Geometry of String Vacua

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Physics Faculty Lunch Talk
Duke University

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String theory is our best candidate for a quantum theory of gravity. This should interest you because:

- Quantum gravitational effects are crucial in understanding physics near a horizon – not just singularity!
- Important in understanding early Universe cosmology
- Guide to physics beyond standard model
Quantum Gravity Matters

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- Dualities
- Holography
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A string theory is defined perturbatively by the worldsheet supersymmetry. A free theory with full Poincaré invariance in 10d is then

- Type II A/B: type-II A/B supergravity. 32 supercharges; odd/even $p$-form fields decoupled from string states.

- Heterotic: $\mathcal{N} = 1$ supergravity. 16 supercharges; gauge group $E_8 \times E_8$ or $\text{Spin}(32)/\mathbb{Z}_2$.

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Geometric Vacua of Type-II Strings

\[ S = \int \frac{1}{2} \sum (g_{IJ} + iB_{IJ}) \partial X^I \cdot \bar{\partial} X^J \]

\[ + \frac{i}{2} g_{IJ} \left( \lambda^I D_z \lambda^J + \psi^I D_z \psi^J \right) \]

\[ + \frac{1}{4} R_{IJKL} \lambda^I \lambda^J \psi^K \psi^L \]

\[ D_z \psi^I = \partial_z \psi^I + \Gamma^I_{JK} \partial \phi^J \psi^K \]

Equations of motion (one-loop)

\[ R_{IJ} = 0 \]

\[ H_{IJK} = \partial [I B_{JK}] = 0 \]

Flat 10d solution: \( g_{IJ} = \eta_{IJ}; B_{IJ} = 0. \)
Type-II String Compactification

Consider $M^{1,3} \times X$. $I = \{ \mu, i \}$. $g_{\mu\nu} = \eta_{\mu\nu}$; $B_{\mu\nu} = 0$. Find exact vacua with $\mathcal{N} = 2$ supersymmetry in 4d for:

- $X$ complex and $g$ Kähler: Calabi–Yau
  - Moduli space of CY metrics factors as $\mathcal{M}_{cx} \times \mathcal{M}_K$.
  - Perturbative expansion valid at Large-Radius Limit in $\mathcal{M}_K$. Metric corrected by world-sheet instantons.
- $S_{\text{int}}$ is $\mathcal{N} = (2, 2)$ superconformal, $c = \bar{c} = 15$.
- Moduli space factors as $\mathcal{M}_{cc} \times \mathcal{M}_{ac}$.

What is the most general $(2, 2)$ SCFT? Do they all have LRL limit points?
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Gauged Linear Sigma Model

Witten’s **GLSM** is a way of constructing a large class of SCFTs with a global model of moduli space. Gauge theory in 2d is asymptotically free in UV. With suitable choices, find nontrivial IR behavior described by desired SCFT.

- Family of theories determined by (Abelian) gauge group $G$ and charges $Q$. Nontrivial IR limit if $\sum Q = 0$.
- Family parameterized by $G$-invariant polynomial $W$ and (complex) FI terms.

\[
Q_a = \begin{pmatrix}
-4 & 1 & 1 & 1 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 1 & -2 & 0
\end{pmatrix}
\]

\[
W = \phi_0 \left( \phi_1^4 + \phi_2^4 + \phi_3^4 + \phi_6^4(\phi_4^8 + \phi_5^8) \right) + (83 \text{ more terms})
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q_a = e^{-2\pi r_a + i\theta_a}
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Semiclassical analysis valid when $G$ broken at high energy: vacua are inequivalent solutions to

$$\partial_i W = 0 \quad F_a = \sum_i (Q_a^i |\phi_i|^2 - r_a) = 0 \quad (3)$$

Phase I

$r_1 >> 0 \quad r_2 >> 0$

$|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_6|^2 >> 0$

$|\phi_4|^2 + |\phi_5|^2 >> 0$

$\phi_6 = \partial_6 W = 0$

Smooth Calabi–Yau
Phases

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$G$ broken to $\mathbb{Z}_4$. Unique vacuum at $\phi_a = 0$ with massless excitations governed by Landau-Ginzburg interactions
Phases

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Phase IV

$r_1 \ll 0 \quad r_2 \gg 0$

$|\phi_6|^2 \gg 0$

$|\phi_4|^2 + |\phi_5|^2 \gg 0$

$G$ broken to $\mathbb{Z}_4$. Inequivalent vacua points on $\mathbb{P}^1$ with massless fields interacting via LG superpotential fibered over this
Lessons from Type-II Moduli Space

We have learned (and are still learning) a lot from and about these vacua. Some examples:

- **Mirror Symmetry**: A duality relating distinct CY spaces such that type-IIA theory on $X$ is equivalent to type-IIB theory on $Y$; in particular $\mathcal{M}_{cx}(X) = \mathcal{M}_K(Y)$.

- A consequence of this is the conjecture (SYZ, 1997) that $X$ and $Y$ admit fibrations by $T^3$. Structure of this is mostly unknown. Conjectures (M, 2010; MP, 2013) exist for families related to GLSMs.

- Singular points in moduli space correspond to singular $X$. Distinct $X$ connected via “extremal transitions” associated to massless charged matter (GMS, 1995), nonabelian gauge symmetry (KMP, 1997), interacting superconformal field theories (??).

- Recently, exact calculations of GLSM partition function on $\Sigma = S^2$. Mirror symmetry of this (GL, 2012; HR, 2013; BPR, 2013?)
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- $X$ complex; $E$ holomorphic with $c_2(E) = c_2(TX)$; $g$ Kähler: Calabi–Yau space with (polystable) bundle.
- Special solution: $E = TM$.
- Moduli space at LRL parameterized by deformations of complex structure, Kähler class, bundle.
- Expect generic semiclassical solutions to be destabilized by world-sheet instantons.
- $S_{\text{int}}$ is $\mathcal{N} = (0, 2)$ superconformal, $c = 26$, $\overline{c} = 15$.
- In some cases a subspace has $(2, 2)$ supersymmetry.
- Moduli space is generated by (some of) the chiral operators.
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- An extension of mirror symmetry (MP, 2010)
- Comparison of dimension of space of first-order deformations between different phases (AMP, 2011)
- An example in which instantons lift some of these (AP, 2011)
- Calculation of exact spectrum of massless states in hybrid limit (BMP, 2013).
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