Non-supersymmetric compactifications of string and F theory

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based on work with T. Grimm and T. Pugh

Introduction

- Aim of the talk: discuss a new class of F-theory constructions
- Compact dimensions ⟶ Spin(7) real 8-fold see T. Grimm's talk
- Outline
  - Spin(7) manifold as quotient space: Calabi-Yau fourfold modded by antiholomorphic involution
  - A proposal for generalizing F-theory/M-theory duality to Spin(7)
  - Effective 3d action as truncation of Calabi-Yau effective action
  - Interplay between 4d and 3d effective action
  - Remarks on weak coupling picture in Type IIB
- Some aspects will not be covered
  - Focus mainly on moduli fields
  - Modes from singularity resolution are not discussed

F-theory on Spin(7) manifolds

- F-theory framework: rich class of 4d vacua
- No 12d effective action → F-theory/M-theory duality

M-theory (11d sugra) —X_8→ 3d effective action

F-theory ('12d') —X_8→ 4d effective action —S^1→ 3d effective action

- X_8 Calabi-Yau fourfold

3d $\mathcal{N} = 2$ ←S^1— 4d $\mathcal{N} = 1$

- From 12d perspective Calabi-Yau is not the minimal case
- Spin(7) is the maximal special holonomy → X_8 Spin(7) manifold? **[Vafa 96]**

3d $\mathcal{N} = 1$? 4d $\mathcal{N} = 0$

Spin(7) manifolds from Calabi-Yau fourfolds

quick reminder

Spin(7) manifold X_8	Calabi-Yau fourfold Y_4
$\nabla \eta = 0$	$\nabla \eta_1 = \nabla \eta_2 = 0$
$\Phi \in H^4_S(X_8)$	$J \, , \, \Omega$

- Special class of Spin(7) manifolds **[Joyce 99]**
- Antiholomorphic involution $\sigma : Y_4 \to Y_4$

$$\sigma^2 = \mathrm{id} \qquad \sigma^* J = -J \qquad \sigma^* \Omega = e^{2i\theta}\, \overline{\Omega}$$

- Natural calibration on the quotient space $X_8 = Y_4/\sigma$

$$\Phi = \frac{1}{\mathcal{V}^2} \left\{ \frac{1}{||\Omega||} \mathrm{Re} \left(e^{-i\theta}\, \Omega \right) + \frac{1}{8} J \wedge J \right\}$$

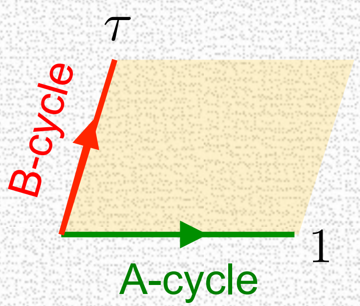
- Singularities have to be resolved in a Spin(7) compatible way
    - beyond present discussion

Elliptically fibered fourfolds and σ

- Elliptically fibered Calabi-Yau fourfold $\pi : Y_4 \to B_3$
- Compatibility between σ and the fibration structure
- Antiholomorphic involution on the base

$$\begin{array}{ccc} Y_4 & \xrightarrow{\sigma} & Y_4 \\ \downarrow \pi & & \downarrow \pi \\ B_3 & \xrightarrow{\sigma} & B_3 \end{array}$$

- Heuristic picture of the action on the torus



$$ds^2 = \frac{v}{\tau_2}\left[(dx + \tau_1\, dy)^2 + \tau_2^2\, dy^2\right]$$

$$\tau = \tau_1 + i\,\tau_2$$

$\tau \to -\bar{\tau}$ ⟹ $x \to x$, $y \to -y$

the B-cycle is turned into an interval $S^1/\mathbb{Z}_2$

- **Proposal**:

$$\text{3d } \mathcal{N} = 1 \xleftarrow{S^1/\mathbb{Z}_2} \text{4d } \mathcal{N} = 0$$

Reminder: some basic facts about M-theory on Y_4

3d $\mathcal{N}=2$ effective action

for simplicity: $b^3(Y_4)=0$

$$S^{\mathrm{3d}}_{\mathcal{N}=2} = \int \tfrac{1}{2} R * 1 - g_{\mathcal{A}\bar{\mathcal{B}}}\, \mathcal{D}M^{\mathcal{A}} \wedge * \mathcal{D}\overline{M}^{\bar{\mathcal{B}}} - \tfrac{1}{4}\Theta_{IJ}\, A^I \wedge F^J - V * 1$$

