Sequences of Type IIB String Vacua

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"New Ideas at the Interface of Cosmology and String Theory"

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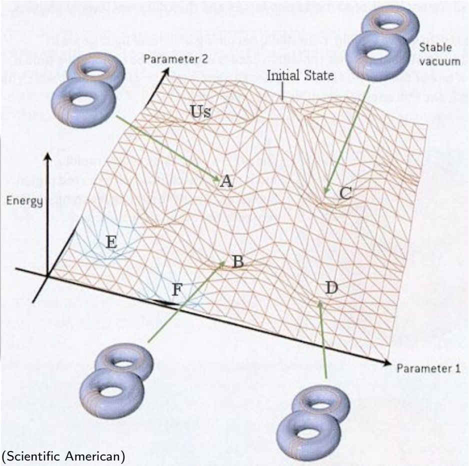
Background and motivation

String compactifications

- 10D supergravity
- $M_{10} = M_4 \times_w M_6$
- Fluxes and branes
- ...



(Scientific American)

Background and motivation

Topology of landscape:

- How many vacua?
- Distribution of vacua?
- Barriers between vacua?

Cosmological questions:

- Cosmological constant?
- Inflation?
- Vacuum stability (classical/quantum)?

Type IIB on warped CY manifolds.

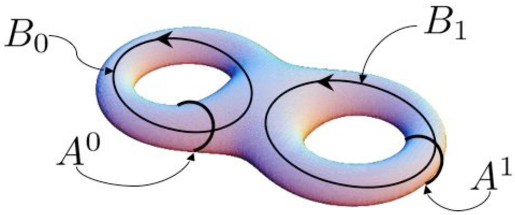
- Mathematically tractable.
- Moduli stabilisation.
- Sequences of connected vacua.

Type IIB compactifications

Some CY geometry

Candelas, de la Ossa:91, ...

Complex structure	$\sim$	Holomorphic 3-form Ω	$\sim$	3-cycles
Kähler structure	$\sim$	Real 2-form J	$\sim$	2,4-cycles



Type IIB compactifications

Some CY geometry

Candelas, de la Ossa:91, ...

Periods: $\Pi_I(z) = \int_{C_I} \Omega(z) = \int_{\mathcal{M}} C_I \wedge \Omega(z)$

collected in vector:

$$\Pi(z) = \begin{pmatrix} \Pi_N(z) \\ \Pi_{N-1}(z) \\ \vdots \\ \Pi_0(z) \end{pmatrix}$$

Intersection matrix: $Q_{IJ} = \int_{C_I} C_J = \oint_{\mathcal{M}} C_I \wedge C_J$

CS moduli space is (special) Kähler

$$K_{cs} = -\ln\left(i \int_{\mathcal{M}} \Omega \wedge \bar{\Omega}\right) = -\ln\left(i\Pi^\dagger \cdot Q^{-1} \cdot \Pi\right)$$

Type IIB compactifications

Fluxes

Giddings, Kachru, Polchinski hep-th/0105097

- Break SUSY: $\mathcal{N} = 2 \to \mathcal{N} = 1$
- Warp geometry

Flux vector: $G = F - \tau H$

Gukov–Vafa–Witten superpotential:

$$W(z, \tau) = G \cdot \Pi$$

Kähler potential:

$$K = -\ln\left(-i(\tau - \bar{\tau})\right) + K_{\rm cs}\left(z, \bar{z}\right) - 3\ln\left(-i(\rho - \bar{\rho})\right)$$

Scalar potential:

$$V = e^K \left(g^{i\bar{\jmath}} D_i W D_{\bar{\jmath}} \bar{W} + g^{\tau\bar{\tau}} D_\tau W D_{\bar{\tau}} \bar{W}\right)$$

Type IIB compactifications

Kähler moduli

Not stabilised at classical level.

W: non-perturbative corrections.
K: perturbative and non-perturbative corrections.

