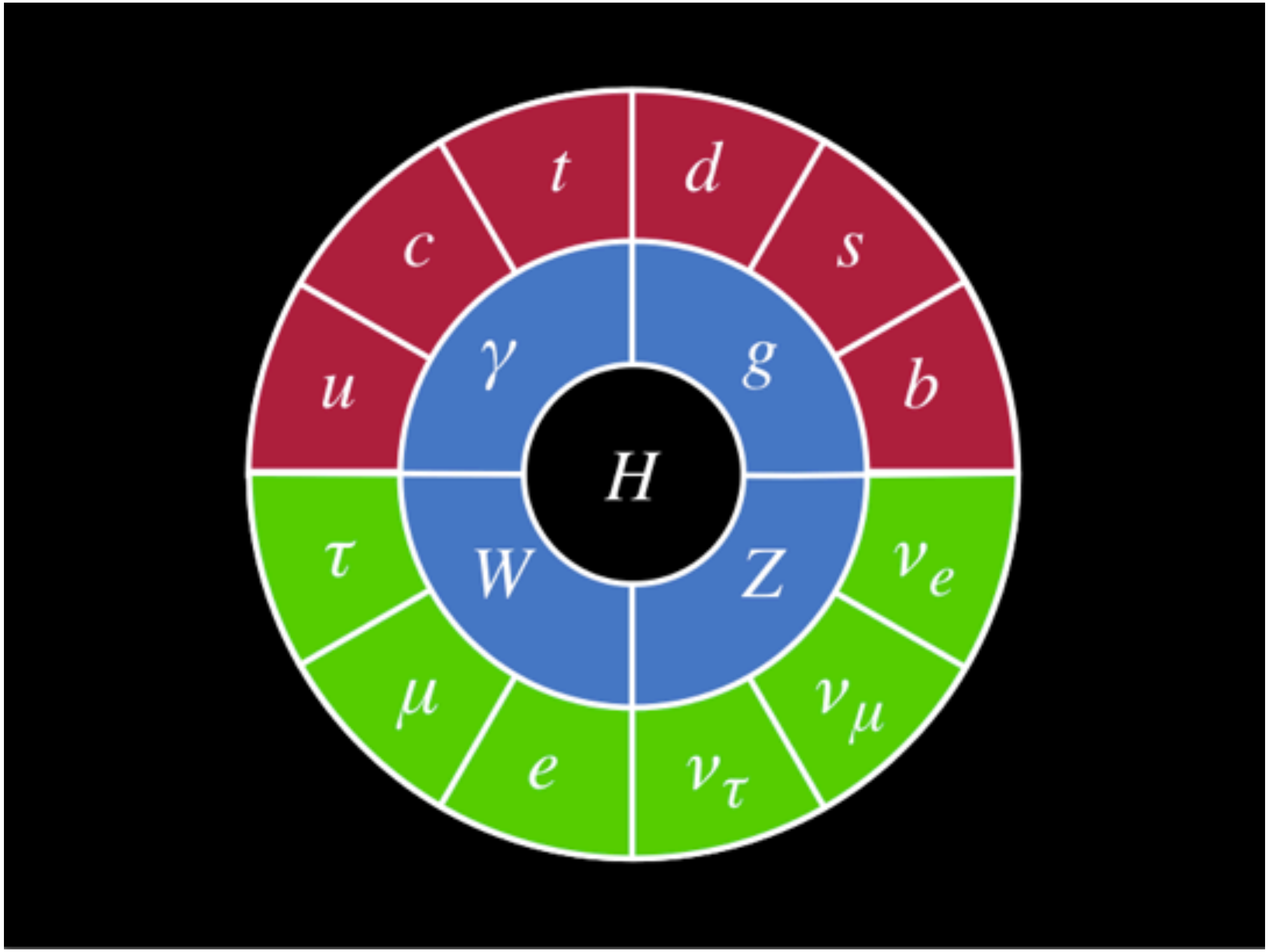


D-branes

Matter? Higgs?



D-branes

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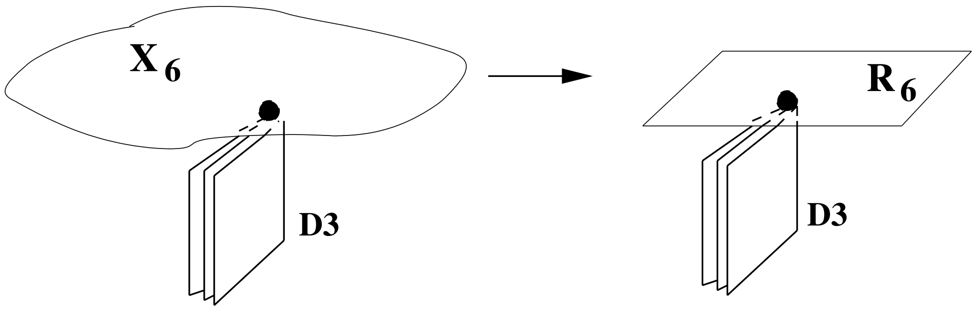

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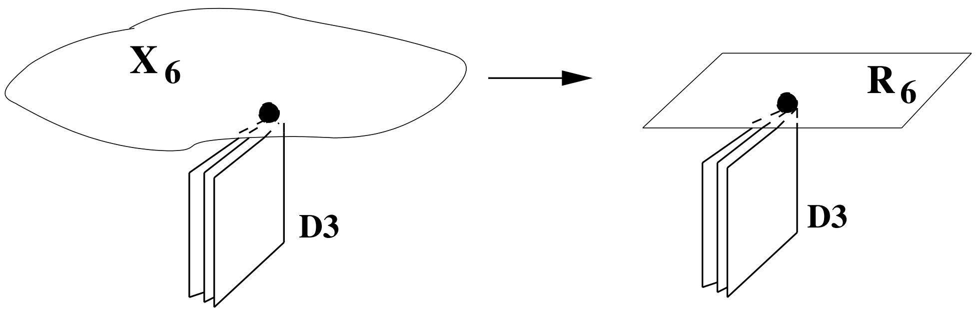

- Setups for SM model building

  - D-branes at singularities

  - Intersecting D-branes

  - Magnetised D-branes

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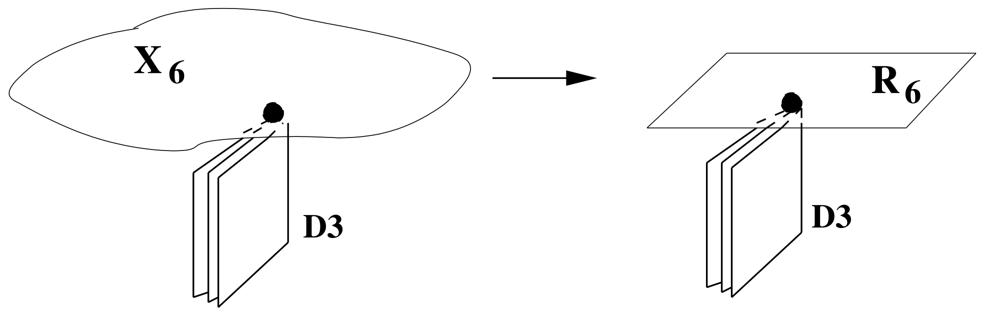

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F-theory

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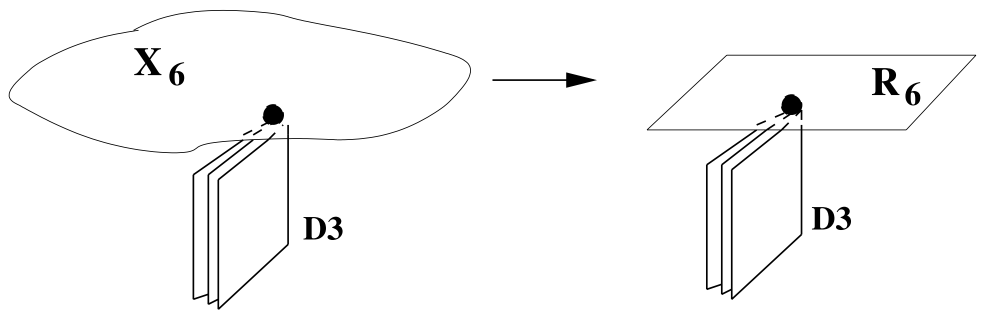

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F-theory

Related to others by string dualities

D-branes

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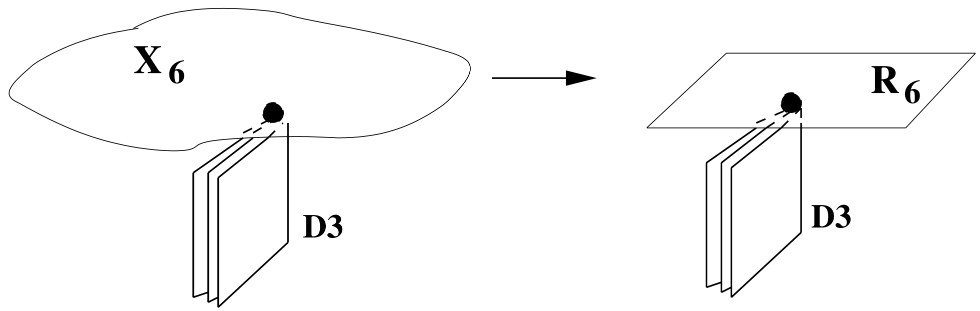

- Setups for SM model building

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Now

  - Intersecting D-branes

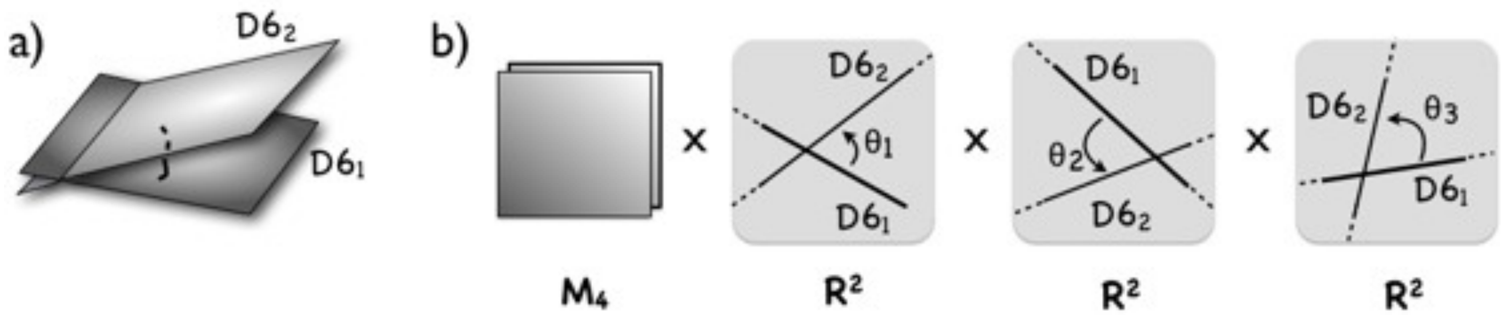
  - Magnetised D-branes

F-theory

Related to others by string dualities

Intersecting D-branes

- Consider type IIA string theory with two stacks of D6-branes (hence 7d subspaces) intersecting over a 4d subspace of their volumes



