Geometric Transitions, Flops and Non-Kähler Manifolds

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in preparation

Usual story:

II A / II B compactification on CY manifolds

$\Downarrow$

$\mathcal{N}=2$ SUSY in 4-dimensions

$\Downarrow$ extra fluxes or/and D-branes

$\mathcal{N}=1$ SUSY in 4-dimensions

Calabi - Yau:
- $dJ \neq 0$ (Kähler form)
- $d\Omega^{(3,0)} \neq 0$ (complex)
- SU(3) holonomy

Non Calabi - Yau:
- SU(3) structure
- $dJ \neq 0$ (non-Kähler)
- $d\Omega \neq 0$
- breaks 1/4 of SUSY

Motivation for Studying Compactifications on Non-Kähler Manifolds:

① They appear as possible compactifications for heterotic strings (Strominger)

K. Becker, M. Becker, K. Dasgupta, P. S. Green, E. Sharpe
hep-th/0209077, 0301161, 0310058, 0312221

D. Lust et al.
hep-th/0211118, 0306088, 0310021

② IIB/IIA compactifications on Non-kähler can be characterized by torsion classes and they are related to M theory compactified on G_2 manifolds with torsion.

③. As I shall show, they are required for a "fine-tuning" of the concept of "Geometric Transitions" to keep track of the NS fields.

②

④

As I shall clarify, there is a T-duality relation between

II B compactified on CY with RR and NS fluxes	$\longleftrightarrow$	II A compactified on non-kähler with fluxes

We now have a nice "Landscape picture" proposal for II B compactification in the presence of fluxes.

It would be nice to be able to have a check by considering a related theory and II A on non-kähler is that "theory"

There are other directions, I shall mention them in the course of my talk.

②

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③

Outline of my talk

1) As the initial motivation was to clarify some aspects of the geometric transition, I shall start with a review:

- tools for obtaining strong coupling results in effective field theories.
- allow tests of open/closed string dualities

2) Concrete Example (Vafa 0008142)

D6 brane on S^3 inside deformed conifold

$$\Updownarrow \text{ dual (open/closed sense)}$$

$\left.\begin{matrix}\text{NS}\\ \text{RR}\end{matrix}\right]$ Fluxes on resolved conifold

The actual results of Vafa: RR fluxes on a resolved conifold

with $d\Omega \neq 0$

$\downarrow$

NS 4-form

④

Our "New Transition":

D6 branes on S^3 inside a non-kähler deformation of Deformed Conifold

$\Updownarrow$ open/closed string

RR fluxes on a non-kähler deformation of the Resolved Conifold

3) Next step: lift to 11 dimensions

D6 branes on S^3 inside non-kähler $\longrightarrow$ Manifold with G_2 structure (torsional G_2 manifolds)

$\downarrow$ flops + reduction

RR fluxes on non-kähler manifolds

4) Conclusions

⑤

Geometric Transitions - based on

Open/closed string dualities involving topological strings:

"Open topological string on T^*S^3 with N topological D-branes

$\Updownarrow$

closed topological strings on resolved conifold"

$\parallel$

Chern-Simons on S^3

t - size of $\mathbb{P}^1$

Partition functions are equal for

$$\boxed{t = i\, g_s N}$$

Vafa (0008142) embedded topological string results into superstrings.

The duality web becomes:

$$
\begin{tikzcd}
\begin{array}{c}\text{N D5 branes on } \mathbb{P}^1 \\ \text{inside res. conifold}\end{array} \arrow[r, leftrightarrow, "\text{geometric}", "\text{transition}"'] \arrow[d, leftrightarrow, "\begin{array}{c}\text{mirror}\\ \text{symmetry}\end{array}"] & \begin{array}{c}\text{RR flux} \\ \text{on } S^3 \text{ of } T^*S^3\end{array} \arrow[d, leftrightarrow, "\begin{array}{c}\text{mirror}\\ \text{symmetry}\end{array}"] \\
\begin{array}{c}\text{N D6 branes on } S^3 \\ \text{inside deformed conifold}\end{array} \arrow[r, leftrightarrow, "\text{geometric}", "\text{transition}"'] \arrow[d, leftrightarrow, "\text{lift}"] & \begin{array}{c}\text{RR flux} \\ \text{on } \mathbb{P}^1 \text{ inside} \\ \text{res. conifold}\end{array} \arrow[d, leftrightarrow, "\text{lift}"] \\
\begin{array}{c}\text{M theory on} \\ \mathbb{R}^4/\mathbb{Z}_N \times S^3 \\ \text{(inside } G_2 \text{ manifolds)}\end{array} \arrow[r, leftrightarrow, "\text{flop}"] & \begin{array}{c}\text{M theory} \\ \text{on } \mathbb{R}^4 \times S^3/\mathbb{Z}_N\end{array}
\end{tikzcd}
$$

⑦

What are the maps?