$\Longrightarrow$ SUSY and non-SUSY vacua:

KKLT — Kachru *et. al.* hep-th/0301240

LARGE volume scenarios — Balasubramanian *et. al.* hep-th/0502058, Conlon *et. al.* hep-th/0505076 ...

Warping

Suppressed at large volume.
Important around special points in moduli space.

Background and motivation

Type IIB compactifications

Vacuum sequences

Finiteness and D-limits

Statistical studies

Finiteness and Warping

Conclusions and outlook

Landscape topography

Vacuum sequences

Danielsson, Johansson, ML hep-th/0612222

Chialva *et. al.* 0710.0620

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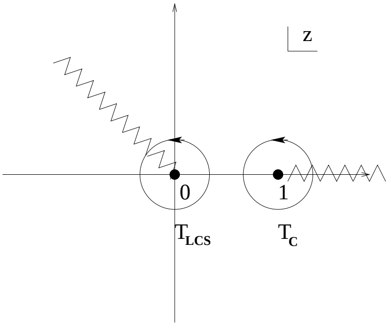
Monodromies:

$$\Pi(z) \to T \cdot \Pi(z)$$



$$W = G \cdot \Pi \to G \cdot T \cdot \Pi \qquad K_{cs} \to K_{cs}$$

Dual description: Π fixed, $G \to G \cdot T$.

Vacuum sequences

Danielsson, Johansson, ML hep-th/0612222

Johnson, ML 0805.3705

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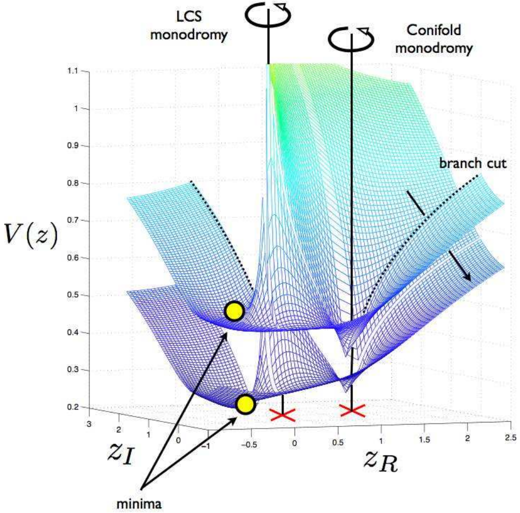
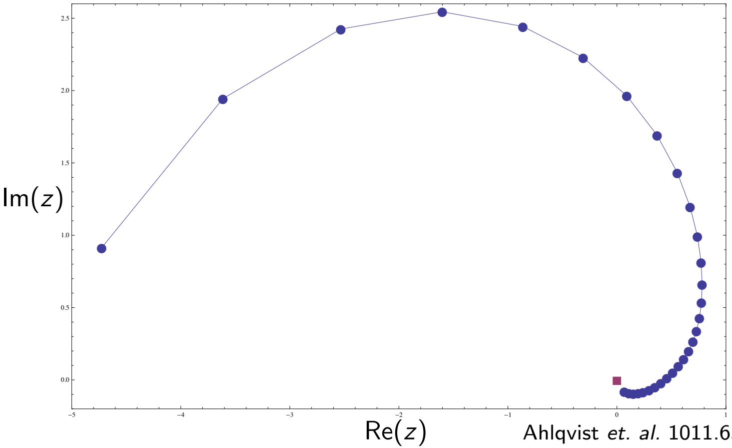


Vacuum sequences

Braun, Johansson, ML, Walliser 1108.1394

Is there a bound on the sequence length?



Ahlqvist *et. al.* 1011.6588

Finiteness and D-limits

No-go theorem

Ashok, Douglas hep-th/0307049

ISD vacua: $D_\tau W = D_i W = 0 \quad \Leftrightarrow \quad *G_{(3)} = iG_{(3)}$

Tadpole condition:

$$\langle F_{(3)}, H_{(3)} \rangle = \int_{\mathcal{M}} F_{(3)} \wedge H_{(3)} \leq L_{max}$$

$$\langle F_{(3)}, H_{(3)} \rangle = \frac{i}{2 \text{ Im } \tau} \langle \bar{G}_{(3)}, G_{(3)} \rangle$$

$$= \frac{1}{2 \text{ Im } \tau} \langle \bar{G}_{(3)}, *G_{(3)} \rangle = \hat{N}^T \cdot (\mathcal{G}_\tau \otimes \mathcal{G}_z) \cdot \hat{N} \geq 0$$

where $\hat{N} = (F, H)$.

