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Recent progress on the gauge theory sector of F-theory

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CERN

arXiv:1507.05954: M. Cvetič, D.K., H. Piragua, W. Taylor
arXiv:1502.06953: M. Cvetič, R. Donagi, D.K., H. Piragua, M. Poretschkin
arXiv:1408.4808: D.K., D. Mayorga Peña, P. Oehlmann, H. Piragua, J. Reuter
arXiv:1303.6970, arXiv:1307.6425: M. Cvetič, D.K., H. Piragua
(arXiv:1503.02068: M. Cvetič, D.K., D. Mayorga Peña, P. Oehlmann, J. Reuter
arXiv:1310.0463: M. Cvetič, D.K., H. Piragua, P. Song
arXiv:1306.3987: M. Cvetič, A. Grassi, D.K., H. Piragua)

Motivation

Why F-theory?

F-theory

1. describes broad class of non-perturbative vacua of string theory,
2. can produce GUT models with promising particle physics & cosmology:

   ➡ features not accessible in perturbative II strings (E_6 to E_8, **10**x**10**x**5**,…).

   Local: [Donagi,Wijnholt; Beasley,Heckman,Vafa;… many works]

   Global: [Blumenhagen,Grimm,Jurke,Weigand;Marsano,Saulina,SchäferNameki;… many works]

3. engineers effective field theories coupled to quantum gravity:

Calabi-Yau (CY) geometry ⟷ **Geometry Physics** ⟷ Effective field theories

➡ Geometry provides tools to control over non-perturbative physics.

Goal of this talk

Calabi-Yau (CY) geometry ⟷ Geometry Physics ⟷ Effective field theories

Goal: Use F-theory to study gauge theory sectors in *N=1* SUGRA theories.

Problem: geometry / physics dictionary incomplete

- Well-understood for non-Abelian groups & simple matter representations.
- less known about U(1)'s, discrete gauge groups & more complicated matter representations.

Today: develop some missing pieces

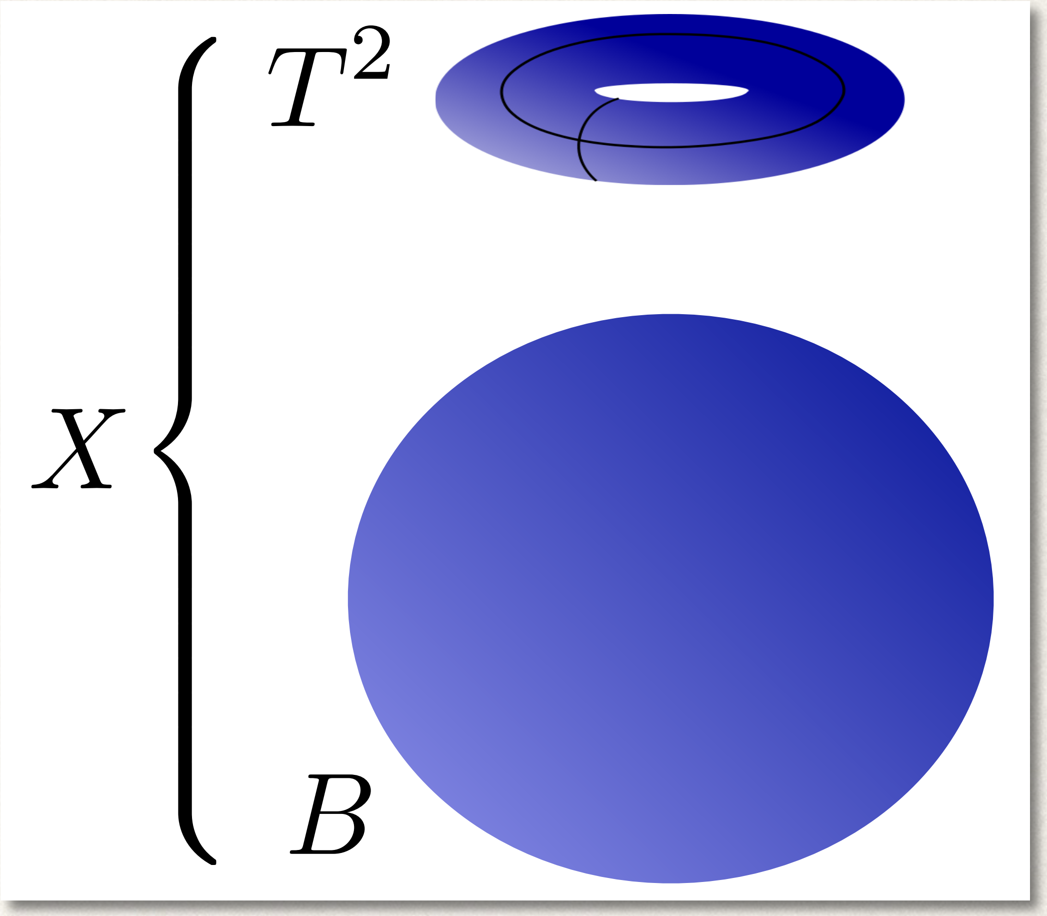
- Arithmetic of CY-elliptic fibrations ⟷ global gauge group
- Enlarge matter sector: new Abelian & non-Abelian representations

1) What is an F-theory vacuum?

