Title: Constructions and distributions of string vacua

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Abstract:

Constructions and distributions of string vacua

Frederik Denef

PI, October 2005

Motivation

- The Landscape
- The good news
- The bad news
- What can we do?

Construction of vacua

- IIB KKLT vacua
- IIB nonsusy AdS vacua with exponentially large volume
- I/IIB with gauge fluxes
- M-theory and IIA flux vacua
- More models: heterotic, non-geometric, ...
- de Sitter vacua

Statistics of vacua

- Susy IIB
- Nonsusy IIB
- M-theory
- Vacua with enhanced (R-)symmetries
- Intersecting brane and Gepner models

Motivation

Not everything that can be counted counts,
and not everything that counts can be counted.
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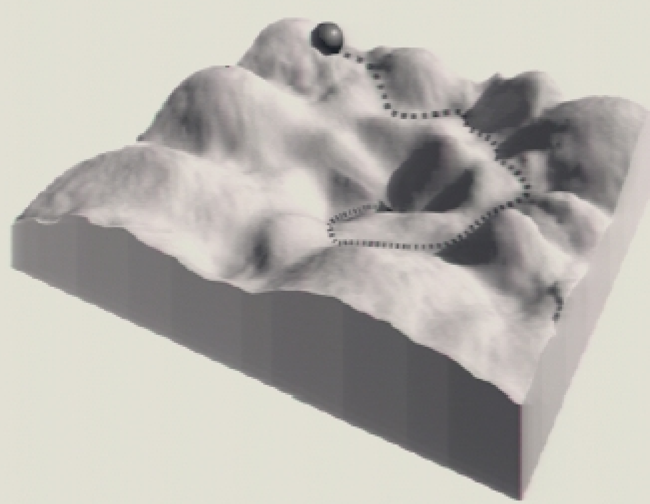
Picture: String theory Landscape [Susskind]



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If sufficiently finely scanned, landscape picture offers at least possibility for a consistent explanation for a number of absurd finetunings of parameters in our universe!

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Type of problem: given parameter range, find discrete quanta (e.g. fluxes) such that vacuum ends up in this range. $\rightsquigarrow$ Hard!

How hard? $\rightsquigarrow$ quantified in computational complexity theory.

Even in simple Bousso-Polchinski toy model, the problem to find the flux vectors N^{α} such that $0 < \Lambda(N) < \epsilon$ is *NP-hard*.

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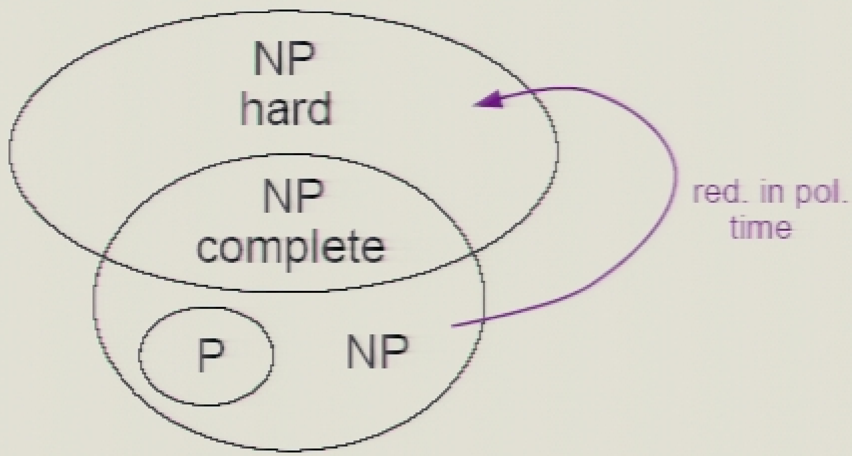

