Multi-Brane Recombination
and Standard Model Flux Vacua

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Compactify IIB on orientifolded CY 3-fold
- **N=1 SUSY**

Turn on Fluxes $\Rightarrow$ fix complex structure moduli and axio-dilaton
- Instantons, gaugino condensation fix Kähler moduli

Add Branes $\Rightarrow$ cancel RR-tadpoles
- Gauss’ Law (O-planes, fluxes contribute)
- Open strings $\Rightarrow$ SM gauge group and matter

$$ W_{GVW} = \int G(\tau) \wedge \Omega(z) $$

$$ W_{NP} \propto e^{-\rho/2l_s^2} $$

$$ Q^{D3}_{flux} = \int F_{RR} \wedge H_{NSNS} $$
We want lots of flux vacua → why?

- Can use statistics to our advantage
  - Each vacuum (sol’n to F-term eqs.) will have different $\langle z \rangle$ → thus different cosmological constant, etc.
- With enough SM vacua, can statistically argue that at least some are phenomenologically viable
  - i.e. match experiments to within precision
- More flux → more flux vacua

$$N_{\text{flux}} \propto \left( \frac{Q_{\text{flux}}^{D3}}{(2n + 2)!} \right)^{2n+2}$$

Denef, Douglas
Limits set by RR-tadpoles

► Let’s take IIB on $\mathbb{T}^6/\mathbb{Z}_2 \times \mathbb{Z}_2(\times \Omega R)$
  - 64 O3-planes, 12 O7-planes
  - 3 Kähler mod., n=51 complex structure moduli
  - Flux charge quantized in units of 32

► **Flux charge** must be positive, and we want it as large as possible
  - So we want D3-brane charge as negative as possible

$$Q_{\text{flux}}^{D3} + \sum Q_{\text{brane}}^{D3} = 16 \quad \sum Q_{\text{brane}}^{D7_i} = 16$$
We put in magnetized D9-branes

- Can describe by wrapping numbers \((m_1, n_1)(m_2, n_2)(m_3, n_3)\)
- SUSY condition (BDL) from mirror is that branes to be at correct angles
- If all charges non-zero, can only satisfy angle equations if 3Q’s > 0, 1Q < 0 (BGHLW)
- Can make D3-charge negative, but not arbitrarily

\[
\sum_{i=1}^{3} \tan^{-1} \left( \frac{m_i A_i}{n_i} \right) = 0 \mod 2\pi
\]

\[
Q_{D3} = n_1 n_2 n_3
\]

\[
Q_{D7_1} = -n_1 m_2 m_3
\]

\[
Q_{D7_2} = -m_1 n_2 m_3
\]

\[
Q_{D7_3} = -m_1 m_2 n_3
\]
Loophole $\rightarrow$ Brane Recombination

- Simple branes can deform and bind
  - Lower energy saturates BPS bound
- In field theory lang., an FI-term is turned on
- If we have scalars with appropriate charge $\rightarrow$ SUSY is restored
  - Number and charge of scalars determined by brane intersection numbers
  - Generically, $r$ equations for $r^2$ scalars $\rightarrow$ enough for recombination

\[
\sum_{i=1}^{3} \tan^{-1} \left( \frac{m_i A_i}{n_i} \right) \approx \xi_{FI}
\]

\[
V_D = \left( \sum_i q_i |\Phi_i|^2 + \xi \right)^2
\]

\[
I_{ab} = \prod_{i=1}^{3} \left( m_i n_i^i - m_i^i n_i \right)
\]
Here are some examples...

► First a model with two stacks in the hidden sector
  ▪ 3 stacks in the visible sector
  ▪ $U(4) \times SU(2)_L \times SU(2)_R$
  ▪ Each satisfies angle eq. at points in moduli space, but not all at same point
  ▪ Add 9 units of flux charge
  ▪ $\sim 10^{33}$ SM flux vacua

► Second example has 4 stacks in the hidden sector
  ▪ Add 5 units of flux charge

► Visible sector
  ▪ $N_a = 8 (1,0)(3,1)(3,-1)$
  ▪ $N_b = 2 (0,1)(1,0)(0,-1)$
  ▪ $N_c = 2 (0,1)(0,-1)(1,0)$

► Two stack hidden sector
  ▪ $N_q = 2 (-6,1)(-5,1)(-5,1)$
  ▪ $N_r = 2 (4,1)(2,-1)(1,-1)$

► Four stack hidden sector
  ▪ $N_q = 2 (-5,1)(-5,1)(-5,1)$
  ▪ $N_r = 2 (1,-1)(1,3)(1,3)$
  ▪ $N_s = 2 (1,3)(1,3)(1,-1)$
  ▪ $N_t = 2 (1,3)(1,-1)(1,3)$
Here’s a problematic example...

- **Puzzle as** \( x \) **becomes large**...
  - Fixed D7-brane charge, does not oversaturate tadpoles
  - But D3-brane charge becomes arbitrarily negative
- Therefore, we can turn on arbitrarily large flux to cancel tadpoles
  - More flux = more SM flux vacua
  - **Good news** \( \rightarrow \) enough SM vacua for some to be viable
  - **Bad news** \( \rightarrow \) an arbitrary number are viable ... bad for predictivity
- **Odd example** \( \rightarrow \) “almost” an anti-brane \( \rightarrow \) better analysis?
  - We get an observational constraint by demanding \( Z \) be real and positive (like D3-brane)

### Hidden sector
- \([- (x-1)^2, 1], [- (x-1)^2, 1], [- (x-1)^2, 1]\)
- \([1, -1], [1, x], [1, t]\)
- \([1, t], [1, -1], [1, x]\)
- \([1, t], [1, x], [1, -1]\)

### Charges
- \( Q_{D3} = 6 - 2(x - 1)^6 \)
- \( Q_{D7} = 4 \)

\[ Z = Q_{D3} + Q_{D71} A_2 A_3 + Q_{D7_2} A_1 A_3 + Q_{D7_3} A_1 A_2 \]
Conclusion...

- Observational cutoff is nice for “formal” predictivity, but still leaves too many vacua for comfort...
  - Using gravitational bounds... #SM vacua $\sim 10^{6172}$
  - Only need $10^{238}$ to fine-tune SM parameters (including c.c.) (Douglas)

- To avoid a “practical” predictivity problem, we need tighter constraints
  - Perhaps more formal constraints on how negative D3-charge of stable bound state can get?
  - Generalization of $\Pi$-stability might be the way to go...
  - Must understand how to define in case with orientifold.