Finiteness and D-limits

Tadpole condition, ISD vacua: $\boxed{0 \leq \hat{N}^T \cdot (\mathcal{G}_\tau \otimes \mathcal{G}_z) \cdot \hat{N} \leq L_{max}}$

If bounded $(\mathcal{G}_\tau \otimes \mathcal{G}_z)$ eigenvaules: $\Lambda_i(z, \tau) > \epsilon$

$\implies$ Admissible $\hat{N} : \hat{N}^2 \leq L_{max}/\epsilon$ **Finite number of vacua.**

Evade no-go: find (z, τ) such that $\Lambda_i(z, \tau) = 0$ **D-limit.**

D-limits

- $\mathcal{G}_\tau$: Decoupling limit $\mathrm{Im}\,\tau \to \infty$
- $\mathcal{G}_z$: LCS and conifold loci.

Finiteness and D-limits: One-parameter models

Refined no-go theorem: LCS (w. bounded $\mathcal{G}_\tau$-eigenvalues)

Let $t \sim -i \log z$, LCS point is at $t_2 = \operatorname{Im} t \to \infty$

Infinite sequence:

$$\lim_{n\to\infty}(t_2)_n = \infty \qquad \hat{N}_n \cdot \mathcal{G}_{\tau_n} \otimes \mathcal{G}_{t_n} \cdot \hat{N}_n^T \neq \infty$$

$$\implies F_n \cdot w_j^n = \mathcal{O}(1/\sqrt{\lambda_j^n}) \qquad H_n \cdot w_j^n = \mathcal{O}(1/\sqrt{\lambda_j^n})$$

LCS limit: can compute $\mathcal{G}_{t_n}$-eigenvalues and -vectors λ_j^n, w_j^n

$$\lambda_1 = a_{11}\, t_2^3 + \mathcal{O}(t_2)\,, \qquad w_1^T = \left[1, \mathcal{O}\left(t_2^{-2}\right), \mathcal{O}\left(t_2^{-4}\right), \mathcal{O}\left(t_2^{-6}\right)\right]$$

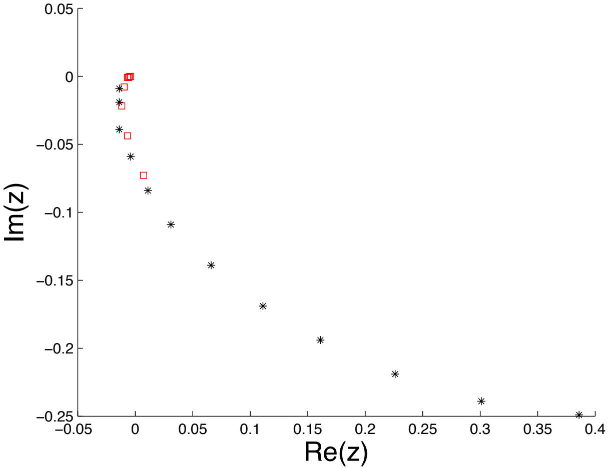
$$\lambda_2 = a_{22}\, t_2 + \mathcal{O}\left(t_2^{-1}\right)\,, \qquad w_2^T = \left[\mathcal{O}\left(t_2^{-2}\right), 1, \mathcal{O}\left(t_2^{-2}\right), \mathcal{O}\left(t_2^{-4}\right)\right]$$

$$\lambda_3 = \frac{a_{33}}{t_2} + \mathcal{O}\left(t_2^{-2}\right)\,, \qquad w_3^T = \left[\mathcal{O}\left(t_2^{-4}\right), \mathcal{O}\left(t_2^{-2}\right), 1, \mathcal{O}\left(t_2^{-2}\right)\right]$$