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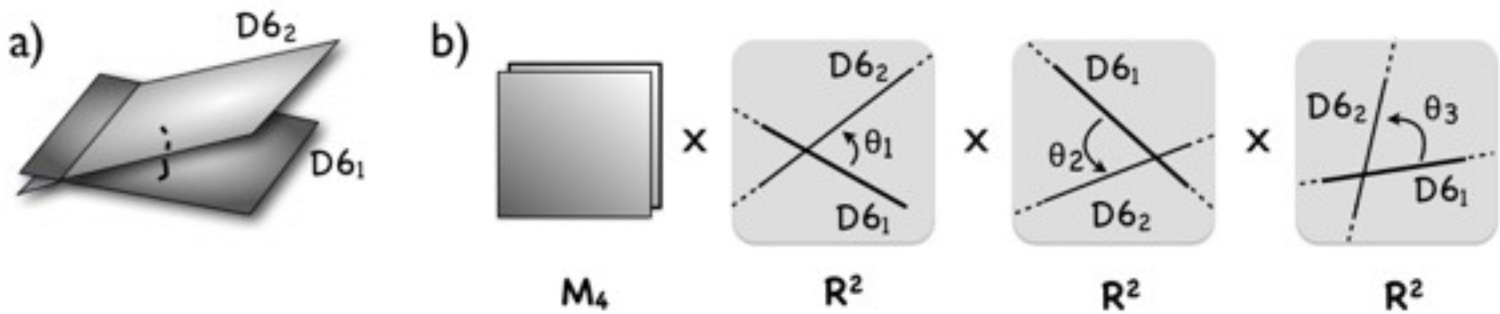

- Three sectors of open strings

  - $D6_1$-$D6_1$: $U(N_1)$ on 7d plane 1
  - $D6_2$-$D6_2$: $U(N_2)$ on 7d plane 2
  - $D6_1$-$D6_2$: 4d chiral fermion in $(N_1,\overline{N}_2)$ on 4d intersection

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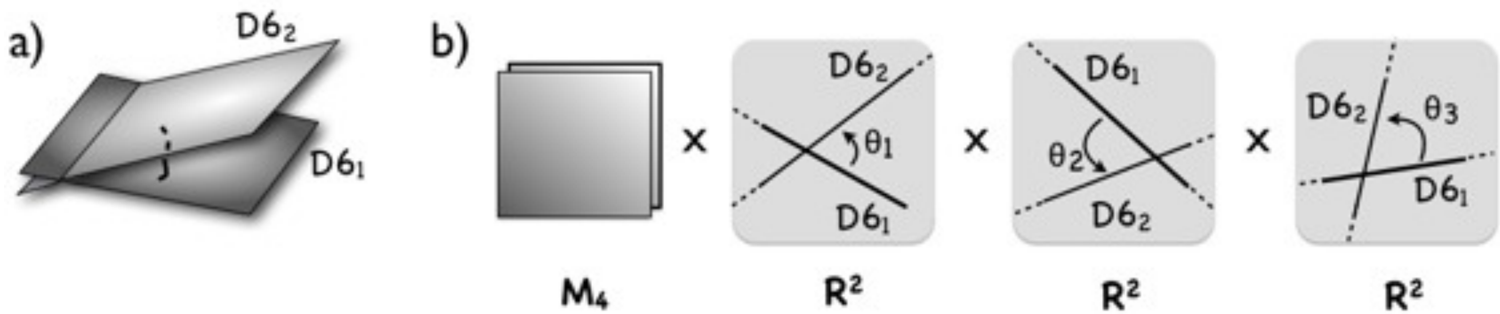

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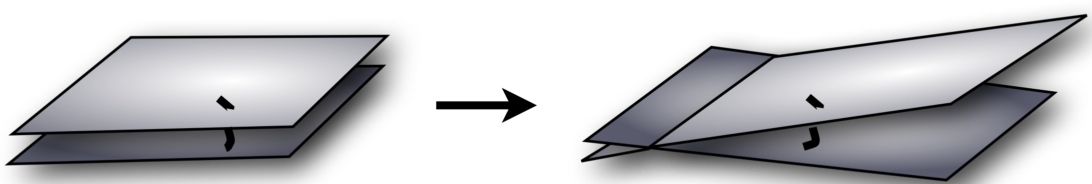
View as 'unfolding' $U(N_1+N_2) \rightarrow U(N_1)\times U(N_2)$

$$Adj \rightarrow Adj_1 + Adj_2 \; (N_1,\overline{N}_2) + cc$$



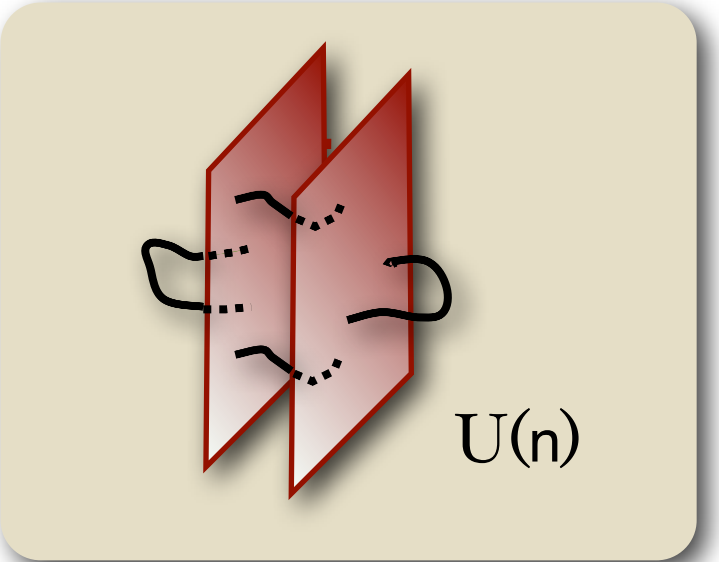
D-branes

D-branes

- Non-abelian U(n) gauge interactions from “n” coincident D-branes

Matrix of open string sectors

$$\begin{pmatrix} 11 & 12 & \dots & 1n \\ 21 & 22 & \dots & 2n \\ \dots & \dots & \dots & \dots \\ n1 & n2 & \dots & nn \end{pmatrix}$$



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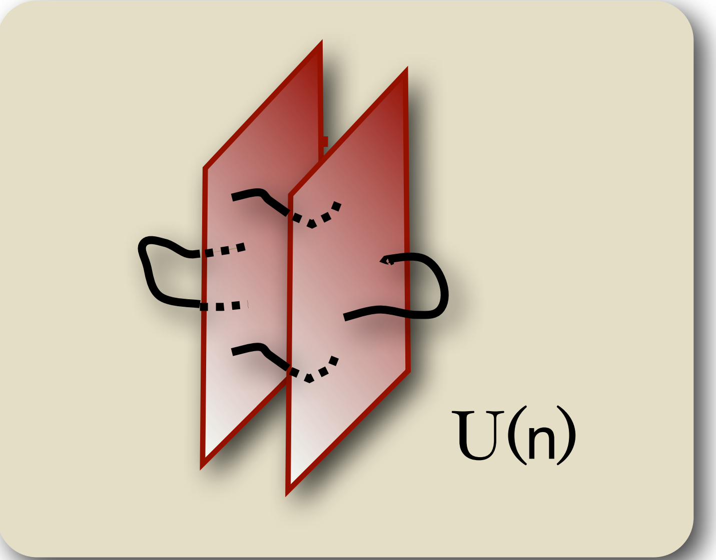

- 4d Charged matter from intersection of stacks of D6-branes

Matrix of open string sectors

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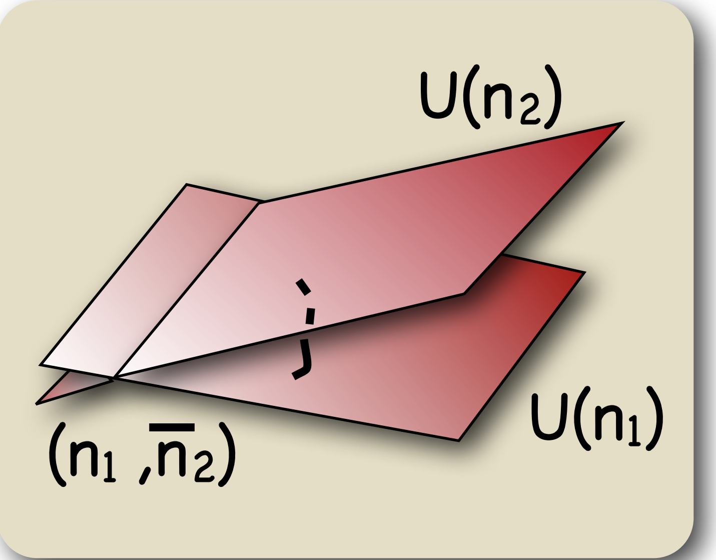

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- Chiral matter cannot get a mass term ⇔ configuration should not admit a continuous deformation making open sector massive

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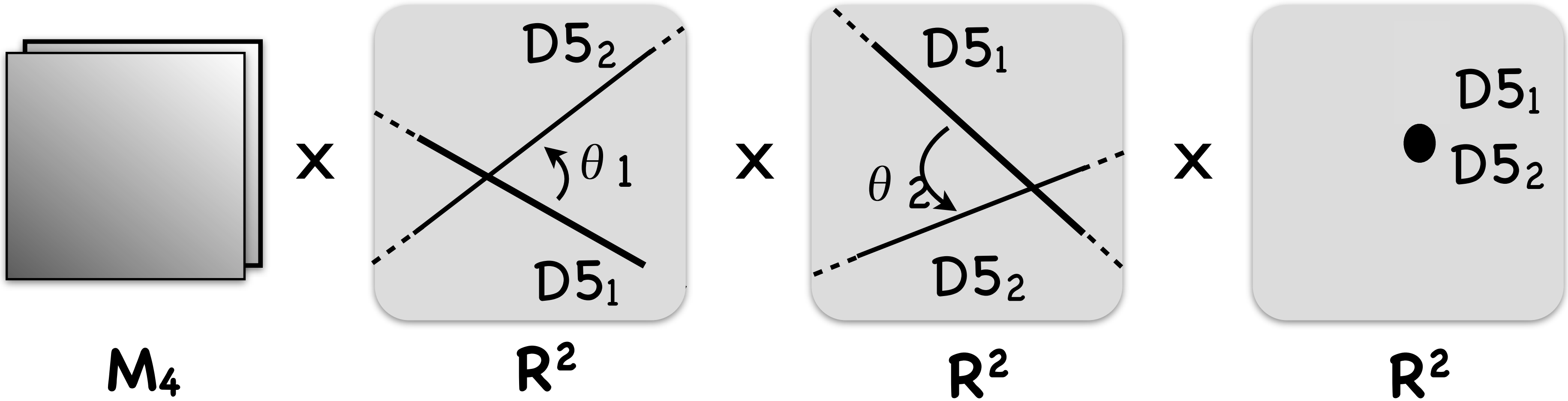
- Consider e.g. D5-branes



