Moduli, Supersymmetry, and Cosmology

M. Dine

SUSY 2K

I. Cosmology, the cosmological constant
and the anthropic principal

II. Is low energy supersymmetry
a prediction of string theory?

III. Moduli and their
cosmological problems

Really understanding the problems of vacuum selection and moduli in string theory will require understanding the cosmological constant.

Now: data $\Omega_\Lambda \cong 0.7$ [?]

New ideas:

(1) Holography [somehow]
(2) Brane World [Somehow]
(3) Saltatory [Wilczek et al, after Brown and Teitelboim; Abbott

Data is uncomfortably suggestive of an anthropic explanation.

Weinberg:

A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you're against it, some people will think you're a little too interested.

(3)

A plausible anthropic explanation requires: (1) a vast no. of metastable states with different values of Λ; $\Delta\Lambda << \Lambda_{obs}$

(2) An explanation why we can only exist for $\Lambda \lesssim \Lambda_{obs.}$

Weinberg: galaxy formation.

$\Lambda \lesssim 100\, \Lambda_{obs}$

Villenkin:

$\Lambda \lesssim 10\, \Lambda_{obs}$

(1) Possible in string theory?
No reliable demonstration of a single metastable state [Non-SUSY]

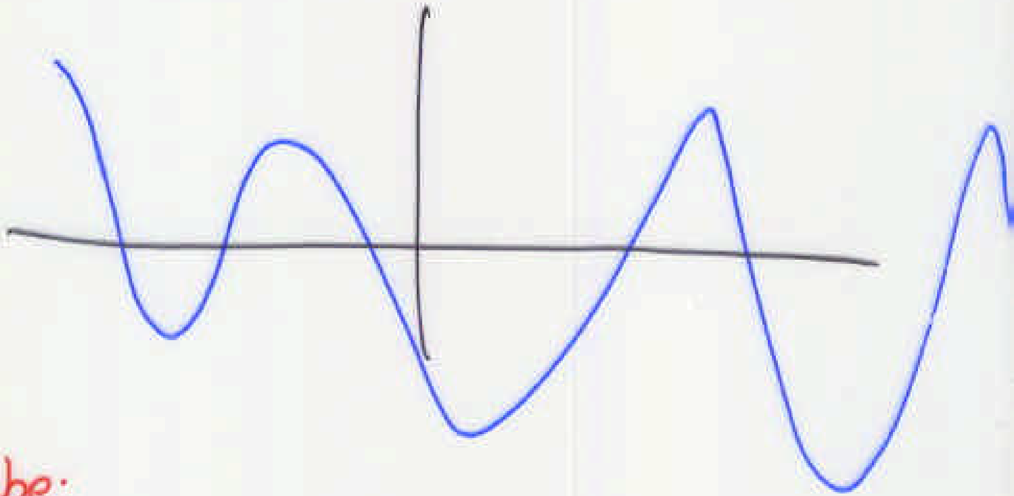
Proposals:

"Irrational axion"

$$V = \mu_1^4 \cos(a/f_1) + \mu_2^4 \cos(a/f_2) + V_0$$

T. Banks, (N. Seiberg, M.D.)

f_1/f_2 : irrational; $\mu_1 \sim \mu_2 > V_0$



Easy to describe;
No known string examples. At best, several groups, f_i/f_j large primes.

More promising: 4-form flux (Bousso - Polchinski Donoghue)

Quantized: $F^{[i]}_{\mu\nu\rho\sigma} = q^{(i)} n^{(i)} \epsilon_{\mu\nu\rho\sigma}$

[Dirac-Teitelboim; one for each 3-cycle]

$E = \sum n_i^2 q^{(i)2} - \Lambda_0$

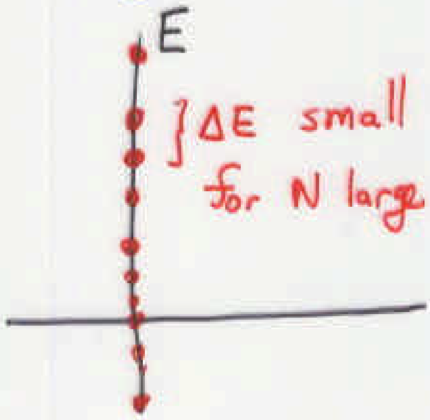
If ~ 120 fluxes, and energy spacing $\sim \frac{1}{30} M_p$, dense set of states with splittings $\ll \Lambda_{obs}$

(no. of states : $\int_{n_i}^{n_i + \Delta n_i} dn\, n^{N-1}\, \Omega_N$)

Examining quantization conditions,

$q_i^{1/2} \sim \frac{1}{R^{1/2}}$ (say)

so small q_i from Large R.