$$\lambda_4 = \frac{a_{44}}{t_2^3} + \mathcal{O}\left(t_2^{-5}\right)\,, \qquad w_4^T = \left[\mathcal{O}\left(t_2^{-6}\right), \mathcal{O}\left(t_2^{-4}\right), \mathcal{O}\left(t_2^{-2}\right), 1\right]$$

$$\implies F_n^0 = F_n^1 = H_n^0 = H_n^1 = 0 \text{ for large } n \implies \boxed{\langle F_{(3)}, H_{(3)}\rangle = 0}$$

Finiteness and D-limits: One-parameter models



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Finiteness and D-limits

One-parameter models: decoupling limit and conifold

No infinite sequences:

- Decoupling limit $\operatorname{Im}\tau \to \infty$ (also for more cs moduli)
- Conifold locus (disclaimer: warping neglected)

Two-parameter model

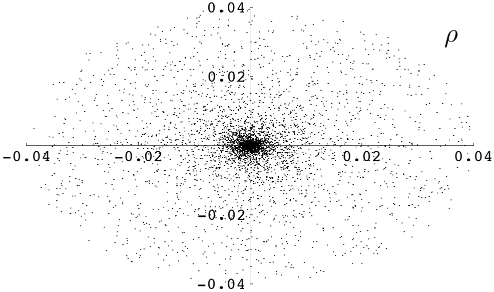
Checked particular LCS limit: no infinite sequences.

Statistical studies

Ashok, Douglas hep-th/0307049, Denef, Douglas hep-th/0404116, Giryavets *et. al.* hep-th/0404243, Eguchi, Tachikawa hep-th/0510061, Acharya, Douglas hep-th/0606212, Torroba hep-th/0611002

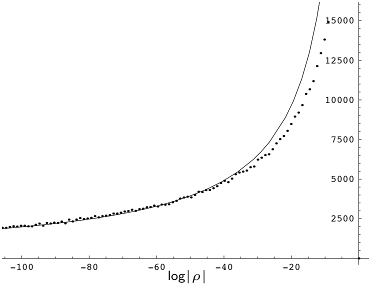
Statistical distribution of flux vacua:

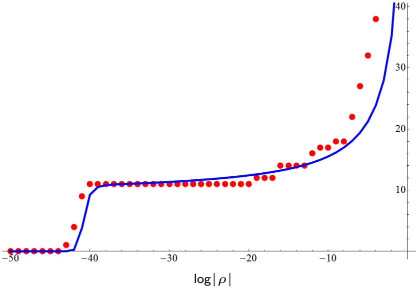
$$dN_{vac}(z) \sim det\left(R(z) + \omega(z)\right)$$



Finiteness and Warping

Ahlqvist *et. al.* 1202.3172, Giryavets *et. al.* hep-th/0404243
Giddings Maharana hep-th/0507158, Douglas *et. al.* 0704.4001,...





$D_\rho W = 0 \implies$
$|\rho| \sim \exp\left(-\frac{A(F,H)}{B(F,H)}\right)$

$D^w_\rho W^w = 0 \implies$
$|\rho| \sim \exp\left(-\frac{C(F,H)}{V_{CY} A(F,H)}\right)$

Vacua pushed away from conifold.

Conclusions and outlook

- Conformal CY compactifications of type IIB string theory.
- Infinite sequences of vacua only possible in D-limits
- One-parameter CY:
  - LCS and decoupling limit: finite
  - Conifold: finite (w/w.o. warping)
- Agrees with statistical result.

To do-list and open questions:

- Multiple D-limits, CY with more parameters...
- Vacuum properties: stability, CC, ...
- Landscape dynamics
  - Inflation — Yang 1202.3388
  - Quantum stability — Johnson, ML 0805.3705, ..., Ahlqvist *et. al.* 1011.6588
- Kähler moduli