The Cosmological Constant Problem and the Multiverse of String Theory

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The (Old) Cosmological Constant Problem

Why the cosmological constant problem is hard

Recent observations

Of ducks and unicorns

The Landscape of String Theory

Landscape Statistics

Cosmology: Eternal inflation and the Multiverse

The Measure 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 into GR,

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

which is (roughly) the largest observable distance scale.

(Old) experimental constraints

Because the universe is large compared to the fundamental length scale

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

it follows that $|\Lambda|$ must be very small in fundamental 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
- ...

The vacuum carries an energy density, ρ_{vacuum}.

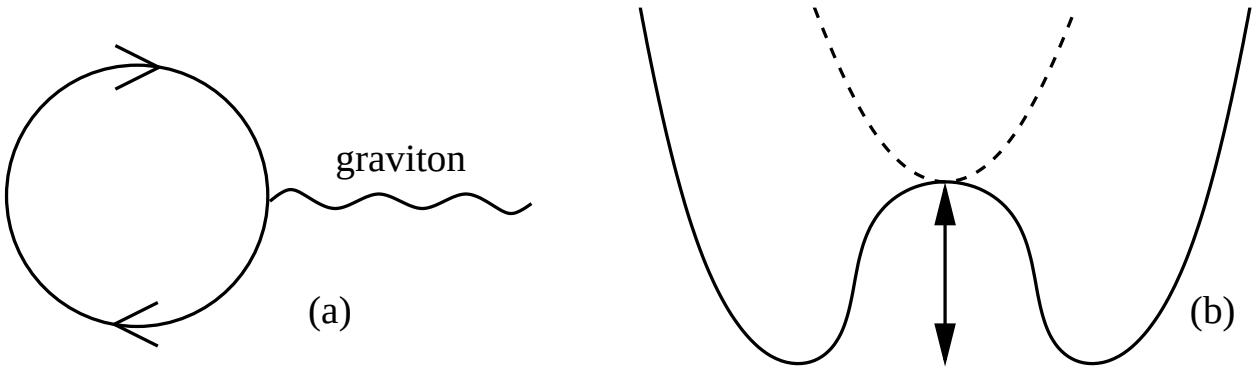
Quantum contributions to Λ

In the Einstein equation, the vacuum energy density is indistinguishable from a cosmological constant. We can absorb it into Λ:

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

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 GeV)$^4 \approx 10^{-67}$
- Chiral symmetry breaking, ...

The cosmological constant problem

- Each known 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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Try solving it

Some ideas, and why they don’t work:

Short- or long-distance modifications of gravity

- *Perhaps general relativity should be modified?*
- We can only modify GR on scales where it has not been tested: below 1 mm and above astrophysical scales.
- If vacuum energy were as large as expected, 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 $-(200\ \text{GeV})^4$ 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}

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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 $\Lambda = 0$.

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 $\Lambda = 0$.

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Calling it a duck

Perhaps $\Lambda = 0$, and dark energy is a new form of matter that just happens to evolve very slowly (quintessence, . . .)?

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Perhaps $\Lambda = 0$, and dark energy is a new form of matter that just happens to evolve very slowly (quintessence, . . .)?

"When I see a bird that
walks like a duck
and swims like a duck
and quacks like a duck,
I call that bird a duck."

Why “dark energy” is vacuum energy

- Well-tested theories predict huge Λ, in conflict with observation.
- There is no well-tested, widely accepted solution to this problem—in particular, none that predicts $\Lambda = 0$.
- It is unwise to interpret an experiment through the lens of a baseless theoretical speculation (such as the prejudice that $\Lambda = 0$).
- If we cannot compute Λ, we should try to measure Λ.
- “Dark energy” is
  - indistinguishable from Λ
  - definitely distinct from any other known form of matter
- So it probably is Λ, and we have succeeded in measuring its value.

Not calling it a duck

Wouldn't it be more exciting if it was a unicorn?

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Not calling it a duck

Wouldn't it be more exciting if it was a unicorn?

- Why is this unicorn wearing a duck suit?
- Why have we never seen a unicorn without a duck suit?
- What happened to the huge duck predicted by our theory?

Dynamical dark energy

- Whether Λ is very small, or zero,
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- . . . which would make sense if we were trying to rescue a compelling theory that predicts $\Lambda = 0$ . . .
- . . . but we have no such theory.

