Hope or No Hope for the String Landscape?

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The Accelerating Universe

Let's begin our discussion today with a quick glance at the observed universe.

Around 1998, observational cosmology suggested that the universe has roughly the following cosmological characteristics.

Namely, we currently believe that:

- The universe is flat
- The universe is accelerating

The critical energy density of the universe approximately consists of,

- 5% Ordinary baryonic matter
- 25% Dark matter
- 70% Dark energy

The observed energy scale for dark energy is tiny relative to the Planck scale:

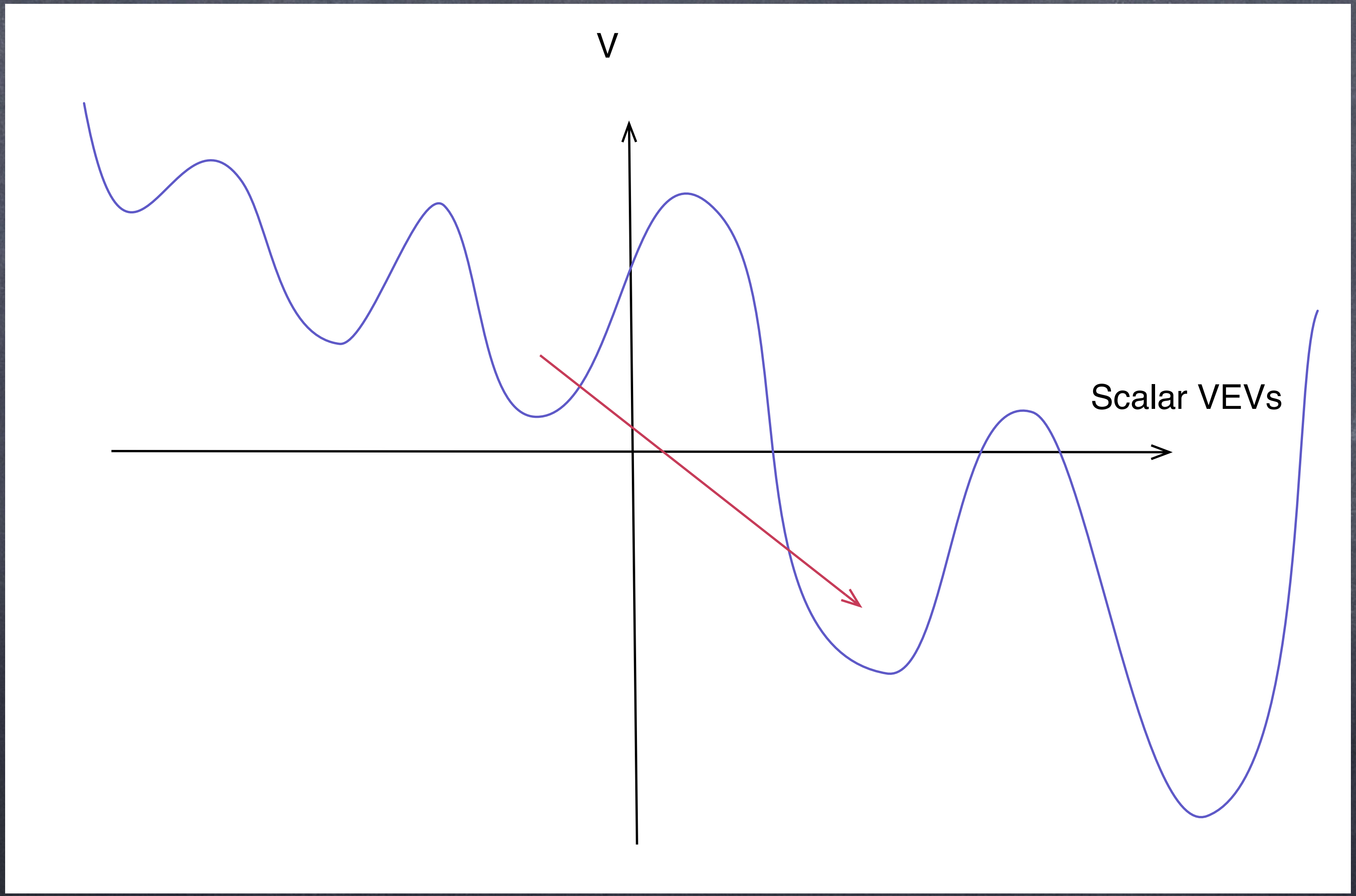
$$M_{obs} \sim 10^{-30} M_{pl}$$

Even aside from this enormous hierarchy, accelerating universes present deep puzzles for quantum theories of gravity in terms of determining what can be measured.

Yet if we believe string theory is the correct theory of quantum gravity then we must reconcile acceleration and string theory!