II B:

N D5 branes on $\mathbb{P}^1$ $\longleftrightarrow$ H_{RR} on S^3

g - coupling ct. for $U(N)$

$$\int_{S^3} H_{RR} = N$$

$$\int_{\mathbb{R}^3} \tau H_{NS} = \frac{1}{g^2}$$

Crucial condition

gluino condensate = size of S^3

$$S = \text{size of } S^3 = \int_{S^3} \Omega^{(3,0)}$$

II A:

N D6 branes on S^3 $\longleftrightarrow$ $B^{(2)}_{RR}$ on $\mathbb{P}^1$

$$S = \text{volume of } \mathbb{P}^1$$

But there is an extra "surprise" for II A!

⑧

Explicit computations of genus 0 open topological string amplitudes (BCOV):

$$W = \sum_h \int d^2\theta \, \underbrace{F_{0,h}}_{\text{part. funct. for topological strings at } g=0,\ h \text{ holes}} [N h S^{h-1}] + \alpha \underbrace{S}_{h=2}$$

⇓

we need a term in the closed string:

$$W \sim \underbrace{t}_{\text{complex volume of } \mathbb{P}^1}$$

This appears from the integral:

$$W = \int_{\text{res. Conif}} t \wedge \Omega^{(4)} \quad \text{- geometric 4-form}$$

So we need an extra $\Omega^{(4)}$.

⑨

Proposal:

$$\left.\begin{array}{c}\Omega^{(4)} = d\,\Omega^{(3,0)}_{\mathrm{IIA}} \\ \text{and} \\ dJ \neq 0\end{array}\right]$$

the resolved conifold becomes non-Kähler and non-complex

The RR 2-form is the same
There is an extra NS field which combines with J to give

$$\int (J + i\, B_{NS}) \wedge \Omega^{(4)}$$

And we also change the geometric transition setup, by considering open string side also compactied on a non-kähler manifold.

We now proceed to build an explicit example.

(10).

Start in IIB: solution for D5 branes wrapped on $\mathbb{P}^1$ inside res. conifold

$$ds^2_{10} = h^{-1/2}(\rho)\, dx^\mu dx_\mu + h^{1/2}(\rho)\, ds^2_6$$

$$ds^2_6 = \gamma' dr^2 + \frac{1}{4}\gamma \sum_{i=1}^{2} (d\theta_i^2 + \sin^2\theta_i\, d\phi_i^2) +$$
$$+ \frac{1}{4}\gamma' r^2 \left(d\psi + \sum_{i=1}^{2} \cos\theta_i\, d\phi_i\right)^2 +$$
$$+ a^2 (d\theta_2^2 + \sin^2\theta_2\, d\phi_2^2)$$ (Pando-Zayas Tseytlin)

a - size of $\mathbb{P}^1$

h - harmonic function of ρ

$$B_{NS} = f_1(\rho)\, d\theta_1 \wedge d\phi_1 + f_2(\rho)\, d\theta_2 \wedge dy$$

$H_{NS} = dB_{NS}$ is very small such that there is no backreaction on the metric

We make the following change of coordinates:

$$(\phi_1, \phi_2, \psi) \longrightarrow (x, y, z)$$

$$(dx, dy, dz) = \Big(\frac{1}{2}\sqrt{h^{1/2}\gamma}\,\sin\theta_1\, d\phi_1,$$

$$\frac{1}{2}\sqrt{h^{1/2}(\gamma+4a^2)}\,\sin\theta_2\, d\phi_2,$$

$$\frac{1}{2} r \sqrt{\gamma' h^{1/2}}\, d\psi \Big)$$

in the new coordinates

$S_1^2(\phi_1, \theta_1)$ are converted into tori
$S_2^2(\phi_2, \theta_2)$

metric on the tori:

$$|dz_1|^2 = |dx - \tau_1\, d\theta|^2$$

complex structure

$$\tau_1 = \frac{i}{2}\sqrt{\gamma\sqrt{h}}$$

Strominger – Yau – Zaslow:
For a manifold admitting a T^3 structure, one can reach a mirror by T-duality on T^3

Mirror Symmetry:
replacing Kähler deformations by Complex Deformation

For a conifold

$xy - uv = 0$

$$\left.\begin{aligned} x\zeta_1 &= u\zeta_2 \\ y\zeta_2 &= v\zeta_1 \end{aligned}\right)$$

$h_{11} = 1$

Resolved conifold

$\frac{\zeta_1}{\zeta_2} \to \mathbb{P}^1$

$xy - uv = \mu$

$x_1^2 + x_2^2 + y_1^2 + y_2^2 = \mu \to T^* S^3$

$h_{21} = 1$

deformed conifold.

