Multi-Brane Recombination and Standard Model Flux Vacua

Jason Kumar
Texas A&M University
w/ James D. Wells (University of Michigan)
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IIB Standard Model Flux Vacua

- Compactify IIB on orientifolded CY 3-fold
  - N=1 SUSY
- Turn on Fluxes → fix complex structure moduli and axio-dilaton
  - Instantons, gaugino condensation fix Kähler moduli
- Add Branes → cancel RR-tadpoles
  - Gauss' Law (O-planes, fluxes contribute)
  - Open strings→ SM gauge group and matter

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

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

$$Q_{flux}^{D3} = \int F_{RR} \wedge H_{NSNS}$$

We want lots of flux vacua → why?

- Can use statistics to our advantage
  - Each vacuum (sol'n to F-term eqs.) will have different ⟨z⟩ → 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

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

Denef,Douglas

Limits set by RR-tadpoles

- Let's take IIB on $T^6/Z_2 x Z_2 (x\Omega R)$
  - 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

$$Q^{D3}_{flux} + \sum Q^{D3}_{brane} = 16 \qquad \sum Q^{D7_i}_{brane} = 16$$

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

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

$$Q_{D3} = n_1 n_2 n_3$$

$$Q_{D7_1} = -n_1 m_2 m_3$$

$$Q_{D7_2} = -m_1 n_2 m_3$$

$$Q_{D7_3} = -m_1 m_2 n_3$$

Loophole → 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 → SUSY is restored
  - Number and charge of scalars determined by brane intersection numbers
  - Generically, r equations for r^2 scalars → enough for recombination

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

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

$$I_{ab} = \prod_{i=1}^{3}\left(m_a^i n_b^i - m_b^i n_a^i\right)$$

Here are some examples....

- First a model with two stacks in the hidden sector
  - 3 stacks in the visible sector
  - $U(4)xSU(2)_L xSU(2)_R$
  - 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 → enough SM vacua for some to be viable
  - Bad news → an arbitrary number are viable ... bad for predictivity
- Odd example → "almost" an anti-brane → 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,x]
  - [1,x], [1,-1], [1,x]
  - [1,x], [1,x], [1,-1]
- Charges
  - $Q_{D3}=6-2(x-1)^6$
  - $Q_{D7}=4$

$$Z = Q_{D3} + Q_{D7_1} A_2 A_3 + Q_{D7_2} A_1 A_3 + Q_{D7_3} A_1 A_2$$

Conclusion....

- Observational cutoff is nice for "formal" predictivity, but still leaves too many vacua for comfort...
  - Using gravitational bounds... #SM vacua ~ 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 Π-stability might be the way to go...
  - Must understand how to define in case with orientifold.