Statistics of M theory Vacua and the Landscape

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March 2005.

(based upon hepth/0502060
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Overview

- **Introduction to the Landscape:**
- Why Statistics?
- Review of IIB Flux Landscape

- **M theory Flux Landscape:**
- Review of G2 and Freund-Rubin Vacua
- The Freund-Rubin Landscape
- The G2 Landscape

The Landscape: an introduction

- There are a plethora of **non-realistic** string vacua (Eg 11d Minkowski, IIB on AdS x S, Heterotic on K3)
- Duality implies non-perturbative **exactness**
- Even though M theory has no free parameters it appears to have a large **Landscape of Vacua**.
- Even by focussing on 4d vacua the Landscape ***appears*** to be **vast (?)**

  (eg many Calabi-Yaus, Braneworlds, G2 manifolds)
- Using quantised fluxes (magnetic fields in the extra dimensions) to stabilise moduli leads to a discretuum of vacua.
- So what do we do?

Why Statistics?

- We could try to do model building, but..
- The story of the unfortunate model builder
- Wanted to realise Large Extra Dimensions
- Tried to use fluxes to stabilise moduli there
- Failed to find a single model
- Statistical studies of flux vacua have shown that flux vacua can become extremely rare at large volume, even non-existent!
- Our model builder could have benefited from this insight. We will see similar examples later of the practical utility of the statistical approach later.

Questions

- Are there finitely many 4d string vacua with finite volume and cosmological constant?
- Are there finitely many vacua which agree with the standard model at low energies?
- Do the vacua with small c.c. and Higgs mass, prefer low scale supersymmetry?

A few other thoughts

- How else can we make sense of the landscape?
- Naturalness becomes an important concern
- Arkani-Hamed et al have constructed extremely interesting particle physics models by employing ``environmental principles''.
- ANDIAMO!

- Until now statistical landscape studies have concerned IIB flux landscapes
- Are these in any way representative?
- Studying other ensembles of vacua will give us a better picture of the landscape
- We will study two different classes of M theory vacua – **Freund-Rubin** and **G2-holonomy**

The IIB Flux Landscape

$$N_{vac} \approx \frac{L^{b3}}{b3!} \int \det[\Re + \omega]$$ Uniform Distribution of Vacua

$$dN \approx N_{vac}\ d\Lambda$$ Uniform Distribution of C.C's

$$dN \approx N_{vac}\ e^{-2V^{2/3}}\ dV^{2/3}$$ Large volume Suppression

$$dN \approx N_{vac}\ dF$$ Uniform Distribution of (small) F-terms

$$dN \approx N_{vac}\ F^5\ dF\ d\Lambda$$ High Scale Susy Favored with small C.C.

G2 holonomy Vacua

D=4 N=1 Compactifications
X must be endowed with particular singularities
to obtain Yang-Mills fields and chiral fermions
(BSA, Atiyah-Witten, BSA-Witten)

Extremely interesting particle physics (Witten):
supersymmetric grand unification, light higgses,
heavy triplets, suppressed dim 4 and 5 proton decay.
Quarks, Leptons localised in the extra dimensions:
Natural hierarchies of Yukawa couplings.

Main outsdanding problem: explicit construction of the
G2 holonomy manifolds with singularities.

Existence: duality.   Local picture: established.

Stabilising G2 Moduli

- Without flux - $b_3(X)$ moduli
- Bulk fluxes don't stabilise the moduli
- BSA hepth/0212294: ***all*** get fixed by fluxes for bulk 4-form G and gauge fields localised on 3-cycle Q.
- X must have an ADE singularity along a 3-manifold Q which admits a complex flat connection with ***non-real*** Chern-Simons invariant $c = c_1 + ic_2$
- By changing the fluxes we get a discretuum of vacua

- How many vacua?
- How are the vacuum energies distributed?