[Haack, Louis 99,01]

$$\Theta_{IJ} = \int_{Y_4} G_4 \wedge \omega_I \wedge \omega_J$$

$$K = -3\log\mathcal{V} - \log \int_{Y_4} \Omega \wedge \overline{\Omega} \qquad W = \int_{Y_4} G_4 \wedge \Omega \qquad \mathcal{T} = \frac{1}{4\mathcal{V}^2}\int_{Y_4} G_4 \wedge J^2$$

Complex scalars: $M^{\mathcal{A}} = (\, T_I \,,\, z^{\mathcal{K}}\,)$

Kähler moduli	Complex structure moduli
$J = v^I \omega_I \xrightarrow{(1)} \mathrm{Re}\, T_I$ $C_3 = A^I \wedge \omega_I \xrightarrow{(2)} \mathrm{Im}\, T_I$ $I = 1, \ldots, h^{1,1}(Y_4)$	$\dfrac{\partial \Omega}{\partial z^{\mathcal{K}}} = \chi_{\mathcal{K}} - K_{\mathcal{K}}\, \Omega$ $\mathcal{K} = 1, \ldots, h^{3,1}(Y_4)$

(1) Legendre transform $\mathrm{Re}\, T_I \sim \partial\mathcal{V}/\partial v^I$ (2) 3d duality between vectors and scalars

M-theory on $X_8 = Y_4/\sigma$: truncation

- Low energy dynamics on $X_8 = Y_4/\sigma$: same couplings up to truncation of σ-odd fields
- Cohomologies are split into positive and negative forms. E.g.

$$H^2(Y_4) = H^2_+(Y_4) \oplus H^2_-(Y_4)$$

$$\omega_I \longrightarrow \{ \omega_{I_+} , \omega_{I_+} \}$$

- Only a subset of Kähler degrees of freedom is allowed by σ-parity

$\sigma^* J = -J$

C_3 is σ-even

$$\Longrightarrow \quad J = v^{I_-} \omega_{I_-} \qquad C_3 = A^{I_+} \wedge \omega_{I_+}$$

- We cannot combine $\mathrm{Re}\, T_{I_-}$ and $\mathrm{Im}\, T_{I_+}$ into complex scalars
- Real slice of complex structure moduli space

deformations must preserve $\sigma^* \Omega = e^{2i\theta}\, \overline{\Omega}$ $\Longrightarrow$ $\mathrm{Im}\, z^{\mathcal{K}} = 0$

- $\mathcal{N} = 2$ is truncated to $\mathcal{N} = 1$: consistent with real moduli space of Spin(7) manifolds

The case of an elliptic fibration

- Calabi-Yau condition for the fibration $\pi : Y_4 \to B_3$

$$c_1(B_3) = 12[\Delta]_{B_3} \qquad (\Delta \equiv \text{7-brane locus on } B_3)$$

both sides are negative under σ

- Refined structure in $H^2(Y_4)$

$$\omega_I \longrightarrow \{\, \omega_0 \,,\, \omega_\alpha \,,\, \omega_i \,\}$$

Poincaré dual to B_3

negative under σ

(the orientation of the torus fiber is reversed)

pull-back from $H^2(B_3)$

split $\omega_\alpha \to \{\omega_{\alpha_+}, \omega_{\alpha_-}\}$ according to $\sigma : B_3 \to B_3$

Poincaré dual to exceptional divisors

negative under σ

(σ reverses the $\mathbb{P}^1$-fiber of the exceptional divisors)

- Simultaneous fibration and σ constraints on the intersection numbers

e.g. $\mathcal{K}_{0\alpha_-\beta_-\gamma_+} = 0\,,\ \mathcal{K}_{0\alpha_-\beta_-\gamma_-} = \kappa_{\alpha_-\beta_-\gamma_-}$

Truncation in four dimensions

- Uplift of 4d fields in the usual Calabi-Yau case

4d	$g_{\mu\nu}$			$\mathrm{Re}\, T_\alpha$	$\mathrm{Im}\, T_\alpha$	$\mathrm{Re}\, z^K$	$\mathrm{Im}\, z^K$	A^i	
3d	$g_{\mu\nu}$	v^0	A^0	v^α	A^α	$\mathrm{Re}\, z^K$	$\mathrm{Im}\, z^K$	v^i	A^i

- $v^0 \sim$ radius of the circle
- $A^0 \sim$ Kaluza-Klein vector
- $A^i \sim$ vectors in the Cartan of the non-Abelian gauge group