Defining data: torus-fibered Calabi-Yau manifold X

1. Base B of X

➡ part of physical space-time of string theory



2. Torus fiber T^2 of X

➡ book-keeping device for Type IIB complexified string coupling $\tau \equiv C_0 + i g_s^{-1}$

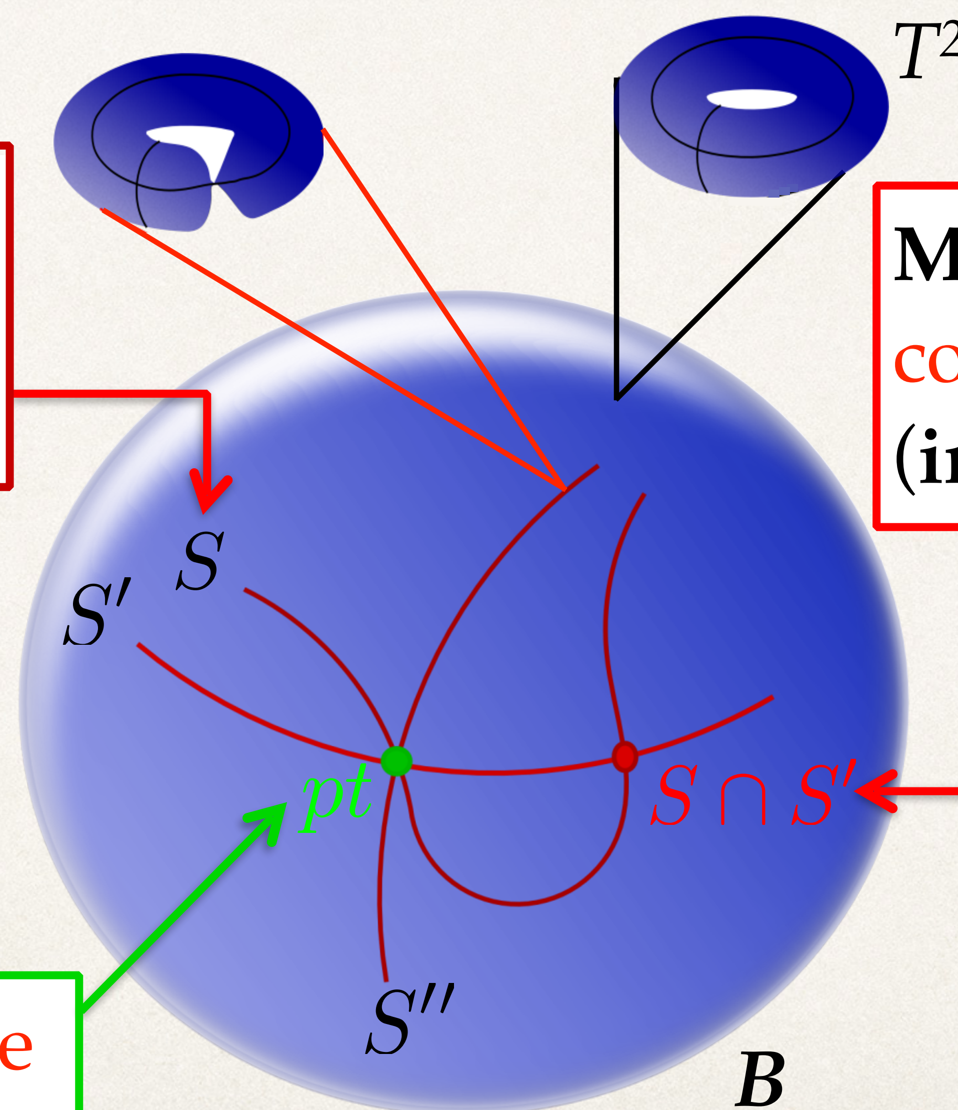
Singularities of CY manifolds & physics

Singularities of T^2-fibration of Calabi-Yau X over base B ⟺ globally well-defined setup of intersecting (p,q)7-branes

Gauge theory in **8D:**
co-dim. one singularity
(**7-branes**)

Matter in **6D :**
co-dim. two sing.
(**intersec. 7-branes**)

[Katz,Vafa]



