Type IIB Flux Vacua via the String Worldsheet

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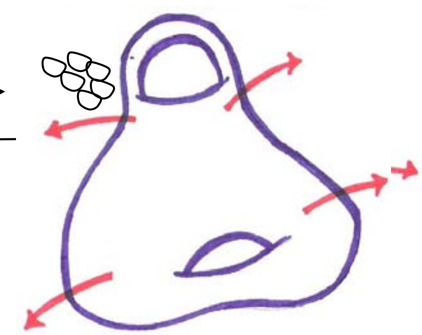
Motivation: Shortcomings and Expectations

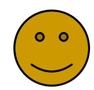
- How to connect with reality? Flux compactifications are important
- Approaches typically confined to SUGRA. Need large volume limit to control α'

String scale cycle: lots of string corrections

SUGRA valid if $l_s \ll R$



$$\langle \mathcal{O}_1 \mathcal{O}_2 \ldots \rangle = \int_{10} d\,[\text{fields}]\, e^{-S} \mathcal{O}_1 \mathcal{O}_2 \ldots$$

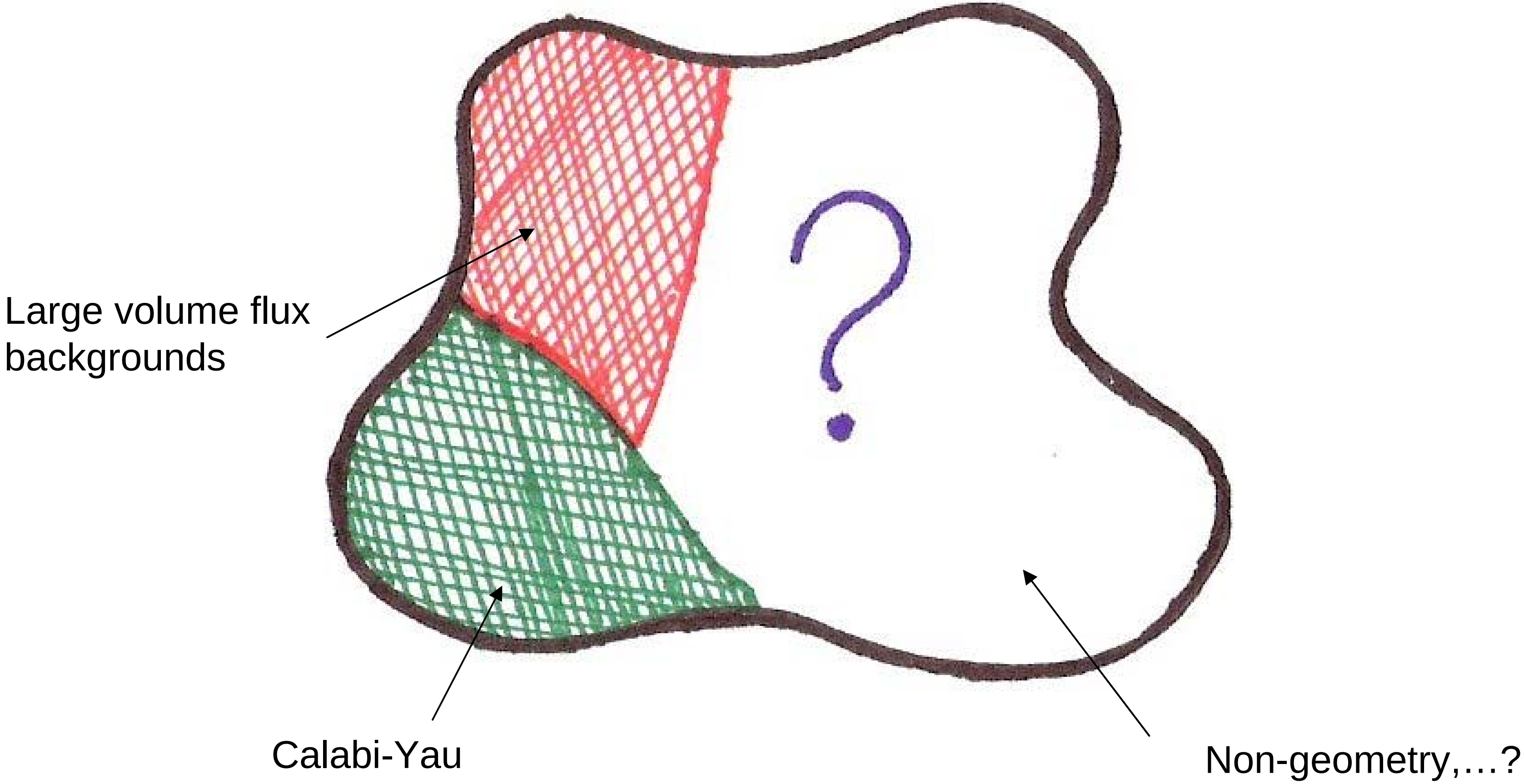


What if a cycle approaches string scale? ***Need a string description!***

- How will string theory change our SUGRA intuition?
  - Generic string solutions are expected to be string scale
  - Phenomenologically desirable to have no moduli -> hard in SUGRA
  - Are there new solutions not seen in SUGRA (eg. Non-geometric..?) Such new solutions may be phenomenologically interesting

Type II String Theory Vacua

Likely still have much to uncover beyond SUGRA



How to Go Beyond Supergravity?

- Traditionally, string descriptions of RR fluxes are hard & not well studied
- Three main approaches
  - Ramond-Neveu-Schwarz (RNS)
    - RR vertex operators have branch cuts, half integral picture, ...
  - Green-Schwarz (GS)
    - No covariant quantization
    - Light cone gauge is inconsistent for general flux vacua
  - D=4 Hybrid *(Berkovits,…)*

$$\mathrm{GS}_{d=4} \oplus \mathrm{RNS}_{\mathcal{M}_6}$$

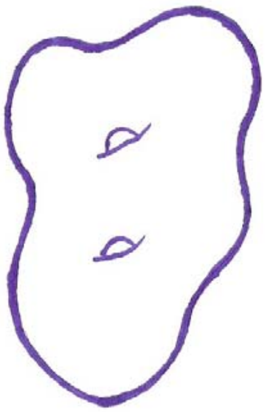
