Some Approaches to String Phenomenology

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Strings 03

Outline

I. What might we like to predict?

II. The discretuum: • are there things it might predict?
• Some cautionary notes

III. Possible problems with non-susy states
• Discrete anomalies?
• Decay to "nothing"

II. String theory and its implications for Beyond the Standard Model Physics
• Patterns of supersymmetry breaking
• $f_A >> M_p$?
⋮

For many years, I have gotten up at String conferences, & said that in light of problem of string vacua, we should think about generic questions.

E.g.

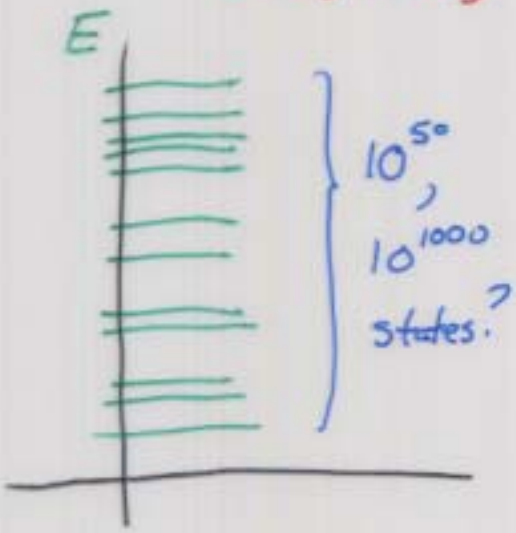
- Low energy SUSY: a prediction of string theory?
- Patterns of SUSY Breaking?
- Axions and Strong CP?
- Cosmology

But the notion "generic" was always somewhat vague.

Now possibility of a discretuum has sharpened the question

(Bousso, Polchinski; Kachru, Kallosh, Linde, Trivedi)

Vacua with fluxes



Douglas: suggests we study an ensemble of states

$\rho(\lambda_i)$

Perhaps predictions: most dense set of states consistent with some (anthropic?) criteria.

Eg Banks, Weinberg, Vilenkin, Linde, ...

Galaxy formation: only states with

Λ comparable to observed value satisfy the modest anthropic criterion that structure forms.

Could this lead to prediction of low energy SUSY?

Maybe.

KKLT: $W = \exp(-N_i/M_j)$ } small Scale of SUSY Breaking

Suppose: $\max\left(\frac{N}{M}\right) = n_{max}$

Suppose: 10^{1000} states

Suppose: 10^{-6} of states have $\frac{N}{M} = n_{max}$

Then in 10^{-6} of states, typical splitting in discretuum is of order

$$10^{-1000}\, e^{-2n_{max}}$$ [typical energy $\sim |W|^2$]

If $n \gg 6$, most states with acceptable Λ will be supersymmetric, with

$$M_{susy} \simeq e^{-n_{max}}$$

[Really need to study distributions, but this single example illustrates main idea]

If, e.g., $n_{max} = 40$,

might explain observed hierarchy.
[conventional low energy susy]

If $n_{max} \ll 40$, might have susy scale $\gg m_W, m_Z$

Still need anthropic (?) explanation of weak scale.

Cautionary Notes

If we are convinced there is a discretuum we will have to face many issues:

(i) Weinberg/Vilenkin analysis assumes only Λ varies. But what about $\delta\rho/\rho$, Ω_0, etc.? Eg If $\left(\frac{\delta\rho}{\rho}\right)$ larger, structure forms earlier, Λ can be (much) larger.

$$\Lambda \gtrsim \left(\frac{\delta\rho}{\rho}\right)^3 \Lambda_0$$

[

(ii) Other features of inflation [Kachru] [Banks]

(iii) Parameters of SM: should either be anthropic or random.

$m_u < m_d \ll \Lambda_{QCD}$: perhaps anthropic

But $m_s, m_b, m_c \ll m_W$?

$V_{ss'}$ off-diagonal $\ll 1$

Why?

Perhaps flavor symmetries [i.e. some rational explanation required].

Note: typical flux vacua break all symmetries.

(iv) Strong CP

If all moduli fixed above SUSY scale, no axions.

So perhaps not all fixed, or no SUSY or no axion.

If no axion, solns?

Generic fluxes break CP, hard to see why small [gauge mediation helps]

⋮

Could supersymmetry emerge from other considerations?

E.g. could it be that non-SUSY states are in some way diseased?

[Non-SUSY = no region of classical moduli space with only 1 gravitino]

Possibilities:

(i) typically tachyons somewhere in moduli space

(ii) Already potentials at one loop for moduli

But perhaps:

Not clear qualitatively different from $N=1$ SUSY case. [e.g. non-SUSY discretuum?]