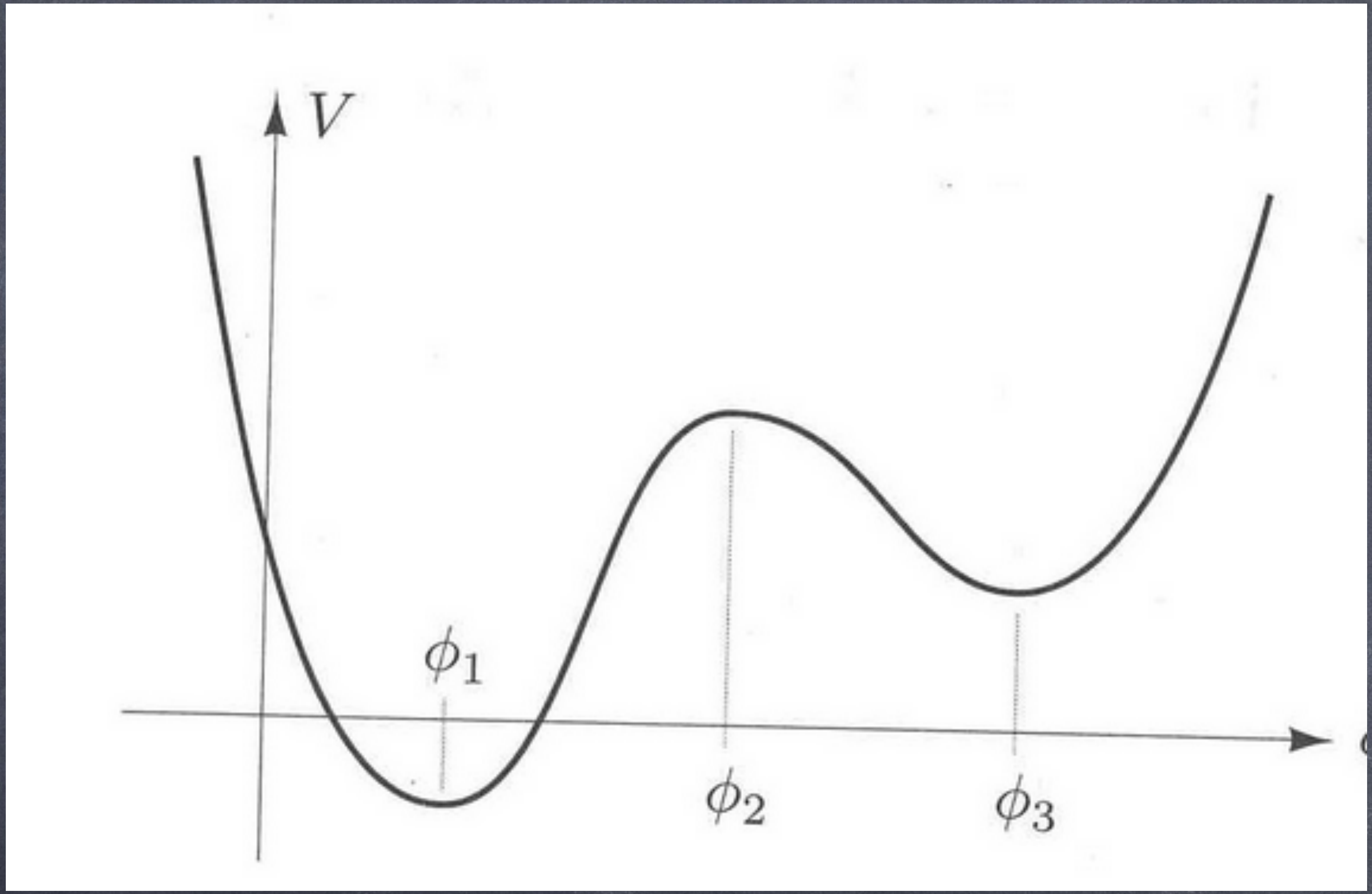
How this reconciliation might happen is the subject of this talk.

One way this reconciliation can happen is if there is a complicated potential "landscape" in string theory, often dubbed the string landscape, where a huge range of values of the cosmological constant are realized in metastable vacua.



Note that de Sitter space-times in effective field theory are easy to construct!

It's not hard to draw a potential that looks something like,



String theory has lots of ingredients that could give rise to a potential of this type:

Metrics, branes, anti-branes, fluxes, higher derivative interactions, instantons … In short, the full richness of string theory.

For this reason, the plausibility of a string landscape has never been a serious issue since the idea of a landscape was floated 19 years ago.

(Feng, March-Russell, S.S., Wilczek; Bousso, Polchinski)

Yet accelerating universes in string theory are really hard to find! There have been sharper and sharper no-go results in recent years.

We'll discuss the no-go results briefly later in the talk.

Today there are three possible views one could adopt:

(a) There is sufficient complexity in the space of string vacua and sufficient ingredients that a landscape of de Sitter solutions, although hard to exhibit, is inevitable.

(b) De sitter space-time is part of the swampland, and dark energy must be time-dependent. String theory has a concrete prediction!

(c) We do not have enough theoretical understanding yet to make a determination.

