Title: The Multiverse Of String Theory, The Measure Problem, And The Cosmological Constant

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Abstract: The vacuum landscape of string theory can solve the cosmological constant problem, explaining why the energy of empty space is observed to be at least 60 orders of magnitude smaller than several known contributions to it. It leads to a 'multiverse' in which every type of vacuum is produced infinitely many times, and of which we have observed but a tiny fraction. This conceptual revolution has raised tremendous challenges in particle physics and cosmology. To understand the low-energy physics we observe, and to test the theory, we will need novel statistical tools and effective theories. We must also solve a long-standing fundamental problem in cosmology: how to define probabilities in an infinite universe where every possible outcome, no matter how unlikely, will be realized infinitely many times. This 'measure problem' is inextricably tied to the quantitative prediction of the cosmological constant.

The Multiverse of String Theory, the Measure Problem, and the Cosmological Constant

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The (Old) Cosmological Constant Problem

Einstein's cosmological constant

The cosmological constant problem began its life as an ambiguity in the general theory of relativity:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Λ introduces a length scale

$$L_\Lambda = \sqrt{\frac{3}{|\Lambda|}}$$

in addition to the Planck length,

$$L_{\text{Planck}} = \sqrt{\frac{G\hbar}{c^3}} \approx 1.6 \times 10^{-33} \text{cm} .$$

(Old) experimental constraints

In General Relativity, this length scale becomes an upper bound:

- $\Lambda > 0$: L_Λ is the maximum size (largest observable distance scale)
- $\Lambda < 0$: $t_\Lambda \sim L_\Lambda / c$ is the maximum age of the universe

Because the universe is large and old, we know that $|\Lambda|$ is very small in Planck units:

$$|\Lambda| \lesssim 10^{-121} .$$

So let's just set $\Lambda \to 0$?

Quantum contributions to Λ

The vacuum of the Standard Model is highly nontrivial:

- Confinement
- Symmetry breaking
- Particles acquire masses by bumping into Higgs
- ...

Not surprisingly, the vacuum carries an energy density, ρ_{vacuum}.

Quantum contributions to Λ

The vacuum stress tensor is proportional to the metric, $T_{\mu\nu}^{\text{vacuum}} = \rho_{\text{vacuum}} g_{\mu\nu}$. We can absorb it into Λ, keeping only the matter stress tensor:

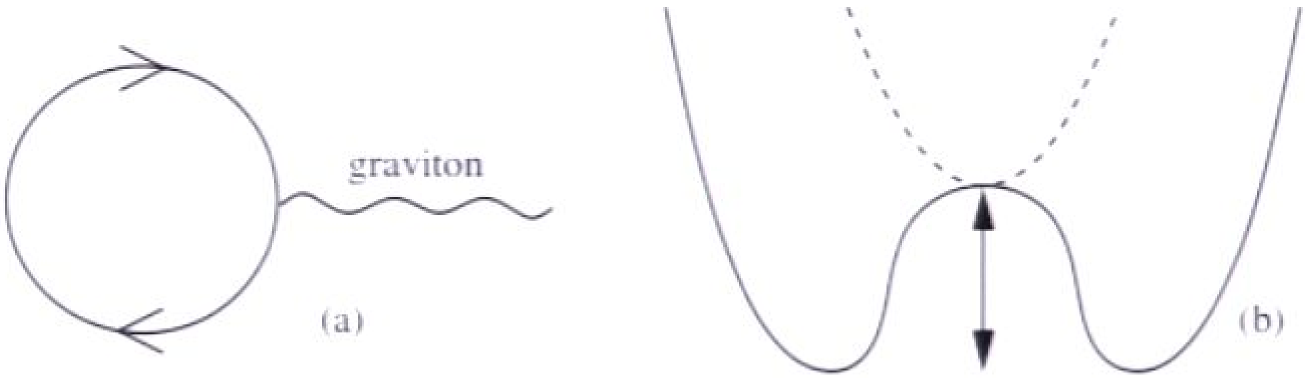
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}^{\text{matter}}$$

with

$$\Lambda = \Lambda_{\text{Einstein}} + 8\pi G \rho_{\text{vacuum}} \ .$$

Einstein could choose to set $\Lambda_{\text{Einstein}} \to 0$.
But we cannot set $\rho_{\text{vacuum}} = 0$. It is determined by the Standard Model and its ultraviolet completion.

Magnitude of contributions to the vacuum energy



- Vacuum fluctuations of each particle contribute (momentum cutoff)^4 to Λ
- SUSY cutoff: $\rightarrow 10^{-64}$; Planck scale cutoff: $\rightarrow 1$
- Electroweak symmetry breaking lowers Λ by approximately $(200\ \mathrm{GeV})^4 \approx 10^{-67}$
- Chiral symmetry breaking, ...

The cosmological constant problem

- Each contribution is much larger than 10^{-121}.
- Different contributions can cancel against each other or against $\Lambda_{\text{Einstein}}$.
- But why would they do so to a precision better than 10^{-121}?

Why is the vacuum energy so small?

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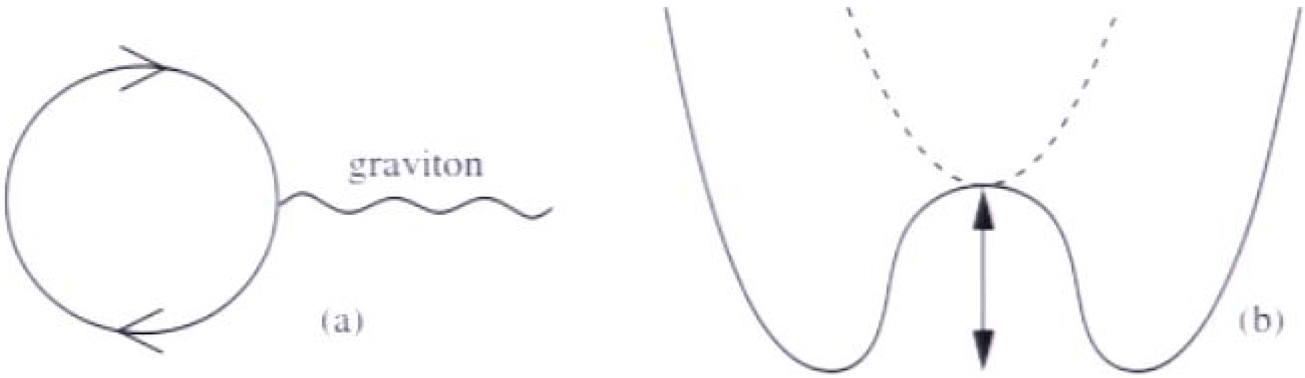

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Why is the vacuum energy so small?

Some Ideas, and Why They Don't Work

Quantum gravity

- *We are combining quantum mechanics and general relativity. Do we know what we're doing? Don't we need quantum gravity?*
- But we always do this! All matter is quantum mechanical: $T_{\mu\nu} \to \langle T_{\mu\nu} \rangle$
- Well tested and successful, as long as we stay below Planck energy, above Planck length.
- For the CC problem it suffices to consider lower energies
- Energies up to 1 MeV $\leftrightarrow$ Universe reaches to the moon

Short- or long-distance modifications of gravity

- *Perhaps general relativity should be modified?*
- We can only modify the theory on scales where it has not been tested: below 1 mm and above cosmological scales.
- If vacuum energy were large, it would in particular act on intermediate scales like the solar system.