4D Yukawa: co-dim three
$pt = S \cap S' \cap S''$

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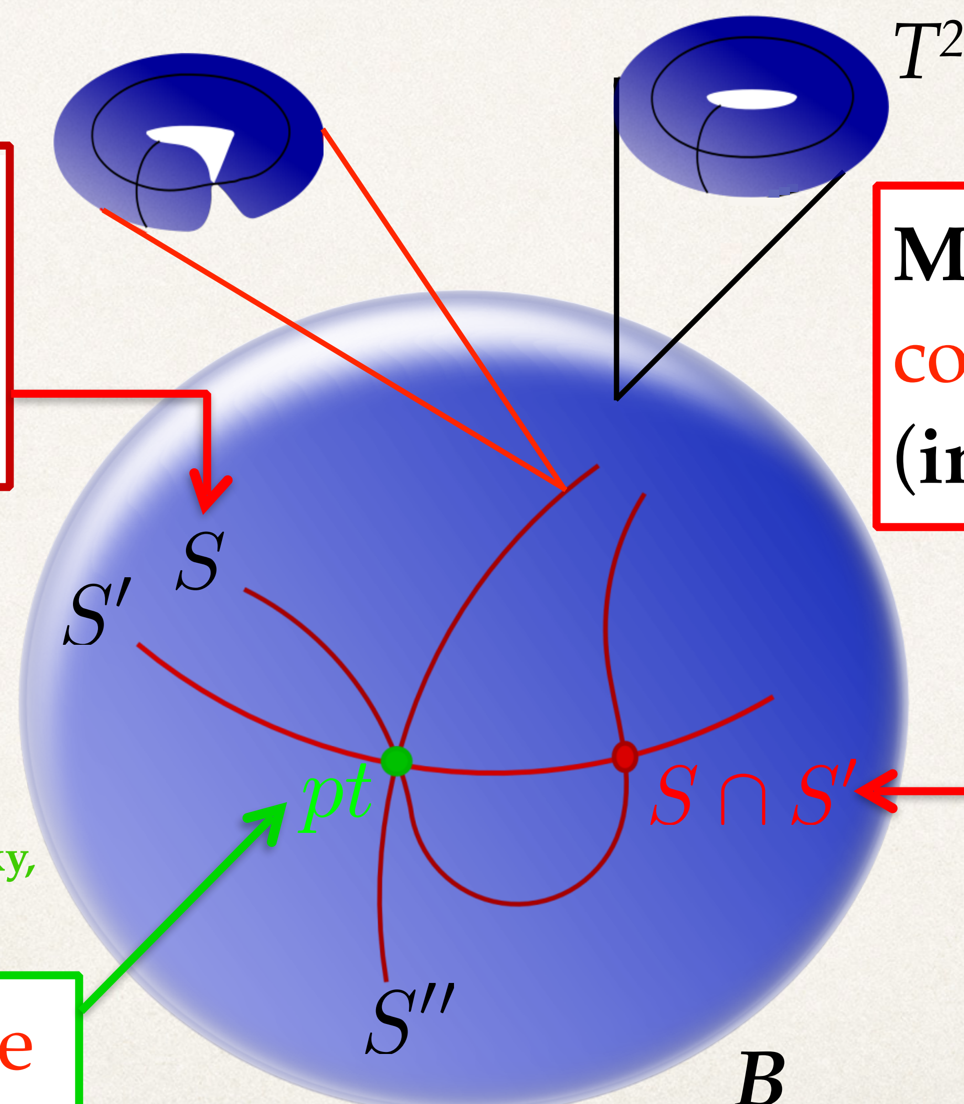
Gauge theory in **8D:**
co-dim. one singularity
(**7-branes**)

obtain only
non-Abelian groups,
no U(1)'s

[Kodaira;Tate;Vafa,Morrison,Vafa;Bershadsky, Intriligator,Kachru,Morrison,Sadov,Vafa]



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2) Global F-theory compactifications with U(1) symmetries