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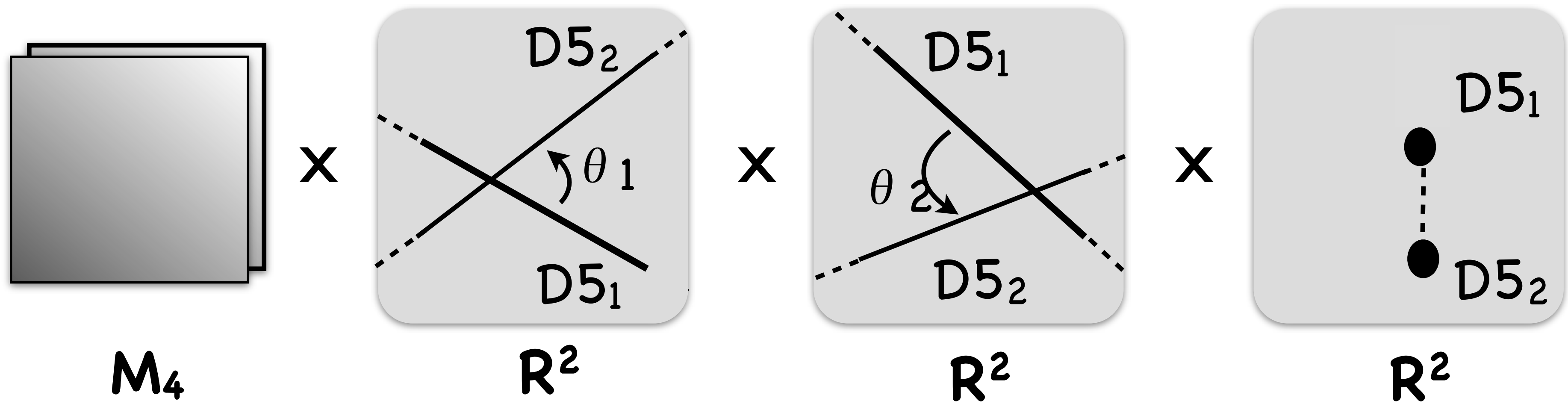

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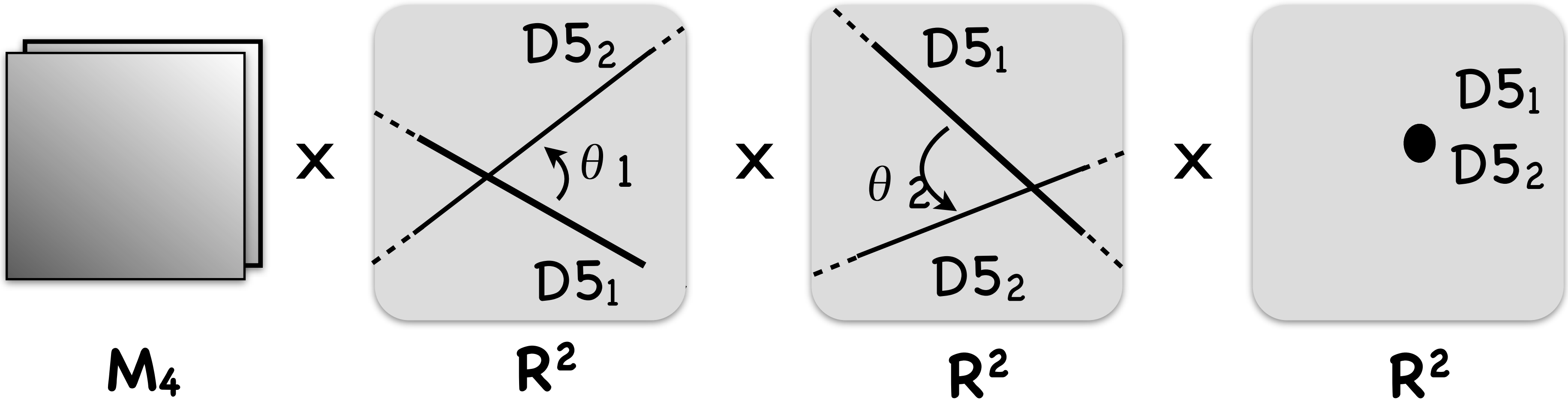
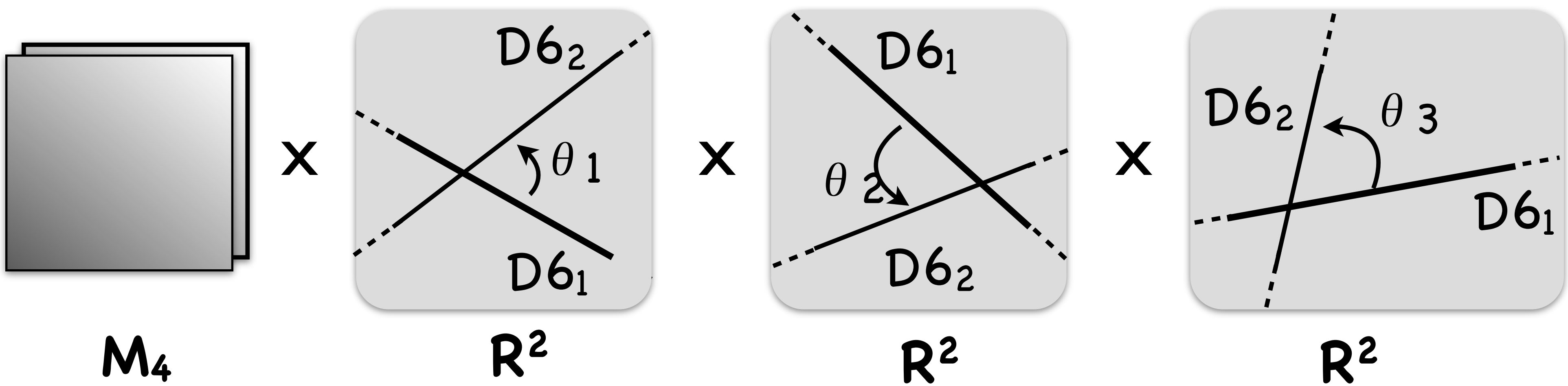


- Now consider D6-branes



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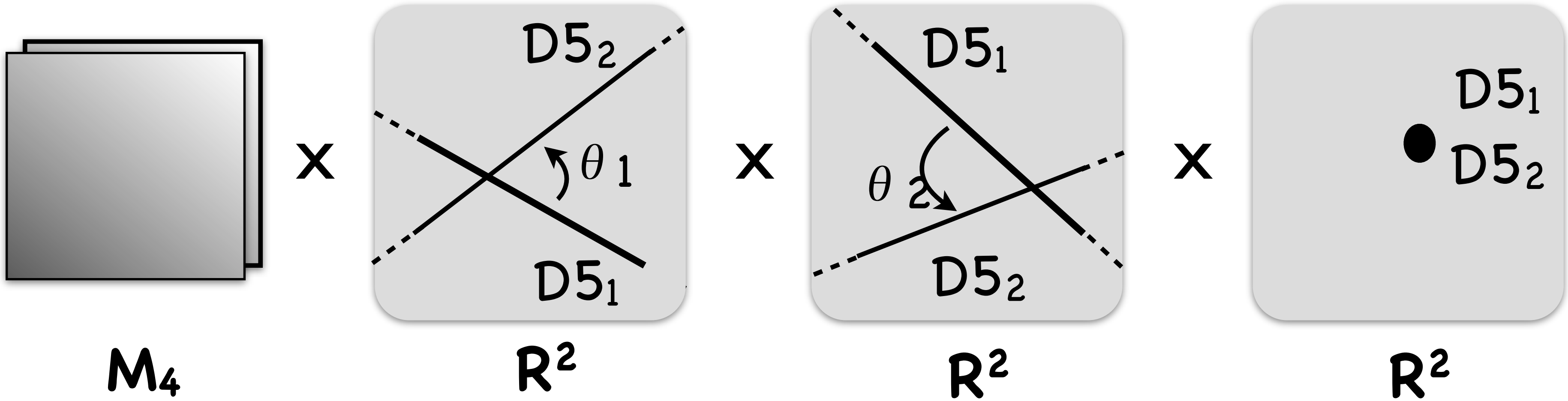

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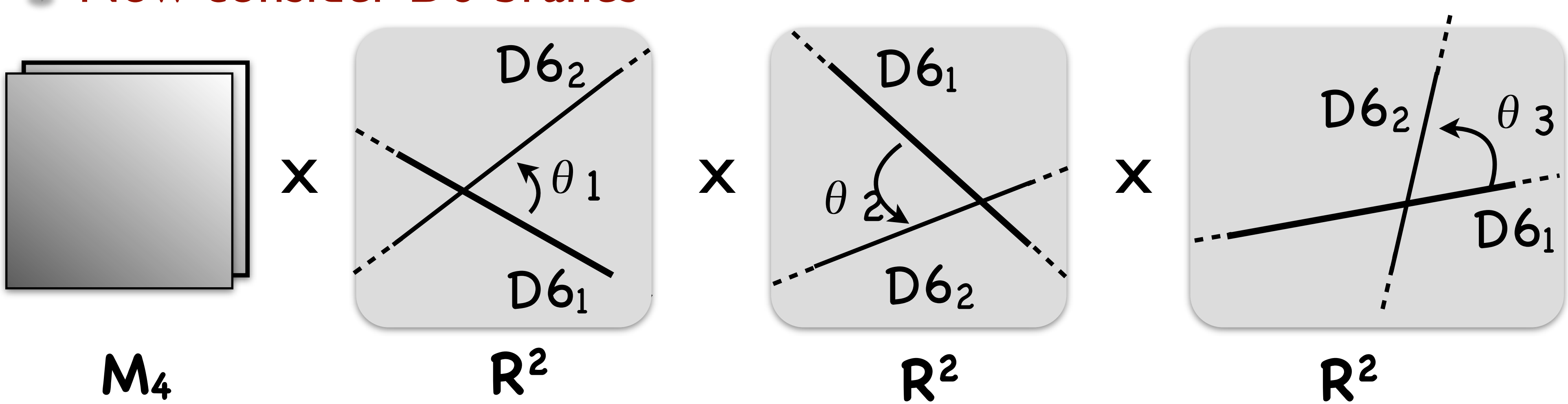

