Symmetries in String Theory

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Symmetries in Particle Physics

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During the last three decades, it has been dogma that symmetries are a good thing in particle physics, and they have played a central role in conjectures about physics beyond the Standard Model. Gauge symmetries, discrete symmetries, supersymmetry natural, plausible. Explanations of hierarchy, fermion masses, other possible features of physics beyond the Standard Model.

As we await the LHC, this dogma merits closer scrutiny.

In string theory, we should be able to decide the question: do we expect symmetries to account for unnatural features of the Standard Model, or to arise in its extensions. We know that in critical string theories:

1. There are no global continuous symmetries in string theory, as expected in a theory of gravity (Banks, Dixon).
2. Gauge symmetries arise by several mechanisms.
3. N=1 supersymmetry, warping, technicolor, as conjectured to solve the hierarchy problem, all arise in string theory.
4. Discrete symmetries arise in string theory. Generally can be thought of as discrete gauge symmetries.

But until recently, we had little idea how string theory might be related to the universe about us, so it was not clear what to make of these observations. In what sense are any of these features generic?

The *Landscape* provides a framework in which these questions can be addressed. There is much about the landscape which is controversial. The very existence of such a vast set of metastable states can hardly be viewed as reliably established; the mechanisms for transitions between states, and by which states might be selected are not understood in anything resembling a reliable or systematic scheme.

But for the first time, we have a *model* in which to address a variety of questions. I claim that the easiest questions to study are precisely those associated with naturalness and symmetries. These can be addressed in model landscapes. Today, mainly IIB flux landscape.

An “easy” question: How common are discrete symmetries? We will argue that they are expensive; only a tiny fraction of states exhibit discrete R symmetries (Z_2 may be common). We will ask: can such states be attractors in cosmology?

Harder: it is known (KKLT, Douglas et al) that approximate N=1 susy, warping, pseudomoduli are common features in the landscape. But just how common? Can we just count (already hard)? Cosmology important?

Discrete Symmetries

While continuous symmetries don't arise in critical string theory, discrete symmetries often arise. Many can be thought of as unbroken subgroups of rotations in compactified dimensions; as such, R symmetries. E.g. Z_3 orbifold:

Invariant under $z_i \longrightarrow e^{2\pi i/6} z_i$, for each i

Many Calabi-Yau vacua exhibit intricate discrete symmetries at points in their moduli spaces.

Symmetries in Flux Vacua

Fluxes and fields transform under symmetries. If we are to preserve a symmetry, it is important that we turn on no fluxes that break the symmetry, and that that vev's of fields preserve the symmetry. One can survey, e.g., IIB orientifold theories compactified on Calabi-Yau (KKLT type models).

Result: Discrete Symmetries are Rare

Why a large number of states in landscape:

N^b possible choices of flux(N a typical flux; b the number of fluxes, both large, say N =10, b=300)

In CY spaces, one finds typically at most 1/3 of fluxes invariant, b reduced by 1/3, and

$$10^{300} \rightarrow 10^{100}$$

Simply counting might be too naïve; we'll return to this question.

Possible Explanations for Hierarchy in the Landscape

- **SUSY states: exponentially large numbers; within these, hierarchies in a finite fraction of states – conventional naturalness.**
- **Warping (with or without susy): likely occurs in a finite fraction of states (Douglas et al). So another possible explanation of hierarchies, dual to technicolor.**
- **Simply very, very many states; a tiny fraction – but a large number -- exhibit hierarchies.**

In all cases, anthropic considerations might be relevant.

Branches of the Landscape

Three distinct branches identified in IIB:

1. Non-supersymmetric
2. Supersymmetric with logarithmic distribution of susy breaking scales $P(m_{3/2}) = dm_{3/2}/m_{3/2}$
3. Supersymmetry with approximate R symmetries: $P(m_{3/2}) = dm_{3/2}/m_{3/2}^3$

Perhaps no “rational” (=symmetry) Explanation of Hierarchy

Non-susy states might vastly outnumber susy [or warped, technicolored] states (Douglas; Silverstein). So there might be many, many more states with light Higgs without susy than with. (E.g. anthropic selection for light Higgs?). Perhaps few or no TeV signals; light Higgs most economical. (Even “split susy” an optimistic outcome.)

