Towards Enumeration of Vacua

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with Mehmet Demirtas, Manki Kim, Jakob Moritz, and Andres Rios-Tascon

string_data 2020

de Sitter space

Simplest explanation for observed universe.

Should try to construct de Sitter solutions of string theory.

de Sitter solutions are not common.

So a search must survey many candidate geometries.

Not feasible with pen and paper.

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So a search must survey many candidate geometries.

Not feasible with pen and paper.

With partial computerization, human steps are rate-limiting.

Need efficient implementation of every step
from topological data to a stabilized vacuum.

SN 2011fe

talks by Bies, Cabo Bizet, Douglas, Krippendorf, Larfors, Liu, Long, Lüst, Vaudrevange

Byrne Observatory at Sedgwick Reserve and the Palomar Transient Factory | LCOGT.net | BJ FULTON

Plan

I will describe progress we have made in this direction:

`CYTools`: software for computing string data

Demirtas, L.M., Rios-Tascon, 20
Demirtas, L.M., Rios-Tascon, to appear
Demirtas, Kim, L.M., Moritz, Rios-Tascon, work in progress

Some first fruits of this approach:

Vacua with small flux superpotential

Demirtas, Kim, L.M., Moritz 19
Demirtas, Kim, L.M., Moritz 20

This talk does not involve ML, but our data is a natural target.

Reality is hard

We seek a de Sitter solution of string theory.

Exact nonsupersymmetric solutions of superstring theories with 4d gravity seem out of reach.

This is not a cosmological issue.

e.g., no derivation of Standard Model + Einstein gravity (with no light moduli) to standard demanded for de Sitter.

Non-supersymmetric compactifications are hard,
but this does not imply they do not exist.

We need systematic approximations.

Fundamental expansions are in α' and g_s .

Strategy for constructing vacua

Conceptually easy, impractical at present:

Find solution preserving $\mathcal{N} = 1$ SUSY, e.g. type II on CY_3-$\mathcal{O}$.
Directly compute 4d EFT to $\mathrm{N^kLO}$, in α' and g_s .
Exhibit de Sitter solutions in EFT at $\mathrm{N^{k-1}LO}$,
show that $\mathrm{N^kLO}$ negligible.

Practical: apply further approximations.

e.g. find parameter regimes where sectors decouple
into modules that interact weakly.
Analyze modules in isolation, then weakly couple them.

Final assembly is a key challenge.

Our aim

Work under bright lamppost: Calabi-Yau compactifications.

Systematically compute topological and geometric data that enter 4d $\mathcal{N} = 1$ EFT, for a vast ensemble of CY_3 hypersurfaces in toric varieties.

Automate the construction of vacua.

In time this may reveal controlled de Sitter vacua, or not.

Long, L.M., McGuirk 14
Long, L.M., Stout 16
Braun, Long, L.M., Stillman, Sung 17
Demirtas, Long, L.M., Stillman 18
Demirtas, Kim, L.M., Moritz 19
Demirtas, L.M., Rios-Tascon, 20
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Blumenhagen, Jurke, Rahn, Roschy 10
Braun, Walliser 11
Gao, Shulka 13
Altman, Gray, He, Jejjala, Nelson 14
Cicoli, Muia, Shukla 16
Braun, Lukas, Sun 17
Taylor, Wang 17
Huang, Taylor 18
Halverson, Long 20

Which string data?

Needs vary depending on model, so try to get ‘everything’.

At least, everything that follows directly from topological data.

Start: 4d reflexive polytope $\Delta^\circ \in$ Kreuzer-Skarke list

Fast Automatic Complete	Fine regular star triangulation $\Rightarrow$ toric variety V Intersection numbers κ_{ijk} of CY$_3$ $X \subset V$ Kähler cone of V, $\mathcal{K}(V) \subset \mathcal{K}(X)$
Fast Automatic Incomplete	True/extended Kähler cone of X Gopakumar-Vafa invariants of curves in X Cone of effective divisors on X
Limited	Orientifolds of X F-theory uplifts Y of orientifolds of X Divisors supporting EM5 $\subset Y$ or ED3 $\subset X$
Limited	Calabi-Yau metric on X — talks by Douglas and Krippendorf
	Perturbative corrections in α', g_s