Scalars and supersymmetry

- In addition, the D6$_1$-D6$_2$ sector contains 4d scalars, which are generically massive, and potentially light

$$M^2 \;=\; \frac{1}{2}(\,\theta_1 \pm \theta_2 \pm \theta_3\,)\, M_s^2$$

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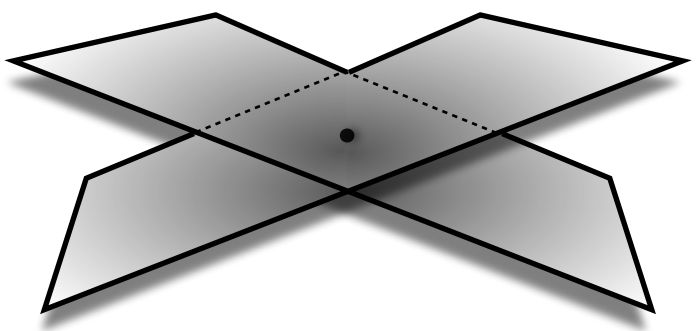
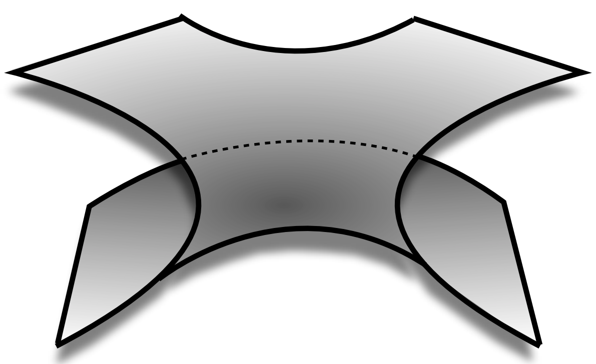
susy if some mass=0

- Could be tachyonic, massless or massive

Possible instability corresponds to possible brane recombination





Higgs effect

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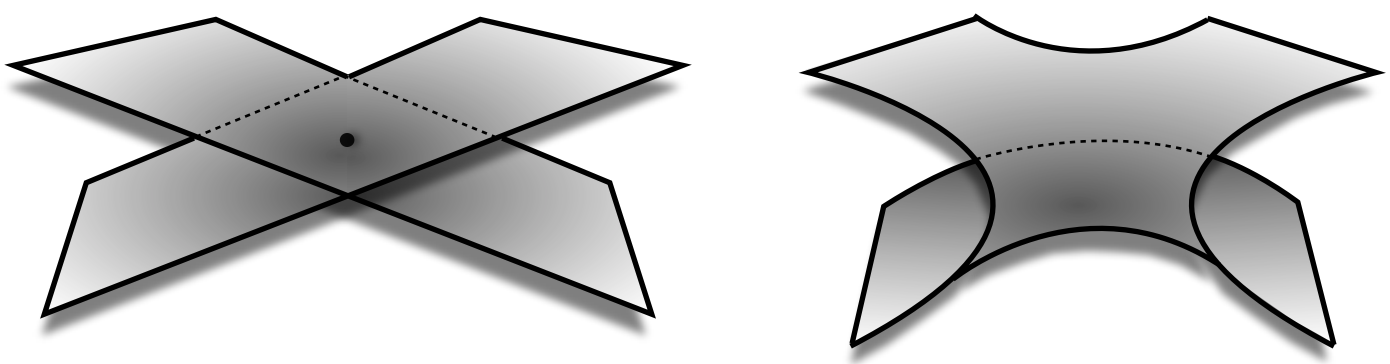

Higgs effect

- Nice geometric interpretation in terms of volume minimization

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- Each flat D6-brane preserves 16 of the 32 supercharges of type II

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- Two D6's preserve a common set of susys iff the SO(6) rotation taking one into the other is actually in SU(3)*

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- Enhanced N=2 supersymmetry for one zero angle e.g.

$$\theta_1 \pm \theta_2 \,=\, 0 \quad ; \quad \theta_3 = 0$$

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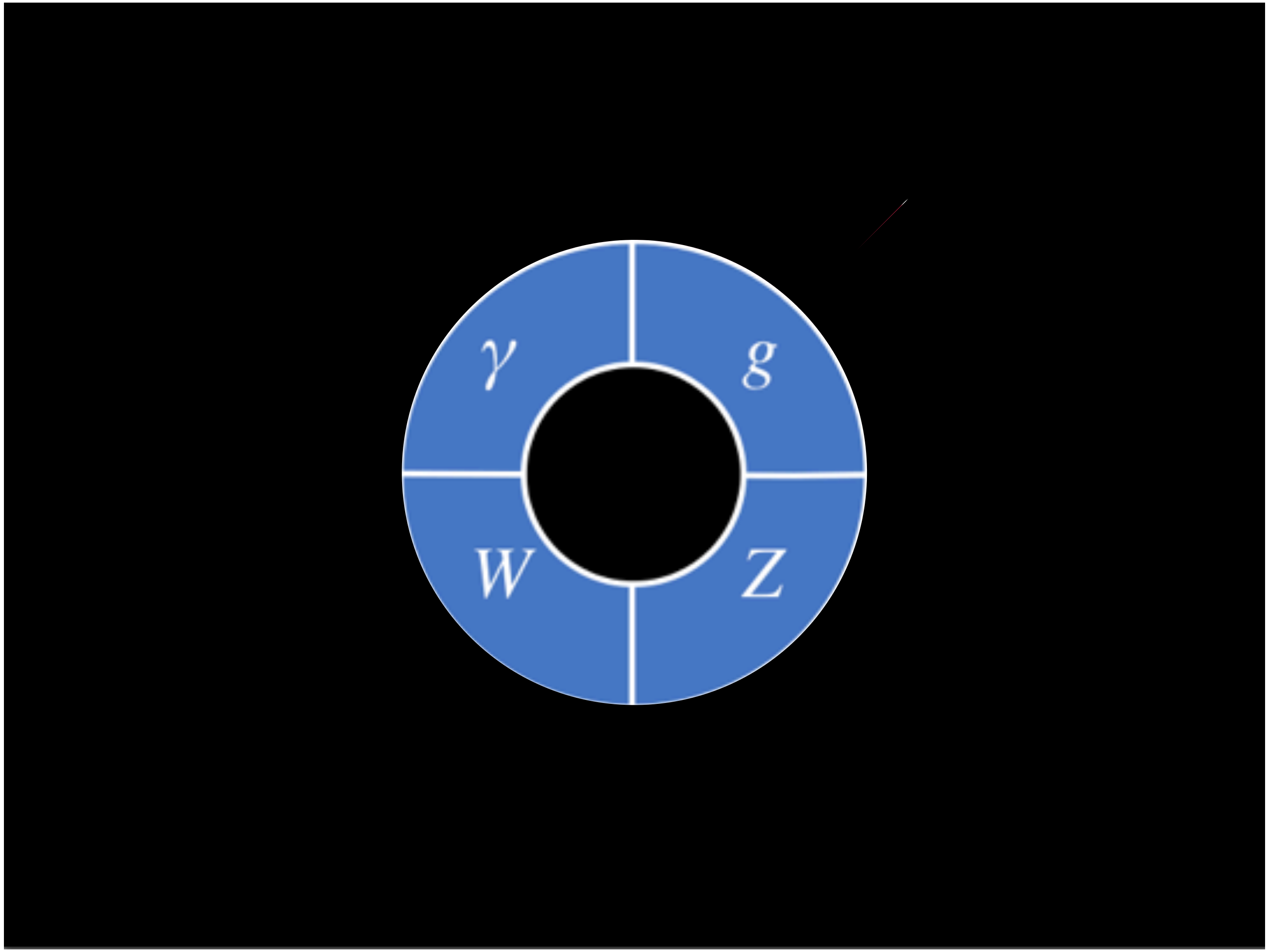
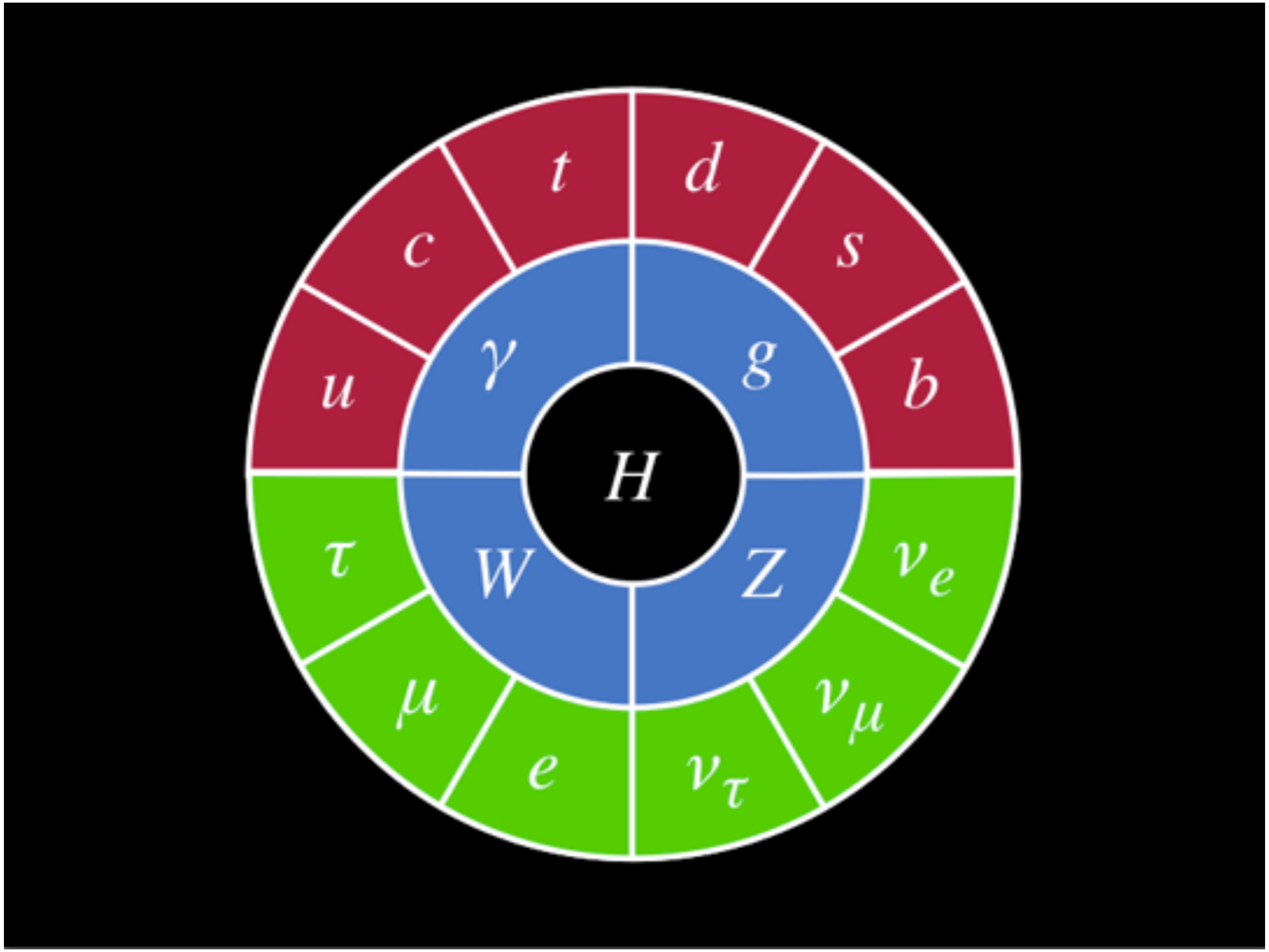
D-branes



D-branes

Matter? Higgs?