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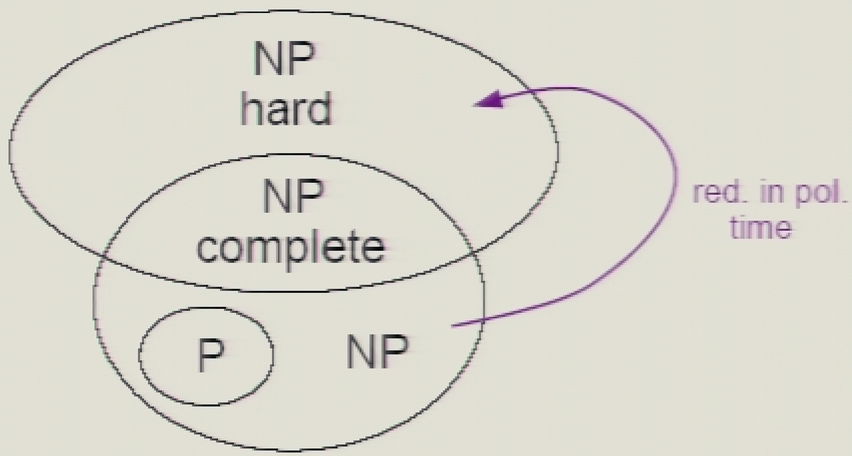

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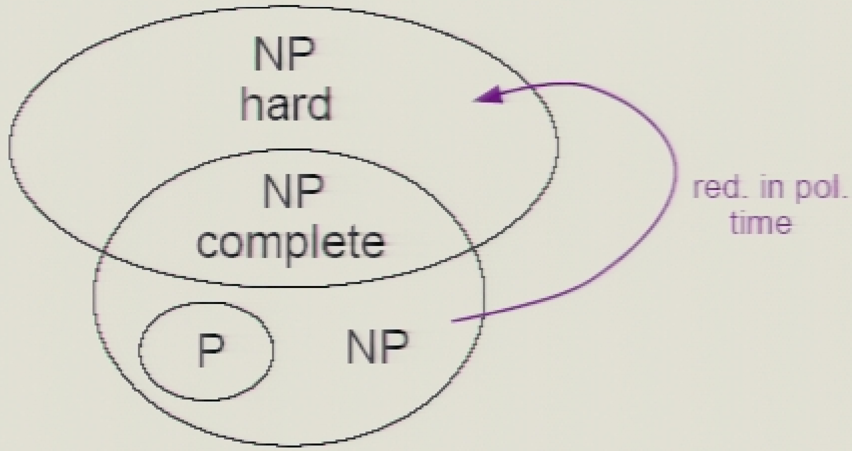

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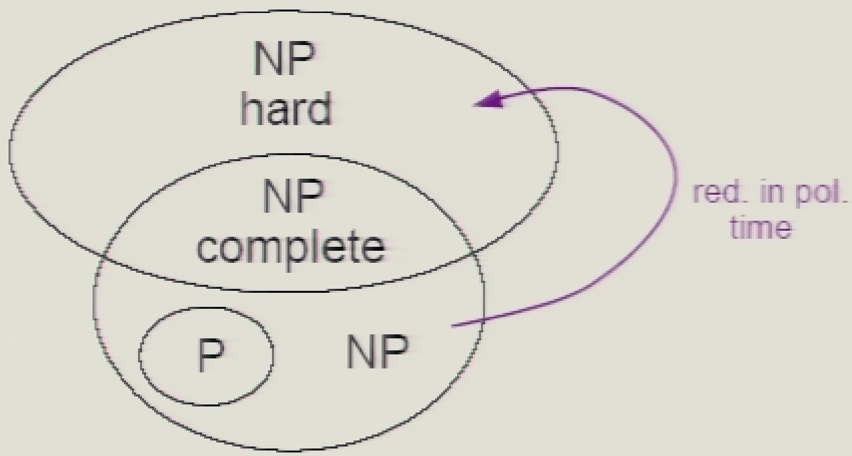

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- NP-complete = NP $\cap$ NP-hard (e.g. subset-sum)

Presumably: NP $\neq$ P, but no proof to date (Clay prize problem).