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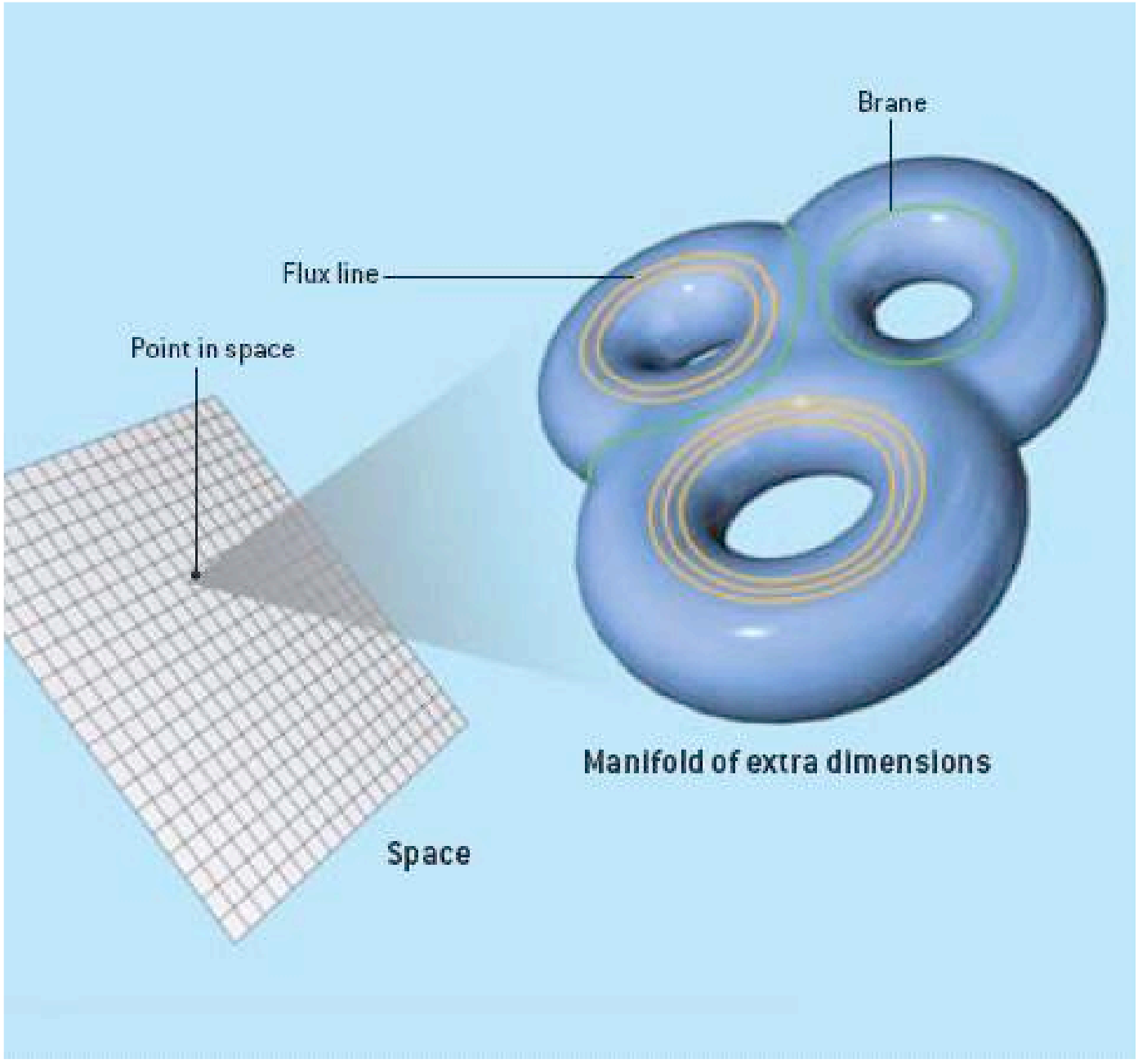
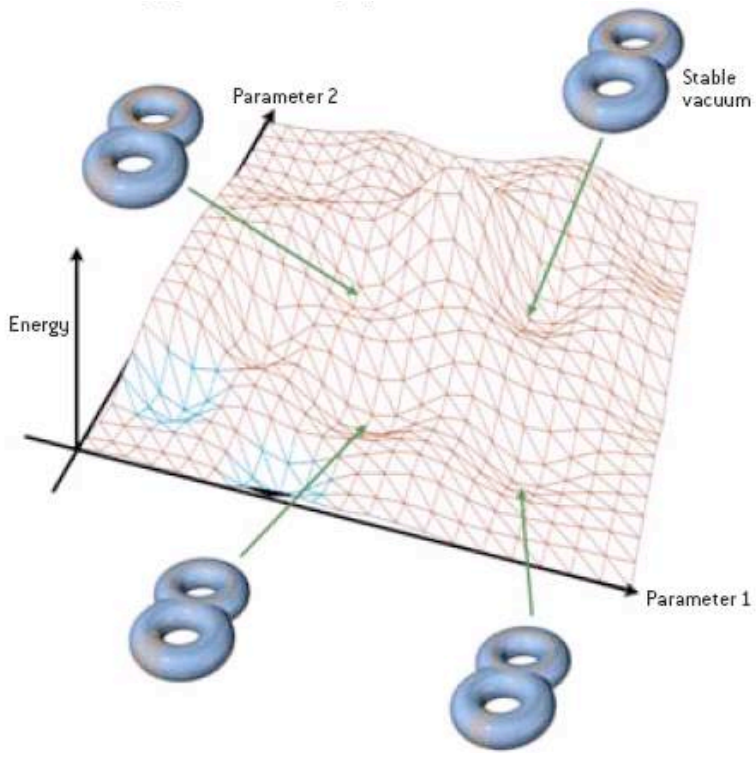
Branes and extra dimensions



Topology and combinatorics



RB & 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.

