Is There a String Theory Landscape?

Some Cautionary Remarks

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The Vacua of String Theory

Too many vacua(?) No ``selection principle”.

Two broad categories:

1) More than four susy’s: no potential for moduli, perfectly well behaved non-pert.
2) Four or less: potentials for moduli, tadpoles (perturbative or non-perturbative).

Why don't we live in a universe with more than four susys? -- probably nothing wrong with these vacua. Some very mild anthropic considerations might rule out (no conventional stars? no inflation? No structure?)

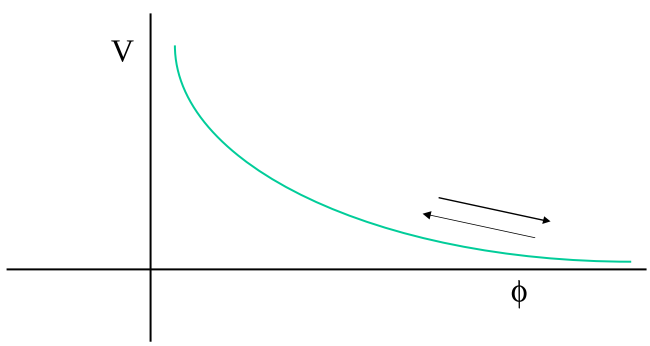
N=0 theories? [=no susy except in limits with 1 nos. of susies]

- One loop tadpoles (so what!)
- Tachyons in parts of moduli space (so what!)
- Witten's decay to nothing (Witten; Fabinger, Horava; Fox, Gorbatov, M.D)

  -- perhaps an indication, but not decisive.

Maybe, eventually, some undesirable features, inconsistencies.

More generally, we don't know how to make sense of any string solution with four or less supersymmetries.



Singularity in past or future. We do not know how to treat such a problem (Banks,M.D.)

The Dreaded Anthropic Principle

Linde probably the first to realize that inflation leads to a framework in which one might sensibly implement the anthropic principle. Perhaps in a very vast universe, the fundamental parameters take different values in different regions.

But is such a possibility implemented in any fundamental theory? If not, don't worry (Don't Give Up). If so, can one rule out or make predictions?

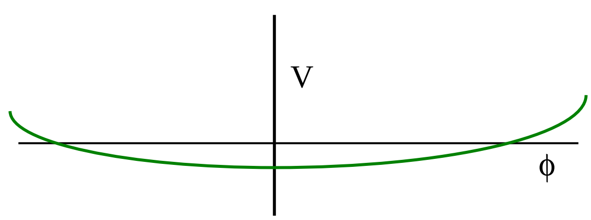
Two simple ideas:

1) Extremely light scalar (Banks)

2) Discretuum (Bousso, Polchinski; Banks, Dine, Seiberg)

Can't Assess These ideas Without Some Sort of Fundamental Framework, Like String Theory.

``Continuum" (very light scalar)



Require $m_\phi << H_o$; $\Delta\phi >> M_p$

Does this happen in string theory?

Answer appears to be no*

1) Ordinary scalars in string theory – masses consistent with dimensional analysis
2) Periodic scalars (axions): Might be candidates, if decay constants >>M_p. But searches in string/M theory yield no candidates (Banks, Fox, Gorbatov, M.D.) [Also would be of interest as candidate inflatons – Arkani-Hamed, Randall, Cheng Creminelli).]

Not a theorem, but it seems unlikely that this sort of implementation of the anthropic principle is realized in string/M theory.

*Dimopoulos, Thomas: perhaps a CFT, with enhanced Z? Need a theory with huge Z; need to make sure light dynamics don't spoil.

Discretuum?

Proposal of Banks, Dine and Seiberg: ``Irrational Axion". No examples in string theory.

Bousso and Polchinski: discretuum from possible quantized fluxes. But many questions, particularly about stabilization of moduli.

KKLT (following Giddings, Kachru, Polchinski, others): proposed a string theory realization of the discretuum. Potentially vast numbers of states. If true, ``anthropics" might not be optional, but inevitable.

The Flux Discretuum (KKLT)

Consider various compactions of string theory (IIB on CY, X, for definiteness). Many possible quantized fluxes,

F_{IJK}, H_{IJK}

b_3 possible fluxes, where b_3 can be of order 100's. Fluxes not highly constrained. Tadpole cancellation conditions:

$$\chi(X)/24 = N_{D3} + ½\, \kappa_{10}^2\, T_3\, \mathrm{s}_M\, H_3\, Æ\, F_3$$

By itself one condition on many fluxes (but more later). Plausibly 10^{100}'s of such states (see Douglas's talk)).

So far, similar to BP. But now a proposal to stabilize moduli.