$\Rightarrow$ if you find a polynomial time algorithm to identify string vacua from parameter data, you're rich...

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  - Distributions also more robust than individual solutions under corrections.
- Try to compute dynamical probabilities on parameter space

Construction of vacua

Any intelligent fool can make things bigger and more complex...
It takes a touch of genius, and a lot of courage, to move in the opposite direction.
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The first part of the program includes

- Intersecting brane models, including Kähler potentials, Yukawa couplings, susy breaking soft terms [Aldazabal, Angelantonj, Antoniadis, Blumenhagen, Camara, Cremades, Cvetic, Dudas, Franco, Görlich, Graña, Grimm, Ibañez, Jockers, Körs, Langacker, Liu, Louis, Lüst, Mayr, Marchesano, Rabadan, Reffert, Richter, Sagnotti, Shiu, Stieberger, Taylor, Uranga, Wang]
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$\Rightarrow$ want mechanism to stabilize moduli at sufficiently high scale.

(Quintessence appears very hard to realize in string theory.)

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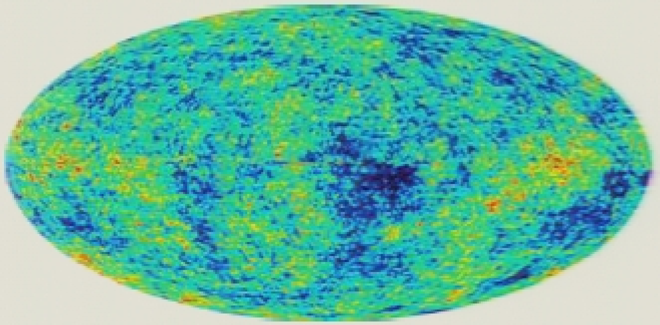

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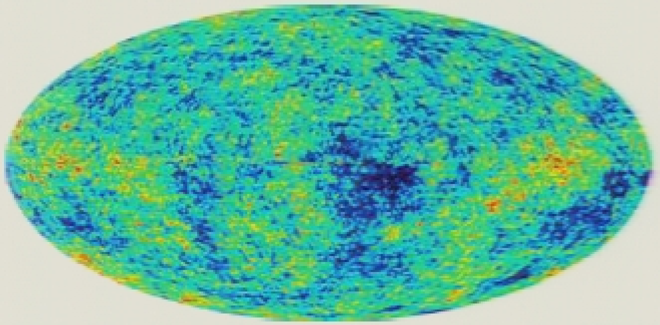

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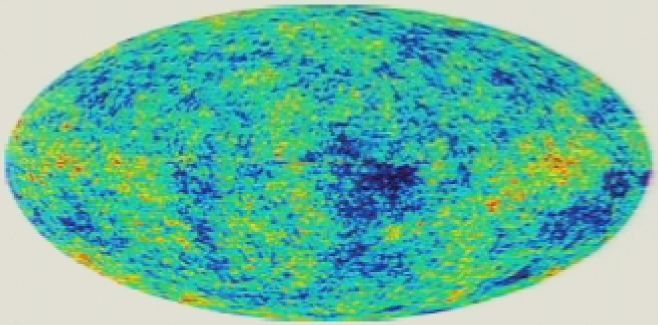

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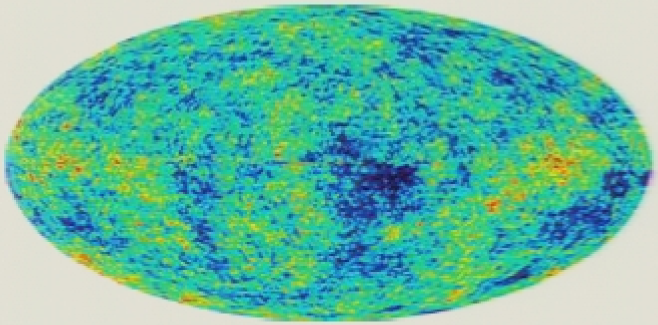

