>Panorama A

>Panorama B

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D-branes wrapped on special lagrangian 3-cycles $\longleftrightarrow$ In large volume limit, D-branes on holomorphic cycles, with holomorphic (and stable) gauge vector bundles

In other regimes, description has no geometric counterpart

Mirror symmetry

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Morally, type IIB on CY with D9, D7, D5, D3-branes

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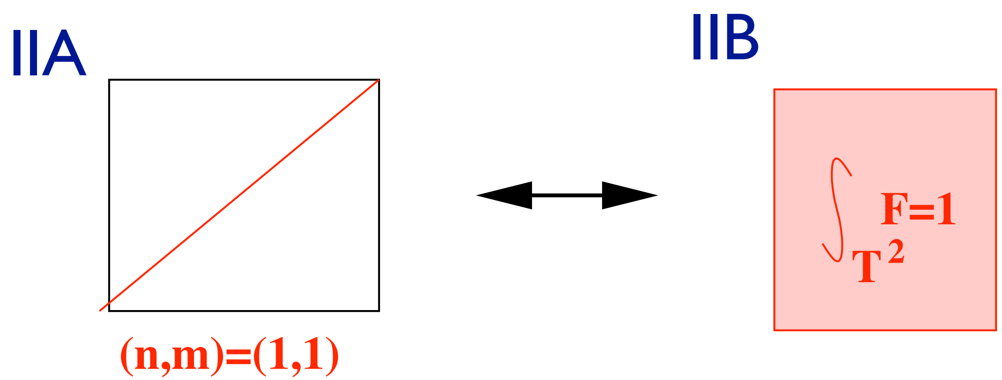
- Example Magnetized D-branes



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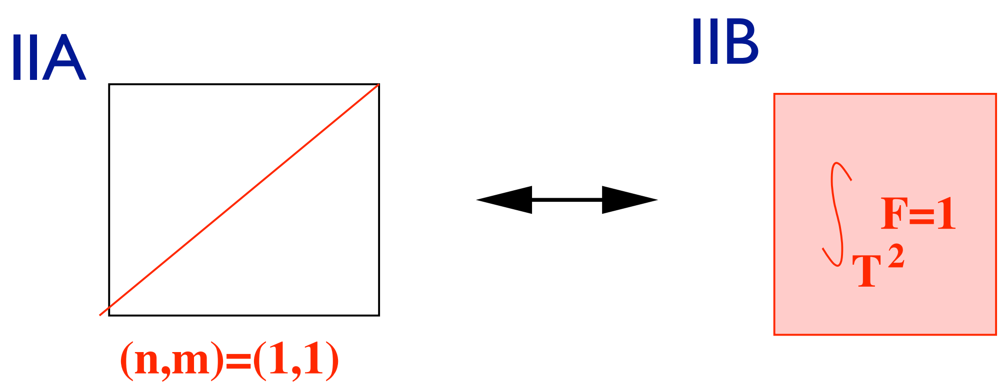
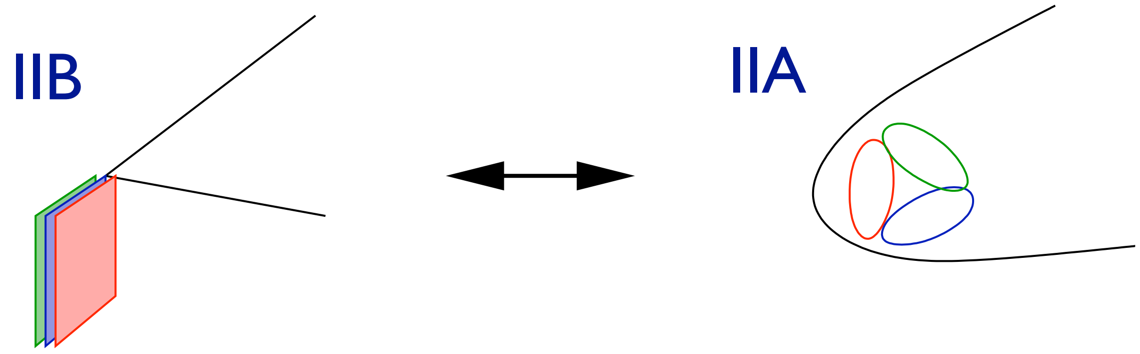
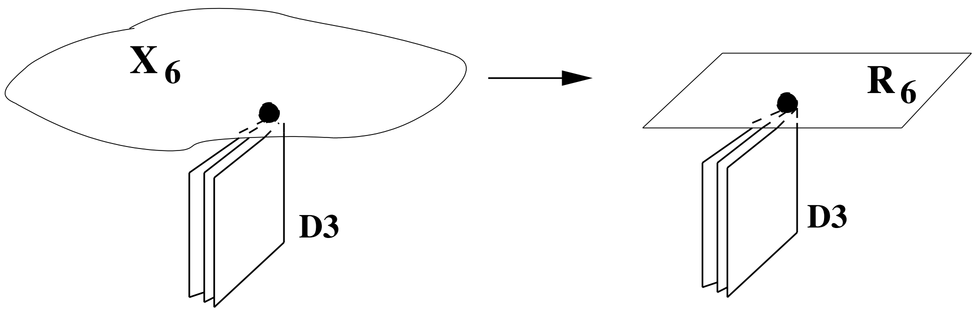


- Example D-branes at singularities



D-branes

- Isolated D-branes in smooth geometries cannot lead to chiral gauge theories

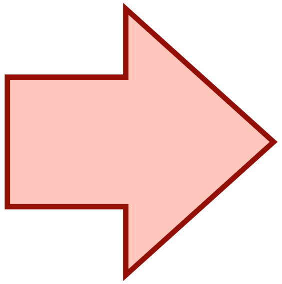


- Setups for SM model building

  - D-branes at singularities

  - Intersecting D-branes

  - Magnetised D-branes



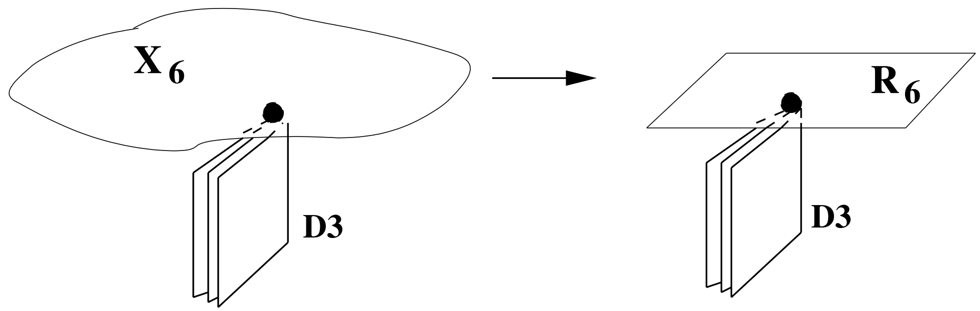
F-theory

Related to others by string dualities

D-branes

Flash back

- Isolated D-branes in smooth geometries cannot lead to chiral gauge theories



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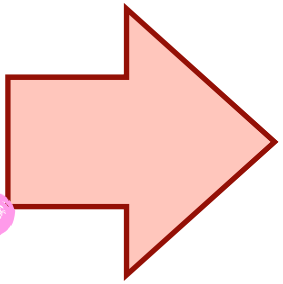

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Magnetized D-branes

- Mirror symmetry is T-duality
  (in large volume / large complex structure limit)

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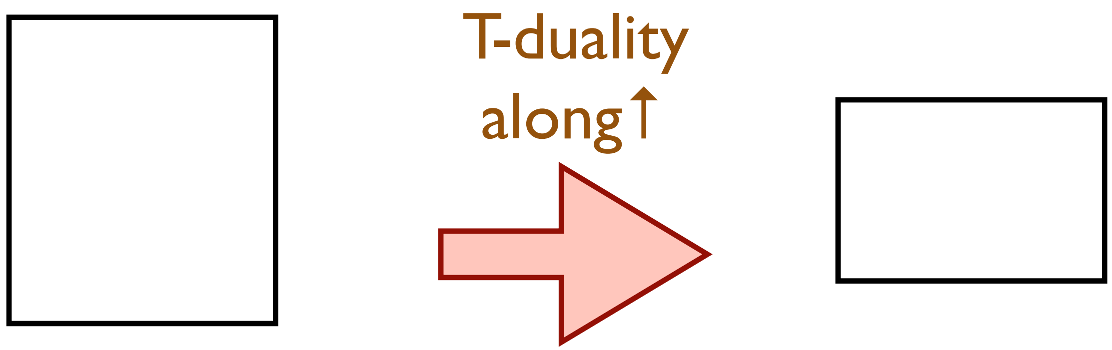

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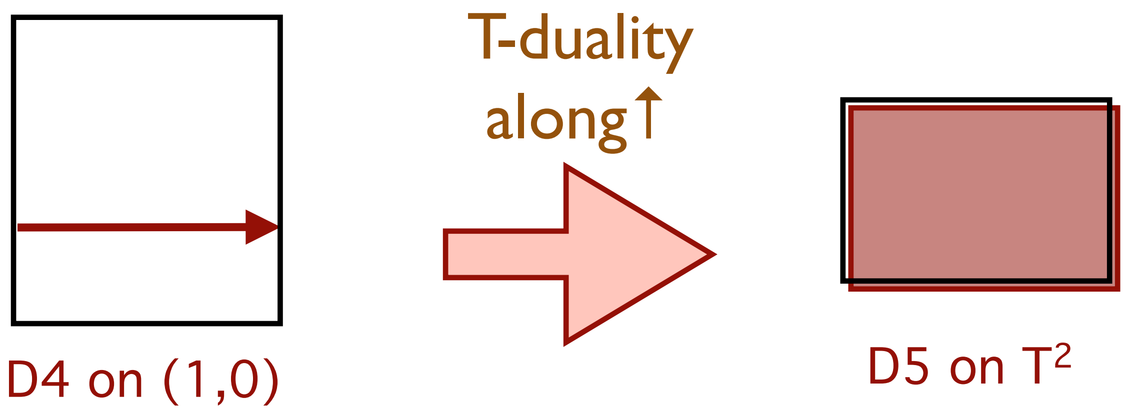

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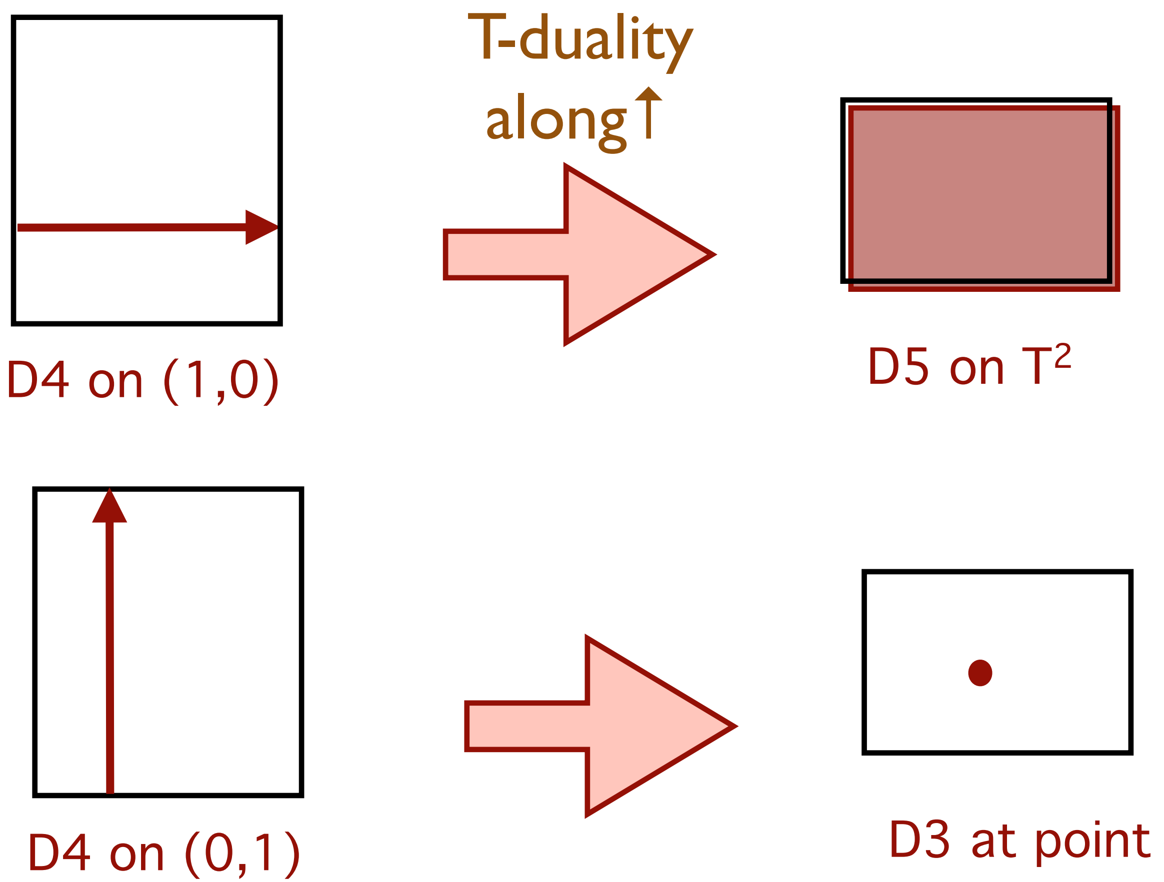

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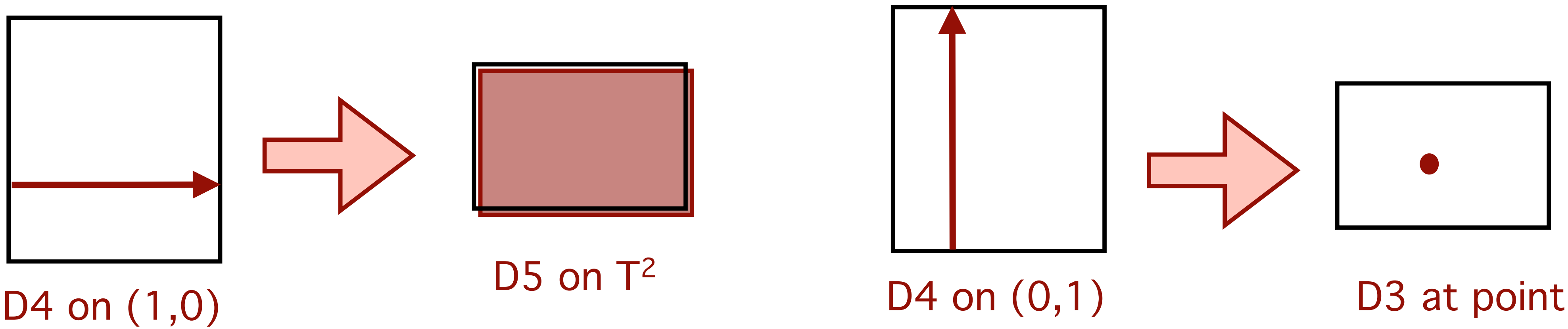

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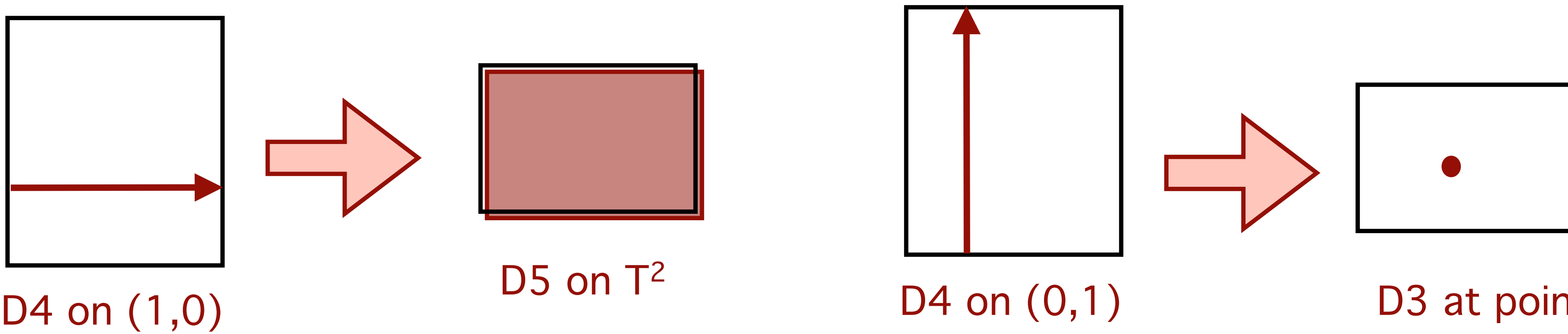

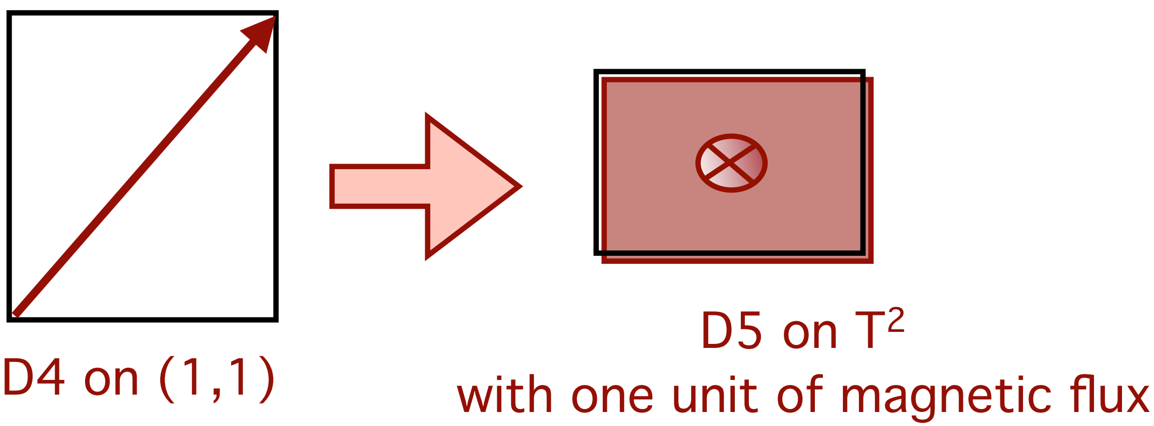

$$\int_{\mathrm{T}^2} F_2 = 1$$

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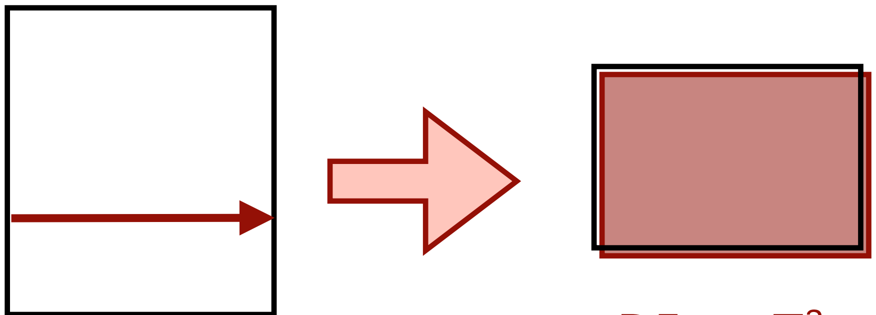
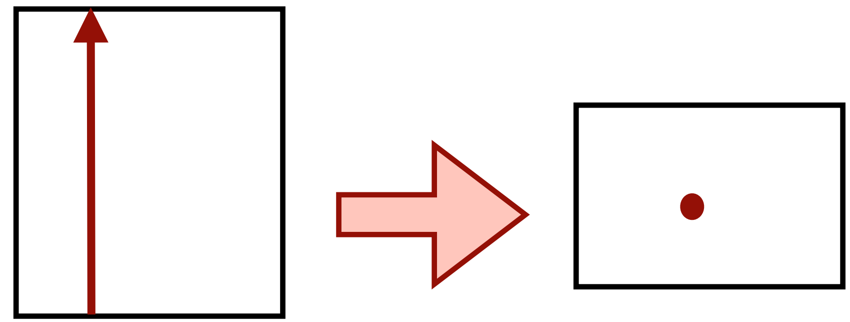
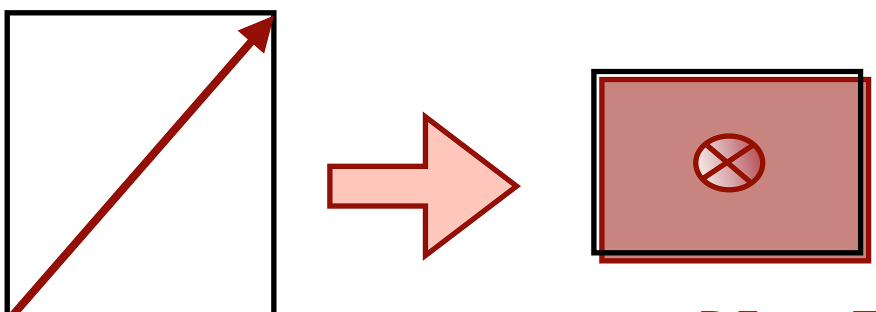