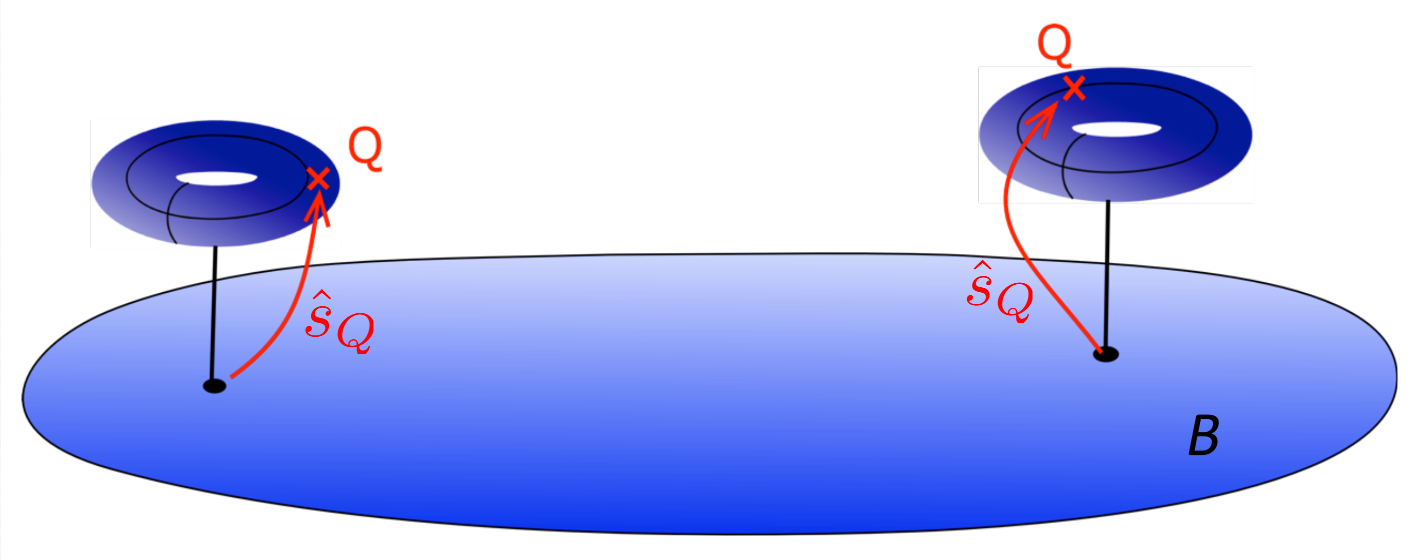
U(1)'s in F-theory & the Mordell-Weil group

- U(1)'s arise by KK-reduction of M-theory three-form $\boxed{C_3 \supset A^m \omega_m}$.
- Not from codimension one singularities: otherwise again non-Abelian groups.

$\boxed{\text{(1,1)-form } \omega_m \Leftrightarrow \text{rational section of } X}$ [Morrison,Vafa II]

Rational section = map $\hat{s}_Q : B \to X$ induced by rational point Q on ***T^2 = elliptic curve E***.

- Rational points form Abelian group: **Mordell-Weil (MW) group** of rational sections of X
- $\hat{s}_Q$ gives rise to a second copy of B in X: new divisor B_Q in X



➡ (1,1)-form ω_m constructed from divisor B_Q.

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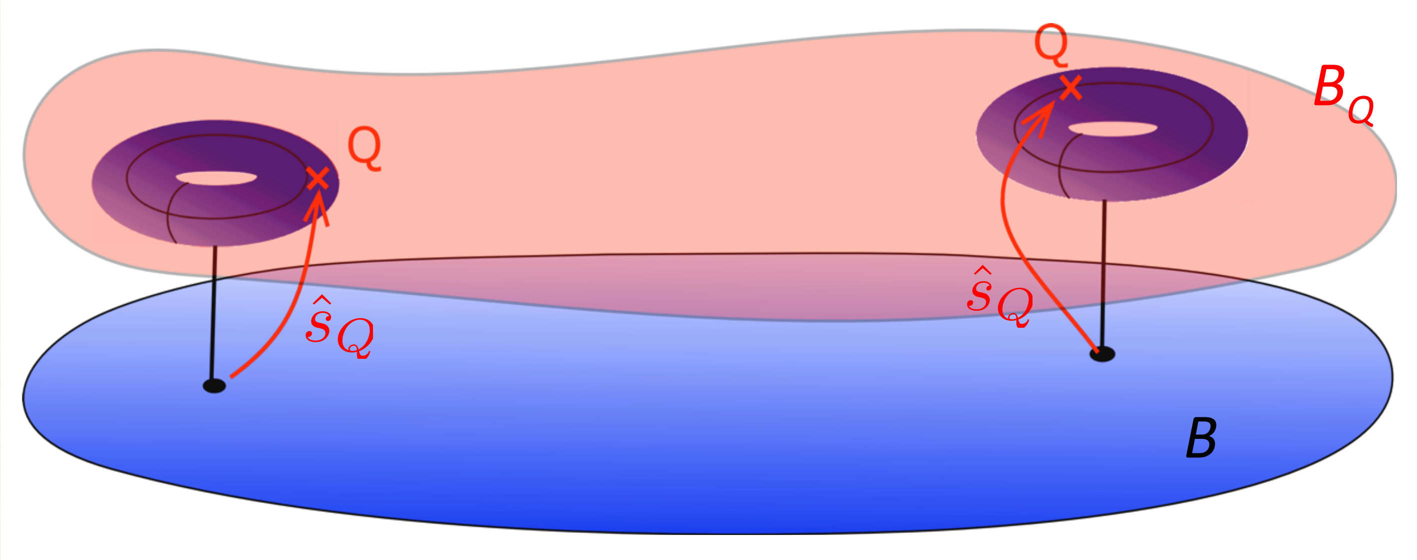

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Systematic construction of F-theory vacua with U(1)'s