Freund-Rubin Vacua

- Flux Compactifications to AdS4 (intrinsic scale)
- Near Horizon (Large N) limit of M2 branes
- Existence of chiral fermions established recently (BSA, Denef, Hofman, Lambert, hepth/0308046)
- Possibilities for realistic particle physics poorly explored – nice project for a grad student!
- Supersymmetric and Non-supersymmetric
- Classically not realistic – fundamental scale too low: must understand quantum corrected potential.
- Much simpler than special holonomy vacua


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Freund-Rubin Statistics

An infinite number of vacua, labeled by N – Freund-Rubin flux
At large N space decompactifies and c.c. goes to zero

As $V(X) = N^{7/6} V_0^{-1/6}$

$\Rightarrow N_{vac}(V \leq V^*) = V^{*6/7}$

Similarly,

$\Lambda = -N^{-3/2} V_0^{1/2}$

$\Rightarrow N_{vac}(\Lambda \leq \Lambda^*) = \Lambda^{*-2/3}$

and $N_{vac}(\Lambda \geq \Lambda^*) = \infty$

What if we also vary X ie sample the topology of the extra dimensions

There are many ensembles of Einstein manifolds labeled by an integer k   eg $X(k) = X/Z_k$

We get Freund-Rubin vacua labelled by (N,k).

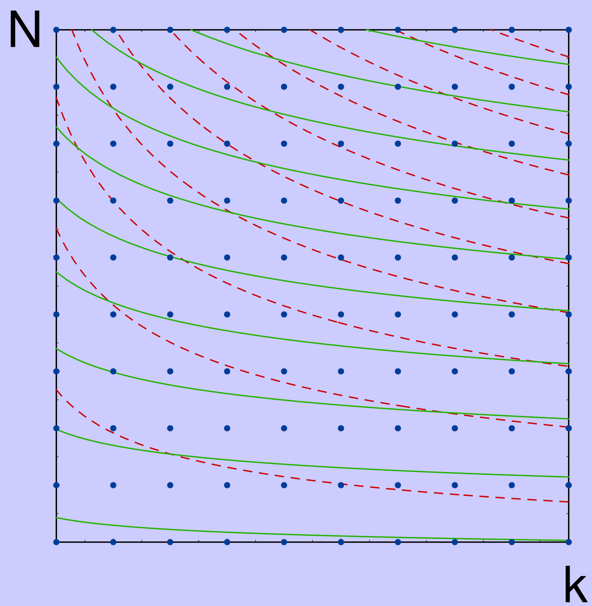
This significantly enhances the previous results for fixed k

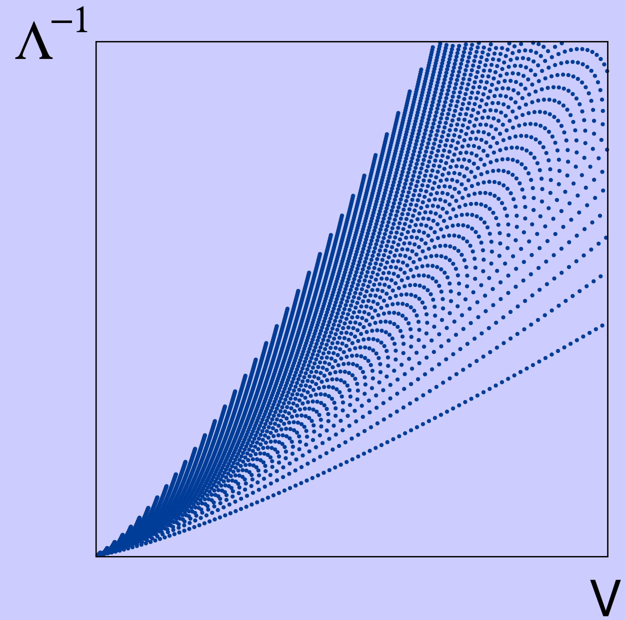
$$N_{vac} (V \leq V^{*}) = V^{*6}$$

and

$$N_{vac} (\Lambda \leq \Lambda^{*}) = \Lambda^{*-2}$$

So sampling the topology of the extra dimensions can really make a big difference to the distributions of vacua.