D4 on (1,0) D5 on T^2



D4 on (0,1) D3 at point



D4 on (1,1)

D5 on T^2
with one unit of magnetic flux

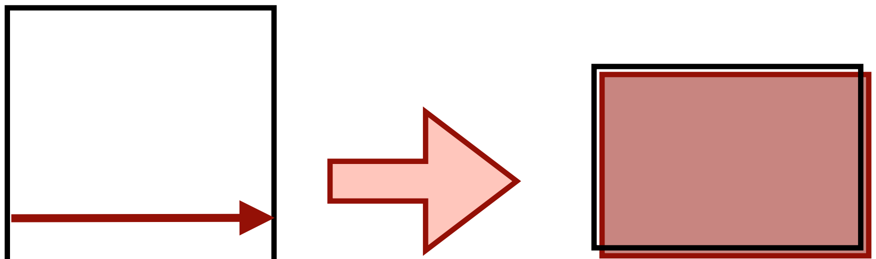
$$\int_{T^2} F_2 = 1$$

Bound state of one D5 on T2 and one D3 at point

$$\int_{D5} C_6 + \int_{D5} F_2 \wedge C_4$$

Magnetized D-branes

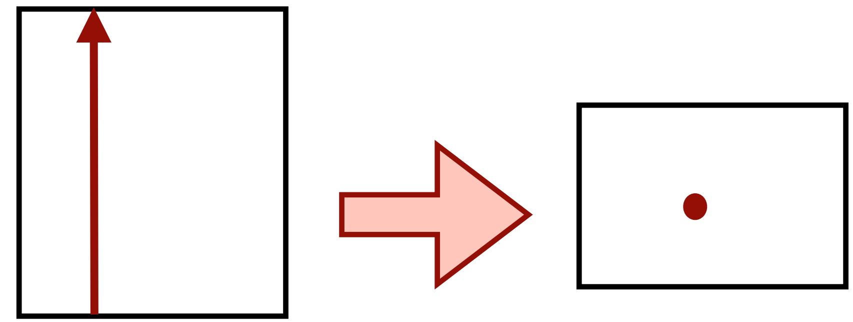
- Apply to toroidal setup, and start one-dimensional



D4 on (1,0)

D5 on T^2

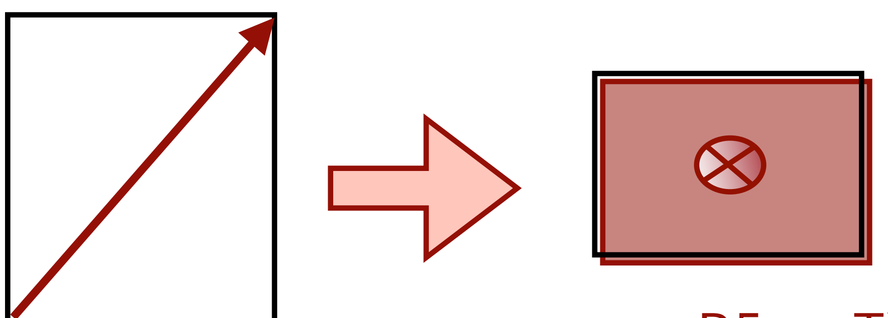
F=0



D4 on (0,1)

D3 at point

F=δ



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$$\tan\theta = F$$

Magnetized D-branes

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Generalize

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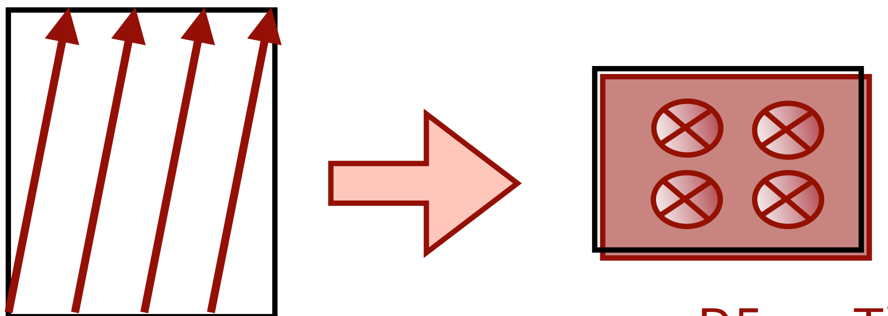
Generalize



D4 on (1,m)

D5 on T^2
with m units of magnetic flux

$$\int_{T^2} F_2 = m$$

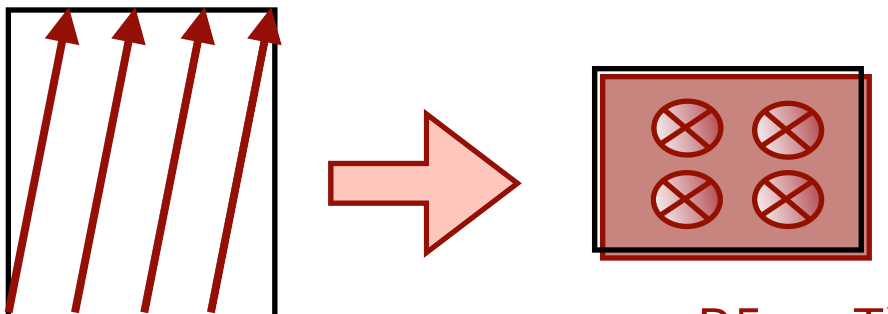
Bound state of one D5 on T^2 and m D3s at point

$$\int_{D5} C_6 + \int_{D5} F_2 \wedge C_4$$

Magnetized D-branes

- Apply to toroidal setup, and start one-dimensional

Generalize



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D5 on T^2
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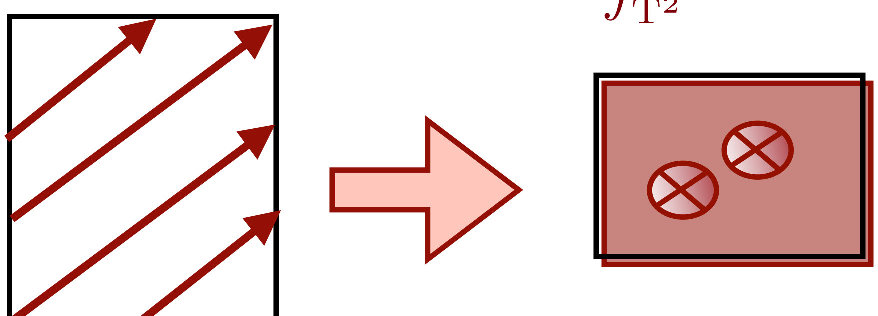


D4 on (n,m)

n D5 on T^2
with m unit of magnetic flux

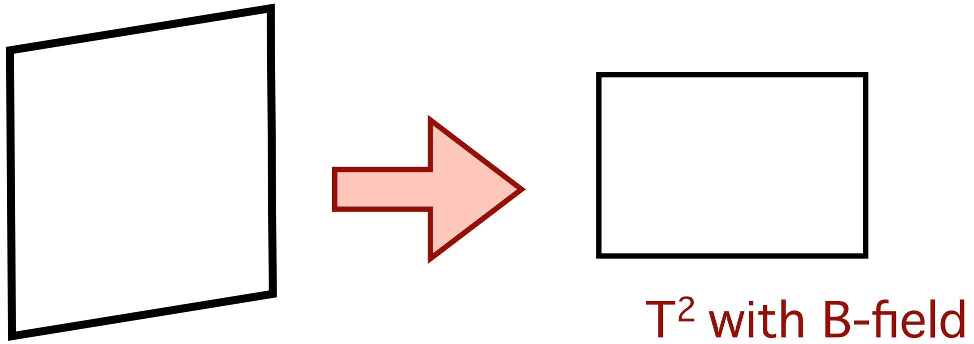
$$n \int_{T^2} F_2 = m$$

Bound state of n D5s on T^2 and m D3s at point

$$n \int_{D5} C_6 + n \int_{D5} F_2 \wedge C_4$$

Magnetized D-branes

- Can tilt the tori



Magnetized D-branes

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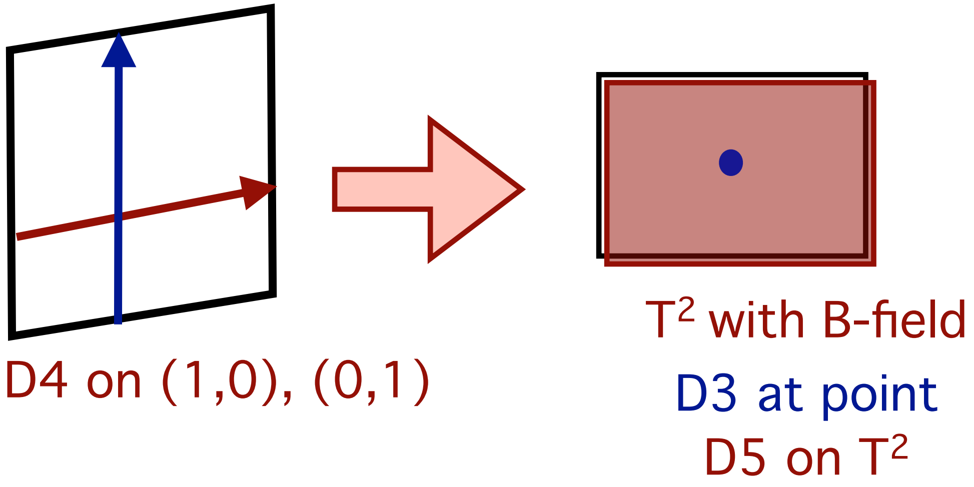

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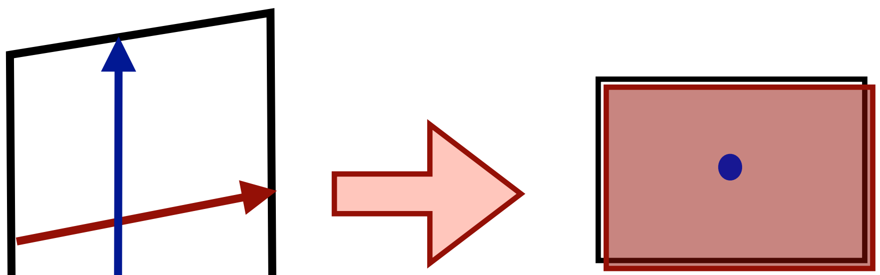

D4 on (1,0), (0,1)

T^2 with B-field

D3 at point

D5 on T^2

Due to B-field, D5 has some induced D3-brane charge

$$\int_{\mathrm{D5}} C_6 + \int_{D5} B_2 \wedge C_4$$

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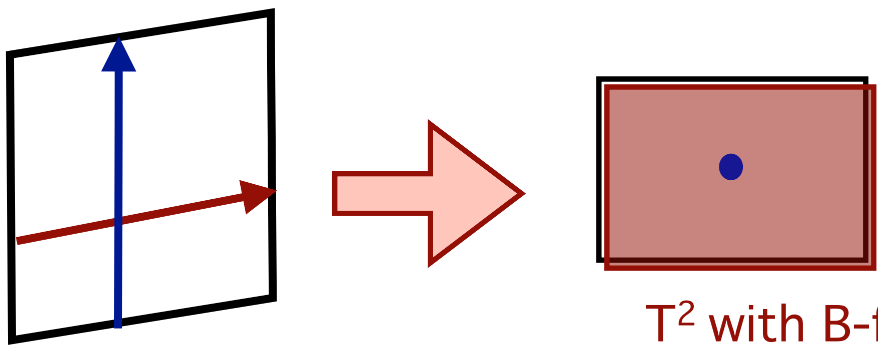

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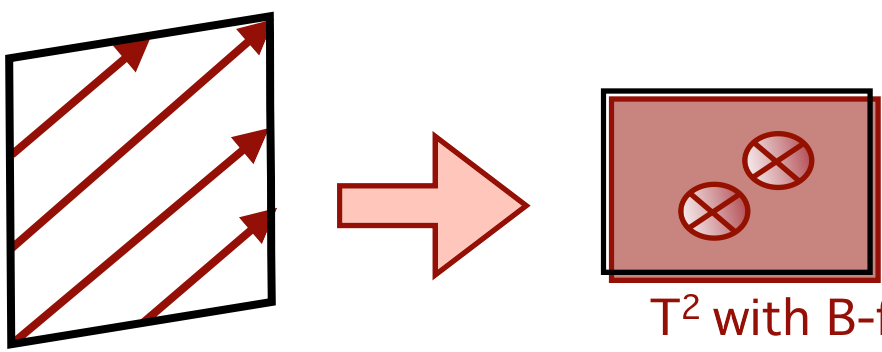


D4 on (n,m)

T^2 with B-field

n D5 on T^2

with m unit of magnetic flux

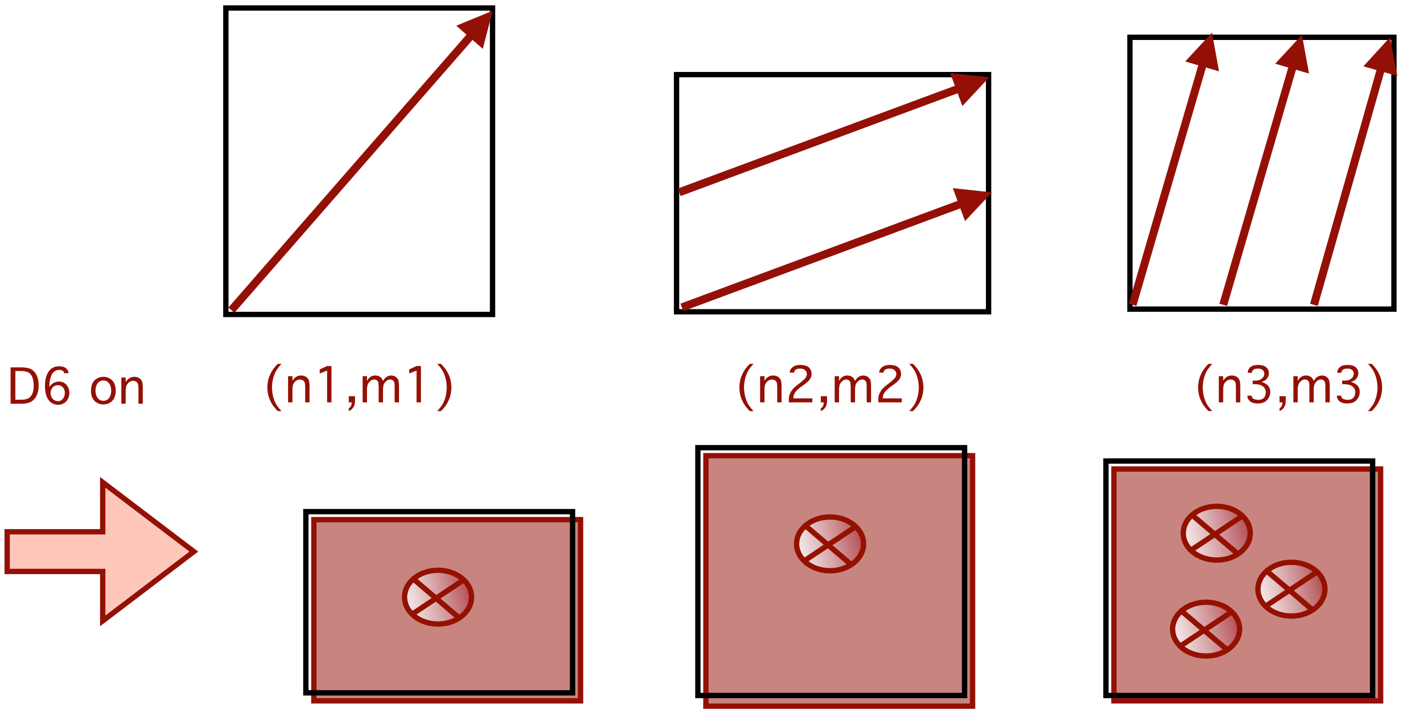
$$n \int_{\mathrm{T}^2} F_2 = m$$

Induced D3 charge from flux and B-field

$$\int_{\mathrm{D5}} C_6 + \int_{D5} (F_2 - B_2) \wedge C_4$$

Magnetized D-branes

- Extends easily to three-dimensional case



Bound state of D9s, D7s, D5s, D3s

$$n_1 n_2 n_3 \left[\int_{D9} C_{10} + \int_{D9} \mathrm{tr}\, F_2 \wedge C_8 + \int_{D9} \mathrm{tr}\, F_2^2 \wedge C_6 + \int_{D9} \mathrm{tr}\, F_2^3 \wedge C_4 \right]$$

n1n2n3 D9s on T^2 x T^2 x T^2
with m_i units of magnetic flux on i-th T^2

- So continue with one-dimensional building block

Magnetized D-branes: Gauge group

- Reproduce rules of intersecting branes in terms of magnetized

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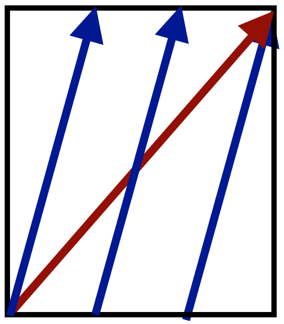
Gauge group