    - SO(3,1) covariant quantization
    - Circumvents the above problems nicely
    - Subjected to many tests (spectrum, scattering amplitudes …)
    - Well suited to flux compactifications

Outline

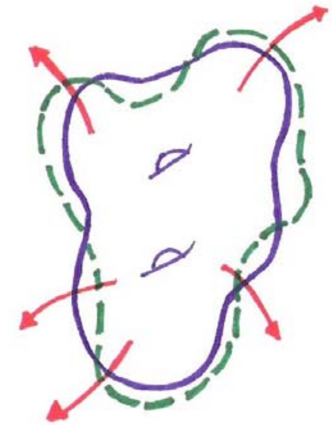
☑ 1. Motivation: Why Do We Care About String Compactifications?
2. ***Some Lessons from Supergravity***
3. Flux Vacua in the Hybrid
4. Physical Effects and Applications
5. Conclusions and Outlook

Some Lessons from Supergravity: CY_3

- Without fluxes: $M_6 = CY_3$
  - Preserves $N = 2$ spacetime supersymmetry.
  - Field content is given by KK reduction on the CY_3
    - Supergravity Multiplet
    - $h^{2,1}$ Vector Multiplets (complex structure moduli)
    - $h^{1;1} + 1$ermutiplets (Kahler moduli and dilaton)



Some Lessons from Supergravity: Conformally CY_3



- Simple Class of Solutions with $G_3 = F_3 - \tau H_3$
  - Supersymmetry broken to $N = 1$
  - SUSY => G_3 is (2,1)
  - Moduli lifted by:

    $$W = \int G_3 \wedge \Omega$$

  - Geometry backreacts:

    $$ds^2 = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + g_{ij}dy^i dy^j \quad \text{with } \Box_{CY} A(y) = g_s^2 |G_{2,1}|^2 + \dots$$

  - Spacetime filling five-form related to warp factor $F_{\mu\nu\rho\tau i} = \epsilon_{\mu\nu\rho\tau}\partial_i A$
- We study these backgrounds in string theory
  - Study non-compactly supported fluxes (evade tadpole, quantization)
  - Hence, work perturbatively in fluxes
  - SUGRA is also valid -> give us a concrete check of our approach

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String Theory for Flux Vacua: D=4 Hybrid