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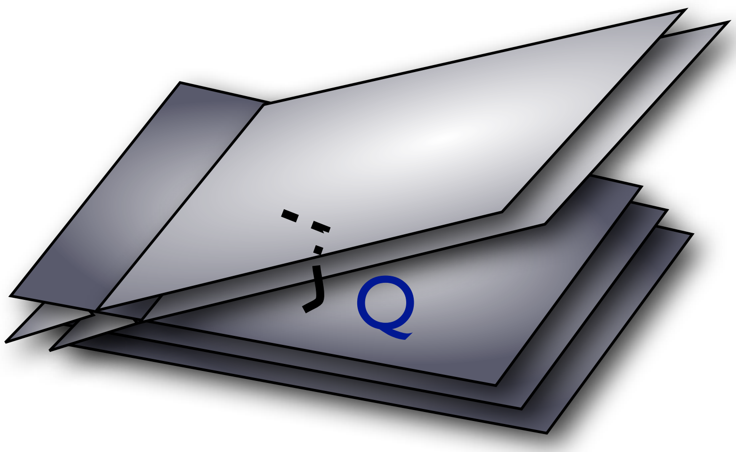

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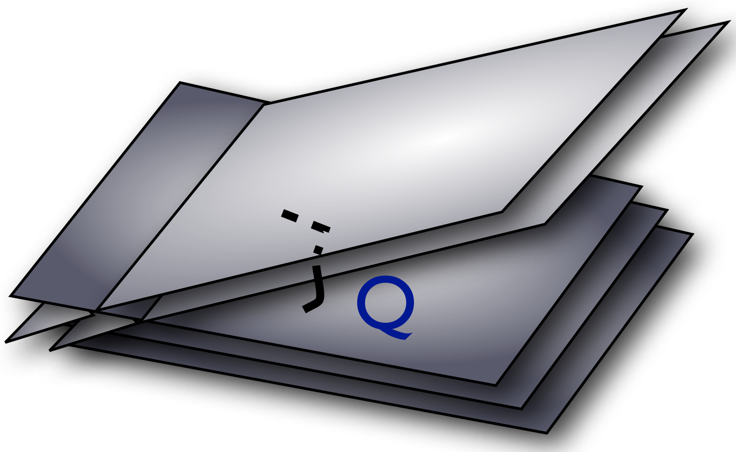

Quarks:
charged under color & EW

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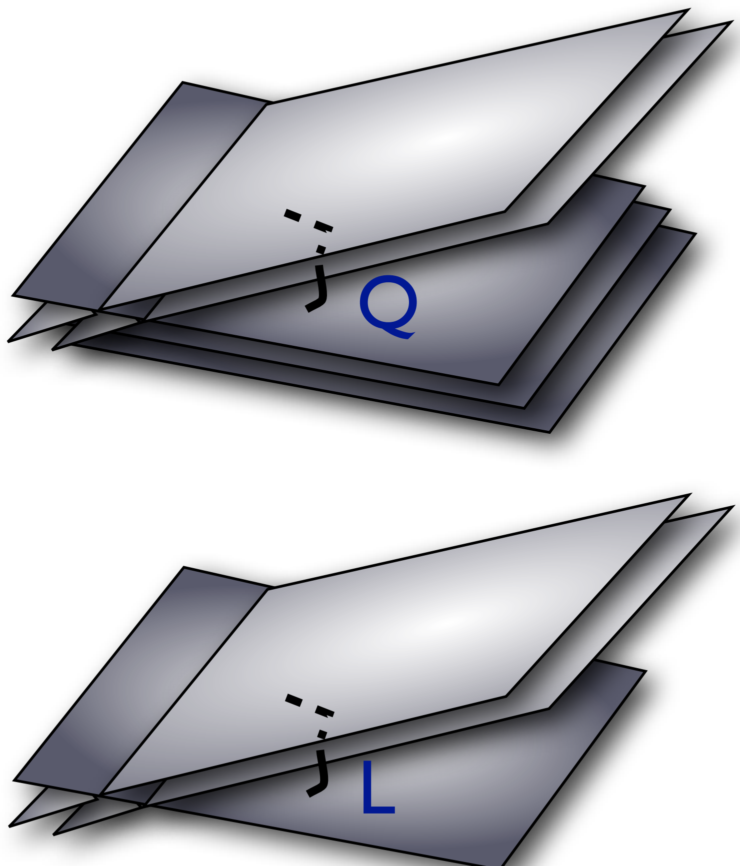

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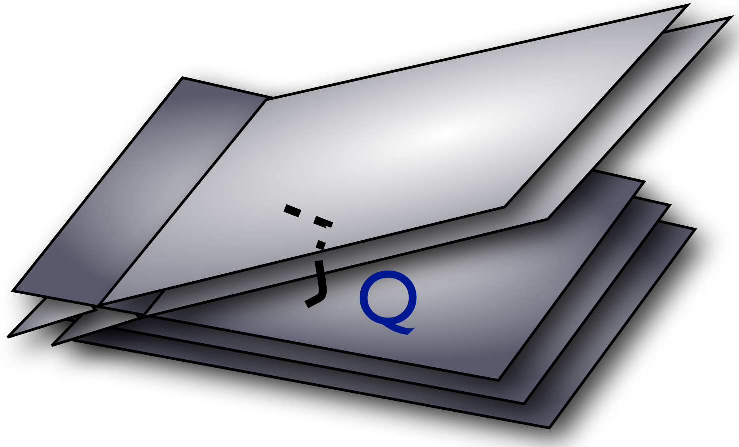

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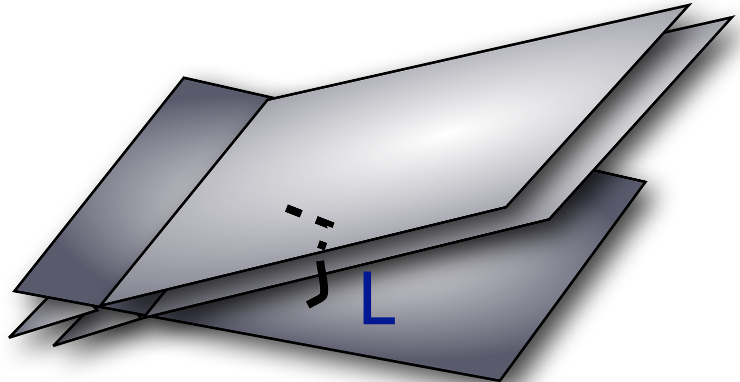

Leptones, Higgs:
no color but EW

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- To obtain 4d gravity, need to compactify

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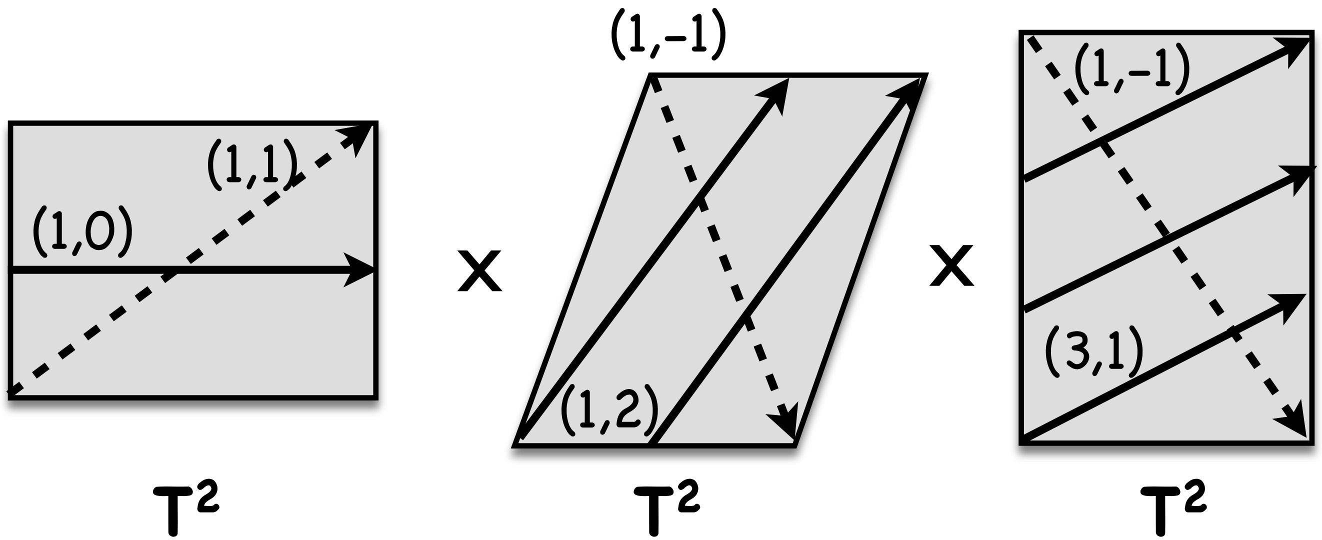