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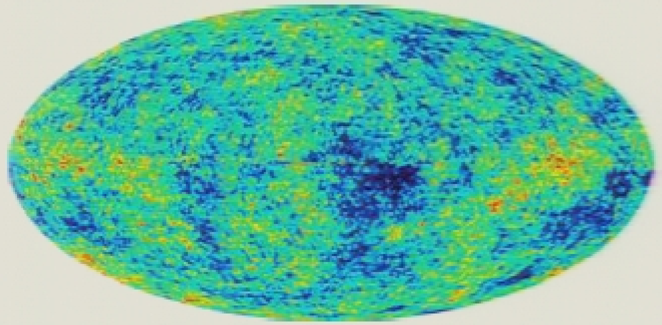

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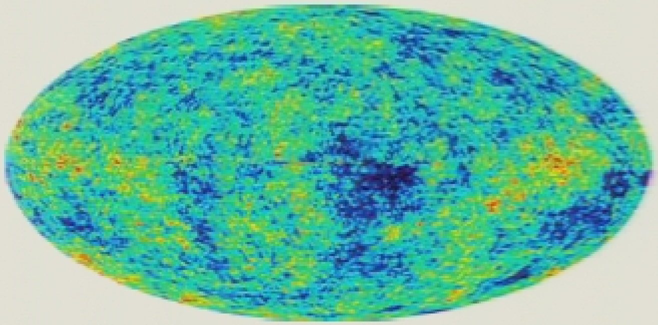

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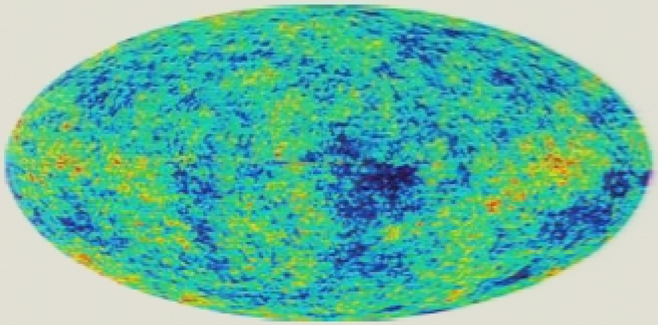

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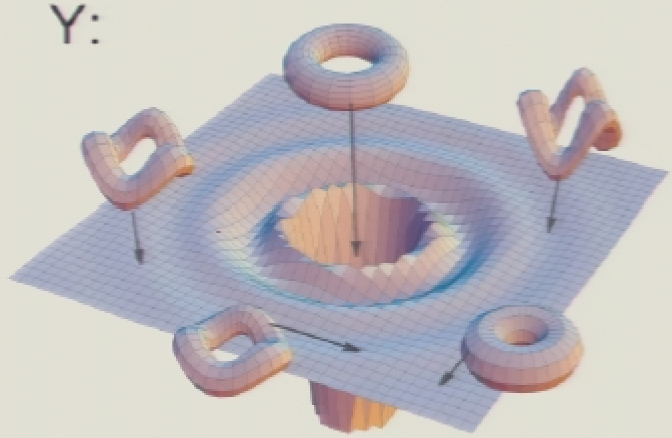

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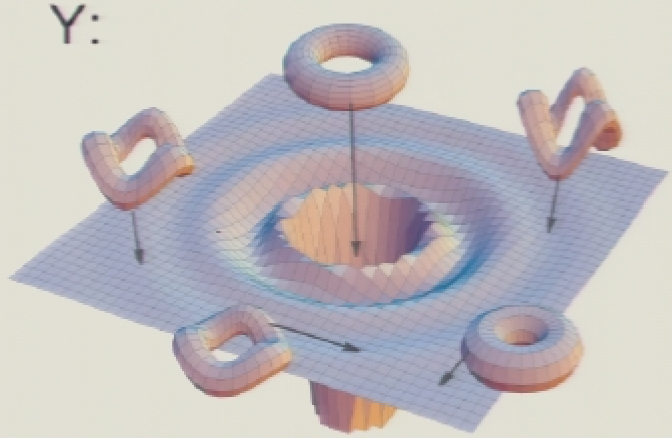
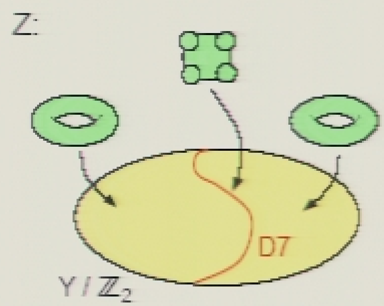