Presence of Fluxes Tends to Stabilize Moduli

E.g. GKP: Type II Orientifold of CY near conifold pt. z: distance from point. Fluxes on collapsing three cycles. Both stabilization and warping.

$$W = (2\pi)^3 \alpha' (M\mathcal{G}(z) - K\tau z) \qquad (1)$$

where M, K: fluxes.

$$\mathcal{G}(z) = \frac{z}{2\pi i} \ln(z) + \text{ holomorphic.} \qquad (2)$$

This has a supersymmetric minimum where

$$D_z W = \frac{\partial W}{\partial z} + \frac{\partial K}{\partial z} W = 0 \qquad (3)$$

Solved by:

$$z \sim exp(-\frac{2\pi K}{M g_s}) \qquad (4)$$

If the ratio N/M is large, then z is very small. The corresponding space can be shown to be highly warped.

$$W_o = < W > \qquad (5)$$

exponentially small.

1

Including additional fluxes, it is possible to fix other complex structure moduli, including τ.

$$W = (2\pi)^3\alpha'[M\mathcal{G}(z) - \tau(Kz + K'f(z))] \qquad (6)$$

$$D_\tau W = \frac{\partial W}{\partial \tau} + \frac{\partial K}{\partial \tau}W = 0$$

for

$$\bar{\tau} = \frac{M\mathcal{G}(0)}{K'f(0)} \qquad W = 2(2\pi)^3\alpha' M\mathcal{G}(0)$$

z is still exponentially small, and the space is highly warped, but W_o is no longer exponentially small.

In the limit that R is very large, there is no potential for R; the compactification radius is not fixed.

Fixing the Remaining Moduli?

KKLT: In flux vacua, W_o generically large (of order some typical flux integer), but among the vast number of possible fluxes, W_o will sometimes be small. Other effects will generate a superpotential for $\rho = R^4 + i\, b$

$$W = W_o + e^{-\rho/c}$$

This has a supersymmetric minimum, with

$$\rho \gg -\ln(W_o)$$

In the great majority of states, this is small, but in some subset will be large; this is required for self-consistency of the analysis.

If there is a systematic approximation, it consists of integrating out the KK modes, then the complex structure and dilaton, then the radial mode. Consistency requires a hierarchy of masses:

$M_{kk}^2 = 1/R^2 >> M_{\tau,z}^2$ ¼ $N^2/R^3 >> m_\rho^2$ ¼ W_o^2/R^2

This is turn requires that R (ρ) is large, and that W_o is exponentially small,

W_o ¼ $\exp(-N^2)$

i.e. only in a tiny fraction of states, at best, is a self-consistent analysis possible.

This suggests reasons for caution about the existence of the discretuum. At best, only a tiny fraction of states can be self-consistently analyzed. Douglas will discuss the problem of counting in a more sophisticated way, but follow KKLT to make a crude estimate. Recall that if all fluxes are similar, from tadpole cancellation condition,

$$|\vec{N}|^2 \approx \frac{\chi}{24} \quad (7)$$

From our discussion of masses, we see that in order to have a controlled approximation, no one flux can become very large.

So the number of states is roughly

$$(\chi/24)^{\frac{b_3}{2}} \quad (8)$$

For many CYs, $b_3 >> \frac{\chi}{24}$, so

$exp(-N^2) << $ number of states. So everything may be consistent.

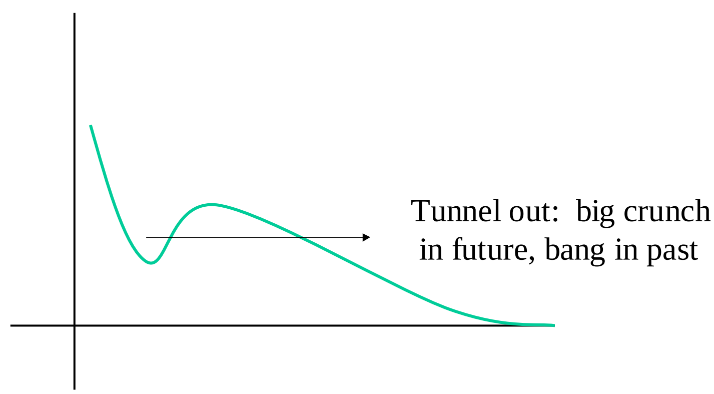
Further reasons for caution:

- Our estimates of masses are crude. Some masses might be larger. For example, in the Gukov-Witten superpotential, the dilaton appears linearly and couples to most or all moduli. Also, the dilaton mass is enhanced by powers of $1/g$. Thus its mass might be expected to be of order

$$(\frac{m_\tau}{m_{kk}})^2 \approx \frac{N^2}{\rho} \times \text{ possibly } [(1/g)^3, b_3, f(z)] \qquad (9)$$

  So there might be no states which can be analyzed self-consistently. These results are very crude. The question of self-consistency is worthy of further investigation.

- Banks: Solutions of a low energy effective theory don't necessarily correspond to an underlying quantum gravity theory. In this context:



For now, assume discretuum exists, universe samples all of these states in cosmic history.

SUSY BREAKING?

1) KKLT: anti D3-branes: can give exponentially small effects in warped geometry.
2) (Easier to think about) Low Energy (Dynamical) Supersymmetry Breaking: presumably occurs in some fraction of this vast array of states. Then

$$V ¼ \exp(-8\pi^2/b_o g^2)$$

If g^{-2} distributed more or less uniformly, V roughly uniform on log scale.