Mirror Symmetry:

Resolved Conifold $\longleftrightarrow$ Deformed Conifold

Consider the 3 isometries

$$\left.\begin{aligned} x &\longrightarrow x + c_1 \\ y &\longrightarrow y + c_2 \\ z &\longrightarrow z + c_3 \end{aligned}\right] \begin{array}{l} \text{natural} \\ T^3 \text{ structure.} \end{array}$$

Can now take

$$|dz_1|^2 = |dx - \tau_1\, d\theta|^2$$
$$|dz_2|^2 = |dy - \tau_2\, d\theta|^2$$

and change

$$\tau_1 \longrightarrow \tau_1 + f_1$$
$$\tau_2 \longrightarrow \tau_2 + f_2$$
$$j_{zz} = 1 \longrightarrow j_{\tilde{z}\tilde{z}} = 1 - \varepsilon$$

Then consider $f_i \to \infty$, $\varepsilon \to 0$

with $f_1 f_2 \varepsilon = \text{finite}$

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Perform T-dualities in x, y, z

$$T_x : \begin{cases} G'_{\mu\nu} = G_{\mu\nu} - \dfrac{G_{x\mu} G_{x\nu} - B_{x\mu} B_{x\nu}}{G_{xx}} \\ B'_{\mu\nu} = B_{\mu\nu} + \dfrac{2 B_{x[\mu} G_{\nu]x}}{G_{xx}} \end{cases}$$

$$\Downarrow \; T_x \cdot T_y \cdot T_{\tilde{z}}$$

$$ds^2_{IIA} = g_1 (dz + \Delta_1 \cot\theta_1 \, d\hat{x} + \Delta_2 \cot\theta_2 \, d\hat{y})^2 + g_2 (d\theta_1^2 + dx^2) + g_3 (d\theta_2^2 + dy^2) + g_4 [f_1 f_2 \varepsilon \, d\theta_1 d\theta_2 - dx \, dy)$$

For $f_1 f_2 \varepsilon = 1$, this is the metric of a "delocalized" deformed conifold.

Def. conifold has an extra term

$$\cos\psi (d\theta_1 d\theta_2 - d\phi_1 d\phi_2 \sin\theta_1 \sin\theta_2) + \sin\psi (d\phi_1 d\theta_2 \sin\theta_1 + d\phi_2 d\theta_1 \sin\theta_2)$$

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"Delocalize in ψ" $\Rightarrow$ ψ = constant.

Dependence on ψ of deformed Conifold

$\Downarrow$

Deformed Conifold is not toric and one needs to start from Resolved Conif.

This can be seen also from following arguments:

a) Resolved Conifold

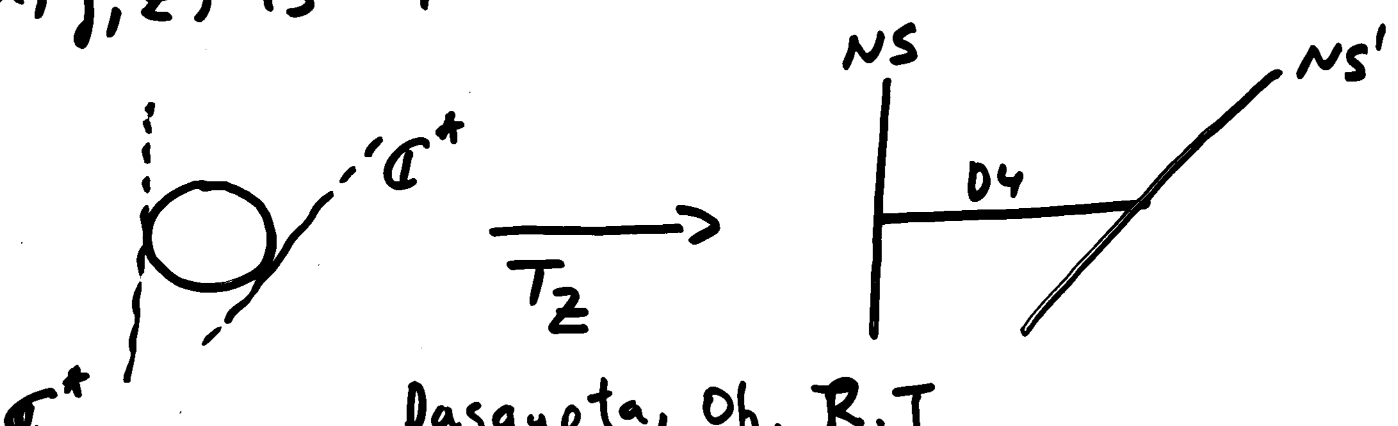
$\mathcal{O}(-1) \oplus \mathcal{O}(-1)$ (y is $S^1 \subset \mathbb{C}^*$)