- Hybrid originally formulated on $\mathbb{R}^{3,1} \times \mathrm{CY}_3$ with field content $\mathrm{GS}_{d=4} \oplus \mathrm{RNS}_{\mathcal{M}_6}$
- Understandable as field redefinition of an N=1 critical RNS string:
  - $\mathrm{GS}_{d=4}$ redefinition of RNS D=4 & ghost variables

$$(X^\mu, \psi_L^\mu, \psi_R^\mu, b, c, \beta, \gamma) \to (X^\mu, \theta_L, \bar{\theta}_L, p_L, \bar{p}_L, \rho_L) + \mathrm{RM's}$$

  - $\mathrm{RNS}_{\mathcal{M}_6}$ usual RNS CY variables. Decoupled from D=4 sector.
- Worldsheet Action

$$S = \int d^2z \left[\partial X^\mu \bar{\partial} X_\mu + p_{L,\alpha} \bar{\partial} \theta_L^\alpha + \bar{p}_{L,\dot{\alpha}} \bar{\partial} \bar{\theta}_L^{\dot{\alpha}} + \mathrm{RM's}\right] + S_{\text{chiral}} + S_{CY}$$

- Comments:
  - Spacetime fermions have no branch cuts => manifest spacetime SUSY
  - Even though internal theory is RNS, we show how it can describe RR fluxes
  - $\mathrm{RNS}_{\mathcal{M}_6}$ described by (2,2) c = 9 SCFT
  - BRST + conformal invariance of N=1 RNS string <=> $\mathrm{GS}_{d=4}$ is a (2,2) SCFT.
    => Entire worldsheet theory $\mathrm{GS}_{d=4} \oplus \mathrm{RNS}_{\mathcal{M}_6}$ is a (2,2) SCFT.
  - (2,2) worldsheet superconformal invariance required for theory to be physically well-defined. We use it as our guiding principle

String Theory for Flux Vacua: Flux Vertex Operators

- Three-form fluxes. By KK reducing on the CY:
  - $F_3 = \sum_{p=1}^{h^{2,1}} F_p^{(2,1)} \omega_{2,1}^p + \text{c.c.}$
  - $H_3 = \sum_{p=1}^{h^{2,1}} H_p^{(2,1)} \omega_{2,1}^p + \text{c.c.}$
- Map RNS vertex operators to Hybrid. Trick: internal fluxes correspond to spacetime auxiliary fields
- For example: F_3

$$\mathcal{V}_{RNS}^p = e^{-\frac{1}{2}\phi_L - \frac{1}{2}\phi_R} \epsilon^{\alpha\beta} \Sigma_{L,\alpha} \Sigma_{R,\beta} \Psi_{RR}^p \longrightarrow \mathcal{V}_{\text{Hybrid}} = \theta_L \theta_R F_p^{(2,1)} \Omega_{1,1}^p$$

  - $p = 1, \ldots, h^{2,1}$ labels the (2,1) cohomology elements
  - Ψ_{RR}^p is RR ground state corresponding to pth cohomology element
  - $\Omega_{1,1}^p$ is the (c,c) element attained by spectral flow of Ψ_{RR}^p
  - $\mathcal{V}_{\text{Hybrid}}$ has no branch cuts. May be integrated into the Hybrid action!

String Theory for Flux Vacua: Flux Vertex Operators

- Have also written down vertex operators for other possible internal fluxes:
  - H_3 :

$$\mathcal{V}_{H_3} = i(\delta\Gamma^p - \frac{1}{2}H^p)\,\theta_L^2\Omega^p_{(1,1)} + i(\delta\Gamma^p + \frac{1}{2}H^p)\,\theta_R^2\Omega^p_{(1,1)} + e^{-\rho_L}E_L + e^{-\rho_R}E_R,$$

    where Γ^p is the correction to the Levi-Civita connection, $e^{-\rho_{L,R}}E_{L,R}$ is the complexified metric in a certain picture
  - F_1 and spacetime filling F_5 :

$$\mathcal{V} = \theta_L\theta_R\bar{\theta}_R^2(F_{1\,a} + iF_{5\,a})\Omega^a_{1,0} + \theta_L\theta_R\bar{\theta}_L^2(F_{1\,b} + iF_{5\,b})\Omega^b_{0,1} + \ldots$$

  - $G_{2,1}$:

$$\mathcal{V}_{G_{2,1}} = (\theta_L + i\theta_R)^2 g_s G^p\Omega^p_{(1,1)} + e^{-\rho_L}E_L + e^{-\rho_R}E_R,$$

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Physical Effects and Applications