(iii) Anomalies in discrete symmetries

Instantons: violation of discrete symmetries might signal anomaly

Extensive searches (asymm. orbifolds, others) no examples (Dine, Graesser)

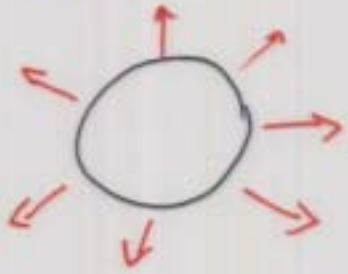
(iv) Catastrophic Vacuum Decay?

Witten: $M^4 \times S^1$

$$ds^2 = \frac{dr^2}{(1-R^2/r^2)} + r^2 d\Omega^2 + (1-R^2/r^2)\,d\phi^2$$

A finite action, Euclidean configuration.

Describes process:



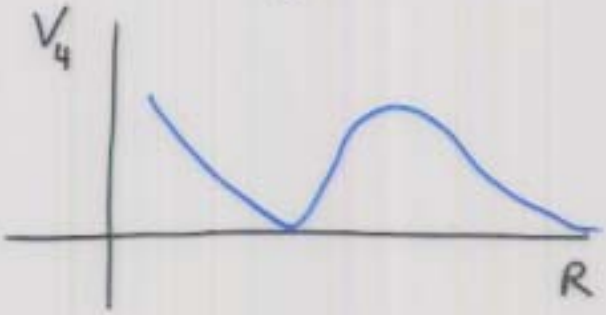
Non-singular. From perspective of 4-D observer, space-time ends at bubble wall.

Solution only exists in non-supersymmetric case.

Generic? [Fabinger-Horava] [M.D., E. Gorbatov, P. Fox, in progress] [Harvey]

Consequences?

If has something to do with real world,



Is there still such a solution?

Yes. [M.D., E. Gorbatov, P. Fox]

Rewrite Witten's soln. as a 4-D soln:

$$ds^2 = \frac{dr^2}{\sqrt{1 - R_0^2/r^2}} + r^2 \sqrt{1 - R_0^2/r^2}\, d\Omega^2$$

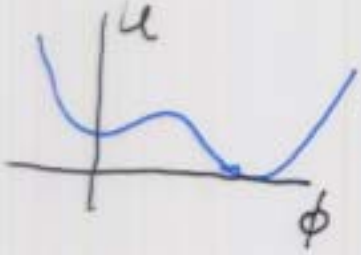
$$R^2(r) = \left(1 - R_0^2/r^2\right) R_0^2$$

Soln. of 4-D equations with a peculiar b.d'y condition as $r \to 1$.

Can find well-behaved solns. with $V_4(R)$ with these b.c.

Usual Coleman-DeLuccia Story

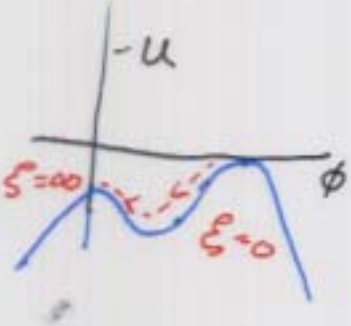
$$\mathcal{L} = \frac{1}{4}(\partial\phi)^2 - V(\phi)$$



$$ds^2 = (d\xi)^2 + \rho(\xi)\, d\Omega^2$$

$$\phi'' + \frac{3\rho'}{\rho}\phi' = \frac{dU}{d\phi}$$

$$\rho'^2 = 1 + \frac{1}{3}K\rho^2\left(\tfrac{1}{2}\phi'^2 - U\right)$$



$$\frac{d\xi}{d\rho} = \sqrt{1 - R^2/\rho^2}$$

$r \to 1$: $\quad r = 1 + \left(\frac{3}{4}R^2\right)^{4/3}$

$$\rho = (r-1)^{1/4} \qquad \phi = \sqrt{3}\ln(r-1)$$

Require this behavior as $r \to 1$ $(\xi \to 0)$.

For model potentials, generally find solutions.

So even with stabilized radius, vacuum is unstable

Questions

(i) Generic?

(ii) Implications?

$\Gamma >>$ age of universe OK?

Or is there a fundamental problem?

Tests of Beyond the Standard Model Speculations

(1) SUSY Breaking

- Gravity mediation – In some limits
- Gauge mediation – might emerge, esp. if all moduli fixed as in flux models
- Anomaly mediation – Not generic (Anisimov, Graesser, Thomas, M.D.)

(2) Pseudoscalars (axions) with

$f_A >> M_P$

Interesting for

- Inflation ("Natural inflation")
- Cosmological constant problem

"Natural inflation"

$$\mathcal{L} = f_a^2 (\partial_\mu \theta)^2 + V(\cos\theta)$$

Inflates if $f_a >> M_p$. Reasonable?