CYTools

A Software Package for Analyzing Calabi-Yau Hypersurfaces

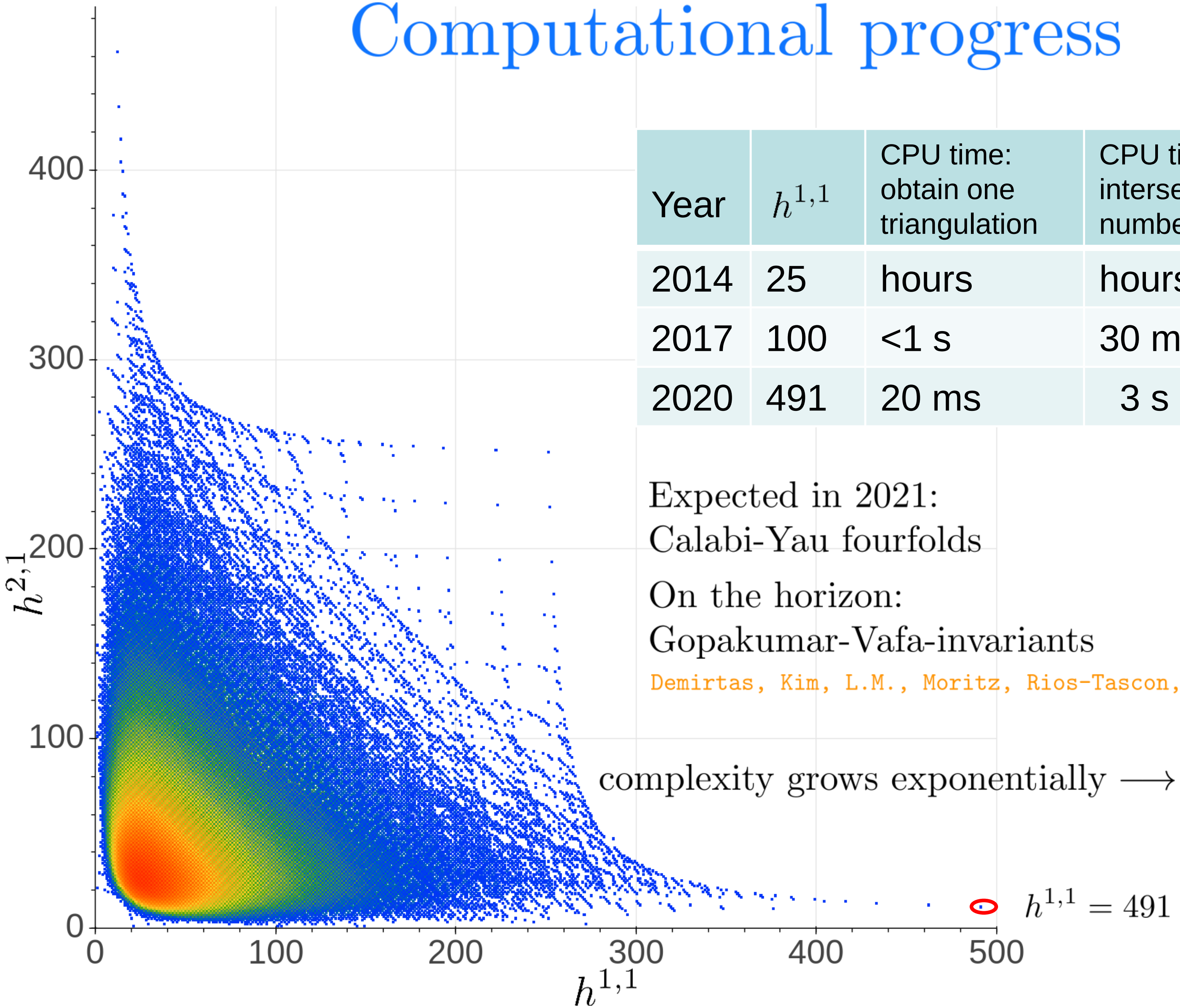
Demirtas, L.M., Rios-Tascon

To appear in January 2021. Beta testers welcome.

Purpose-built to construct and analyze triangulations, and associated Calabi-Yau hypersurfaces in toric varieties.

Orders of magnitude faster than available codes like `Sage`.