One theory, many solutions

- String theory: Unique theory, no adjustable parameters, many metastable solutions
- Combine D-branes and their associated fluxes to tie up 6 extra dimensions $\rightarrow$
- Huge number of different choices
- . . . each with its own low energy physics and vacuum energy

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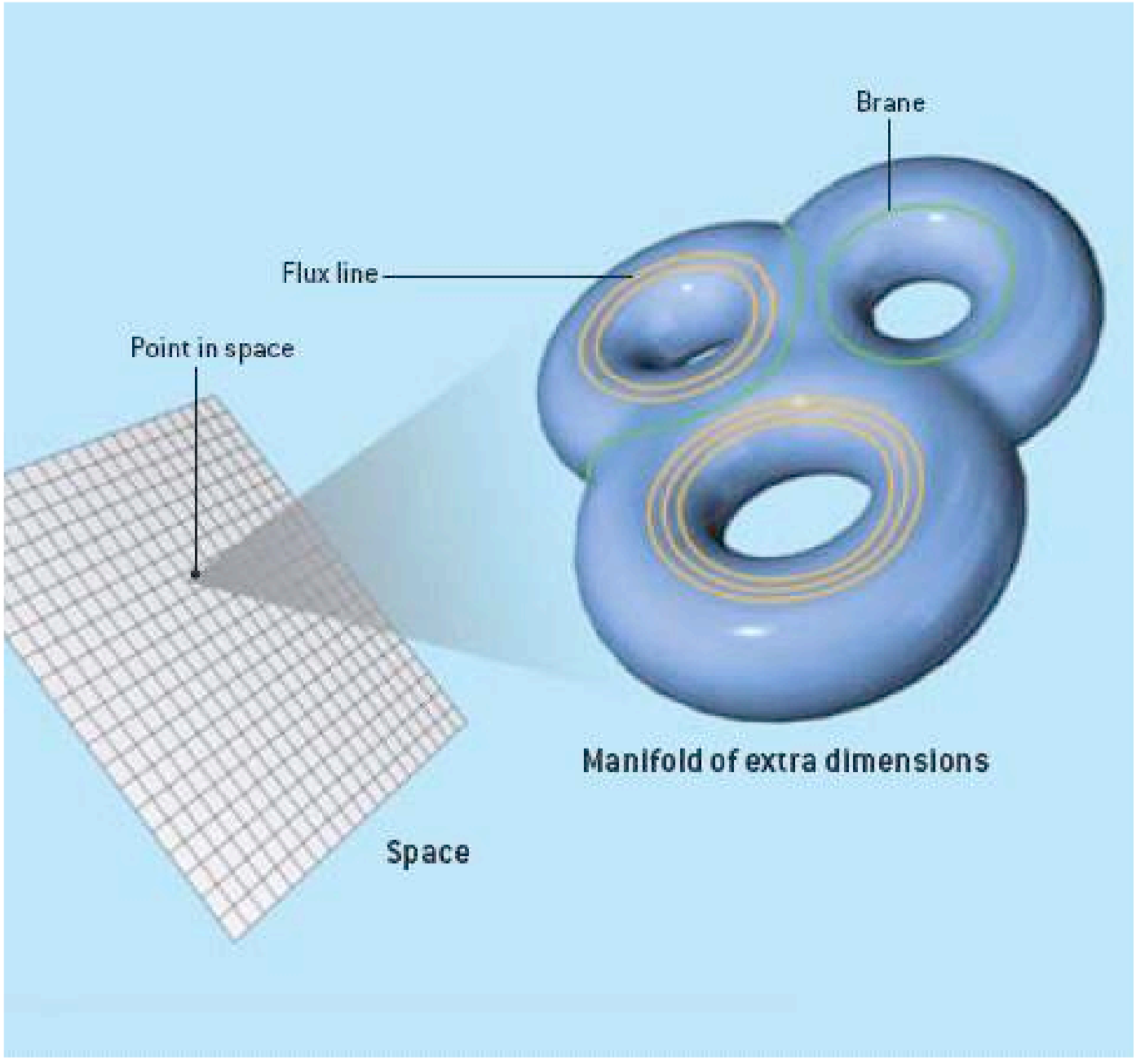
- Standard model: A few adjustable parameters, many metastable solutions
- Combine many copies of fundamental ingredients (electron, photon, quarks) $\rightarrow$
- Huge number of distinct solutions (condensed matter)
- . . . each with its own material properties (conductivity, speed of sound, specific weight, etc.)

Many ways to make empty space



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.