In this framework, anthropic explanation of all quantities inevitable.

(Banks, Moore, Motl, M.D)

E.g.

$$F_{\mu\nu\rho\sigma}^{2}\,|H|^2 \Rightarrow m_H^2$$

$$F_{\mu\nu\rho\sigma}^{2}\,F_{\mu\nu}^{(i)\,2} \Rightarrow g_{(i)}^{-2} \quad \text{etc.}$$

No empty universe problem as in Abbot:

E.g. in last jump, big shift in minimum of inflaton field ($F^2 I^2$ terms in V)

More appealing: very large dimensions.

Topological charges responsible for stabilizing large dimensions

(as in Arkani-Hamed, Dimopoulos, Dvali, March Russell

Cancellation of cosmo. const. requires $d=2$, bulk SUSY

S.M. parameters not very sensitive to fluxes. Main difficulty: empty universe. Solvable?

Still, a potentially natural, plausible use of anthropic principle.

In conclusions, a much more restrained role conjectured for anthropic principle.

Supersymmetry and String Theory?

Is supersymmetry [softly broken $N=1$] a prediction of string theory?

Last two years: plausible alternative solutions to hierarchy problem.

The more supersymmetry, the more we know: [e.g. that vacua exist]

(a) $N \geq 1$ in $D \geq 5$
(b) $N \geq 2$ in $D = 4$

} Exact moduli spaces exist non-perturbatively [Support from dualities]

(c) $N = 1$ in $D = 4$?

- Exact moduli spaces exist. Dualities, etc.
- Generically, approximate moduli spaces. Dual descriptions agree where appropriate ⇒ Exist

Exact moduli: guaranteed, in some cases, by discrete symmetries, trivial in dynamics. Can often study dual descriptions.

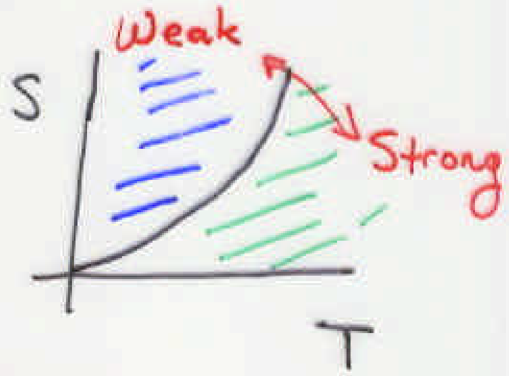
Approximate moduli: generically, superpotentials lift moduli (e.g. $W(S) = e^{-S/b_0}$ for gluino condensation).

At weak coupling, [Heterotic]

$$S = g^{-2} V/\ell_s^6 \qquad T = R^2/\ell_s^2$$

Strong coupling (Horava-Witten)

$$T = V^{1/3} R^{11}/\ell_{11}^3 \qquad S = V/\ell_{11}^6$$



One can pass from weak to strong coupling keeping S, T large. Holomorphic quantities agree.

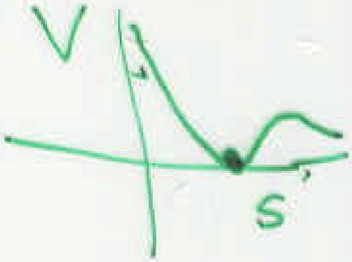
$$f^a = S - n^a T + \mathcal{O}(e^{-S}, e^{-T})$$ [see Kaplunovsky Waldron this meeting]

$$W = e^{-3S/b_0}\left[1 + \mathcal{O}(e^{-nS})\right]$$

Assuming string theory describes nature, it seems likely that the moduli are stabilized on the approximate moduli space (small gauge couplings, hierarchy)

This seems unlikely to be generic.

Proposals:



- Kahler stabilization
- Racetrack (requires particular gauge groups; not generic)

[Cosmological constant]

Predictive power: limited in both cases (holomorphic) but any prediction would be spectacular!