Cosmological constant: $V ¼ [\exp(-8 \pi^2/b_o g^2)-3|W_o|^2]$

ANTHROPICS

Many, many states.

Low energy physics varies:
•Gauge groups
•Matter content
•Values of parameters

Perhaps universe samples all of these states.
Only observers in a subset with suitable properties.

Most compelling application: Cosmological Constant (Banks, Weinberg, Linde, Vilenkin)

Λ: if all else fixed, suitable structure (galaxies, etc.) only if $\Lambda < 10$ x observed value

[But (Aguirre): much broader range if allow other cosmological parameters to vary – see also Dimopoulos's talk]

Note: if SUSY Breaking Scale as small as 10^3 GeV, this already requires $\gg 10^{60}$ states.

Before considering other parameters, might the flux discretuum predict low energy susy?

Suppose anthropic argument for Λ. Probability of small Λ without susy?

$$P(\Lambda) \approx \frac{\Lambda}{M_p^4}.$$

Small Λ with SUSY? $\rightarrow$ small W_o.

$$P(W_o) \approx \frac{W_o}{M_p^3}.$$

Potentially Many More Vacua with Small Λ

But typically small W_o, small Λ implies small susy breaking.

What might we expect for the distribution of states with different amounts of susy breaking?

$$P(W_o) \approx \frac{W_o}{M_p^3} \tag{10}$$

(probability $< W > \quad \leq W_o$)

[See Douglas's talk; crudely, think of

$$W_o = \sum a_i N_i \approx |\vec{N}||\vec{a}| \cos(\theta) \approx |\vec{N}||\vec{a}|(\pi/2 - \theta)] \tag{11}$$

Suppose $\frac{8\pi^2}{g^2}$ roughly uniformly distributed. Then, e.g., if $W_o = 10^{-28}$ (susy breaking $\sim 10^4$ GeV), in about 10^{-3} of states,

$$V_o = e^{-\frac{8\pi^2}{bg^2}} - 3|W_o|^2 < |W_o|^2$$

Need more anthropic input:

M_w/M_p? (e.g. from stars?)

[Need also for non-susy!]

An estimate of fraction of suitable states:

- 10^{-10} have suitable susy breaking
- 10^{-2} have susy breaking comparable to W_o
- 10^{-13} have suitable W_o
- 10^{-60} of these have small Λ

10^{-85} vs. 10^{-120} x 10^{-32} for non-susy.

So SUSY wins unless there are an overwhelmingly large number of non-susy states.

Note that this picture favors susy breaking at the lowest possible scale (gauge mediation?)

So real possibility of an anthropic prediction. But before getting too excited, there are other issues to face in the flux discretuum.

ANTHROPIC PITFALLS

Need to explain:

- Gauge Group
- Particle Content
- Couplings

Organize in order of increasing scale, using the language of effective actions and the renormalization group.

- Unbroken U(1)? -- Plausibly Anthropic
- SU(3)? -- if can vary m_u, m_d, can probably reproduce many features of nuclear physics with other groups. Deuterium?
- m_e/Λ_{qcd}? -- Molecular physics?
- M_u, $m_{\underline{d}}$: proton stability, details of nuclear physics?

But at higher energies, more problematic to predict couplings:

- $m_{\underline{s}},m_{\underline{c}},m_{\underline{b}},V_{\underline{km}}$?
- $\theta_{\underline{qcd}}$?

No clear anthropic argument for these. If random variables, will get **wrong**!

Still higher energies:

- SU(2) x U(1)??
- Proton decay (if susy)?
- Dark Matter?
- Cosmological parameters (inflationary fluctuations, no. of e-foldings?

All of these quantites will require some rational explanation. But within the flux discretuum, it is not obvious what this might be. E.g. proton decay (anthropically, $>10^{16}$ years) might be explained by symmetries. But most states of the flux discretuum don't have symmetries. θ_{qcd} through axions? But then it is important not to fix all of the moduli.

Symmetries:

T^6/Z_2 orientifold (Trivedi et al):

At some points in moduli space has Z_2^5 x S_6 symmetry.

But half of all fluxes must vanish to preserve even one Z_2

(in discretuum, 10^{200} ! 10^{100}?)

Conceivably still enough states, and discrete symmetries required by anthropic reasoning, but…

CONCLUSIONS

- Flux Vacua: not implausible, but hardly established. Both fundamental conceptual difficulties, as well as more technical ones.
- Anthropics: anthropic constraints probably not enough to fix all of the couplings that vary in the flux discretuum to their observed values. Rational explanations are required, and not immediately apparent. Still, the prediction of low energy susy is intriguing.

As for ``giving up”, if the flux discretuum is established, we will have no choice but to face these issues.

But perhaps there is some alternative viewpoint or set of principles. The fact that we really don’t understand any interesting, i.e. non-susy state of string theory, perhaps holds out some hope.