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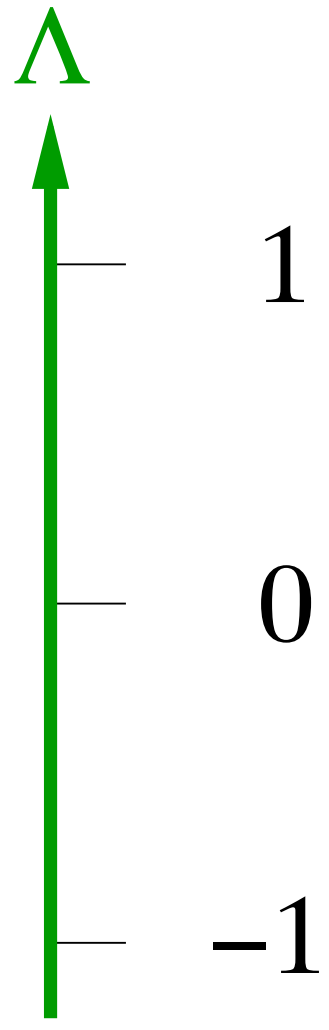
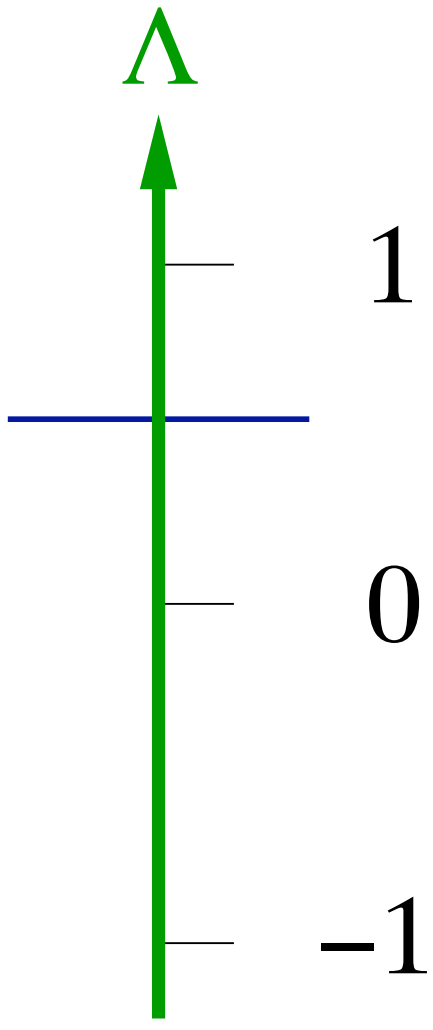
The spectrum of Λ

- In each vacuum, Λ receives many different large contributions



The spectrum of Λ

- In each vacuum, Λ receives many different large contributions
- $\rightarrow$ random variable with values between about -1 and 1



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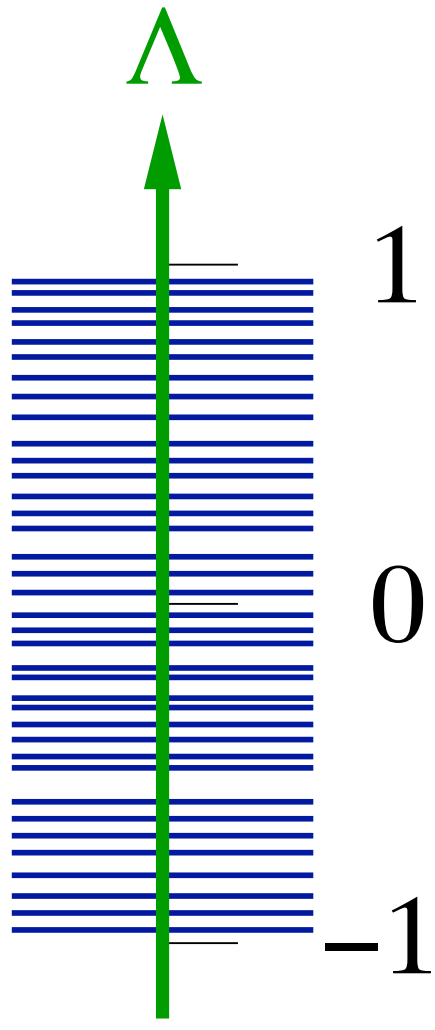

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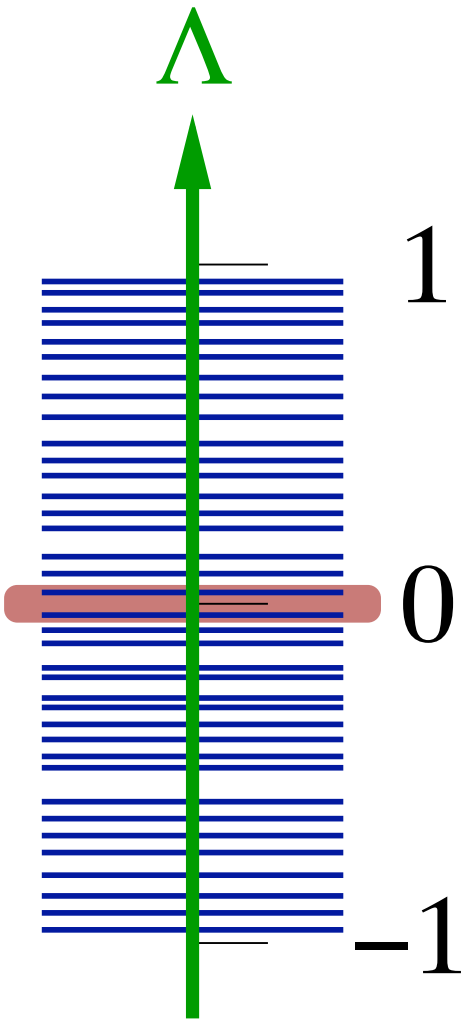
- About 10^{379} vacua with $|\Lambda| \sim 10^{-121}$