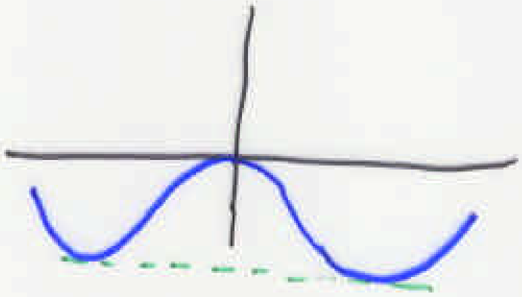
$\mathcal{N}=0$

What distinguishes $\mathcal{N}=1$, $\mathcal{N}=0$?

Approximate maduli space and its properties. Asymptotically regions with 4D, $\mathcal{N}=1$, or not.

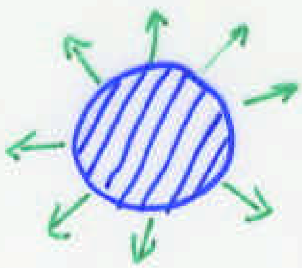
Generically, $\mathcal{N}=0$ theories have problems; perhaps the germ of a string prediction?

- Tachyons



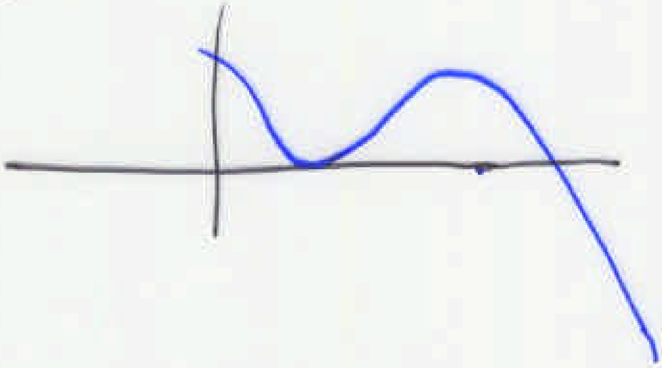
$V_0 \propto -1/g^2 \to -\infty$

- Catastrophic vacuum decay (Witten; Fabinger-Horava)



With our current state of knowlege, not decisive. E.g. stabilization in a regime with no moduli? Very metastable?

$\Gamma \sim e^{-(RM)^a}$



Other (dark horse) possibilities?

Non-perturbative anomalies?

Witten (1985-6): none in field theory limit under weak conditions? *

Inherently stringy:

Look for discrete gauge anomalies, SU(2) anomalies in a variety of theories

* Berkooz, Leigh, Polchinski, Schwarz, Seiberg, Witten: examples in open strings ("dual" to closed)

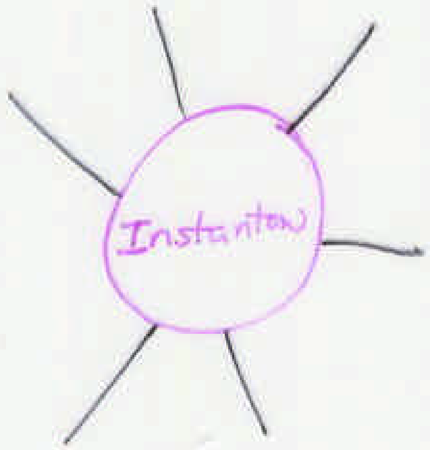
Can we find non-perturbative consistency conditions in closed string theories?

SU(2) (global) anomalies?

Anomalies in discrete symmetries? (T. Banks & M.D.; D. MacIntire & M.D.)

Belief: discrete symmetries in string theory are gauged, so anomalies would signal an inconsistency. (Krauss-Wilczek) Ibanez, Ross; Banks, M.D.

$$\psi\psi\ldots\psi \to \alpha^r \psi\psi\ldots\psi$$



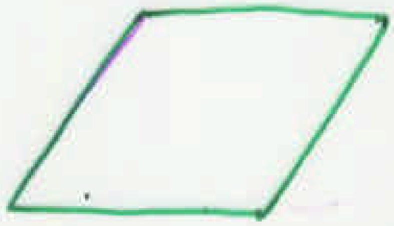
Must allow GS mechanism:

$$aF\tilde{F}$$

$$a \to a + k\frac{2\pi}{N}$$

Discrete symmetries: are they gauged?