- *n* rational sections of CY-manifold X ➡ F-theory with $U(1)^n$ gauge group
- <u>Deligne:</u> Systematic construction of CY X with *n* rational sections

➡ $\boxed{\text{elliptic curve } E \text{ embedded into } W\mathbb{P}^m}$

<u>Examples:</u>

<u>one *U(1)*</u>: elliptic curve E is generic CY in $\mathrm{Bl}_1\mathbb{P}^2(1,1,2)$ **[Morrison,Park]**

➡ Construction yields only matter with U(1)-charge q=2,

➡ extension to models with q=3 matter: E is cubic CY in dP_1. **[DK,Mayorga-Pena, Oehlmann,Piragua,Reuter]**

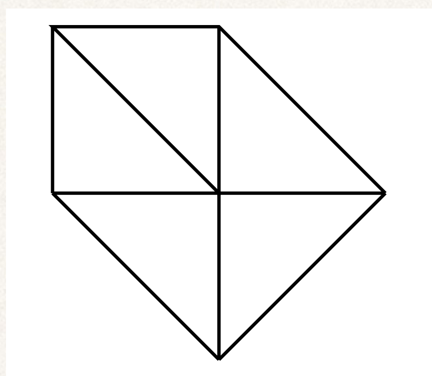
Systematic construction of F-theory vacua with U(1)'s

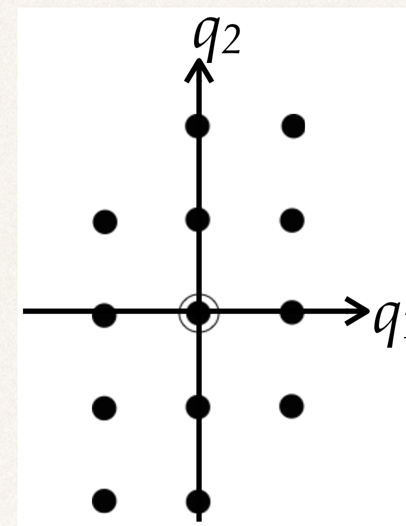
$U(1)^2$: E is non-generic cubic in $\mathbb{P}^2$

1. generic CY in dP_2: has restricted matter spectrum with $U(1)^2$ charges (q_1,q_2)

[Borchmann,Mayrhofer,Palti,Weigand;Cvetič,DK, Piragua]

toric dP_2:





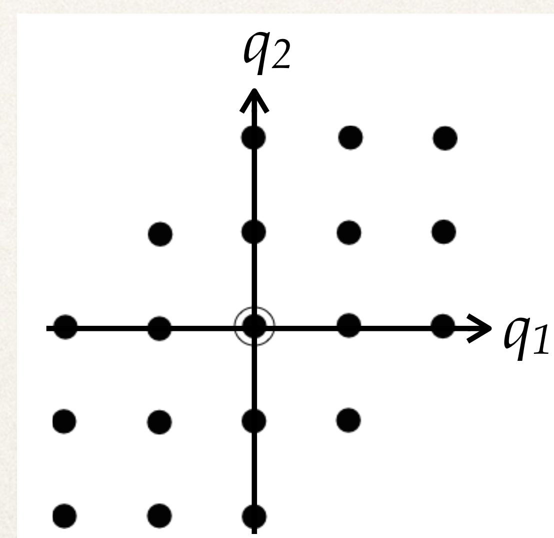
2. generalization: CY with $U(1)^2$ has fully symmetric matter spectrum

[Cvetic,DK,Piragua,Taylor]

non-toric model:

$$u f_2(u,v,w) + \prod_{i=1}^{3}(a_i v + b_i w) = 0$$

$$f_2 = s_1 u^2 + s_2 uv + s_3 v^2 + s_5 uw + s_6 vw + s_8 w^2$$



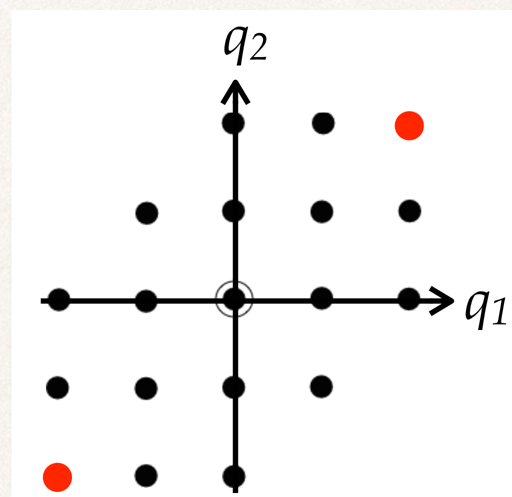
➡ All spectra automatically anomaly-free.

