DE SITTER VACUA
AT LEADING ORDER

based on [upcoming work] with Naomi Gendler, Liam McAllister, Richard Nally and Andreas Schachner

+ series of work leading up to this, involving Mehmet Demirtas, Manki Kim and Andres Rios-Tascon

11/29/2023 at Landscapia workshop, Saclay

Jakob Moritz (CERN)

upshot:

First concrete examples of de Sitter vacua as envisioned by Kachru, Kallosh, Linde and Trivedi 20 years ago.

important caveat: our vacua "live" at leading order in (g_s, α') (including some known corrections) but are potentially vulnerable to unknown corrections.

PLAN

1. Motivation
2. the KKLT scenario
3. supersymmetric AdS_4 vacua
4. uplift to de Sitter
5. control over corrections
6. Conclusions

Motivation

important goal of many in our field: study the imprint of quantum gravity on the physics at observable scales.

possible avenue: construct and study semi-realistic cosmologies and models of particle physics in string theory.

by constructing solutions realizing exponential hierarchies, one might begin to understand the UV origin of the hierarchies that dominate our universe, e.g.

$$\rho_{cc} \sim 10^{-123} M_{\rm pl}^4$$

because the tuning of the cosmological constant is not *technically natural*, constructing such solutions with realistic SUSY breaking scale $M_{SUSY} \gtrsim$TeV is not feasible.

but one can study a supersymmetric cc problem by finding vacua of F-term potential

$$V_F = e^K (g^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2)$$

with $\langle W \rangle \ll 1$, and $|DW| \sim |W|$.

In this way one can hope to construct controlled AdS_4 and dS_4 vacua...

the KKLT scenario

Kachru, Kallosh, Linde, Trivedi '03: *recipe* for constructing de Sitter vacua in type IIB string theory

list of ingredients:

1. a Calabi-Yau threefold X.
2. a holomorphic O3/O7 orientifold projection.
3. a choice of threeform fluxes yielding very small flux superpotential $W_0 \ll 1$.
4. sufficiently generic D3-instanton corrections to superpotential.
5. an F-term vacuum for Kähler moduli.
6. a tuned warped throat region $|z|^{\frac{2}{3}} \sim W_0$ with $\overline{\mathrm{D3}}$ uplift.

Calabi-Yau orientifolds (1. and 2.)

Given Calabi-Yau threefold X, type IIB string theory on X gives a $4d$ $\mathcal{N}=2$ effective supergravity

Dividing string spectrum by $\mathcal{I} \circ \mathcal{P} \circ (-1)^{F_L}$, with

$$\mathcal{I}:\, X \to X\,,$$

holomorphic and with fixed points at dimension 0 and 4,

$\to$ $4d$ $\mathcal{N}=1$ effective supergravity with axio-dilaton τ and

$h^{1,1}_{+}$ Kähler moduli T_i
$h^{2,1}_{-}$ complex structure moduli z^a

we will consider special case $h^{1,1}_{-} = h^{2,1}_{+} = 0$.

Flux vacua (3.)

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flux background $(F_3, H_3) \neq 0$ generates classical superpotential

$$W_{\mathrm{GVW}}(z^a, \tau) = \int_X (F_3 - \tau H_3) \wedge \Omega(z^a)$$

Assuming there exist vev's

$$\langle z^a, \tau \rangle \quad \text{s.t..} \quad \langle D_{z^a,\tau} W_{\mathrm{GVW}} \rangle = 0$$

can attempt to solve F-terms of Kähler moduli...

D3-instanton corrections (4.) & Kähler moduli stabilization (5.)

[Witten'96]: D3-instantons wrapped on rigid, orientifold invariant holomorphic four-cycles D_i contribute to the superpotential

$$W \supset \mathcal{A}_i(z, \tau) e^{-2\pi T_i}$$

and condensing gauge groups on 7-branes similarly correct W.