(1) Torus



Symmetries $X \to e^{2\pi i/6} X$

- remnant of general coord. invariance.

(2) $E_8 \times E_8$ $E_8 \leftrightarrow E_8$

subgroup of a continuous group unbroken on subspace of moduli space.

(3) T duality in heterotic string (as above)

(4) CP in heterotic string

Others not so obvious. Discrete symmetries of orbifold models? S-dualities?

Another approach: construct cosmic string solutions, ask what happens when bring particle around string.

$\psi \to \alpha \psi$

$\phi = v e^{i\theta}$

$A_\theta = \frac{1}{N}$

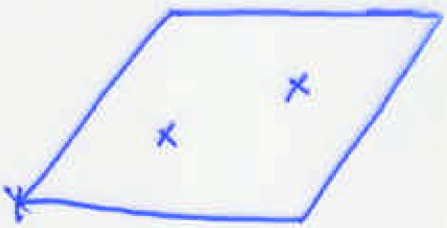
$L_z = m - \frac{2\pi}{N}$

Analogs in string theory?

"Orbifold cosmic string" (Bagger, Callan, Harvey)

"Internal" Z_N, $N = 2, 3, 4, 6$

Compactify x_2, x_3 on torus with Z_N symmetry, mod out by product



Difficulties; alternatives (Banks, Motl, MD)

Previous searches (Banks, M.D., Macintire) limited. Currently attempting a broader search (non-SUSY, asymm. orbifolds,...

(with K. Choi, M. Graesser, J. Gray)

If find examples:

Inconsistency?

Evidence some discrete symmetries not gauged?

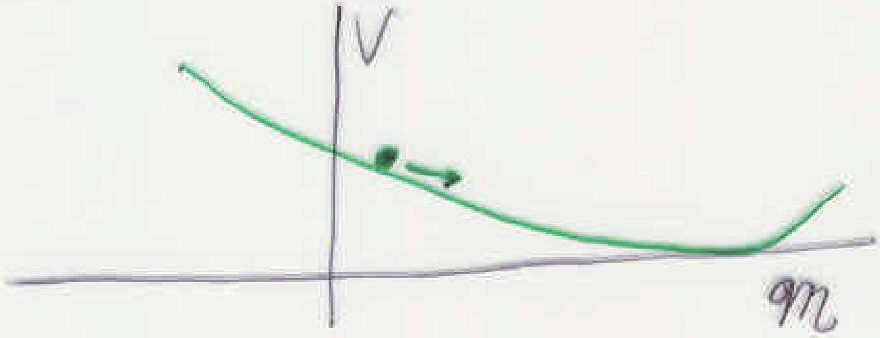
We have hardly proven supersymmetry, but in spirit of conference, assume for rest of discussion*, and consider

Cosmology

Moduli + Cosmology

Potential inflatons (Binetruy, Gaillard)
(recently: Banks)

Potential problems: if associated with supersymmetry breaking, tend to store too much energy.



Solutions: Moduli heavy (10's of TeV)
[Tuning?] [Baryons - via A.D. (Yanagida et al)
Late inflation, Enhanced symmetries?