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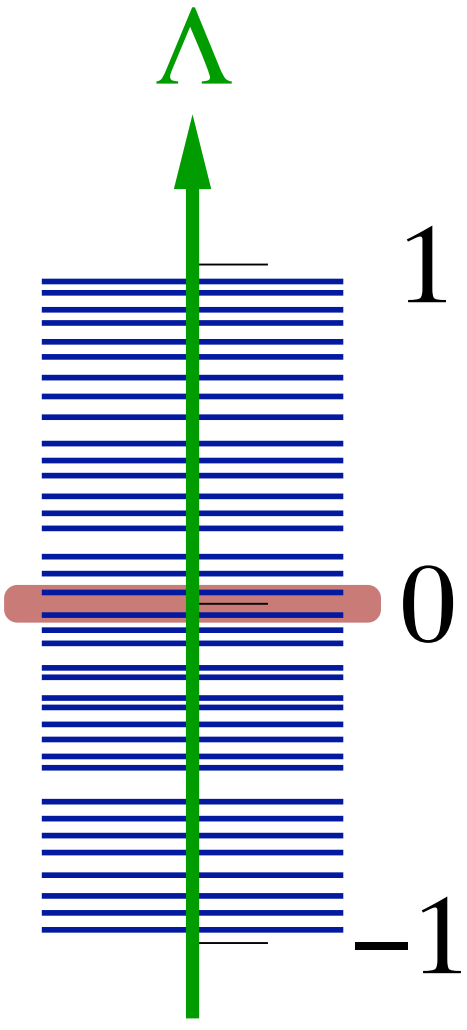
- $\rightarrow$ random variable with values between about -1 and 1
- With 10^{500} vacua, Λ has a dense spectrum with average spacing of order 10^{-500}
- About 10^{379} vacua with $|\Lambda| \sim 10^{-121}$
- *But will those special vacua actually exist somewhere in the universe?*



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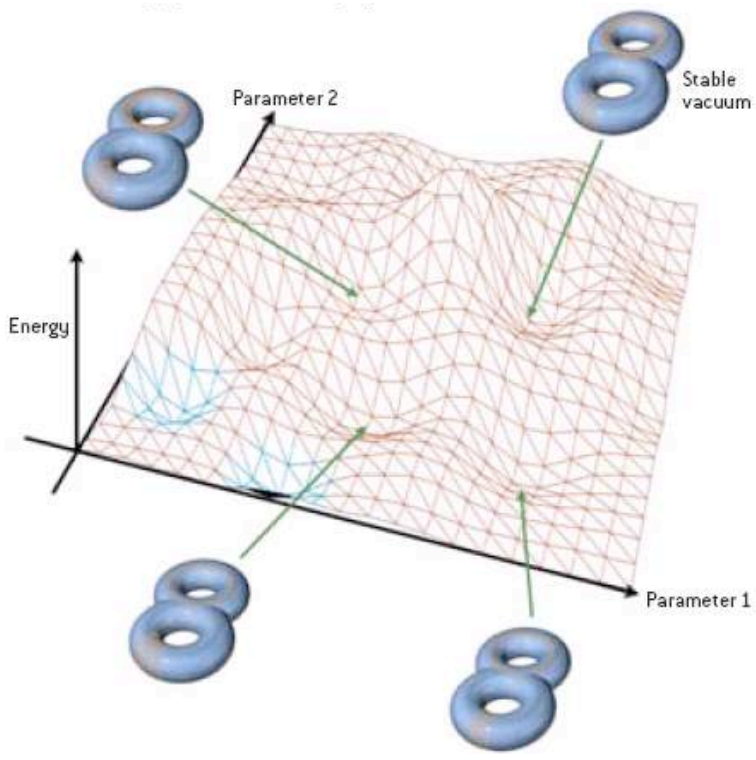
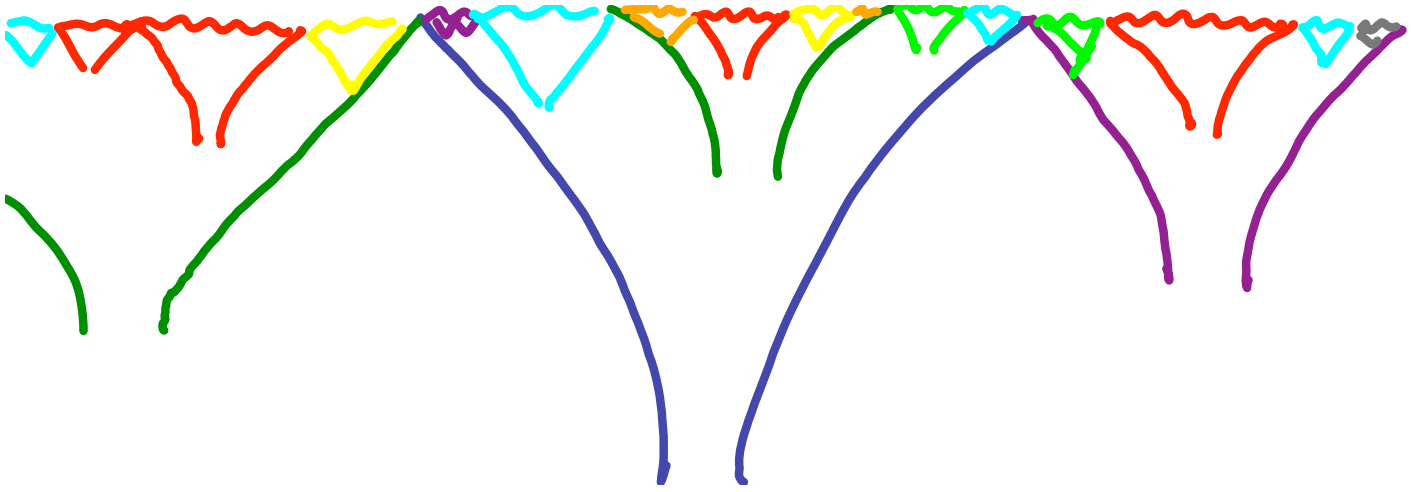
Metastability and eternal inflation