Computational progress



Year	$h^{1,1}$	CPU time: obtain one triangulation	CPU time: intersection numbers
2014	25	hours	hours
2017	100	<1 s	30 min
2020	491	20 ms	3 s

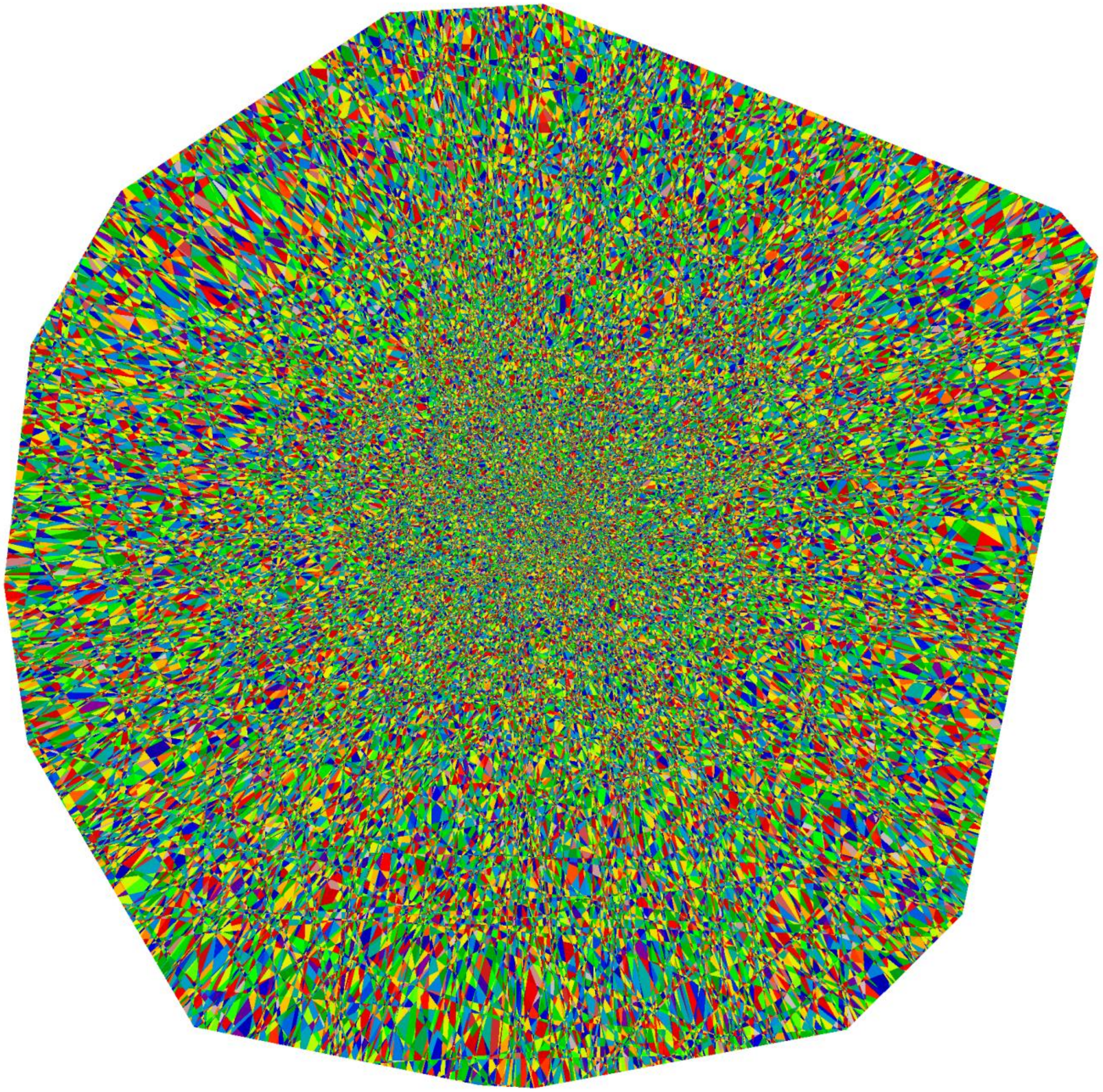
Expected in 2021:
Calabi-Yau fourfolds

On the horizon:
Gopakumar-Vafa-invariants

Demirtas, Kim, L.M., Moritz, Rios-Tascon, work in progress

complexity grows exponentially $\longrightarrow$

2d cross-section of Kähler cone in $h^{1,1} = 491$ threefold



Demirtas, L.M., Rios-Tascon, 20

Application:

Vacua with Small Flux Superpotential

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Computer-aided discovery of analytic results.

Finding de Sitter

KKLT de Sitter vacua

Compactification of type IIB on an orientifold X of a CY_3,
including:

three-form flux $G_3 = F_3 - \tau H_3 \in H_3(X, \mathbb{Z})$

an $\mathcal{N} = 1$ pure SYM sector on $N_c > 1$ D7-branes

a warped deformed conifold region Klebanov, Strassler 00

containing one or more anti-D3-branes

Claim [KKLT]: in a suitable parameter regime,

these sources can yield metastable dS_4,

and corrections to approximations are small.