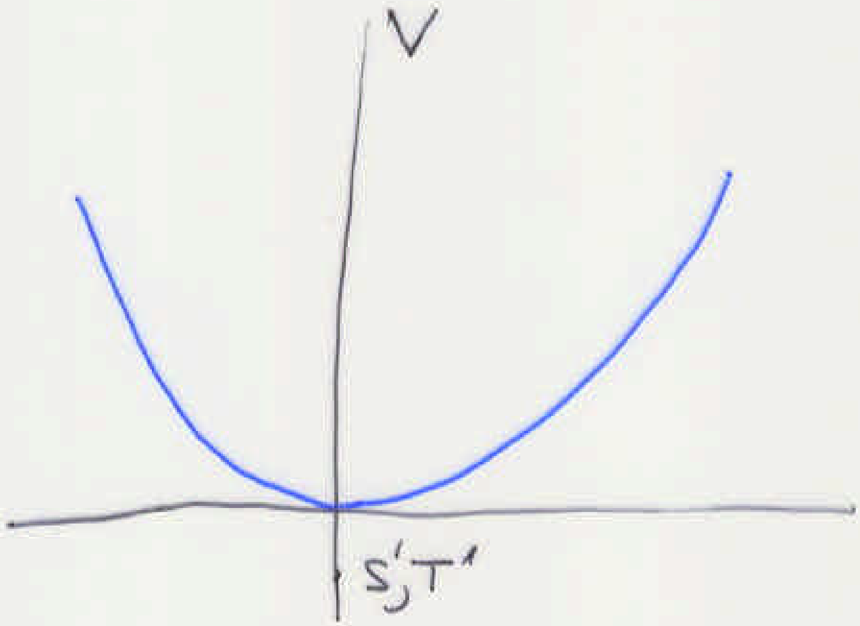
Enhanced symmetries

Familiar from studies of duality.

Indeed, pts. in moduli space exist where <u>all</u> moduli transform under broken symmetries. Naturally minima of potential both now + in early universe.

E.g. IIB

Fixed pt. of $\tau \to -1/\tau$



This provides a natural soln. to the moduli problem since enhanced symmetry points are stationary pts. of effective action (necessarily!) (Randall, Thomas, M.D.)

Candidate minima. [Giudice, Tkachev, Riotto; Felder, Linde, Kofman]

But troubling: expect (compare self-dual pt. of $\vec{E} \leftrightarrow -\vec{B}$ duality)

$\alpha \sim 1$.

Perhaps sometimes simply small

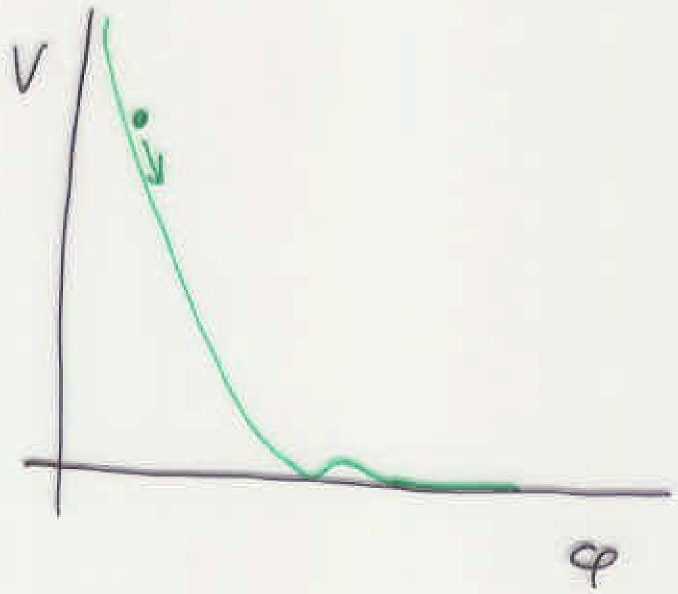
but racetrack models (esp. Izawa-Yanagida) suggests alternative: S fixed with unbroken SUSY at a high scale. No associated moduli problem. (Shadmi, Shirman, Nir, M.D.)

Suppose stabilization as in racetrack or Kahler:

Brustein - Steinhardt

$S = e^{\varphi}$

$V = e^{-\frac{1}{N}e^{\varphi}}$



$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$

Inevitably overshoot.

Horne, Moore: moduli space has finite volume.

Finite (not too small) probability that start not too far from minimum.

Banks, Berkooz, Moore, Shenker, Steinhardt:

Kahler potential corrections?

Focus on zero modes ($\vec{k}=0$) inconsistent.

Kahler potential corrections:

Don't help Even allowing arbitrary K,

a large no. of tunings. (Nir, Shirman, Shadmi, M.D.)

Non-zero momentum?