New realizations of matter singularities

[Cvetic,DK,Piragua,Taylor]

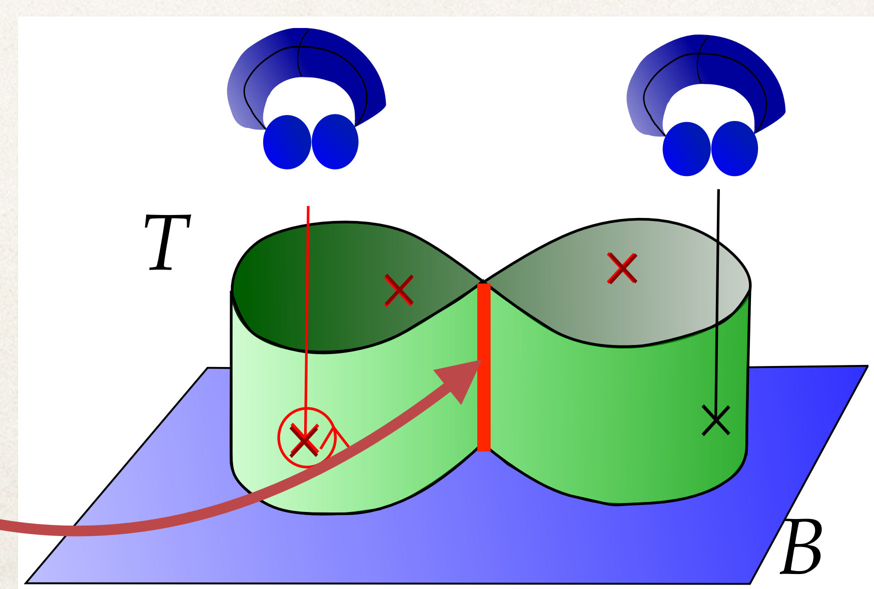
"UnHiggs" $U(1)^2 \longrightarrow SU(3)$

- $(q_1,q_2)=(2,2)$ matter becomes symmetric representation $\boldsymbol{6}$ of $SU(3)$: first concrete construction in global F-theory.



- related to new algebraic description of I_3^s singularities over divisor T

locus of $\boldsymbol{6}$ matter:
ordinary double point



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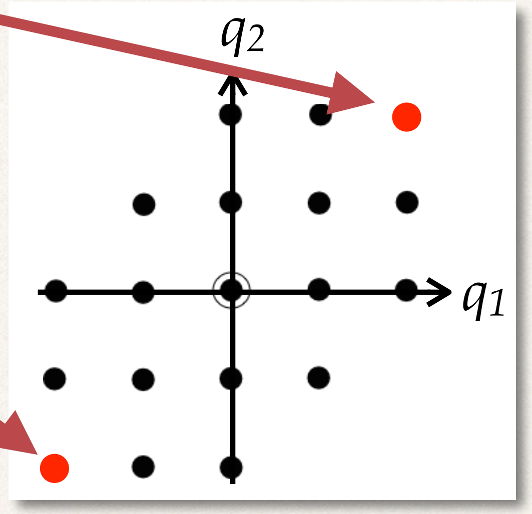

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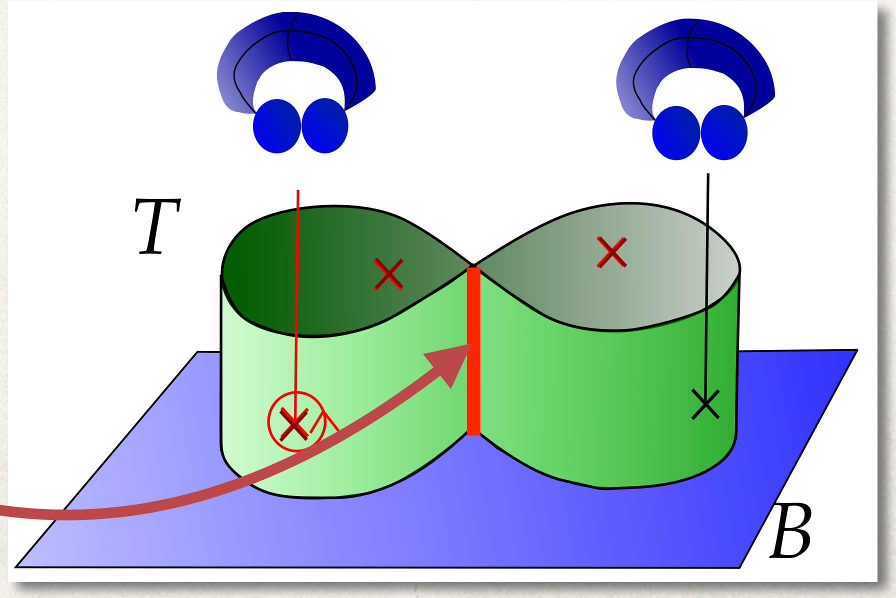