Kachru, Kallosh, Linde, Trivedi 03

Setup

Type IIB string theory compactified on O3/O7 orientifold, X, of a CY_3.

$$ds^2 = G_{AB} dX^A dX^B = e^{-6u(x)+2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{2u(x)-2A(y)} g_{ab} dy^a dy^b$$

Take $h^{1,1}_+ = 1$, $\Sigma \in H_4(X, \mathbb{Z})$. Choose $G_3 = F_3 - \tau H_3 \in H_3(X, \mathbb{Z})$.

Moduli: axiodilaton $\tau := C_0 + i e^{-\phi}$

complex structure U_a, $a = 1, \dots h^{2,1}$

Kähler: $T = e^{4u} + i \int_\Sigma C_4$.

4d $\mathcal{N} = 1$ supergravity:

$$W_{\text{flux}} = \int_X G_3 \wedge \Omega$$

Gukov, Vafa, Witten 99

$$\mathcal{K} = -3 \log\left(T + \overline{T}\right) - \log\left(-i(\tau - \bar{\tau})\right) - \log\left(-i \int_X \Omega \wedge \Omega\right)$$

For generic G_3, solutions of $D_\tau W = D_{U_a} W = 0$ are isolated $\Rightarrow \tau, U_a$ fixed.

Giddings, Kachru, Polchinski 01 Kachru, Kallosh, Linde, Trivedi 03

Setup

Below the scale $m_{U_a} \sim \frac{\alpha'}{\sqrt{\mathrm{Vol}(X)}}$ of the complex structure moduli masses,

$$\mathcal{K} = -3\log(T+\overline{T}) \qquad W_{\text{flux}} \to \left\langle \int_X G_3 \wedge \Omega \right\rangle =: W_0$$

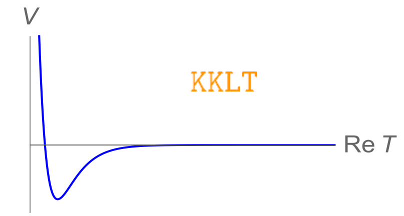
Consider a stack of D7-branes on Σ that support pure $SU(N_c)$ SYM.

[or, ED3 on Σ]
Witten 96

$$W_{\text{np}} = -\frac{N_c}{32\pi^2}\langle\lambda\lambda\rangle = \mathcal{A}\, e^{-\frac{2\pi}{N_c}T} \qquad W = W_0 + \mathcal{A}\, e^{-\frac{2\pi}{N_c}T}$$

This supergravity theory has a SUSY AdS_4 minimum:

$$D_T W = 0 \Leftrightarrow W_0 = -\mathcal{A}\, e^{-\frac{2\pi}{N_c}T}\left(1 + \frac{2\pi}{3N_c}(T+\overline{T})\right)$$



If $W_0 \ll 1$, the minimum is at large volume, $(T+\overline{T})_{\text{min}} \approx -\frac{N_c}{\pi}\ln(|W_0|)$

Statistical argument: $W_0 \ll 1$ is not generic, but should occur for some of the many choices of G_3.

Ashok, Douglas 03 Giryavets, Kachru, Tripathy, Trivedi 03 Denef, Douglas 04

One should ask:

MODULI STABILIZATION

Do there exist consistent global models with:

i. Quantized fluxes giving small classical superpotential yes

ii. *and* a warped conifold region yes

iii. *and* D7-brane gaugino condensates

Demirtas, Kim, L.M., Moritz 19
Demirtas, Kim, L.M., Moritz 20
Alvarez-Garcia, Blumenhagen, Brinkmann, Schlechter 20

Can one exhibit an explicit and fully-controlled compactification that unifies all necessary components? TBD

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Small Flux Superpotentials

$$(T+\overline{T})_{\rm min} \approx -\frac{N_c}{\pi}\ln(|W_0|) \Rightarrow \text{ control requires } |W_0| \ll 1$$

Statistical arguments suggest $|W_0| \ll 1$ should occur,
but exponentially rarely,
and preferentially when moduli space dimension is large.

Our tools permit exploring such moduli spaces.