Violating the equivalence principle

- *We have tested GR using ordinary matter, like stars and planets. Perhaps virtual particles are different? Perhaps they don't gravitate?*
- But we know experimentally that they do!
- Virtual particles contribute different fractions of the mass of different materials (e.g., to the nuclear electrostatic energy of aluminum and platinum)
- If they did not gravitate, we would have detected this difference in tests of the equivalence principle (in this example, to precision 10^{-6})

Degravitating the vacuum

- *Perhaps virtual particles gravitate in matter, but not in the vacuum?*
- But physics is local.
- What distinguishes the neighborhood of a nucleus from the vacuum?
- What about nonperturbative contributions, like scalar potentials? Why is the energy of the broken vacuum zero?

Initial conditions

- *Perhaps there are boundary conditions at the big bang enforcing $\Lambda = 0$?*
- But this would be a disaster:
- When the electroweak symmetry is broken, Λ would drop to $-(200\ \mathrm{GeV})^4$ and the universe would immediately crunch.

Gravitational attractor mechanisms

- *Perhaps a dynamical process drove Λ to 0 in the early universe?*
- Only gravity can measure Λ and select for the "right" value.
- General relativity responds to the total stress tensor
- But vacuum energy was negligible in the early universe
- E.g. at nucleosynthesis, spacetime was being curved by matter densities and pressures of order 10^{-86}
- There was no way of measuring Λ to precision 10^{-121}

The New Cosmological Constant Problem

Measuring the cosmological constant

- Supernovae as standard candles
  $\rightarrow$ expansion is accelerating
- Precise spatial flatness (from CMB) $\rightarrow$ critical density
  $\rightarrow$ large nonclustering component
- Large Scale Structure: clustering slowing down
  $\rightarrow$ expansion is accelerating
- ...

is consistent with

$$\Lambda \approx 0.4 \times 10^{-121}$$

and inconsistent with $\Lambda = 0$.

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The cosmological constant problem

This result sharpens the cosmological constant problem:

Why is the energy of the vacuum so small, and why is it comparable to the matter density in the present era?

- Favors theories that predict Λ comparable to the current matter density;
- Disfavors theories that would predict $\Lambda = 0$.

The Landscape of String Theory

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The Landscape of String Theory

One theory, many solutions

- Standard model: A few adjustable parameters, many metastable solutions
- Combine many copies of fundamental ingredients (electron, photon, quarks) to form huge number of distinct solutions (condensed matter)
- Anything goes? No: finite number of elements; specific material properties;

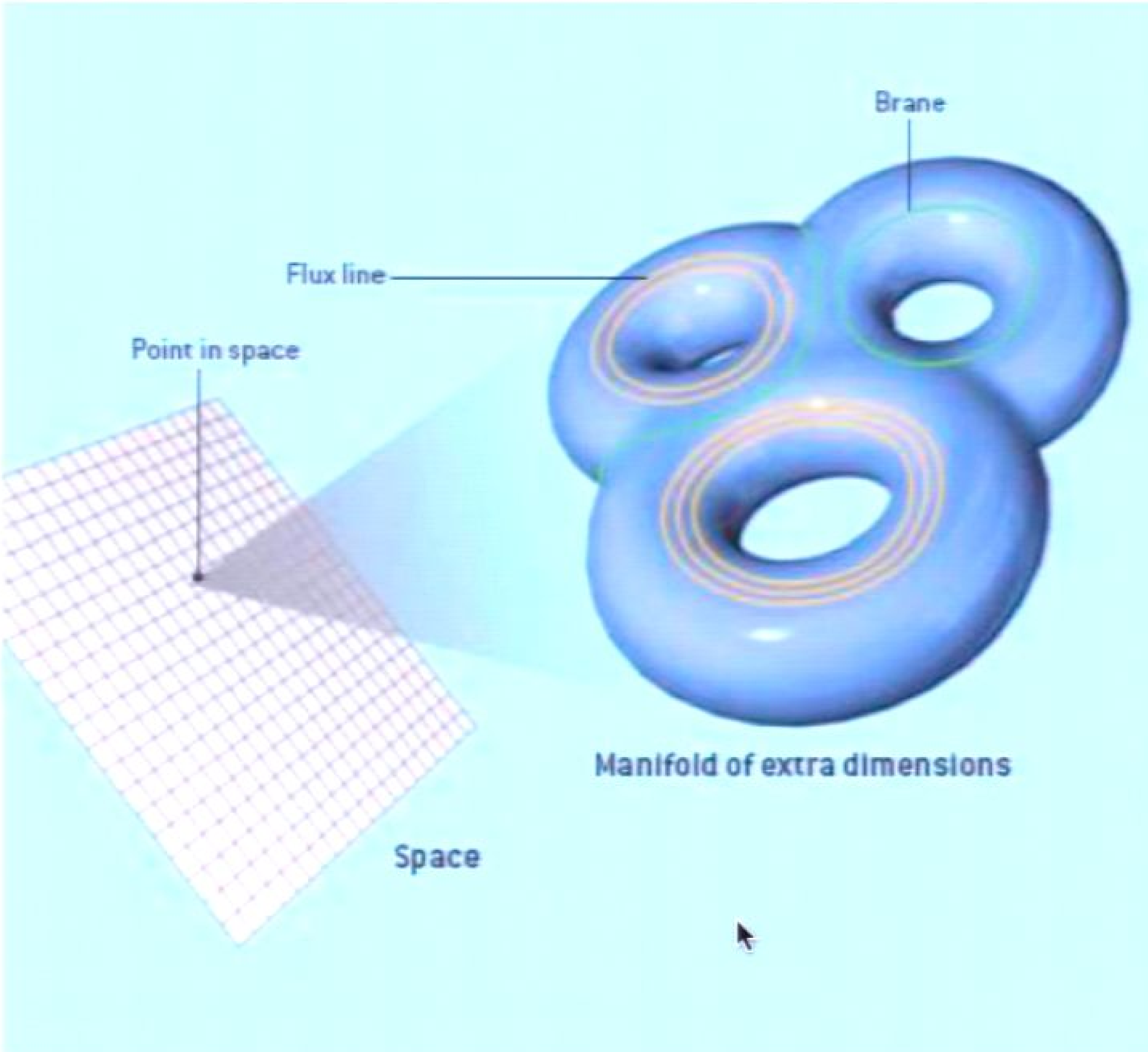
  . . .
- Reliable predictions thanks to statistics (large numbers help)

One theory, many solutions

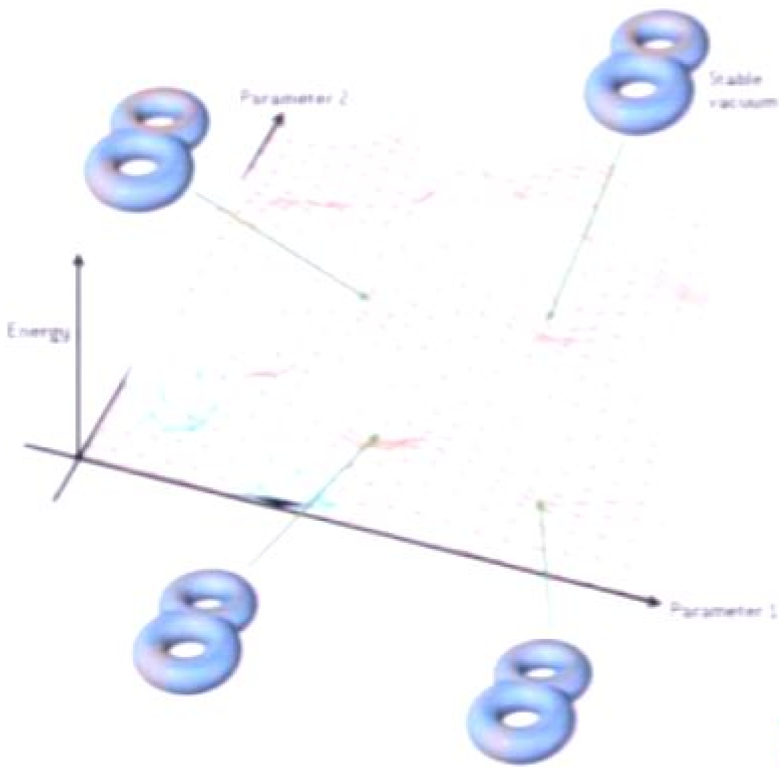
- Standard model: A few adjustable parameters, many metastable solutions
- Combine many copies of fundamental ingredients (electron, photon, quarks) to form huge number of distinct solutions (condensed matter)

- String theory: Unique theory, no adjustable parameters, many metastable solutions
- Combine D-branes and their associated fluxes, to tie up 6 extra dimensions

Branes and extra dimensions



Topology and combinatorics



R.B. & J. Polchinski (2000)

- A six-dimensional manifold contains hundreds of topological cycles, or "handles".
- Suppose each handle can hold 0 to 9 units of flux, and there are 500 independent handles
- Then there will be 10^{500} different configurations.

