The High Country region of the string landscape

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String Phenomenology @ Penn

The High Country region of the string landscape

- Goal: Study string vacua which reproduce the MSSM (or close cousins thereof) at low energies
    - String landscape is huge, but High Country region may be much smaller
- Questions:
    - How many such vacua?
    - Do they have common properties (predictions)?
    - Constraints coming from string UV completion?
- Crucial: Must require global consistency of the string vacuum

A particular corner of the string landscape:

$E_8 \times E_8$ heterotic string on $\mathbb{R}^{3,1} \times X$ with gauge instanton V, where X is a smooth compact Calabi-Yau threefold

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Outline

1. General overview of heterotic compactifications
2. Exploring the High Country
3. Present and Future

References:

- Many many papers over the years
- hep-th/0512149, 0704.3096, 0804.2096 with R. Donagi
- hep-th/0602096 with M. Cvetič and R. Donagi
- work in progress with A. Bak and R. Donagi

Outline

SUSY heterotic vacua

Data:

- X: smooth compact Calabi-Yau threefold
- $V \to X$: hol. vector bundle with structure group $G \subset E_8$

Consistency constraints:

- V is polystable w.r.t a Kähler class [DUY: connection soln to HYM]
- $c_2(X) - c_2(V) = [M5]$ [anomaly cancellation with $M5$-branes]

Phenomenological requirements:

- Commutant H of G in E_8 is low-energy GUT group
- $\pi_1(X) = F$ to break H to MSSM gauge group with discrete Wilson line
- Various extra phenomenological constraints:
  - $c_1(V) = 0$ [$G = SU(n)$]
  - $c_3(V) = \pm 6$ [3 generations]
  - $H^1(V), H^2(V), H^1(\wedge^2 V), H^2(\wedge^2 V), \ldots$ [Particle spectrum]
  - Triple products of cohomology groups, ... [Tri-linear couplings]

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Summary and examples

Heterotic vacuum:

1. Non-simply connected Calabi-Yau threefold X
2. Polystable bundle $V \to X$ satisfying a lot of constraints

Examples:

- $\pi_1(X) = \mathbb{Z}_2$, $G = SU(5)$
  - $SU(5)$ GUT
  - $SU(5) \xrightarrow{\mathbb{Z}_2} SU(3) \times SU(2) \times U(1)$
- $\pi_1(X) = \mathbb{Z}_6$ or $(\mathbb{Z}_3)^2$, $G = SU(4)$
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1st step: Constructing non-simply connected CY 3-folds X

Consider a smooth simply connected Calabi-Yau threefold $\tilde{X}$ admitting a group K of automorphisms acting freely on $\tilde{X}$

$\rightarrow X = \tilde{X}/K$ is a smooth Calabi-Yau threefold with $\pi_1(X) = K$

- $\tilde{X}$ is a smooth fiber product of two rational elliptic surfaces [Schoen]
  - We classified all possible finite groups K acting freely on $\tilde{X}$ [VB-Donagi]
- $\tilde{X}$ is the small resolution of a particular complete intersection of four quadrics in $\mathbb{P}^7$ [Gross]
  - free $(\mathbb{Z}_8)^2$ action [Gross]
  - 2 non-Abelian groups of order 64 act freely [Borisov-Hua]
- Hypersurfaces/complete intersections in toric threefolds, ...

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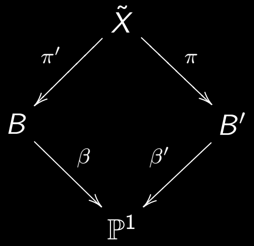
Let B and B' be RES, and $\tilde{X} = B \times_{\mathbb{P}^1} B'$ a smooth fiber product:



Idea: Consider special B and B' s.t. $\tilde{X}$ admits a free group of automorphisms $K_{\tilde{X}}$.

Free quotients of Schoen's threefolds

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$$\begin{array}{ccccc} & & \tilde{X} & & \\ & \swarrow^{\pi'} & & \searrow^{\pi} & \\ B & & & & B' \\ & \searrow_{\beta} & & \swarrow_{\beta'} & \\ & & \mathbb{P}^1 & & \end{array}$$

Idea: Consider special B and B' s.t. $\tilde{X}$ admits a free group of automorphisms $K_{\tilde{X}}$.