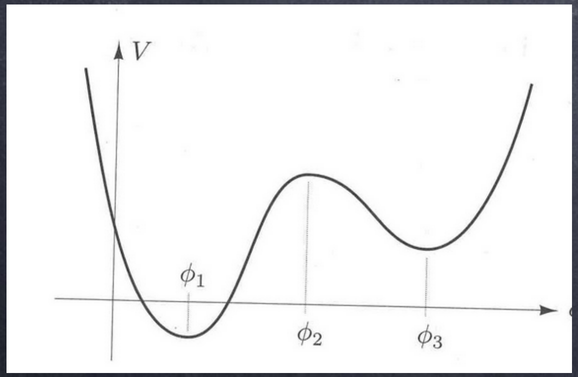
The strongest version of option (b) so far is the (refined) de Sitter conjecture:

(Obied, Ooguri, Spodyneiko, Vafa, ... hep-th/1806.08362)

$$M_P \frac{|V'|}{V} \equiv \lambda \gtrsim O(1)$$

or

$$-M_P^2 \frac{V''}{V} \equiv c^2 \gtrsim O(1)$$



This forces dark energy to be some kind of dynamical quintessence field.

For single field models, the most conservative bounds from current data come from using the two test cases:

$$V(\phi) = A\exp(-\lambda\phi)$$

$$V(\phi) = B\cos(c\phi)$$

The Hubble constant is particularly key in establishing strong constraints since quintessence models exacerbate the current tension in ΛCDM.

Data set	c 68% (95%) C.L.	$\lambda_{\rm eff}$ 68% (95%) C.L.	$\lvert\Delta\phi\rvert$ $[M_P]$ 68% (95%) C.L.
CMB	$c < 2.3\,(3.1)$	$\lambda_{\rm eff} < 1.4\,(2.2)$	$\lvert\Delta\phi\rvert < 0.51\,(0.66)$
CMB + SN	$c < 0.25\,(1.4)$	$\lambda_{\rm eff} < 0.40\,(0.71)$	$\lvert\Delta\phi\rvert < 0.11\,(0.19)$
CMB + H_0	$c < 0.17\,(0.84)$	$\lambda_{\rm eff} < 0.31\,(0.58)$	$\lvert\Delta\phi\rvert < 0.09\,(0.16)$
ALL	$c < 0.16\,(0.73)$	$\lambda_{\rm eff} < 0.29\,(0.53)$	$\lvert\Delta\phi\rvert < 0.08\,(0.15)$

The theorist's takeaway is that current bounds don't kill dynamical dark energy yet, but there are perhaps some numbers to explain at the 68% confidence level.

It really depends on what you view as O(1).

(Raveri, Hu, S.S., hep-th/1812.10448)

On the other hand, there have been many proposed constructions of de Sitter space in string theory.

In 2017, I revisited the the most popular type IIB string landscape constructions, motivated by the improved no-go results of recent years.

(S.S., hep-th/1709.03554)

This talk consists of two parts:

Part I is to explain that 2017 result as clearly as I can, and the status of type IIB landscape constructions. It is a mystery to me why there is any continued discussion of the past IIB landscape constructions. This is likely my failure to communicate the physics.

Part II is an explanation of my view on the landscape/swampland debate and some of the questions I'm trying to concretely address.

Part I

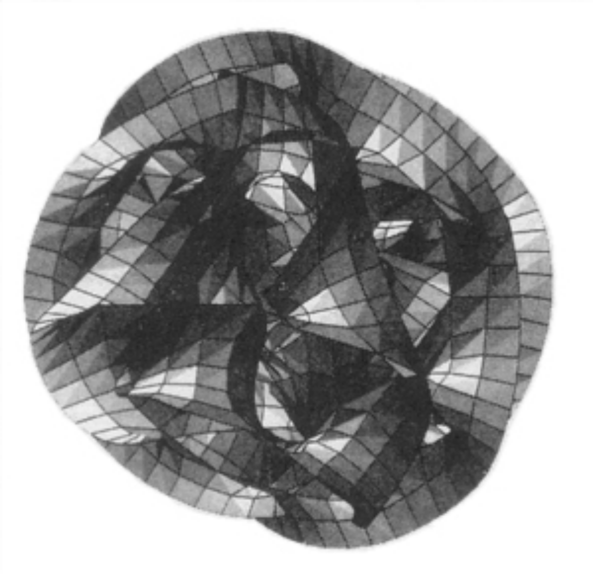
No Hope

The most serious contenders for a de Sitter construction are the models built using type IIB orientifolds or F-theory vacua with flux.

(Dasgupta, Rajesh, S.S. '99)

I will quickly summarize the main conclusion then explain it in more detail.

Compactify type IIB from D=10 to D=4 on something:



(Either an orientifold of a CY 3-fold, or the base of a CY 4-fold.)

If the something has interesting internal flux then there's a Gauss Law type constraint forbidding a classical compact SUGRA solution.