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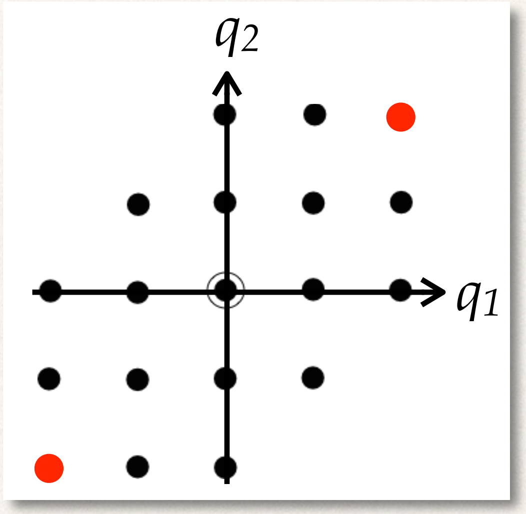

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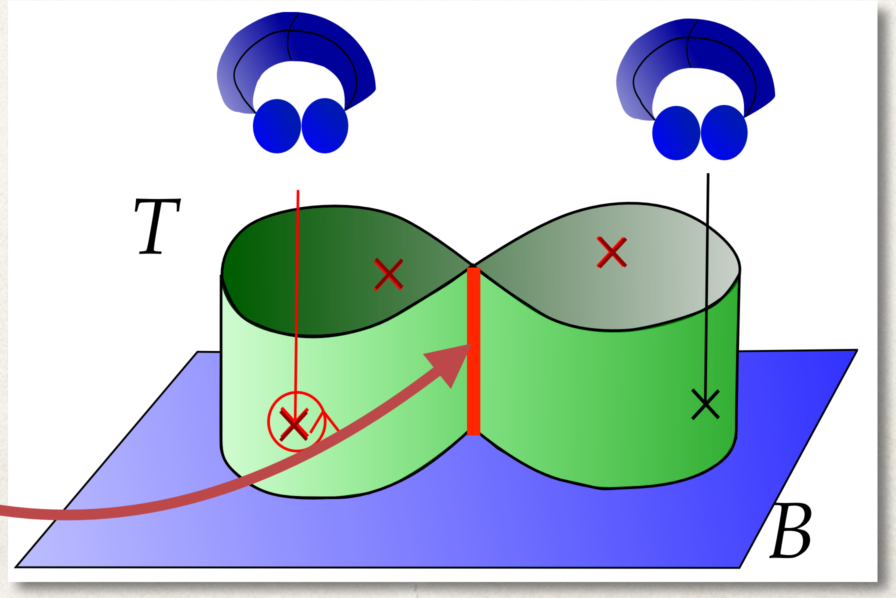
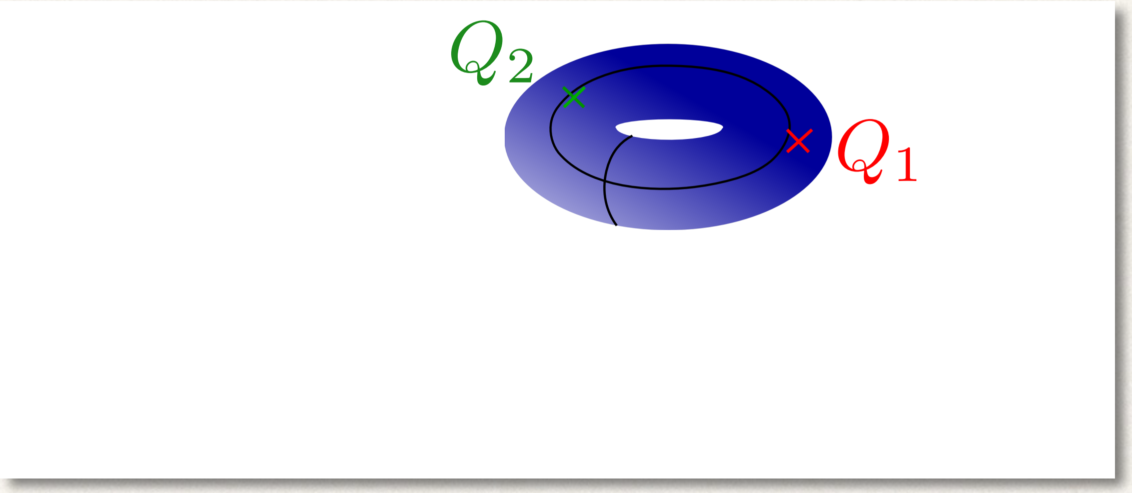


3) Global F-theory compactifications with discrete gauge groups

F-theory with discrete gauge groups

Torus fibration X has has no sections, only n-section: genus-one fibration

➡ X has n rational sections "locally" but they are interchanged globally.



➡ only sum well-defined globally

$$Q^{(n)} = Q_1 + \ldots + Q_n$$

Obstruction to gluing points together globally: Tate-Shafarevich (TS) group ➡ visible in physics as discrete gauge group of F-theory.

