The Standard Model Quiver in de Sitter String Compactifications

Figure credits: Getty Images

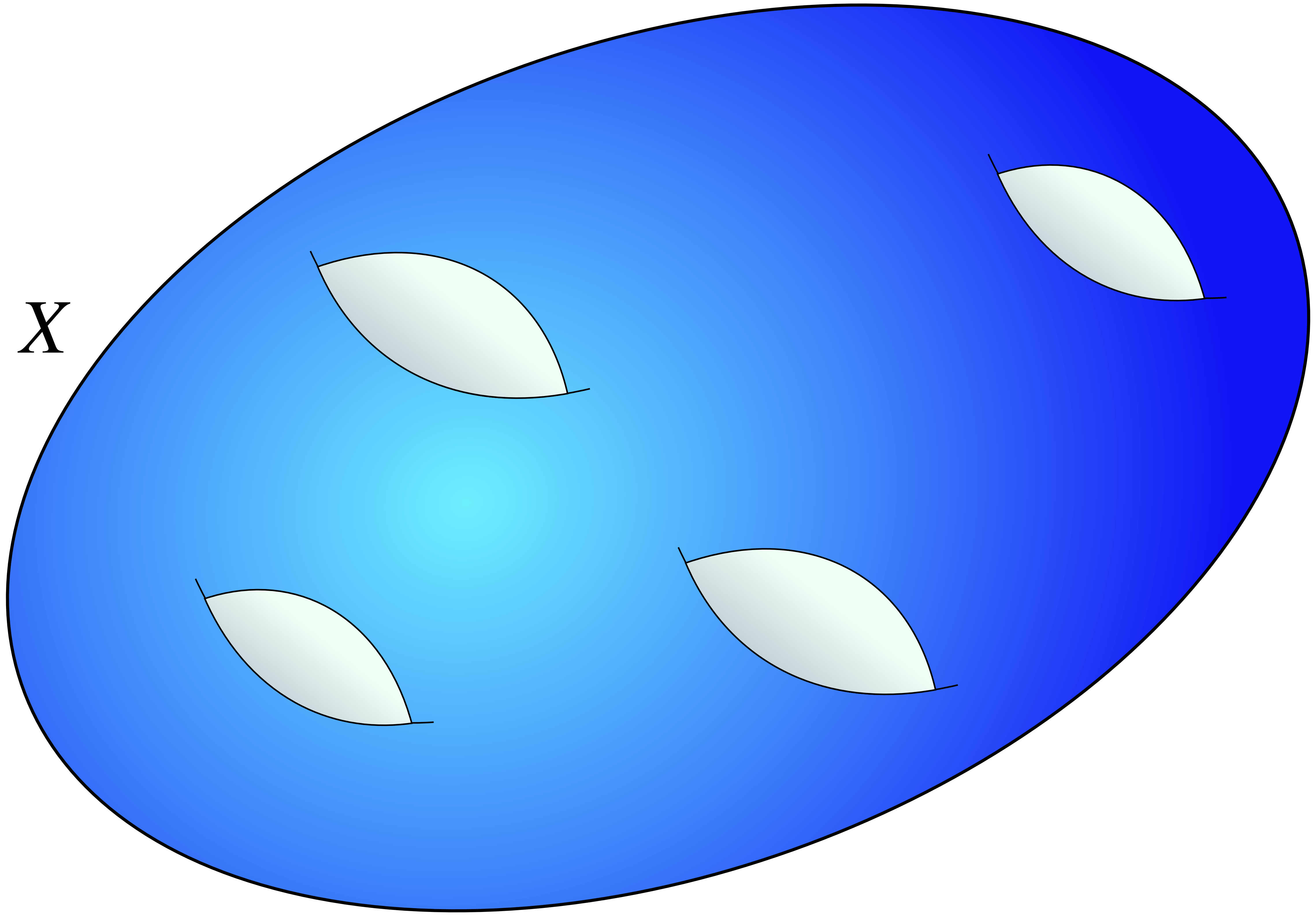
Department of Applied Mathematics
and Theoretical Physics

University of Cambridge

in collaboration with M. Cicoli, I. García Etxebarria, F. Quevedo, P. Shukla and R. Valandro

JHEP 08(2021)109   ArXiv: 2106.11964

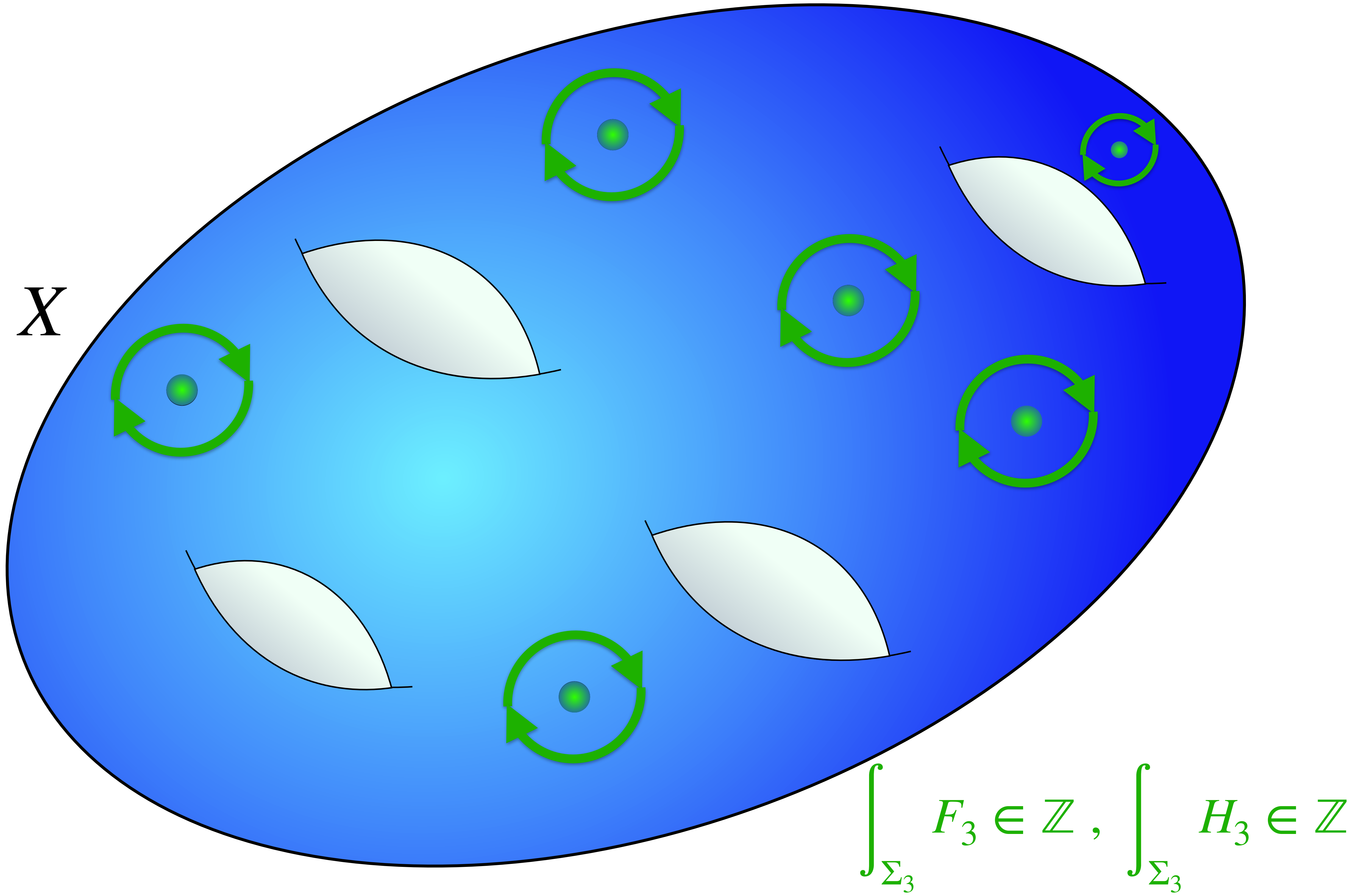
Aspects of Type IIB Model Building



Global aspects:

- Compact Calabi-Yau manifold X

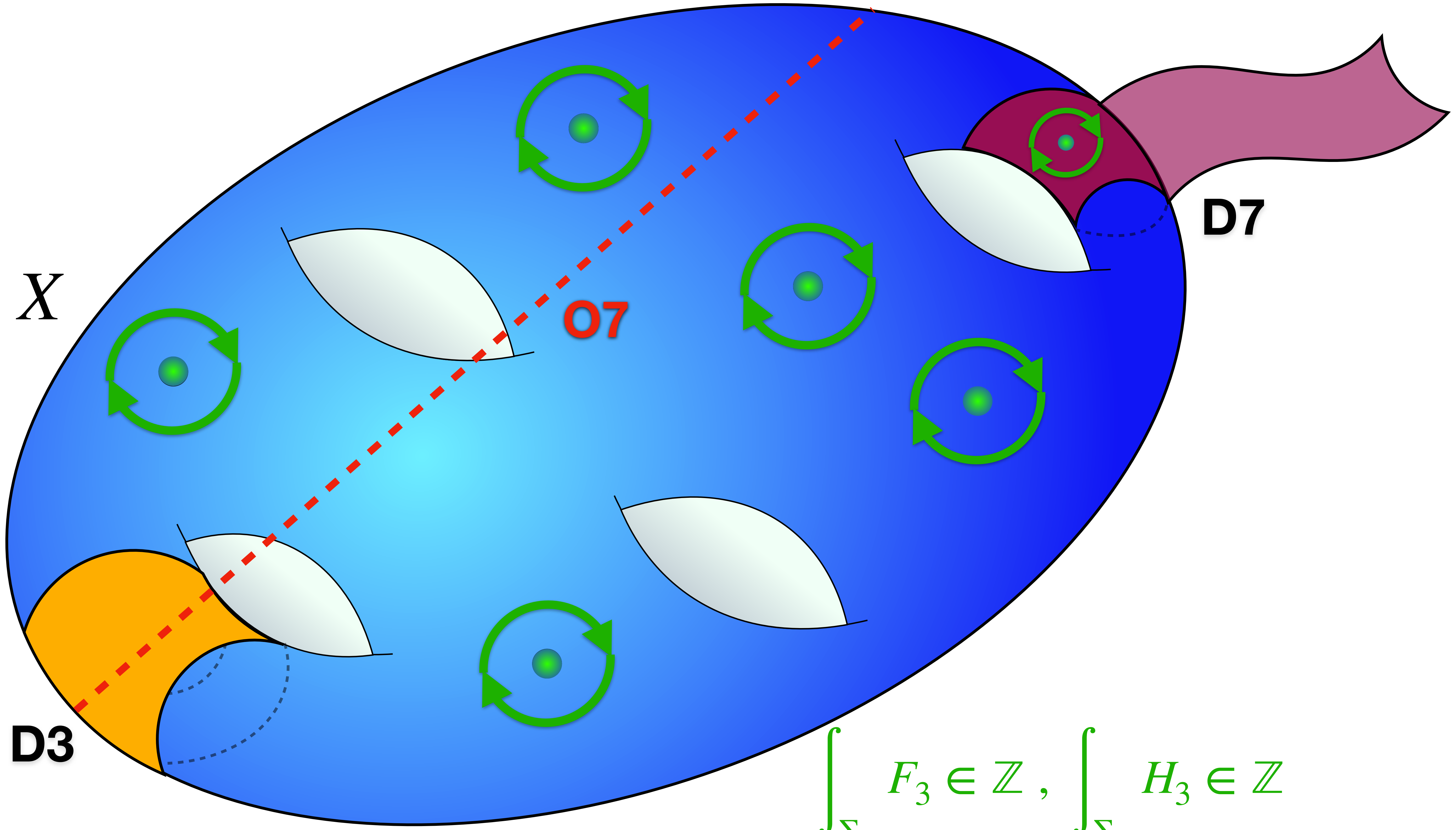
Aspects of Type IIB Model Building



Global aspects:

- Compact Calabi-Yau manifold X
- Flux background

Aspects of Type IIB Model Building

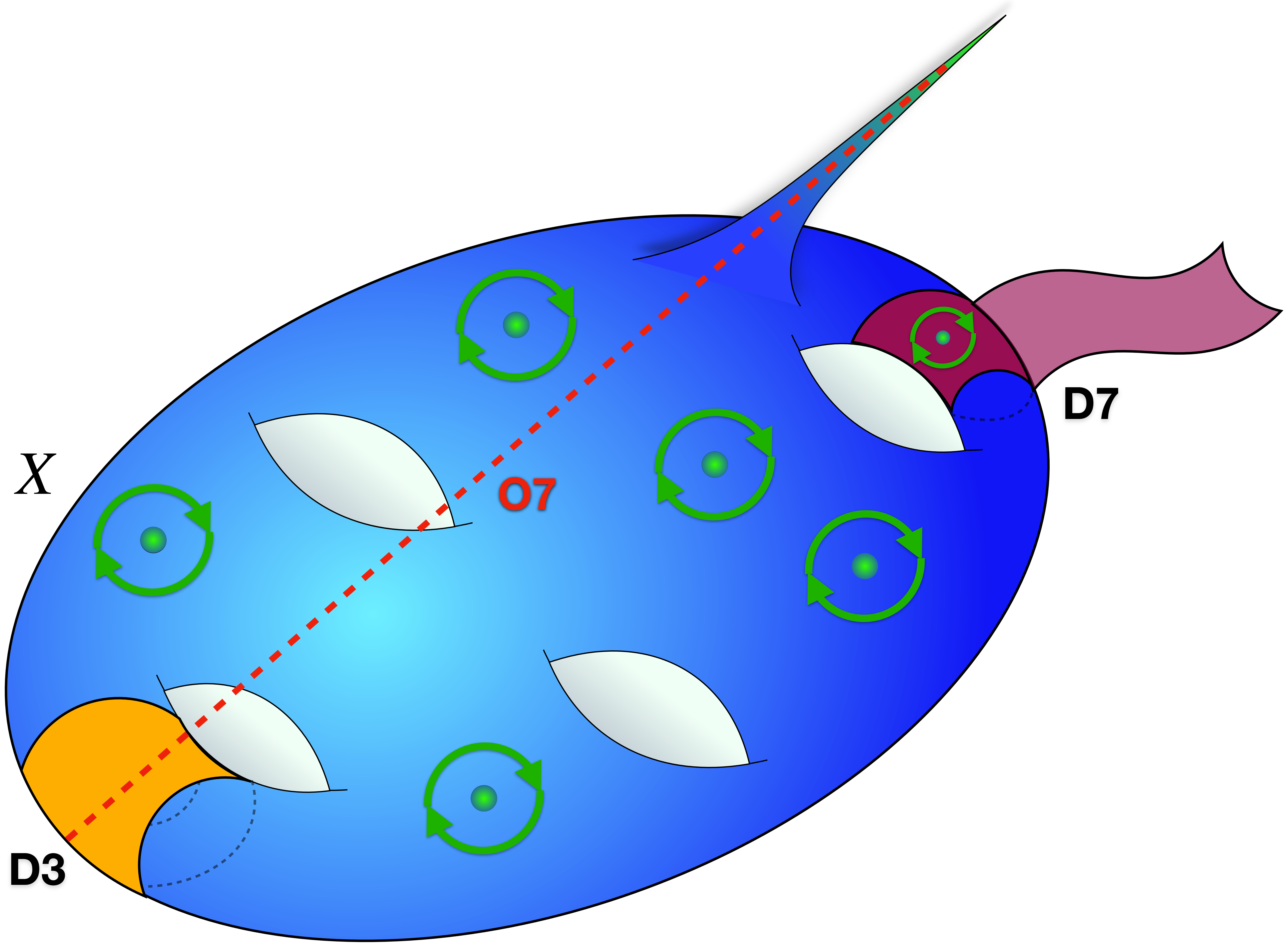


$$\int_{\Sigma_3} F_3 \in \mathbb{Z}\,,\ \int_{\Sigma_3} H_3 \in \mathbb{Z}$$

Global aspects:

- Compact Calabi-Yau manifold X
- Flux background
- D-brane and O-plane configuration
- Tadpole cancellation
- Moduli stabilisation in de Sitter minima
- …

Aspects of Type IIB Model Building

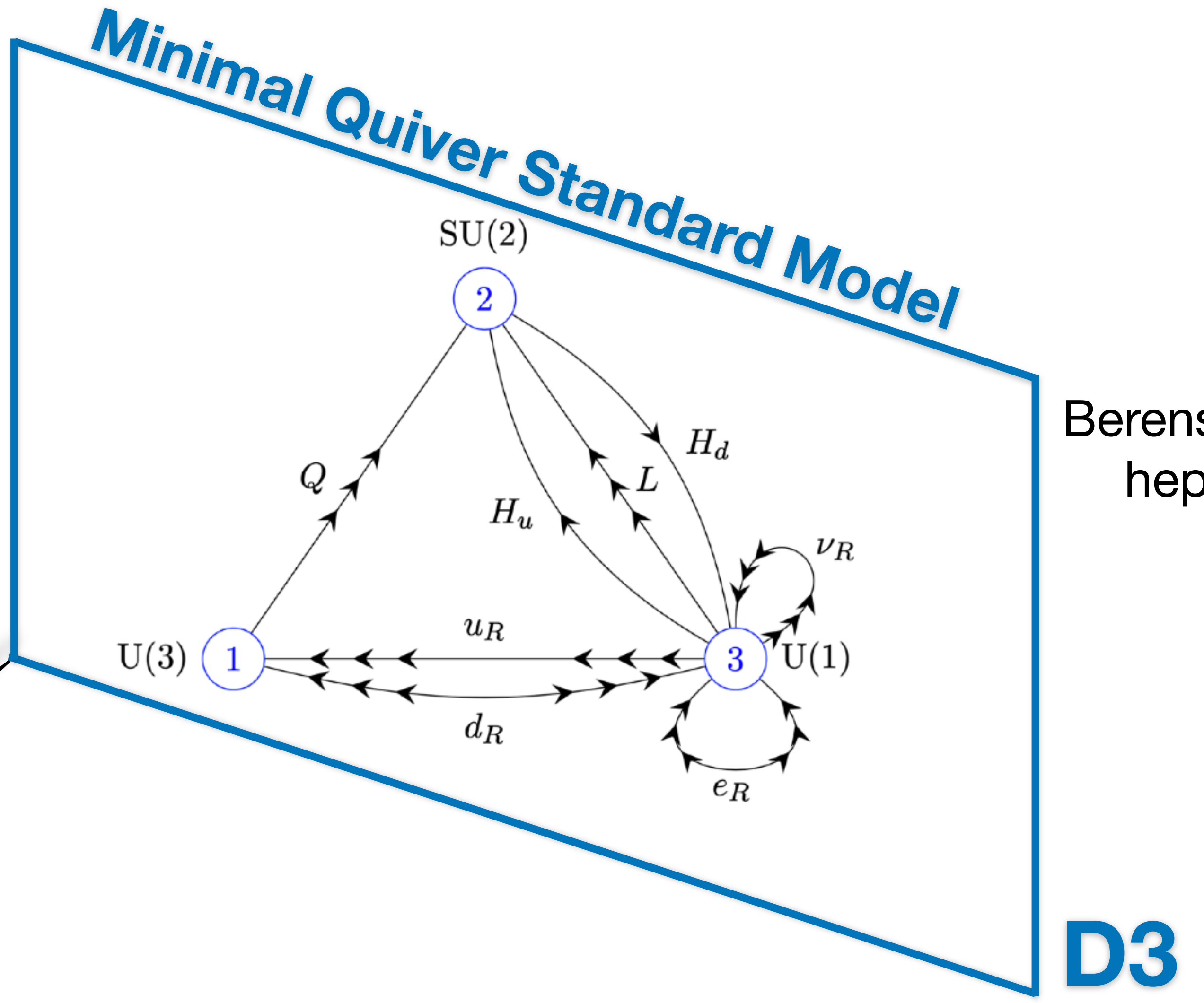


Global aspects:

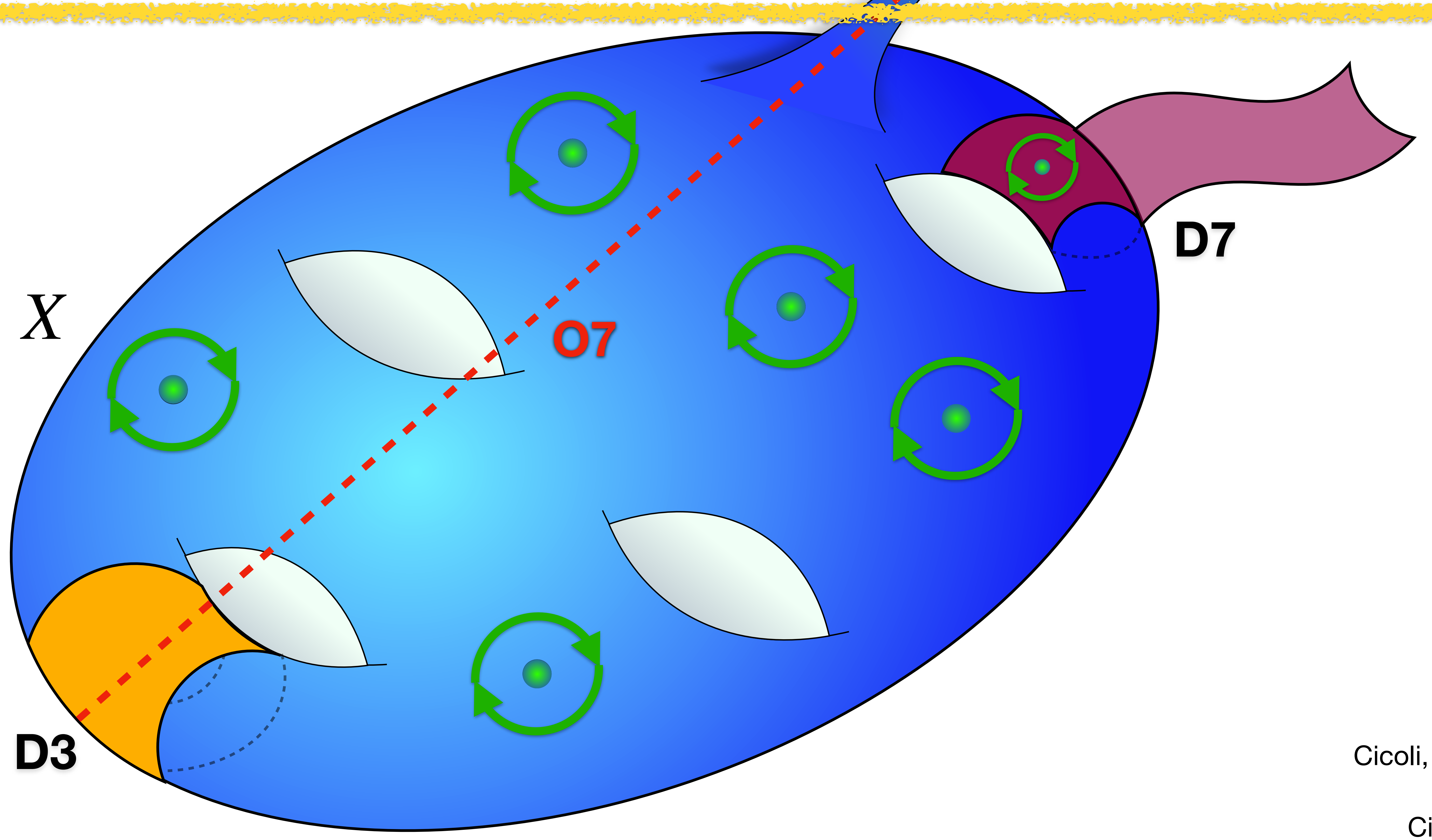
- Compact Calabi-Yau manifold X
- Flux background
- D-brane and O-plane configuration
- Tadpole cancellation
- Moduli stabilisation in de Sitter minima
- …

Local model building:

- Choice of singularity
- Standard Model gauge group
- Spectrum of 3 chiral families
- Non-chiral matter
- Global anomalous U(1)’s
- Hierarchies in Yukawas
- …



Berenstein, Pinansky: hep-th/0610104



Global aspects:

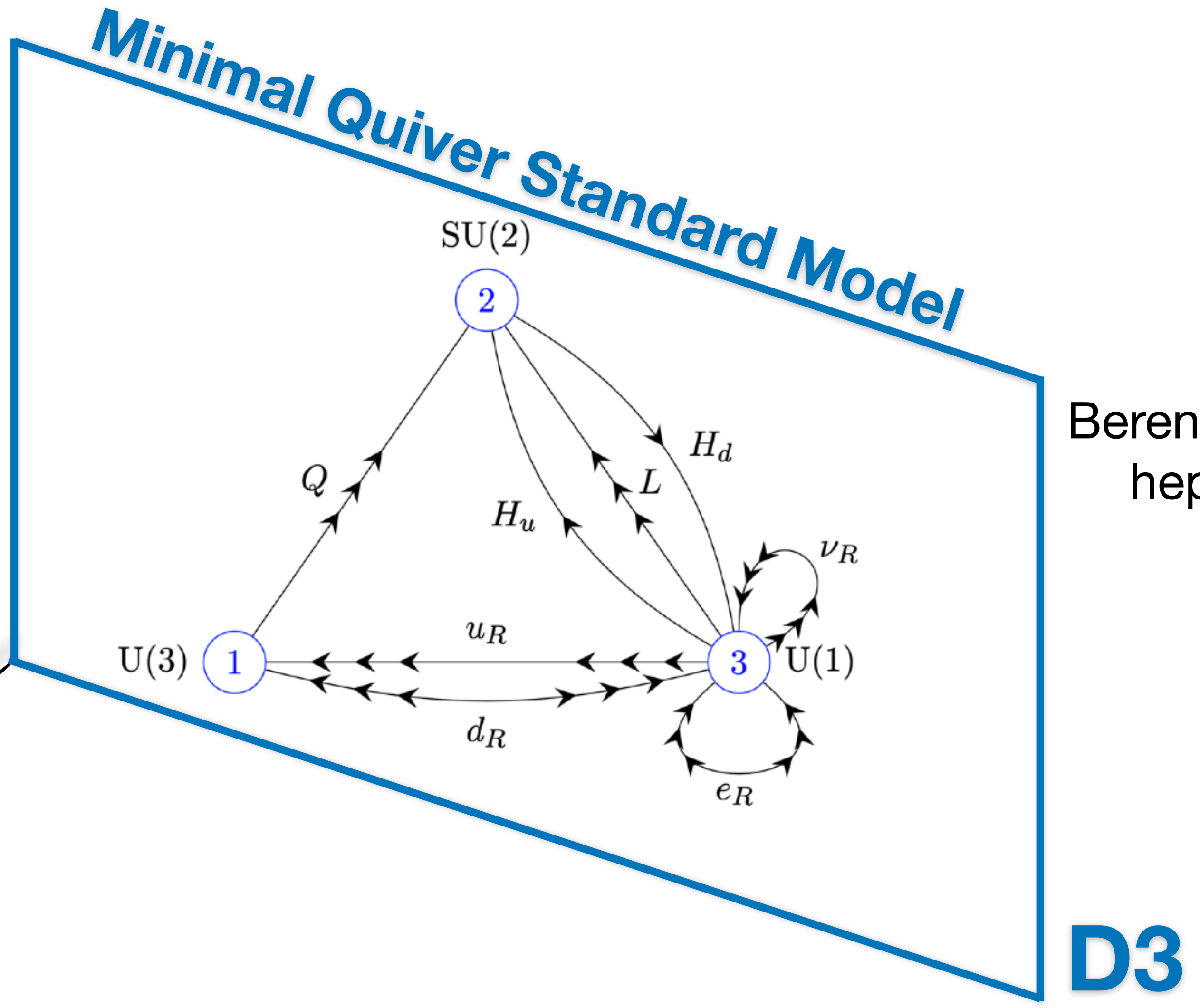
- Compact Calabi-Yau manifold X
- Flux background
- D-brane and O-plane configuration
- Tadpole cancellation
- Moduli stabilisation in de Sitter minima
- …

Previous global constructions:

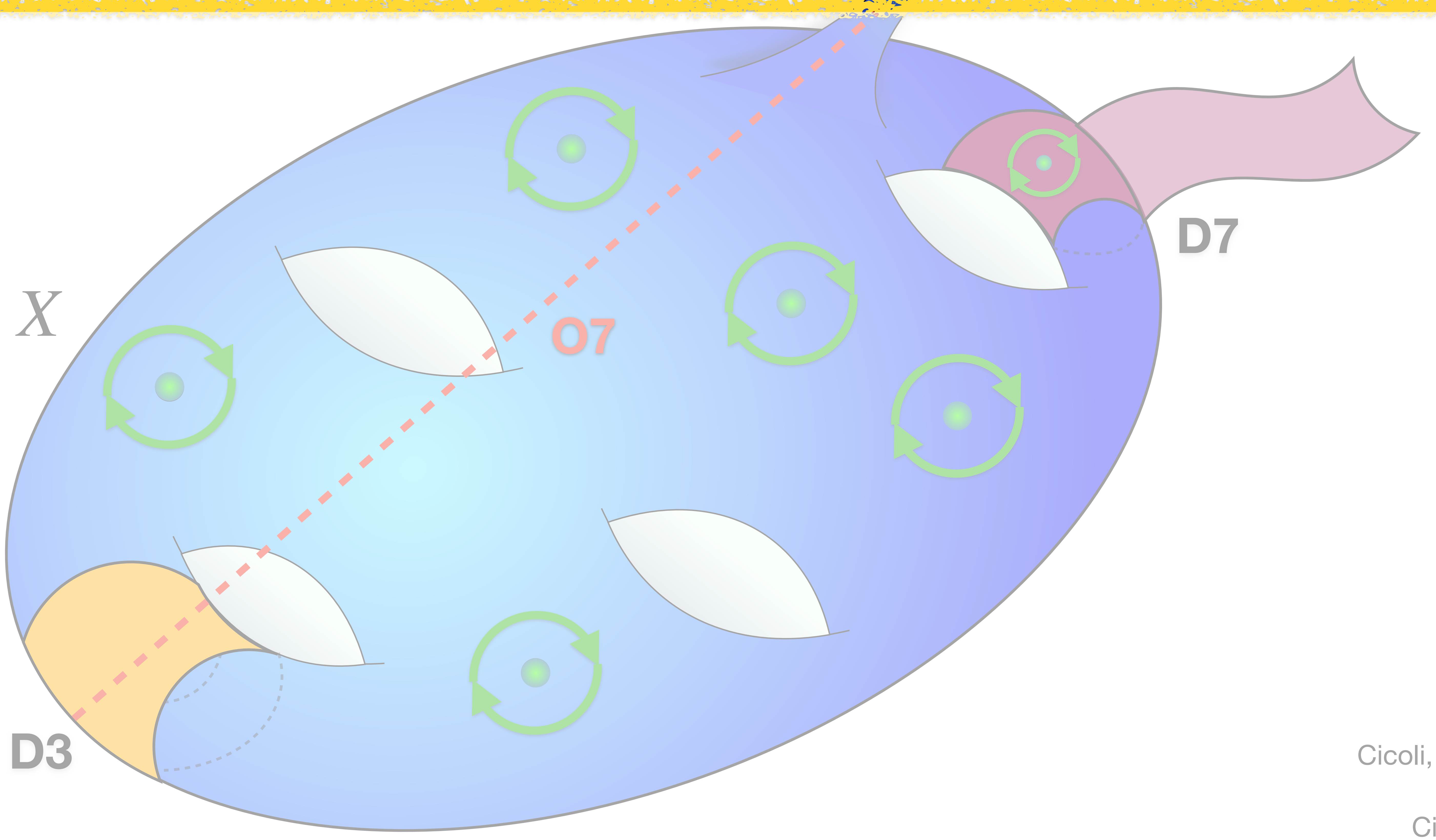
Dolan, Krippendorf, Maharana, Quevedo: 1002.1790
Dolan, Krippendorf, Quevedo: 1106.6039
Cicoli, Krippendorf, Mayrhofer, Quevedo, Valandro: 1206.5237, 1304.0022, 1304.2771
Cicoli, Klevers, Krippendorf, Mayrhofer, Quevedo, Valandro: 1312.0014
Cicoli, García Etxebarria, Mayrhofer, Quevedo, Shukla, Valandro: 1706.06128

Local model building:

- Choice of singularity
- Standard Model gauge group
- Spectrum of 3 chiral families
- Non-chiral matter
- Global anomalous U(1)'s
- Hierarchies in Yukawas
- …



Berenstein, Pinansky: hep-th/0610104



Global aspects:

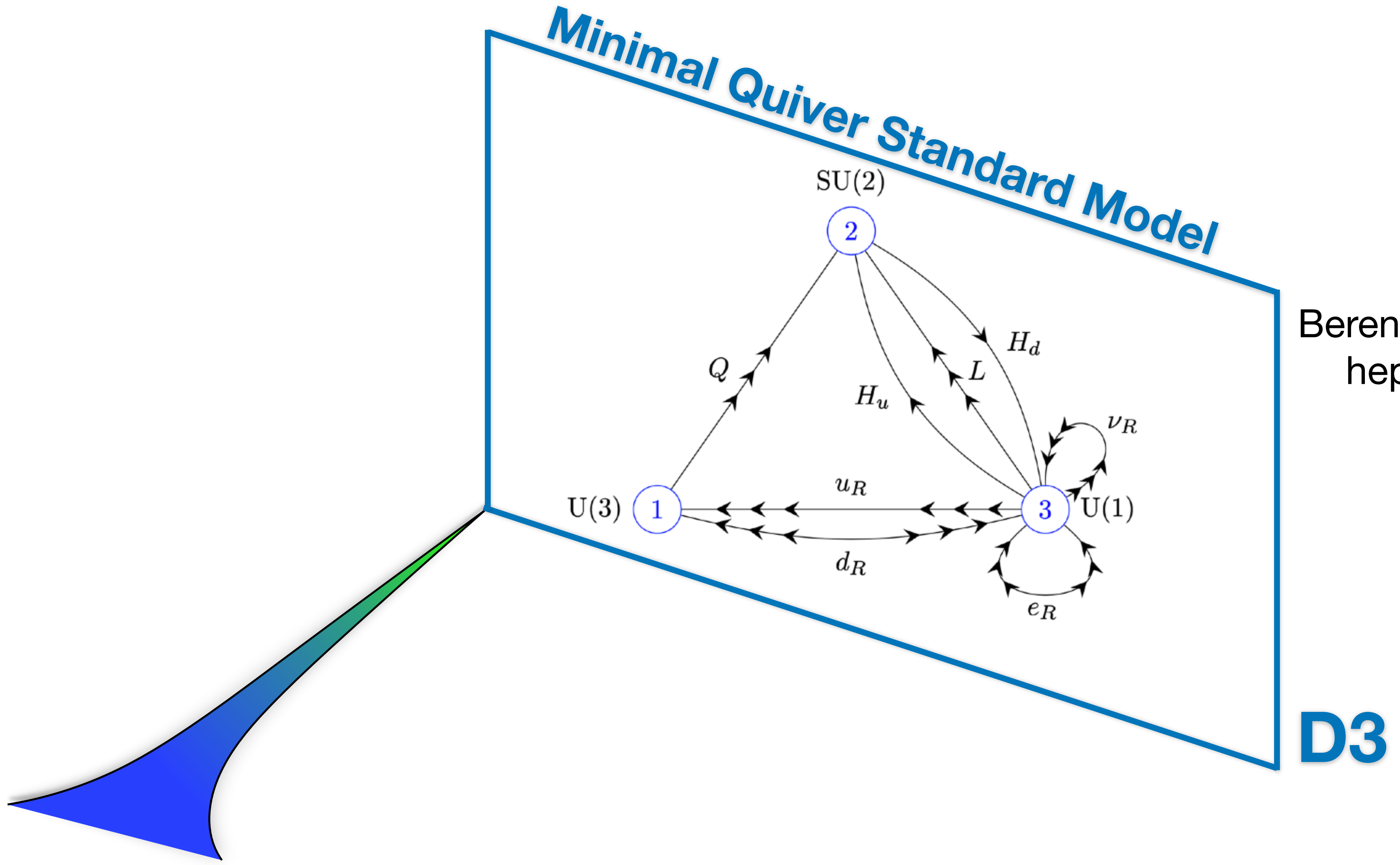
- Compact Calabi-Yau manifold X
- Flux background
- D-brane and O-plane configuration
- Tadpole cancellation
- Moduli stabilisation in de Sitter minima
- …

Previous global constructions:

Dolan, Krippendorf, Maharana, Quevedo: 1002.1790
Dolan, Krippendorf, Quevedo: 1106.6039
Cicoli, Krippendorf, Mayrhofer, Quevedo, Valandro: 1206.5237, 1304.0022, 1304.2771
Cicoli, Klevers, Krippendorf, Mayrhofer, Quevedo, Valandro: 1312.0014
Cicoli, García Etxebarria, Mayrhofer, Quevedo, Shukla, Valandro: 1706.06128

Local model building:

- Choice of singularity
- Standard Model gauge group
- Spectrum of 3 chiral families
- Non-chiral matter
- Global anomalous U(1)'s
- Hierarchies in Yukawas
- …



Berenstein, Pinansky:
hep-th/0610104

What type of singularity?

del Pezzo surfaces:
Complex 2-dimensional Fano surfaces, i.e., projective algebraic surfaces with ample anti-canonical divisor class $-K \cdot C > 0$ for every curve C.
We distinguish $\mathbb{P}^1 \times \mathbb{P}^1$ or dP_n corresponding to $\mathbb{P}^2$ blown up at n points.

Attractive features of D-branes at dP_n singularities:

A. Huge variety of gauge theories from a single D3 brane
B. Oriented quiver always comes with 2 anomalous $U(1)$'s
C. Chiral spectrum from intersections of 2- and 4-cycles

To a point shrinkable 4-cycle must be of del Pezzo type by **Grauter's criterion**

See e.g. Cordova: 0910.2955
Malyshev, Verlinde:0711.2451

Today:

dP_5 singularity as simplest setup
to give rise to exact MSSM locally!