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- String theory: Unique theory, no adjustable parameters, many metastable solutions
- Different flux combinations yield distinct 3+1 dimensional worlds ("vacua")
- each with its own low energy physics and vacuum energy

Three challenges

To make predictions and test the landscape of string theory, we face three challenges:

- Landscape statistics
- Cosmological dynamics
- Measure problem

The prediction of the cosmological constant is sensitive to all three.

Landscape Statistics: The spectrum of Λ

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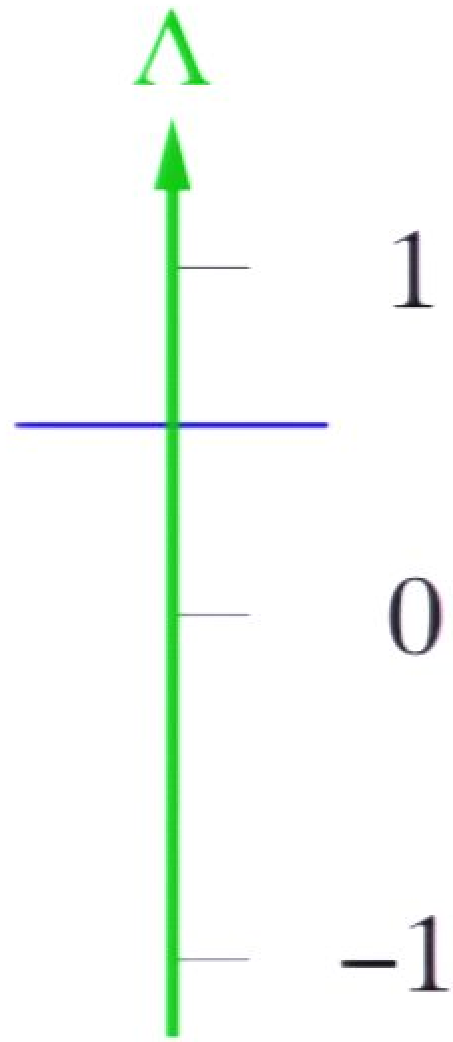

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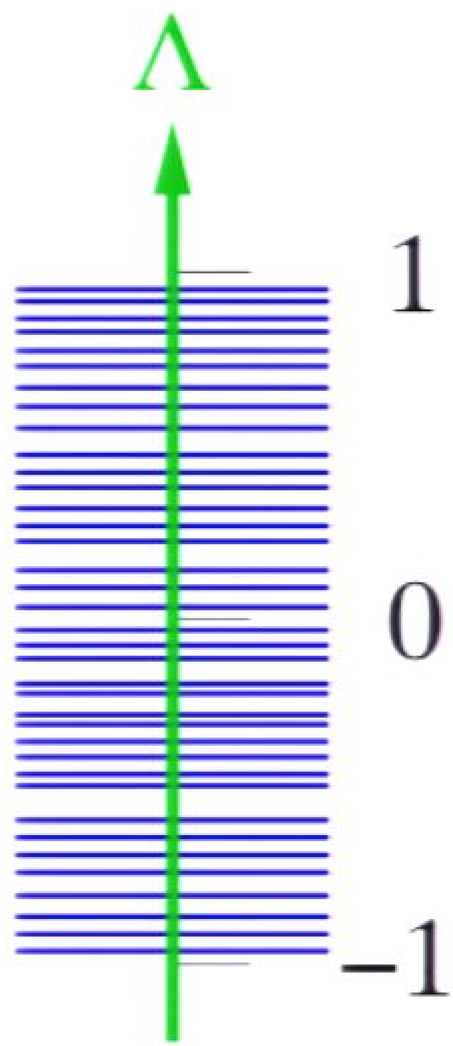

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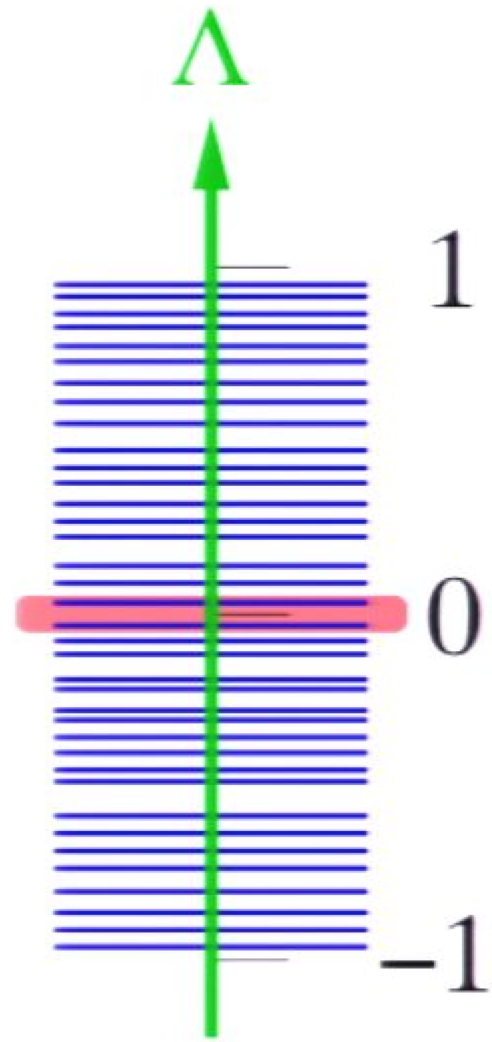

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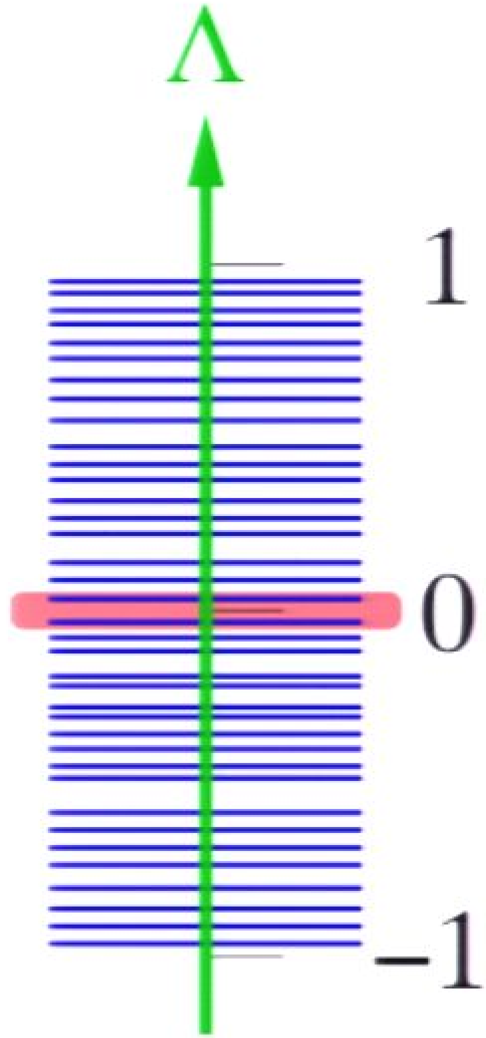