N_a, N_b D4s on (n_a,m_a), (n_b,m_b)

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- Reproduce rules of intersecting branes in terms of magnetized

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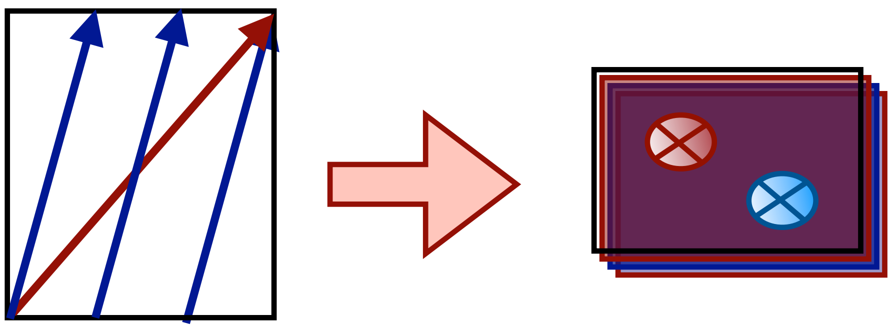

$N_a n_a$, $N_b n_b$ D5s on T^2

with m_a, m_b units of magnetic flux

N_a, N_b D4s on (n_a,m_a), (n_b,m_b)

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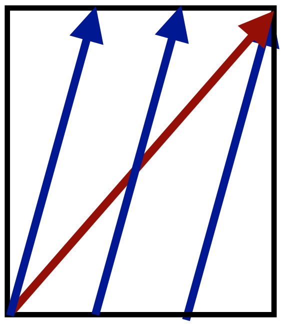

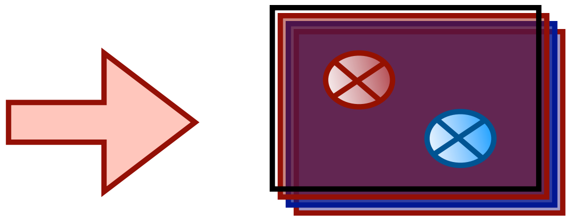

$N_a n_a$, $N_b n_b$ D5s on T^2

with m_a, m_b units of magnetic flux

N_a, N_b D4s on (n_a,m_a), (n_b,m_b)

$$F = \begin{pmatrix} \frac{m_a}{n_a}\mathbf{1}_{n_a N_a} & \\ & \frac{m_b}{n_b}\mathbf{1}_{n_b N_b} \end{pmatrix}$$

$$U(N_a n_a) \times U(N_b n_b) \;\to\; U(N_a)^{n_a} \times U(N_b)^{n_b} \;\to\; U(N_a) \times U(N_b)$$

Magnetized D-branes: Matter

- Reproduce rules of intersecting branes in terms of magnetized

Matter multiplicity. Start with n_a=n_b=1

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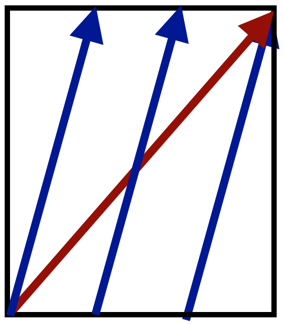
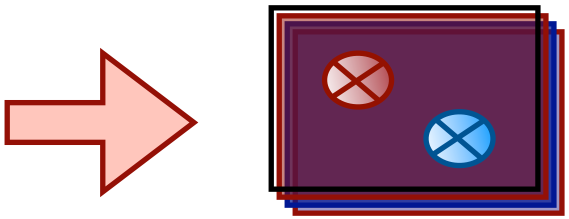


N_a, N_b D4s on $(1,m_a)$, $(1,m_b)$



N_a, N_b D5s on T^2

with m_a, m_b units of magnetic flux

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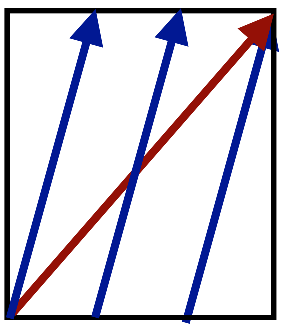

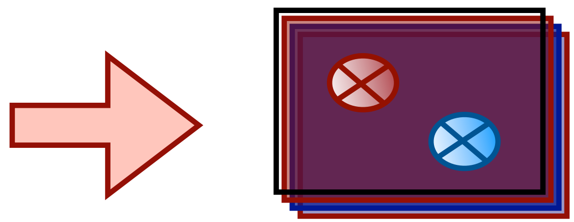

N_a, N_b D4s on $(1, m_a)$, $(1, m_b)$

N_a, N_b D5s on T^2

with m_a, m_b units of magnetic flux

$$F = \begin{pmatrix} m_a \mathbf{1}_{N_a} & \psi_{ab} \\ \psi_{ab}^\dagger & m_b \mathbf{1}_{N_b} \end{pmatrix}$$

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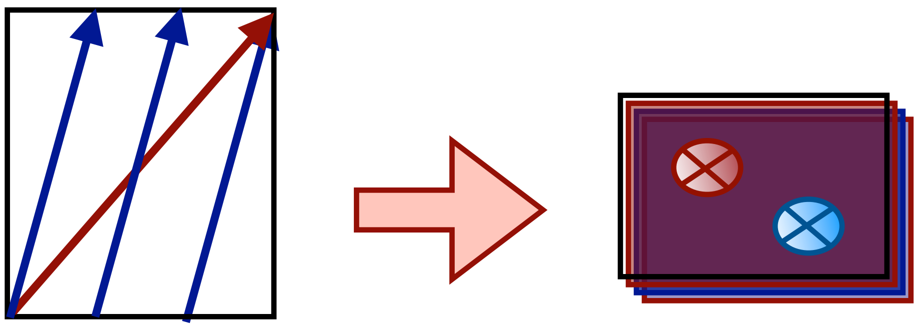

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N_a, N_b D4s on $(1, m_a)$, $(1, m_b)$

$$F = \begin{pmatrix} m_a \mathbf{1}_{N_a} & \psi_{ab} \\ \psi^\dagger_{ab} & m_b \mathbf{1}_{N_b} \end{pmatrix}$$

\# chiral fermions in (N_a, N_b)

$$\mathrm{ind} \not{D} = \int_{T^2} F_a - F_b = m_a - m_b \equiv I_{ab}$$

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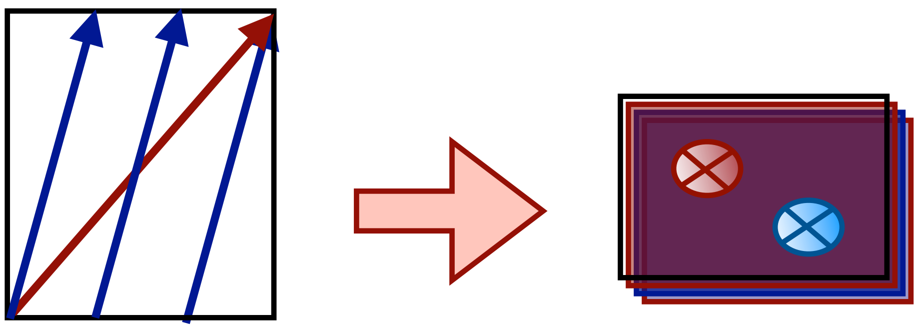

$N_a n_a$, $N_b n_b$ D5s on T^2

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N_a, N_b D4s on (n_a,m_a), (n_b,m_b)

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$$U(N_a n_a) \times U(N_b n_b) \;\rightarrow\; U(N_a)^{n_a} \times U(N_b)^{n_b} \;\rightarrow\; U(N_a) \times U(N_b)$$

$$(\Box_a, \overline{\Box}_b) \quad \rightarrow \quad (\underline{\Box_a, \ldots, 1}, \underline{\Box_a, \ldots, 1}) \quad \rightarrow n_a n_b (\Box_a, \overline{\Box}_b)$$

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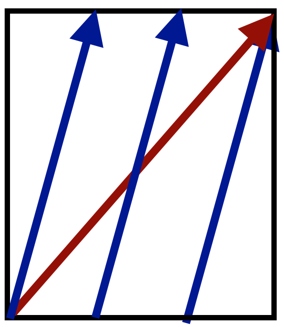

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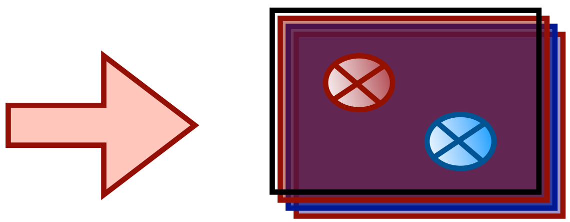

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$$(\square_a, \overline{\square}_b) \quad \rightarrow \quad (\underline{\square_a, \ldots, 1}, \underline{\square_a, \ldots, 1}) \quad \rightarrow n_a n_b (\square_a, \overline{\square}_b)$$

\# chiral fermions in (N_a, N_b)

$$n_a n_b \, \mathrm{ind} \not{D} \int_{T^2} (F_a - F_b) = m_a n_b - n_a m_b \equiv I_{ab}$$

Magnetized D-branes: Susy

- Reproduce rules of intersecting branes in terms of magnetized

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Actually "Holomorphic and stable sheaves"
(to allow for lower dimensional branes: skyscraper sheaf)

Away from large volume limit, alpha' corrections: "Pi-stability"

Towards the SM

Flash back

- Rephrase models of intersecting branes in terms of magnetized ones

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)
$N_c = 1$	(0,1)	(0,-1)	(1,0)
$N_d = 1$	(1,0)	(1,3)	(1,-3)

(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

Towards the SM

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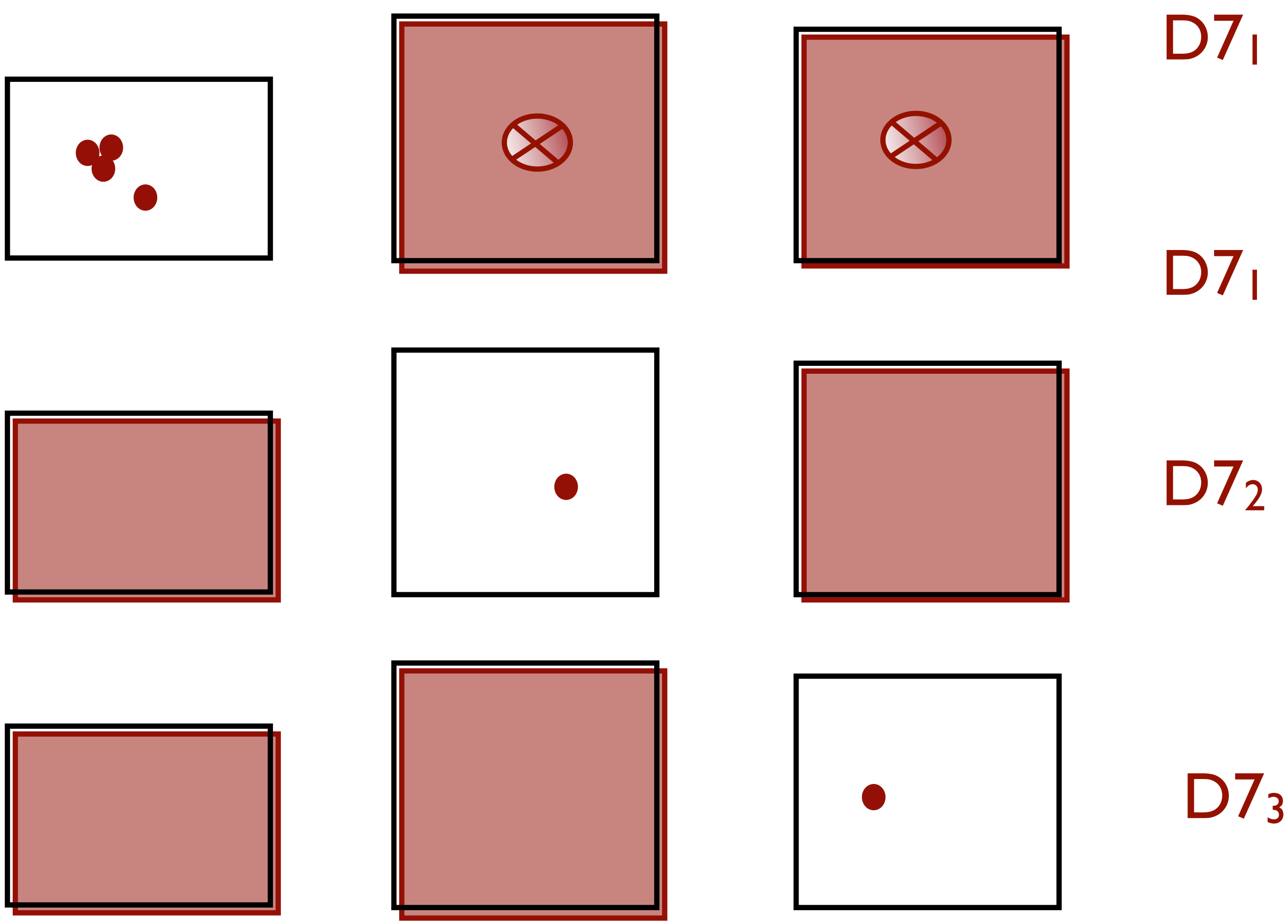
- Similar analysis of properties