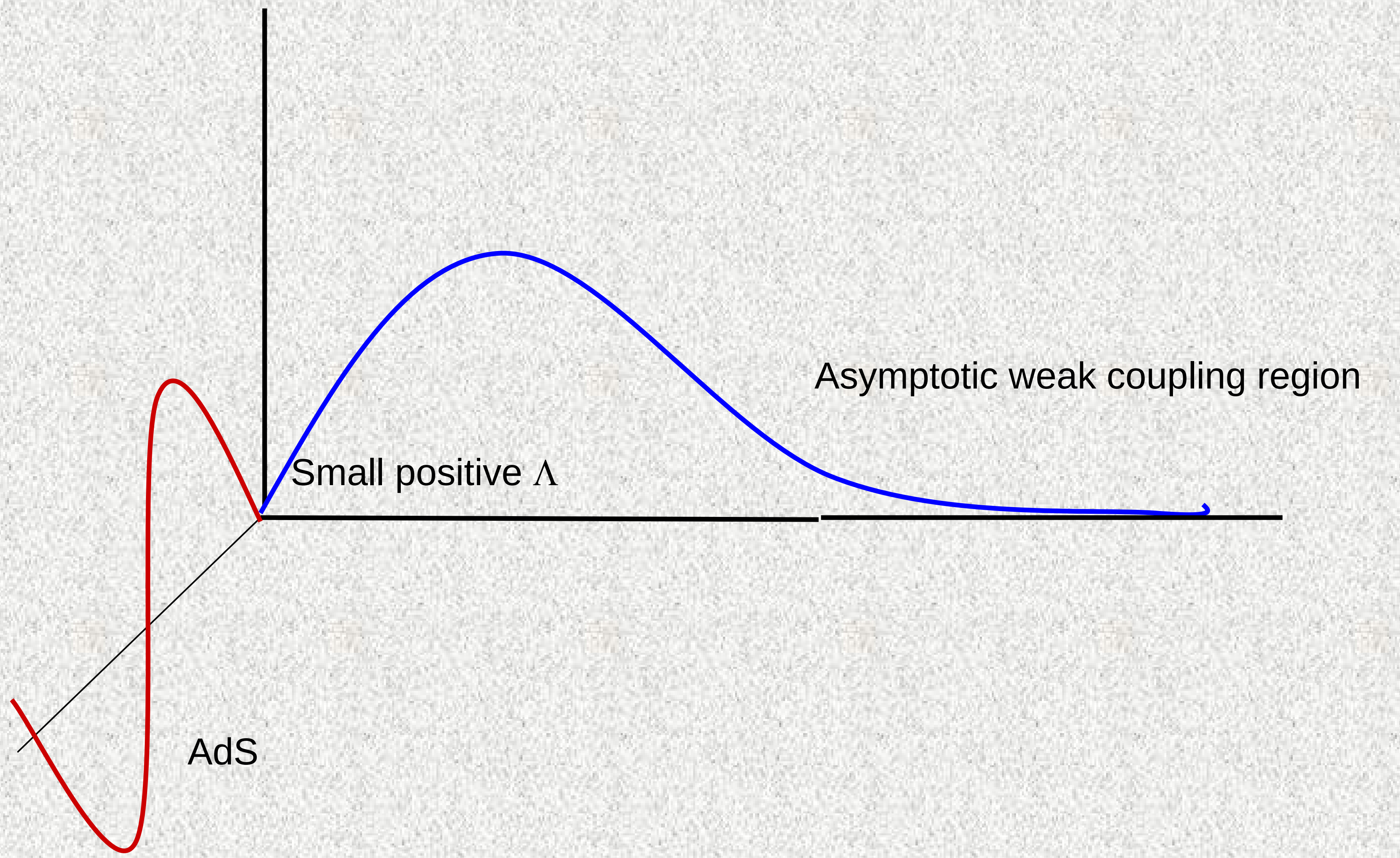
Counting of states, statistics, interesting, but probably naïve to think this is the only consideration (though success of Weinberg argument suggests some level of democracy among states).