Arkani-Hamed, Randall, Cheng, Creminelli:

Higher dimensional theory with Wilson line: $e^{i\int A_5 dx^5}$ $\quad x^5 = x^5 + 2\pi R$

$$A_5 \to A_5 + 1/R \qquad A = \theta/2\pi R$$

$$\mathcal{L} = g_5^{-2} R (\partial A)^2 + \tilde{V}(A)$$

$$= \frac{1}{R^2}(\partial\theta)^2 + V(A) \qquad \text{[Weyl rescaling]}$$

$$f_A^2 = 1/R^2 \to \infty \text{ as } R \to 0$$

But (as they note) $R \to 0$ T-dual to $R \to \infty$ (small f_A) in some string theories

What's going on (e.g heterotic string on torus)

(a) exact T-duality, maps $A \to A'$.

A' has exact periodicity, $f_a \propto R$.

(b) As $R \to 0$, light states (windings)

In terms of original variables,

$$k_{LS} = \frac{n}{R} + \frac{wR}{\alpha'} - q^I A_S^I - \frac{wR}{2} A_S^I A_S^I$$

$1/R$ periodicity manifest.

Small R: approx. R/α' periodicity.

So

$$V = \sum_n a_n \cos(n A_S R)$$

converges slowly; $n \sim 1/R^2\alpha'$ for small R.

So rapid variation; effective $f_A \sim R$.

String theory is replete with periodic moduli.

Survey other possibilities, where T-duality not present:

- Type II near conifold singularity $(S_2 \times S_3)$

$$\Theta = M_s^3 \int_{S_3} C_{IJK}\, d\Sigma^{IJK}$$

has unit periodicity

$$f_A^2/M_p^2 = g^2 \frac{1}{(M_s^3 V_{S_3})^2}$$

But

(1) Light states as $V_{S_3} \to 0$ (wrapped D4 branes

(2) D2 instantons: $S_0 = V_{S_3}/g \to 0$ as $f_A \to \infty$

$e^{-nS_0}\cos(n\theta)$

Instanton series only terminate for $n \sim f_A/M_p$;

$\cos(f_A/M_p\,\theta) \to f_A^{eff} \sim M_p$.

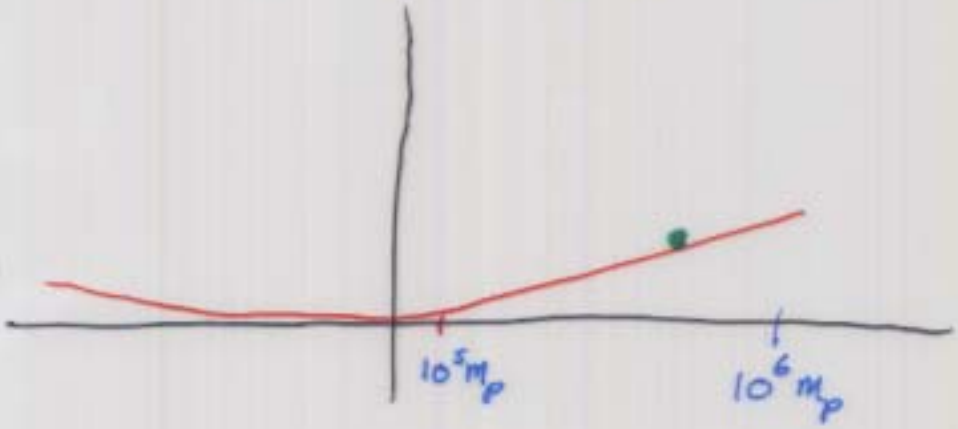
Similarly, Type I, IIA at conifold: similar behaviors.

But no theorem. No precise statement

$$f_A \lesssim M_P$$

↖ ?

These results lead us back to our starting point. Apart from discretuum, another proposed realization of anthropic principle: very light scalar (Banks, Vilenkin, ..)



Nearly frozen today, $m << H$

but $m^2\phi^2 \sim |\Lambda_0|$ (10^{12}, 10^{44}?...)

So far, no examples of such fields in string theory. Probably not there.

Can we find or rule out?

Conclusions

As much as many of us may be allergic to the anthropic principle, we may be forced to confront it. A serious scientific issue

Two ideas to implement:

a) extremely light [flat] scalar

b) Discretuum

Good news: we can [more or less] rule out (a).

b? [See Douglas' talk]

If not, many issues. But perhaps predictions of SUSY, form of SUSY breaking; rational explanations of

- flavor
- strong CP

probably required.