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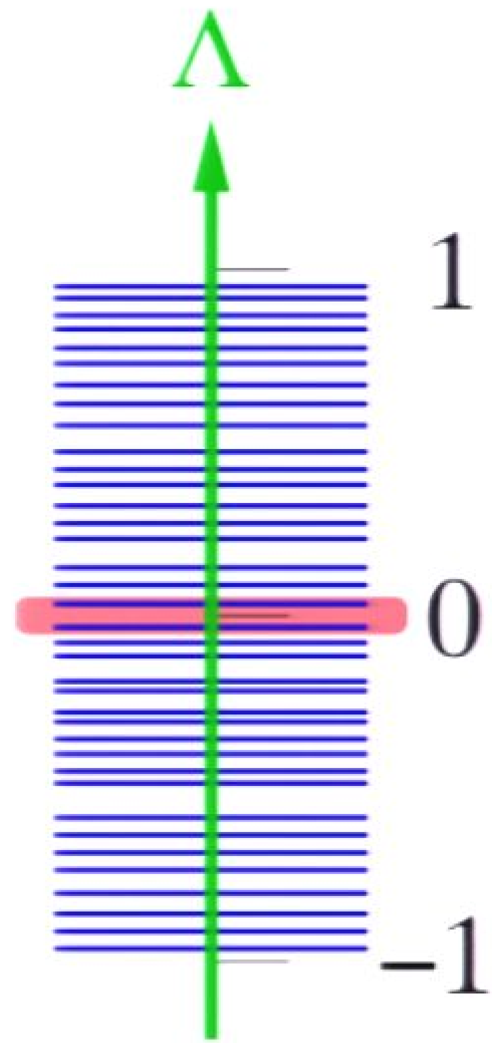
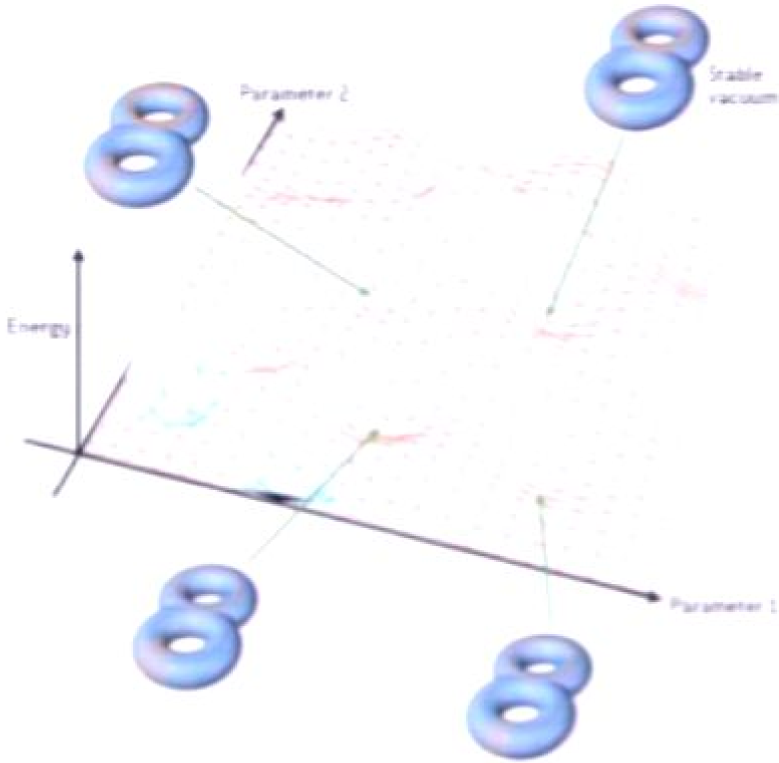
- And why should we find ourselves in such a rare vacuum?



Cosmology: Eternal inflation and the Multiverse

Metastability and eternal inflation



- Fluxes can decay spontaneously (Schwinger process)
- $\rightarrow$ landscape vacua are metastable
- First order phase transition
- Bubble of new vacuum forms locally.

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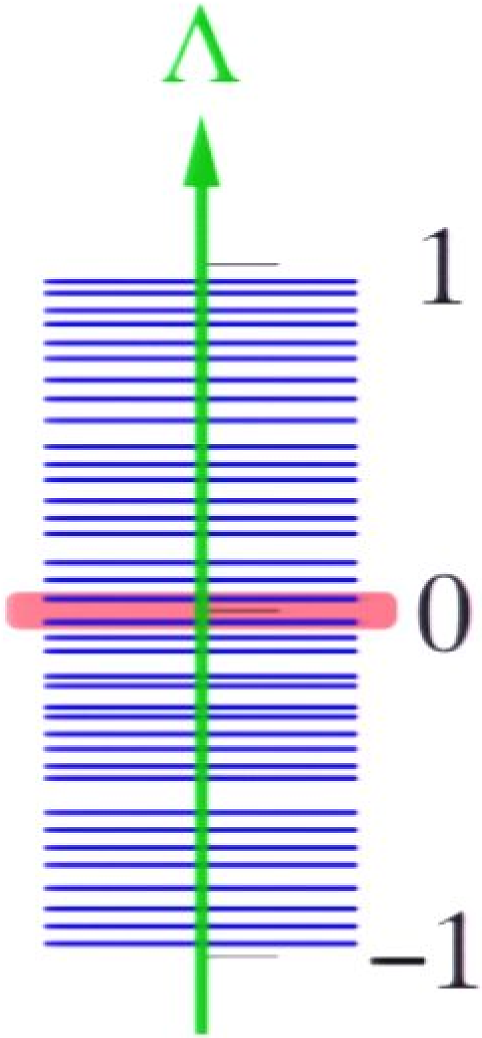

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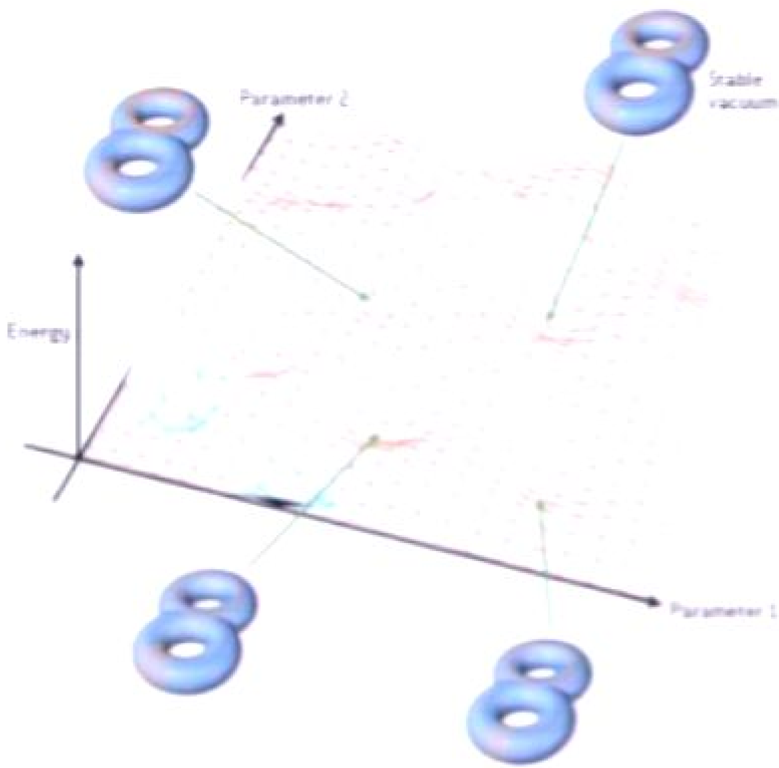