Surely, though, it is important to think about cosmology.

A Primitive Cosmological Question: Metastability

A candidate "state" (=stationary point of some effective action), say with small Λ, is surrounded by an exponentially large number of states with negative Λ. (Possibly also many states with positive Λ)

Metastability only if decay rate to *every one of these states* is small. One more anthropic accident? Or insured by some general principle? A ``selection principle"? (or more precisely, a pointer to the types of states which might actually exist?)


Asymptotic weak coupling region
Small positive Λ
AdS

Stability in the Landscape

Naïve landscape picture: large number of possible fluxes (b) taking many different values (N_i, i=1,…, b; N » 10, say, b » 100).

Structure of potential (IIB, semiclassical, large volume):

$$V(z) = N_i\, N_j\, f_{ij}(z_l)$$

Focus on states with small Λ. Many nearby states with negative Λ

$$\Lambda \sim -N$$

Typical Decay Rates (non-susy)

Potential:

$$V(\phi) = \frac{N^2}{V^2} f(\phi).$$

Tension:

$$T = \int^{\Delta\phi} d\phi \sqrt{2V(\phi)} \sim \frac{1}{V} \quad (\Delta\phi \sim 1/N)$$

Splitting:

$$\Delta\Lambda = N/V^2$$

So

$$S_b = V^2/N^3$$

Gravitational corrections:

$$R_b = \frac{T}{\Delta E} \sim V/N$$

For small cosmological constant in the initial state:

$$R_{AdS} = V/\sqrt{N}$$

So gravitational corrections not important.

These naïve scalings of tensions and cosmological constants can be checked in explicit string constructions, e.g. GKP.

Not really a surprise. In general, without small parameters, expect tunneling very rapid. Bousso-Polchinski model gives similar scalings; BP assumed, that in *every* state, there was a small parameter which accounts for metastability. Crucial to much thinking about eternal inflation. Critical for the candidate small cc states which could describe our universe.

In a landscape, this is a strong assumption. For typical choice of fluxes, no small parameter. But since there are many nearby states, it is critically important that all tunneling amplitudes be small. E.g. if

$$\Delta N < 4$$

then 3^b decay channels, all of which must be suppressed (3^{100} ¼ 10^{48}).

Seek classes of states which are metastable.

- Weak (string) coupling by itself not sufficient.
- From our formulas above, we see large volume stable. Not clearly from any existing analysis why a typical (dS) state should have large volume; may single out an important subset.
- No evidence that warping enhances stability
- Supersymmetry? Actually, this is the easy (and well-known) one.

With zero c.c., can define global energy, momentum, and supersymmetry charges. Obey:

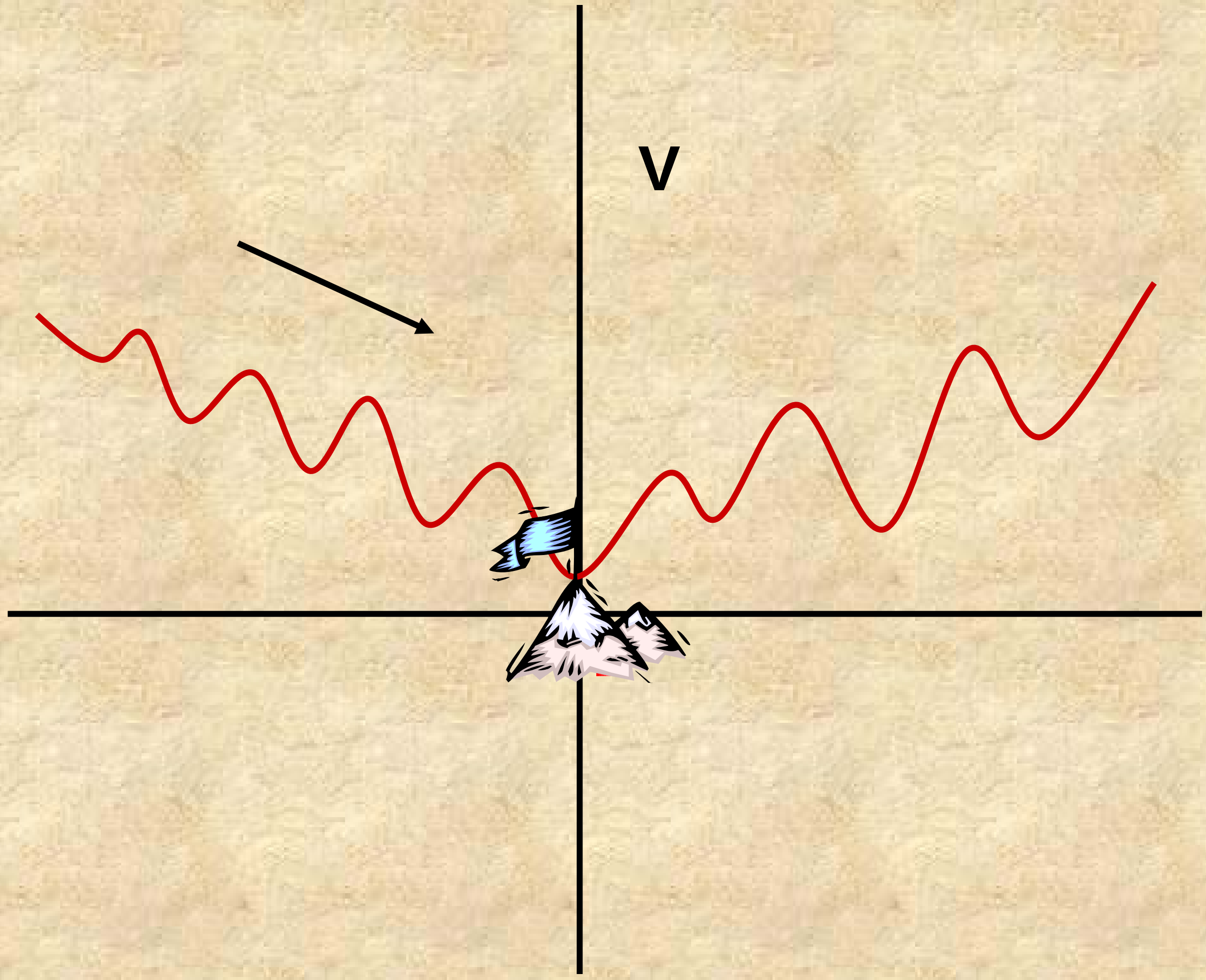
$$\{Q_\alpha, Q_\beta\} = P^\mu (\gamma_\mu)_{\alpha\,\beta}$$

As a consequence, all field configurations have positive energy, so exact supersymmetry in flat space should be stable (note this is true even if potential is negative in some regions of field space). **[Thanks to T. Banks,E. Witten and others]**

Expect that if nearly supersymmetric, nearly flat, decay amplitudes are zero or exponentially small (exp ($-M^4/F^2$)). Can check in many simple examples.

A Path To A Symmetric Universe

- **Non-susy, *metastable* states: perhaps not particularly numerous compared to susy states. Then hierarchy (even with anthropic considerations) might favor “low energy supersymmetry”**
- **KKLT vacua: surrounded by numerous susy, non-susy AdS states. Cosmological evolution *into* such states might be problematic.**
- **Symmetric states (R symmetric states) might be cosmological attractors within a picture of eternal inflation.**



Perhaps R Symmetry points cosmological attractors?

Don't give up on the symmetric points yet!

R Symmetric states as attractors?