Truncation in four dimensions

- The 3d truncation induces a 4d truncation

				$\mathrm{Re}\, T_{\alpha_-}$	$\mathrm{Im}\, T_{\alpha_+}$				
4d	$g_{\mu\nu}$			~~$\mathrm{Re}\, T_\alpha$~~	~~$\mathrm{Im}\, T_\alpha$~~	$\mathrm{Re}\, z^K$	~~$\mathrm{Im}\, z^K$~~	A^i	
3d	$g_{\mu\nu}$	v^0	~~A^0~~	~~v^α~~	~~A^α~~	$\mathrm{Re}\, z^K$	~~$\mathrm{Im}\, z^K$~~	v^i	~~A^i~~
				v^{α_-}	A^{α_+}				

- The 4d moduli sector is non-supersymmetric
- In 3d A^0 and A^i are truncated but the 4d metric and vectors are kept

4d to 3d reduction on an interval → boundary conditions at the endpoints → some KK zero-modes are removed from the 3d theory

- The interval halves the components of 4d massless fermions

4d $\mathcal{N} = 0$ can yield 3d $\mathcal{N} = 1$

Weak coupling picture in Type IIB string theory

- Weak coupling limit in F-theory: Calabi-Yau orientifold **[Sen 97]**

$$B_3 = \frac{Y_3}{\sigma_{\text{hol}}}$$

holomorphic involution
$\sigma_{\text{hol}} : Y_3 \to Y_3$

- When the antiholomorphic involution σ is included we get an additional quotient
- **Proposal**: Type IIB on Y_3 modded out by

$$\mathcal{O}_1 = (-)^{F_L}\Omega\,\sigma_{\text{hol}} \qquad \mathcal{O}_2 = (-)^{F_L}P_3\,\sigma$$

- σ induces a Pin-odd transformations on spinors on Y_3
  → not a symmetry of Type IIB!
- Compensating Pin-odd transformation
  → reflection in 4d spacetime

$$P_3 : (x^0, x^1, x^2, x^3) \mapsto (x^0, x^1, x^2, -x^3)$$

x^3 parameterizes the interval that decompactifies in the F-theory limit

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- 10d fields in Type IIB have intrinsic parities under σ

$x \to x \quad y \to -y$

IIB	ϕ	$g_{\mu\nu}$	$g_{\mu y}$	g_{yy}	$B_{\mu\nu}$	$B_{\mu y}$	C_0	$C_{\mu\nu}$	$C_{\mu y}$	$C_{\mu\nu\rho y}$
IIA	ϕ	$g_{\mu\nu}$	$B_{\mu y}$	g_{yy}	$B_{\mu\nu}$	$g_{\mu y}$	C_y	$C_{\mu\nu y}$	C_μ	$C_{\mu\nu\rho}$
M	g_{xx}	$g_{\mu\nu}$	$C_{\mu yx}$	g_{yy}	$C_{\mu\nu x}$	$g_{\mu y}$	g_{xy}	$C_{\mu\nu y}$	$g_{\mu x}$	$C_{\mu\nu\rho}$

σ-even (columns ϕ through $B_{\mu y}$) $\qquad$ σ-odd (columns C_0 through $C_{\mu\nu\rho y}$)

Conclusions

- Proposed generalization of F-theory/M-theory duality
  - Spin(7) internal space
  - Uplift from 3d to 4d on an interval
- More tractable case: Spin(7) manifold as quotient of Calabi-Yau fourfold
- 3d truncation from $\mathcal{N} = 2$ to $\mathcal{N} = 1$
- 4d uplift to non-supersymmetric theory
- Many interesting problems
  - charged matter
  - Spin(7) resolution modes
  - phenomenological features
  - characterization of Spin(7) manifolds suitable for F-theory

Conclusions

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Thank you for your attention!

Some remarks on charged matter

- 4d charged chiral matter is not accessible directly in the M-/F-theory duality
- Hard to proceed with the previous methods
- Type IIB picture at weak coupling: open strings stretching between intersecting magnetized D7-branes

4d $\mathcal{N} = 1$ chiral matter ⟵ holomorphic embedding & (1,1) worldvolume flux

- **Possible strategy**: consider weak coupling at toroidal orbifold point for Y_3
  - explicit worldsheet description available
  - projection onto invariant states under $\mathcal{O}_1$ and $\mathcal{O}_2$
- Any image brane under σ has still holomorphic embedding and (1,1) flux
- All intersections yield at least one massless complex scalar together with a chiral fermion before the projection is performed
- Some examples: the projection is democratic in bosons and fermions
- Further analysis needed to clarify charged matter spectrum