More generally we find significantly different results for joint distributions of vacua as these plots indicate.

G2 holonomy Statistics

- More complicated. Not much known about the Kahler potential. This contains all the information about X.
- We obtained many results independent of the choice of Kahler potential
- Also studied explicit models based upon an ensemble of Kahler potentials

Distribution of vacua extremely uniform:

$$N_{vac}(R) = c_2^{b_3}\ \mathrm{Vol}(R) \quad R \subset M$$

Like IIB, but simpler.

Large volumes are suppressed:

$$dN = c_2^{b_3}\ dV^{-3b_3/7} \ \text{ and } \ V < c_2^{7/3}$$

Small cosmological constants are suppressed also:

$$dN = (c_2^{b_3})^{5/7}\ d\Lambda^{b_3/7} \ \text{ and } \ \Lambda > 1/c_2^5$$

Very different from IIB case. We have a non-uniform distribution.

Distribution of supersymmetry breaking scales for small cosmological constant is determined by the distribution of volumes:

$$M^2_{susy} = \frac{c_2}{V^{3/2}} M^2_p$$

$$\Rightarrow \quad M^2_{susy} > c_2^{-5/2} M^2_p$$

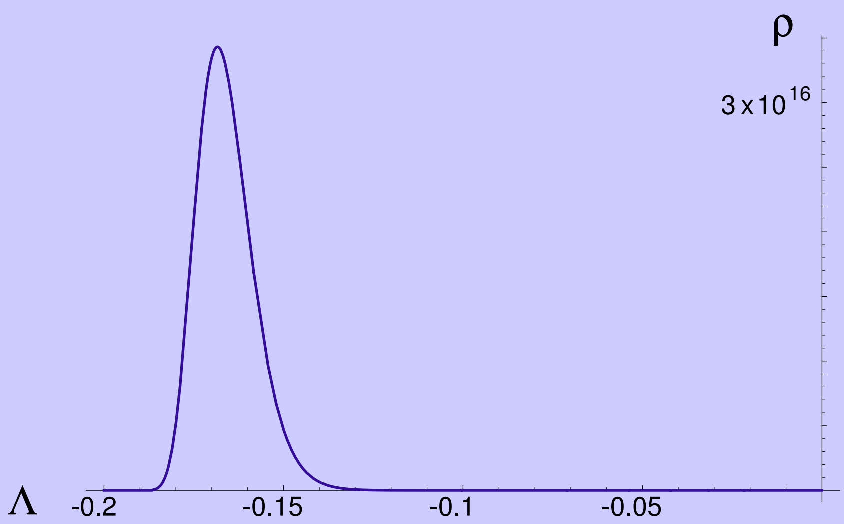
So High Scale supersymmetry breaking is preferred