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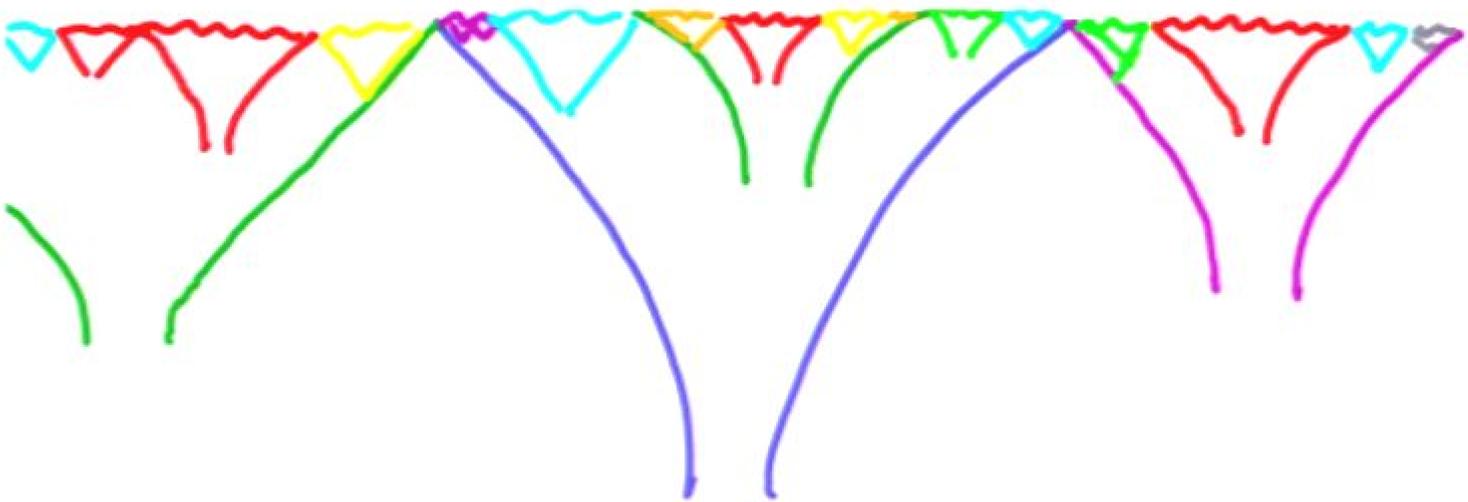
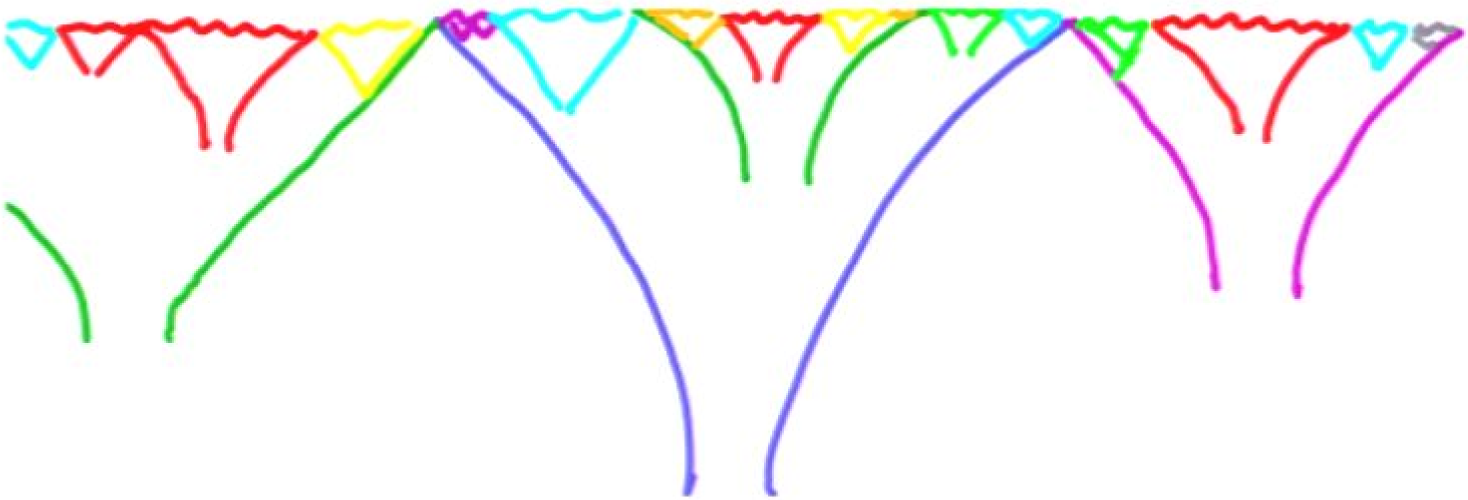


- New bubble expands to eat up the old vacuum
- But for $\Lambda > 0$, the old vacuum expands even faster
  Guth & Weinberg (1982)
- So the old vacuum can decay again somewhere else
- $\rightarrow$ Eternal inflation

Eternal inflation populates the landscape



- The new vacuum also decays in all possible ways
- and so on, as long as $\Lambda > 0$
- Eventually all vacua will be produced as "pocket universes"
- Each vacuum is produced an infinite number of times
- $\rightarrow$ "Multiverse"

Connecting with standard cosmology

The observable universe fits inside a single pocket:

- Vacua can have exponentially long lifetimes
- Each pocket is spatially infinite
- Because of cosmological horizons, typical observers see just a patch of their own pocket
- $\rightarrow$ Low energy physics (including Λ) appears fixed