But brute-force search still very challenging. Halverson and Ruehle 18, Cole, Schachner, Shiu 19

Previous record: $\mathcal{O}(0.01)$ Denef, Douglas, Florea 04, Denef, Douglas, Florea, Grassi, Kachru 05

Better to invent and apply a **mechanism.**

Giryavets, Kachru, Tripathy, Trivedi 03
Denef, Douglas, Florea 04
Demirtas, Kim, L.M., Moritz 19

Racetrack Superpotential

$$W = W_{\rm pert}(U) + W_{\rm inst}(U)$$

$$W_{\rm inst}(U) = \mathcal{A}_1 e^{2\pi i p_1 U} + \mathcal{A}_2 e^{2\pi i p_2 U} + \dots$$

$$\to 0 \text{ for } U \to i\infty$$

Goal: minimize potential at $U_{\rm min}$ s.t. $|W(U_{\rm min})| \ll 1$

Suppose that

$$D_U W_{\rm pert} = W_{\rm pert} = 0 \text{ along } U = \{U_{\rm flat}\}$$

$$\Rightarrow W_{\rm eff}(U \in U_{\rm flat}) = W_{\rm inst}(U)$$

$$U_{\rm min} := U \in U_{\rm flat} \text{ s.t. } D_U W_{\rm inst}\big|_{U_{\rm min}} = 0$$

Racetrack Superpotential

$$W_{\rm inst}(U) = \mathcal{A}_1 e^{2\pi i p_1 U} + \mathcal{A}_2 e^{2\pi i p_2 U} + \ldots$$

$$2\pi i \, U_{\rm min} = -\frac{\log\left(-\frac{\mathcal{A}_1 p_1}{\mathcal{A}_2 p_2}\right)}{(p_1 - p_2)}$$

$$W_{\rm inst}(U_{\rm min}) = \frac{\mathcal{A}_2 \, (p_1 - p_2)}{p_1} \left(-\frac{\mathcal{A}_2 p_2}{\mathcal{A}_1 p_1}\right)^{\frac{p_2}{p_1 - p_2}}$$

$$\ll 1 \text{ if } |p_1 - p_2| \ll p_2, \quad \mathcal{A}_2 \ll \mathcal{A}_1$$

Incarnation as Flux Superpotential

Need to show that, in a bona fide solution of string theory:

$$W_{\text{flux}} = W_{\text{pert}}(U) + W_{\text{inst}}(U)$$

(1) with $W_{\text{inst}}(U) = \mathcal{A}_1 e^{2\pi i p_1 U} + \mathcal{A}_2 e^{2\pi i p_2 U} + \ldots$

(2) s.t. $D_U W_{\text{pert}} = W_{\text{pert}} = 0$ along $U = \{U_{\text{flat}}\}$

(3) and $|p_1 - p_2| \ll p_2$ and $\mathcal{A}_2 \ll \mathcal{A}_1$

Then we'll have succeeded:

$$W_0 := \langle W_{\text{flux}} \rangle = W_{\text{inst}}(U_{\text{min}}) = \frac{\mathcal{A}_2(p_1-p_2)}{p_1}\left(-\frac{\mathcal{A}_2 p_2}{\mathcal{A}_1 p_1}\right)^{\frac{p_2}{p_1-p_2}} \ll 1$$

(1) is immediate: IIA worldsheet instantons

(2) we established a sufficient condition on topological data

(3) we found explicit examples

Demirtas, Kim, L.M., Moritz 19

Flux Superpotential in a Calabi-Yau

Let X be a Calabi-Yau threefold, $\{A_a, B^b\}$ a symplectic basis for $H_3(X, \mathbb{Z})$

$$A_a \cap A_b = 0, A_a \cap B^b = \delta_a{}^b, B^a \cap B^b = 0.$$

$$\Pi = \begin{pmatrix} \int_{B^a} \Omega \\ \int_{A_a} \Omega \end{pmatrix} = \begin{pmatrix} \mathcal{F}_a \\ U^a \end{pmatrix}.$$

$\mathcal{F}(U) = \mathcal{F}_{\mathrm{pert}}(U) + \mathcal{F}_{\mathrm{inst}}(U)$ — work around large complex structure.

$$\mathcal{F}_{\mathrm{pert}}(U) = -\frac{1}{3!}\mathcal{K}_{abc}U^a U^b U^c + \frac{1}{2}a_{ab}U^a U^b + b_a U^a - \frac{\zeta(3)\chi}{2(2\pi i)^3},$$

$$\mathcal{F}_{\mathrm{inst}}(U) = \frac{1}{(2\pi i)^3}\sum_{\vec{q}} A_{\vec{q}}\, e^{2\pi i \vec{q}\cdot\vec{U}}.$$

$$W_{\mathrm{flux}} = \sqrt{\tfrac{2}{\pi}}\left(F - \tau H\right)^T \cdot \Sigma \cdot \Pi, \qquad \Sigma = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix},$$

$$W_{\mathrm{flux}} = W_{\mathrm{pert}} + W_{\mathrm{inst}}$$

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computable, rational data

$$W_{\text{flux}} = \sqrt{\tfrac{2}{\pi}}\Big(F - \tau H\Big)^T \cdot \Sigma \cdot \Pi, \qquad \Sigma = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix},$$