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

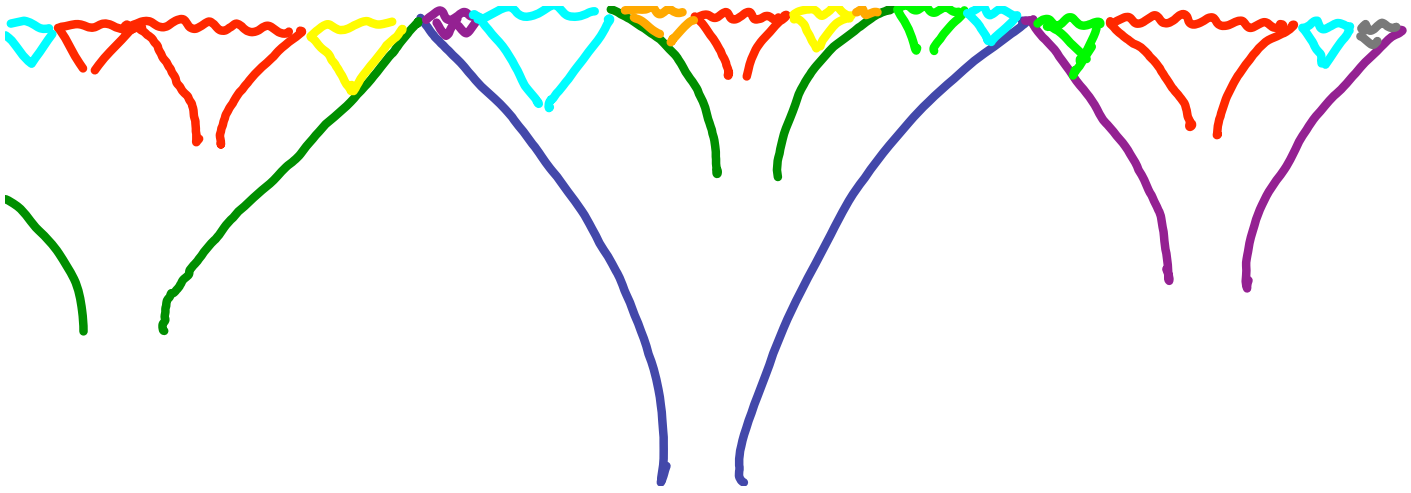
Metastability and eternal inflation



- 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

Our place in the multiverse

- Eternal inflation makes sure that vacua with $\Lambda \ll 1$ are cosmologically produced
- *But why do we find ourselves in such a special place in the Multiverse?*

Our place in the multiverse

- Eternal inflation makes sure that vacua with $\Lambda \ll 1$ are cosmologically produced
- *But why do we find ourselves in such a special place in the Multiverse?*
- Typical regions have $\Lambda \sim 1$ and admit only structures of Planck size, with at most a few quantum states (according to the holographic principle). They do not contain observers.
- Because of cosmological horizons, such regions will not be observed.

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

Collisions with other pockets may be detectable in the CMB

Connecting with standard cosmology

- What we call big bang was actually the decay of our parent vacuum
- Neighboring vacua in the string landscape have vastly different Λ
- $\rightarrow$ The decay of our parent vacuum released enough energy to allow for subsequent nucleosynthesis and other features of standard cosmology

The string multiverse is special

- This way of solving the cosmological constant problem does not work in all theories with many vacua
- In a multiverse arising from an (ad-hoc) one-dimensional quantum field theory landscape, most observers see a much larger cosmological constant
- (This is a theory that leads to a multiverse *and* has been falsified!)