Wijnholt: hep-th/0703047

Unoriented quivers from D3-branes at dP_5 singularities

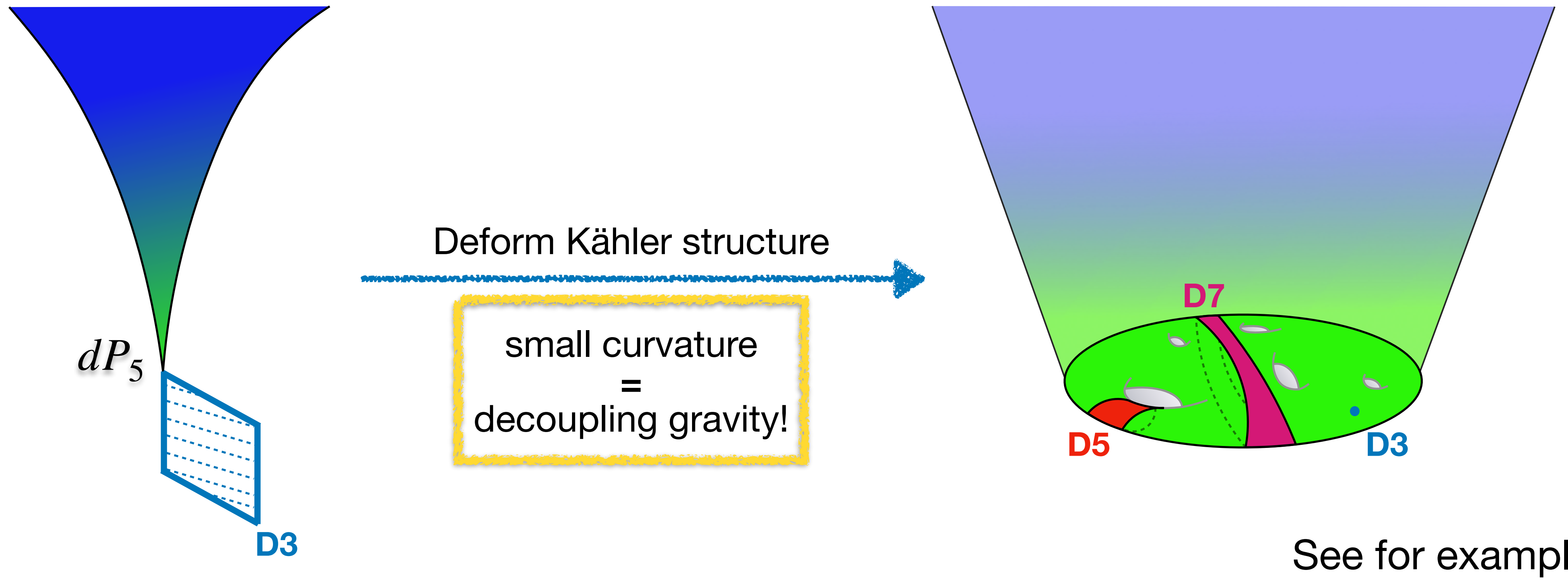
Fractional branes F_i :
Bound states of several
D-branes supported on cycles

Spectrum of open strings from **quiver diagrams:**

$\mathrm{U}(N_i)$ (i) ⟷ N_i copies of a fractional brane F_i

$\mathrm{U}(N_i)$ (i) ⟶ (j) $\mathrm{U}(N_j)$ ⟷ Chiral multiplet in bi-fundamental of $U(N_i) \times U(N_j)$

Geometric description of local model in the large volume limit:



See for example:
Wijnholt: hep-th/0212021
Verlinde, Wijnholt: hep-th/0508089

Unoriented quivers from D3-branes at dP_5 singularities

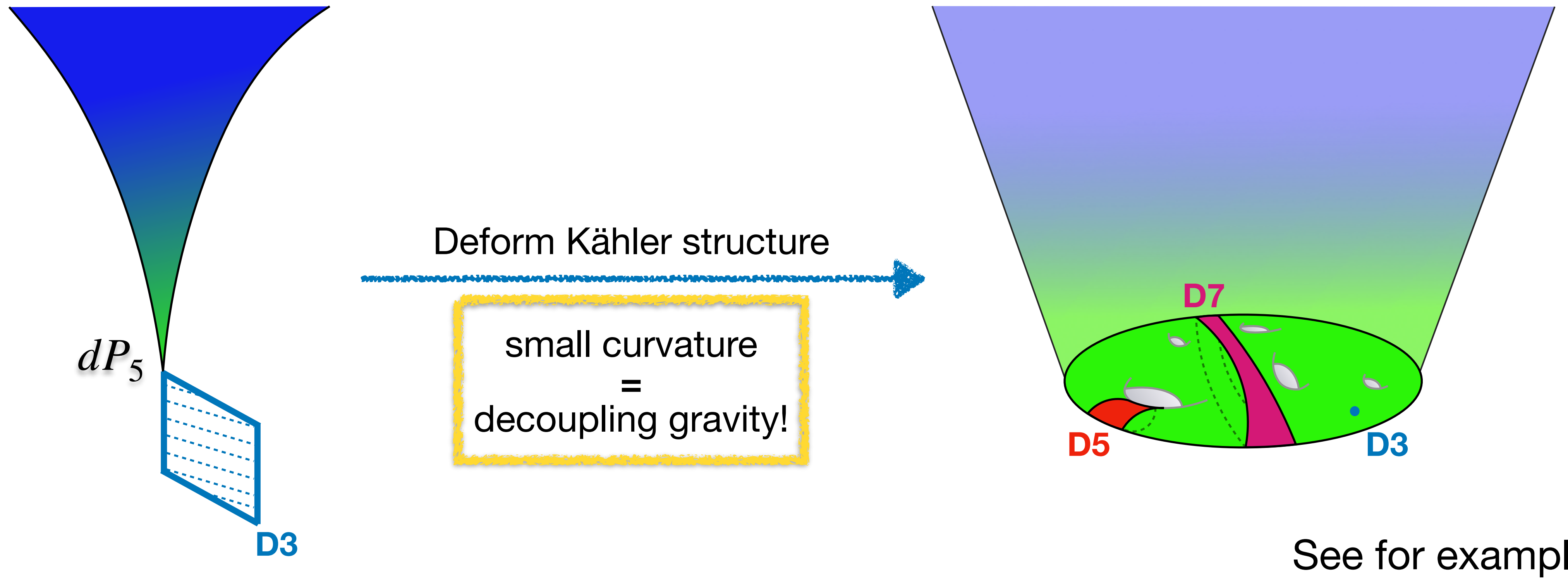
Fractional branes F_i :
Bound states of several
D-branes supported on cycles

Spectrum of open strings from **quiver diagrams:**

$\mathrm{U}(N_i)$ (i) ⟷ N_i copies of a fractional brane F_i

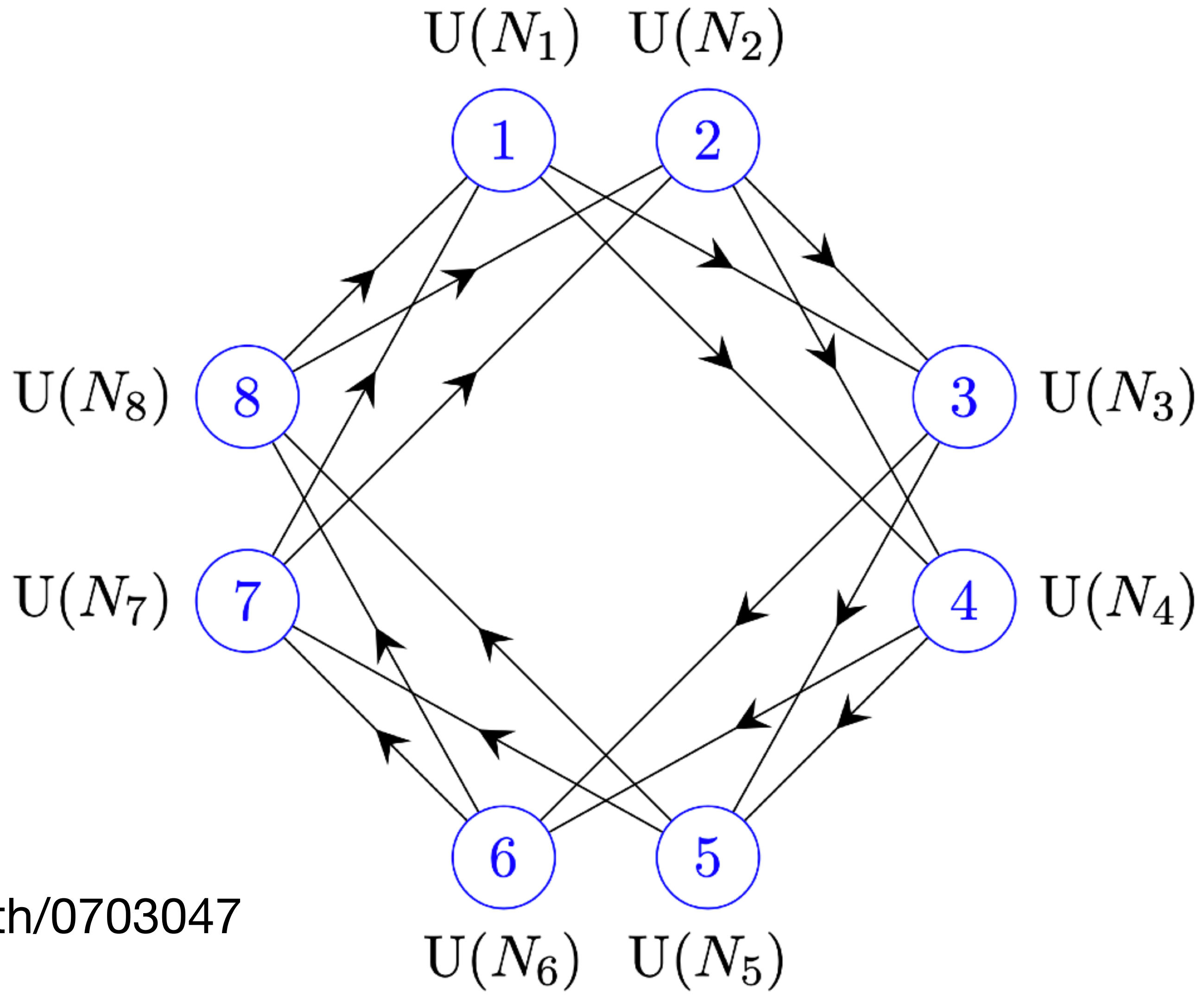
$\mathrm{U}(N_i)$ (i) ⟶ (j) $\mathrm{U}(N_j)$ ⟷ Chiral multiplet in bi-fundamental of $U(N_i) \times U(N_j)$

Geometric description of local model in the large volume limit:



See for example:
Wijnholt: hep-th/0212021
Verlinde, Wijnholt: hep-th/0508089

dP_5 quiver diagram:



Wijnholt: hep-th/0703047

Unoriented quivers from D3-branes at dP_5 singularities

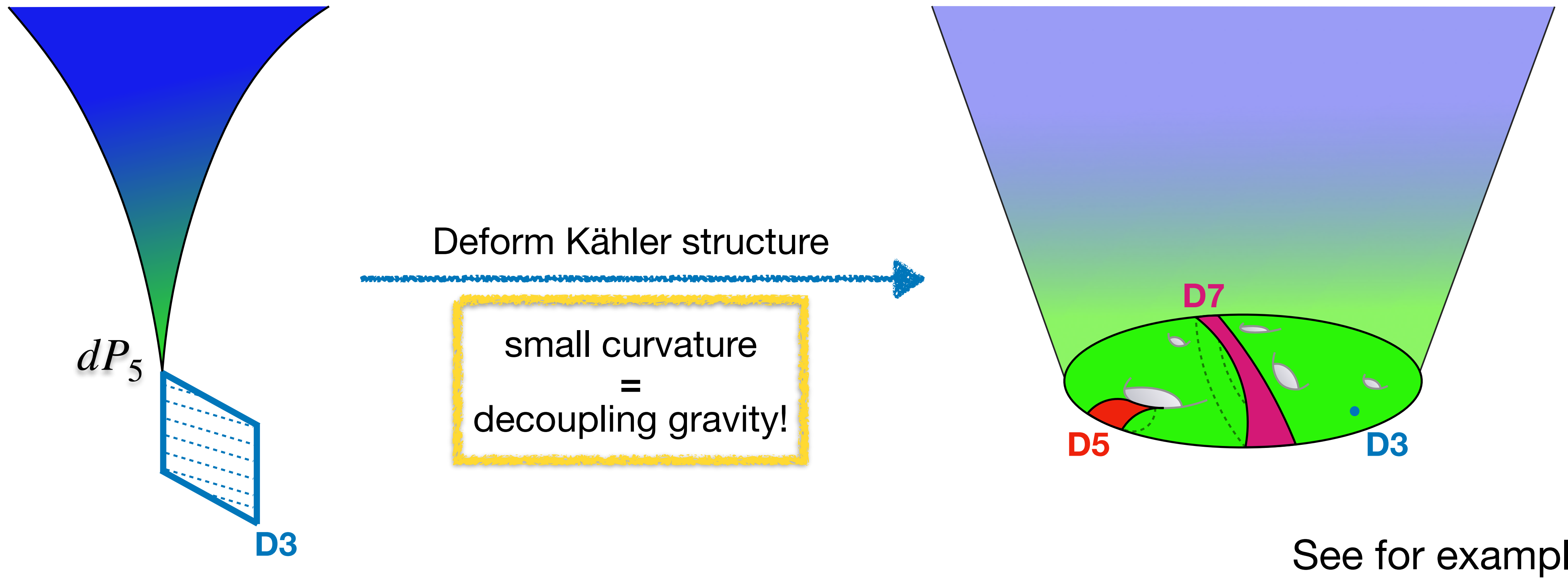
Fractional branes F_i:
Bound states of several D-branes supported on cycles

Spectrum of open strings from **quiver diagrams:**

$\mathrm{U}(N_i)$ (i) ⟷ N_i copies of a fractional brane F_i

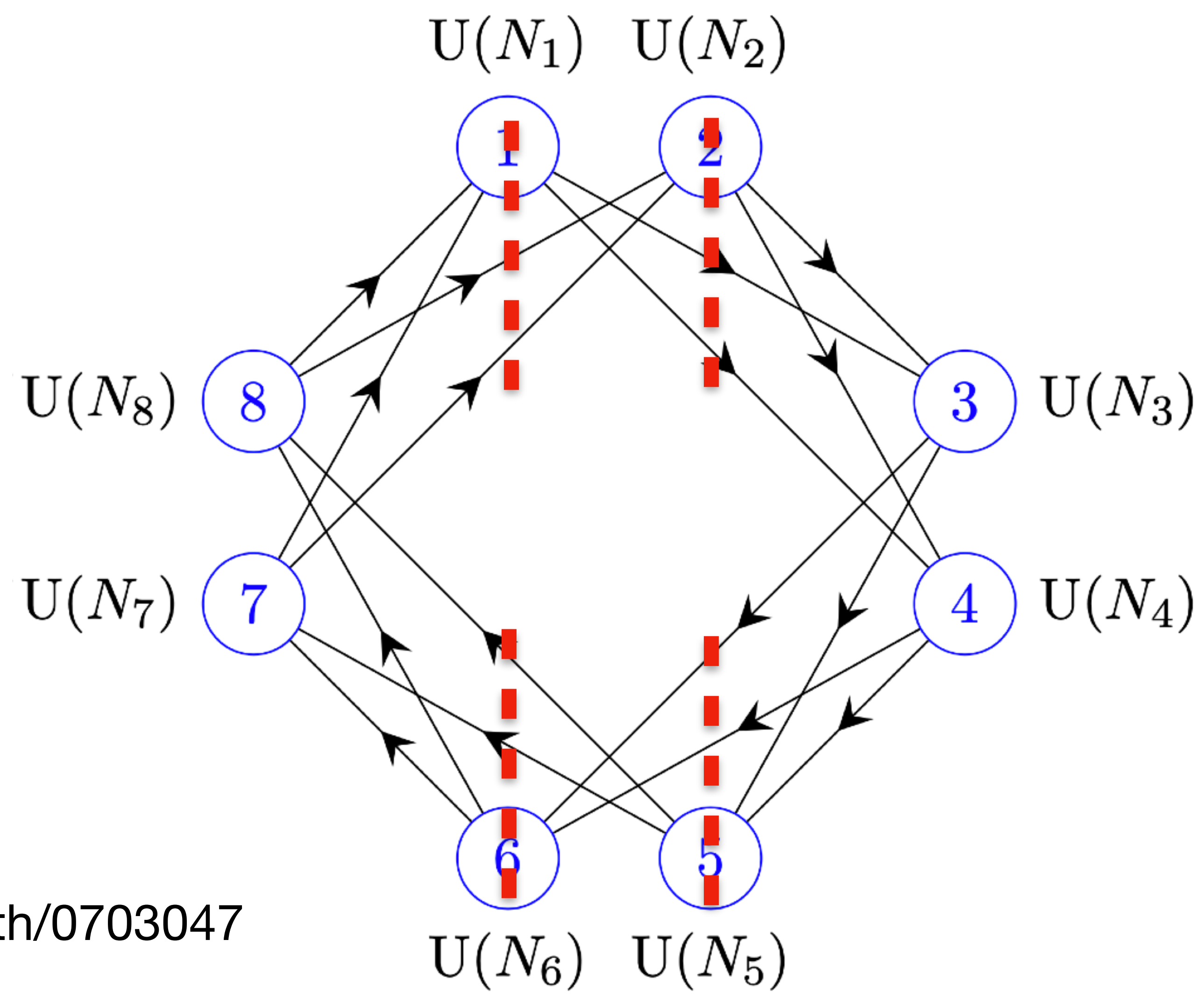
$\mathrm{U}(N_i)$ (i) → (j) $\mathrm{U}(N_j)$ ⟷ Chiral multiplet in bi-fundamental of $U(N_i) \times U(N_j)$

Geometric description of local model in the large volume limit:



See for example:
Wijnholt: hep-th/0212021
Verlinde, Wijnholt: hep-th/0508089

dP_5 quiver diagram:



Wijnholt: hep-th/0703047

Orientifold involution:

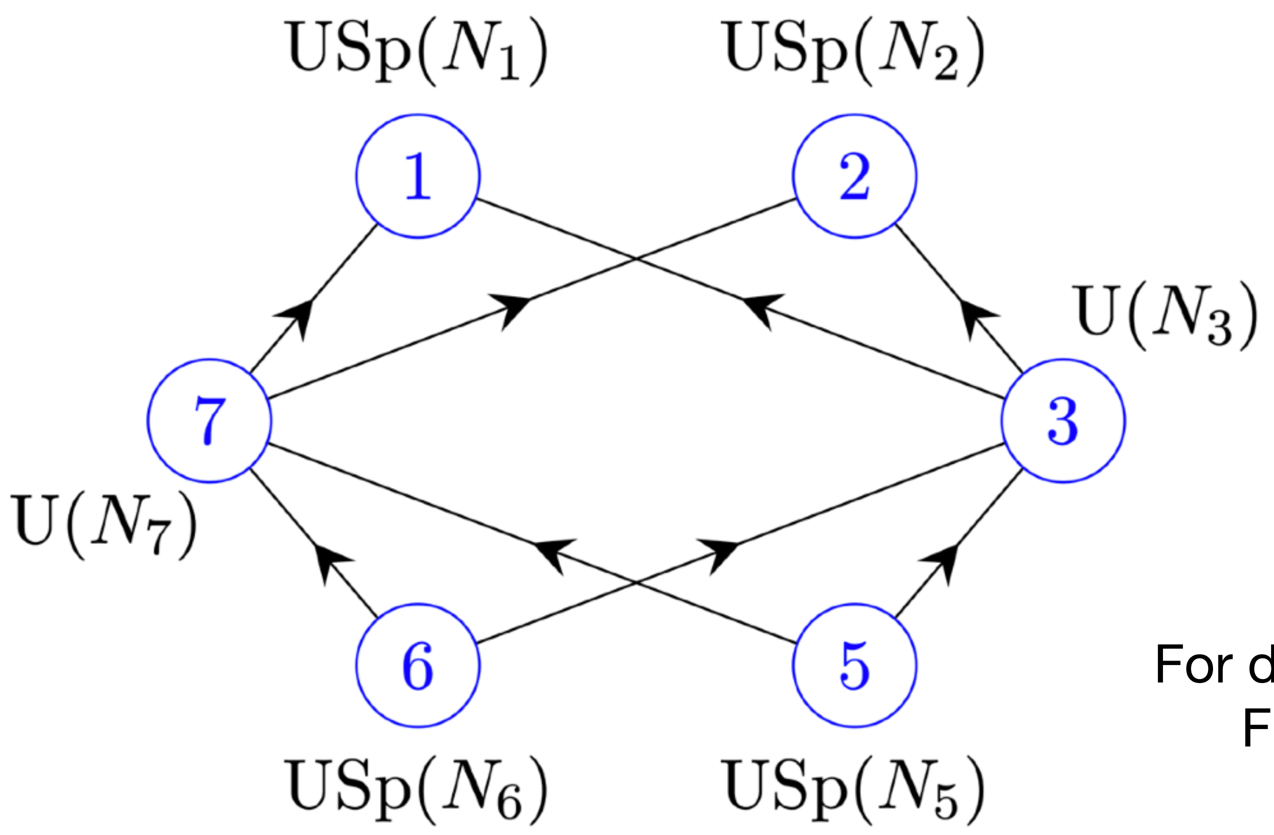
$1 \leftrightarrow 1^*\,,\quad 2 \leftrightarrow 2^*\,,\quad 3 \leftrightarrow 8^*$

$4 \leftrightarrow 7^*\,,\quad 5 \leftrightarrow 5^*\,,\quad 6 \leftrightarrow 6^*$

The Standard Model quiver itself is unoriented!