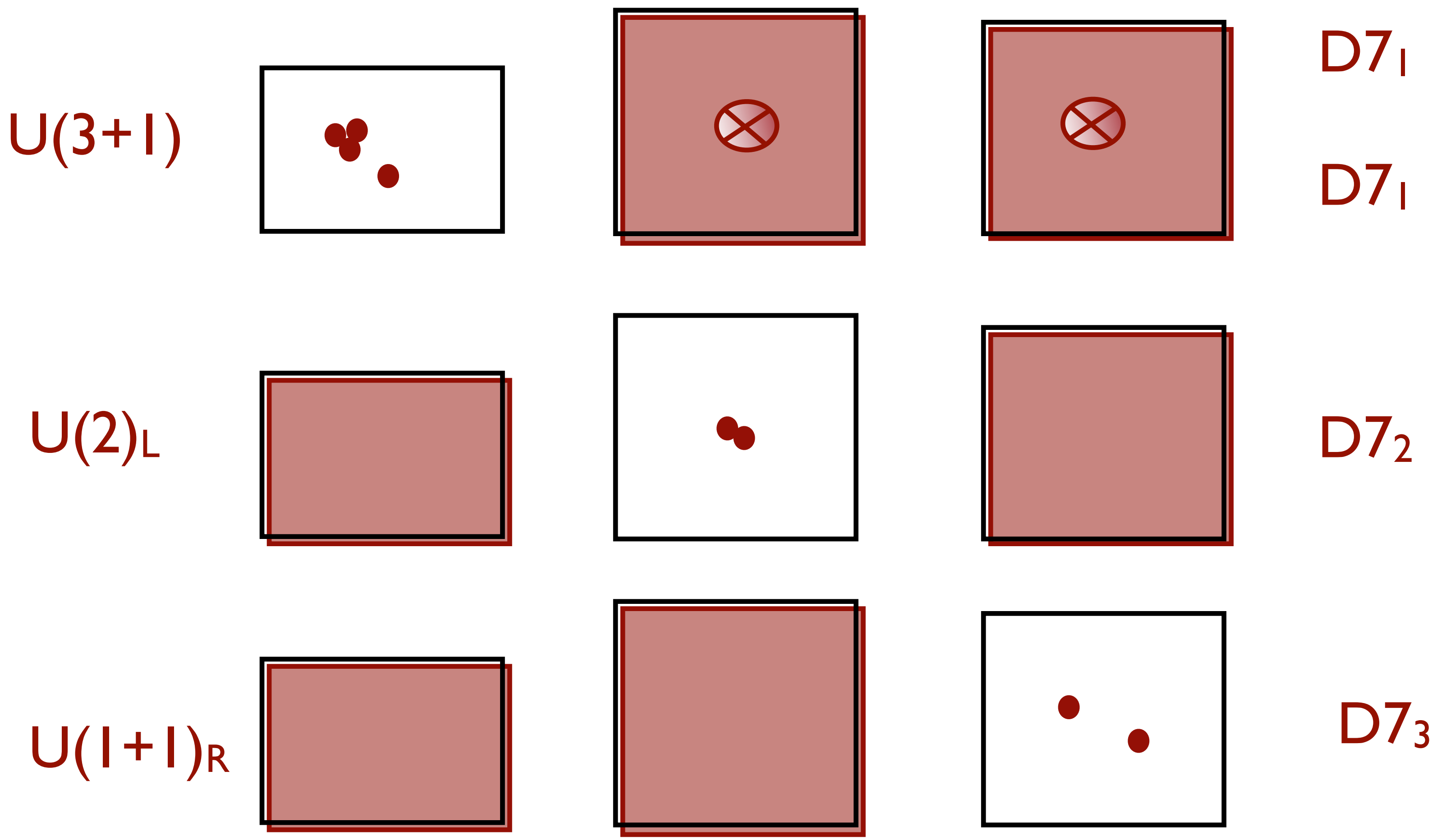
Towards the SM

- Rephrase models of intersecting branes in terms of magnetized ones



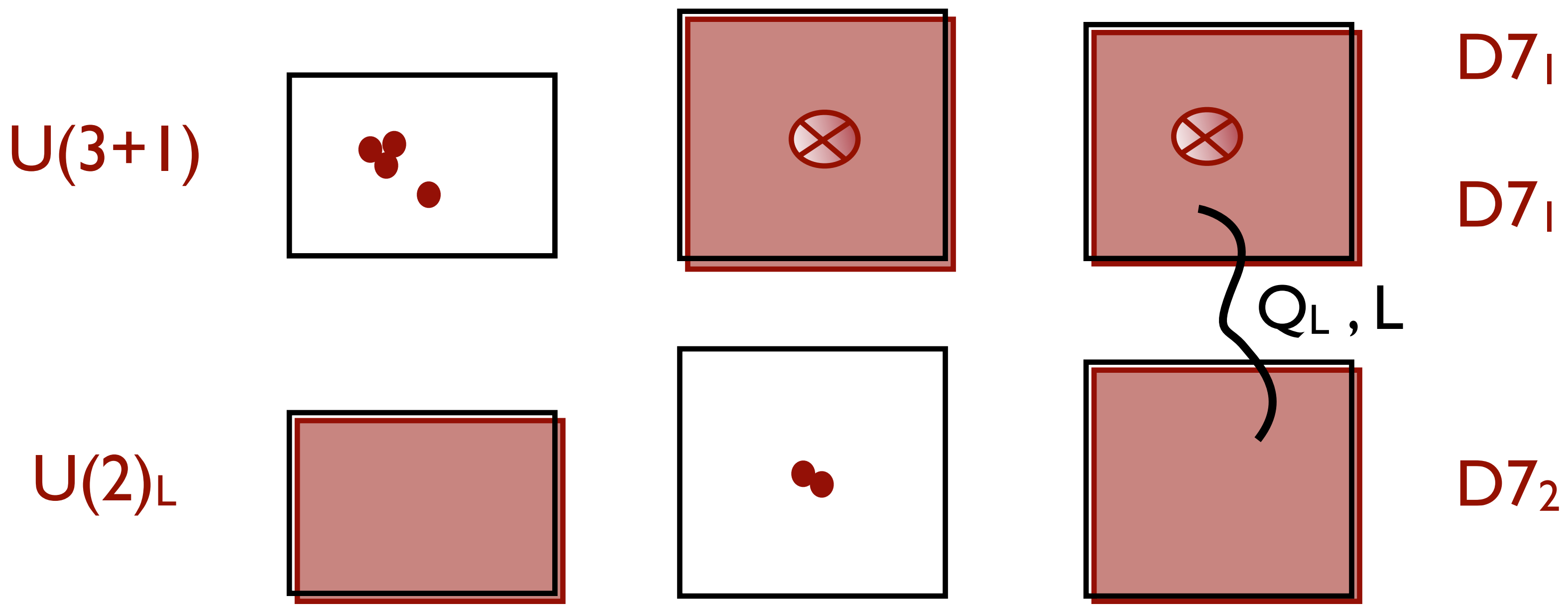
Towards the SM

- Gauge group on 4-cycles



Towards the SM

- Matter on 2-cycles, chiral due to magnetization



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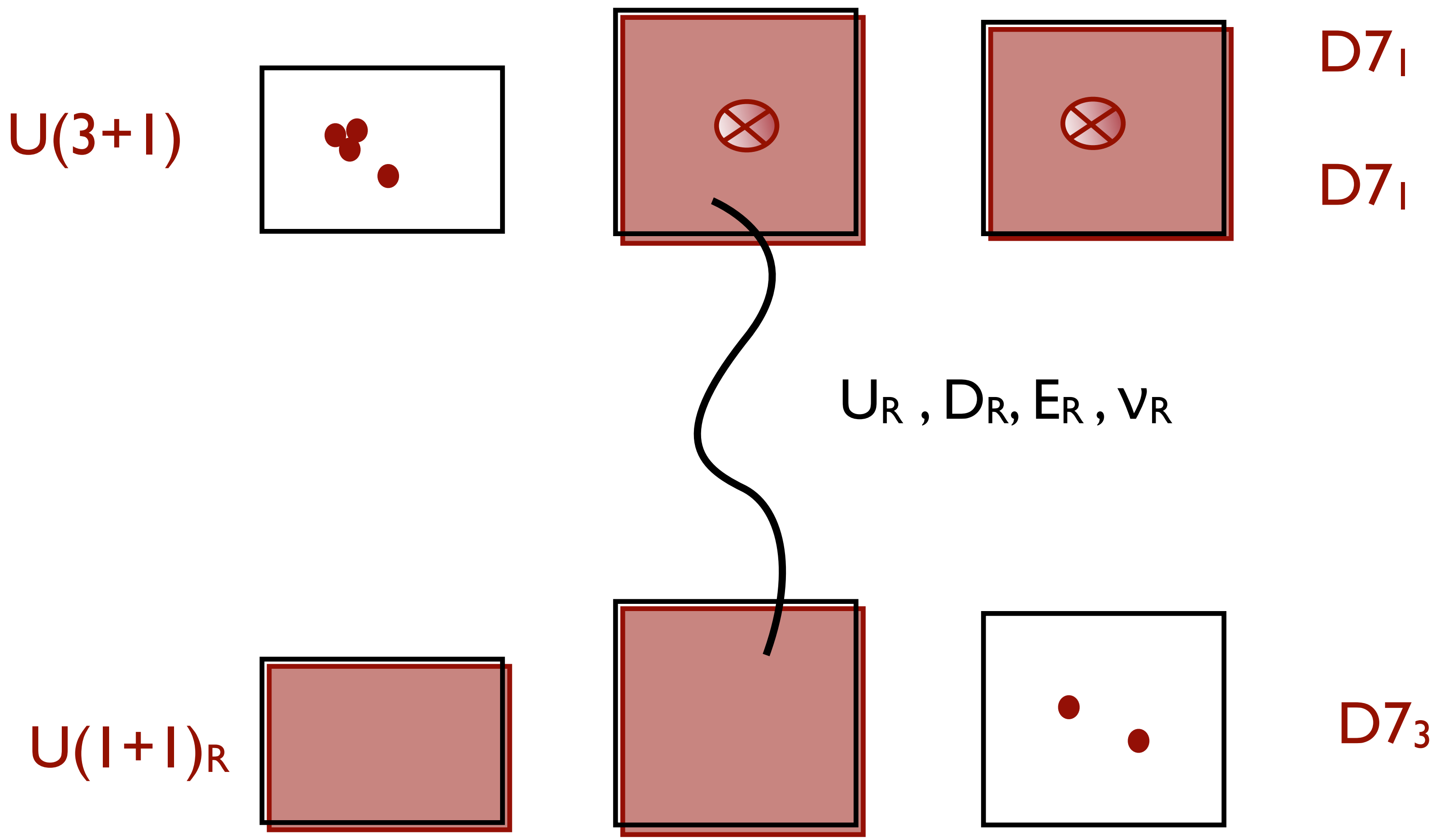

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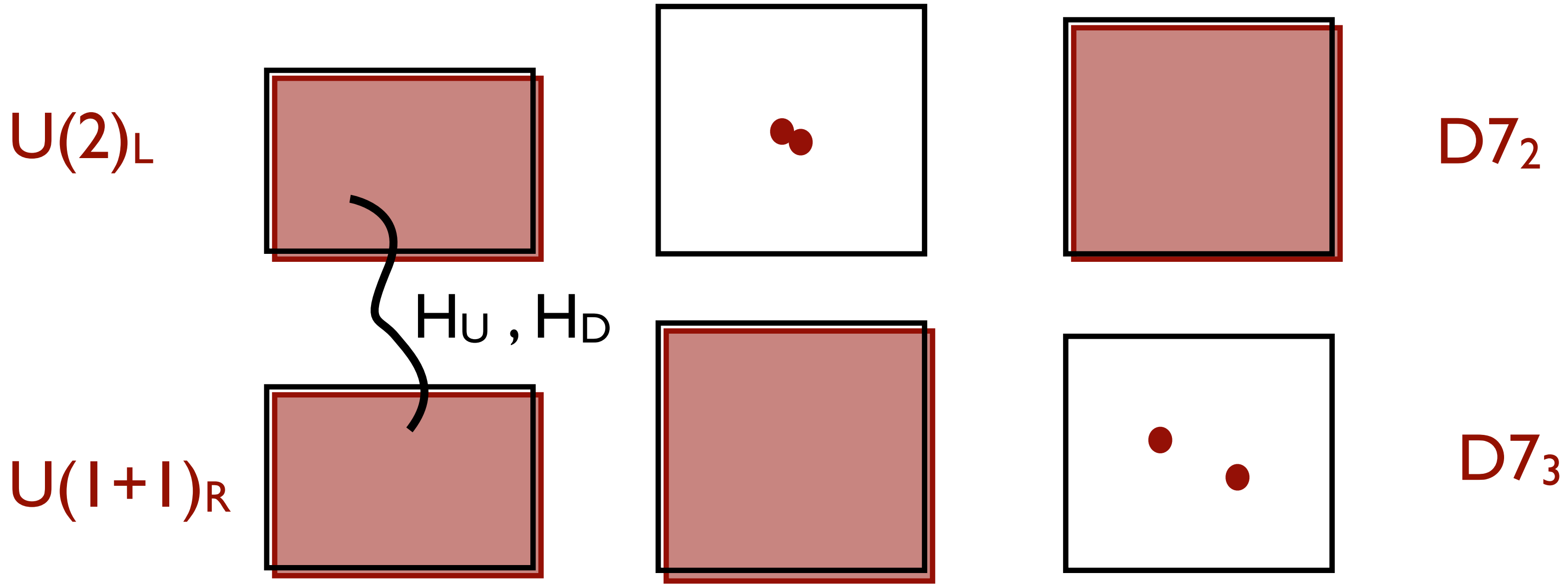
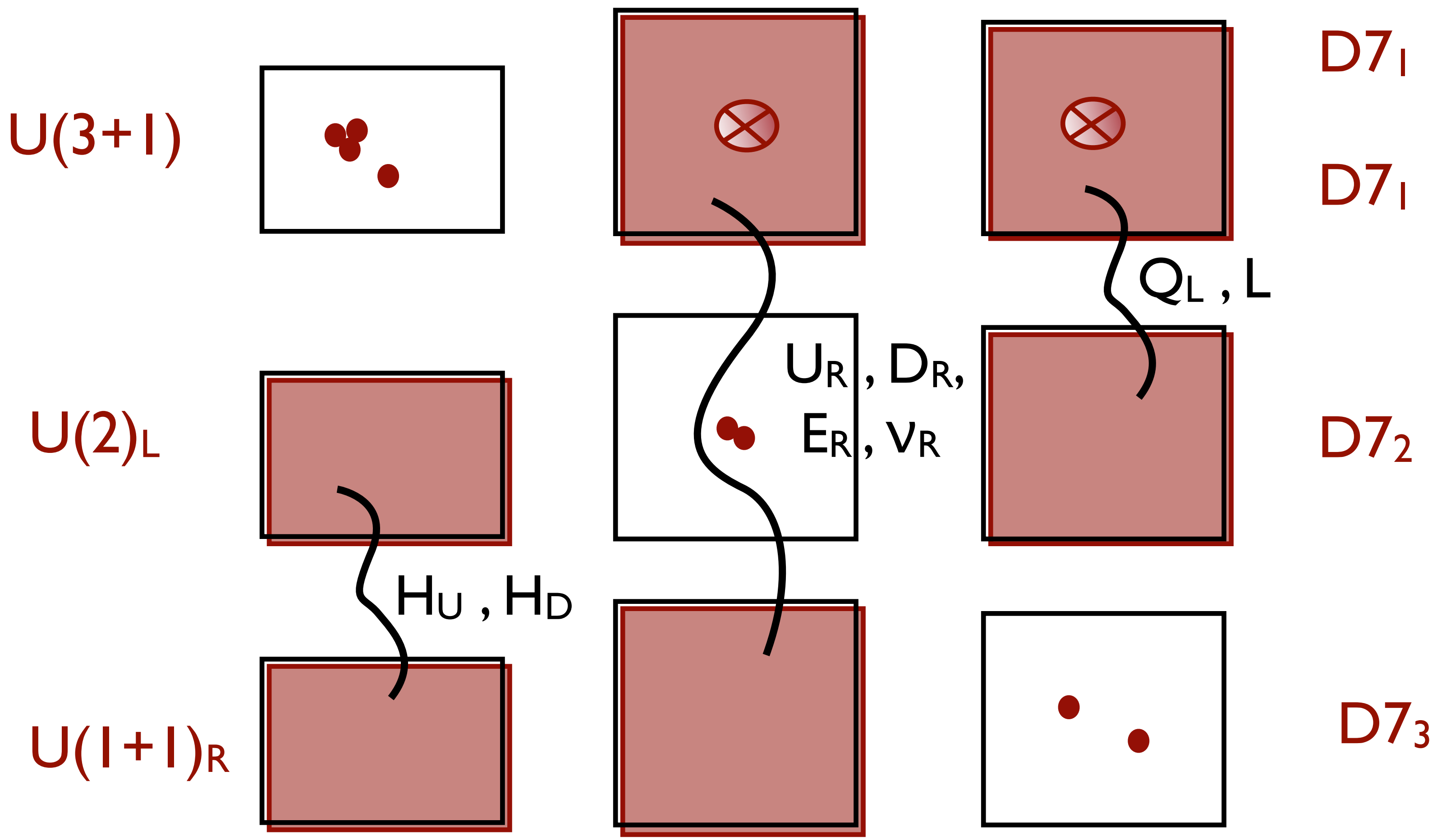


Towards the SM

- Yukawa couplings at points



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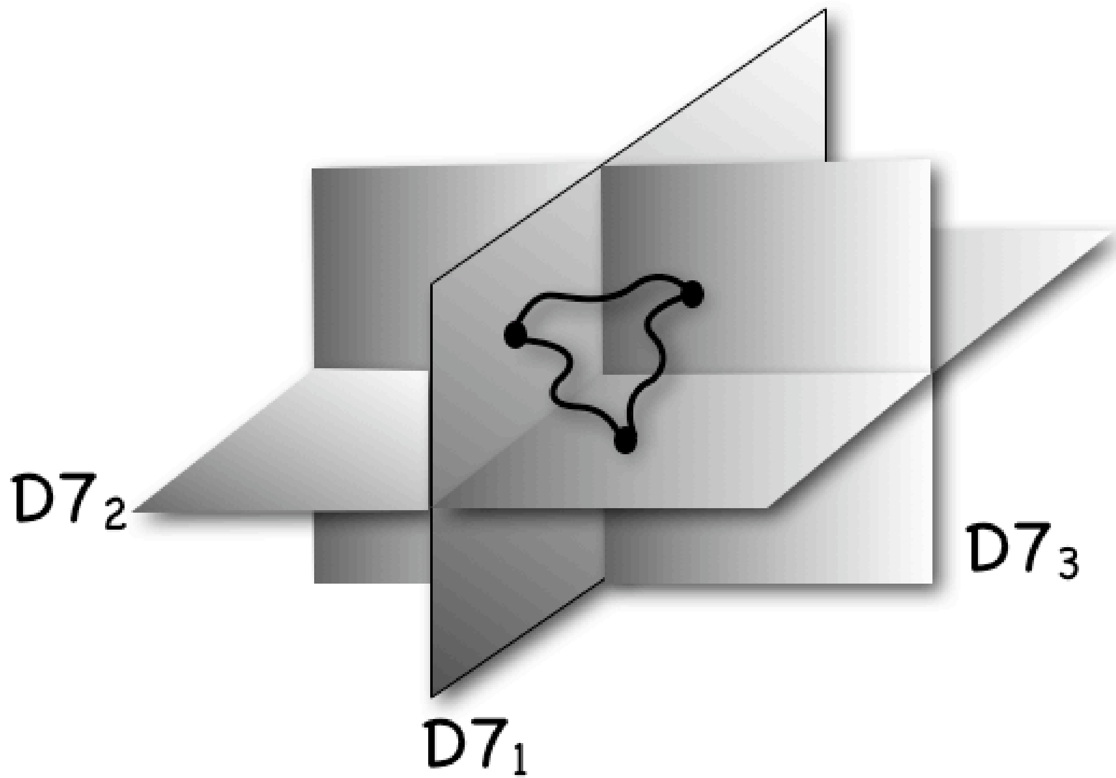

Generalization

Type IIB on CY orientifold with “B-branes”

- Orbifolds etc: D-branes at singularities

- Large volume: wrapped branes

  Susy conditions: Holomorphic cycles with holomorphic & stable bundles

$$F_{(2,0)} = 0 \quad , \quad \mathrm{Im}(e^{J+i(B+F)})|_{\Pi} = 0$$

F-term D-term

At large volume, reproduces Donaldson, Uhlenbeck, Yau, slope stability, etc

[cf. heterotic on CY]

Non-perturbative version: F-theory

Perturbative U(1)s prevent some phenomenologically interesting couplings

- Right-handed neutrino masses

- top quark Yukawa in SU(5) GUTs

- ...

Flash back

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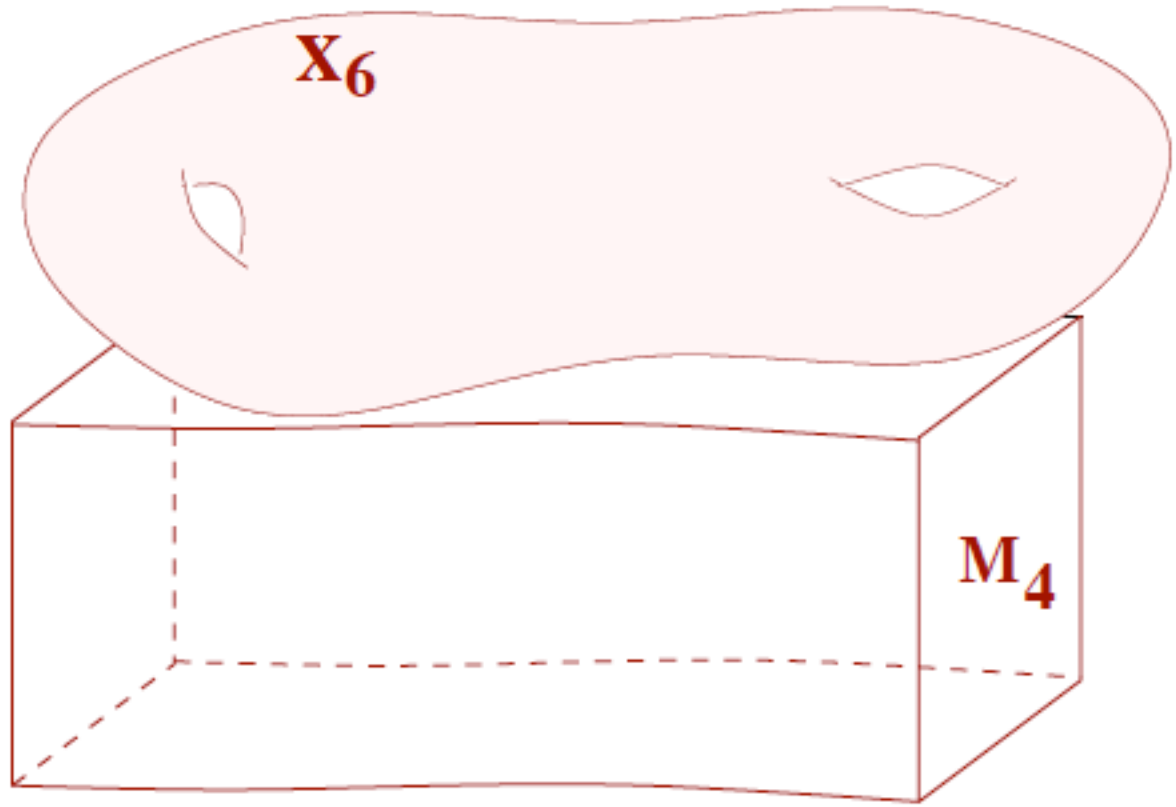
- F-theory: type IIB sugra