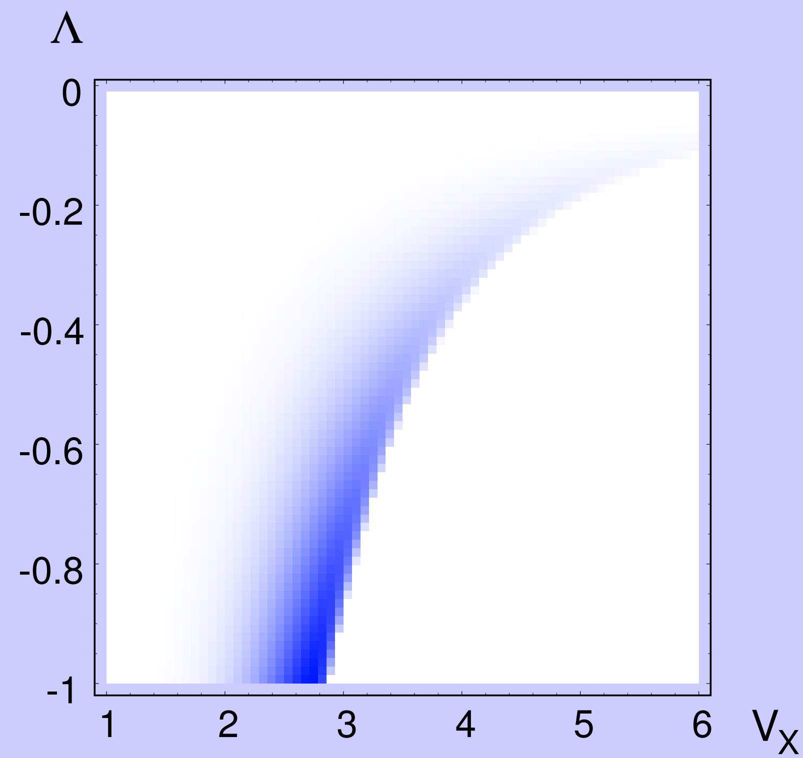
From the explicit model ensembles we studied we found some additional information:

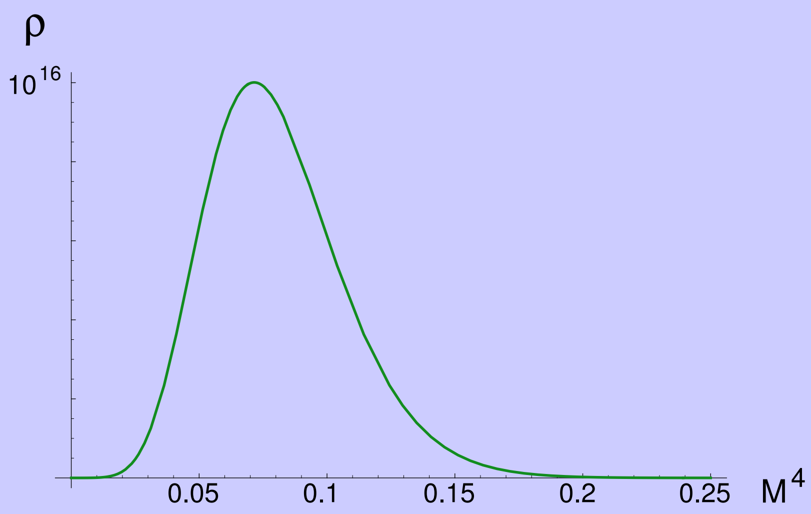
All de Sitter vacua were unstable.