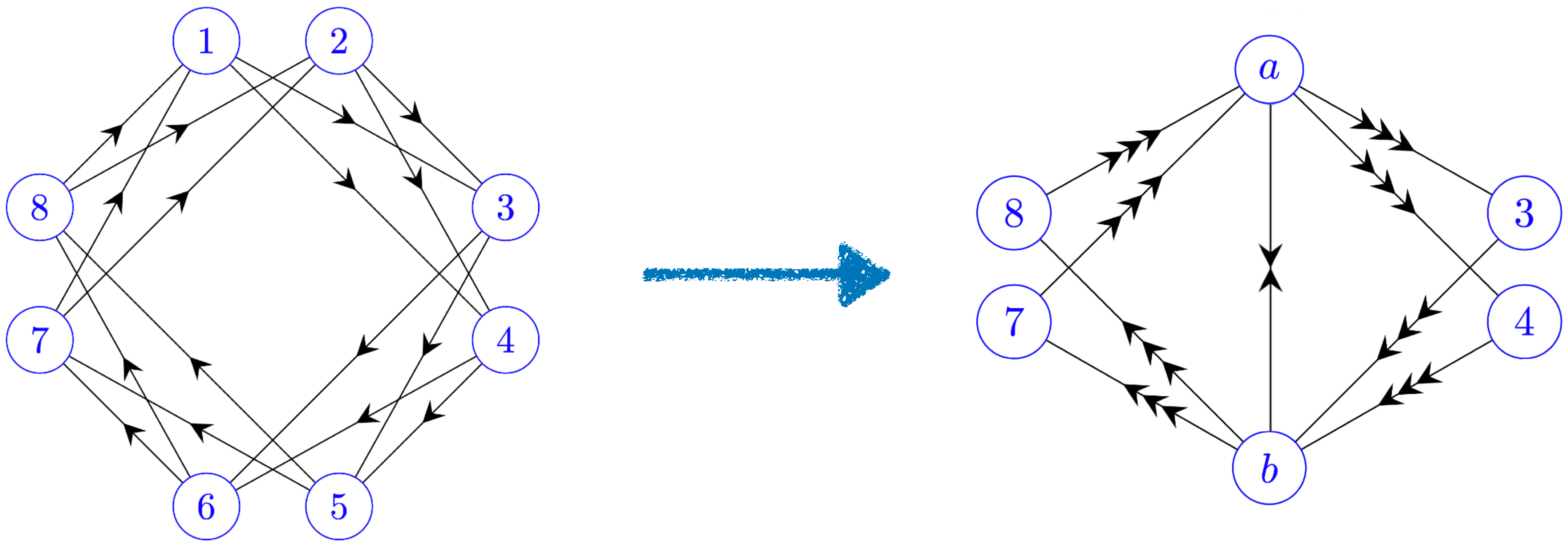
Berenstein, Pinansky: hep-th/0610104

Orientifolded dP_5 quiver diagram:



For details on orientifolded quivers:
Franco, Hanany, Krefl, Park, Uranga, Vegh: 0707.0298
García Etxebarria, Heidenreich, Wrase: 1210.7799

Higgsing the dP_5 quiver gauge theory



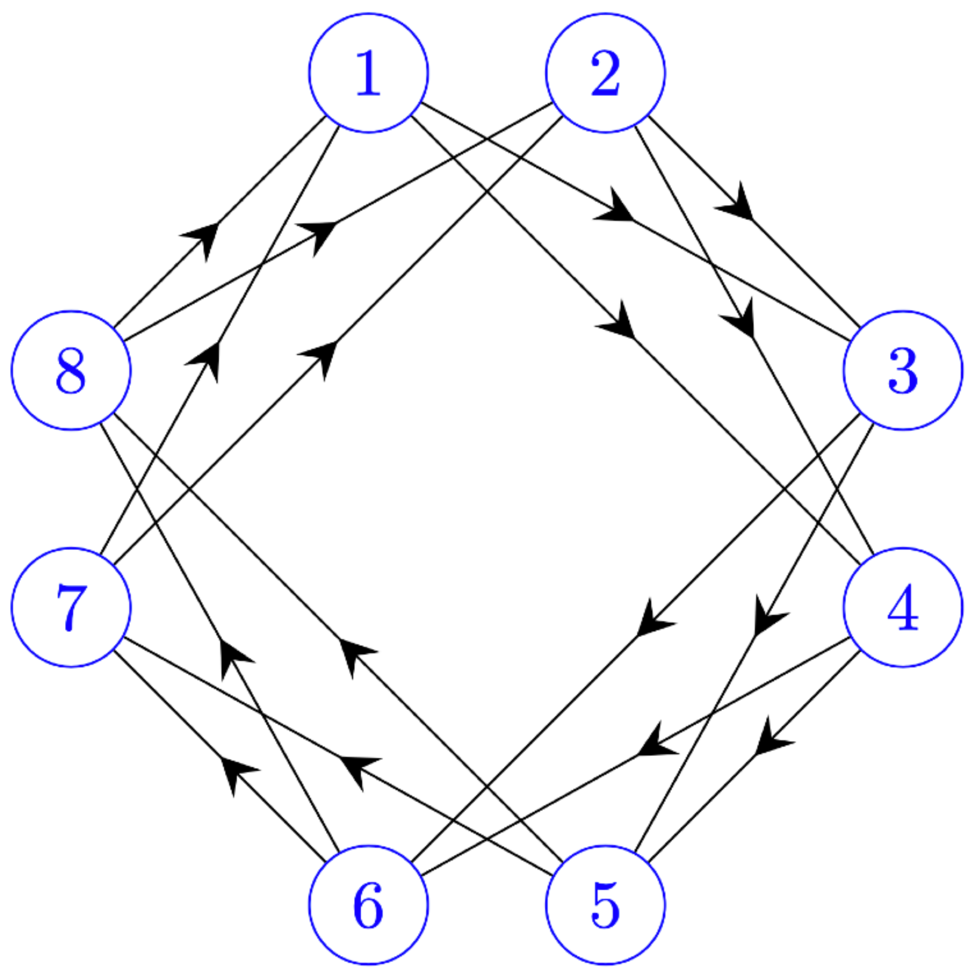
Missing features:

A. Chiral spectrum with 3 families

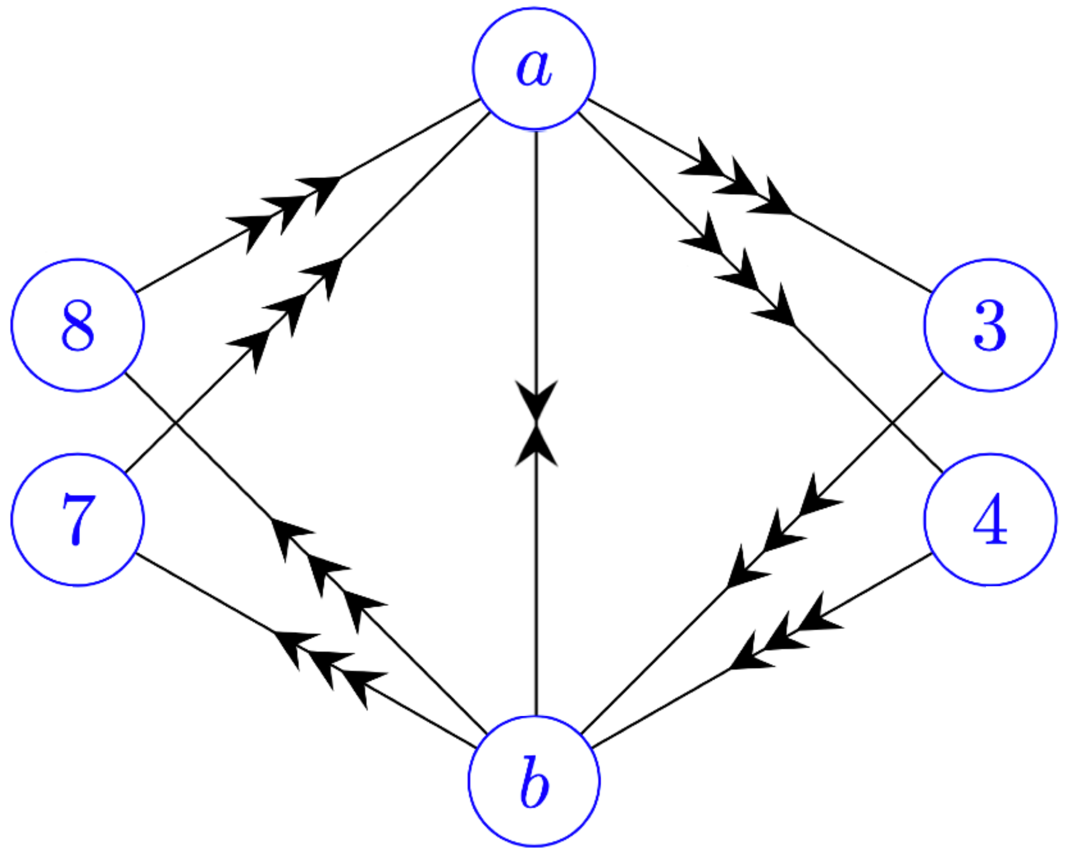
B. Standard Model gauge group

C. Non-chiral matter

Higgsing the dP_5 quiver gauge theory



Higgsing
=
Bound states of
fractional branes



Missing features:

A. Chiral spectrum with 3 families

B. Standard Model gauge group

C. Non-chiral matter

All of the above is achieved by **turning on VEVs for bi-fundamental fields!**

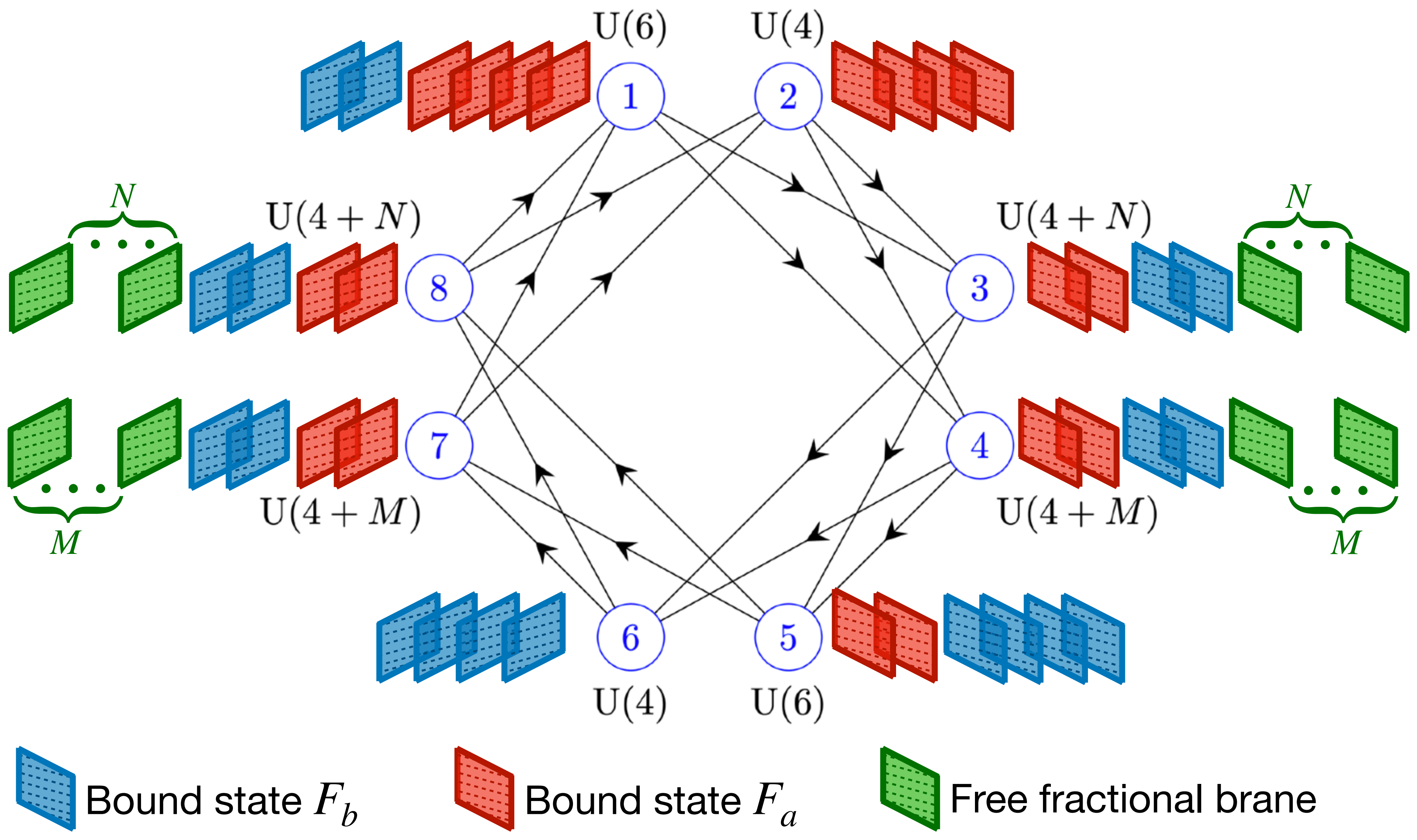
Interpretation:

- **Fractional brane perspective:** bound states of fractional branes

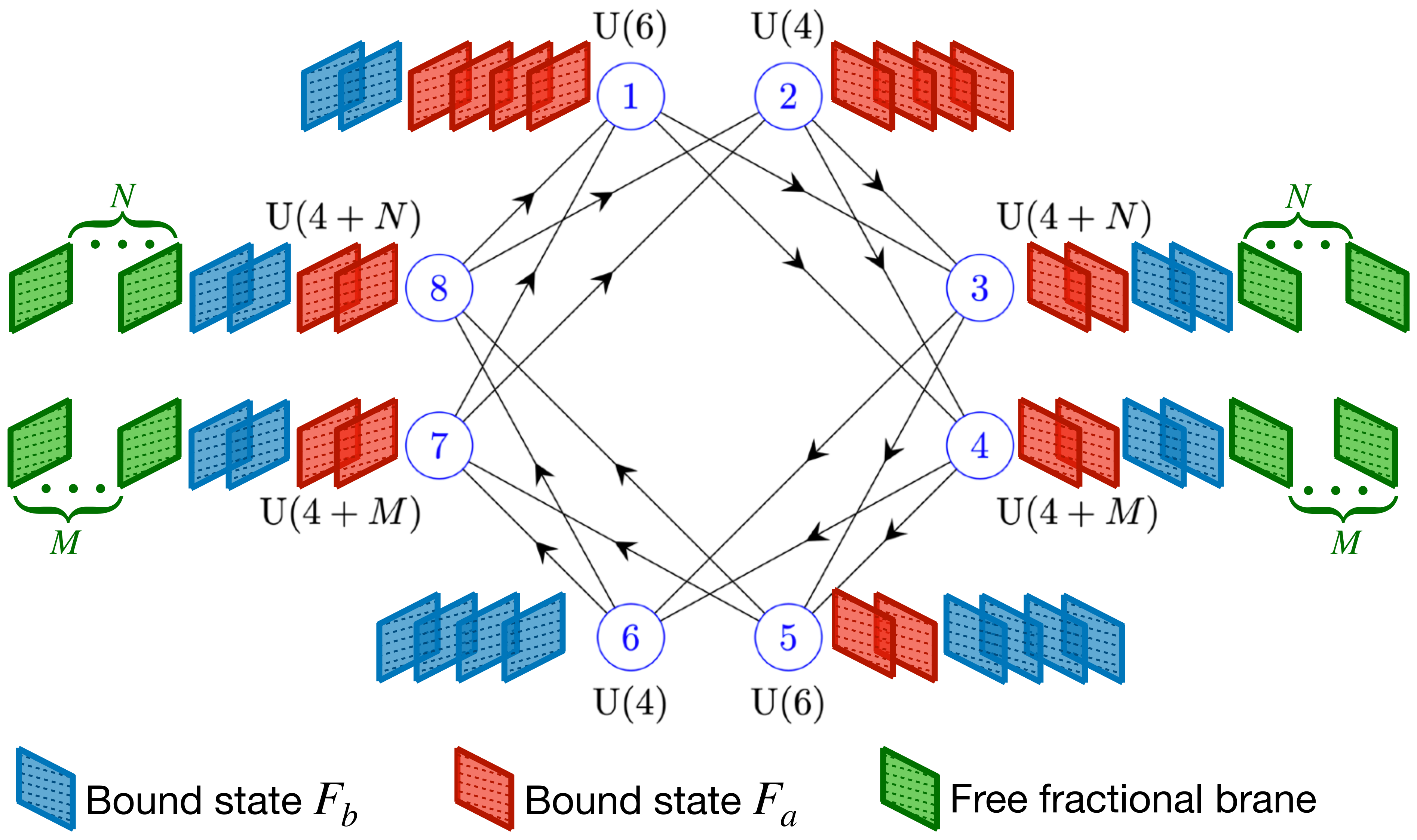
$$\{F_1, \ldots, F_8\} \to \{F_a, F_3, F_4, F_b, F_7, F_8\}$$

- **Geometrically:** partial resolution of singularity

Original quiver



Original quiver



Turn on VEVs:

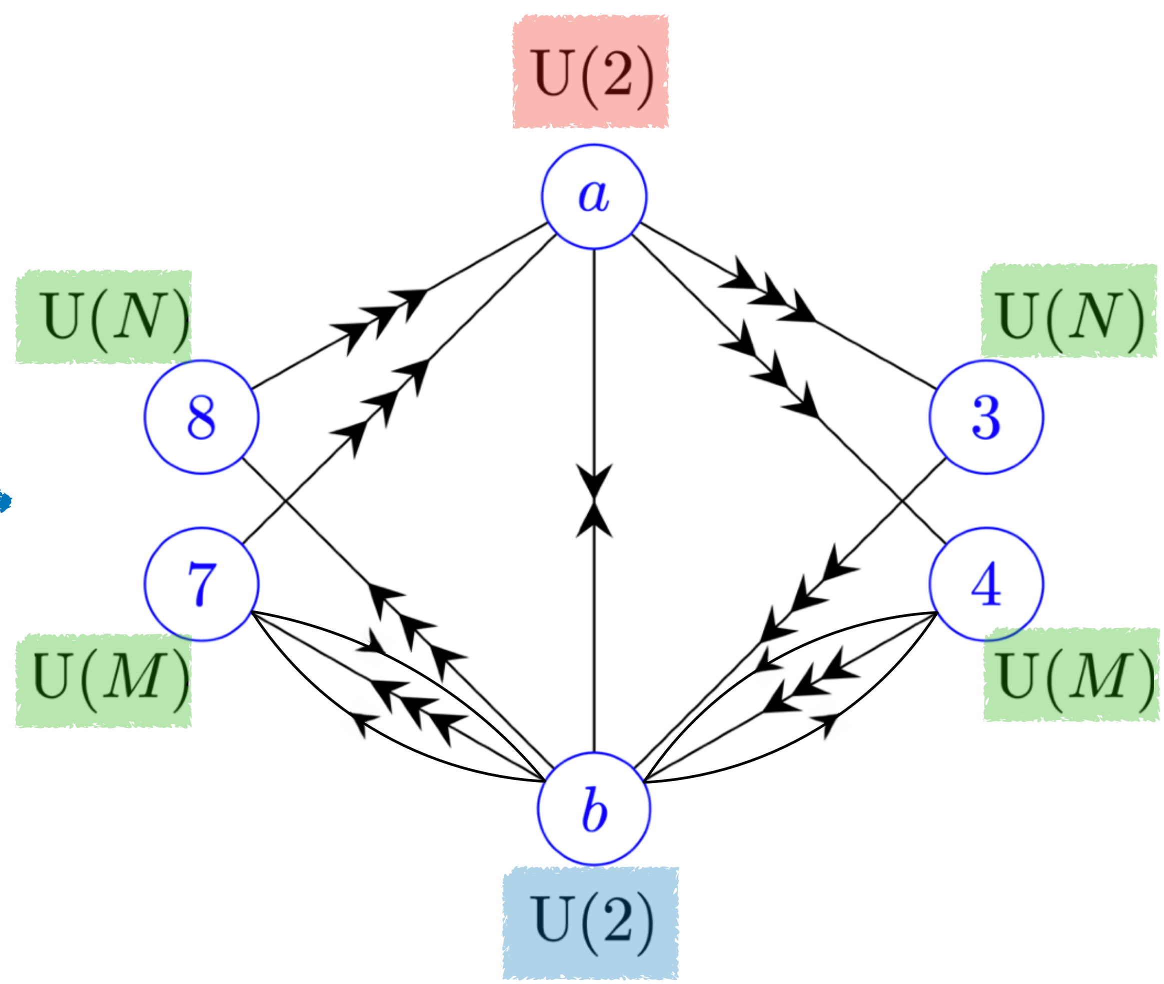
$$\langle X_{13}\rangle = \begin{pmatrix} a_1 & 0 & \cdots \\ 0 & a_2 & \cdots \\ 0 & a_3 & \cdots \end{pmatrix}, \quad \langle X_{14}\rangle = \begin{pmatrix} b_1 & 0 & \cdots \\ 0 & b_2 & \cdots \\ 0 & b_3 & \cdots \end{pmatrix},$$

$$\langle X_{23}\rangle = \begin{pmatrix} 0 & c_1 & \cdots \\ 0 & c_2 & \cdots \end{pmatrix}, \quad \langle X_{24}\rangle = \begin{pmatrix} 0 & d_1 & \cdots \\ 0 & d_2 & \cdots \end{pmatrix},$$

$$\langle X_{35}^T\rangle = \begin{pmatrix} x_1 & 0 & \cdots \\ x_2 & 0 & \cdots \\ 0 & x_3 & \cdots \end{pmatrix}, \quad \langle X_{45}^T\rangle = \begin{pmatrix} z_1 & 0 & \cdots \\ z_2 & 0 & \cdots \\ 0 & z_3 & \cdots \end{pmatrix},$$

$$\langle X_{36}^T\rangle = \begin{pmatrix} y_1 & 0 & \cdots \\ y_2 & 0 & \cdots \end{pmatrix}, \quad \langle X_{46}^T\rangle = \begin{pmatrix} w_1 & 0 & \cdots \\ w_2 & 0 & \cdots \end{pmatrix}$$