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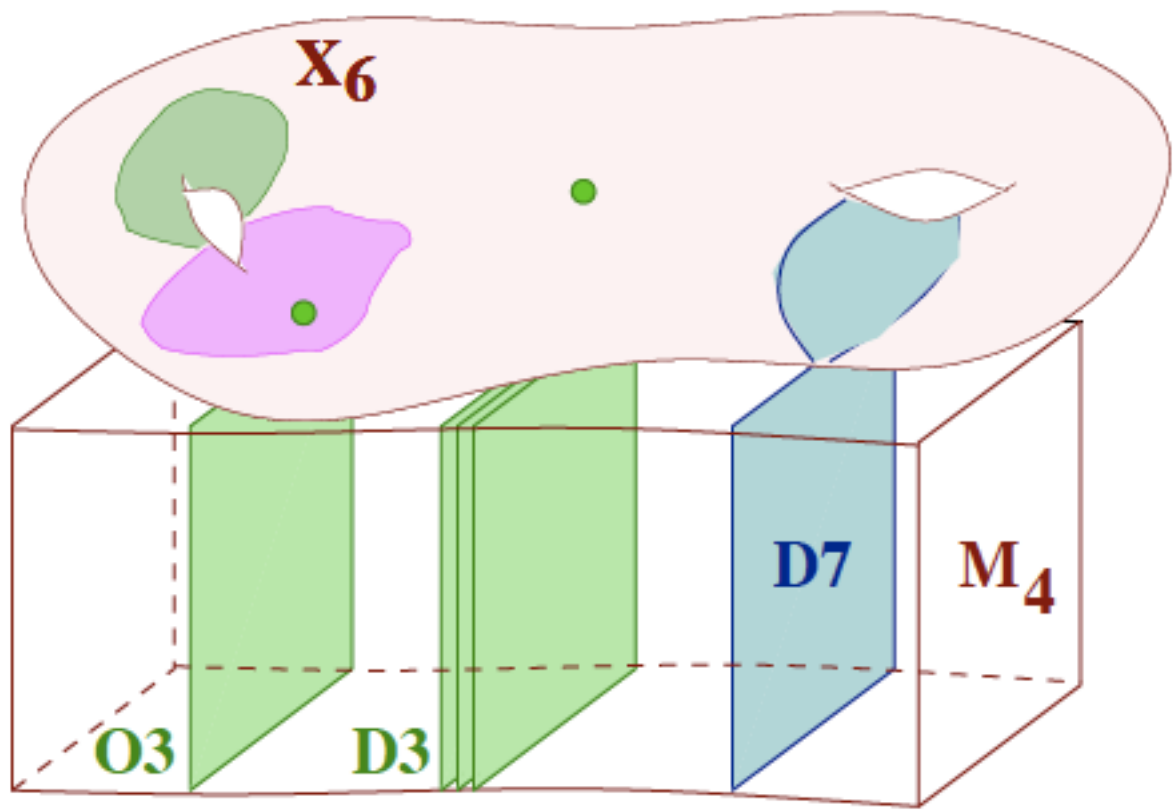

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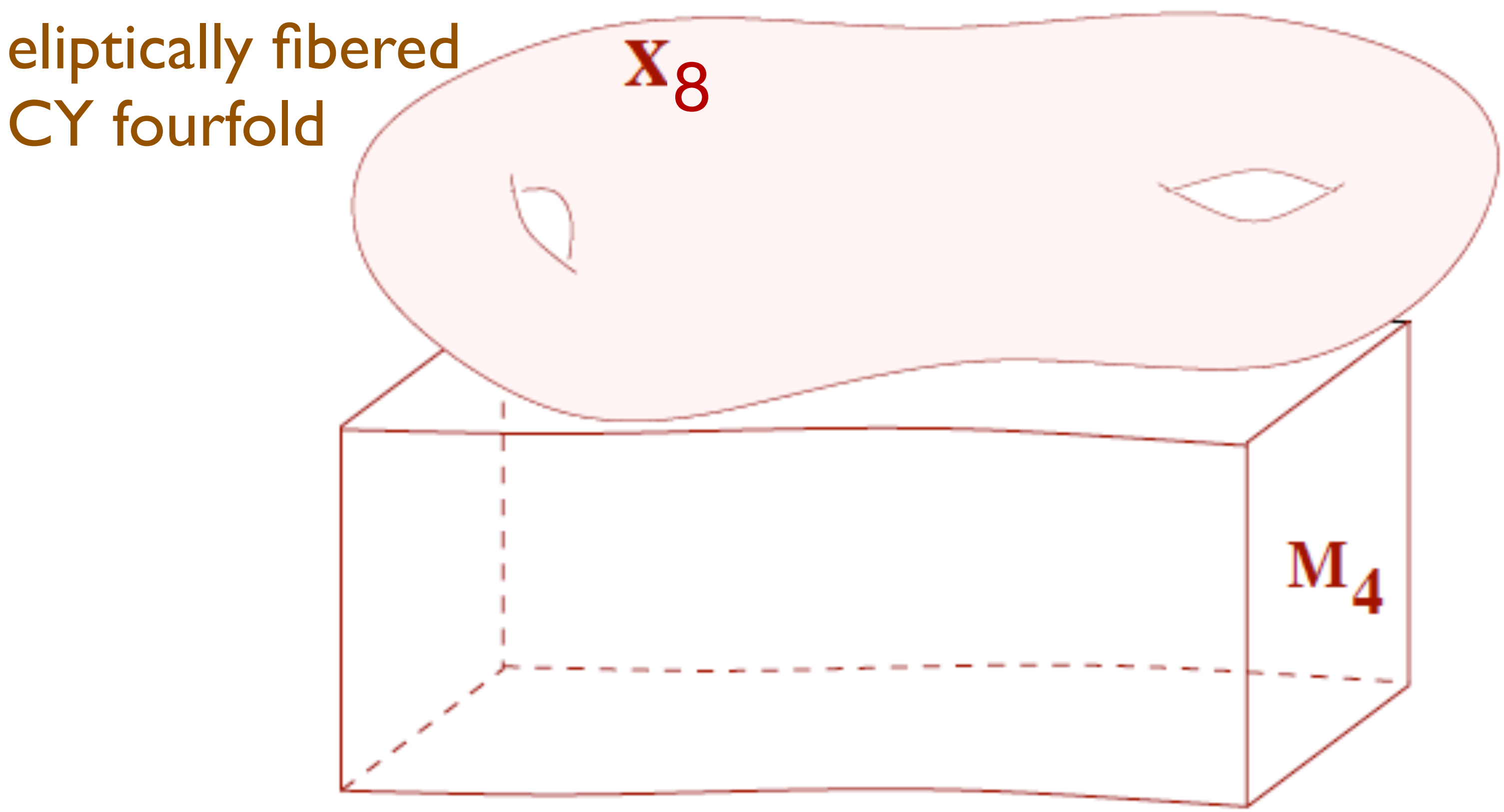

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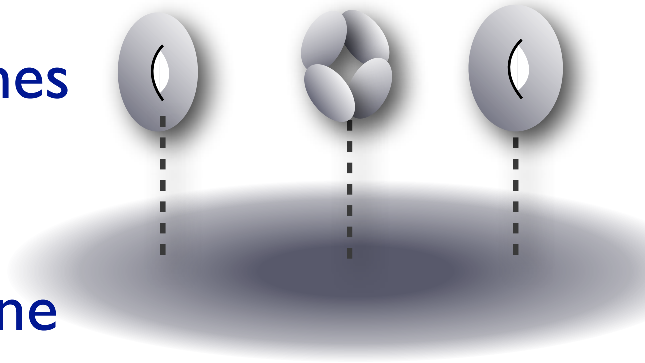
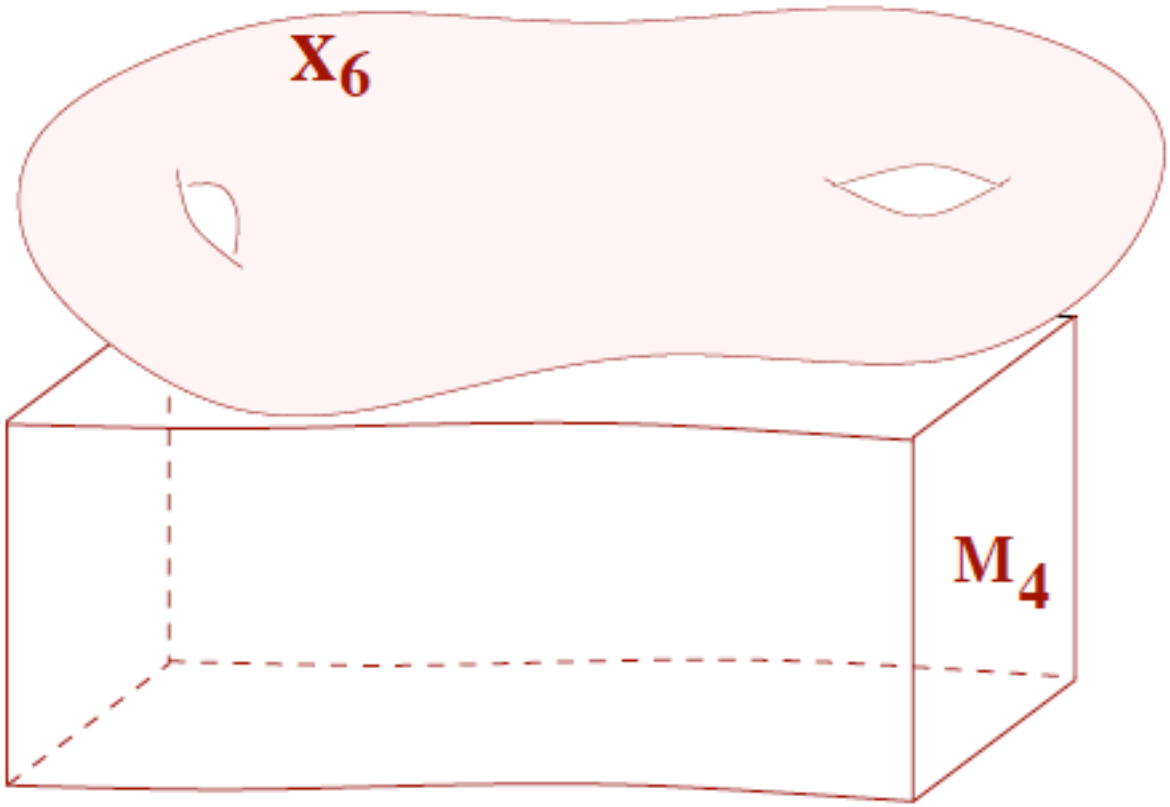
- F-theory: Geometrization of IIB with (p,q) 7-branes in terms of a T^2 fibered CY_4 with degenerate fibers



- Singular locus is 4-cycle on base, describing 7-brane geometry

F-theory GUTs

- Local models as first step previous to global embedding



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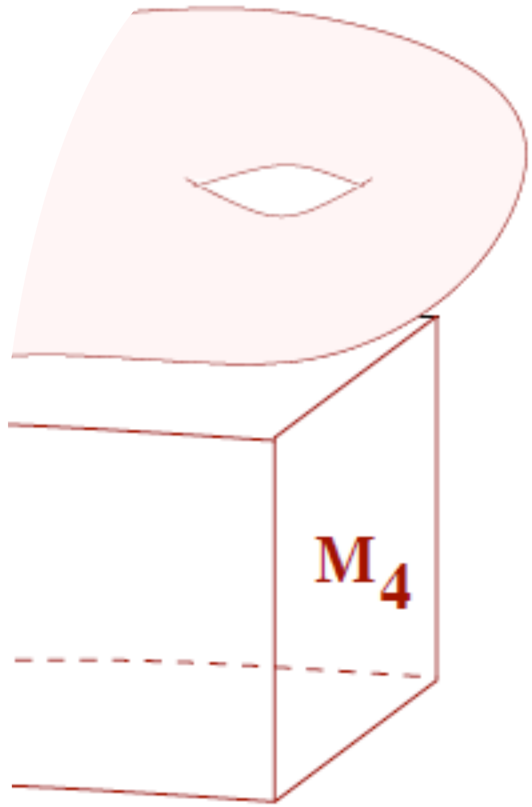

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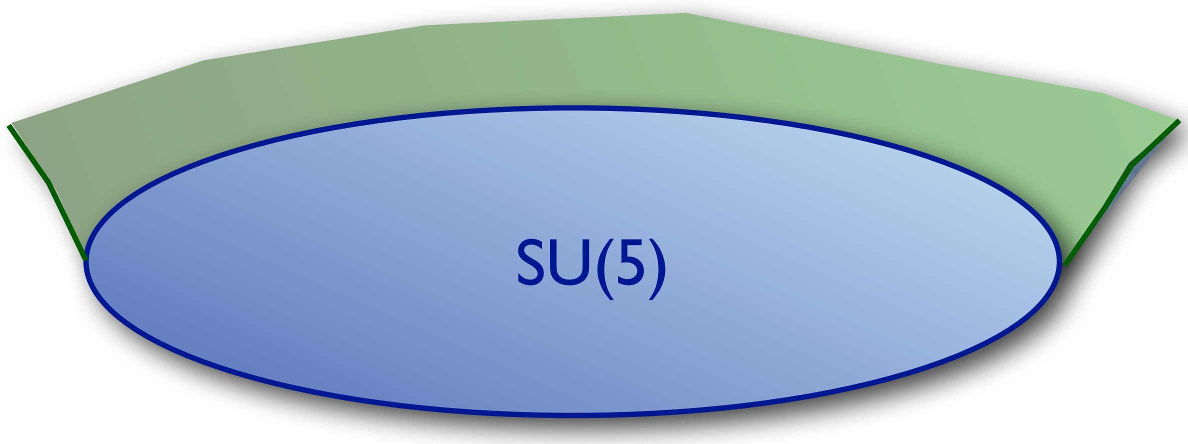

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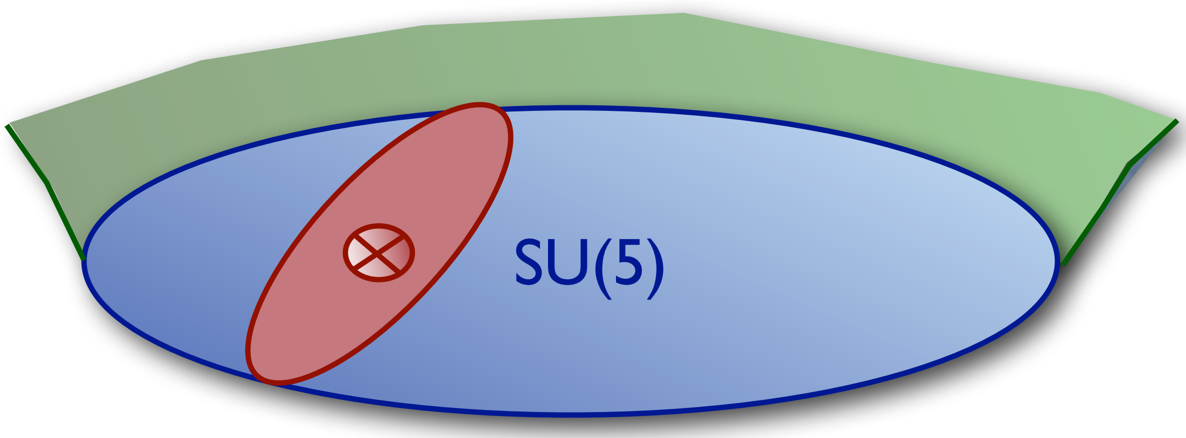
SU(5) → SU(3) x SU(2) x $U(1)_Y$



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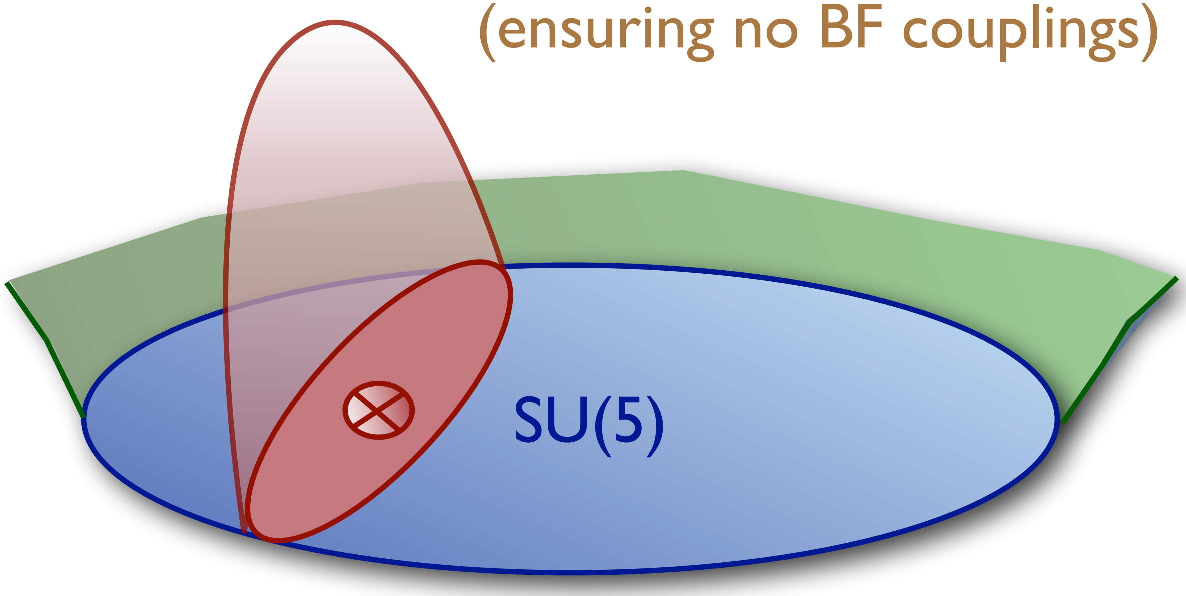
(ensuring no BF couplings)



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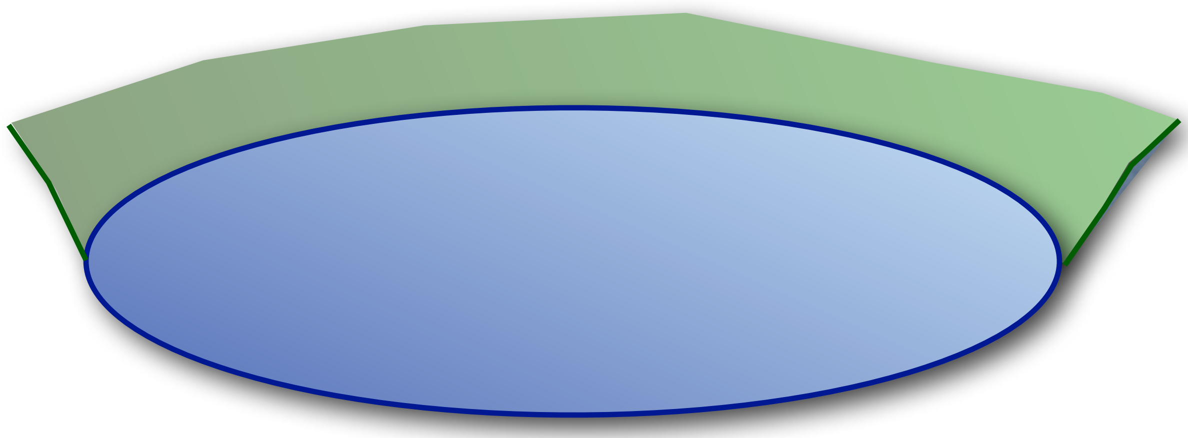