R symmetry: vanishing W (classically). Obtain by setting many fluxes to zero. Nearby states: turn on "small" fluxes. Types of flux: N_I (symmetric); n_α (break symmetry), N_I À n_α

Model like Bousso-Polchinski:
$E_0 = q_I^2\, n_I^2$
Then n_I ! 0 in successive tunnelings, and symmetry is restored.

But Bousso-Polchinski does not capture some features of typical landscapes. Energy exhibits more complicated dependence on fluxes. Signs not definite. For example, T_6 orientifold of IIB theory (Kachru, Schulz, Trivedi); fluxes, a, b (we neglect dilaton; seeking a simple model)

$$W = a_0 \det(\tau) + a_1 \mathrm{cof}(\tau) + b_1 \tau + b_0$$

and

$$K = -\log(i \det(\tau - \tau^\dagger))$$

An easy limit to example still has symmetries

$$a_1 = a_1 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad b_1 = b_1 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

At minimum:

$$\tau = ix \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

If one treats x as the only field of the model, then the x potential has the form

$V(x) = 3/x(a_1 b_0 - b_1^2 + x^2 (a_0 b_1 - a_1^2))$. Where the potential is well behaved,

minimum of the x potential lies at

$$x_0^2 = \frac{a_1 b_0 - b_1^2}{a_0 b_1 - a_1^2} \qquad V_0 = \sqrt{(a_1 b_0 - b_1^2)(a_0 b_1 - a_1^2)}$$

Consider the region of fluxes with large a_0, b_0. One might worry about transitions which increase a_1, for example, heading off into the region that the potential is ill behaved. But transitions which decrease a_0, b_0 are faster, I.e. fluxes tend to equalize.

But including off-diagonal elements of \tau, \tau = ix + h, one finds that the h fields are tachyonic, I.e. SU(3) is broken.

As an alternative model, include also ρ (size of internal manifold) and suppose somehow fixed. In this case, behavior of potential is better (no longer unbounded below for range of fluxes) and, for a range of fluxes, h fields have positive curvature at minimum.For a range of fluxes, the elements of the octet are massive.

Now, turning on off-diagonal fluxes,

$a_{ij} = a\,\delta_{ij} + n_{ij}$

Then

$E = E_0 + q_i^2 n_{ij}^2$

(as in BP).

System can be shown to flow in the direction of the symmetric point.

Conclusion: A Rationale for Symmetries

All of our analysis based on toy models for the landscape. But within these one can see that symmetries (supersymmetry, discrete symmetries)

- **Are likely uncommon in the landscape**
- **May well be cosmologically favored. Note the sense in which this is true. Not all initial conditions lead to states exhibiting discrete symmetries, but quite plausibly a non-negligible fraction.**
- **Stability may favor supersymmetric states; may be counterweight to naïve notion that supersymmetry is special, non-generic.**

Status of the Old Dogma

Perhaps we are seeing the beginnings of a picture for how predictions (low energy susy? large compactification volume? Perhaps a pattern of discrete symmetries?) might emerge from string theory.

As another expatriate friend of mine used to say, not everything that we were told growing up was wrong.

Aside on Small Volume

It is tempting not to think about small volume, since few tools, in general. But KKLT analysis illustrates how small volume may arise. Standard story: small W_0, large ρ. Argue distribution of W_0 is uniform at small W_0. But if W_0 large, expect susy minima at small ρ, with a uniform distribution of <W>. So expect that, while can't calculate, many states with large AdS radius, small compactification volume (Kachru).

Large Compactification Volume, Weak Coupling

These results confirm our earlier estimates. Large volume does lead to suppression of decay amplitudes.

$$S_b \gg V^2/N^3$$

Even for weak coupling, however, there are decay channels with no suppression by powers of τ. So to obtain large number of stable, large volume states, need $V \gg N^{3/2}$.

In IIB case, little control over volume (except KKLT: approximate susy, large volume). Can model this with IIA theories (but AdS), Silverstein's constructions. These suggest that there might be many metastable large volume, dS states.