$$W_{\text{flux}} = W_{\text{pert}} + W_{\text{inst}}$$

Flux Superpotential in a Calabi-Yau

Let $\tilde{X}$ be the Calabi-Yau threefold hypersurface in $\mathbb{CP}_{[1,1,1,6,9]}$

$$h^{1,1}(\tilde{X}) = 2, \quad h^{2,1}(\tilde{X}) = 272$$

$$X = \text{ mirror of } \tilde{X} = \text{ resolution of } \tilde{X}/\left(\mathbb{Z}_6 \times \mathbb{Z}_{18}\right)$$

$$h^{2,1}(X) = 2, \quad h^{1,1}(X) = 272$$

$$\mathcal{F}_{\text{pert}}(U) = -\frac{1}{3!}\mathcal{K}_{abc}U^aU^bU^c + \frac{1}{2}a_{ab}U^aU^b + b_aU^a - \frac{\zeta(3)\chi}{2(2\pi i)^3}\,,$$

$$\mathcal{K}_{111} = 9\,, \quad \mathcal{K}_{112} = 3\,, \quad \mathcal{K}_{122} = 1\,,$$

$$a_{ab} = \frac{1}{2}\begin{pmatrix} 9 & 3 \\ 3 & 0 \end{pmatrix}, \quad b_a = \frac{1}{4}\begin{pmatrix} 17 \\ 6 \end{pmatrix}.$$

$$\mathcal{F}_{\text{inst}}(U) = \frac{1}{(2\pi i)^3}\sum_{\vec{q}} A_{\vec{q}}\, e^{2\pi i \vec{q}\cdot\vec{U}}\,.$$

$$(2\pi i)^3\mathcal{F}_{\text{inst}}(U_1, U_2) = -540q_1 - 3q_2 - \frac{1215}{2}q_1^2 + 1080q_1q_2 + \frac{45}{8}q_2^2 + \ldots$$

$$q_a := \exp(2\pi i U^a)$$

Candelas, de la Ossa, Katz, Morrison 93

Flux Superpotential in a Calabi-Yau

We find an O3/O7 orientifold of X, and quantized fluxes F, H

$$F = (\vec{M}\cdot\mathbf{b}, \vec{M}^T\cdot\mathbf{a}, 0, \vec{M}^T)\,, \quad H = (0, \vec{K}^T, 0, 0)\,,$$

$$\text{with } \vec{M} = \begin{pmatrix} -16 \\ 50 \end{pmatrix}, \quad \vec{K} = \begin{pmatrix} 3 \\ -4 \end{pmatrix}, \qquad Q_{\rm D3}^{\rm flux} = 124$$

s.t. $\vec{U} = \tau \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \frac{\tau}{10}\begin{pmatrix} 4 \\ 3 \end{pmatrix}$ is a flat direction, and

$$W_{\rm inst} = \mathcal{A}_1 e^{2\pi i p_1 \tau} + \mathcal{A}_2 e^{2\pi i p_2 \tau} + \ldots$$

$$\text{with} \quad p_1 = \frac{2}{5}, \;\; p_2 = \frac{3}{10} \qquad \frac{\mathcal{A}_2}{\mathcal{A}_1} = -\frac{5}{288}$$

Moduli are stabilized at

$$\langle\tau\rangle = 6.856i\,, \quad \langle U_1\rangle = 2.742i\,, \quad \langle U_2\rangle = 2.057i\,,$$

$$\text{with} \quad |W_0| = 2.037\times 10^{-8}\,.$$

Demirtas, Kim, L.M., Moritz 19

Single-instantons dominate

Totally explicit, no unknown factors in leading-order data.

Just a finite set of computable rational numbers.

Higher orders strongly suppressed:

$$(2\pi i)^3 \mathcal{F}_{\rm inst}(U_1, U_2) = -540 q_1 - 3 q_2 - \frac{1215}{2} q_1^2 + 1080 q_1 q_2 + \frac{45}{8} q_2^2 + \dots$$

$\mathcal{O}(10^{-5})$ smaller $\quad$ $\mathcal{O}(10^{-10})$ smaller

Remark: mass^2 along previously-flat direction is $\mathcal{O}(|W_0|)$

Comments

We easily find many more examples.