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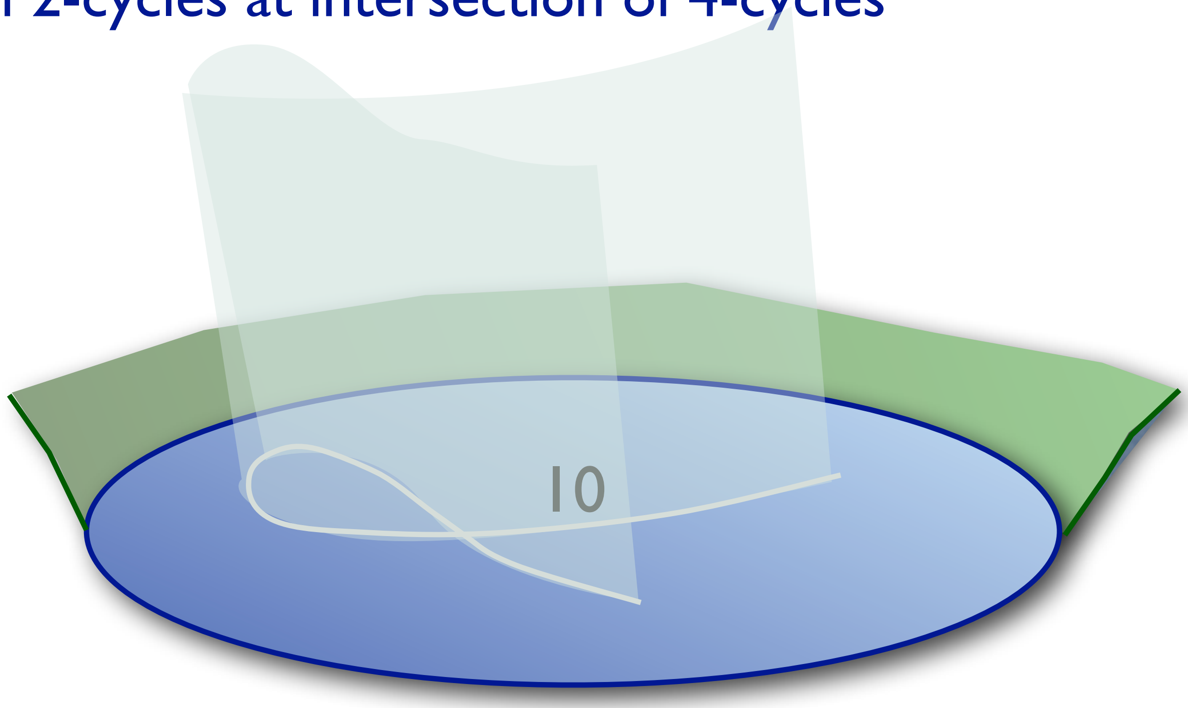

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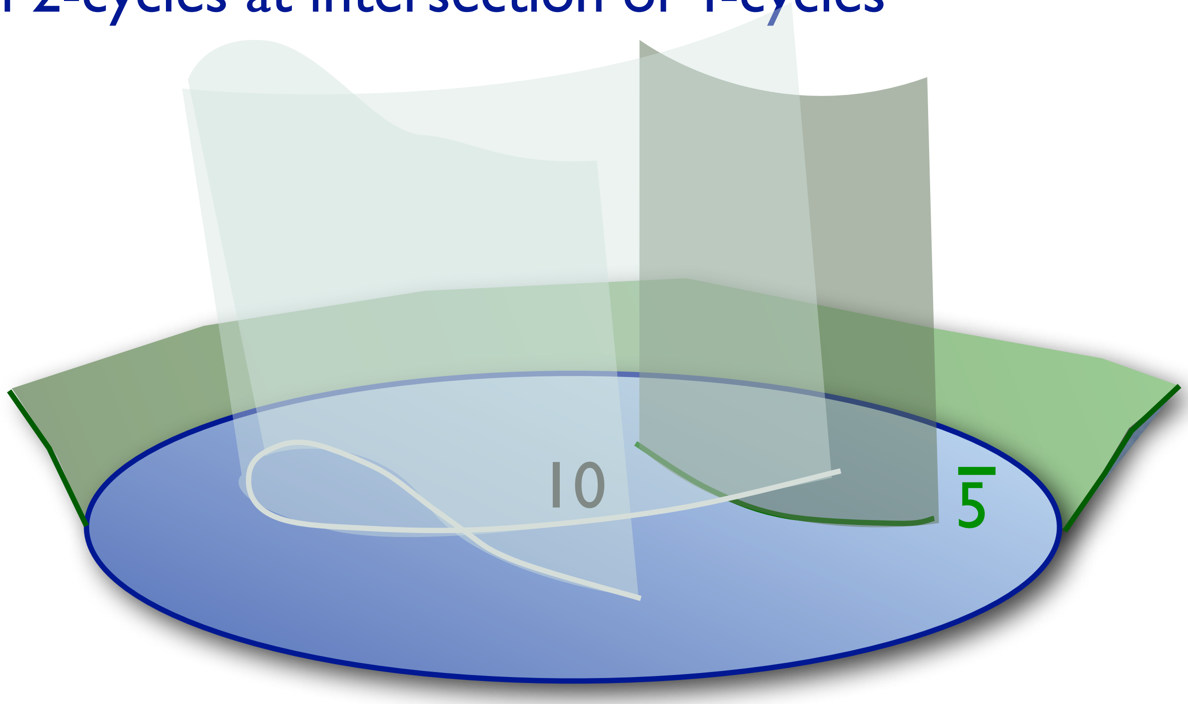

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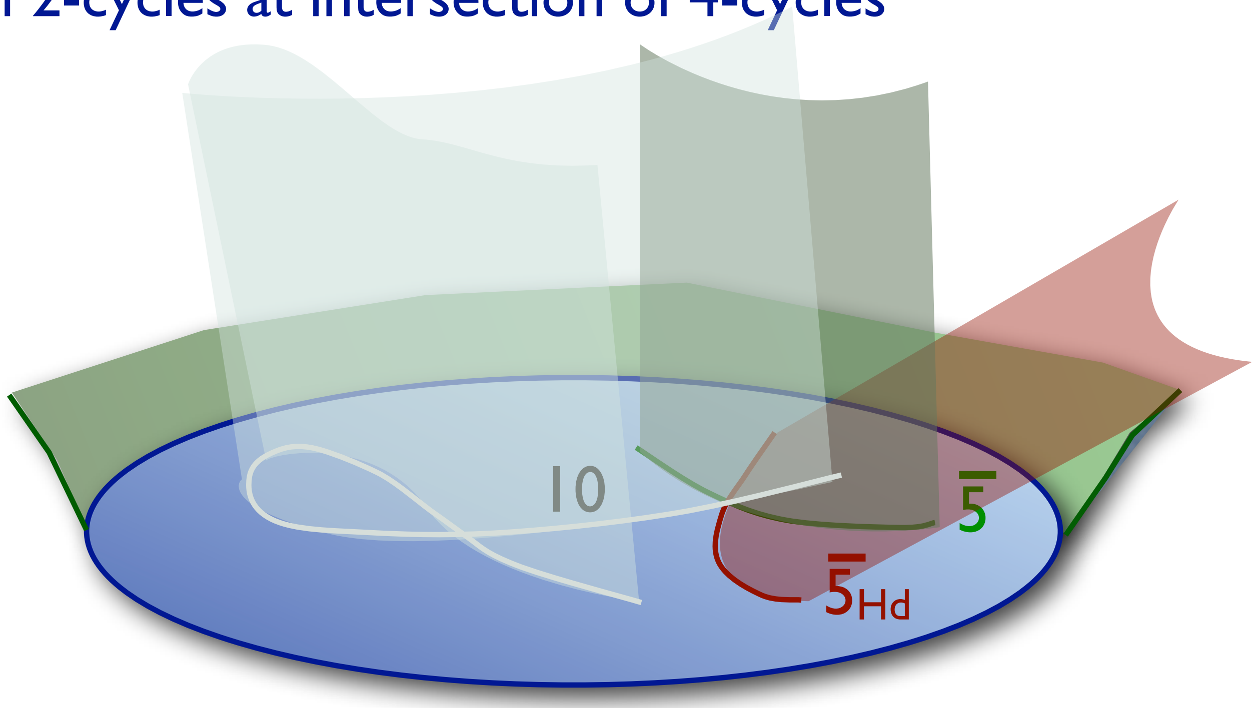

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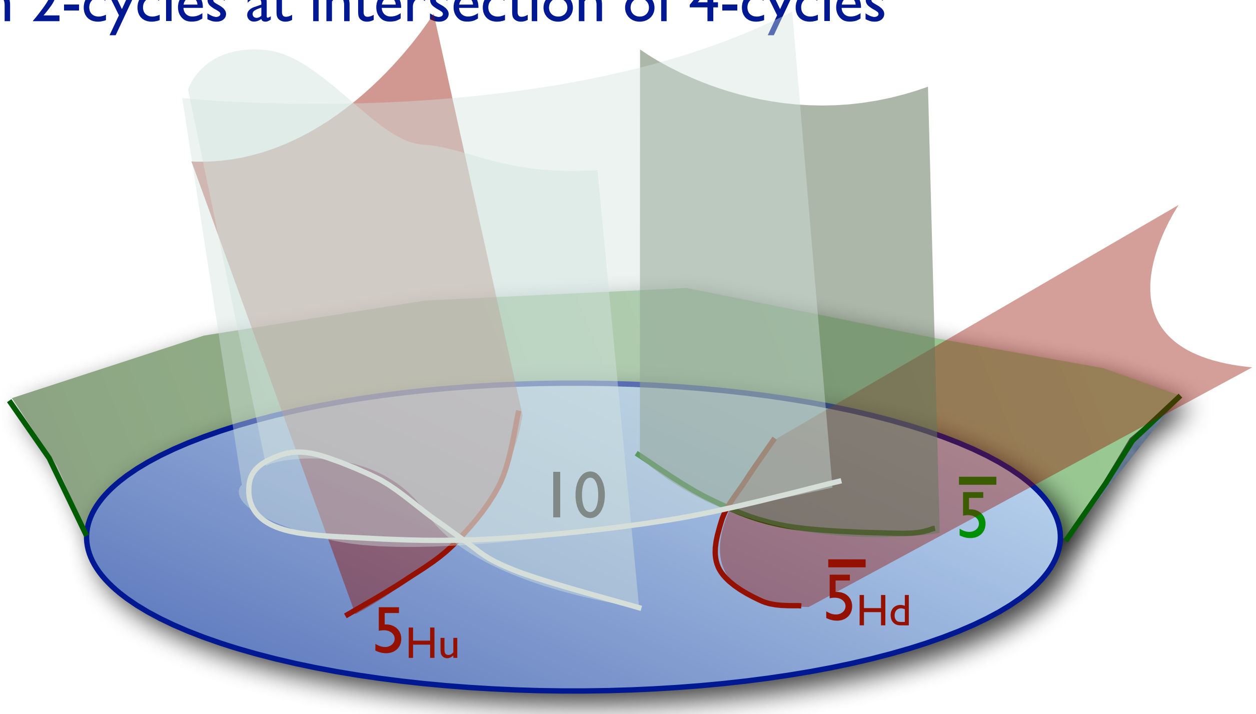

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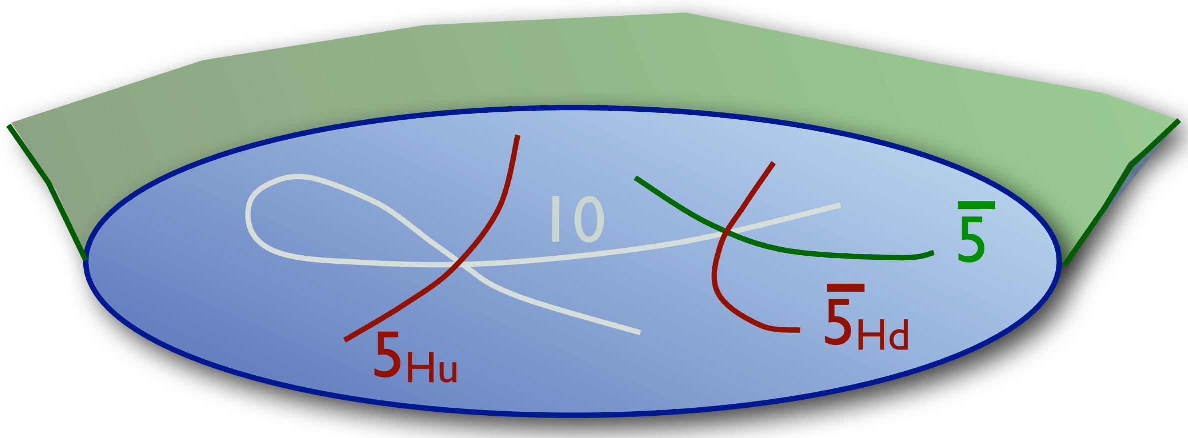

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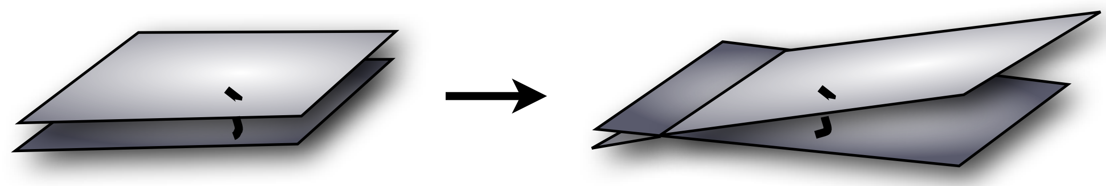
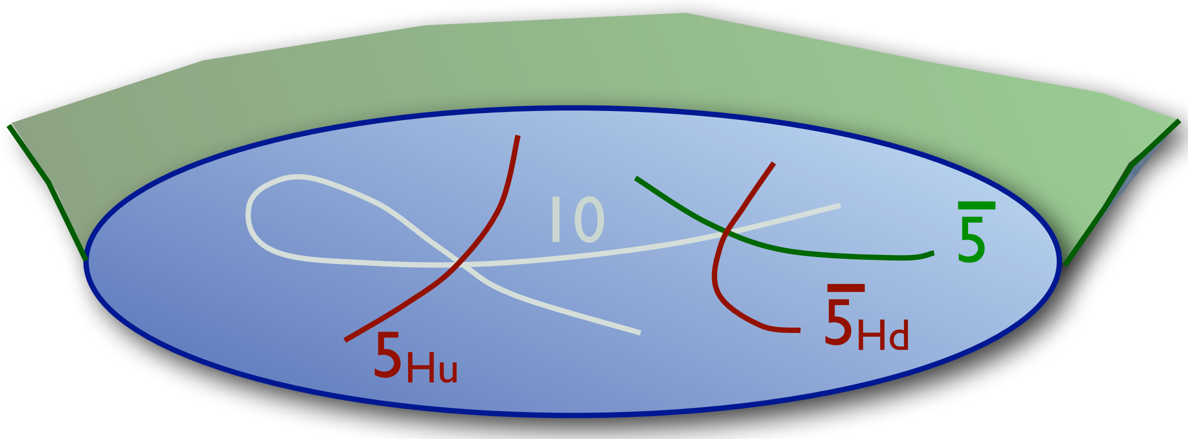
- Representations from unfolding G→H1 x H2





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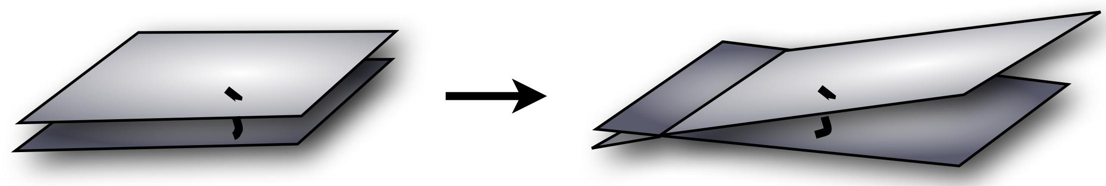

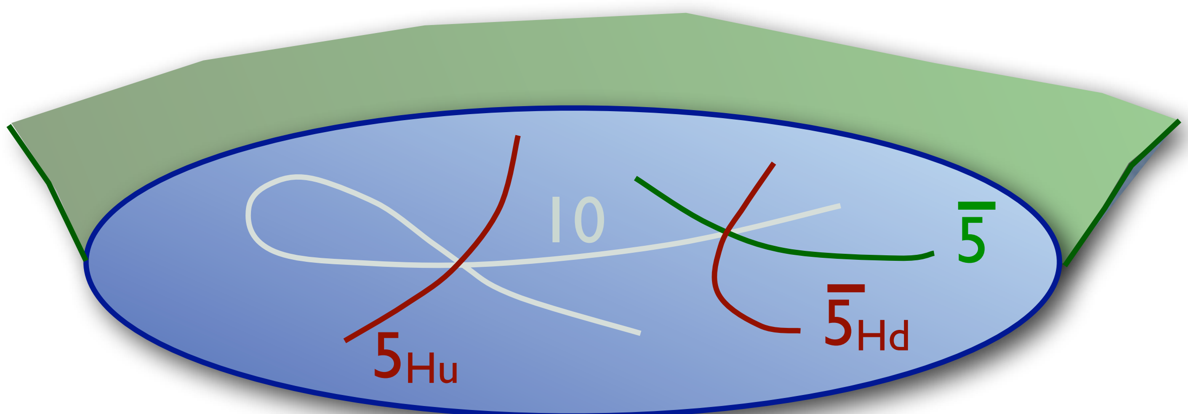

SO(10) → SU(5) x U(1)
45 → 24 + 1 + 10 + 10b

SU(6) → SU(5) x U(1)
35 → 24 + 1 + 5 + 5b

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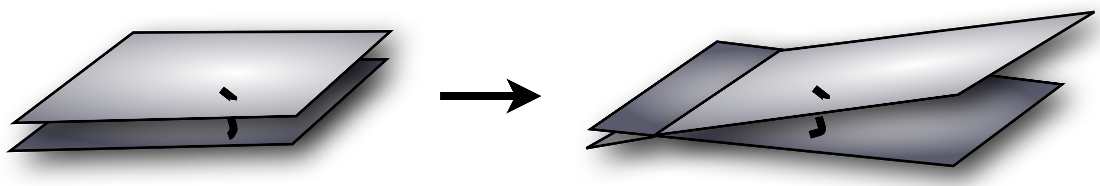