- Start with non-compact Calabi-Yau background
- Turn on small amount of $G_{(2,1)}$. Some expectations from Supergravity:
  1. Spacetime becomes warped
  2. Superpotential generated
- We see each of these effects in string theory
  - Construct the integrated vertex operator for G3 flux

    $\delta S_{G_{2,1}} = \int d^2 z \mathcal{O}_{G_{2,1}}$ where $\mathcal{O}_{G_{2,1}} = G_L^- G_R^- \cdot \mathcal{V}_{G_{2,1}} + \text{c.c.}$ and

    $$\mathcal{V}_{G_{2,1}} = (\theta_L + i\theta_R)^2 g_s G^p \Omega^p_{(1,1)} + e^{-\rho_L} E_L + e^{-\rho_R} E_R,$$

  - Deform worldsheet action by $\delta S_{G_{(2,1)}}$
  - As spacetime SUSY manifest, easy to see this breaks half the SUSY corresponding to $(Q_L + iQ_R)^2$

Physical Effects and Applications: Warping & F$_5$

- The deformed action $S_0 + \delta S_{G_3}$ is not conformally invariant at 1-loop in α'
- The 1-loop beta function given by the UV structure of the two point function:

$$\mathcal{V}(z)_{G_{2,1}}\mathcal{V}(0)_{G_{2,1}} \sim \frac{(\theta_L\theta_R)(\bar\theta_L\bar\theta_R)|G^p|^2}{|z|^2} + \ldots,$$

Divergence breaks conformal invariance

- To maintain conformal invariance we add a counter-term. Requiring D=4 Poincare, the only vertex operator with the correct μ structure is:

$$U = (\bar\theta_L\sigma^\mu\theta_L)(\bar\theta_R\sigma^\nu\bar\theta_R)(\eta_{\mu\nu}A(y)) + \ldots \quad \text{giving} \quad \delta S_{\text{warp}} = \int d^2z \mathcal{Z}_L\mathcal{Z}_R \cdot U(z,\bar z)$$

- The deformation $\delta S_{G_3} + \delta S_{\text{warp}}$ preserves conformal invariance provided

$$\Box_{CY} A(y) = g_s^2|G^p|^2 + \ldots$$

- Implies the spacetime metric has been adjusted to give precisely warping!

$$ds^2 = (1 + A + \ldots)\eta_{\mu\nu}dx^\mu dx^\nu + g_{ij}dy^i dy^j$$

- Similarly, one can show conformal invariance preserved only if we have

$$F_{\mu\nu\rho\tau i} = \epsilon_{\mu\nu\rho\tau}\partial_i A$$

Physical Effects and Applications: Superpotential

- Presence of flux => potential generated at tree level which lifts moduli
- See this in string theory by tree-level scattering amplitude

$$\langle \mathcal{V}^q \mathcal{V}^r \rangle_{S_0 + \delta S_{G_{(2,1)}}} = \langle \mathcal{V}_{G_{(2,1)}} \mathcal{V}^q \mathcal{V}^r \rangle_{S_0} \neq 0$$

$\mathcal{V}^p$ = vertex operator for complex structure modulus

- In a CY_3 background, SL(2,C) and worldsheet SUSY => $\langle \mathcal{V}^q \mathcal{V}^r \rangle_{S_0} = 0$
- Flux background inserts a vertex operator, rendering the amplitude non-zero
- Manifest spacetime SUSY => scattering amplitude automatically computes a superpotential

$$\mathcal{W} = 3 \int d^4x d^2\theta^- g_s G^p_{(2,1)} \mathcal{V}^q(x, \theta^-) \mathcal{V}^r(x, \theta^-) C_{pqr}$$

Integration over zero modes and unbroken SUSY

Topological invariant of CY

- This may be recast in a more familiar form:

$$\mathcal{W} = \int G \wedge \delta\Omega.$$

Conclusions and Outlook

- Summary:
  - Important to have string theory description of flux vacua
  - This may lead to new string solutions, which are phenomenologically viable (no moduli, string scale, understanding of the landscape…)
  - We have shown how to identify flux vertex operators in the Hybrid
  - Computed using string theory effects well-known in supergravity

- Future and Current Work:
  - Tip of the iceberg: many *computable* interesting physical effects.
  - Need to understand finite flux deformations and orientifolding (compact solutions)
  - Construction of a Hybrid GLSM (*work in progress with J. Park, C. Quigley, D. Robbins, S. Sethi*)
  - Eventually understand vacua that are string scale: eg. non-geometric, no volume modulus.