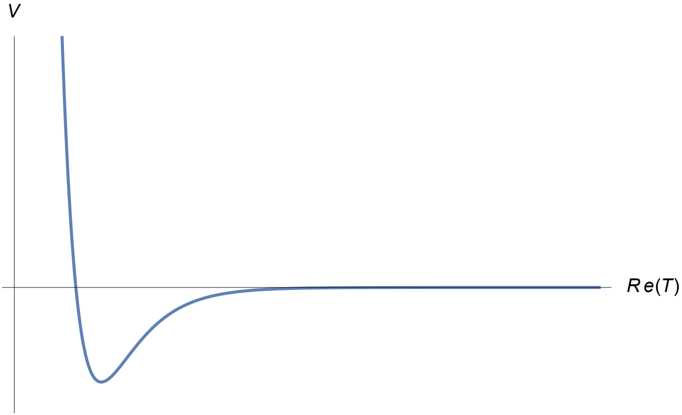
Assuming at least $h^{1,1}$ such corrections, one expects Kähler moduli are stabilized at

$$\langle \mathrm{Re}(T_i) \rangle \sim \frac{\log(|W_0|^{-1})}{2\pi} \quad \text{with} \quad W_0 := \langle W_{\mathrm{GVW}} \rangle$$

Control over large volume expansion requires $|W_0| \ll 1$.

[Kachru,Kallosh,Linde,Trivedi'03]

F-term potential for single modulus toy example:



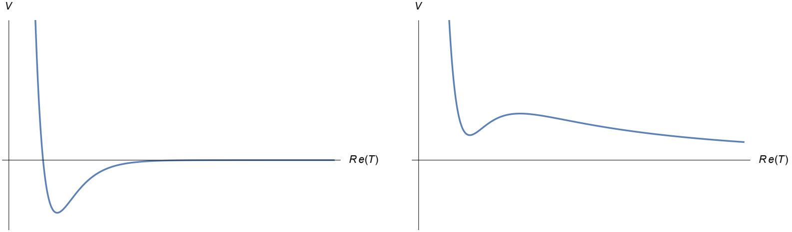
$\overline{D3}$-brane uplift (6.)

[Kachru,Kallosh,Linde,Trivedi'03]

Further assuming a warped Randall-Sundrum throat with tuned hierarchy of scales

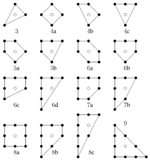
$$e^{4\mathcal{A}_{\mathrm{IR}}} \sim |W_0|^2$$

the SUSY breaking potential of a warped meta-stable $\overline{\mathrm{D3}}$-brane can uplift the solution to dS_4.

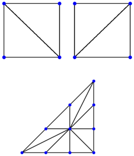


supersymmetric AdS_4 vacua

Calabi-Yau orientifolds



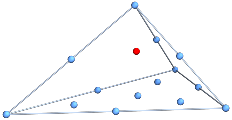
In practice, we start with the Kreuzer-Skarke dataset of $4d$ reflexive polytopes Δ°.



[Demirtas,McAllister Rios-Tascon'22]

Given a reflexive polytope Δ° one can enumerate O3/O7 orientifold projections, and compute data of orientifold fixed loci [JM'23].

A simple class of orientifolds with $h^{1,1}_- = 0$ $h^{2,1}_+ = 0$ arises from special polytopes:



The D3-tadpole is: $\frac{1}{2}\int_X H_3 \wedge F_3 \leq Q_{D3} := \frac{1}{2}(h^{1,1} + h^{2,1}) + 1$

perturbatively flat vacua (PFV's)

[Demirtas,Kim,McAllister,JM'19]

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at large complex structure (LCS), and for special ansatz in fluxes $(\mathbb{M}^a, \mathbb{K}_a)$, the superpotential is

$$W_{\text{GVW}} = \frac{1}{2}\mathbb{N}_{ab} z^a z^b - \tau \mathbb{K}_a z^a + \mathcal{O}(e^{2\pi i z})\,, \quad \mathbb{N}_{ab} := \kappa_{abc}\mathbb{M}^c$$

If the fluxes satisfy, in addition the Diophantine equation

$$p^a \mathbb{K}_a = 0 \quad p^a := (\mathbb{N}^{-1})^{ab}\mathbb{K}_b$$

the polynomial part vanishes exactly along $z^a = p^a \tau$.

vacua with small flux superpotential

[Demirtas,Kim,McAllister,JM'19]

The effective superpotential for τ is then naturally exponentially small, and computable in terms of GV-invariants.

For example: for a Calabi-Yau orientifold with $h^{1,1}_+ = 113$ and $h^{2,1}_- = 5$, we get a

$$W_{\text{eff}}(\tau) \propto -2e^{2\pi i \frac{7}{29}\tau} + 252 e^{2\pi i \frac{7}{28}\tau} + \dots$$

This racetrack superpotential has an F-term solution where

$$W_0 \propto \left(\frac{2}{252}\right)^{29} \approx 1.23 \times 10^{-61}$$

[Demirtas,Kim,McAllister,JM,Rios-Tascon'21]

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Kähler moduli stabilization

[Demirtas,Kim,McAllister,JM,Rios-Tascon'21]

So far we have stabilized 5 CS moduli z^a, and the axio-dilaton τ, but held fixed the 113 Kähler moduli.