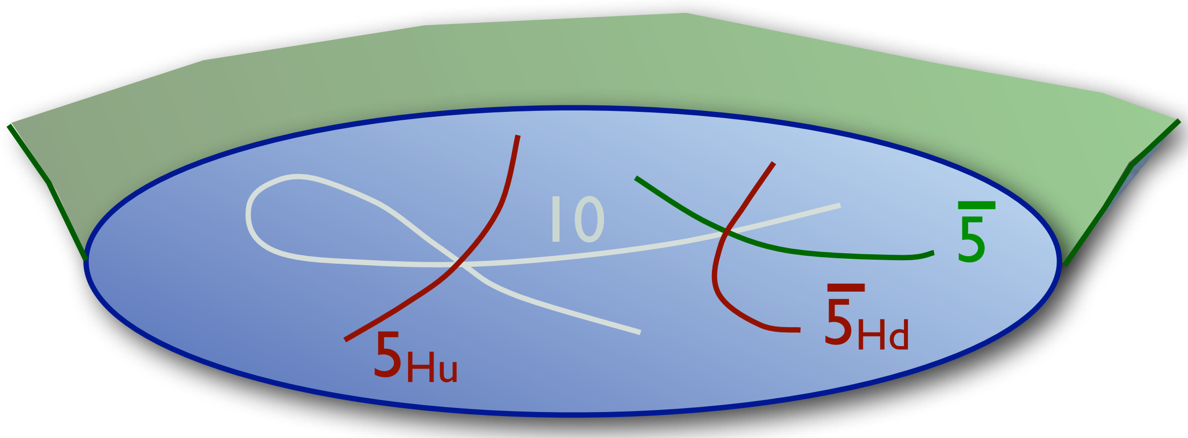

Must turn on worldvolume magnetic fluxes to produce 4d chirality

Intersecting magnetized 7-brane models

F-theory GUTs

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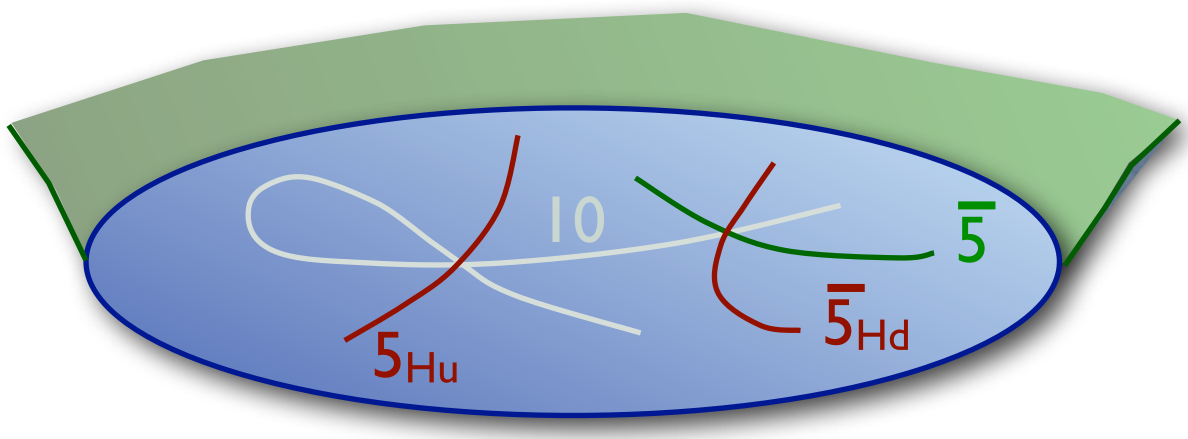

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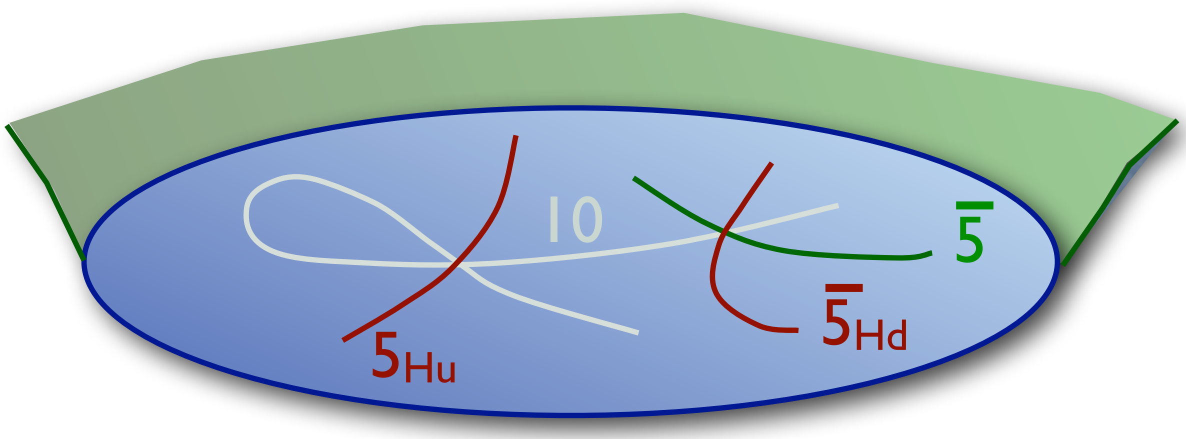

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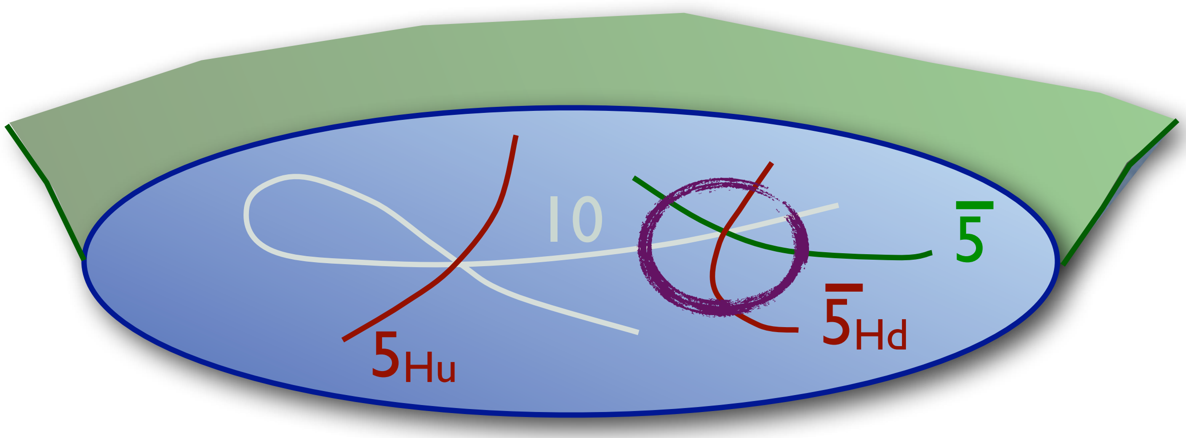

SO(12) → SU(5) x U(1) xU(1)
66 → 24 + 1 +1+ 10b + 5 + 5
+ **10 + 5b +5b**

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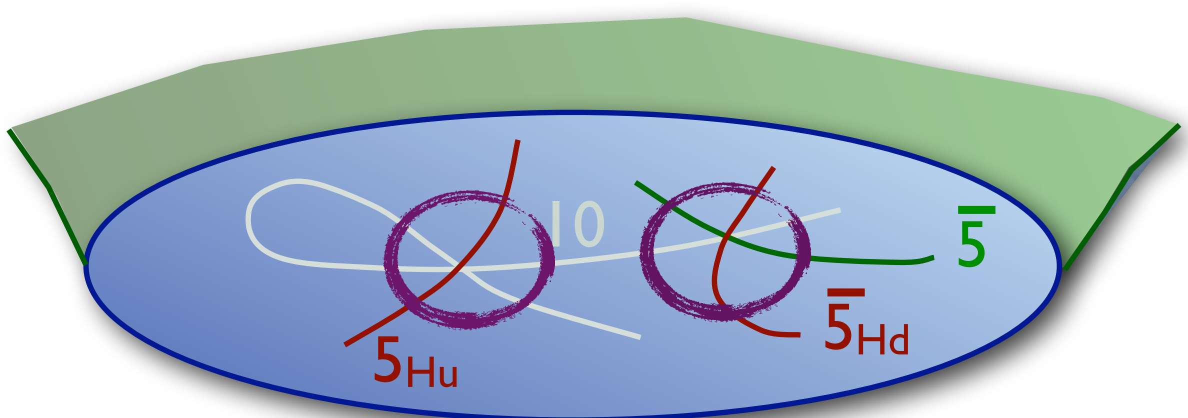

SO(12) → SU(5) x U(1) xU(1)
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+ **10 + 5b +5b**

E6 → SU(5) x U(1) x U(1)
78 → 24+1+1+1+1+ 10b + 10b + 5b
+ **10 + 10 + 5**

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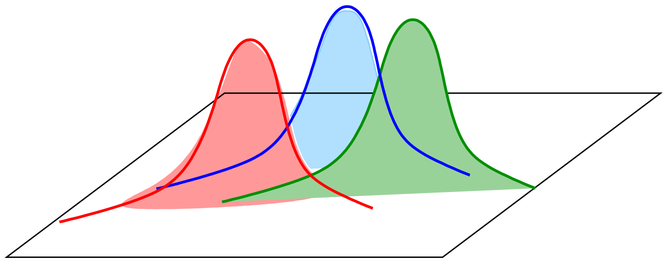
Overlap of chiral matter wavefunctions

$$\int \phi_1 \phi_2 \phi_3$$



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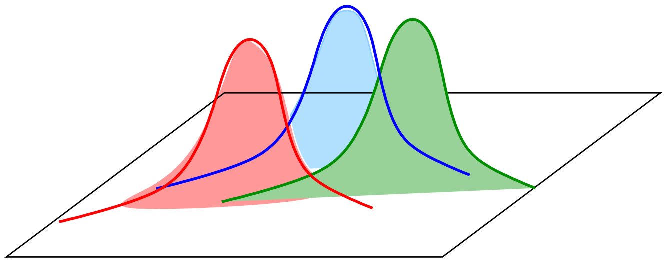

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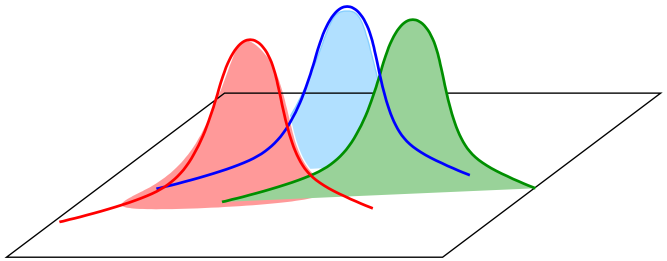

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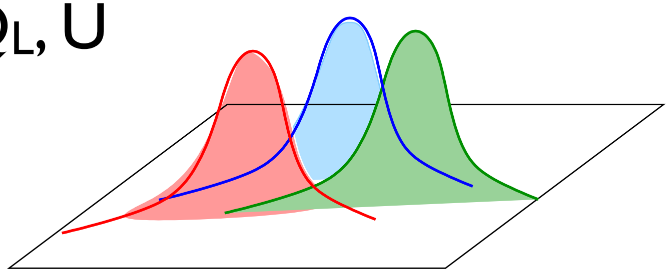
Choose local coords z, u, v for e.g. H_U, Q_L, U



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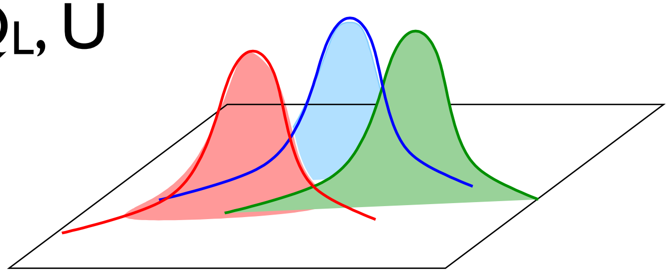
Three families: 1,u, u^2 ; 1,v, v^2 for Q_L, U



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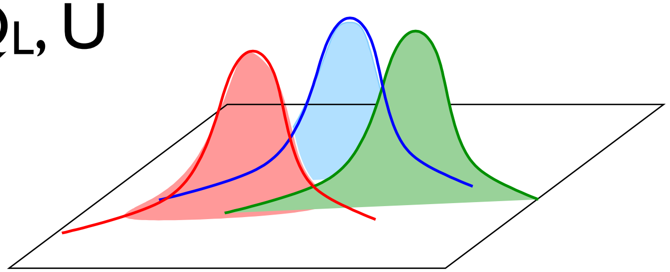

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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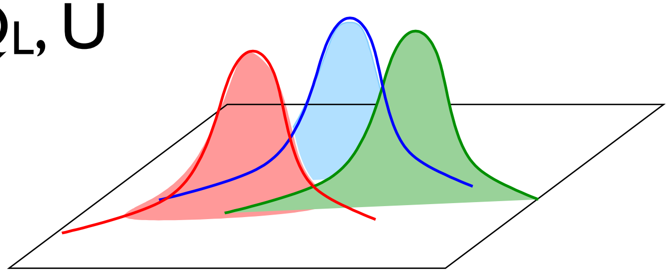

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Order 1 top Yukawa. Everyone else massless

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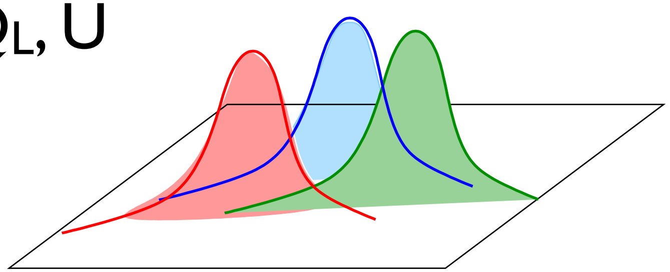
Choose local coords z, u, v for e.g. H_U, Q_L, U

Three families: 1,u, u^2 ; 1,v, v^2 for Q_L, U



$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Order 1 top Yukawa. Everyone else massless

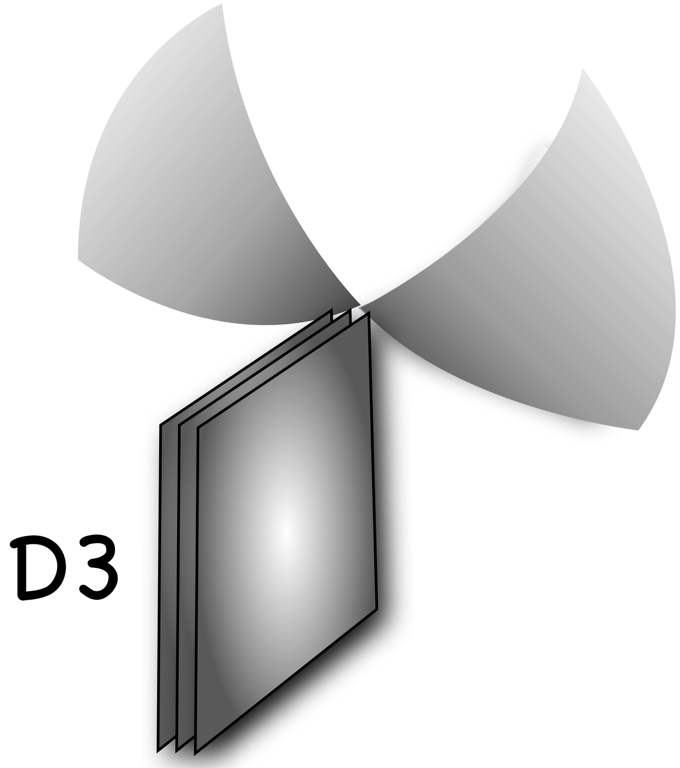
A whole industry of refinement

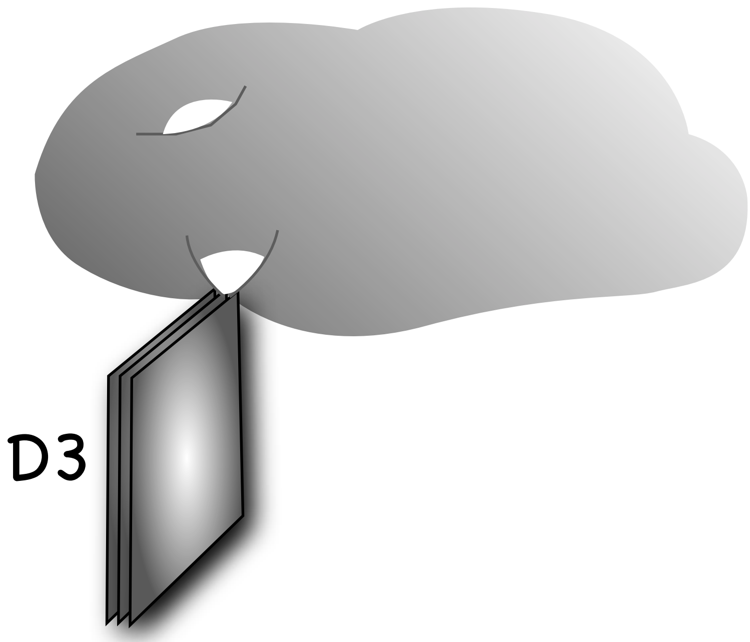
Branes at singularities

- A different setup of B-branes

Branes at singularities

- A different setup of B-branes
- Physics depends on local structure of the singularity





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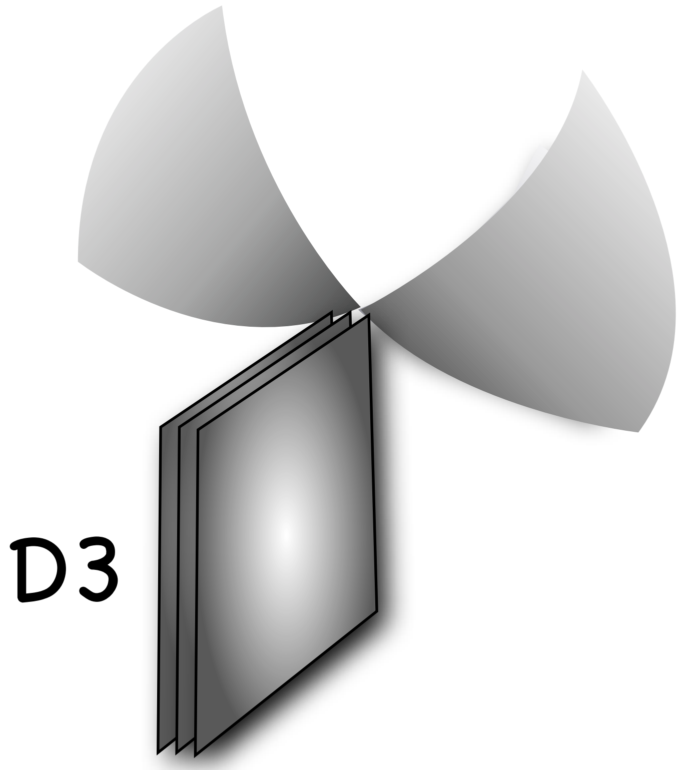