If zero modes dominate, $p = \rho$

$R \sim t^{1/3}$ $H \sim \frac{1}{3t}$

$\ddot{\varphi} + \frac{1}{t}\dot{\varphi} = 0$ (neglecting potential)

$\varphi = a \ln t + b$ $\dot{\varphi}^2 \sim \frac{1}{t^2} \sim \frac{1}{R^6}$

$(V \sim e^{-t^a}\,!)$

Non-zero modes:

$$\ddot{\varphi} + \frac{1}{t}\dot{\varphi} + k^2/t^{2/3}\,\varphi = 0$$

$$\varphi \sim t^{-1/3} \cos\left(\tfrac{3}{2} t^{2/3} k\right)$$

$$\dot{\varphi}^2 \sim t^{-4/3} \sim 1/R^4\,!$$

22

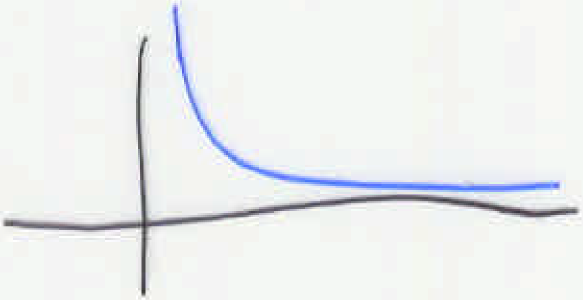
Model for non zero modes: temperature. (Ovrut, Huey, Steinhardt, Waldram, M.D.)

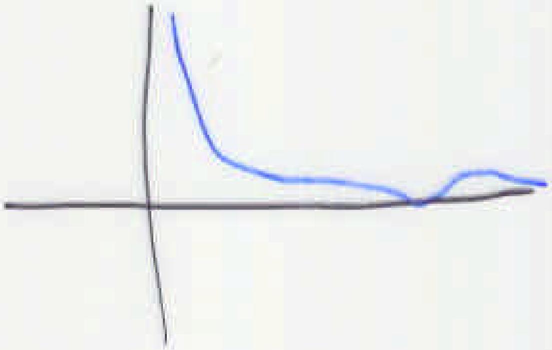
$$\Omega(g,T) = -\frac{(N^2-1)}{24}\pi^2 T^4\left(1 - \frac{3}{8}\frac{g^2 N}{\pi^2} + \frac{g^3 N^{3/2}}{\sqrt{2}\,\pi^3} + \dots\right)$$

For slowly varying g, a potential

for $g = e^{\phi}$. Valid for $\Lambda(g) \ll T$

$\Lambda(g) \gg T$: $\exp\left(-\frac{8\pi^2}{g^2 N}\right)$





$p = \frac{1}{3}\rho$ $\quad R^{-1} = \frac{1}{\sqrt{t}}$ $\quad H = \frac{1}{2t}$

$\varphi \sim \frac{1}{\sqrt{t}} + C$ $\quad \dot{\varphi}^2 \sim \frac{1}{t^3}$

So competition between potential, damping term.

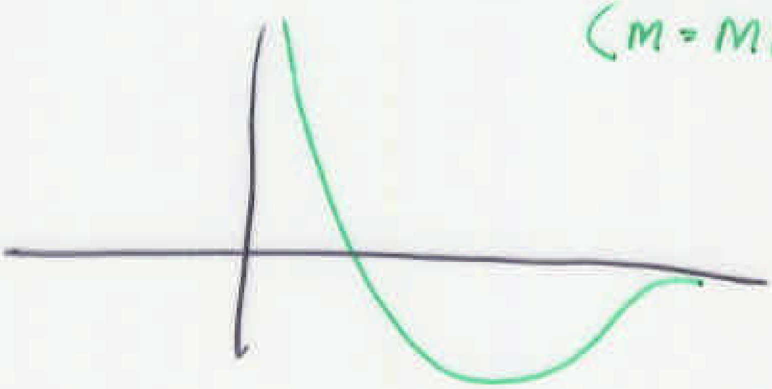
For large N, reasonable range of initial cond:

- soft landing in min.

System need not really be in thermal equilibrium.

If $V = -g^2 M^4 + V_{np}$

$(M = M(t))$



- system easily finds true minimum.

So a picture for modulus stabilization

+ solution of the moduli problems

of string cosmology.

But many questions:

- Cosmological constant
- Inflation
- Vacuum selection
  (why not $N > 1$, $d > 4$?

⋮

Conclusions: Anthropic "Lite"

Suppose a smaller set of vacuum states, $N>1$, $d>4$, $N=1$ (approx. moduli), etc. "Early" universe samples all.

Perhaps generic states can't grow large, develop structure.

E.g. $N \geq 2$ exact moduli space.

Non-zero modes dominate evolution.

(Always radiation dominated).

$N=1$: metastable vacua not generic [?].

⋮

If we understood Λ, moduli stabilization, rest might not be so hard.