Free quotients of Schoen's threefolds

- Automorphisms $\tau_{\tilde{X}} : \tilde{X} \to \tilde{X}$ have the form $\tau_{\tilde{X}} = \tau_B \times_{\mathbb{P}^1} \tau_{B'}$
- Classification of $(\tilde{X}, K_{\tilde{X}})$ reduces to classification of (B, K_B), for suitable groups of automorphisms K_B

We produced such a classification, and we obtained a large class of $\tilde{X}$ with $K_{\tilde{X}}$ one of the following: [VB-Donagi]

$$(\mathbb{Z}_3)^2, \quad \mathbb{Z}_4 \times \mathbb{Z}_2, \quad \mathbb{Z}_6, \quad \mathbb{Z}_5,$$
$$\mathbb{Z}_4, \quad (\mathbb{Z}_2)^2, \quad \mathbb{Z}_3, \quad \mathbb{Z}_2$$

2nd step: Constructing stable vector bundles $V \to X$

- Fourier-Mukai transform [FMW, Donagi]
  - Use dual Fourier-Mukai data to construct the bundle
  - Needs X to be fibered (usually torus-fibered, but can be generalized)
  - Pros: Easy to prove stability from FM data [FMW]
  - Cons: If start with $\tilde{V} \to \tilde{X}$, invariance under $K_{\tilde{X}}$ hard to prove
- Serre construction by extension

$$0 \to V_1 \to V \to V_2 \to 0$$

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Best (and only) model so far [VB-Donagi, VB-Cvetič-Donagi]

- The manifold: $\tilde{X} = B \times_{\mathbb{P}^1} B'$, with special B and B' such that $K_{\tilde{X}} \simeq \mathbb{Z}_2$ acts freely on $\tilde{X}$
- The bundle: $SU(5)$, $\mathbb{Z}_2$-invariant, stable bundle $\tilde{V} \to \tilde{X}$ constructed by

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where V_3 and V_2 are rank 3 and 2 bundles on $\tilde{X}$ constructed using Fourier-Mukai transform

- Anomaly is cancelled, either with $M5$-branes, or without $M5$-branes but with a non-trivial hidden bundle

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Phenomenology of this model

- MSSM gauge group $SU(3) \times SU(2) \times U(1)$ with no extra $U(1)$'s
- Precisely the MSSM massless spectrum with no exotic particles, up to moduli fields
- Semi-realistic tri-linear couplings at tree level
- R-parity is conserved at tree level (proton is stable)
- Higgs μ-terms and (possible) neutrino mass terms

To be addressed

- SUSY breaking? (hidden sector)
- Moduli stabilization?
- Higher order corrections?
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Constructing other realistic models

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  $\longrightarrow$ No realistic bundle [VB-Donagi]
  - Main insight: strong tension between inequalities coming from anomaly cancellation and stability

- Work in progress: physical bundles on Gross' threefold with $\pi_1(X) = (\mathbb{Z}_8)^2$ [Bak-VB-Donagi]
  - We constructed bundles phenomenologically viable at the topological level (up to a few subtelties that remain to be checked), using Fourier-Mukai transform on Abelian surface fibrations, and Hecke transforms
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Relaxing the constraints (...)

Recall: strong tension between anomaly cancellation and stability

- In principle, one can "forget" about anomaly cancellation
  - non-SUSY vacua with $M5$- and anti-$M5$-branes [B,BBO]
  - SUSY broken at the compactification scale :-(

- We get infinite families of such non-SUSY vacua with exactly the phenomenological properties above [VB-Donagi]
- Also get infinite families of models on $\tilde{X}$ with $\pi_1(\tilde{X}) = \mathbb{Z}_6$
- One such model on $\tilde{X}$ with $\pi_1(\tilde{X}) = (\mathbb{Z}_3)^2$ [BHPO], perhaps more

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  $\rightarrow$ phenomenological cutoff on scale of SUSY breaking

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- Perhaps other models in the class of threefolds constructed as quotients of Schoen's threefolds, but not on the $\mathbb{Z}_6$ one, at least with current bundle construction methods
- Hope to get more physical models on Gross' threefold (more to come soon :-)
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Avenues of research

- More threefolds and more physical bundles!
  - Necessary if we want to study common properties etc.
- Moduli stabilization? [B,BBO,GLO]
  - Find F-theory dual picture? [DW,BHV]
- SUSY breaking? [BBO]
  - Using hidden sector, either a la Intriligator-Seiberg-Shih, or racetrack mechanism, or . . .
- Calabi-Yau metrics and Kähler potential? [BBDO]
- Systematize study of the High Country using algebro-geometric methods? [AHL]

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