(Gibbons '84)

The resulting theory is characterized by a D=4 N=1 SUGRA with a superpotential and a Kahler potential,

$$K, W$$

with physical potential:

$$V = e^K \left(K^{i\bar{\jmath}} D_i W D_{\bar{\jmath}} \bar{W} - 3|W|^2 \right), \qquad D_i = \partial_i + \partial_i K.$$

From KK reduction, K and W have been argued to take the form:

$$K = -3\log(\rho + \bar{\rho}), \quad W = W_0.$$

$\int G_3 \wedge \Omega_3$

If this "no-scale structure" is valid, there is no physical energy; a static Minkowski solution is an approximate starting point. SUSY is broken if W is non-vanishing.

One can then try to adorn the theory with quantum corrections, like instantons, to get a new AdS vacuum and then "uplift" to dS:

$$K = -3\log(\rho + \bar{\rho}), \qquad W = W_0 + Ae^{-\rho}.$$

Is there anything wrong with using effective field theory?

No! It's fine to use effective field theory to discuss the low-energy physics, but you have to use the RIGHT effective field theory.

This is the WRONG effective field theory.

Claim: for the RIGHT effective field theory, the no-scale structure is essentially always broken in the CLASSICAL background.

This has nothing to do with quantum corrections. Without such breaking the SUGRA no-go theorem cannot be evaded.

$$K = -3\log(\rho + \bar{\rho}) + \delta K, \quad W = W_0.$$

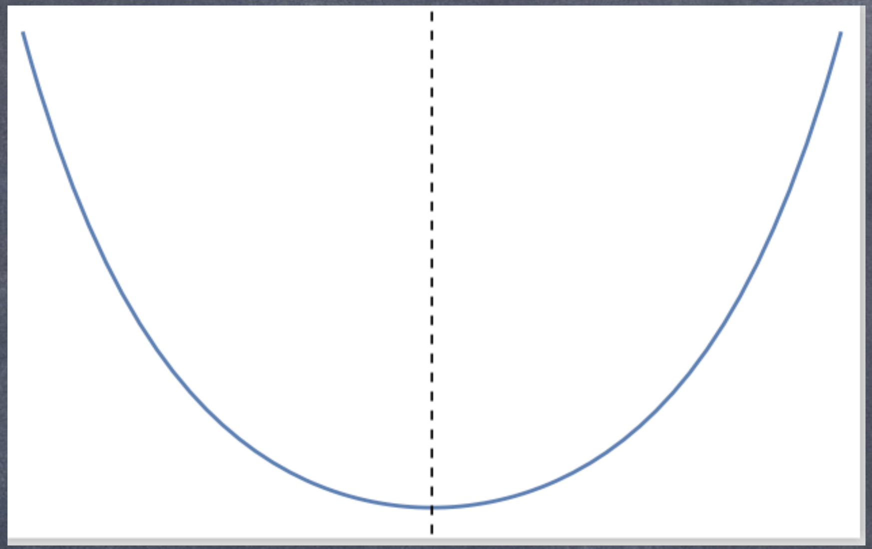
Equivalently: you have failed to solve for a classical static background in the SUSY breaking case.

The right picture is classical rolling; then one might try to understand the quantum mechanics of the rolling background. This is completely different from what has been done for the past 18 or so years.

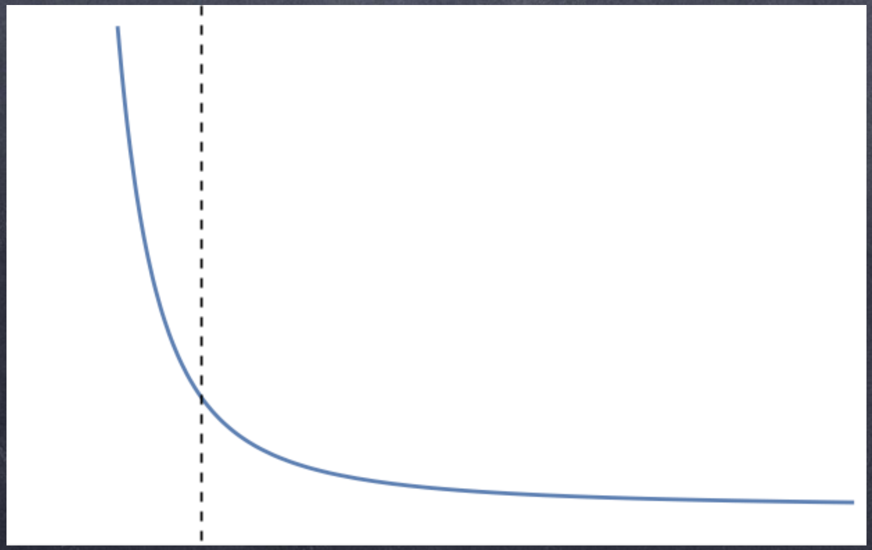
I will say it one other way:

The price you pay for evading the SUGRA no-go theorem is that the classical Kahler potential is never no-scale.

If we turn on a SUSY breaking flux, the right CLASSICAL picture is not this,



but this:



Quantum corrections must be computed around some CLASSICAL background.

There is no recipe for defining non-perturbative corrections around an off-shell gravity configuration.

In string theory, there is no recipe for defining even perturbative corrections around an off-shell configuration (this might be possible in the future).