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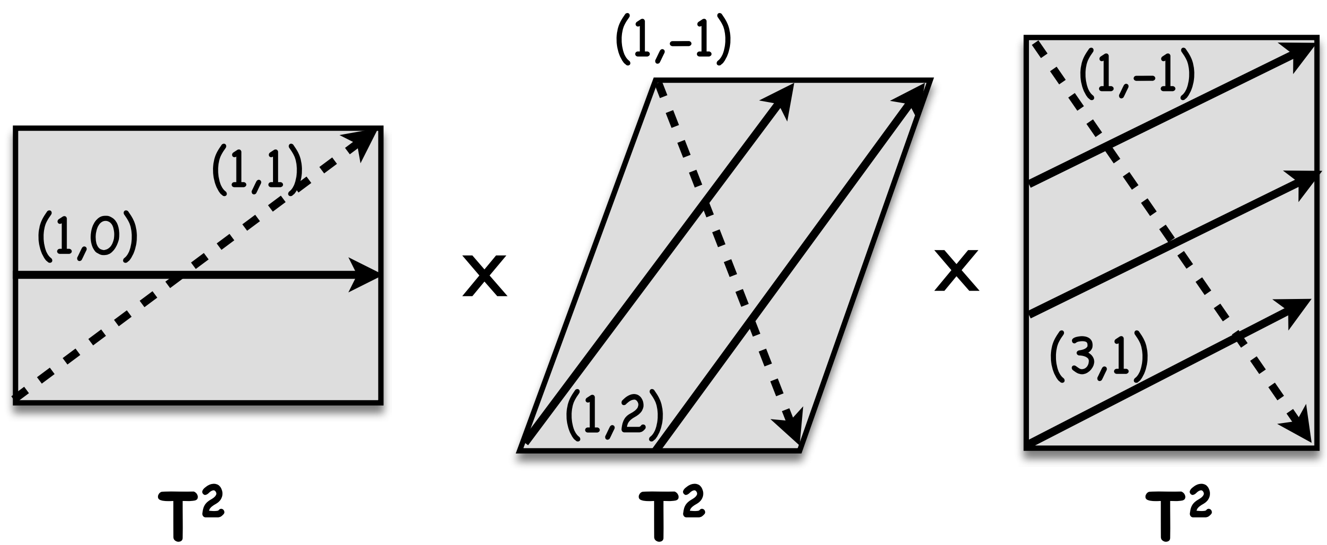

- Configurations of D6-branes in sets of N_a $D6_a$-branes wrapping 3-cycles Π_a described as products of 1-cycles (n_a^i, m_a^i) on each $(T^2)^i$

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- Closed string sector is maximally supersymmetric
  4d N=8 supergravity multiplet

  (more realistic 4d N=1 supergravity in non-toroidal models: graviton, gravitino, plus additional moduli multiplets)

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  - Chiral part can be determined with just the above topological data

Gauge group $\prod_a U(N_a)$

Chiral fermions $\sum_{a,b} I_{ab}\,(N_a, \overline{N}_b)$

$$I_{ab} = (n_a^1 m_b^1 - n_b^1 m_a^1) \times (n_a^2 m_b^2 - n_b^2 m_a^2) \times (n_a^3 m_b^3 - n_b^3 m_a^3)$$

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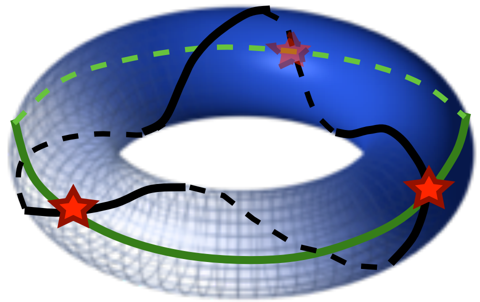

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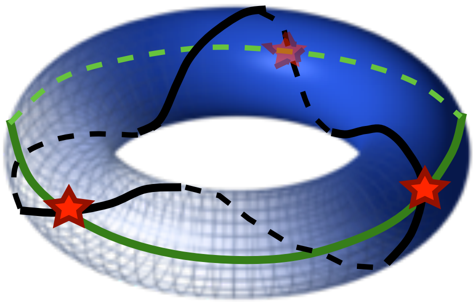

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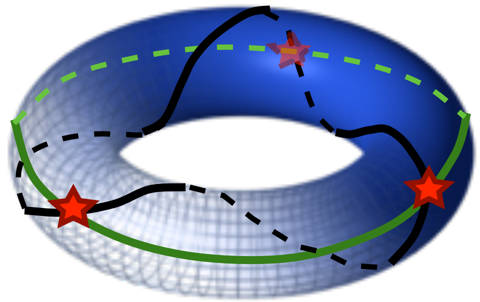

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- Non-chiral features of the spectrum (susy, scalars,...) depend on detailed configuration

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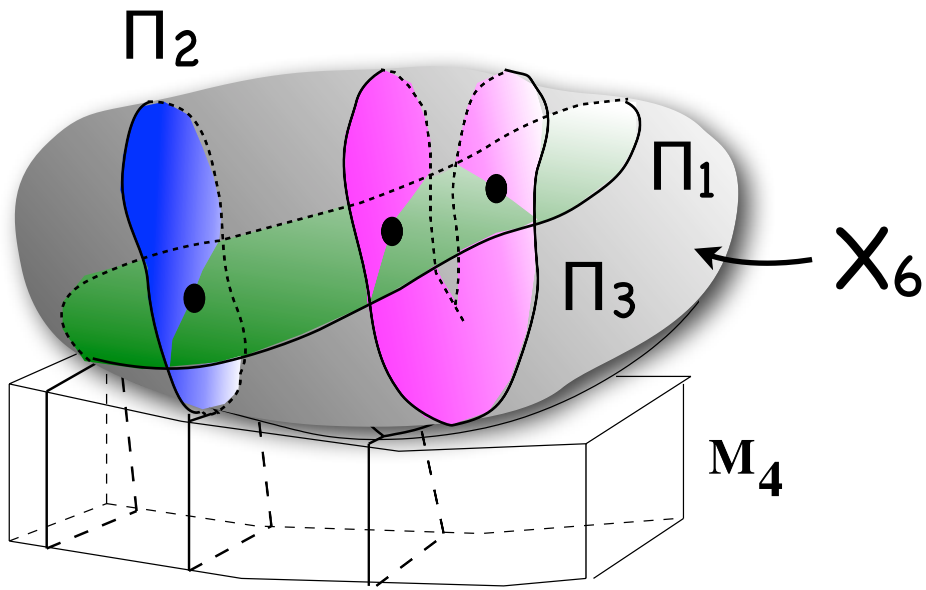

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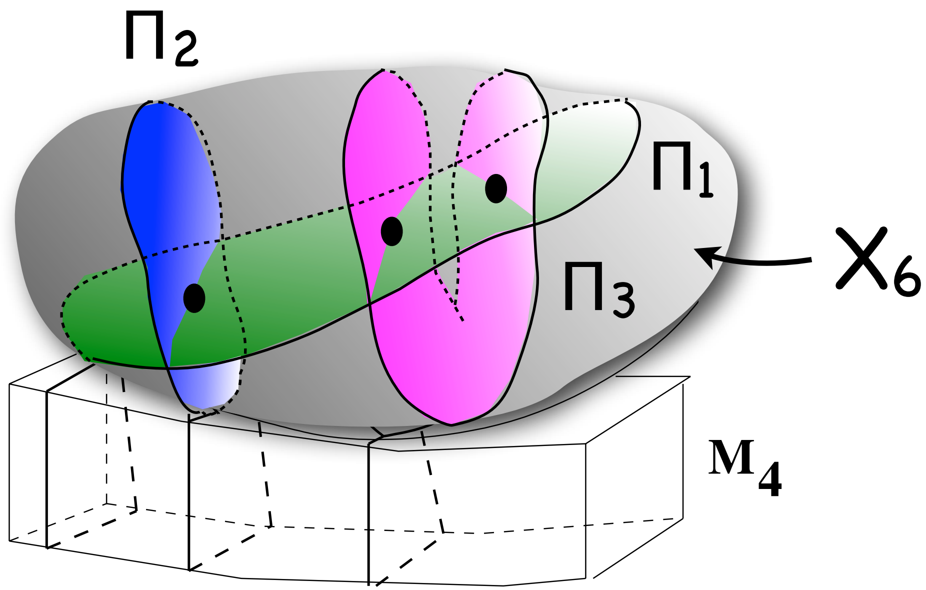

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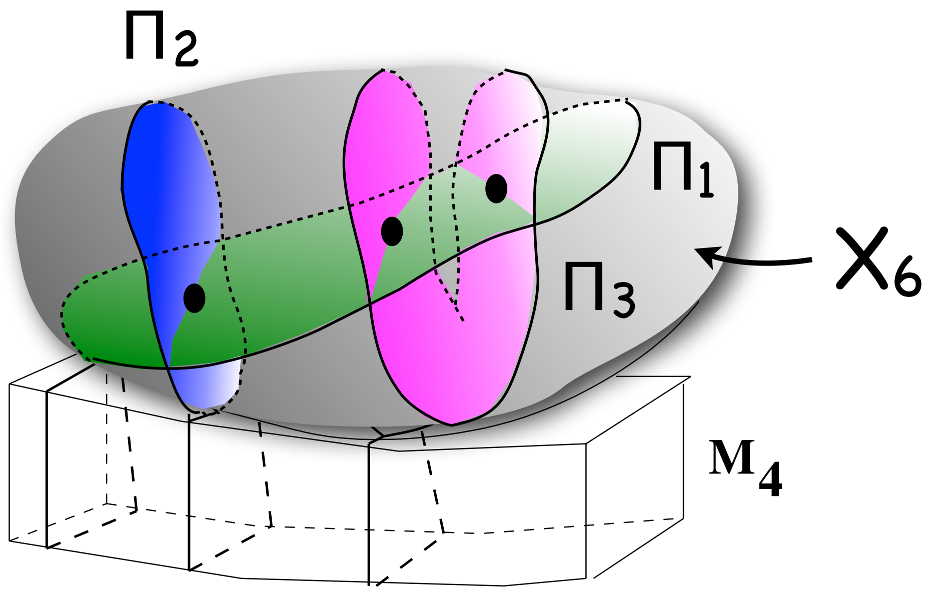

D6-branes wrapped on "Special lagrangian 3-cycles" of CY (* hard!)