(x is $S^1 \subset \mathbb{C}^*$) $\downarrow$

$\mathbb{P}^1$ (z - angular direction)

(x, y, z) is T^3

T_z:



Dasgupta, Oh, R.T.
hep/th-0105166

b) Deformed Conifold

$$xy - uv = \mu$$

$$S^1_1 : \begin{cases} x \to e^{i\theta} x \\ y \to e^{-i\theta} y \end{cases} \quad ; \quad S^1_2 : \begin{cases} u \to e^{i\psi} u \\ v \to e^{-i\psi} v \end{cases}$$

But we cannot identify the third S^1

$\Rightarrow$ The mirror symmetry can be considered

$$\left. \begin{array}{c} \text{II B on res. conif.} \\ \Downarrow \\ \text{II A on def. conif.} \end{array} \right] \text{open string side}$$

As the "delocalization" will go through the transition, the mirror symmetry will be possible to discuss for

$$\left. \begin{array}{c} \text{II A on res. conif.} \\ \Downarrow \\ \text{II B on def. conif.} \end{array} \right] \text{closed string side.}$$

Result:

$$ds^2 = g_1\left[d\hat{z} + \Delta_1 \cot\hat{\theta}_1\, d\hat{x} + \Delta_2 \cot\hat{\theta}_2\, d\hat{y}\right]^2$$

$$+ g_2\left[d\theta_1^2 + d\hat{x}^2\right] + g_3\left[d\theta_2^2 + d\hat{y}^2\right]$$

$$+ g_4\left[d\theta_1\, d\theta_2 - d\hat{x}\, d\hat{y}\right]$$

$$\left[\begin{array}{l} d\hat{z} = dz - b_{z\mu}\, dx^{\mu} = dz \\ d\hat{x} = dx - b_{x\theta_1}\, d\theta_1 \\ d\hat{y} = dy - b_{y\theta_2}\, d\theta_2 \end{array}\right. \qquad (1)$$

This is exactly the metric for wrapped D6 on S^3, but with redefinitions (1).

$$\left.\begin{array}{l} d b_{x\theta_1} \neq 0 \\ d b_{y\theta_2} \neq 0 \end{array}\right] \text{ but small}$$

Our II A manifold has an almost complex structure $J_i^{\,k}$ and the fundamental 2-form:

$$J_{ij} = J_i^{\,k}\, g_{kj}$$

Also, there is a (3,0) form:

$$\Omega_{ijk} \sim e_i \wedge e_j \wedge e_k$$

We observe that

$$\left.\begin{aligned} dJ &\neq 0 \\ d\Omega &\neq 0 \end{aligned}\right] \quad \text{Non-kähler and Non-complex manifold}$$

We have thus described the first half of the "modified geometric transition".

The modified type II A transition:

D6 branes on a
non-Kähler deformation of a
Deformed Conifold

$\updownarrow$ open-closed duality

RR flux on $\mathbb{P}^1$
of a non-kähler deformation of a
resolved Conifold

$$d\Omega_{D.C.} \neq 0 \longleftrightarrow d\Omega_{R.C.} \neq 0$$

Continous way to understand this?
Use G_2 manifolds (7 dim. manifolds preserving $N=1$ in 4d

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Observations

① Topological duality:

Chern-Simons on S^3 (inside non-Kähler)

$$\Updownarrow$$

Topological Strings on non-Kähler

Need to clarify the computation of superpotential for almost Komplex manifold

② Compute torsion classes

$\tau_1, \dots, \tau_5$

Usual story (Atiyah-Maldacena-Vafa)

II A: N D6 $\underset{(0123456)}{}$ on S^3 (456)