If you think you can make sense out of a background with SUSY broken by fluxes, here is your burden:

(1) Find a classical solution of the D=10 space-time theory. It will be time-dependent, and probably horribly singular in either the far past or future, assuming it even exists.

(2) Define what perturbative and non-perturbative corrections mean in such a cosmology and how they depend on initial conditions. This is your ultraviolet description.

(3) Exhibit a metastable vacuum!

This looks like a HOPELESS task to me even at step (1).

This problem afflicts all type IIB scenarios which start with GKP SUSY breaking fluxes. For example:

(1) The original KKLT scenario, which requires an anti-brane for uplifting.
(2) The LARGE volume scenario, which includes a perturbative correction to K.
(3) The Kahler uplift scenario which involves no extra ingredients.

$$K = -3\log(\rho + \bar{\rho}), \qquad W = W_0 + Ae^{-\rho}.$$

Why do I say this is the case?

Let me briefly sketch the argument in the pedagogically friendly setting of M-theory. You can find the IIB/F-theory argument in my paper.

There are really 3 related backgrounds to consider.

The basic input data is an elliptic CY 4-fold $\mathcal{M}_8$ with a choice of flux.

F-theory on $\mathcal{M}_8$ gives a D=4 background (IIB on B_6).

↓

M-theory on $\mathcal{M}_8$ gives a D=3 background.

↓

IIA on $\mathcal{M}_8$ gives a D=2 background.

These are related by circle compactification and strong-weak coupling.

Take M-theory on the space: $\mathcal{M}_8 = CY_4.$

(Becker & Becker)

Take a warped metric of the form:

$$ds^2_{D=11} = e^{-W(y)}\eta + e^{\frac{1}{2}W(y)}\left(g^{(2)}_{ij} + g^{(8)}_{ij} + \ldots\right) dy^i dy^j .$$

The internal metric is a conformally Kahler metric but not generally conformally CY.

(Grimm, Pugh, Weissenbacher)

This must solve the space-time equations of motion. At lowest two derivative order, the M-theory effective action takes the form:

$$S_2 = \frac{1}{2\kappa_{11}^2} \int d^{11}x \sqrt{-G} \left(R - \frac{1}{2}|G_4|^2 \right) - \frac{1}{12\kappa_{11}^2} \int C_3 \wedge G_4 \wedge G_4 + \ldots$$

There is no solution with flux at this order as we already discussed. We must include the next order terms.

$$S_8 = \frac{1}{(2\pi)^6 3^2 2^{13} \ell_p^3} \int \sqrt{-G} \left(t_8 t_8 - \frac{1}{24}\epsilon_{11}\epsilon_{11} \right) R^4 - T_{M2} \int C_3 \wedge X_8 + O([G_4]^2).$$

Cancels the flux stress-energy

$\sim \frac{\chi}{24}$

Let's estimate the size of terms. Flux quantization implies that,

$$\left[\frac{\widehat{G}_4}{2\pi}\right] - \frac{p_1(\mathcal{M})}{4} \in H^4(\mathcal{M}, \mathbb{Z})$$

and therefore,

$$G_4 \sim \ell_p^3/\ell_{\mathcal{M}}^4.$$

The stress-energy contribution from the flux is down by ℓ_p^6 which is the same size as the R^4 terms.

They cannot be neglected. Space-time SUSY implies all 8 derivative terms are therefore relevant.

The 8 derivative terms are not generating "quantum corrections" to anything. They are part of the classical space-time equations that must be solved to describe any compact flux solution.

There is no approximate solution about which to expand, which does not involve these higher derivative interactions. The same thing is true in type IIA and in F-theory.

The ideal way to proceed is to simply compute whether there is a physical potential from the 8 derivative terms.

This should come from the 8 derivative terms, which involve

$$O([G_4]^2).$$

These are down by ℓ_p^6 from the R^4 terms. Unfortunately, they are partly but not completely known. So we would have to be lucky that the unknown terms don't contribute.

We will take another approach and ask if the space-time Kahler potential is corrected by the R^4 terms. This is also a hard question but more tractable.

$$V = e^K \left(K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2 \right), \qquad D_i = \partial_i + \partial_i K.$$

The only assumption here is that we can use a superspace formalism to describe the low-energy physics i.e., that SUSY is broken spontaneously.