Moduli: complex (shape) and Kähler (size)

IIB KKLT vacua

$\Leftrightarrow$ M/F-theory on elliptically fibered CY_4 Z + flux G_4.



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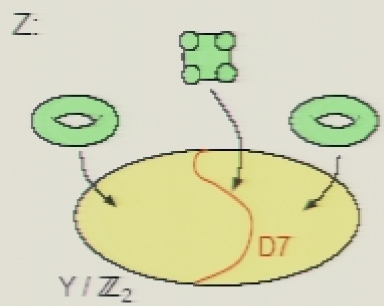

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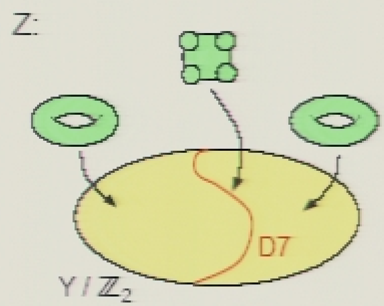

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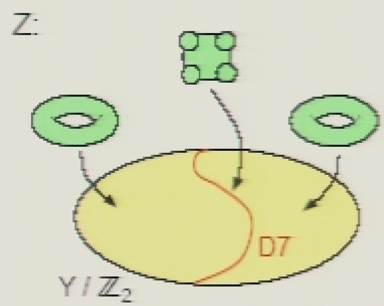

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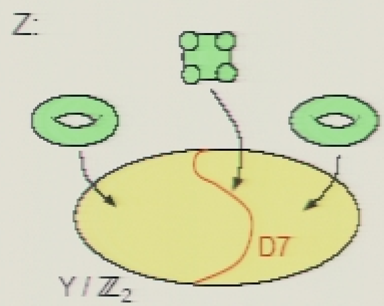

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In controlled regime? Yes, if $W_{flux} \ll 1$; possible in IIB because of Bousso-Polchinski like tuning by flux discretuum.

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By now, several examples known:

- [Denef-Douglas-Florea]: various constructions of models with a sufficient number of D3 instanton divisors with exactly 2 fermion zeromodes ($h^{0,i}(M5) = 0$ [Witten]).
- [Denef-Douglas-Florea-Grassi-Kachru]: completely explicit, simple model: $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$; *all* moduli (open, closed, untwisted *and* twisted) fixed. Gen. by [Lüst-Reffert-Schulgin-Stieberger].
- [Aspinwall-Kallosh]: Stabilize M-theory on $K3 \times K3$, making use of prev. work of [Saulina, Kallosh - Kashani-Poor - Tomasiello] showing topological conditions on divisors to contribute to W substantially relaxed in the presence of flux. Refined recently by [Lüst-Reffert-Schulgin-Tripathy].

IIB nonsusy AdS vacua with exponentially large volume

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Rough idea: keep some divisor volumes $\rho_i \sim O(1)$ while sending overall vol to infinity, and balance nonperturbative $e^{-\rho_i}$ off against perturbative α'^3/Vol corrections.

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Unlike KKLT, apparently also in well-controlled regime for $O(1)$ values of W_{flux}.

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(= mirror to slag cond.), and F-terms, constraining complex structure and open string moduli:

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Original AM/AKM models have some problems with tadpole cancellation (also only closed string moduli stabilization). Scenario could still be realizable, though perhaps only with broken susy?