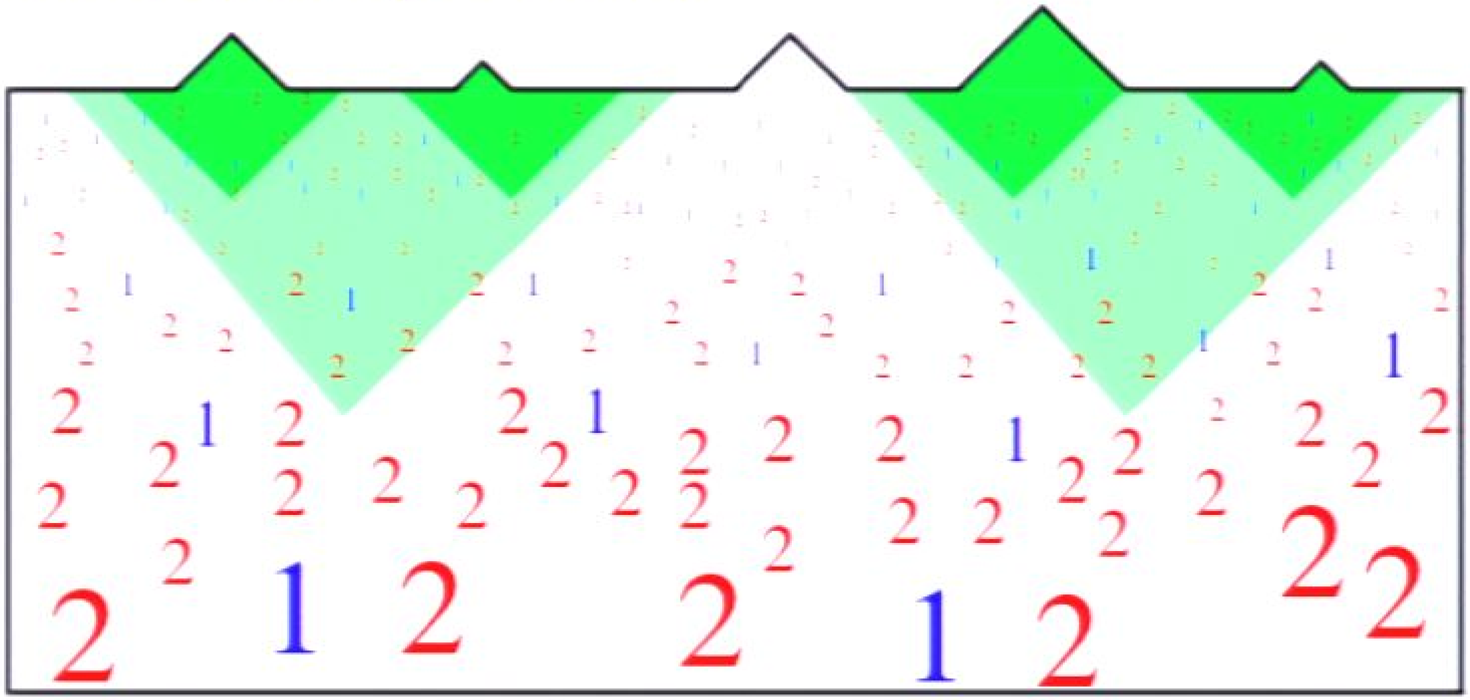
Connecting with standard cosmology

Matter and radiation can be produced:

- Neighboring vacua in the string landscape have vastly different Λ
- $\rightarrow$ The decay of our parent vacuum (the big bang) released enough energy to allow for subsequent slow-roll inflation, reheating, nucleosynthesis, etc. (R.B. & Polchinski, 2000)
- This would not have worked in a one-dimensional landscape (Abbott; Brown & Teitelboim, 1980s)

The Measure Problem

The measure problem

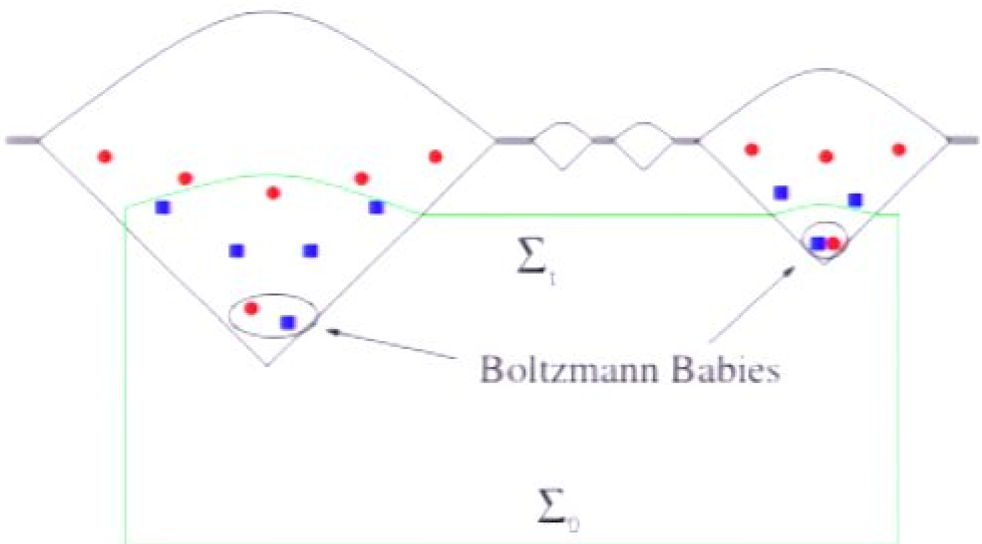


- Infinitely many pockets of each vacuum
- Each contains infinitely many observers (if any)
- Everything happens infinitely many times
- What is the relative abundance of different outcomes of a given experiment? What outcomes are typical/likely?
- Need a cutoff or regularization procedure to define probability distributions for observables such as Λ

The measure problem

- Robust problem; precedes landscape [Goncharov, Linde & Mukhanov; Linde et al., Vilenkin et al., . . . (pre-landscape); R.B., DeSimone, Easter, Freivogel, Garriga, Lim, Linde, Martin, Noorbala, Olum, Salem, Schwartz-Perlov, Tegmark, Vanchurin, Vilenkin, Winitzki, Yang, . . . (post-landscape)]
- Treat this as any other scientific problem
- Build quantitative models subject to usual criteria:
  - simple, well-defined, predictive
  - not in conflict with observation
- Measures are hard to "tune" if stated geometrically—you don't know what you're going to get
- Identify "catastrophies" that depend only on the measure; proceed by elimination [R.B., Freivogel, Yang (2006–2008)]

Catastrophe 1: Why do we live so late?



- Proper time cutoff; take ratios as $t \to \infty$

  Linde *et al.* (1993)

- Most observations are made in recently formed pockets
- They see a hot universe
- $p(T_{\text{CMB}} \leq 3\ \text{K}) = \exp(-10^{60}) \to$ Measure ruled out

Catastrophe 2: Why do we live so early?

- Cutoff: observers-per-baryon Weinberg (1989)
- Infinitely many observers arise from thermal fluctuations at late times, in empty de Sitter space
- They see a cold, empty universe
- $p(T_{\text{CMB}} \geq 2\text{ K}) \approx 0 \rightarrow$ Measure ruled out

Surviving measures

There are other examples of such extreme failures ("Q-catastrophe", "Staggering Problem", ...). They are useful litmus tests for measures. Many proposals have been ruled out by such catastrophies. Currently, two measures survive:

- The causal diamond measure
  (motivated by black hole complementarity)
  R.B. (2006); R.B, Freivogel & Yang (2006)
- The scale factor measure
  DeSimone, Guth, Salem & Vilenkin (2008), building on Linde *et al.* (1990s)

Both may yet be ruled out; and other possibilities remain to be formulated/tested. But interestingly, both give reasonable predictions for the cosmological constant.

Predicting the Cosmological Constant

Λ from the causal diamond measure

- The causal diamond measure counts the number of observers inside the cosmological horizon
- Let Λ vary, hold t_{obs} fixed
- Matter inside the horizon dilutes exponentially, with characteristic time $t_\Lambda \sim 1/c\sqrt{\Lambda}$
- If $t_\Lambda < t_{\text{obs}}$, then the number of observations inside the horizon is suppressed by a factor