$\downarrow$

M theory $\underbrace{\underset{(789,10)}{\mathbb{R}^4/\mathbb{Z}_N} \times \underset{(456)}{S^3}}$

Cone over $\tilde{S}^3/\mathbb{Z}_N \times S^3$

$\downarrow$

Flop $\tilde{S}^3 \longleftrightarrow S^3$

$\tilde{S}^3/\mathbb{Z}_N \times S^3 \longrightarrow \tilde{S}^3 \times S^3/\mathbb{Z}_N$

$\downarrow$ $\downarrow$ Hopf fiber

II A $\mathbb{P}^1$ with N units of RR flux

Resolved conifold with N units of RR flux on $\mathbb{P}^1$

$\boxed{5}$ (Brandhuber, Gomis, Gubser, Gukov)

Symmetries: $x_1^2 + x_2^2 + x_3^2 + x_4^2 = \mu$

rotation $SO(4) \sim SU(2) \times SU(2)$

$\mathbb{Z}_2 : x_i \longleftrightarrow -x_i$

$U(1)$: M theory circle

$\Rightarrow$ G_2 holonomy metric has $SU(2)^2 \times U(1) \times \mathbb{Z}_2$

$SU(2)_1$: $d\sigma_a = -\frac{1}{2} \varepsilon_{abc}\, \sigma_b \wedge \sigma_c$

$SU(2)_2$: $d\Sigma_a = -\frac{1}{2} \varepsilon_{abc}\, \Sigma_b \wedge \Sigma_c$

$U(1)$: $\begin{pmatrix} \sigma_1 \\ \sigma_2 \end{pmatrix} \to \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \end{pmatrix}$

$\mathbb{Z}_2$: $\sigma_a \longleftrightarrow \Sigma_a$

Most general metric:

$e^i = A(r)\,(\sigma_i - \Sigma_i)$, $i = 1,2$; $e^3 = D\,(\sigma_3 - \Sigma_3)$

$e^5 = B(r)\,(\sigma_2 + \Sigma_2)$; $e^6 = C(r)\,(\sigma_3 + \Sigma_3)$

$e^7 = \frac{dr}{C(r)}$; $e^4 = B(r)\,(\sigma_1 + \Sigma_1)$

What happens if one starts with D6 on a non-Kähler deformed conifold?

Need the 11-dimensional metric.

$$G^{M}_{\mu\nu} = e^{-\frac{2\phi}{3}} g^{\mathrm{IIA}}_{\mu\nu} - e^{\frac{4\phi}{3}} A_\mu A_\nu$$

$$G^{M}_{\mu\, 11} = - e^{\frac{4\phi}{3}} A_\mu$$

A_μ - gauge field in $\underline{\mathrm{II}}$ A

To get $\underline{\mathrm{II}}$ A gauge field, start with $\underline{\mathrm{II}}$ B RR 3-form and 5-form

$$H^{(3)} = c_1 (dz \wedge d\theta_2 \wedge dy - dz \wedge d\theta_1 \wedge dx) +$$
$$+ c_2 \cot \hat{\theta}_1 \, dx \wedge d\theta_2 \wedge dy -$$
$$- c_3 \cot \hat{\theta}_2 \, dy \wedge d\theta_1 \wedge dx$$
$$F^{(5)} = K(r) (1 + *) \, dx \wedge dy \wedge dz \wedge d\theta_1 \wedge d\theta_2$$

Apply T-duality rules:

$$\tilde{F}^{(n)}_{ijk\ldots} = F^{(n+1)}_{xijk} - n\, B_{x[i} F^{(n-1)}_{jk\ldots]} + n(n-1)\, j^{-1}_{xx} \cdot B_{x[i}\, j_{xj}\, F^{(n-1)}_{x\, k\ldots]}$$

$$\tilde{F}^{(n)}_{xij\ldots} = F^{(n-1)}_{ij\ldots} - (n-1)\, j^{-1}_{xx}\, j_{x[i}\, F^{(n-1)}_{xjk\ldots]}$$

We get:

$H^{(3)}$:

$$F_{z\theta_1} = -c_3 \cot\theta_2$$

$$F_{z\theta_2} = -c_2 \cot\theta_1$$

$$F_{y\theta_1} = C_1 - 2c_3 \alpha B \cot\theta_2$$

$$F_{x\theta_2} = C_1 - 2C_2 \alpha A \cot\theta_1$$

F_5:

$$F_{\theta_1\theta_2} = K(r) - c_1(b_{x\theta_1} - b_{y\theta_2}) - 2C_3 \alpha B\, b_{y\theta_2} \cot\theta_2 + 2c_2 \alpha A\, b_{x\theta_1} \cot\theta_1$$