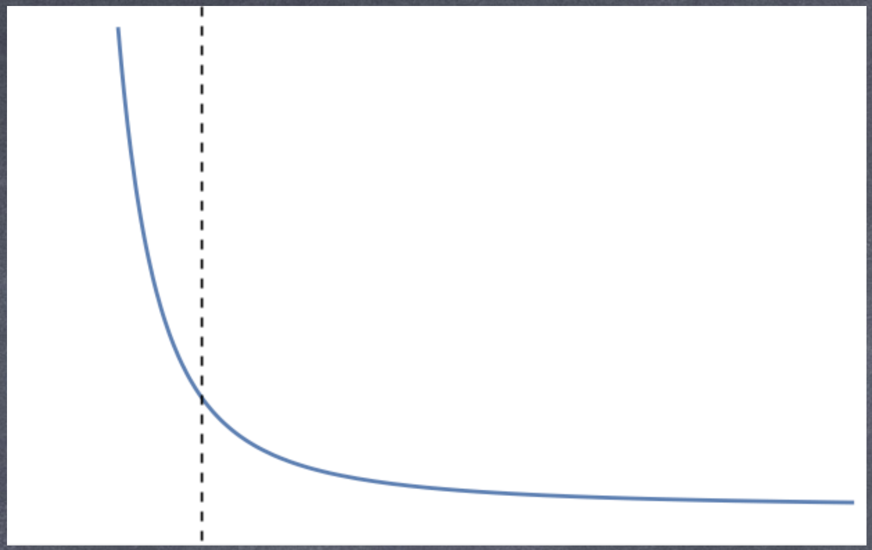
The intuitive answer should be yes because these same terms correct the kinetic terms in CY 3-fold backgrounds without flux.

For our situation, the correct K should be expressed in CY 4-fold quantities. No complete expression is known today, unfortunately, but we have considerable data and it all gives a breaking of no-scale.

Omitting details, the upshot is that the R^4 term both cancels the flux stress-energy AND renormalizes the space-time Kahler potential. You can't choose to ignore one effect over the other.

What I've said may sound provocative given the enormous effort devoted to these landscape constructions.

In actuality, what is far bolder is ignoring the lack of a classical solution and making claims about instanton effects!



(UV complete theories)

There is a fun problem motivated by this picture of studying quantum-mechanical systems with classical rolling coupled to time-dependent instanton effects.

(Kleban, Maxfield, S.S., Verlinde, to appear)
(See also Pimentel, Stout 1905.00219)

This should be contrasted with stabilization in no-scale QFT models, where the breaking of no-scale can be treated as a perturbative effect.

(Kachru & Trivedi 1808.08971)

Lastly, type IIA flux vacua are on much worse footing. Both with and without a Roman's mass.

I don't have time today to describe the issues there, but they are interesting and in need of resolution.

Part II

Hope

Landscape VERSUS Swampland

I still suspect there is a landscape in string theory.

However, the existence of a landscape is not a topic for philosophical debate. It should be established to the satisfaction of reasonable physicists firmly one way or the other.

How do we do this?

Over the last 20 years, there have been a couple of developments that have somewhat changed my perspective on this question.

Today, there are believed to be at least $O(10^{3000})$ Calabi-Yau 4-folds, which are a basic ingredient in landscape constructions.

If you add fluxes, the degeneracy of Minkowski SUSY vacua goes up to a very coarse estimate $O(10^{272,000})$ for a single specific Calabi-Yau.

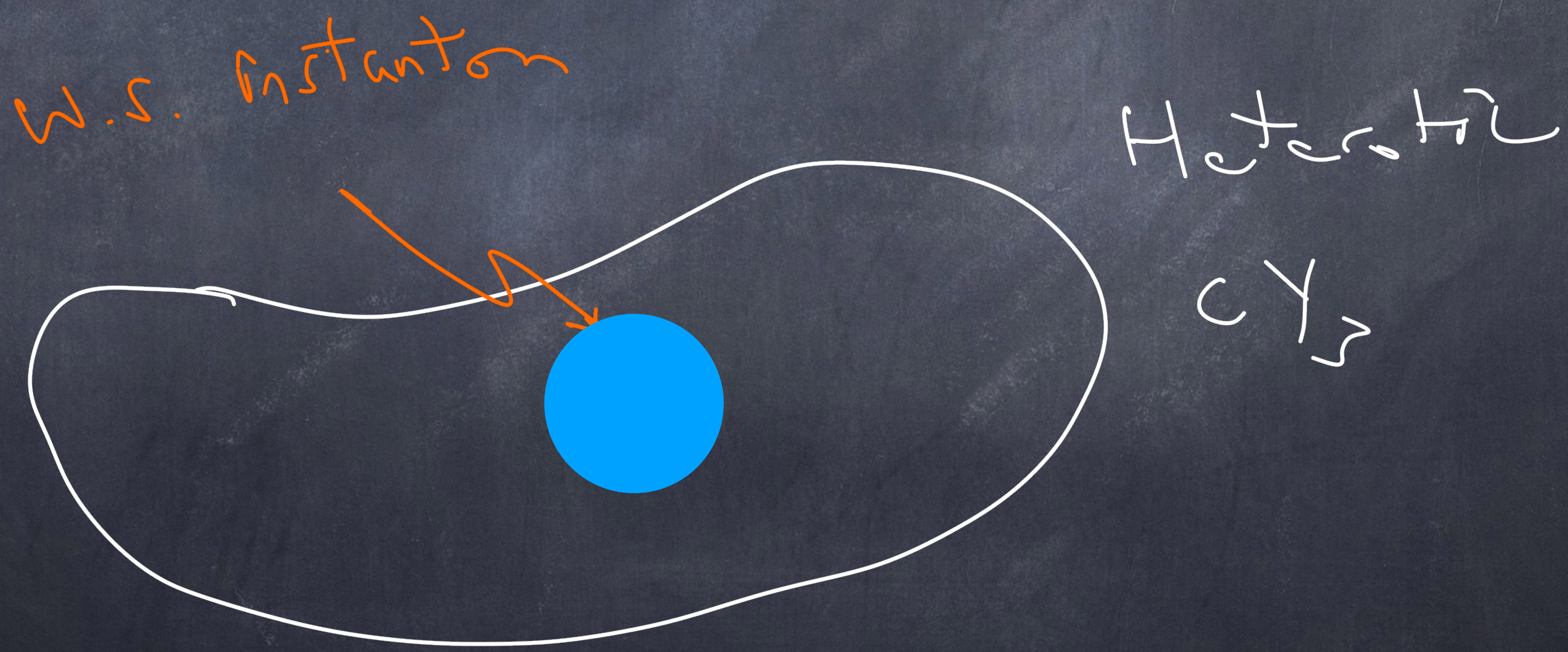
"Experimentally" your typical CY space appears to be elliptically-fibered and even K3-fibered, often in multiple ways.