Need: knowledge of prepotential $\mathcal{F}$ around LCS

suitable orientifold

some luck with the numbers p_1, p_2, $\mathcal{A}_2/\mathcal{A}_1$, $Q_{\rm D3}^{\rm flux}$

Upshot: **small $|\mathbf{W_0}|$ is in the landscape.**

But for KKLT we want much more:

warped conifold region

Kähler moduli stabilization ($h^{1,1} = 272$ in example!)

anti-D3-brane supersymmetry breaking

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anti-D3-brane supersymmetry breaking

Conifold vacua

Thus far, have expanded around LCS: $\mathcal{F}(U) = \mathcal{F}_{\text{pert}}(U) + \mathcal{F}_{\text{inst}}(U)$

Want flux vacuum near a conifold point and with $|W_0| \ll 1$.

So, analytically continue from LCS to conifold.

$$\mathcal{F}_{\text{inst}}(U) = -\frac{1}{(2\pi i)^3}\sum_{[\mathcal{C}]} n^0_{\mathcal{C}}\,\text{Li}_3(q^{\mathcal{C}})\,,\qquad q^{\mathcal{C}} := \exp\left(2\pi i b^a_{\mathcal{C}} U_a\right)\qquad \text{Li}_k(q) := \textstyle\sum_{n=1}^{\infty} q^n/n^k$$

$\mathcal{C} = b^a_{\mathcal{C}}\Sigma_a$ effective, Σ_a basis of $H_2(\tilde{X},\mathbb{Z})$

$n^0_{\mathcal{C}}$: genus-0 Gopakumar-Vafa invariant

Mirror of developing conifold singularity in X can be:

collapsing $\tilde{X}$
collapsing divisor(s) in $\tilde{X}$
collapsing curve(s) in $\tilde{X}$

Often, infinite instanton sum contributes at conifold.

Conifold vacua

But **if** the conifold singularity is mirror to collapsing

a curve $\mathcal{C}_1$ s.t. $n^0_{k\mathcal{C}_1} \neq 0$ only for **finitely many** k

then one need only continue finitely many polylogs!

$$-\frac{\mathrm{Li}_2(e^{2\pi i z})}{(2\pi i)^2} = \frac{1}{24} + \frac{z}{2\pi i}\ln\left(1-e^{2\pi i z}\right) + \frac{\mathrm{Li}_2(1-e^{2\pi i z})}{(2\pi i)^2}$$

Euler 1729

We obtained an analytic result for $\mathcal{F}$ in such cases:

$$\mathcal{F}_1 = n_{\mathrm{cf}}\frac{z_1}{2\pi i}\ln\left(1-e^{2\pi i z_1}\right) + n_{\mathrm{cf}}\left(\frac{1}{24}+\frac{\mathrm{Li}_2(1-e^{2\pi i z_1})}{(2\pi i)^2}\right)$$
$$-\frac{1}{2}\mathcal{K}_{1ab}z^a z^b + a_{1a}z^a + b_1 - \frac{1}{(2\pi i)^2}\sum_{[\mathcal{C}]\neq[\mathcal{C}_1]} n^0_{\mathcal{C}} b^{\mathcal{C}}_1\,\mathrm{Li}_2(q^{\mathcal{C}})\,.$$

In an explicit orientifold with $h^{1,1} = 99$, $h^{2,1} = 3$,
we exhibited near-conifold vacua with $e^{2A} \approx |W_0| \ll 1$.

Demirtas, Kim, L.M., Moritz 20

Conclusions

KKLT scenario for de Sitter vacua requires special structures in classical flux compactification:

exponentially small flux superpotential W_0

warped conifold region

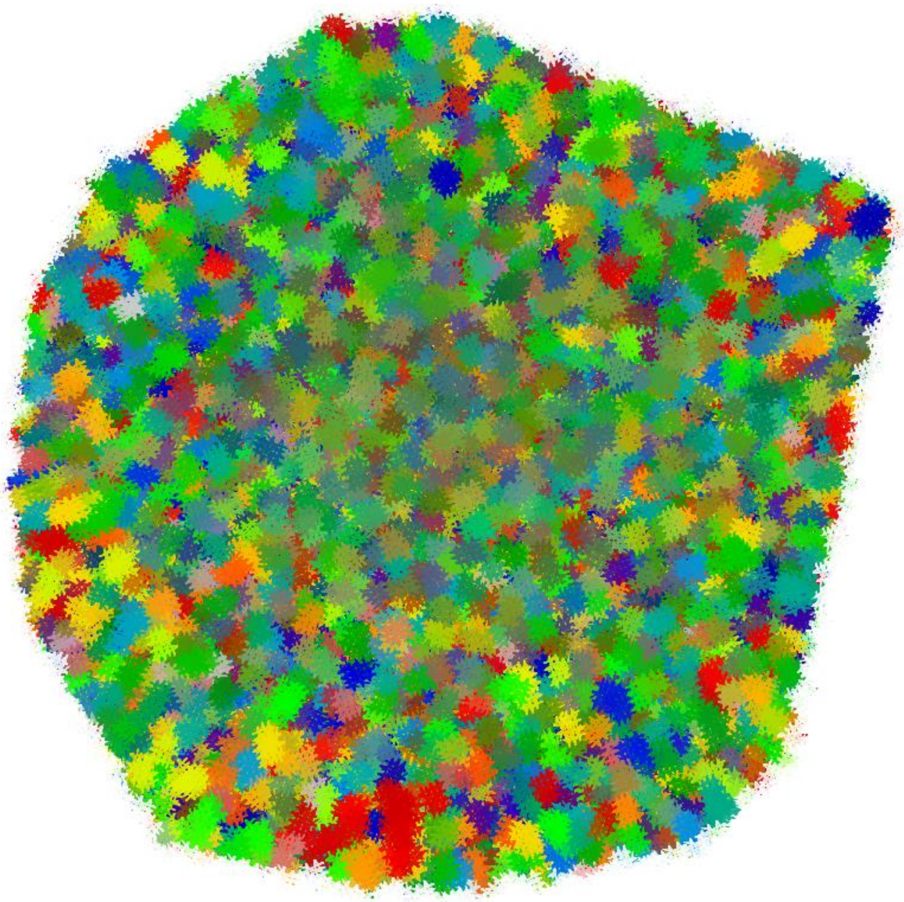
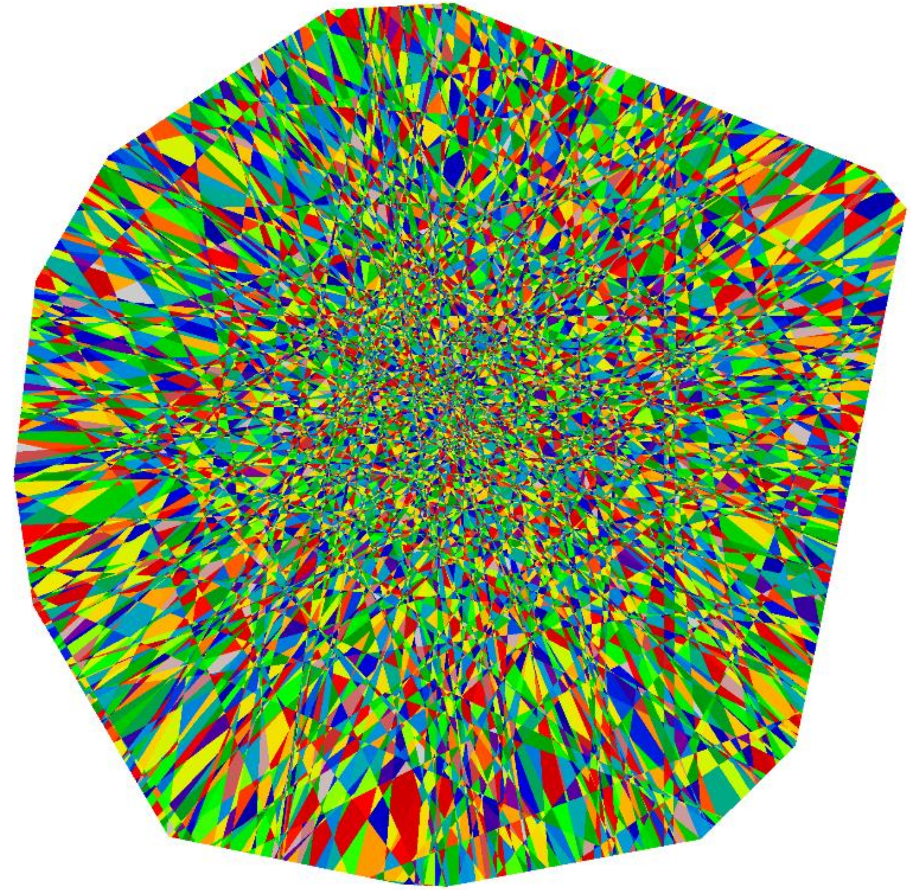
We presented a mechanism for constructing such solutions, via a racetrack of IIA worldsheet instantons.

We gave complete explicit examples.

Small $|W_0|$ is in the landscape.

Our search is automated; large-scale studies possible.

Quantum side of KKLT, and uplift, remain challenging.

Thanks!