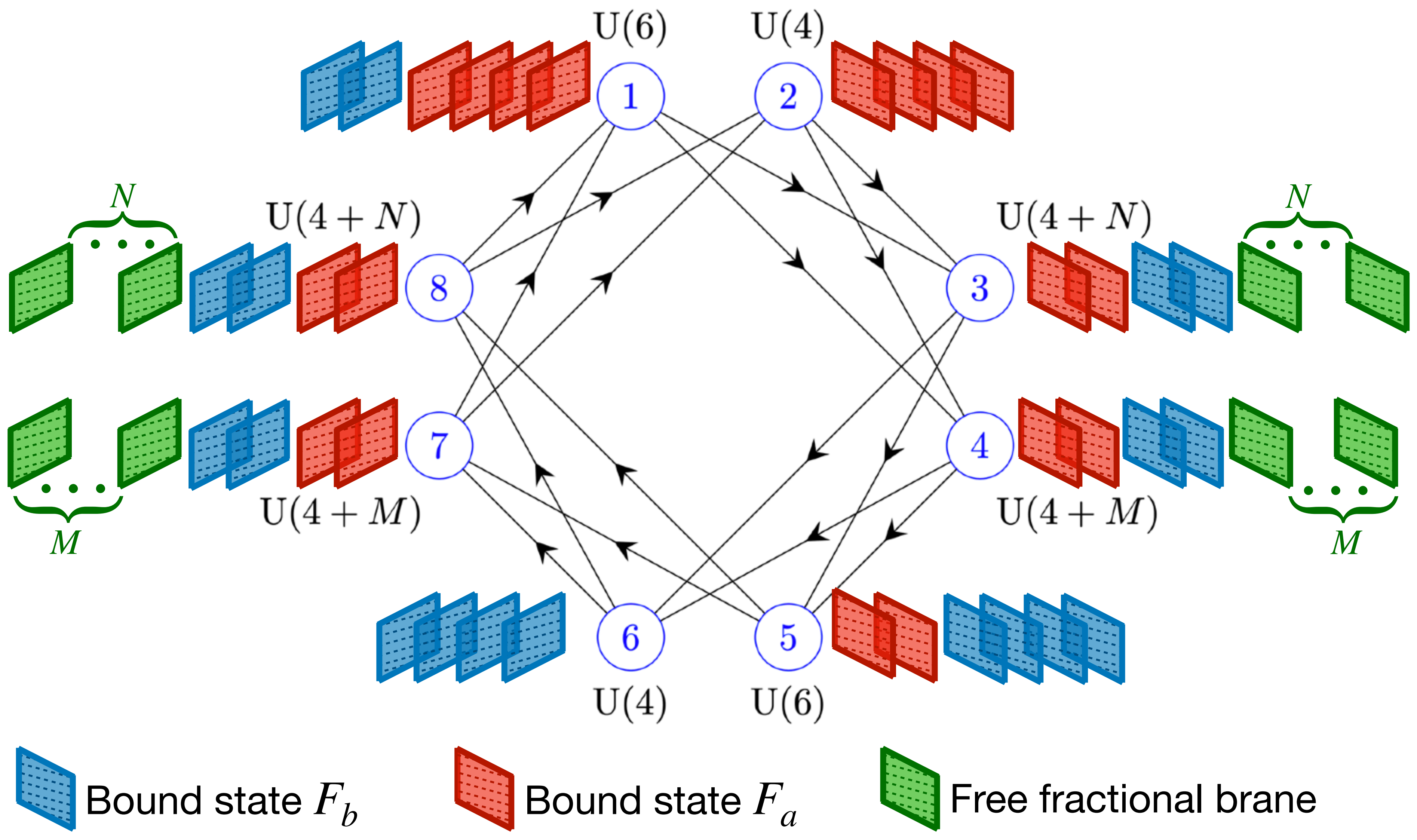
Higgsed quiver



$$G = (\mathrm{U}(6)\times\mathrm{U}(4+N)\times\mathrm{U}(4+M)\times\mathrm{U}(4))^2 \rightarrow H = (\mathrm{U}(2)\times\mathrm{U}(N)\times\mathrm{U}(M))^2$$

Breaking pattern confirmed by computing mass matrix for gauge bosons!

Original quiver



Turn on VEVs:

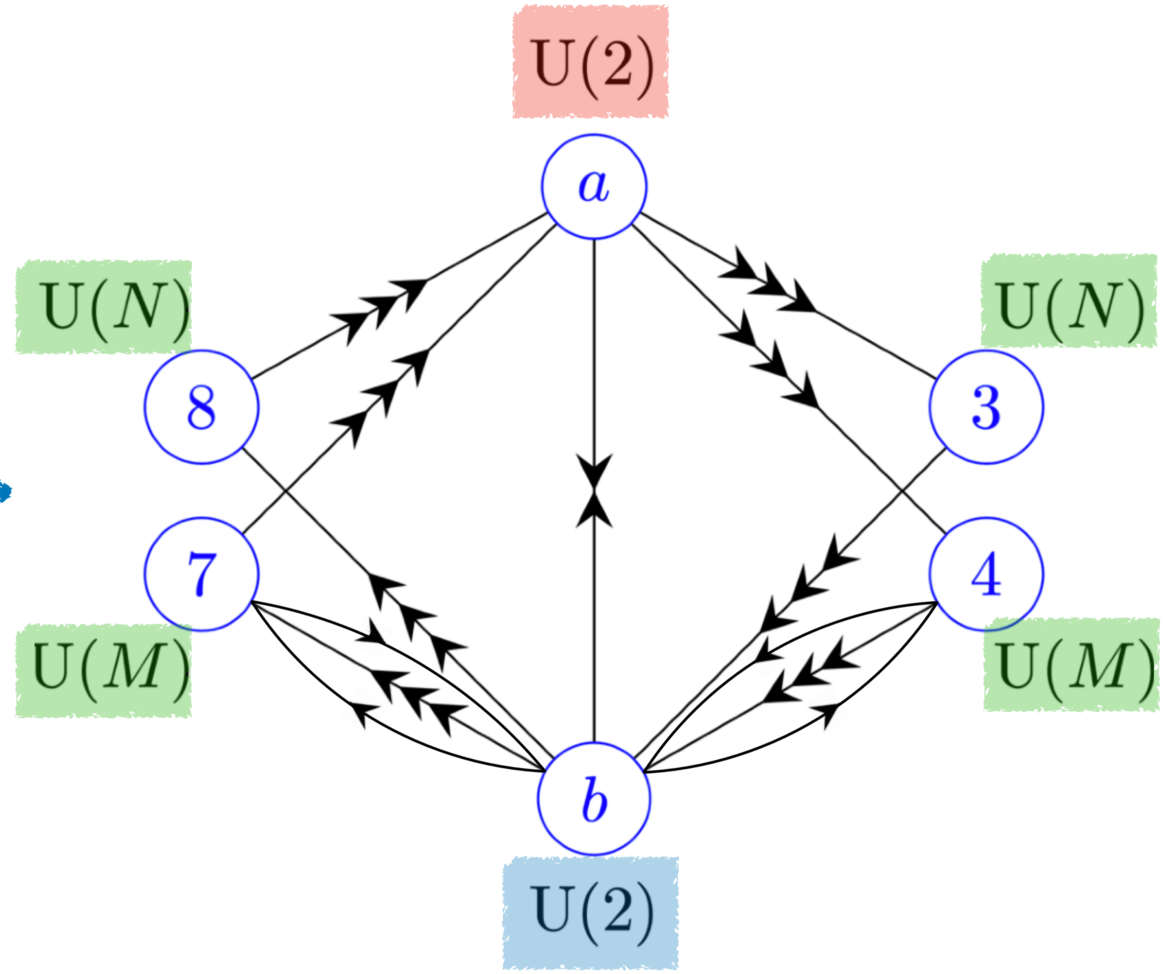
$$\langle X_{13}\rangle = \begin{pmatrix} a_1 & 0 & \cdots \\ 0 & a_2 & \cdots \\ 0 & a_3 & \cdots \end{pmatrix}, \quad \langle X_{14}\rangle = \begin{pmatrix} b_1 & 0 & \cdots \\ 0 & b_2 & \cdots \\ 0 & b_3 & \cdots \end{pmatrix},$$

$$\langle X_{23}\rangle = \begin{pmatrix} 0 & c_1 & \cdots \\ 0 & c_2 & \cdots \end{pmatrix}, \quad \langle X_{24}\rangle = \begin{pmatrix} 0 & d_1 & \cdots \\ 0 & d_2 & \cdots \end{pmatrix},$$

$$\langle X_{35}^T\rangle = \begin{pmatrix} x_1 & 0 & \cdots \\ x_2 & 0 & \cdots \\ 0 & x_3 & \cdots \end{pmatrix}, \quad \langle X_{45}^T\rangle = \begin{pmatrix} z_1 & 0 & \cdots \\ z_2 & 0 & \cdots \\ 0 & z_3 & \cdots \end{pmatrix},$$

$$\langle X_{36}^T\rangle = \begin{pmatrix} y_1 & 0 & \cdots \\ y_2 & 0 & \cdots \end{pmatrix}, \quad \langle X_{46}^T\rangle = \begin{pmatrix} w_1 & 0 & \cdots \\ w_2 & 0 & \cdots \end{pmatrix}$$

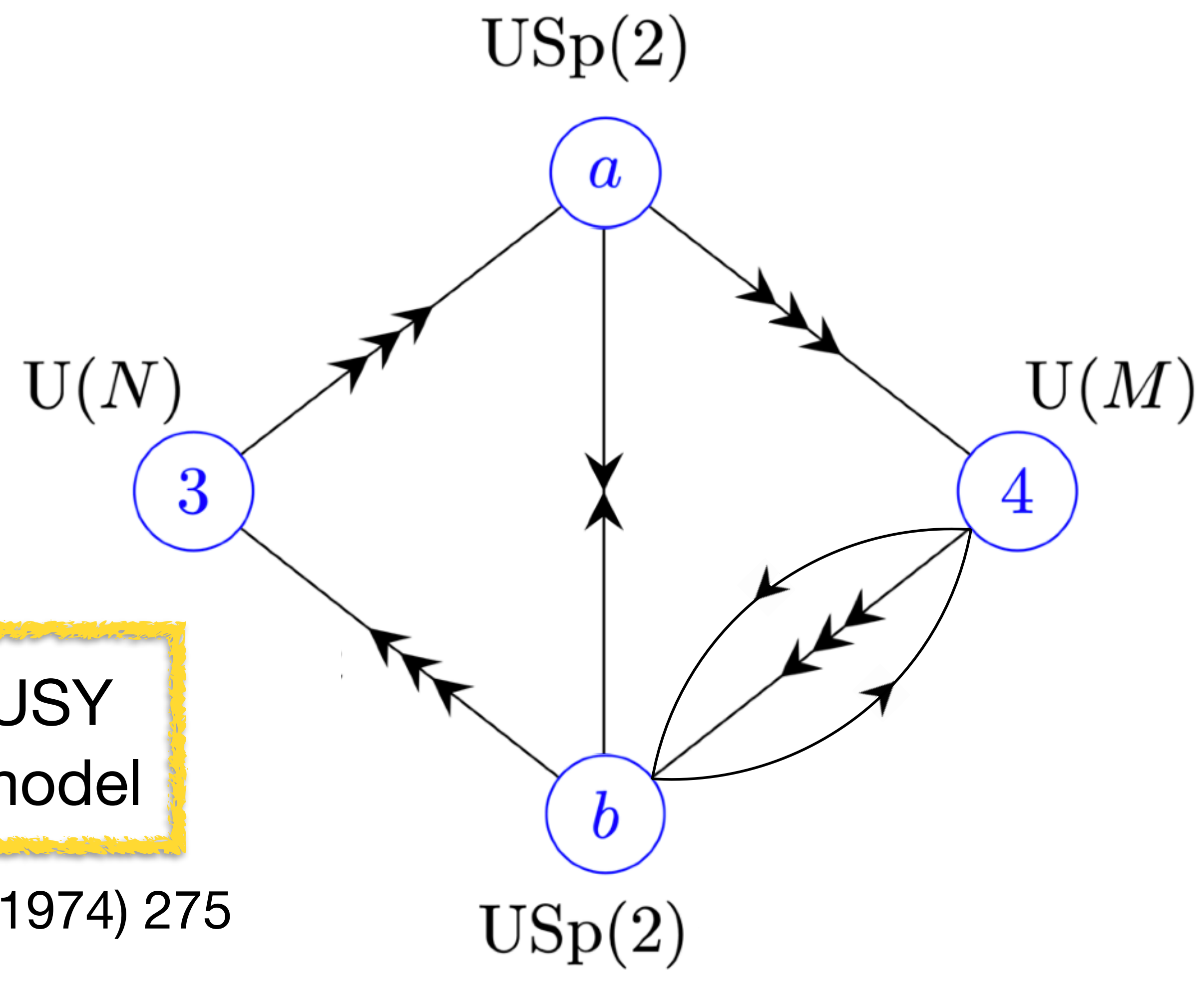
Higgsed quiver



$$G = (\mathrm{U}(6)\times\mathrm{U}(4+N)\times\mathrm{U}(4+M)\times\mathrm{U}(4))^2 \to H = (\mathrm{U}(2)\times\mathrm{U}(N)\times\mathrm{U}(M))^2$$

Breaking pattern confirmed by computing mass matrix for gauge bosons!

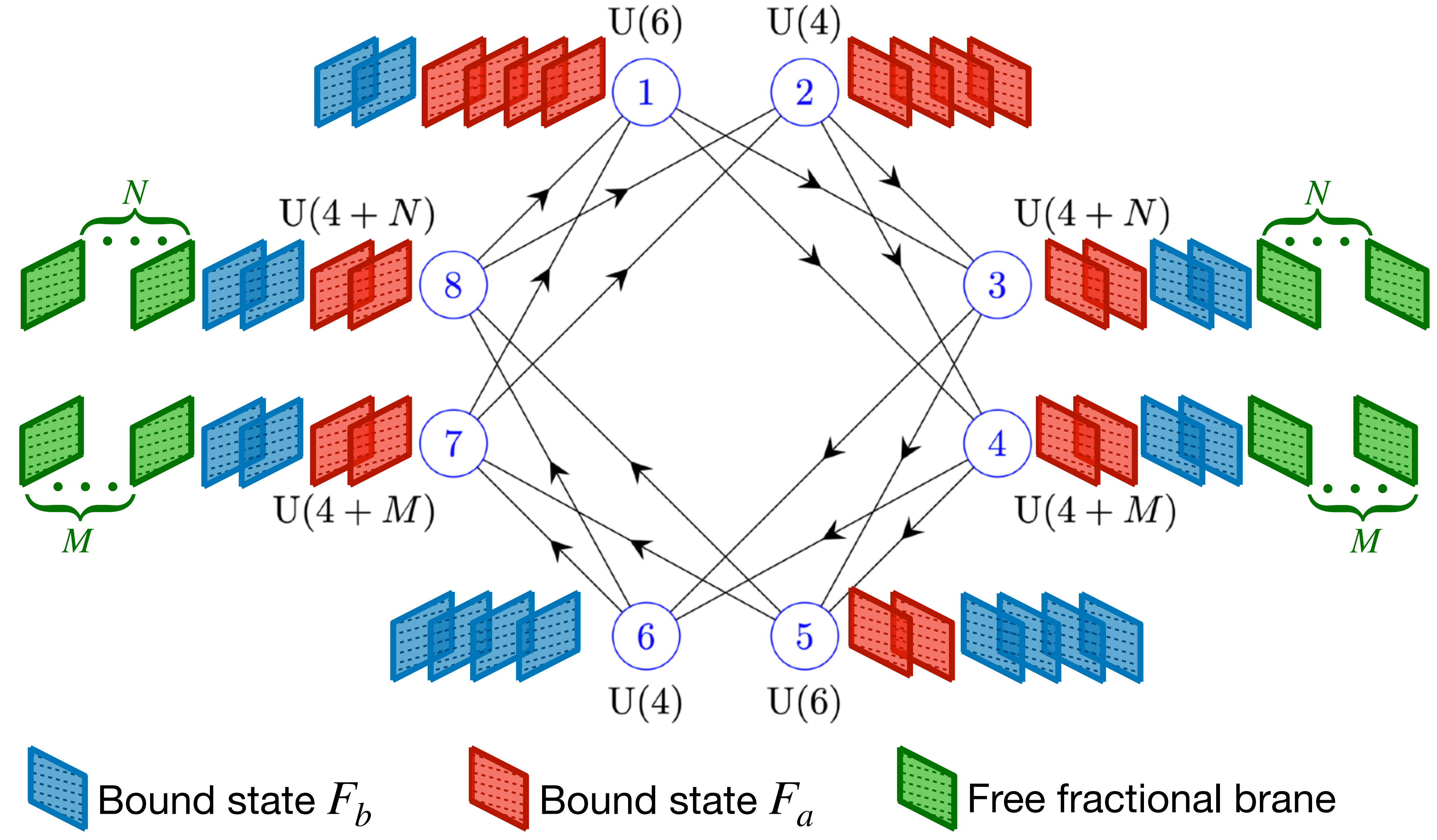
Higgsed, orientifolded quiver



For $N = 3, M = 1$: SUSY Left-Right symmetric model

Pati, Salam: Phys. Rev. D10 (1974) 275

Original quiver



Turn on VEVs:

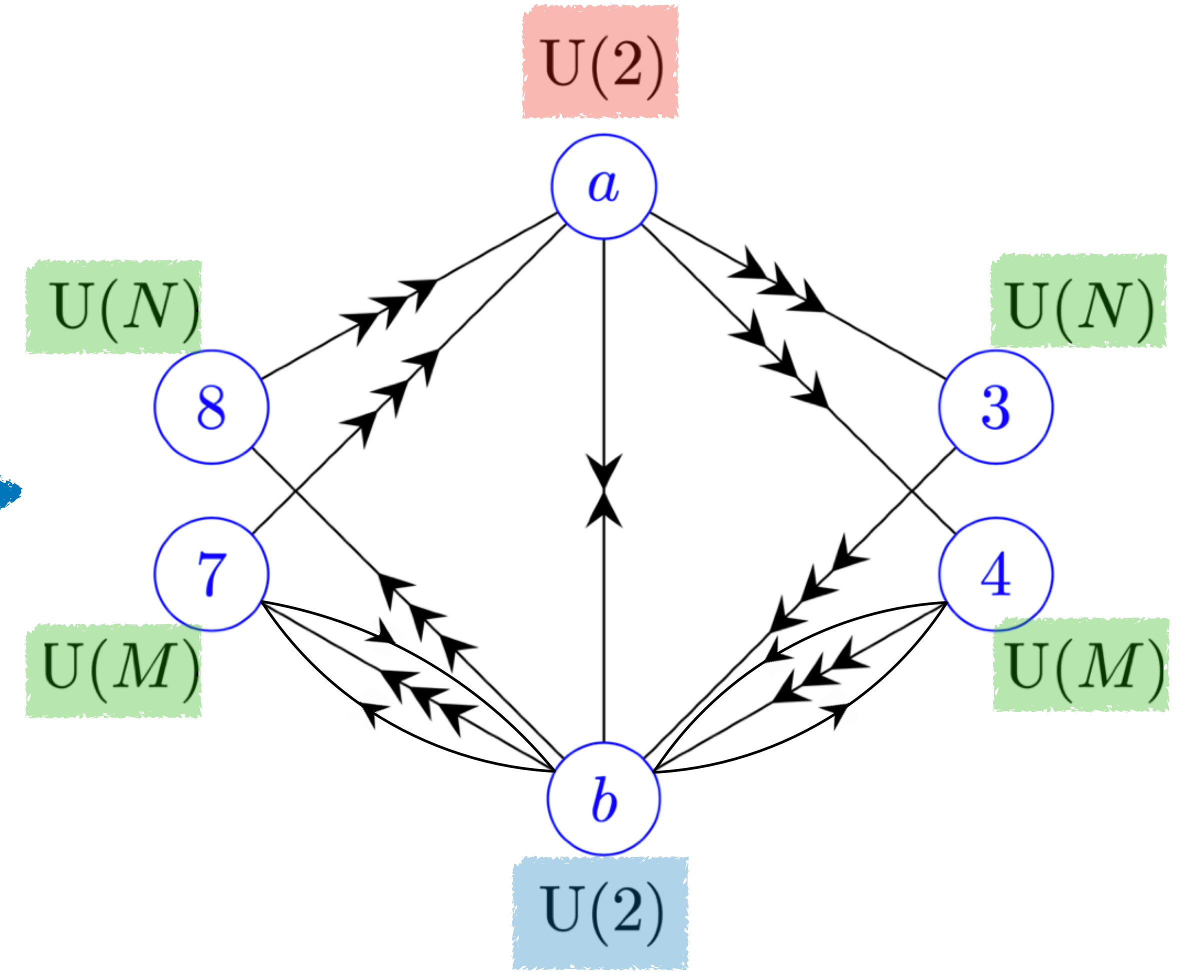
$$\langle X_{13}\rangle = \begin{pmatrix} a_1 & 0 & \cdots \\ 0 & a_2 & \cdots \\ 0 & a_3 & \cdots \end{pmatrix}, \quad \langle X_{14}\rangle = \begin{pmatrix} b_1 & 0 & \cdots \\ 0 & b_2 & \cdots \\ 0 & b_3 & \cdots \end{pmatrix},$$

$$\langle X_{23}\rangle = \begin{pmatrix} 0 & c_1 & \cdots \\ 0 & c_2 & \cdots \end{pmatrix}, \quad \langle X_{24}\rangle = \begin{pmatrix} 0 & d_1 & \cdots \\ 0 & d_2 & \cdots \end{pmatrix},$$

$$\langle X^T_{35}\rangle = \begin{pmatrix} x_1 & 0 & \cdots \\ x_2 & 0 & \cdots \\ 0 & x_3 & \cdots \end{pmatrix}, \quad \langle X^T_{45}\rangle = \begin{pmatrix} z_1 & 0 & \cdots \\ z_2 & 0 & \cdots \\ 0 & z_3 & \cdots \end{pmatrix},$$

$$\langle X^T_{36}\rangle = \begin{pmatrix} y_1 & 0 & \cdots \\ y_2 & 0 & \cdots \end{pmatrix}, \quad \langle X^T_{46}\rangle = \begin{pmatrix} w_1 & 0 & \cdots \\ w_2 & 0 & \cdots \end{pmatrix}$$

Higgsed quiver

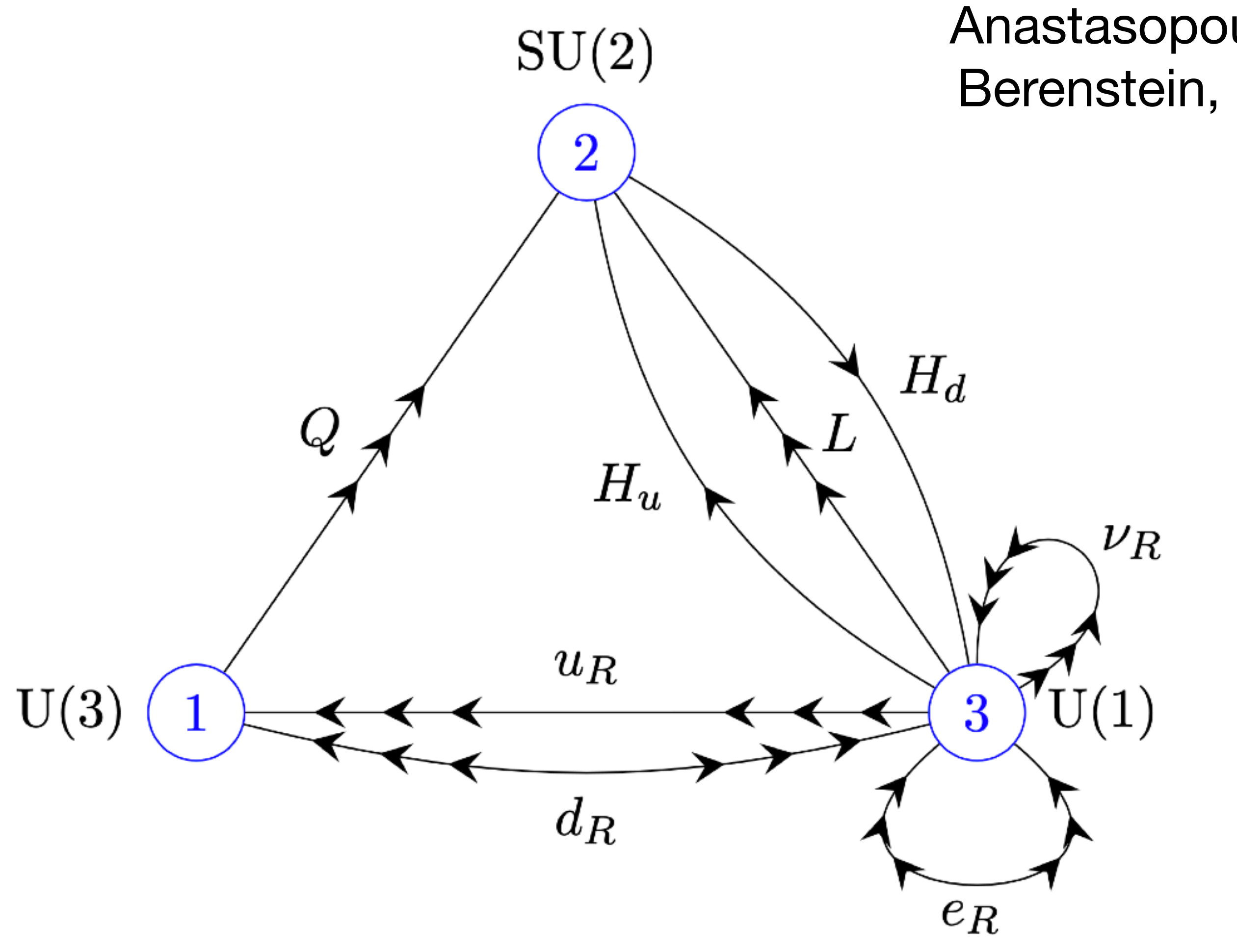


$G = (\mathrm{U}(6)\times \mathrm{U}(4+N)\times \mathrm{U}(4+M)\times \mathrm{U}(4))^2 \to H = (\mathrm{U}(2)\times \mathrm{U}(N)\times \mathrm{U}(M))^2$

Breaking pattern confirmed by computing mass matrix for gauge bosons!

Minimal Quiver Standard Model:

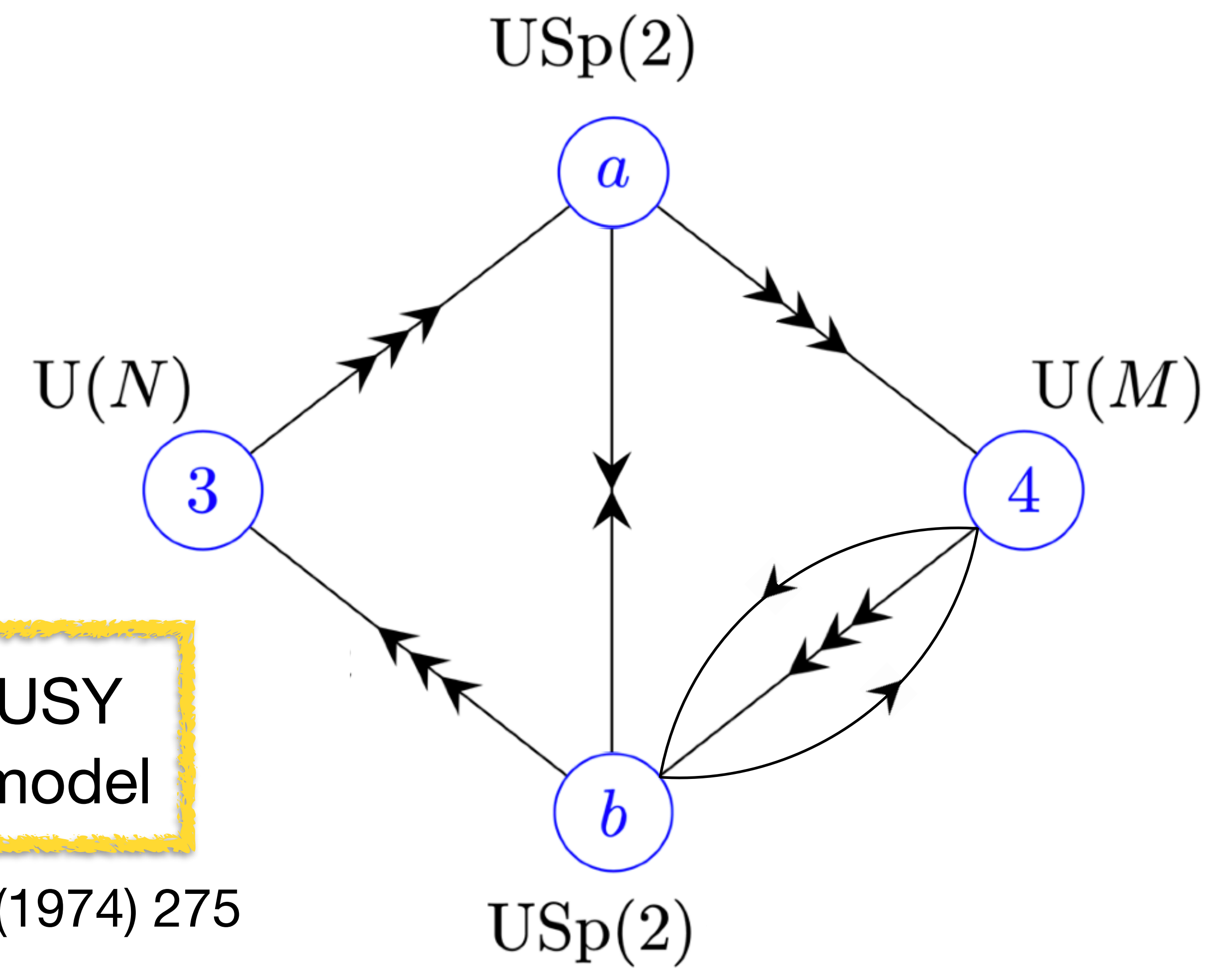
Anastasopoulos et al.: hep-th/0605226
Berenstein, Pinansky: hep-th/0610104



Conventional Higgsing
$SU(2)_R \times U(1)_{B-L} \to U(1)_Y$

See e.g. Heckman, Vafa, Verlinde, Wijnholt: 0711.0387

Higgsed, orientifolded quiver

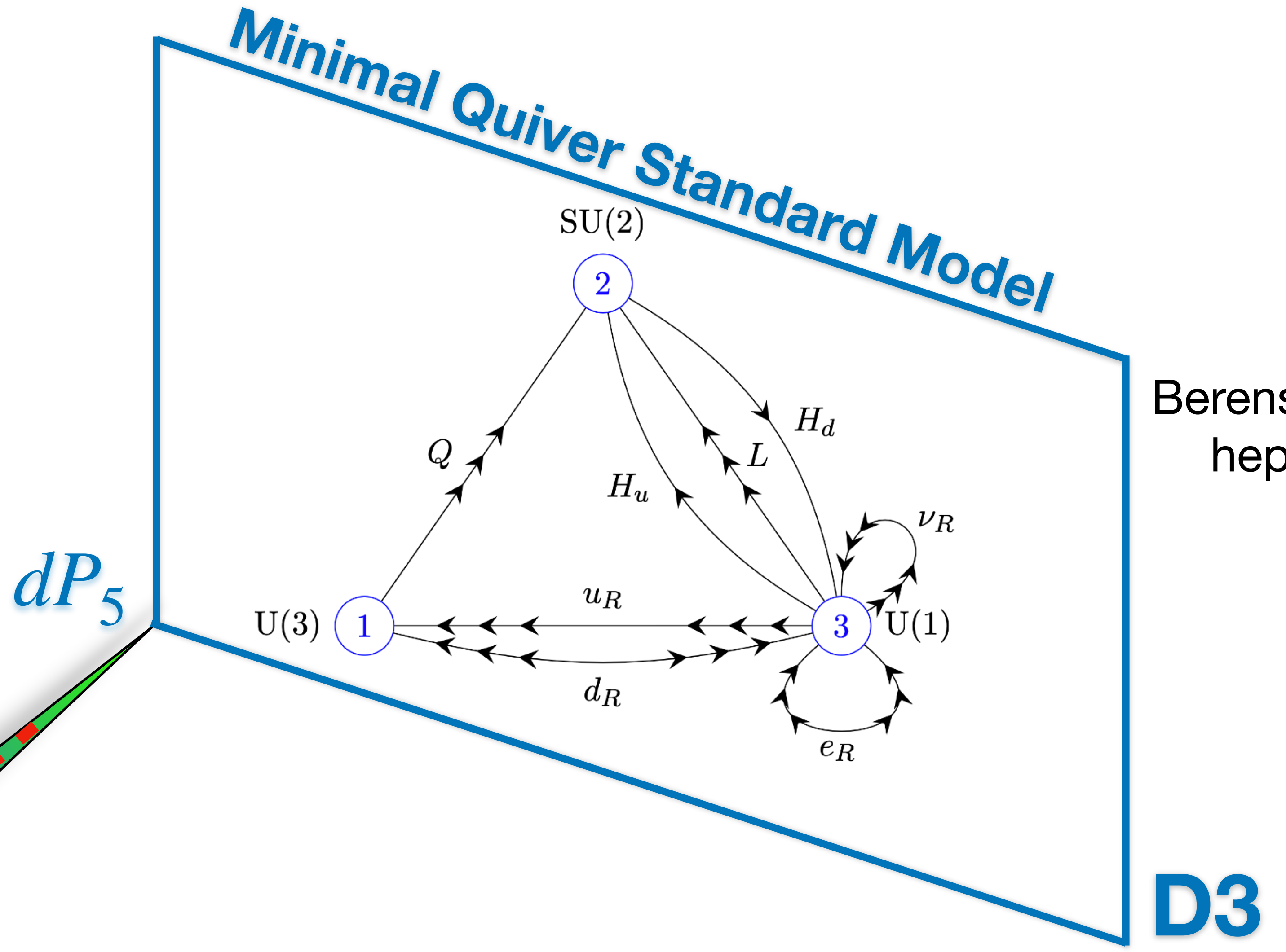


For $N = 3, M = 1$: SUSY Left-Right symmetric model

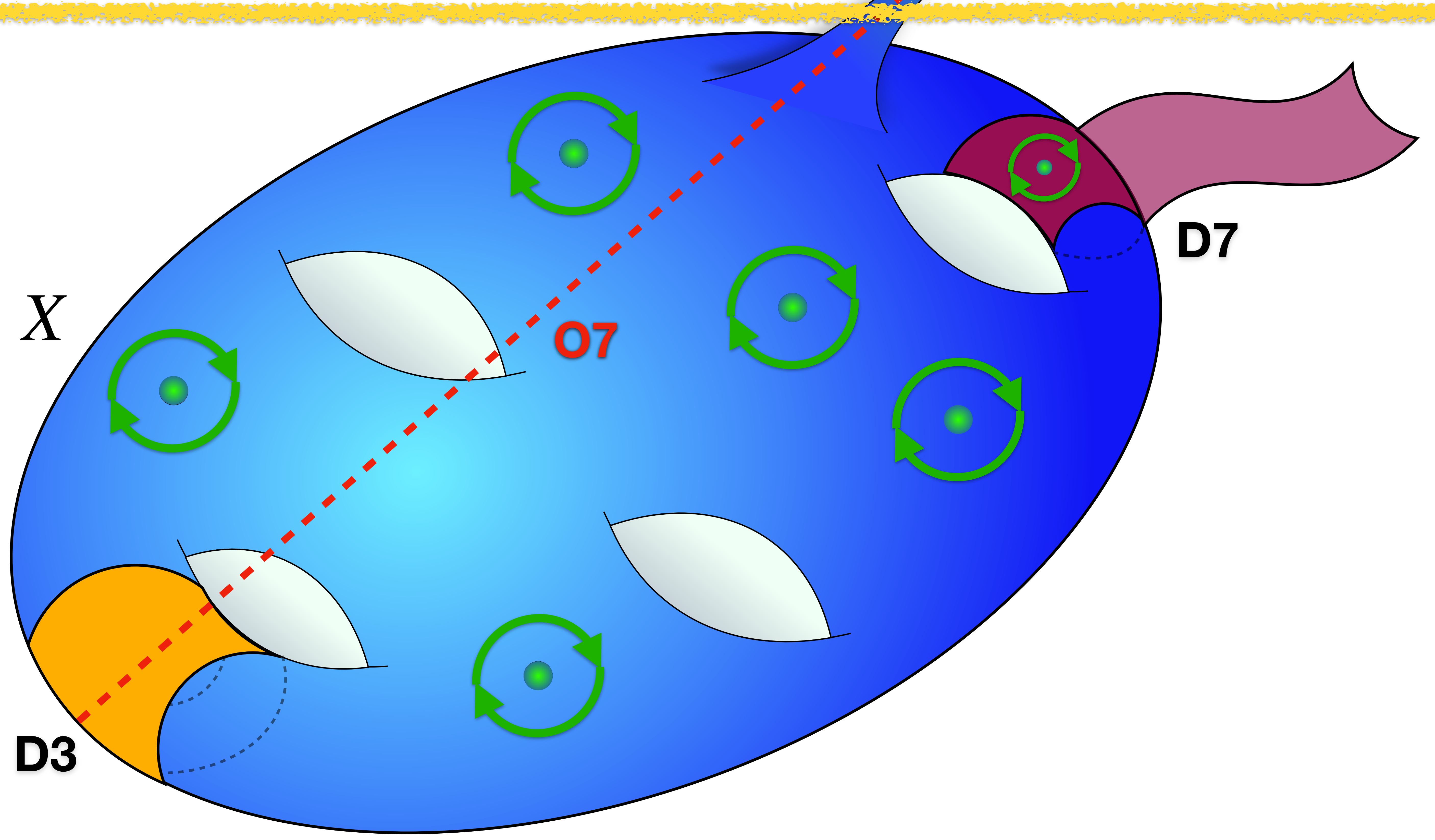
Pati, Salam: Phys. Rev. D10 (1974) 275

Local model building:

- Choice of singularity
- Standard Model gauge group
- Spectrum of 3 chiral families
- Non-chiral matter
- Global anomalous U(1)'s
- Hierarchies in Yukawas
- …



Berenstein, Pinansky:
hep-th/0610104



Global aspects:

- Compact Calabi-Yau manifold X
- Flux background
- D-brane and O-plane configuration
- Tadpole cancellation
- Moduli stabilisation in de Sitter minima
- …

The search for a global model in the KS database

For a del Pezzo divisor D_s of type dP_n

$$\int_{X_3} D_s^3 = k_{sss} = 9 - n\,, \qquad \int_{X_3} D_s^2\, D_i \leq 0 \qquad \forall\, i \neq s$$

Diagonality condition for dP_5

$$k_{sss}\; k_{sij} = k_{ssi}\; k_{ssj} \quad \forall\;\; i,j$$

Necessary condition to ensure correct singularity structure!