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Therefore

$$A_\mu \, dx^\mu = \Delta_1 \cot\theta_1 \, d\hat{x} - \Delta_2 \cot\theta_2 \, d\hat{y}$$

Δ_i - functions of θ_i, x, y, z

M-theory metric:

$$ds^2 = e^{-\frac{2\phi}{3}}\left(h^{-1/2} \, dS^2_{0123} + h^{1/2} \gamma' \, dr^2\right) + e^{-\frac{2\phi}{3}}\left(dz + \Delta_1 \cot\theta_1 \, d\hat{x} + \Delta_2 \cot\theta_2 \, d\hat{y}\right) + e^{\frac{4\phi}{3}}\left(dx_{11} + \Delta_1 \cot\theta_1 \, dx - \Delta_2 \cot\theta_2 \, dy\right)^2$$

We can then identify

$$dz = d\psi_1 - d\psi_2$$

$$dx_{11} = d\psi_1 + d\psi_2$$

and we can write our metric as

$$\sigma_3 = d\psi_1 + \Delta_1 \cot\hat{\theta}_1 \, d\hat{x}$$

$$\Sigma_3 = d\psi_2 + \Delta_2 \cot\hat{\theta}_2 \, d\hat{y}$$

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$$ds_7^2 = \alpha_1^2 \sum_{a=1}^{2} (\sigma_a + \Sigma_a)^2 + \alpha_2^2 \sum_{a=1}^{2} (\sigma_a - \Sigma_a)^2$$

$$+ \alpha_3^2 (\sigma_3 + \Sigma_3)^2 + \alpha_4 (\sigma_3 - \Sigma_3)^2 +$$

$$+ \alpha_5^2 \, dr^2$$

$$\alpha_1 = \frac{1}{2} \sqrt{g_4 + 2 g_2} \qquad \alpha_3 = 1$$

$$\alpha_2 = \frac{1}{2} \sqrt{2 g_2 - g_4} \qquad \alpha_4 = \sqrt{g_1}$$

$$\alpha_5 = \sqrt{\gamma' \sqrt{h}}$$

Torsion:

$$\tau = - * d \tilde{\Omega} - * \left[\frac{1}{3} * (* d \tilde{\Omega} \wedge \tilde{\Omega}) \wedge \tilde{\Omega} \right]$$

$$\tilde{\Omega} = J \wedge e^7 + \Omega_+$$

We have 4 torsion classes

τ_1	τ_2	τ_3	τ_4	
1	14	27	1	of $SO(7)$

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What about flop?

- we lifted the deformed conifold on x_{11}
- we can now descend on Z and result is:

$$ds^2 = A\left[d\theta_1^2 + (d\alpha - b_{x\theta_1}\, d\theta_1)^2\right] +$$
$$+ B\left[d\theta_2^2 + (dy - b_{y\theta_2}\, d\theta_2)^2\right] +$$
$$+ C\left[dx_{11} + \Delta_1 \cot\theta_1 (dx - b_{x\theta_1}\, d\theta_1) + \right.$$
$$\left. + \Delta_2 \cot\theta_2 (dy - b_{y\theta_2}\, d\theta_2)\right]^2$$

This is exactly the metric of a non-kähler resolved conifold.

The final result is a non-Kähler deformation of a resolved conifold

$$dJ \neq 0$$

$$d\Omega \neq 0$$

Superpotential $\int (J + iB) \wedge d\Omega$

Torsion classes:

$$\begin{tikzcd}
\begin{array}{c}\text{open IIA} \\ (W_1, \dots, W_5)\end{array} \arrow[d] & & \begin{array}{c}\text{closed IIA} \\ (W_1', \dots, W_5')\end{array} \\
\begin{array}{c}G_2 \\ (\tau_1, \dots, \tau_4)\end{array} \arrow[rr, "\text{flop}"'] & & \begin{array}{c}G_2 \\ (\tau_1', \dots, \tau_4')\end{array} \arrow[u]
\end{tikzcd}$$

it is neccesary a consistency check.

Conclusions

- claims about non-Kählerity turn out true
- the specific example of mirror symmetry deformed conifold $\longleftrightarrow$ resolved conifold: detailed description of mirror symmetry and the flop transition
- Main lesson: nonKähler geometry is a necessary ingredient

One should learn much more about them (classification, SUSY preserved, etc.)