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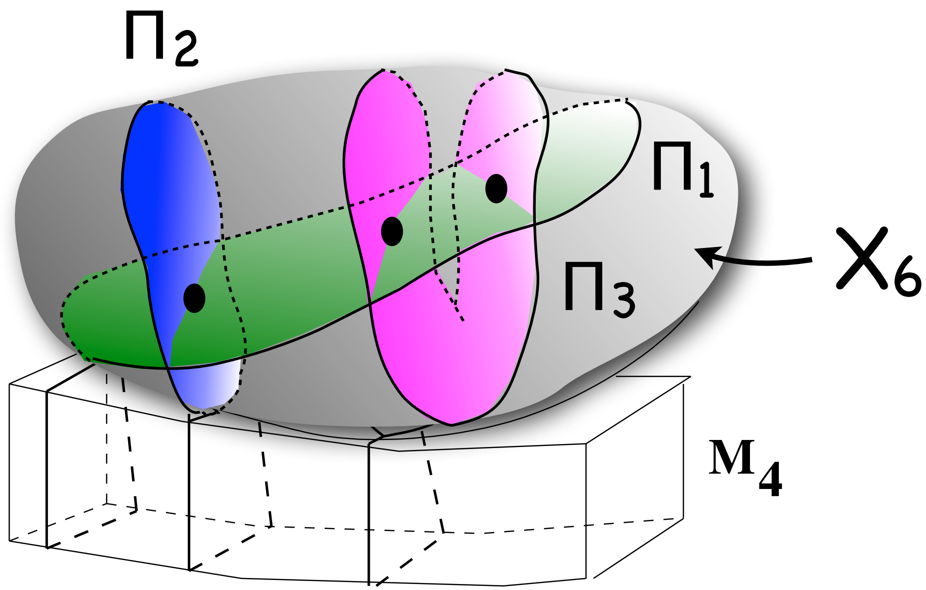

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General class of string compactifications with non-abelian gauge symmetry and replicated charged chiral fermions

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Tadpoles, anomalies and all that

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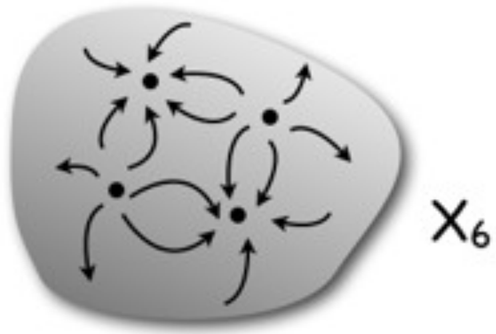

Gauss' law

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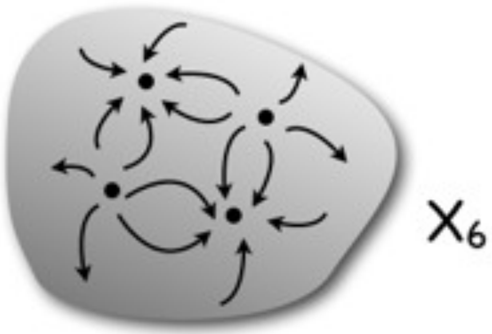

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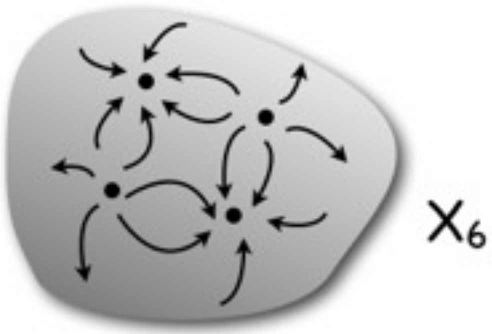

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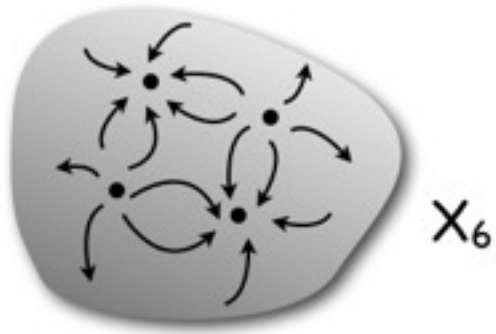

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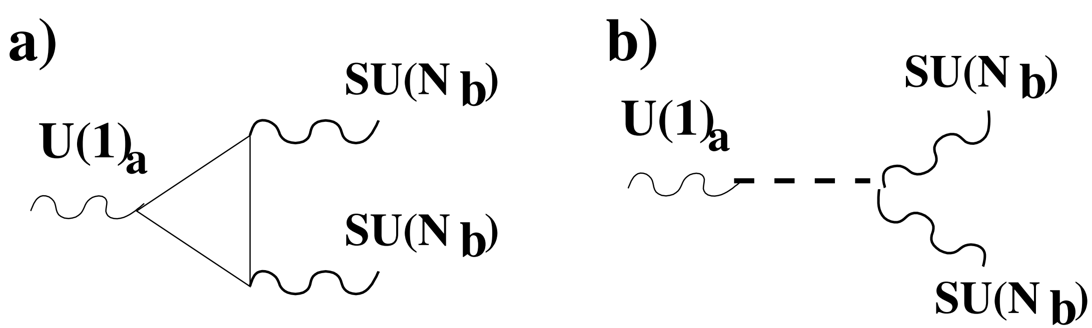
  - $U(1)_a$-$SU(N_b)^2$ mixed cancel via Green-Schwarz mechanish involving the D6-brane couplings $\sum_{k,a} \int_{4d} B_k \wedge \mathrm{tr}\, F_a$ & $\sum_{k,a} \int_{4d} a_k\, \mathrm{tr}\, (F_b \wedge F_b)$



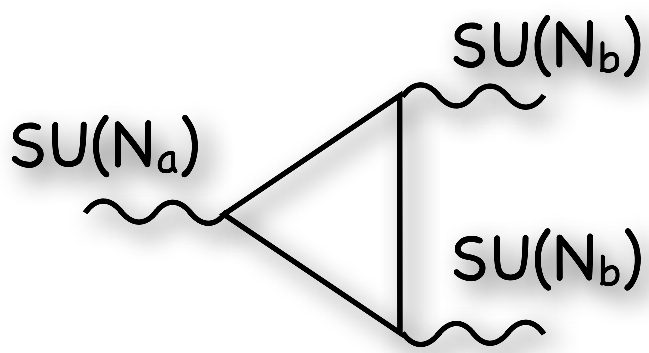
Tadpoles, anomalies and all that

- RR tadpole cancellation

$$dF_2 = \sum_a N_a \delta(\Pi_a) \;\to \sum_a N_a [\Pi_a] = 0$$

- Non-abelian anomaly cancellation

$$SU(N_a)^3 \;:\; A_a = \sum_b I_{ab} N_b$$



$$0 = [\Pi_a] \cdot \sum_b N_b [\Pi_b] = \sum_b N_b I_{ab}$$

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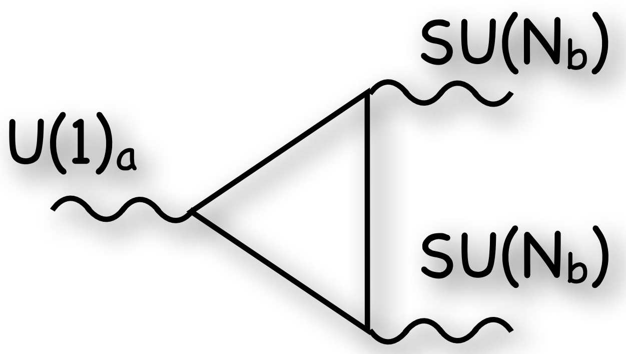

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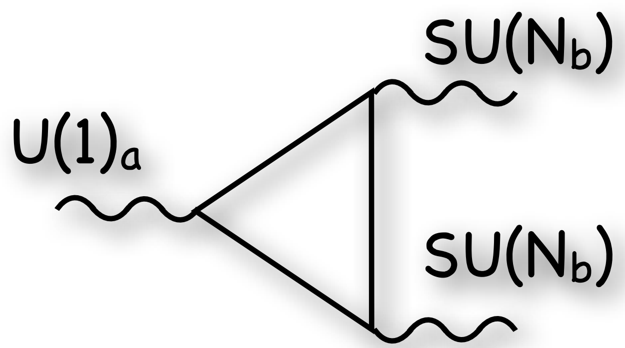

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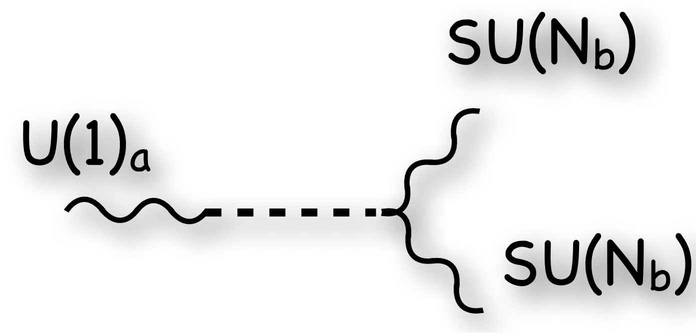

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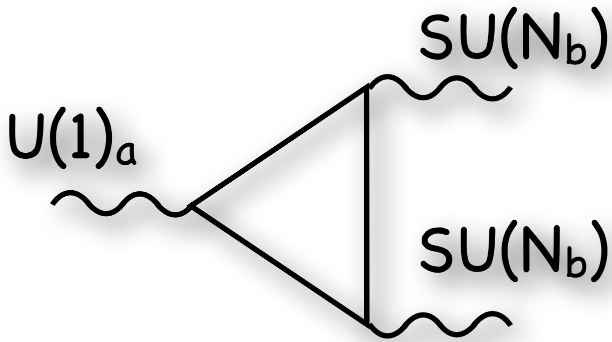

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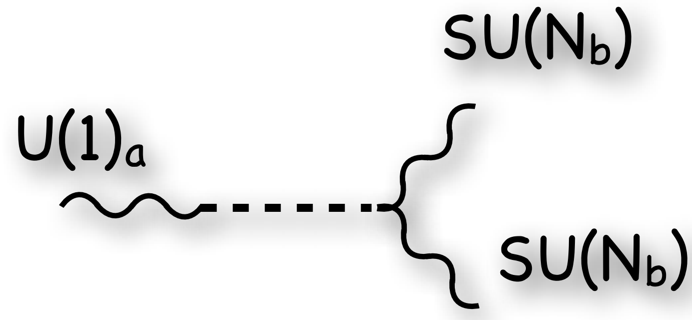

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$$(B_2)_k = \int_{[\Lambda_k]} C_5 \quad , \quad \phi_{\tilde{l}} = \int_{[\Lambda_{\tilde{l}}]} C_3 \qquad \text{with } d\phi_{\tilde{l}} = -\delta_{k\tilde{l}} *_{4d} (B_2)_k$$

Tadpoles, anomalies and all that

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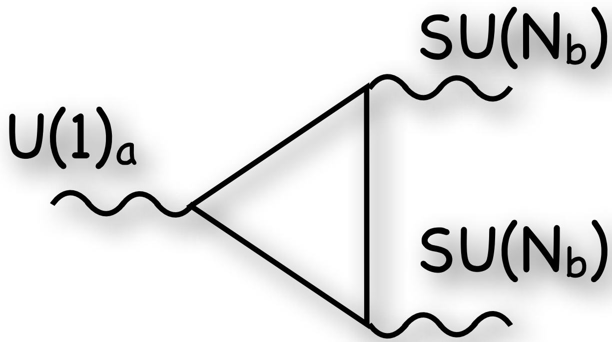