M-theory flux vacua

M-theory on G_2 hol. manifold X: turning on G_4-flux in X gives

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Rather different compactification is obtained when taking G_4 along 4d spacetime $\rightsquigarrow$ Freund-Rubin; X = weak G_2 (Einstein), e.g. $X = AdS_4 \times S^7$. Often moduli-free, and can support chiral fermions [Acharya-Denef-Hofman-Lambert], but typically $R_{KK} \sim R_{AdS}$.

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More general M-theory compactifications on weak G_2 + fluxes have been discussed e.g. by [Lambert] and in more detail recently by [Dall'Agata-Prezas].

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Studied in [Derendinger-Kounnas-Petropoulos-Zwirner], in particular for $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ with RR, NS-NS, and *metric* fluxes (torsion), by relating it to 4d gauged sugra. Find all untwisted geometrical moduli can be stabilized.

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Analysis of toroidal case with metric fluxes refined and generalized in [Camara-Ibañez-Font], including tadpole cancellation conditons involving metric fluxes, and inclusion of intersecting brane models.

More models: heterotic, non-geometric, ...

- Heterotic moduli stabilzation has been studied by [Gukov-Kachru-Liu-McAllister, Buchbinder-Ovrut, Cardoso-Curio-Dall'Agata-Lüst, Becker-Becker-Dasgupta-Green-Sharpe, Curio-Krause-Lüst, Gurrieri-Lukas-Micu]. Complications due to lack of tuning with only H-flux and difficulty describing metric flux (non-Kähler).

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- [Maloney-Silverstein-Strominger, Silverstein]: Susy broken at string scale (noncritical string theories).

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- Particle physics constraints.
- Cosmological constraints. Strong! E.g. [Kofman-Yi]: reheating after brane-antibrane inflation in Giddings-Kachru-Polchinski type warped compactifications produces angular KK modes severely overclosing the universe.

Statistics of vacua

We can't solve problems by using the same kind of thinking
we used when we created them
– Albert Einstein

Statistics: general idea

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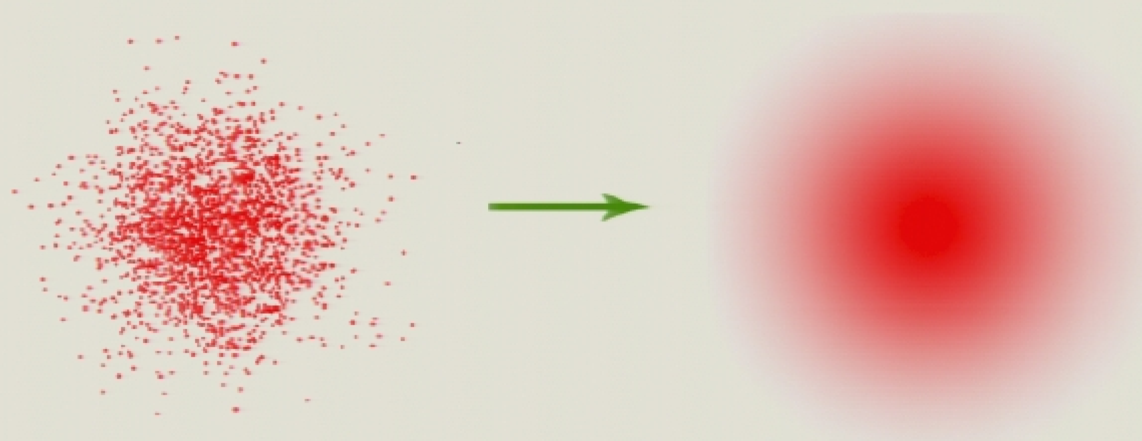

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$\rightsquigarrow$ not very practical: need some more structure + approx.