Warping

No evidence that warping enhances stability. We did not see any growth of tensions with z^{-1} in GKP analysis. More generally, if a collapsing cycle, as in Giddings, Kachru, Polchinski, then can change fluxes on cycles which are "far away" with little effect on the warping; earlier estimates seem to apply.

Quintic in CP^4

In CP^4:

$$P = z_1^5 + z_2^5 + z_3^5 + z_4^5 + z_5^5 = 0$$

Symmetries:

- $Z_5^4 : z_1 \to \alpha z_1, \quad \alpha = e^{2\pi i/5}$, etc.
- S_5: permutations of z_i.

These are R symmetries, e.g. $W \to \alpha W$. Light fields (moduli): associated with deformations of P, e.g.

$$\phi \leftrightarrow z_1^3 z_2^2$$

under R: $\phi \to \alpha^3 \phi$.

Branches of the landscape

1. Non-susy: hard to explore this branch. No systematic approximation. Most states at high susy breaking,

$$\frac{dN}{dF} \propto \Lambda F^5$$

2. Susy, $W \neq 0$: for fixed, small Λ, logarithmic of susy breaking scales expected.

$$\frac{dN}{dF} \propto \frac{\Lambda}{F}$$

Consistent with conventional notions of naturalness.

3. Susy, $W = 0$: pileup of states at small susy breaking scale (low energy gauge mediation?)

$$\frac{dN}{dF} \propto \frac{\Lambda}{F^2}.$$

(Terminology refers to classical analysis; real distinction is in statistics).

Supersymmetry in the IIB Landscape

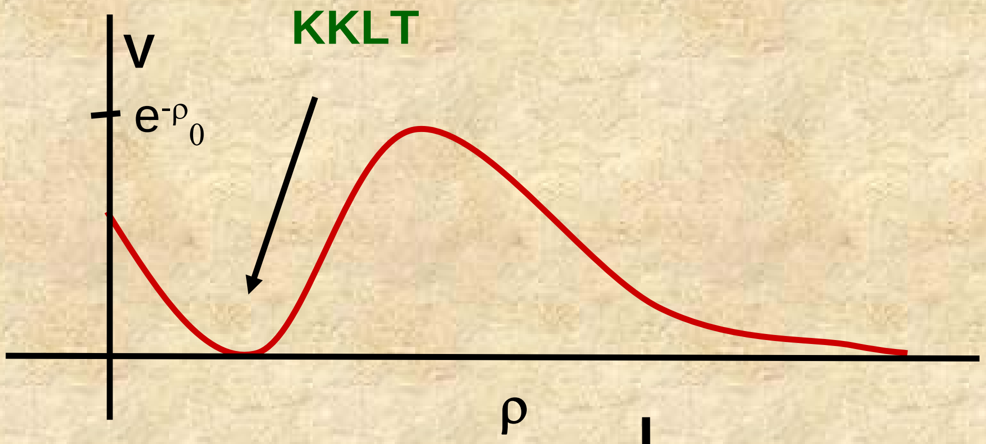
- **IIB landscape as a model; suspect some observations below generic.**
- **Possesses an exponentially large set of flux states with N=1 supersymmetry (KKLT, Douglas et al).**
- **A large, possibly infinite set of non-supersymmetric states. Douglas, Denef count by introducing a cutoff on the scale of susy breaking (more on rationale later). Most states near cutoff.**