The quintic was misleading!

(Halverson, Long, Sung; Taylor, Wang; Anderson, Gao, Gray, Lee)

There is also significantly improved technology for computing heterotic world-sheet instantons, particularly in terms of bundle moduli-dependence.

(Buchbinder, Donagi, Ovrut, ...)



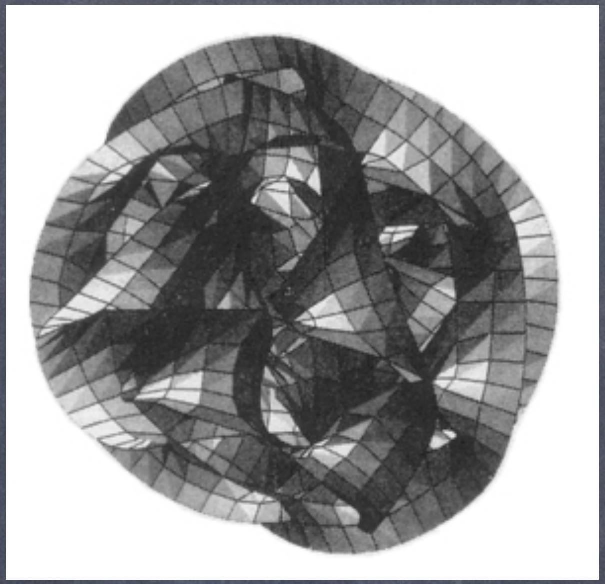
In this talk, I've sharply contrasted two cases:

$$W_0 = 0 \qquad \text{(DRS)}$$

$$W_0 \neq 0 \qquad \text{(GKP)}$$

The former supersymmetric case is analogous to a standard CY compactification. In this case, notions of BPS instantons make sense. Wrapped branes make sense (kappa symmetry makes sense).

Recall that in string theory we always start with a classical background, which usually defines a conformal field theory at weak coupling.



For pure metric, this is a Ricci-flat space up to corrections small at large volume, which can be systematically taken into account to give a world-sheet CFT:

$$R_{\mu\nu} = 0 + O(\alpha')$$

Here corrections do NOT generate a physical potential from an effective field theory perspective because W=0.

This is why we reasonably believe there is a classical string theory solution associated to each CY 3-fold.

The same argument applies to SUSY flux vacua. It's the only reason to take them seriously.

I'd like to revisit the computation of instantons in flux backgrounds. There are a number of issues that need to be understood more carefully, but the basic idea goes as follows:

$$W = \int \Omega_4 \wedge G_4 + \sum A_i e^{-\vec{t}\cdot\vec{\theta}_i}$$

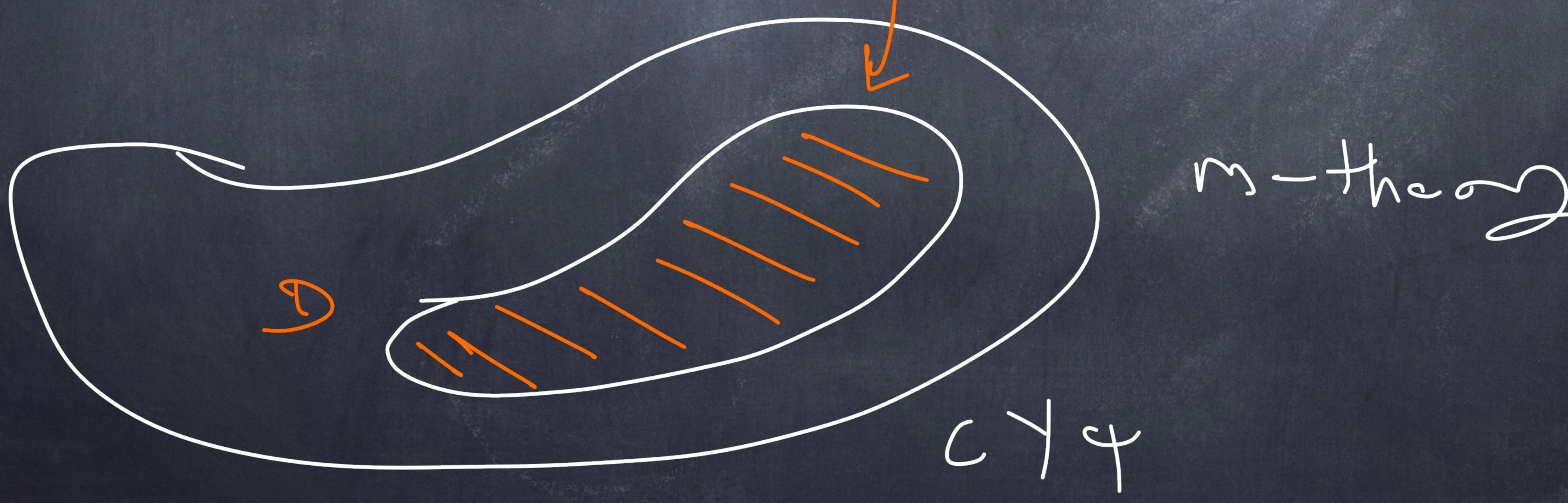
classically zero!