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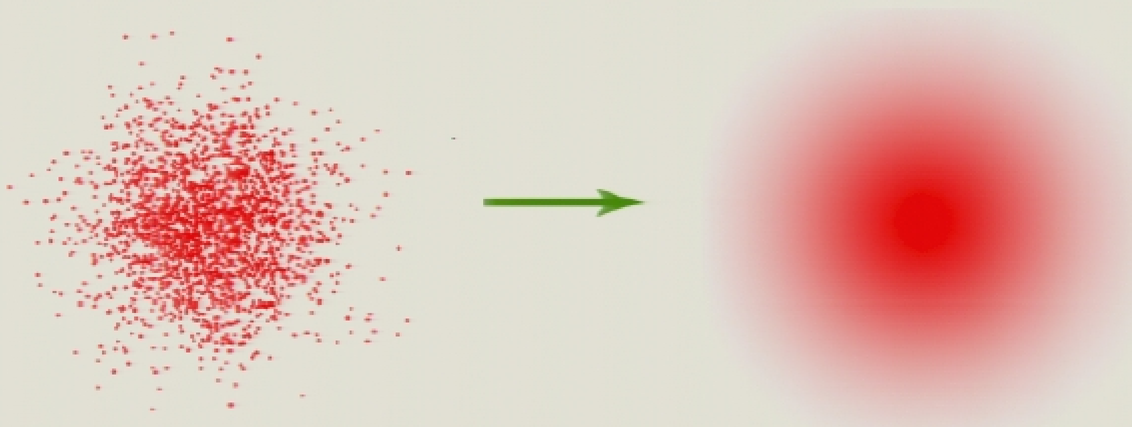

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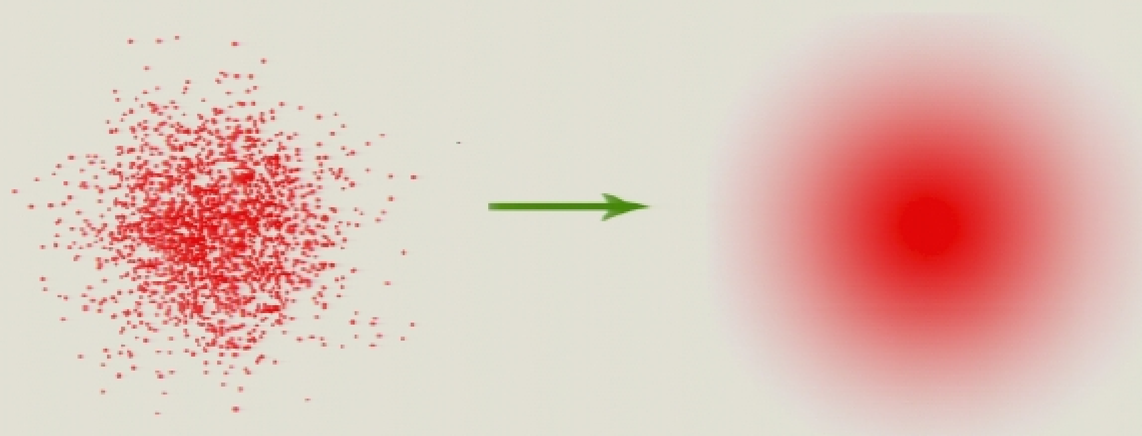
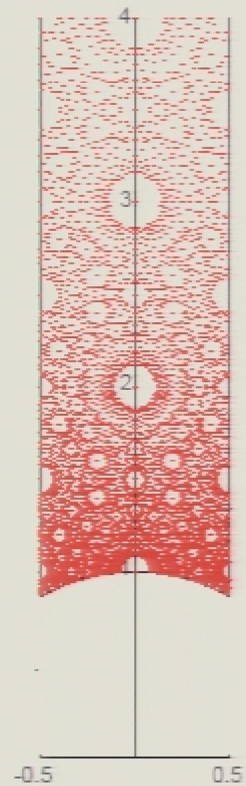


$\Rightarrow \rho(z) = \int d\mu_0[W, F, M, Y]_z \, f(W, F, M, Y)_z \rightarrow$ finite dim. int!

Toy example

Type IIB on rigid CY ($\Rightarrow$ only dilaton-axion τ).