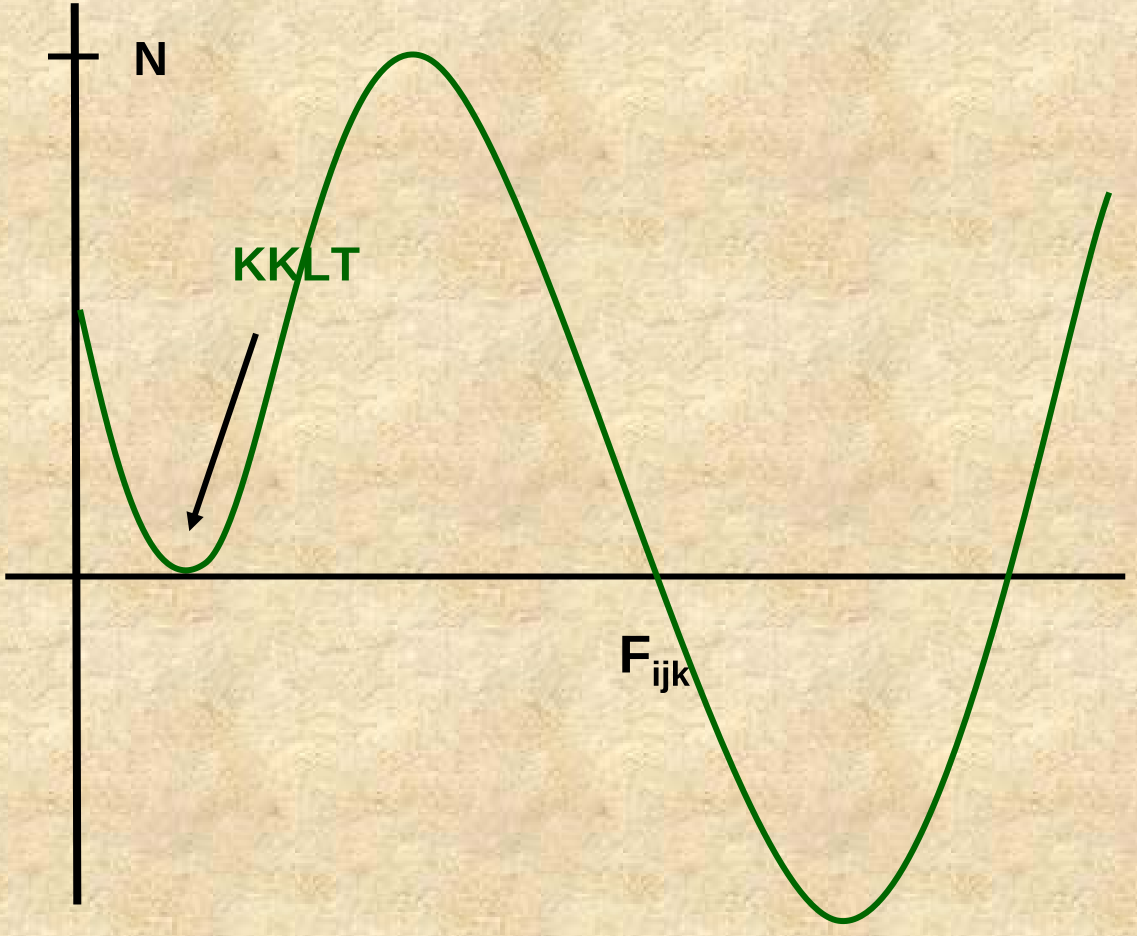
Remark: Tempting to believe that non-susy states, I.e. non-susy stationary points of some effective action, are more typical than susy, which seems special. On more thought, might be true, but not obvious. E.g. not true of renormalizable susy models. Not clear if true if IIB on Calabi-Yau. Real non-susy constuctions limited, hard to draw a general conclusion.

Known classes of states in the landscape:

1. N=1 supersymmetric
2. Weak string coupling
3. Large volume
4. Warping
5. Pseudomoduli

I'll report some preliminary investigations of the (meta)stability of these classes of states.





KKLT as example,
But general

Much of what I will say is tentative. Most work on the landscape has involved supersymmetric or nearly supersymmetric states (also non-susy AdS); features of dS, non-susy states [Douglas, Silverstein] less throughly studied, but it is precisely these states which are at issue. I will also indulge in a conjecture: certain symmetric states might be cosmological attractors. Hard to establish, but I think plausible, and again relatively simple within the space of ideas about string cosmology.