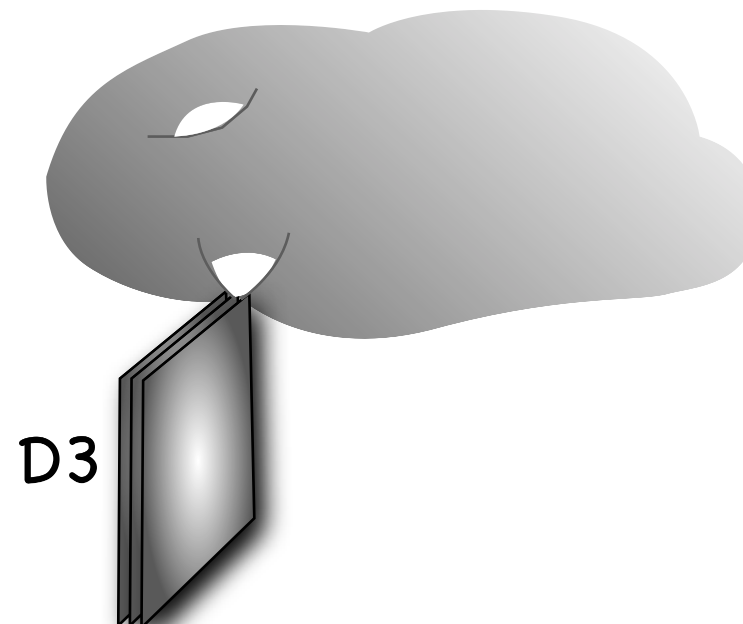

- Basic branes are "fractional branes": D-branes wrapped on collapsed 4- and 2-cycles

Branes at singularities

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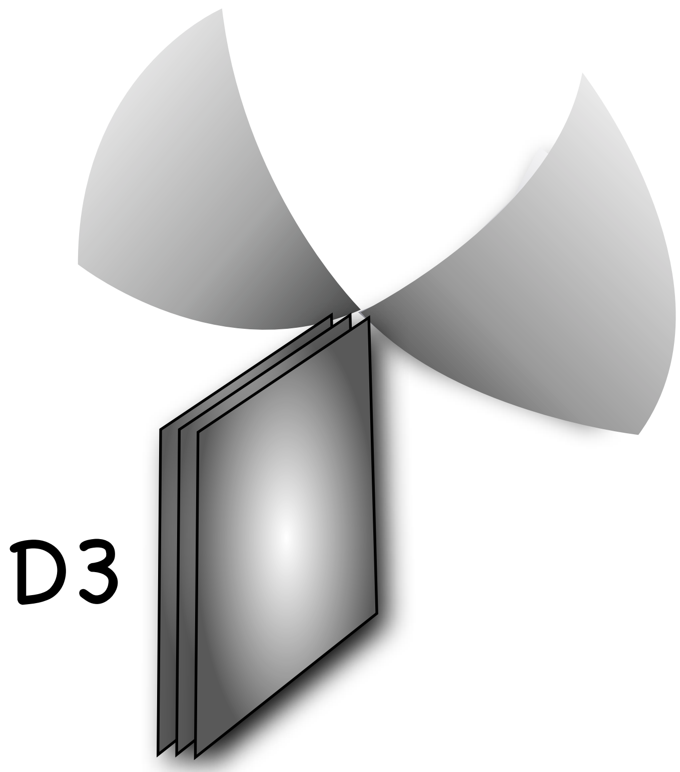

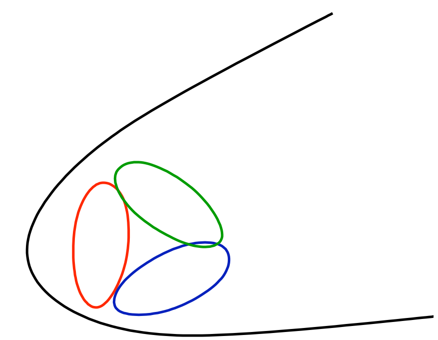

Mirror to local IIA models of intesecting D6s at local CYs

- Basic branes are "fractional branes": D-branes wrapped on collapsed 4- and 2-cycles

Branes at singularities

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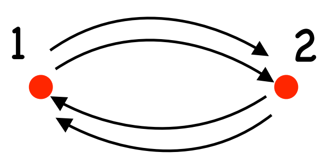
Conifold



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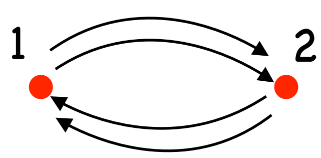
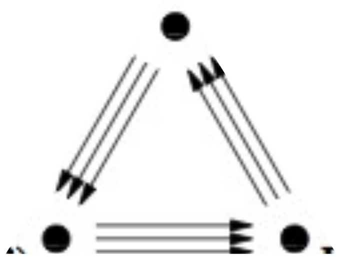


C3/Z3



Branes at singularities

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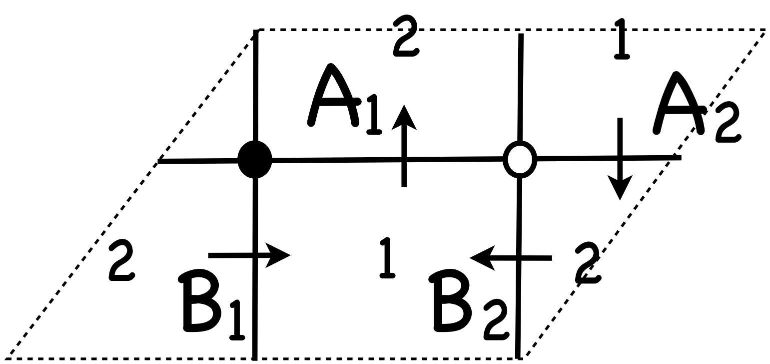
Toric singus: Inclusion of superpotential data using dimer diagrams

Conifold



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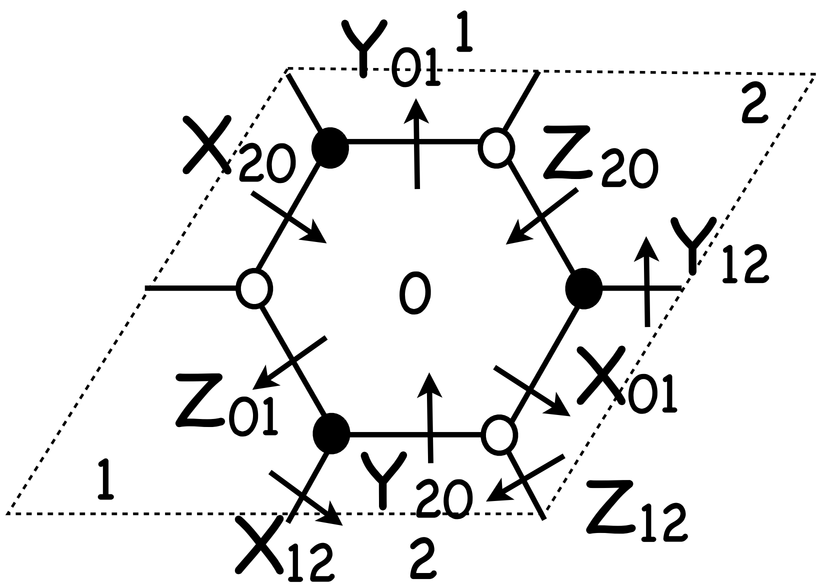
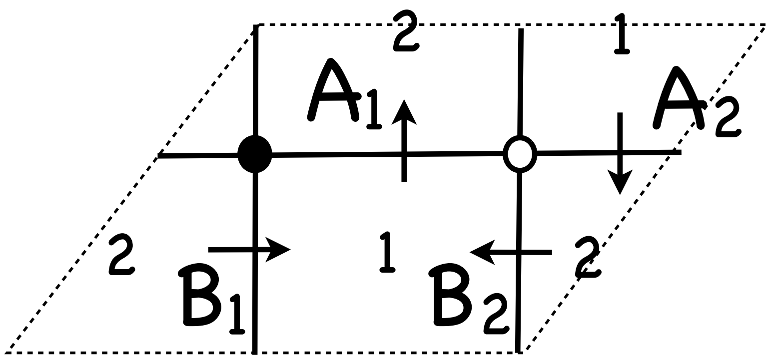
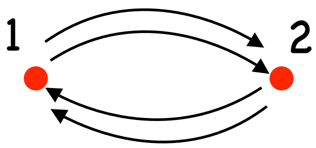


Branes at singularities

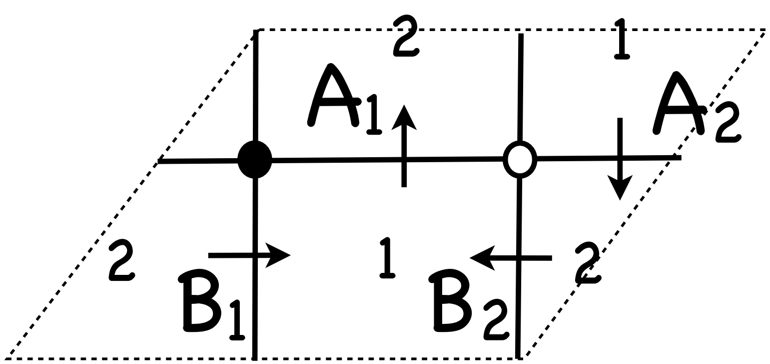
- Dimer diagrams

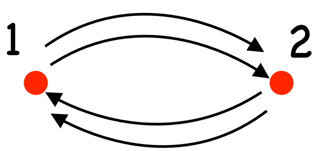




Branes at singularities

- Dimer diagrams   Dictionary





Branes at singularities

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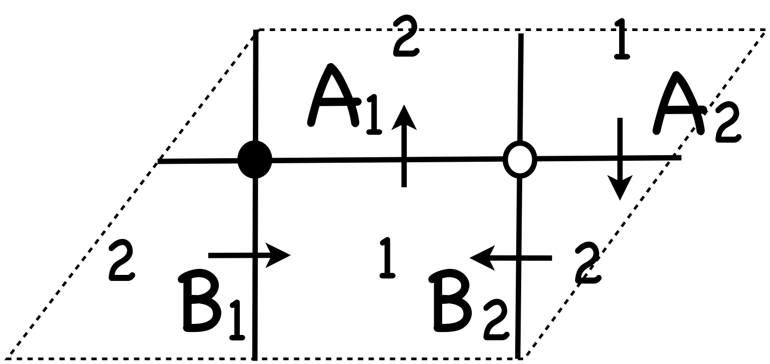
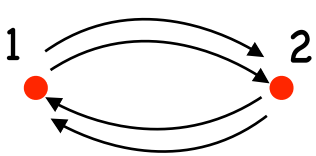
Dictionary

Faces ⇔ Gauge factors





Branes at singularities

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Dictionary

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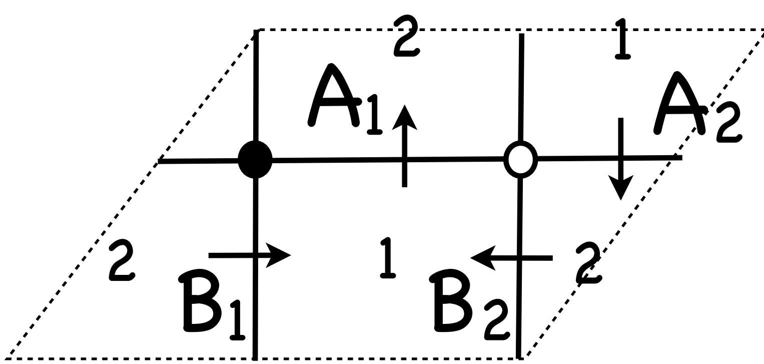

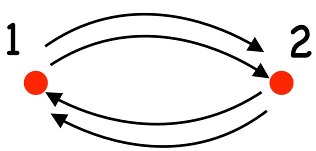

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Dictionary

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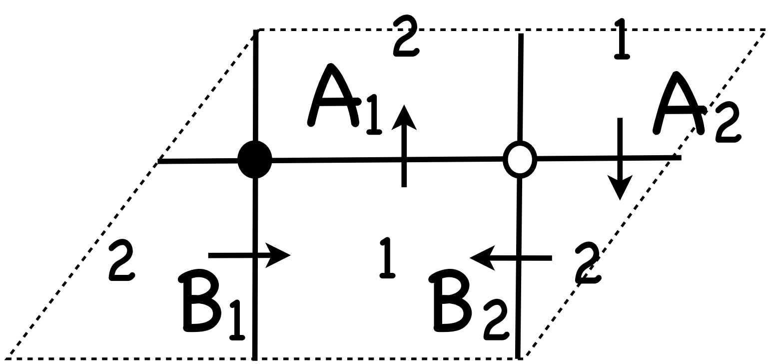

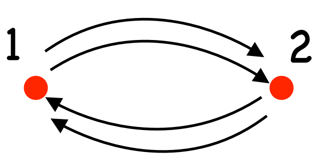

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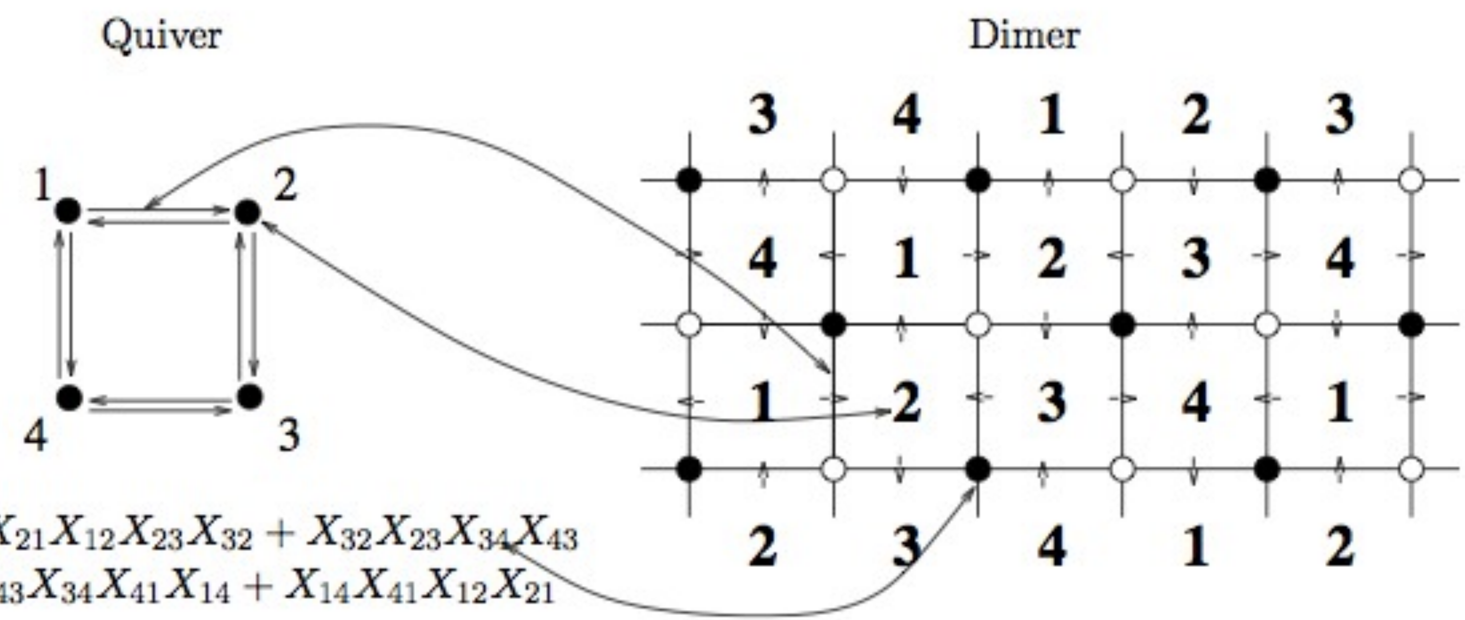
Orbifold of conifold



$$W = -X_{21}X_{12}X_{23}X_{32} + X_{32}X_{23}X_{34}X_{43} - X_{43}X_{34}X_{41}X_{14} + X_{14}X_{41}X_{12}X_{21}$$

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- Well developed technology to move back and forth geometry & gauge th

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  Notion of stability depending on Kahler parameters (FIs in gauge th)

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- In singular configuration: no bound states, only the fractional branes
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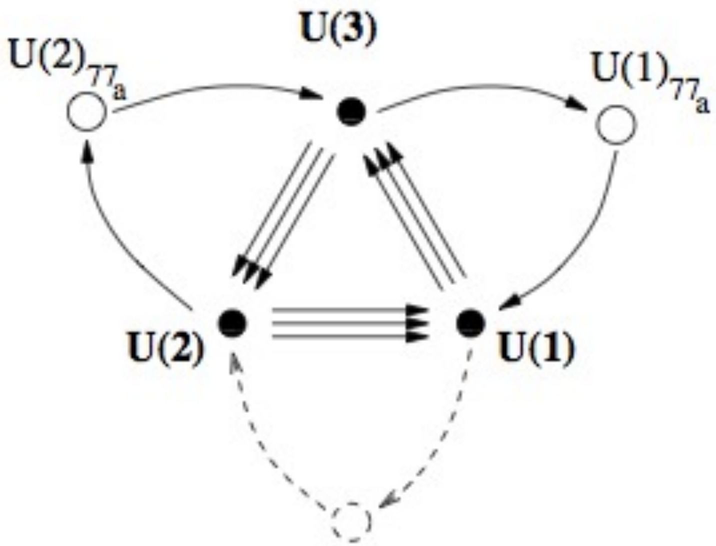
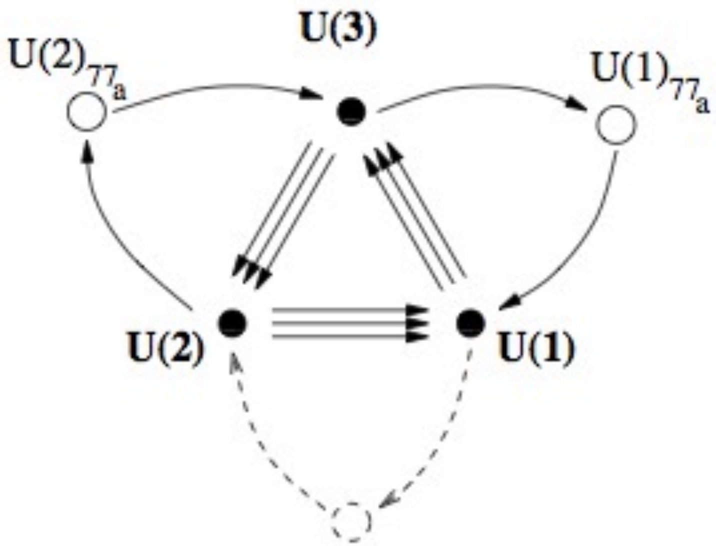
Branes at singularities



- SM model building with D3/D7s at singus, possible but very restrictive

Branes at singularities



- SM model building with D3/D7s at singus, possible but very restrictive
- Often used to describe holographi duals of warped throats

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    - Flux compactifications, see lecture 4