4-cycle volume becomes complete square

$$\tau_s = \frac{1}{2}\, k_{sij} t^i\, t^j = \frac{1}{2\, k_{sss}}\; \left(k_{ssi}\, t^i\right)^2$$

Refer to diagonal dP_n divisor D_s as ddP_n **divisor**

We looked at the divisor structure of CY geometries in the Kreuzer-Skarke (KS) database with $h^{1,1} \leq 5$

Kreuzer, Skarke: hep-th/0002240

$h^{1,1}$	Poly*	Geom*	dP_0	dP_1 or $\mathbb{F}_0$	dP_2	dP_3	dP_4	dP_5	dP_6	dP_7	dP_8
1	5	5	0	0	0	0	0	0	0	0	0
2	36	39	9	4	0	0	0	0	2	4	5
3	243	305	55	88	4	4	2	9	20	62	64
4	1185	2000	304	767	146	135	52	175	213	566	506
5	4897	13494	2107	6518	1960	2094	880	2005	2011	4358	3837

Distinct favourable polytopes and geometries

$h^{1,1}$	Poly*	Geom* (n_{CY})	ddP_0	$d\mathbb{F}_0$	ddP_n $1 \leq n \leq 5$	ddP_6	ddP_7	ddP_8	n_{LVS} ($\mathrm{ddP}_n \geq 1$)
1	5	5	0	0	0	0	0	0	0
2	36	39	9	2	0	2	4	5	22
3	243	305	55	16	0	16	37	34	132
4	1185	2000	304	140	0	97	210	126	750
5	4897	13494	2107	901	0	486	731	374	4104

Kreuzer-Skarke ddP_n conjecture:

Calabi-Yau threefolds arising from fine, regular, star triangulations of 4d reflexive polytopes in the Kreuzer-Skarke database do not exhibit diagonal dP_n divisors with $1 \leq n \leq 5$

Further checks of ~300.000 distinct geometries at $6 \leq h^{1,1} \leq 40$ with ***CYTools*** confirm this trend!

Demirtas, McAllister, Rios-Tascon: 2008.01730

Global model construction

Let us focus on specific model with $(h^{2,1}, h^{1,1}) = (52,4)$

HY_1	HY_2	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
4	4	1	0	0	0	2	2	1	1	1
2	2	0	1	0	0	1	1	0	0	1
2	2	0	0	1	0	1	1	0	1	0
2	2	0	0	0	1	1	1	1	0	0
		NdP_{17}	dP_5	dP_5	dP_5	SD1	SD1	SD2	SD2	SD2

Euler characteristic

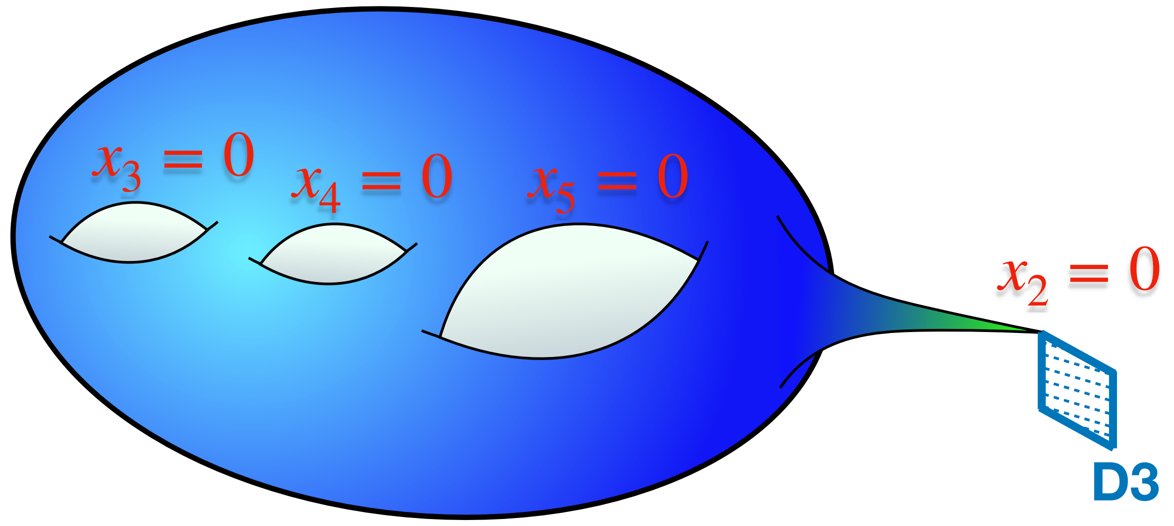
$$\chi = -96$$

Construction plan:
CY threefolds as complete intersections of 2 equations in a 5-dimensional toric space

Stanley-Reisner ideal

$$SR = \{x_2x_3,\ x_2x_4,\ x_2x_9,\ x_3x_4,\ x_4x_7,\ x_1x_7x_9,\ x_3x_5x_6x_8,\ x_1x_5x_6x_7x_8,\ x_1x_5x_6x_8x_9\}$$

We take the singular limit $t_2 \to 0$ which gives rise to a dP_5 singularity!



Global model construction

Let us focus on specific model with $(h^{2,1}, h^{1,1}) = (52,4)$

HY_1	HY_2	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
4	4	1	0	0	0	2	2	1	1	1
2	2	0	1	0	0	1	1	0	0	1
2	2	0	0	1	0	1	1	0	1	0
2	2	0	0	0	1	1	1	1	0	0
		NdP_{17}	dP_5	dP_5	dP_5	SD1	SD1	SD2	SD2	SD2

Euler characteristic

$$\chi = -96$$

Construction plan:

CY threefolds as complete intersections of 2 equations in a 5-dimensional toric space

Stanley-Reisner ideal

$$SR = \{x_2x_3,\ x_2x_4,\ x_2x_9,\ x_3x_4,\ x_4x_7,\ x_1x_7x_9,\ x_3x_5x_6x_8,\ x_1x_5x_6x_7x_8,\ x_1x_5x_6x_8x_9\}$$

We take the singular limit $t_2 \to 0$ which gives rise to a dP_5 singularity!

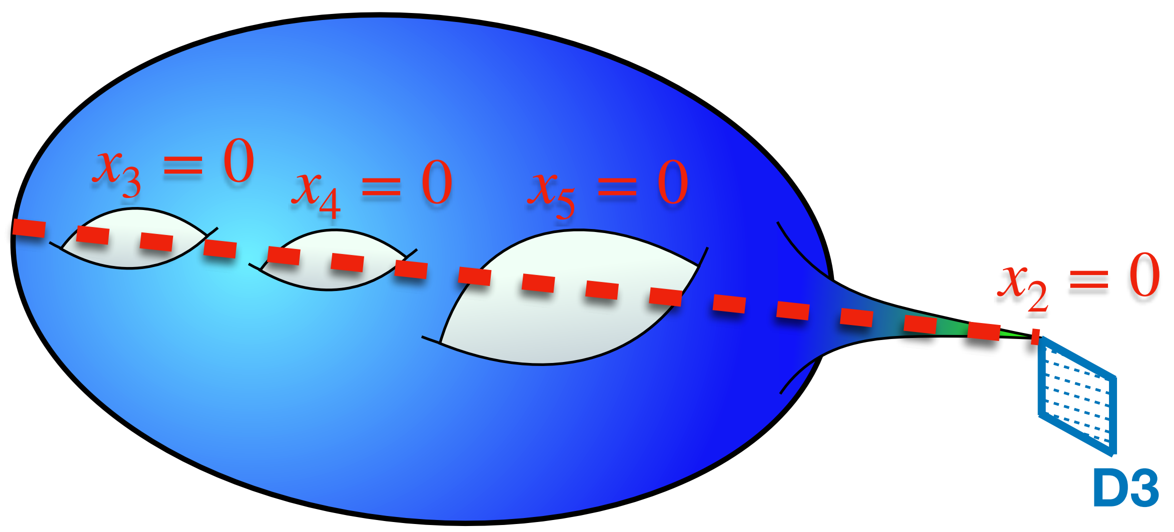
Orientifold involution

$$\sigma\ :\ x_5 \mapsto -x_5$$

Single O7-plane on

$$D_5 = 2D_b - D_2 - D_3 - D_4$$

We checked that the local model can indeed be embedded as well as that the **global and local involutions are consistent!**



Global model construction

Let us focus on specific model with $(h^{2,1}, h^{1,1}) = (52,4)$

HY_1	HY_2	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
4	4	1	0	0	0	2	2	1	1	1
2	2	0	1	0	0	1	1	0	0	1
2	2	0	0	1	0	1	1	0	1	0
2	2	0	0	0	1	1	1	1	0	0
		NdP_{17}	dP_5	dP_5	dP_5	SD1	SD1	SD2	SD2	SD2

Euler characteristic

$$\chi = -96$$

Construction plan:
CY threefolds as complete intersections of 2 equations in a 5-dimensional toric space

Stanley-Reisner ideal

$$SR = \{x_2x_3,\ x_2x_4,\ x_2x_9,\ x_3x_4,\ x_4x_7,\ x_1x_7x_9,\ x_3x_5x_6x_8,\ x_1x_5x_6x_7x_8,\ x_1x_5x_6x_8x_9\}$$

We take the singular limit $t_2 \to 0$ which gives rise to a dP_5 singularity!

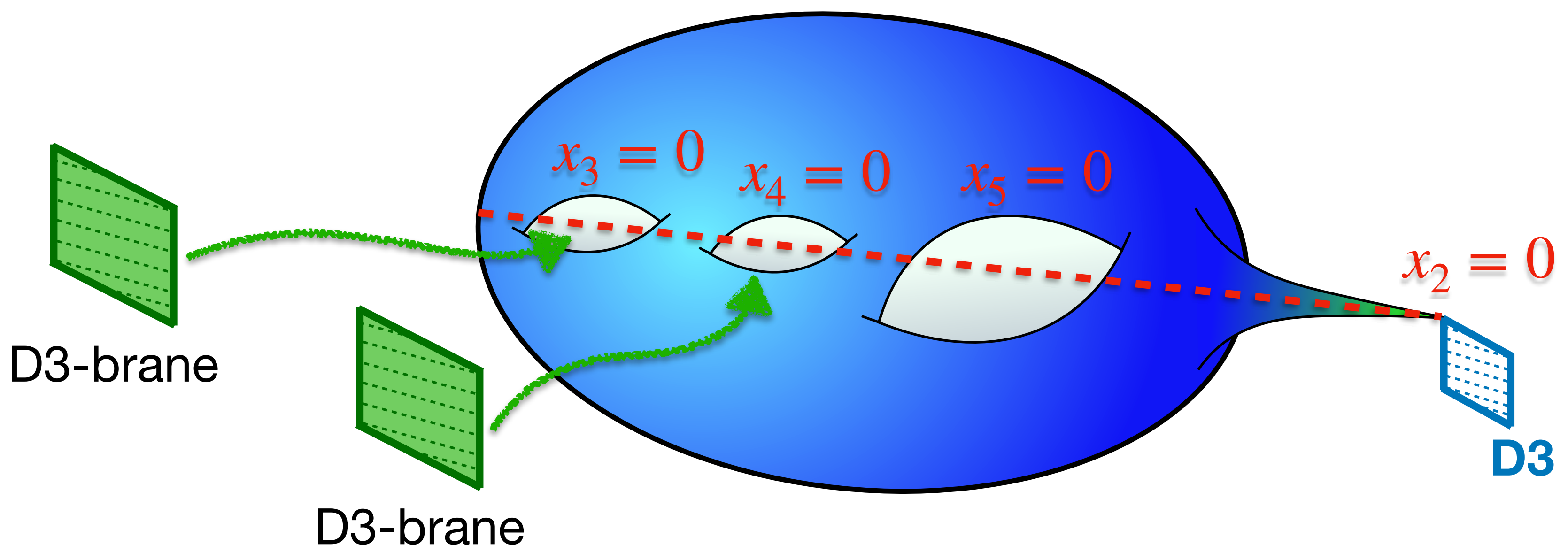
Orientifold involution

$$\sigma \ :\ x_5 \mapsto -x_5$$

Single O7-plane on

$$D_5 = 2D_b - D_2 - D_3 - D_4$$

We checked that the local model can indeed be embedded as well as that the **global and local involutions are consistent!**



D3-branes on dP_5 divisors at $x_3 = 0$ and $x_4 = 0$ for **non-perturbative effects**

D-brane and T-brane setup:

A. D3-branes on additional dP_5 divisors for **non-perturbative effects**

B. D7-branes to cancel D7-tadpole induced by O7-plane

Global model construction

Let us focus on specific model with $(h^{2,1}, h^{1,1}) = (52,4)$

HY_1	HY_2	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
4	4	1	0	0	0	2	2	1	1	1
2	2	0	1	0	0	1	1	0	0	1
2	2	0	0	1	0	1	1	0	1	0
2	2	0	0	0	1	1	1	1	0	0
		NdP_{17}	dP_5	dP_5	dP_5	SD1	SD1	SD2	SD2	SD2

Euler characteristic

$$\chi = -96$$

Construction plan:
CY threefolds as complete intersections of 2 equations in a 5-dimensional toric space

Stanley-Reisner ideal

$$SR = \{x_2x_3,\ x_2x_4,\ x_2x_9,\ x_3x_4,\ x_4x_7,\ x_1x_7x_9,\ x_3x_5x_6x_8,\ x_1x_5x_6x_7x_8,\ x_1x_5x_6x_8x_9\}$$

We take the singular limit $t_2 \to 0$ which gives rise to a dP_5 singularity!

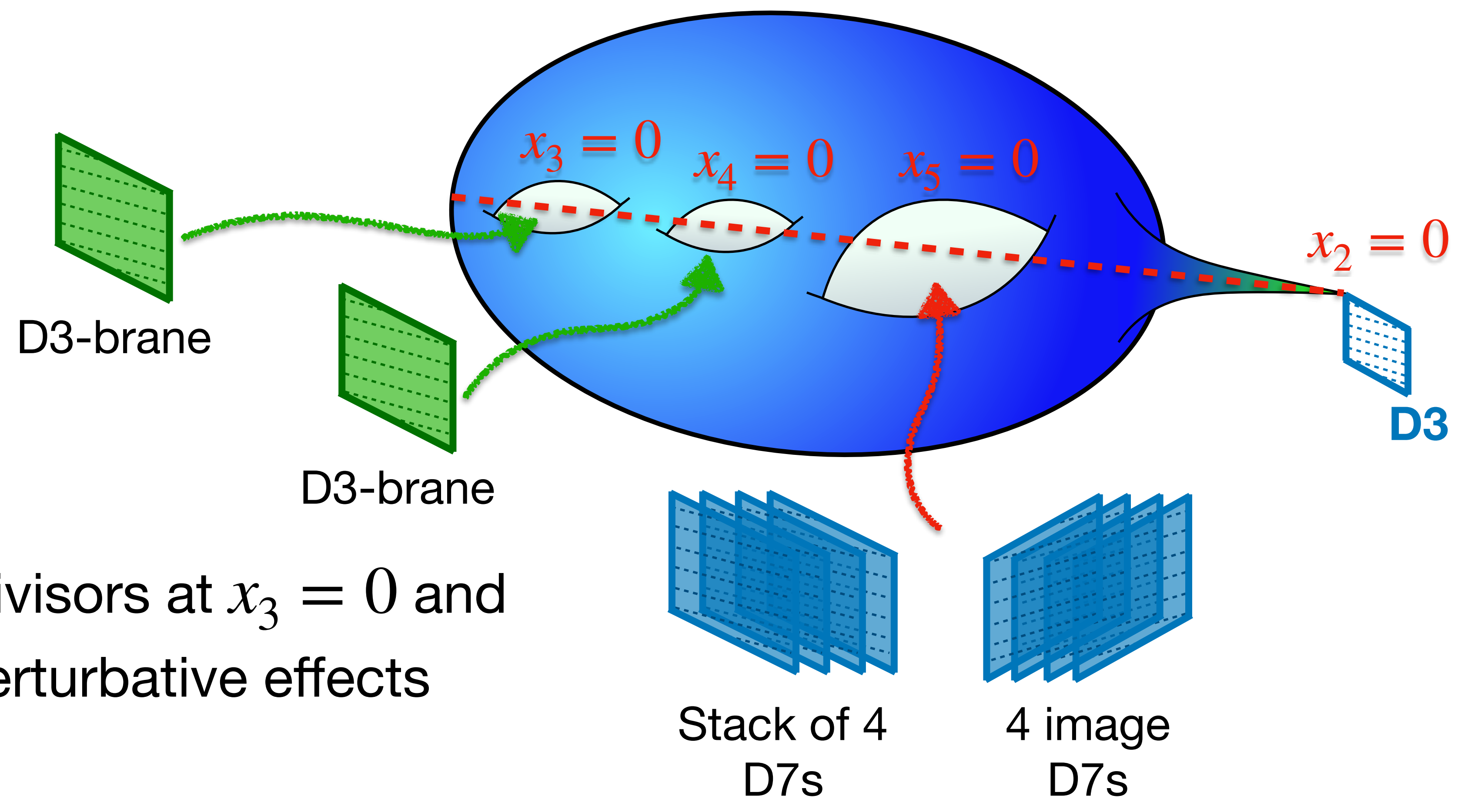
Orientifold involution

$$\sigma\ :\ x_5 \mapsto -x_5$$

Single O7-plane on

$$D_5 = 2D_b - D_2 - D_3 - D_4$$

We checked that the local model can indeed be embedded as well as that the **global and local involutions are consistent!**



D3-branes on dP_5 divisors at $x_3 = 0$ and $x_4 = 0$ for non-perturbative effects

Stack of 4 D7-branes (plus their 4 images) wrapping $x_5 = 0$ with **SO(8) gauge group** and **flux**

$$\mathcal{F} = F - B = \left(n_b - \frac{1}{2}\right) D_b + \left(n_2 - \frac{1}{2}\right) D_2 \qquad n_b, n_2 \in \mathbb{Z}\,.$$

D-brane and T-brane setup:

A. D3-branes on additional dP_5 divisors for non-perturbative effects
B. D7-branes to **cancel D7-tadpole** induced by O7-plane

Global model construction

Let us focus on specific model with $(h^{2,1}, h^{1,1}) = (52{,}4)$

HY_1	HY_2	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
4	4	1	0	0	0	2	2	1	1	1
2	2	0	1	0	0	1	1	0	0	1
2	2	0	0	1	0	1	1	0	1	0
2	2	0	0	0	1	1	1	1	0	0
		NdP_{17}	dP_5	dP_5	dP_5	SD1	SD1	SD2	SD2	SD2

Euler characteristic

$$\chi = -96$$

Construction plan:
CY threefolds as complete intersections of 2 equations in a 5-dimensional toric space

Stanley-Reisner ideal

$$SR = \{x_2x_3,\ x_2x_4,\ x_2x_9,\ x_3x_4,\ x_4x_7,\ x_1x_7x_9,\ x_3x_5x_6x_8,\ x_1x_5x_6x_7x_8,\ x_1x_5x_6x_8x_9\}$$

We take the singular limit $t_2 \to 0$ which gives rise to a dP_5 singularity!