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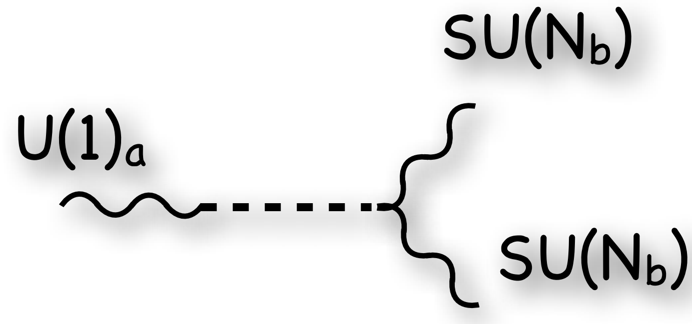

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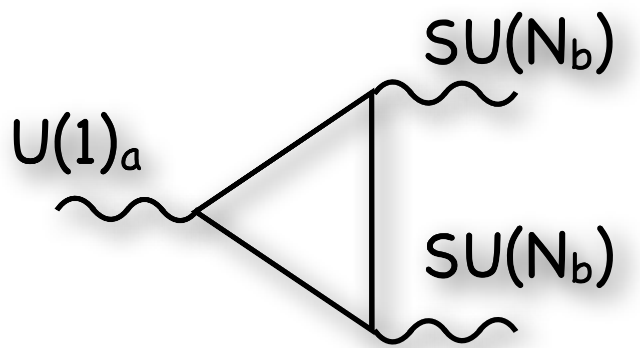

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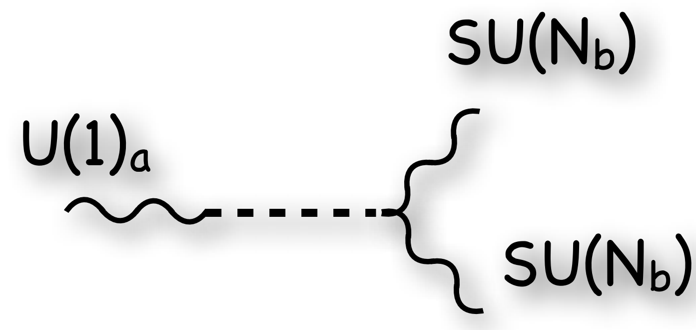

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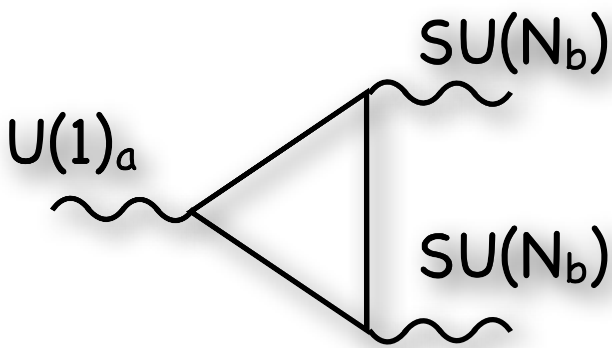

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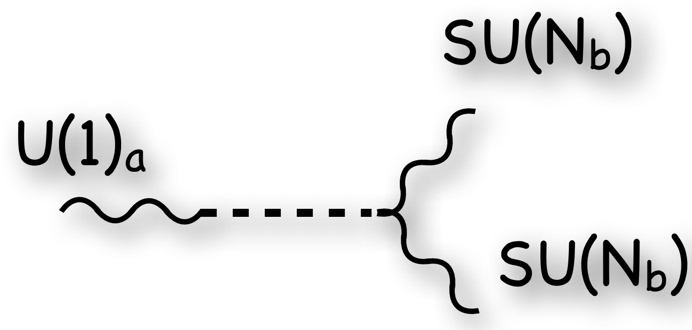

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- Due to BF couplings, all ‘anomalous’ and some ‘non-anomalous’ U(1)’s become massive, with mass of order the string scale

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- Consequences
  - Impose that hypercharge generator remains massless
  - Additional U(1)'s removed
    remain as global symmetries exact in perturbation theory
  - Operators violating the latter can appear non-perturbatively
    D-brane instantons, see later

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  Take type IIA on CY X, and mod out by ΩR, where Ω flips the string orientation, and R is a Z2 symmetry of the CY X

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- Fixed points of R are regions where string orientation can flip:

  $\Rightarrow$ Orientifold planes

  Focus on R flipping 3 coords of CY X, then O6-plane on 3-cycle

Compact orientifolds

- Compact susy models using orientifold projections

  Take type IIA on CY X, and mod out by ΩR, where Ω flips the string orientation, and R is a Z2 symmetry of the CY X

- Fixed points of R are regions where string orientation can flip:

  ⇒ Orientifold planes

  Focus on R flipping 3 coords of CY X, then O6-plane on 3-cycle

- O6-planes carry negative charge and negative tension

  Supersymmetric D6/O6 systems with zero total charge/tension can still be non-trivial

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- Technical modifications of configuration, tadpoles, anomalies,... skip!

  - Every D6-brane stack has an orientifold image D6'
  - Intersections ab and ab'
  - D6-brane staks on top of O6 have SO/Sp group rather than U(N)

Towards the SM

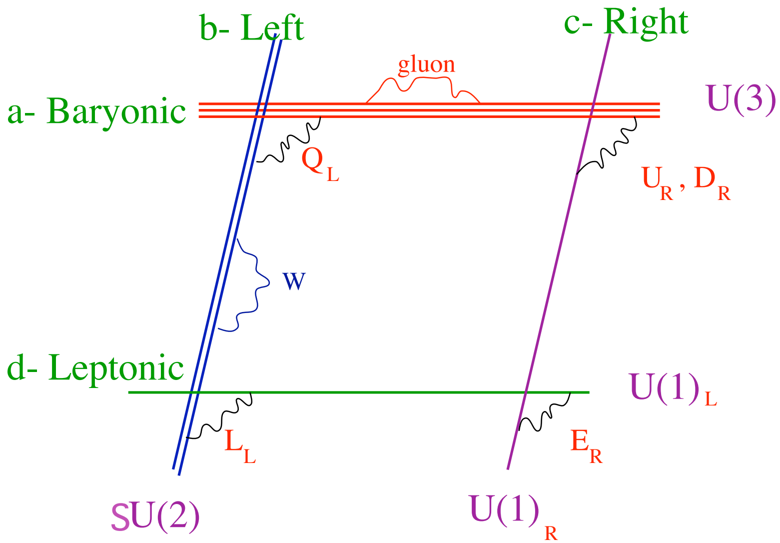
- Simplest road to SM

[Ibáñez, Marchesano, Rabadán; Cremades, Ibáñez, Marchesano;'01]

Introduce four stacks of D6's a,b,c,d with

$$U(3)_a \times USp(2)_b \times U(1)_c \times U(1)_d$$

$$I_{ab} = 3 \to \quad Q_L$$
$$I_{ac} = -3,\ I_{ac'} = 3 \to \ U_R,\ D_R$$
$$I_{db} = 3 \to \quad L$$
$$I_{dc} = -3,\ I_{dc'} = -3 \to \ E_R,\ \nu_R$$



Spectrum of SM with hypercharge

$$Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$$

- Look for models realizing these intersection numbers:
  $\Rightarrow$ surprisingly easy!

Towards the SM

- Explicit realization in toroidal models

N_α	(n_α^1, m_α^1)	(n_α^2, m_α^2)	(n_α^3, m_α^3)
$N_a = 3$	(1,0)	(1,3)	(1,-3)
$N_b = 1$	(0,1)	(1,0)	(0,-1)
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$$I_{ab} = I_{ab'} = 3 \qquad I_{ac} = I_{ac'} = -3$$

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Intersection	Matter fields		Q_a	Q_c	Q_d	Y	Y’	$3Q_a - Q_d$
ab, ab'	Q_L	$3(3,2)$	1	0	0	1/6	1/3	3
ac	U_R	$3(\bar{3},1)$	-1	1	0	-2/3	2/3	-3
ac'	D_R	$3(\bar{3},1)$	-1	-1	0	1/3	-4/3	-3
$bd, b'd$	L	$3(1,2)$	0	0	-1	-1/2	-1	1
cd	E_R	$3(1,1)$	0	-1	1	1	0	-1
cd'	ν_R	$3(1,1)$	0	1	1	0	2	-1

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(need few extra branes, adding few extra matter)

- Supersymmetric for suitable choices of T^2 geometry

  MSSM with pair of Higgs doublets in non-chiral bc sector

- Realizations in other setups

  Orientifolds of type II Gepner models leads to some 200.000 models

- Towards more detailed analysis of properties

Towards the SM

Towards the SM

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  A priori no natural unification at string scale

  Each coupling depends on wrapped volume $$\frac{1}{g_a^2} = \frac{V_{\Pi a}}{g_s}$$

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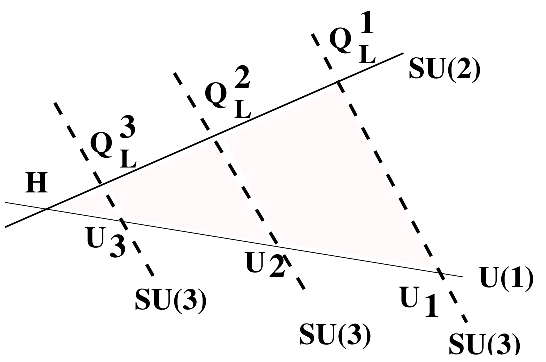
  Mediated by open string worldsheet instantons $Y_{jk} \simeq e^{-A_{Hjk}+i\phi_{jk}}$



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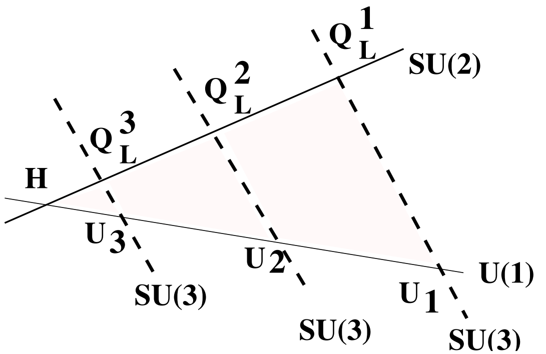

Exponential dependence potentially explains fermion mass hierarchy

Extensive computations of general formula

Complicated functions of open and closed string (Kahler) moduli

Need to face moduli stabilization

Geometrical interpretation possibly useful in search for textures

Towards the SM

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  - In susy models, can 'choose' string scale
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Lectures 2,3

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Lecture 4

U,D
γ
E, ν_R
Z
g
Thanks!
W
Q
L