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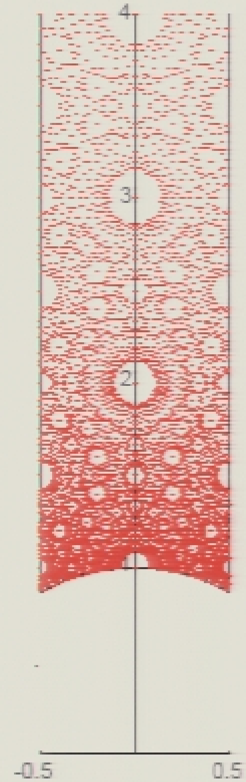

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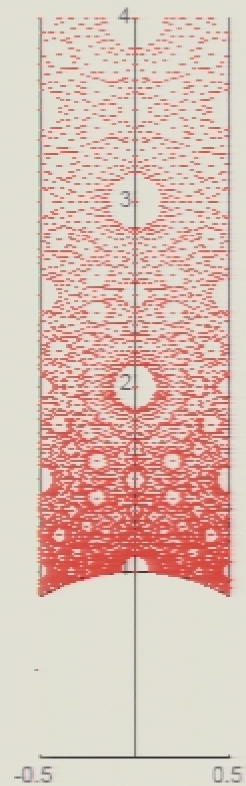

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General distributions of susy IIB flux vacua

- Number of flux vacua in region $\mathcal{S}$ of moduli space

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$$d\mathcal{N}[\Lambda] \sim d\Lambda$$

$\Rightarrow$ smallest c.c. $\sim M_s^4/\mathcal{N}_{vac}$.

- String coupling g_s: again uniformly distributed.

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All of above tested by Monte Carlo simulations [Giryavets-Kachru-Trivedi, Conlon-Quevedo].

Nonsusy IIB

F-breaking vacua, $F =: M_{susy}^2 \ll M_p^2$, for $\Lambda \sim 0$ or $\Lambda > 0$:

$$d\mathcal{N}[F,\Lambda] \sim F^5 dF\, d\Lambda$$

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$\rightarrow$ low breaking scale disfavored
(but much less than naive guess dF^{2n})

Above worked out in detail in [Denef-Douglas 2], but there is more intuitive argument in 1-field model [Dine-O'Neil-Sun]:

$$W = W_0 + F\,z + M\,z^2 + Y\,z^3$$

Solving $V'(0) = 0$ requires $M = 2W_0$, c.c. near zero requires $|F|^2 \approx 3|W_0|^2$ and stability in this case requires $|Y| < |F|$.

$\Rightarrow$ in addition to tuning c.c. three complex parameters need to be tuned small, of order $|F|$. In generic ensmemble: independent $\Rightarrow$ $d\mathcal{N} \sim d\Lambda\, d|F|^6$.

M-theory on G_2

[Acharya-Denef-Valandro]

- Number of susy flux vacua in region $\mathcal{S}$ of moduli space

$$\mathcal{N}_\mathcal{S} \sim c_2^{b_3} \int_\mathcal{S} \det g$$

- Large volumes strongly suppressed:

$$d\mathcal{N}[V] \sim (kc_2)^{b_3} dV^{-3b_3/7} \quad \Rightarrow V < (kc_2)^{7/3}$$

- Small cc's strongly suppressed because

$$\Lambda \sim 1/V^3$$

- Small F-breaking susy breaking scales strongly suppressed because

$$M_{susy}^2 \sim 1/V^{3/2}$$

Vacua with enhanced (R-)symmetries

[DeWolfe-Giryavets-Kachru-Taylor, DeWolfe, Dine-Sun]: study explicit constructions and statistics of IIB flux vacua with discrete symmetries (mostly R-symmetries).

Intersecting brane and Gepner models

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  - SU(3): 0.08
  - SU(2): 0.99
  - U(1): 0.42
  - No symm. rep: 0.84
  - 3 gen. quarks: 3×10^{-5}
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