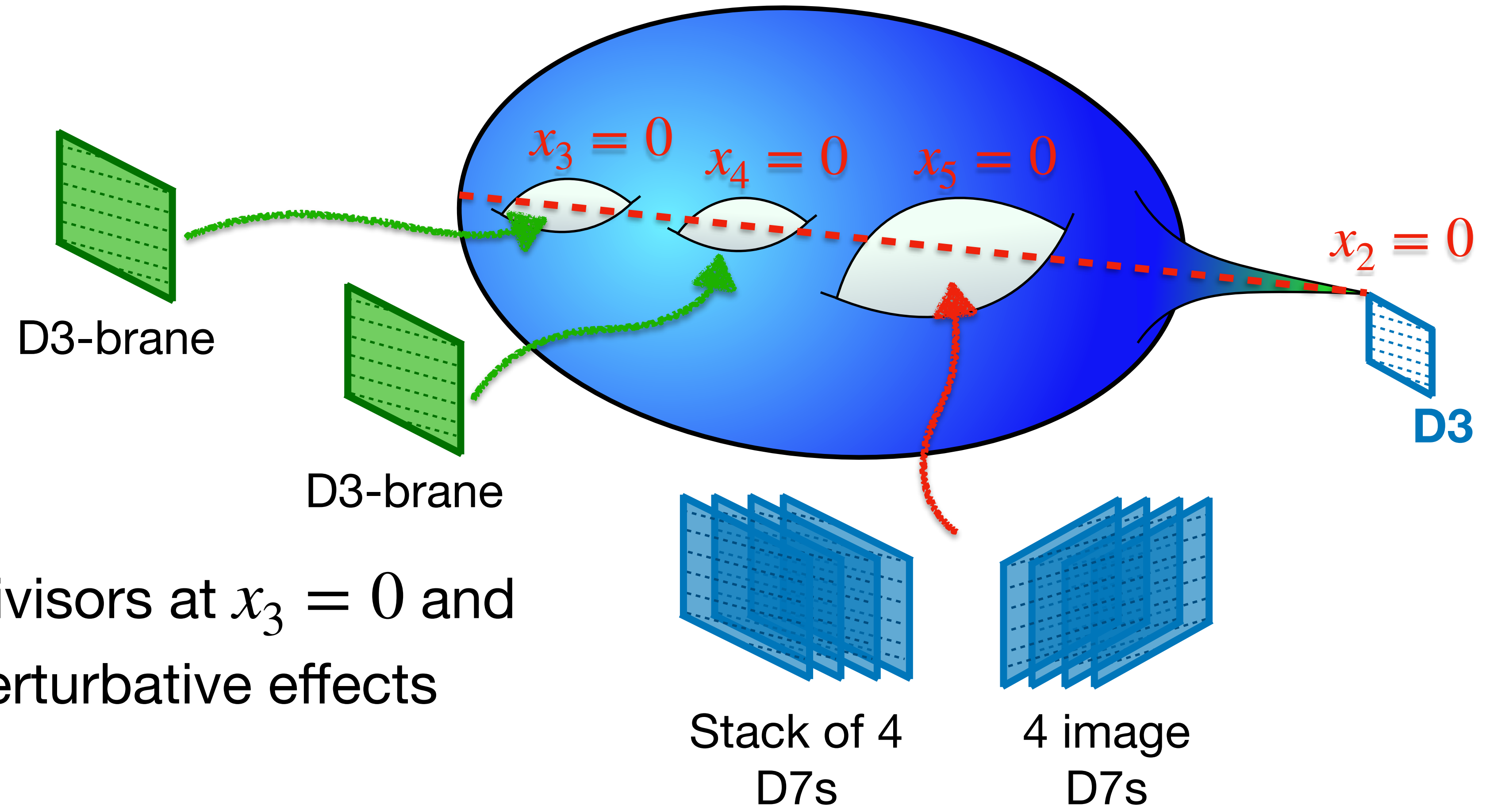
Orientifold involution

$$\sigma \;:\; x_5 \mapsto -x_5$$

Single O7-plane on

$$D_5 = 2D_b - D_2 - D_3 - D_4$$

We checked that the local model can indeed be embedded as well as that the **global and local involutions are consistent!**



D3-branes on dP_5 divisors at $x_3 = 0$ and $x_4 = 0$ for non-perturbative effects

Stack of 4 D7-branes (plus their 4 images) wrapping $x_5 = 0$ with SO(8) gauge group and flux

$$\mathcal{F} = F - B = \left(n_b - \frac{1}{2}\right) D_b + \left(n_2 - \frac{1}{2}\right) D_2 \qquad n_b, n_2 \in \mathbb{Z}\,.$$

D-brane and T-brane setup:

A. D3-branes on additional dP_5 divisors for non-perturbative effects
B. D7-branes to cancel D7-tadpole induced by O7-plane

Flux breaks **SO(8) to U(4)** with **Fayet-Iliopoulos (FI) terms**

$$\xi_{D7} = \frac{1}{4\pi\mathcal{V}} \int_{D7} \mathcal{F} \wedge J \xrightarrow{t_2 \to 0} \frac{1}{\pi\mathcal{V}} (2n_b - 1) t_b$$

Non-vanishing FI-term implies we have to switch on VEV for adjoint complex scalar Φ living on D7 stack $\rightarrow$ **T-brane background**

Cicoli, Quevedo, Valandro: 1512.04558

Moduli stabilisation

$(\alpha')^3$-corrected Kähler potential

$$K = \underbrace{-\ln\left(S+\bar{S}\right) - \ln\left(-i\int_X \Omega\wedge\bar{\Omega}\right)}_{\text{Complex structure moduli}} \underbrace{-2\ln\left(\mathcal{V}+\frac{\zeta}{2}\right)}_{\text{Kähler moduli}} + \underbrace{K_Q}_{\text{Quiver}} \qquad \zeta = -\frac{\chi(X)\,\zeta(3)}{2(2\pi)^3\, g_s^{3/2}}$$

$$\mathcal{V} = d_1\tau_b^{3/2} - d_3\tau_3^{3/2} - d_4\tau_4^{3/2}\,, \qquad d_1 = d_3 = d_4 = \frac{1}{3\sqrt{2}}$$

Full **D/F-term scalar potential** for bulk and quiver:

$$V = V_F^{\text{Flux}} + V_F^{\text{quiver}} + V_D^{\text{quiver}} + V_D^{\text{bulk}} + V_F^{\text{LVS}} + V_{\text{soft}}$$

Superpotential with $a_3 = 2\pi$

$$W = \underbrace{\int_X G_3\wedge\Omega}_{\text{Flux}} + \underbrace{A_3\, e^{-a_3 T_3}}_{\text{Non-perturbative}} + \underbrace{W_Q(X,U)}_{\text{Quiver}}$$

Supersymmetric minima at leading order in the volume $\mathcal{O}(\mathcal{V}^{-2})$

$$V_F^{\text{Flux}} = V_F^{\text{quiver}} = V_D^{\text{quiver}} = V_D^{\text{bulk}} = 0$$

Stabilises complex structure and open string moduli

Moduli stabilisation

$(\alpha')^3$-corrected Kähler potential

$$K = -\ln\left(S+\bar{S}\right) - \ln\left(-i\int_X \Omega\wedge\bar{\Omega}\right) - 2\ln\left(\mathcal{V}+\frac{\zeta}{2}\right) + K_Q \qquad \zeta = -\frac{\chi(X)\,\zeta(3)}{2(2\pi)^3\, g_s^{3/2}}$$

Complex structure moduli — Kähler moduli — Quiver

Superpotential with $a_3 = 2\pi$

$$W = \int_X G_3\wedge\Omega + A_3\, e^{-a_3 T_3} + W_Q(X,U)$$

Flux — Non-perturbative — Quiver

$$\mathcal{V} = d_1\tau_b^{3/2} - d_3\tau_3^{3/2} - d_4\tau_4^{3/2}\,, \quad d_1 = d_3 = d_4 = \frac{1}{3\sqrt{2}}$$

Full D/F-term scalar potential for bulk and quiver:

$$V = V_F^{\rm Flux} + V_F^{\rm quiver} + V_D^{\rm quiver} + V_D^{\rm bulk} + V_F^{\rm LVS} + V_{\rm soft}$$

Supersymmetric minima at leading order in the volume $\mathcal{O}(\mathcal{V}^{-2})$

$$V_F^{\rm Flux} = V_F^{\rm quiver} = V_D^{\rm quiver} = V_D^{\rm bulk} = 0$$

Stabilises complex structure and open string moduli

Total scalar potential for Kähler moduli

$$V_{\rm tot} = \frac{e^{K_{\rm cs}}}{2\,{\rm Re}(S)}\left(V_{\rm LVS} + \frac{\mathcal{F}_{\rm up}\,|W_0|^2}{\mathcal{V}^{8/3}}\right)\,, \quad \mathcal{F}_{\rm up} = \frac{1}{4\pi}\left(\frac{1}{d_1}\right)^{1/3} \approx 0.1822$$

From T-brane background!

Vacuum energy at non-SUSY LVS minima

$$\langle V_{\rm tot}\rangle \simeq \frac{e^{K_{\rm cs}}|W_0|^2}{18\,{\rm Re}(S)\,\mathcal{V}^3}\left[\mathcal{F}_{\rm up}\mathcal{V}^{1/3} - \sum_{i=3}^{4}\frac{27 d_i}{4a_i}\frac{(1-4\epsilon_i)}{(1-\epsilon_i)^2}\sqrt{\tau_i}\right]$$

Conditions for LVS minima

Balasubramanian, Berglund, Conlon, Quevedo: hep-th/0502058

$$\mathcal{V} = \frac{3d_i\sqrt{\tau_i}\,(1-4\epsilon_i)}{4a_i(1-\epsilon_i)}\frac{|W_0|}{|A_i|}e^{a_i\tau_i} \qquad \epsilon_i = \frac{1}{4a_i\tau_i}$$

$$e^{a_3\tau_3 - a_4\tau_4} = \frac{a_3|A_3|d_4}{a_4|A_4|d_3}\frac{1-\epsilon_3}{1-4\epsilon_3}\frac{1-4\epsilon_4}{1-\epsilon_4}\frac{\sqrt{\tau_4}}{\sqrt{\tau_3}}$$

$$\frac{\zeta}{2} = \sum_{i=3}^{4}\frac{d_i(1-4\epsilon_i)}{(1-\epsilon_i)^2}\tau_i^{3/2} - \frac{16\,\mathcal{F}_{\rm up}}{27}\mathcal{V}^{1/3}$$

Minkowski minima

$$\frac{\zeta}{2} = \sum_{i=3}^{4}\frac{d_i(1-4\epsilon_i)(1-16\epsilon_i)}{(1-\epsilon_i)^2}\tau_i^{3/2}$$

$$\langle\mathcal{V}\rangle_{\rm Mink.} = \frac{1}{\mathcal{F}_{\rm up}^3}\left(\sum_{i=3}^{4}\frac{27 d_i}{4a_i}\frac{(1-4\epsilon_i)}{(1-\epsilon_i)^2}\sqrt{\tau_i}\right)^3$$

At the Minkowski minimum, the volume is **not** exponentially large, but grows like $(h^{1,1}-2)^2$

Minkowski minima, mass spectrum and SUSY breaking

Numerical analysis for $|A_s| = |A_3| = |A_4| \quad \tau_s = \tau_3 = \tau_4$

g_s	$\lvert W_0\rvert/\lvert A_s\rvert$	$\langle\tau_s\rangle$	$\langle\mathcal{V}\rangle$	$\lvert W_0\rvert/\lvert A_s\rvert$	$\langle\tau_s\rangle$	$\langle\mathcal{V}\rangle$
0.10	$3.57\cdot10^{-6}$	3.23	115.6	$2.88\cdot10^{-9}$	4.42	188.6
0.05	$2.22\cdot10^{-13}$	5.98	301.1	$1.05\cdot10^{-19}$	8.35	503.2
0.03	$3.72\cdot10^{-23}$	9.63	626.4	$8.38\cdot10^{-34}$	13.59	1057.4
0.02	$1.79\cdot10^{-35}$	14.21	1131.3	$1.61\cdot10^{-51}$	20.15	1919.3
0.01	$1.21\cdot10^{-72}$	27.94	3145.2	$6.85\cdot10^{-105}$	39.82	5363.7

$\chi_{eff} = -56$ $\qquad\qquad$ $\chi = -96$

Minasian, Pugh, Savelli: 1506.06756 $\quad \chi_{\text{eff}} = \chi(X) + 2\int_X D_{O7}^3$

At the Minkowski minimum:

$$\frac{|W_0|}{|A_3|} \simeq \frac{4a_3}{3d_3}\left(\frac{27d_3}{2a_3\mathcal{F}_{\text{up}}}\right)^3 \left(\frac{\zeta}{4d_3}\right)^{2/3} e^{-a_3\,[\zeta/(4d_3)]^{2/3}}$$

Tuning in W_0 is model dependent and avoided for gaugino condensation or $h^{1,1} > 4$

Small W_0 could be achieved via

A. explicit solutions — Demirtas et al.: 1912.10047
B. stochastic search optimisation — Cole, AS, Shiu: 1907.10072

Minkowski minima, mass spectrum and SUSY breaking

Numerical analysis for $|A_s| = |A_3| = |A_4| \quad \tau_s = \tau_3 = \tau_4$

g_s	$\lvert W_0\rvert/\lvert A_s\rvert$	$\langle\tau_s\rangle$	$\langle\mathcal{V}\rangle$	$\lvert W_0\rvert/\lvert A_s\rvert$	$\langle\tau_s\rangle$	$\langle\mathcal{V}\rangle$
0.10	$3.57\cdot 10^{-6}$	3.23	115.6	$2.88\cdot 10^{-9}$	4.42	188.6
0.05	$2.22\cdot 10^{-13}$	5.98	301.1	$1.05\cdot 10^{-19}$	8.35	503.2
0.03	$3.72\cdot 10^{-23}$	9.63	626.4	$8.38\cdot 10^{-34}$	13.59	1057.4
0.02	$1.79\cdot 10^{-35}$	14.21	1131.3	$1.61\cdot 10^{-51}$	20.15	1919.3
0.01	$1.21\cdot 10^{-72}$	27.94	3145.2	$6.85\cdot 10^{-105}$	39.82	5363.7

$\chi_{eff} = -56$ $\qquad\qquad$ $\chi = -96$

$M_{\rm soft} \sim m_{3/2} \sim |W_0| M_p/\mathcal{V}$

$m_{3/2} \sim 10^{10}\,\mathrm{GeV}$

$m_{3/2} \sim 1\ \mathrm{TeV}$

Soft masses below LHC scales

At the Minkowski minimum:

$$\frac{|W_0|}{|A_3|} \simeq \frac{4a_3}{3d_3}\left(\frac{27d_3}{2a_3\mathcal{F}_{\rm up}}\right)^3 \left(\frac{\zeta}{4d_3}\right)^{2/3} e^{-a_3\,[\zeta/(4d_3)]^{2/3}}$$

Tuning in W_0 is model dependent and avoided for gaugino condensation or $h^{1,1} > 4$

Small W_0 could be achieved via

A. explicit solutions — Demirtas et al.: 1912.10047

B. stochastic search optimisation — Cole, AS, Shiu: 1907.10072

Field	Name	Mass
dP_5 modulus	τ_2, ρ_2	$\sim M_s$
cx str moduli	U_α	$\sim m_{3/2}$
dilaton	S	$\sim m_{3/2}$
blow-up cycles	τ_3, τ_4	$\sim m_{3/2}$
blow-up axions	ρ_3, ρ_4	$\sim m_{3/2}$
volume modulus	τ_b	$\sim m_{3/2}/\sqrt{\mathcal{V}}$
volume axion	ρ_b	$\sim M_p\, e^{-\mathcal{V}^{2/3}}$

SUSY broken **spontaneously** through non-vanishing **hidden sector F-terms**:

$$\frac{F^{T_b}}{\tau_b} \sim \frac{F^{T_3}}{\tau_3} \sim \frac{F^{T_4}}{\tau_4} \sim m_{3/2} \quad , \quad F^S \sim F^{U_\alpha} \sim \frac{m_{3/2}}{\mathcal{V}}$$

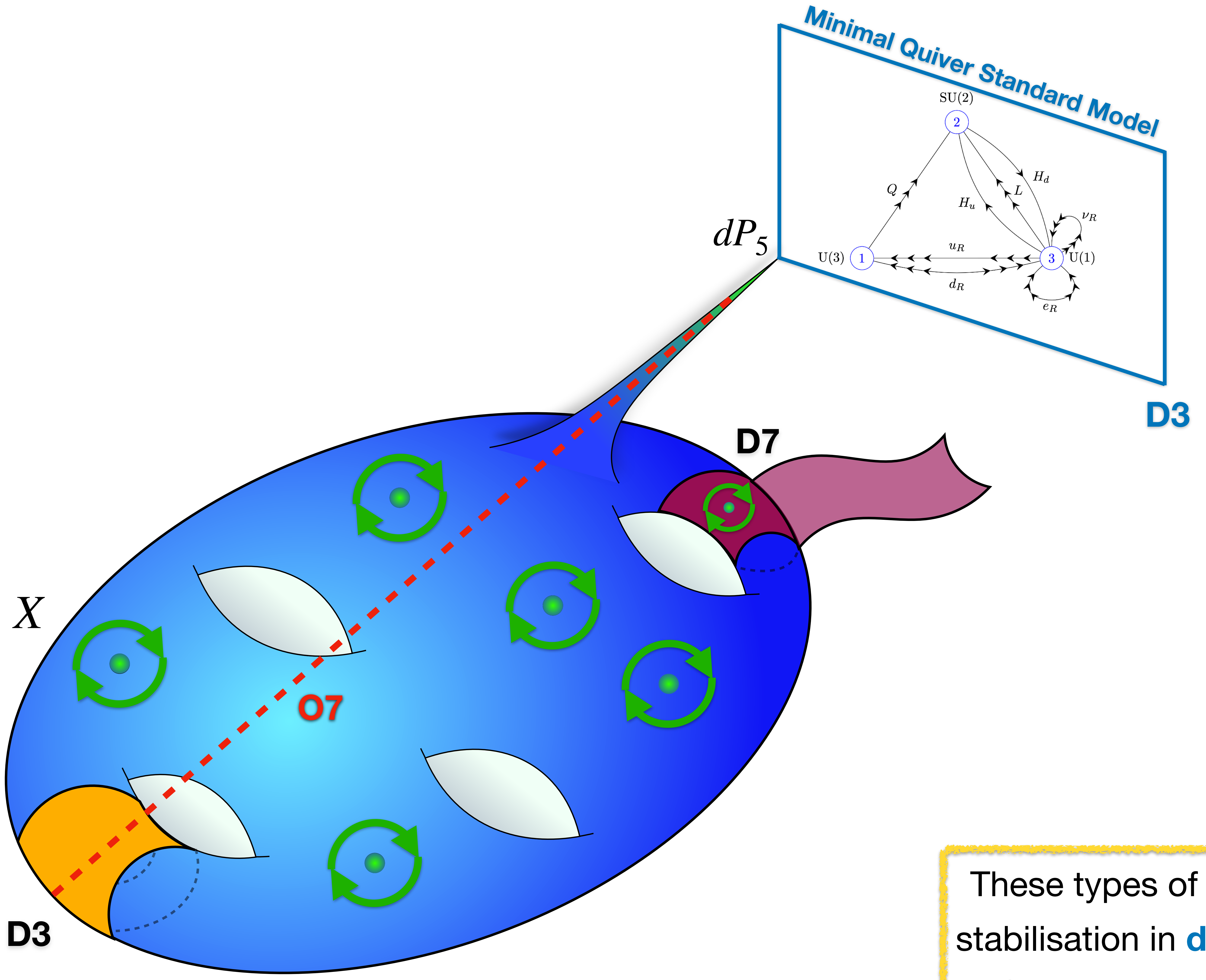
Threshold corrections to the gauge kinetic function for orientifolded singularities amount to

$$\tau_2 \;\rightarrow\; \tau_2^{\rm new} = \tau_2 - \alpha \ln\mathcal{V} \qquad F^{T_2} = 0 \;\rightarrow\; F^{T_2} \sim \alpha m_{3/2}$$

Conlon, Palti: 0906.1920, 0907.1362
Conlon, Pedro: 1003.0388

Breaks sequestering effects and hence one obtains soft masses $M_{\rm soft} \sim m_{3/2} \sim |W_0| M_p/\mathcal{V}$

Conclusions



Summary:

- Standard Model quiver from a single D3-brane at dP_5 singularity
- Explicit construction of compact CY threefolds
- Consistent global embedding with tadpole cancellation etc.
- Moduli stabilisation in de Sitter minimum from T-brane uplift

Future directions:

- Systematic study of models with $dP_{n\geq 5}$
- Local orientifold action on exceptional collections
- Models with many Kähler moduli $h^{1,1} > 4$
- Combine with model for inflation
- Gaugino condensation and additional uplifting sources

Concluding remark

These types of constructions are the **most explicit** models with moduli stabilisation in **de Sitter** minima and a realisation of the **Standard Model** (and **inflationary cosmology**) in **string theory compactifications**!

Thank you!