In the above example Witten's criterion for a non-vanishing D3-instanton superpotential term is satisfied for 114 holomorphic 4-cycles

$$W(T) = W_0 + \sum_{I=1}^{114} \mathcal{A}_{D_I} e^{-\frac{2\pi}{c_I} \mathcal{Q}_I{}^i T_i}$$

On general grounds, one expects an isolated KKLT-like minimum for the T_i...

... but finding it is slightly non-trivial.

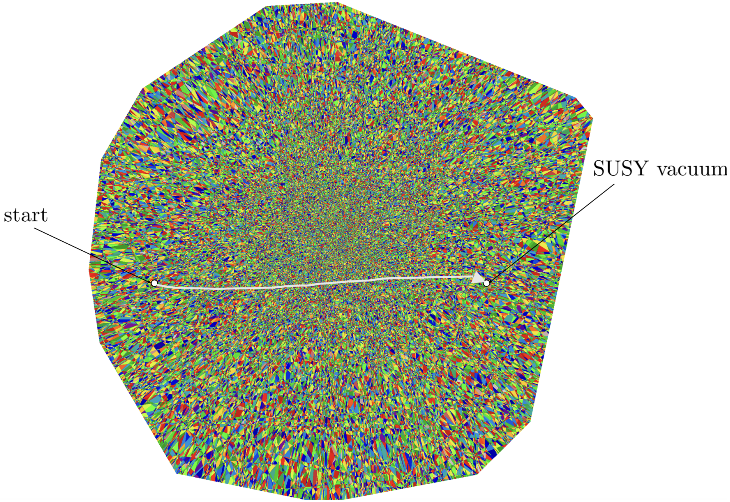
The following strategy is (usually) successful:

- Define an initial guess $\mathcal{Q}_I^i T_i^* = \frac{c_I \log(|W_0|^{-1})}{2\pi}$.
- Define arbitrary Calabi-Yau from some FRST of the polytope Δ°, and choose arbitrary point t_0^i in Kähler cone.

If $\mathrm{Re}(T_i^*)$ exists, it can be found by traversing a straight line

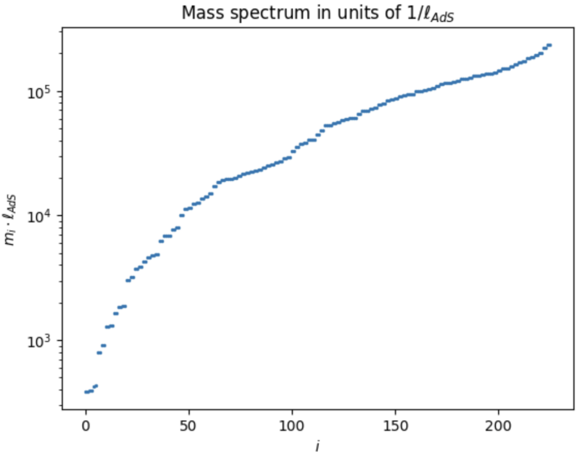
$$\mathcal{T}_i^0 := \frac{1}{2}\kappa_{ijk} t_0^j t_0^k \longrightarrow T_i^*$$

Along the way, one encounters $\mathcal{O}(100)$ flop transitions!



path from start to SUSY vacuum can be implemented as a discretized BPS attractor flow.

Once the point $T_i = T_i^*$ is identified,
one can find the true F-term minimum using simple minded methods (e.g. Newton's method).



The mass spectrum at the F-term solution is tachyon-free!

uplift to de Sitter

Klebanov-Strassler throats [Klebanov,Strassler'00]

For uplift to de Sitter, one has to engineer a warped throat

$$ds^2 = e^{2\mathcal{A}(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2\mathcal{A}(y)}g_{mn}dy^m dy^n$$

using fluxes $M := \int_A F_3$ and $K := \int_B H_3$
on deformed conifold 3-cycles,

$$z_{\text{cf}} \sim e^{-\pi \frac{K}{g_s M}} \quad \longrightarrow \quad e^{4\mathcal{A}_{IR}} \sim e^{-\frac{4\pi}{3}\frac{K}{g_s M}}$$

[Giddings,Kachru,Polchinski'01]

For a single anti-D3 brane to uplift to de Sitter without decompactification instability one needs

$$\frac{|z_{\text{cf}}|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5\times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}}\tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1$$

$\longrightarrow$ need to stabilize CS s.t. both z_{cf} and W_0 are small...