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Probabilities in a large universe

The probability for observing the value I of some observable is proportional to the expected number of times $\langle N_I \rangle$ this value is observed in the entire universe.

$$\frac{p_1}{p_2} = \frac{\langle N_1 \rangle}{\langle N_2 \rangle} \,.$$

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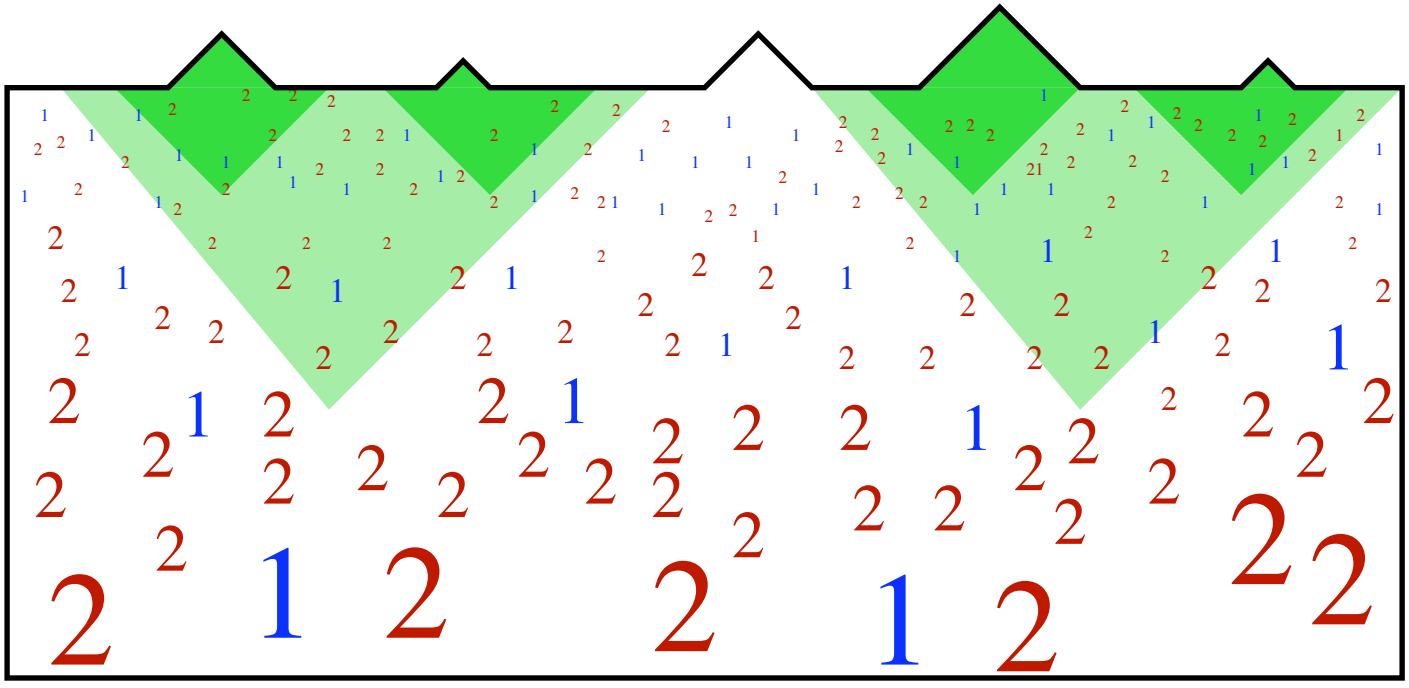
$$\frac{p_1}{p_2} = \frac{\langle N_1 \rangle}{\langle N_2 \rangle} \, .$$

(Strictly speaking, this is an *assumption*: We are typical observers. This assumption has been very successful in selecting among theories.)

The measure problem



- Infinitely many pockets of each vacuum
- Each pocket contains infinitely many observers (if any)
- Relative probabilities are ill-defined:

$$\frac{p_1}{p_2} = \frac{\langle N_1 \rangle}{\langle N_2 \rangle} = \frac{\infty}{\infty}$$

- Need a cutoff to render $\langle N_I \rangle$'s finite

Holographic approach to the measure problem

Ultimately, the measure should be part of a unique, fundamental description of the multiverse.

The holographic principle is widely expected to be central to any such theory. Different aspects of holography have been used to motivate different choices of measure:

- Black hole complementarity $\longrightarrow$ causal patch cut-off [RB '06]
- UV/IR relation in AdS/CFT $\longrightarrow$ light-cone time cut-off [Garriga & Vilenkin '08; RB '09; RB, Freivogel, Leichenauer & Rosenhaus '10]