$$\exp\left[-3\frac{t_{\text{obs}}}{t_\Lambda}\right]$$

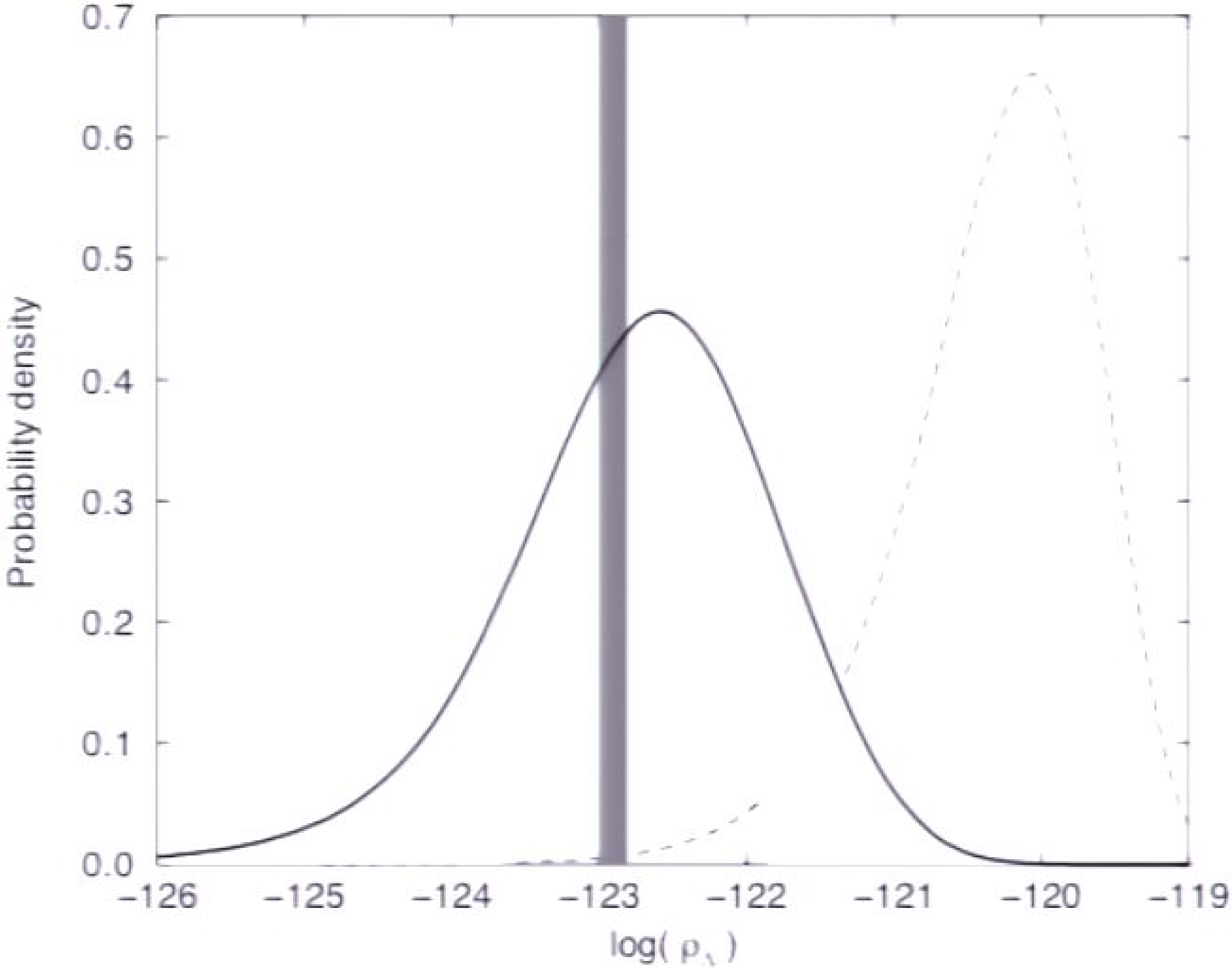
- To avoid this exponential dilution, need $t_\Lambda \gtrsim t_{\text{obs}}$
- Therefore, expect

$$\Lambda \sim t_{\text{obs}}^{-2},$$

in excellent agreement with observation

R.B., Harnik, Kribs & Perez (2007)

The probability distribution over Λ



$$\Lambda_{CD} \sim \Lambda_{obs} \sim 10^{-3}\Lambda_{SF}$$

[R.B., Harnik, Kribs & Perez (2007); R.B., Freivogel & Yang (2008)]

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Λ from the scale factor measure

- This measure cuts off the universe at a finite time, as measured by the local expansion
- In the formulation of DeSimone, Guth, Salem & Vilenkin (2008), it (roughly) reproduces Weinberg's 1987 analysis, putting it on a firm footing and evading its Boltzmann brain problem.
- This measure ties t_Λ to the time when galaxies first form, preferring

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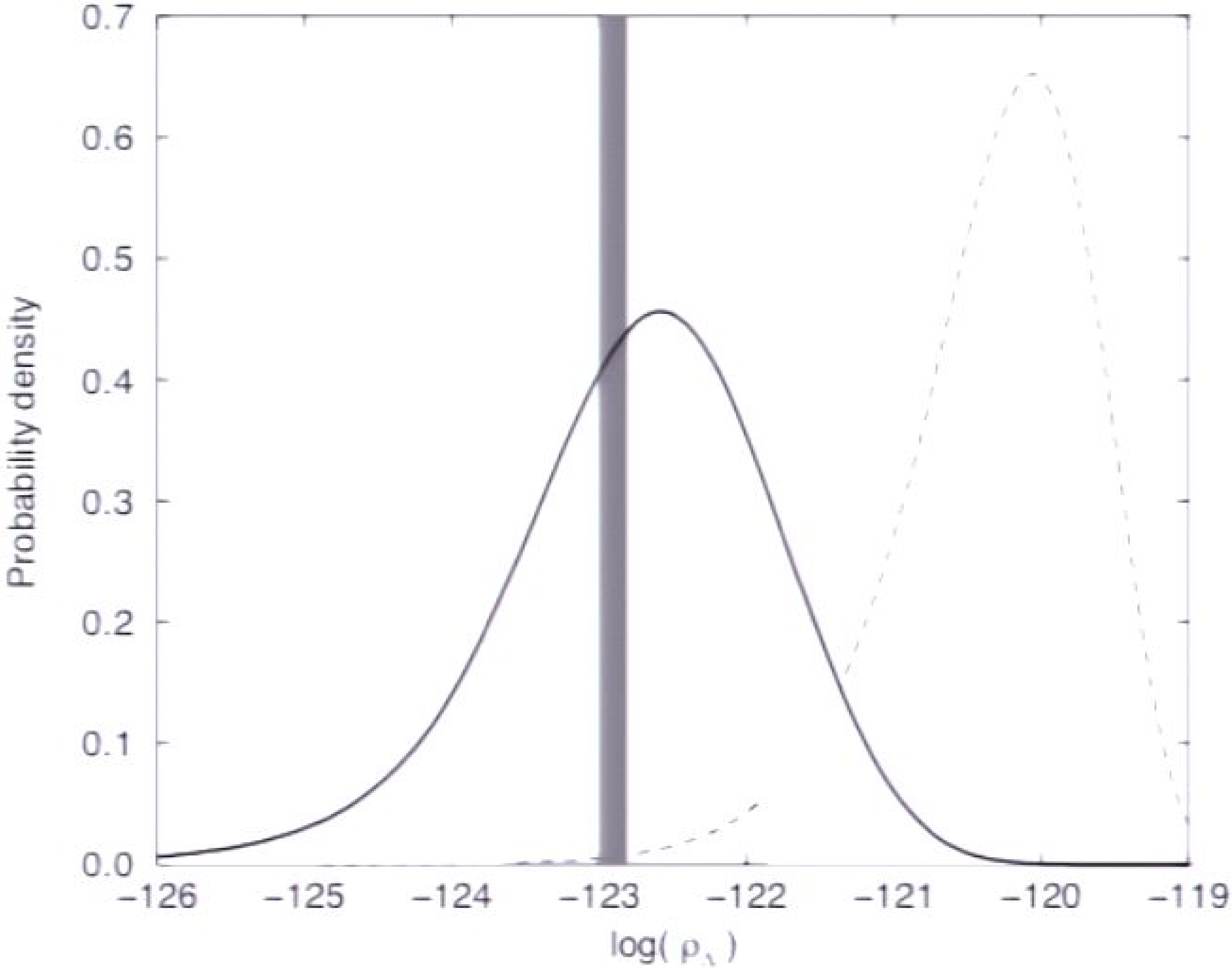