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Near a facet of the LCS cone, where a conifold becomes singular, one can systematically compute the superpotential

[Álvarez-García,Blumenhagen,Brinkmann,Schlechter'20] [Demirtas,Kim,McAllister,JM'20]

$$W_{\mathrm{GVW}} = W_{\mathrm{bulk}}(z^\alpha, \tau) + z_{\mathrm{cf}} W^{(1)}(z_{\mathrm{cf}}, z^\alpha, \tau) + \mathcal{O}(z_{\mathrm{cf}}^2)$$

where the famous logarithmic branch cut appears in

$$W^{(1)}(z_{\mathrm{cf}}, z^\alpha, \tau) = \frac{2M}{2\pi i}\left(\log(-2\pi i z_{\mathrm{cf}}) - 1\right) - \tau K + k_\alpha z^\alpha + \mathcal{O}(e^{2\pi i z^\alpha})$$

By solving a slightly adapted Diophantine equation in flux quanta one find $\langle W_{\mathrm{bulk}}\rangle \ll 1$, at $z^\alpha = p^\alpha \tau$.

In terms of such a solution, one then stabilizes z_{cf} at

$$\langle z_{\mathrm{cf}}\rangle = \frac{i}{2\pi} e^{\pi i \tau \frac{K - k_\alpha p^\alpha}{M}}$$

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Meta-stable $\overline{D3}$-brane

In addition to constructing a strongly warped throat, one needs to ensure meta-stability of an $\overline{D3}$-brane uplift.

At leading order in α' this requires $M > 12$. [Kachru,Person,Verlinde'01]

and the control parameter for the α' corrections to KPV is

$$g_s M \overset{!}{\gtrsim} 1.$$

Requiring uplift to dS limits control:

$$\frac{e^{-\frac{4\pi}{3}\frac{g_s Q_{D3}}{(g_s M)^2}}}{2\pi (g_s M)^2} \lesssim \frac{|z_{\rm cf}|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5 \times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}} \tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1$$

E.g. for largest D3-tadpole in KS, $Q_{D3} = 252$ and control parameters $1/(g_s M) = g_s = 0.2$ and $W_0 = 10^{-2}$ saturate this bound for typical volumes $(\mathcal{V}_E, \tilde{\mathcal{V}}_s)$...

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Everything, everywhere, all at once [Kwan,Scheinert'22]

So far: constructed all components
of KKLT proposal separately.

Finding concrete solutions that feature them all
has required a substantial pipeline:

[Gendler,McAllister,JM,Nally,Schachner (upcoming)]

1. $201,829$ polytopes in Kreuzer-Skarke in range $4 \leq h^{2,1} \leq 8$.
2. $3,148$ favorable polytopes admitting orientifold with $h^{1,1}_{-} = h^{2,1}_{+} = 0$.
3. 388 polytopes with $Q_{D3} \geq 75$ and $\#(\text{rigid divisors}) \geq h^{1,1}$.
4. 262 Calabi-Yau orientifolds with suitable conifold limits (away from O-planes).
5. $150,095,837$ PFVs with conifolds.
6. $87,870,693$ vacua with small W_0 (and conifolds).
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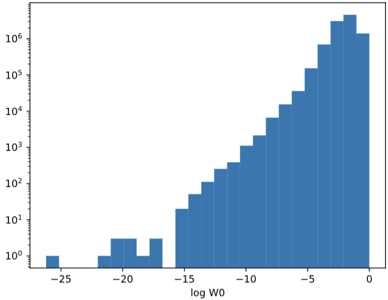
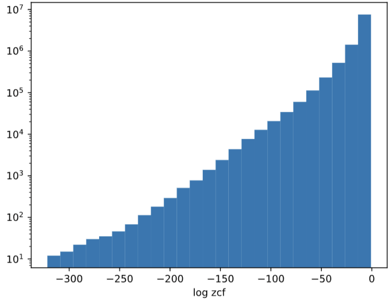
In remaining set of 26, 795 vacua,

one wants to find examples with $z_{\text{cf}}^{\frac{2}{3}} \sim W_0$.

the distributions for (z_{cf}, W_0) are encouraging:





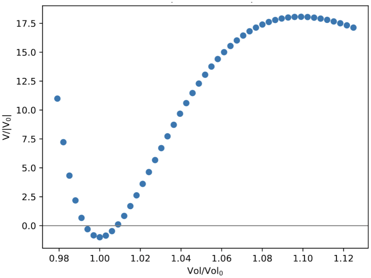
[Gendler,McAllister,JM,Nally,Schachner (upcoming)]

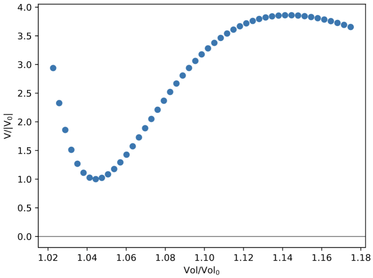
Indeed here is a very explicit example with $h^{1,1} = 167$ and $h^{2,1} = 7$:

$$\mathbb{M} = \begin{pmatrix} 16 & -8 & 16 & 34 & 48 & 22 & -6 \end{pmatrix}$$
$$\mathbb{K} = \begin{pmatrix} -7 & -2 & 0 & 1 & -3 & 1 & -1 \end{pmatrix}$$

with $g_s = 0.087$, $W_0 = 0.01$ and $g_s M = 1.39$.

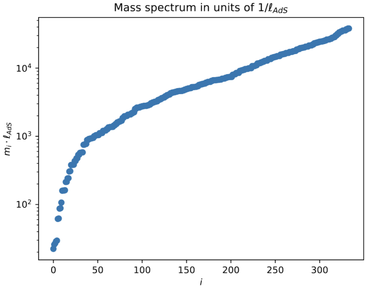
after uplift, the vacuum energy becomes positive:

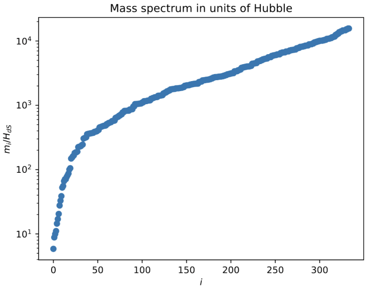




[Gendler,McAllister,JM,Nally,Schachner (upcoming)]

The vacuum is tachyon-free both before and after uplift:





[Gendler,McAllister,JM,Nally,Schachner (upcoming)]

control over corrections

The control parameters in these solutions are the best we could do in 2023,

and might not be good enough to survive α' corrections to the KPV analysis of meta-stability of the $\overline{D3}$. [Hebecker,Schreyer,Venken'22].

my take: question of meta-stability of vacua at $g_s M \sim 1$ is so far not conclusive.

Similarly, the string coupling is not extremely small, and Einstein-frame cycle volumes are not impressively large.

With simple models of loop corrections to the Kähler potential (and holomorphic) coordinates à la [Berg,Haack,Pajer'07] and from warping effects [Carta,JM,Westphal'19; Gao,Junghans,Hebecker'20] one estimates $\mathcal{O}(20-30\%)$ corrections.

Control over α' corrections at fixed order in g_s is not parametric, but we establish control at $\mathcal{O}(1/g_s^2)$ by computing $g=0$ Gopakumar-Vafa invariants to high order, using mirror symmetry. [Demirtas,Kim,McAllister,JM,Rios-Tascon'23]

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Conclusions and outlook

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03:

1. compute superpotentials from fluxes and D3-instantons using toric geometry, and enumerative invariants.
2. find vacua by solving Diophantine equations in flux quanta, and identify F-term solutions in effective 1d PFV theory featuring explicit racetrack superpotential.
3. compute the F-term minima in Kähler moduli via a discretized BPS attractor flow in the extended Kähler cone.
4. explicitly construct warped throat regions suitable for anti-D3 uplift to de Sitter.

This is not the last word on this subject...

... within constraints set by D3-tadpole, one should be able to find much better values for the control parameters

$$g_s \qquad W_0 \qquad g_s M$$

Furthermore, one can improve control by better understanding the structure of corrections along lines of recent work

...[Alexandrov,Firat,Kim,Sen,Stefanski'22] [Gendler,Kim,McAllister,JM,Stillman'22] [Liu,Minasian,Savelli,Schachner'22] [Kim'22] [Hebecker,Schreyer,Venken'22] [Schreyer,Venken'22] [Gao,Hebecker,Schreyer,Venken'22] [3× Kim'23] [Cho,Kim'23]

Thank you!