[DeBoer,Dijkgraaf,Hori,Keurentjes,Morgan,Morrison,Sethi]

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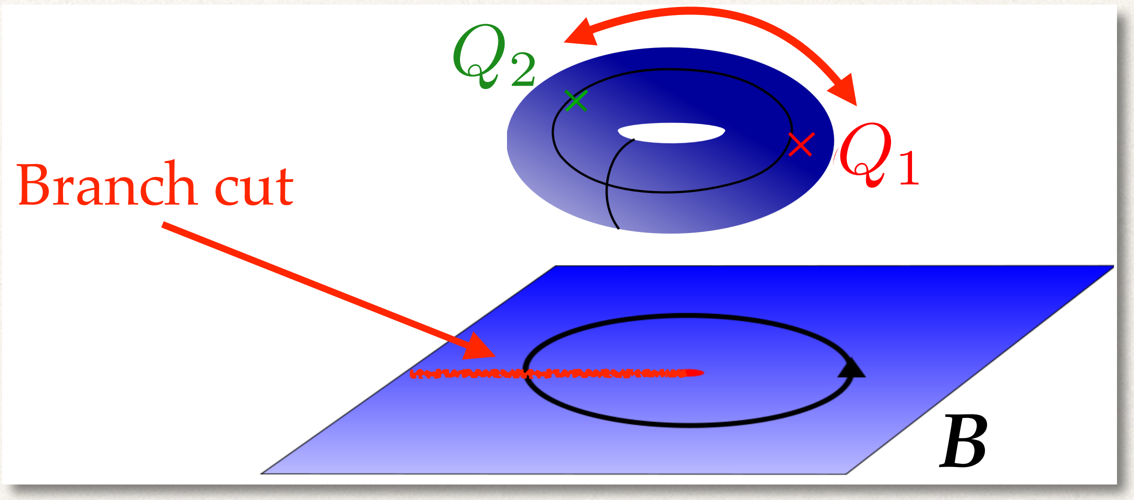

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All known examples

F-theory vacua with $\mathbb{Z}_n$ discrete gauge groups identified

- $\mathbb{Z}_2$ gauge group: $T^2 =$ quartic in $\mathbb{P}^2(1,1,2)$
  - ➡ $\mathbb{Z}_2$ and $(\mathrm{SU}(2) \times \mathbb{Z}_4)/\mathbb{Z}_2$

[Braun,Morrison; Morrison,Taylor
Anderson,García-Etxebarria,Grimm,Keitel; DK,Mayorga-Pena,Oehlmann,Piragua,Reuter; García-Etxebarria,Grimm,Keitel;Mayrhofer,Palti,Till,Weigand]

- $\mathrm{U}(1) \times \mathbb{Z}_2$ gauge group: $T^2 =$ bi-quadric in $\mathbb{P}^1 \times \mathbb{P}^1$

[DK,Mayorga-Pena,Oehlmann,Piragua,Reuter]

- $\mathbb{Z}_3$ discrete gauge group: $T^2 =$ cubic in $\mathbb{P}^2$

[DK,Mayorga-Pena,Oehlmann,Piragua,Reuter; Cvetič,Donagi,DK,Piragua,Poretschkin]

In all cases we have found

- matter carrying non-trivial $\mathbb{Z}_n$ discrete charge,
- all gauge invariant Yukawas exist, including $\mathbb{Z}_n$ selection rules.

4) Conclusions

Summary

- Systematic construction of F-theory vacua with $U(1)^n$ $(n \leq 3)$:

Mordell-Weil group ⟺ U(1)'s

- Construction of F-theory vacua with $\mathbb{Z}_n$ $(n \leq 4)$ discrete gauge groups:

Tate-Shafarevich group ⟺ discrete gauge group

- New matter representations:
  - ➡ charge $q=3$ for one $U(1)$, new $U(1)^2$ models with up to charges $(2,2)$
  - ➡ matter with charges under discrete gauge group,
  - ➡ first concrete construction of symmetric representation of $SU(3)$.

Things I didn't have time to talk about

Construction of *$U(1)^3$*: E is pencil of non-generic quadrics in $\mathrm{Bl}_4\mathbb{P}^4$.
[Cvetic,DK,Piragua,Song]

Pheno applications: Use *U(1)'s* for construction of SM in F-theory

Construction in **[Cvetič,DK,Mayorga-Pena,Oehlmann,Reuter]**

- $U_Y(1)$ ⟺ rational section
- *SM* non-Abelian gauge group *SU(3)*x*SU(2)* is automatically present
- add G_4-flux to generate 4D chirality following **[Cvetic,Grassi,DK,Piragua]**
- solve D3-brane tadpole

➡ get 4D three-family Standard models in F-theory.

➡ natural embedding into Pati-Salam & Trinification

Thank you