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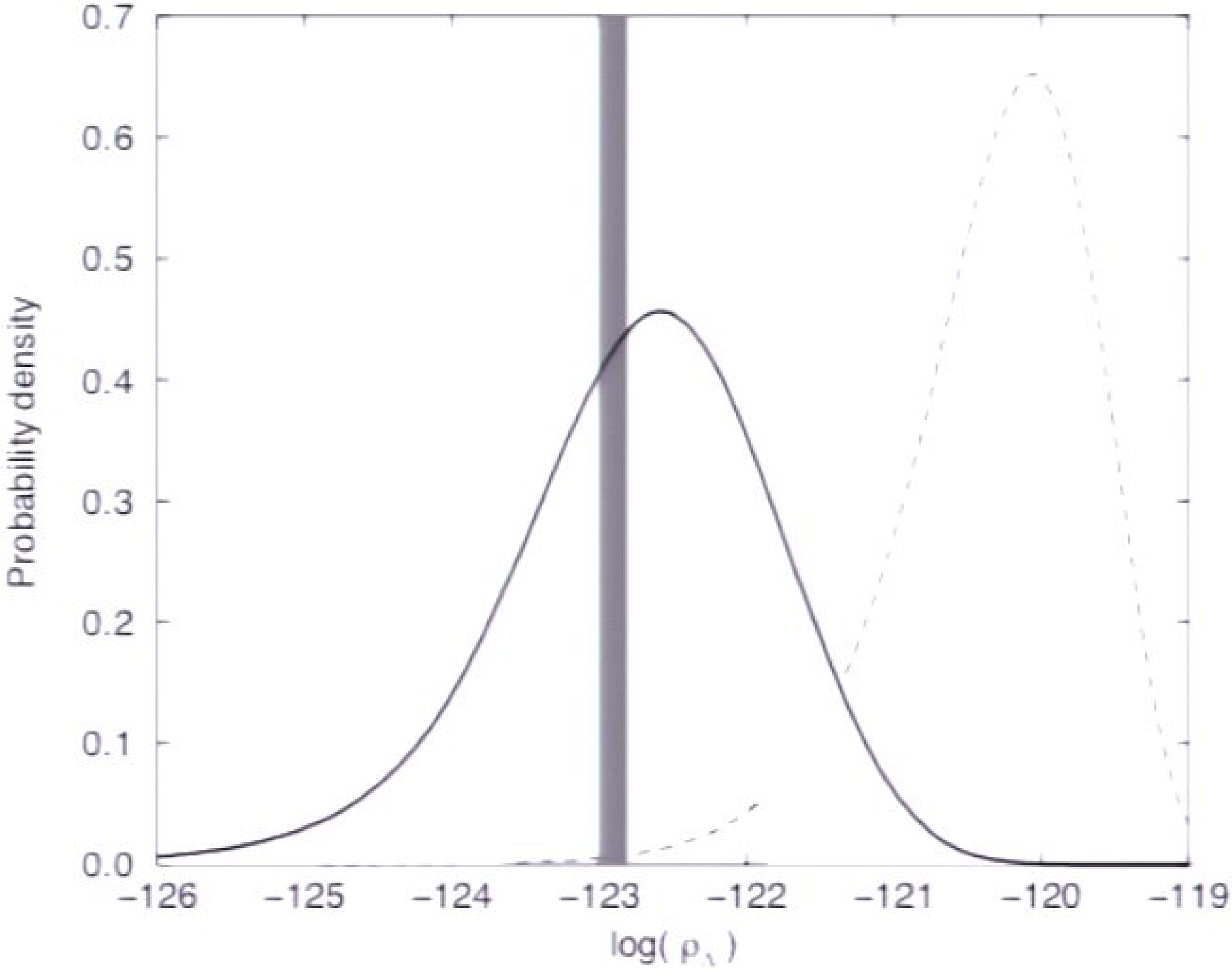

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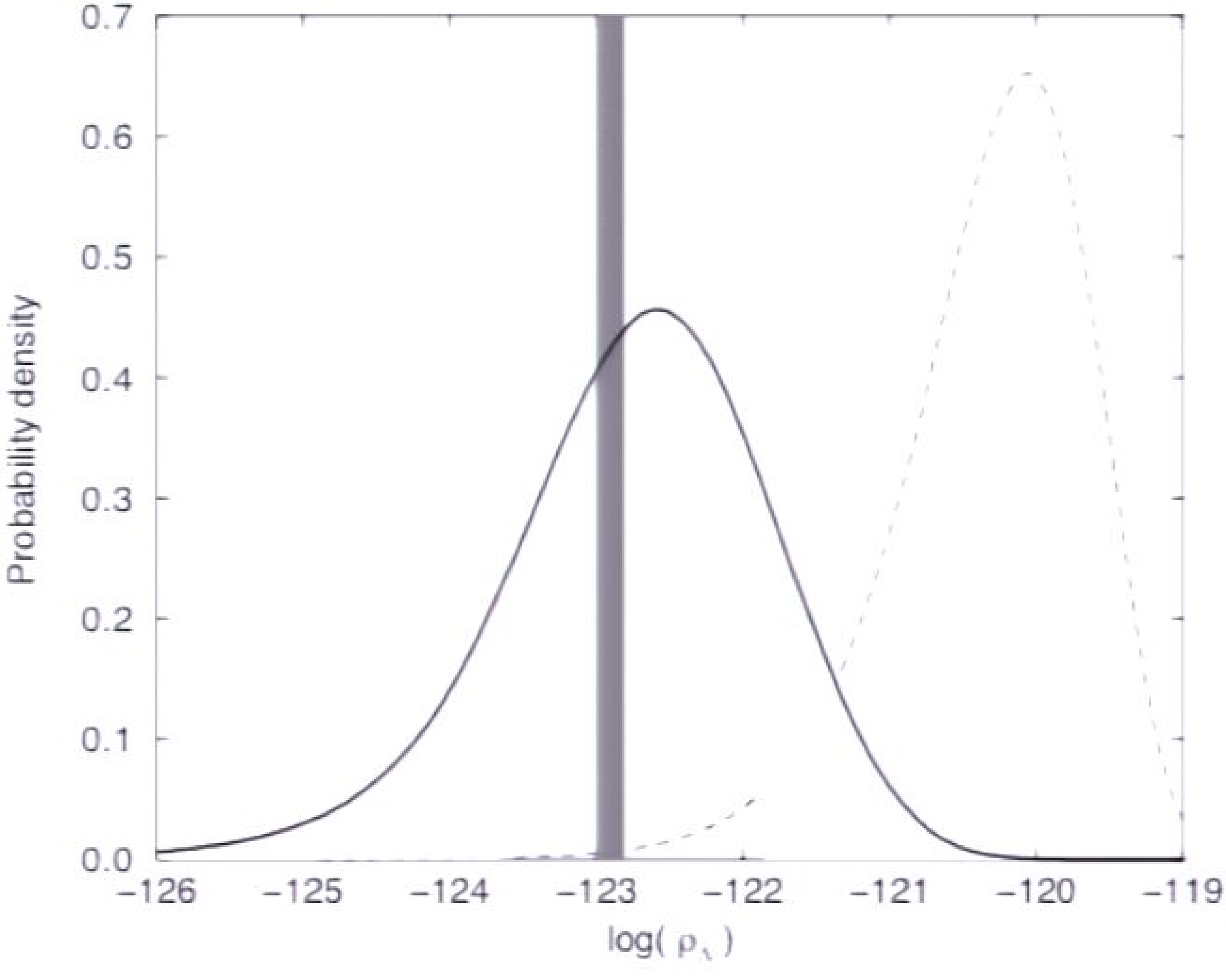

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Conclusions

We are slowly learning how to make predictions in the landscape. They depend on

- Landscape statistics
- Cosmological dynamics
- Cosmological measure

Like in most theories, we cannot calculate everything.
Make progress by asking the right questions:

- Make predictions that depend only on one or two of the above items
- Consider observables (such as Λ) where we know how to compute
- Gradually increase number of parameters, classes of vacua

Plenty of opportunities to falsify individual ingredients, or the whole theory