Non-generic solns.

flux-dependent

Euclidean M5

(Witten — fluxless)

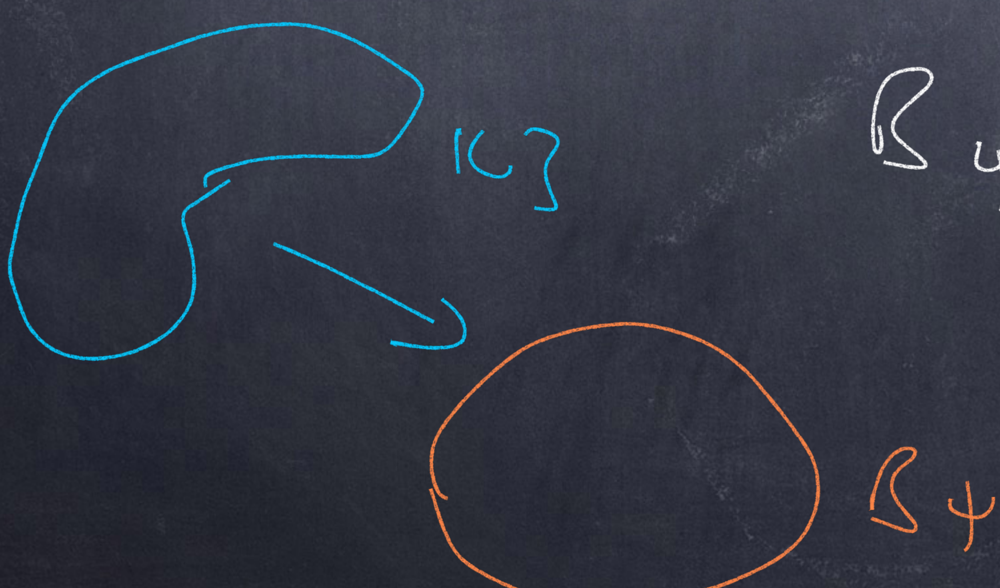


Concretely, three cases look most promising:

(1) CY_4 $\quad h^{1,1} = 1$ (for F-theory $h^{1,1} = 2$)

(2) $K3 \longrightarrow CY_4$ with low $h^{1,1}$

$$\begin{array}{c} CY_4 \\ \downarrow \\ B_4 \end{array}$$



Duality w/ het string.

(3) Models with very large gauge groups — gaugino condensation.

(Acharya, Bobkov, Braun, Kane, ...)

The picture that emerges is a richer race-track model, with likely stabilization in the interior of Kahler moduli space.

I invite you to join me in exploring the issues that need to be addressed in either proving, or providing evidence against a landscape. Some of those issues include:

- Counting Minkowski SUSY flux vacua!
- Understanding gravitational CS on Euclidean branes.
- Transverse flux couplings on branes.
- The brane partition function correctly accounting for flux.
- Determining whether a critical point can be established without detailed knowledge of the Kahler potential.

Additional Slides

Using localization, one can compute the exact tree-level K for type IIA on $\mathcal{M}_8$,

$$e^{-K(t)} = \frac{1}{4!}\kappa_{ijkl}(t^i - \bar{t}^i)(t^j - \bar{t}^j)(t^k - \bar{t}^k)(t^l - \bar{t}^l) + \frac{i}{4\pi^3}\zeta(3)\alpha'^3(t^k - \bar{t}^k)\times$$

$$\int_{\mathcal{M}} J_k \wedge c_3 + O(e^{2\pi i t}),$$

$$\kappa_{ijkl} = \int_{\mathcal{M}} J_i \wedge J_j \wedge J_k \wedge J_l,$$

(Honma, Manabe)
(Halverson, Jockers, Lapan, Morrison)

which has a perturbative correction from the R^4 terms.

This breaks no-scale.