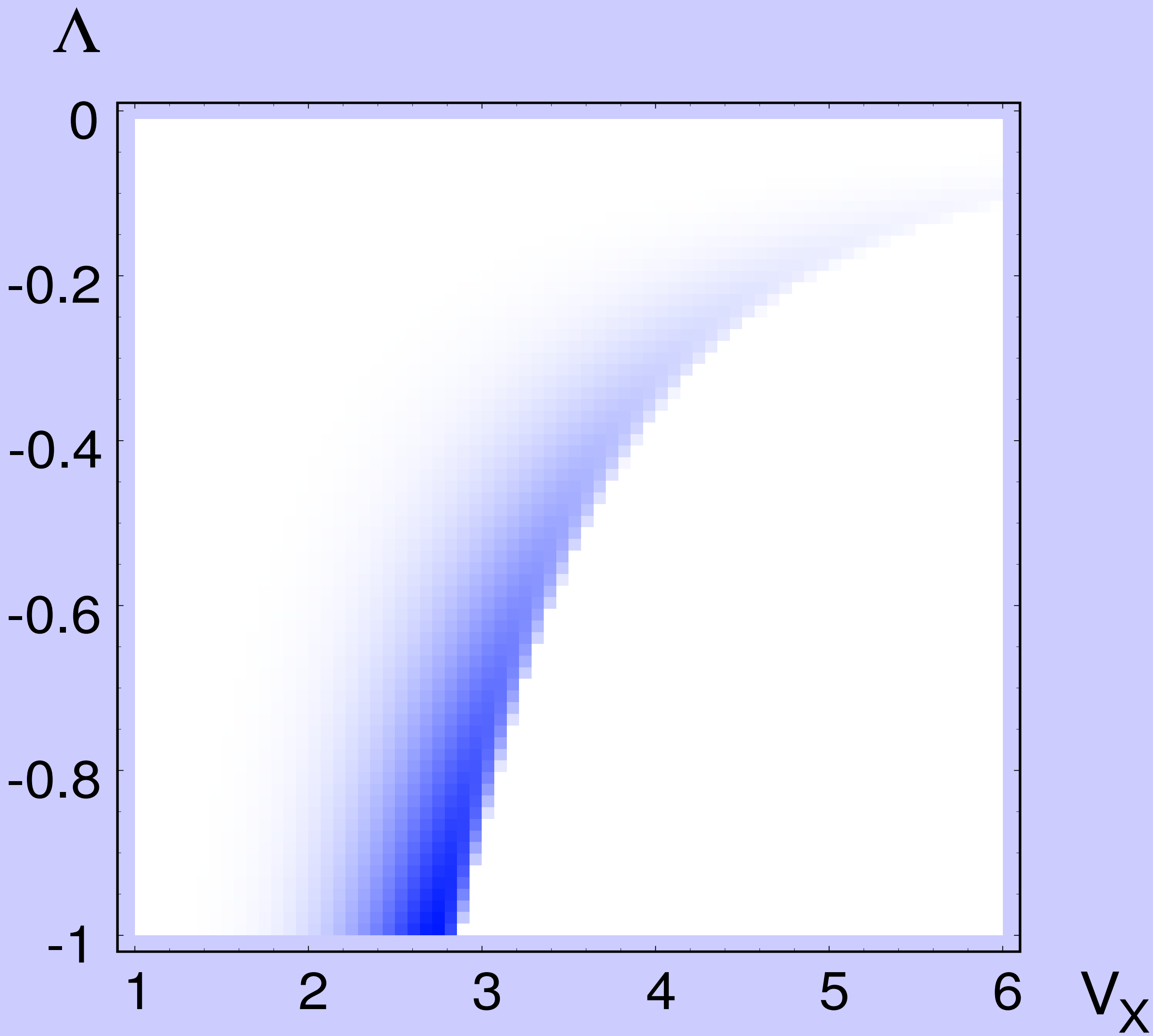
Exponentially large numbers of anti de Sitter vacua stable.

Highly peaked distributions:

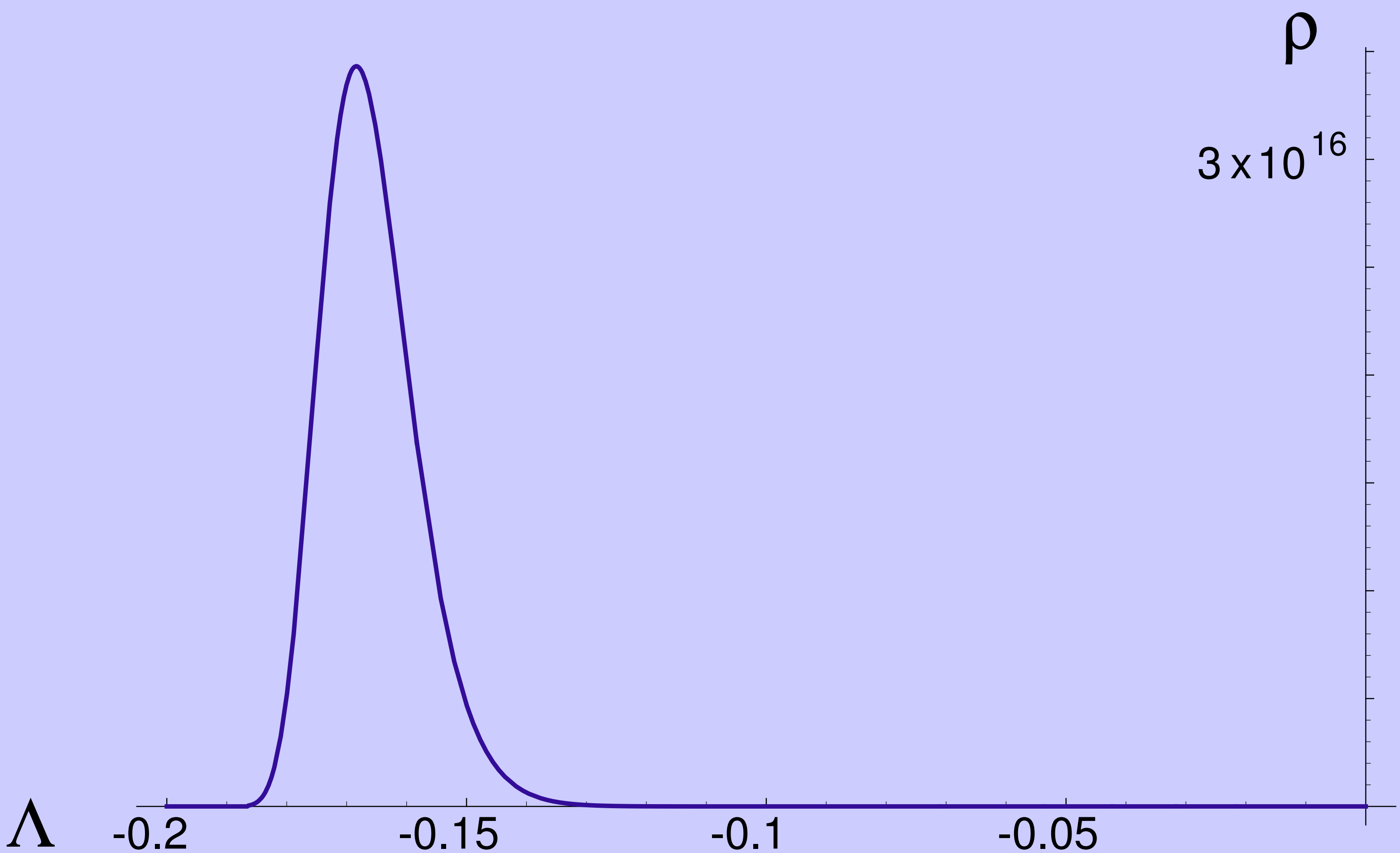

ρ
3 x 10^16
Λ
-0.2
-0.15
-0.1
-0.05


Λ
0
-0.2
-0.4
-0.6
-0.8
-1
1
2
3
4
5
6
V_X

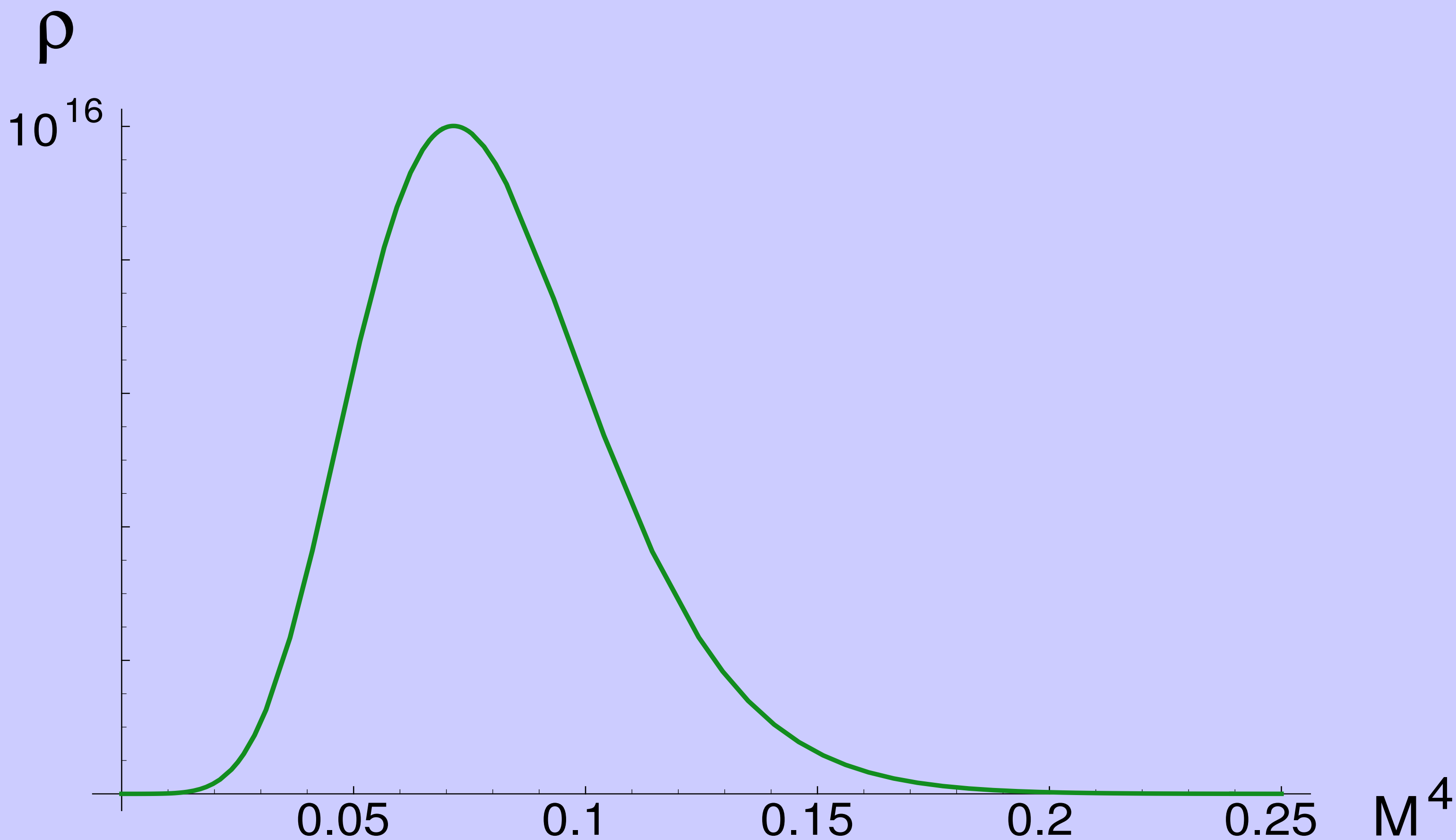

ρ
10^16
0.05
0.1
0.15
0.2
0.25
M^4



Joint distibution of vacua.



Distribution of Cosmological Constants.



Distribution of SUSY breaking scales.

These highly peaked distributions are reminiscent of the ``friendly landscapes'' recently introduced by Arkani-Hamed, Dimopoulos and Kachru in hep-th/0501082.

- However, Yukawa couplings appear to ``scan'' many orders of magnitude in these G2 flux landscapes which is very unfriendly (work in progress).

Final Thoughts

- We have initiated a statistical study of other regions of the landscape.
- So far all the landscape studies suggest that the number of 4d vacua with finite volume and c.c. is finite.
- Our results suggest that most of the stable vacua on the landscape have a high scale of supersymmetry breaking.
- Do metastable de Sitter universes exist??

die Rinne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