Holographic measures

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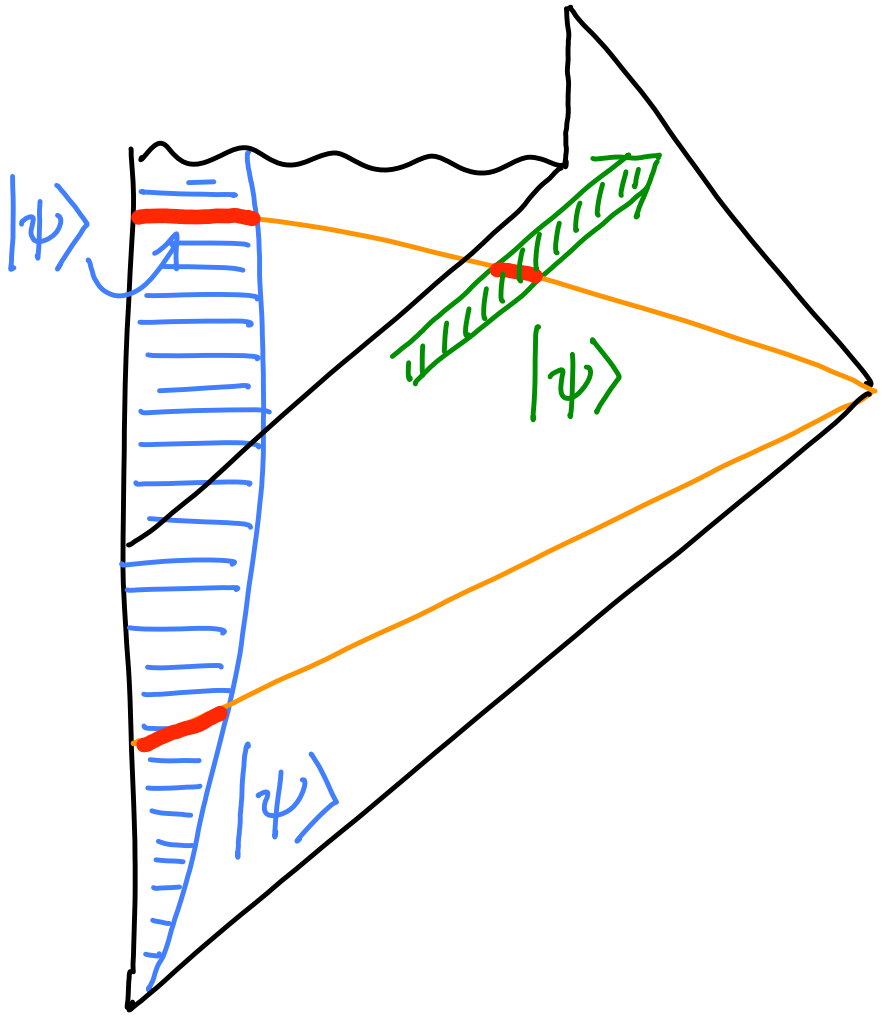
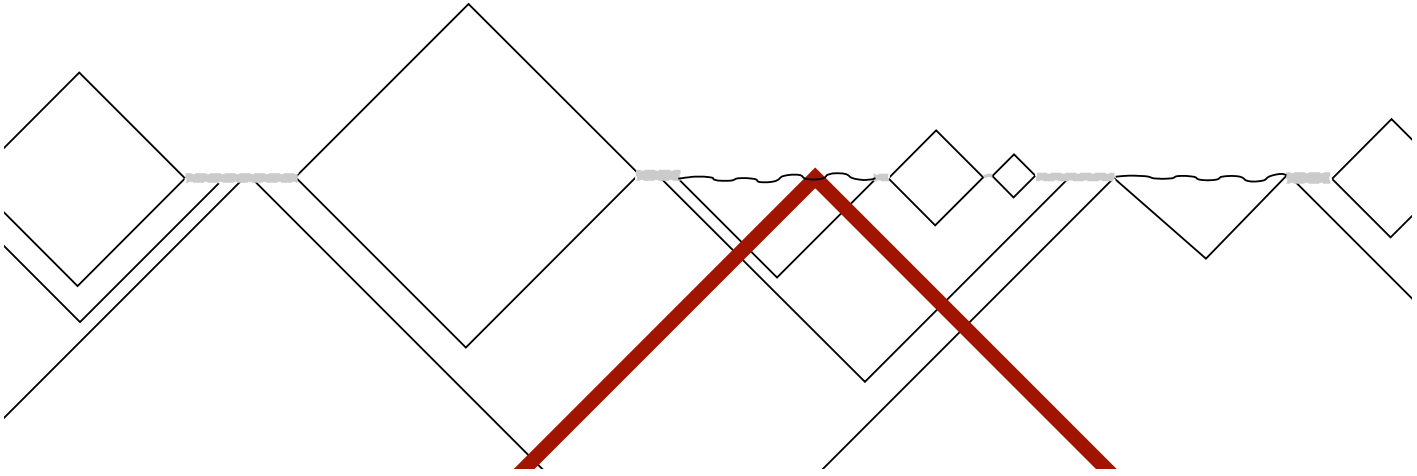
1. They both avoid catastrophic predictions, which plagued many older proposals (I won't show this here)
2. They both give probability distributions for Λ and other parameters that agree well with observation (which I will show explicitly for Λ)
3. Despite appearing very different, they are precisely equivalent (which I will not show) [RB & Yang '09]

The quantum xeroxing paradox



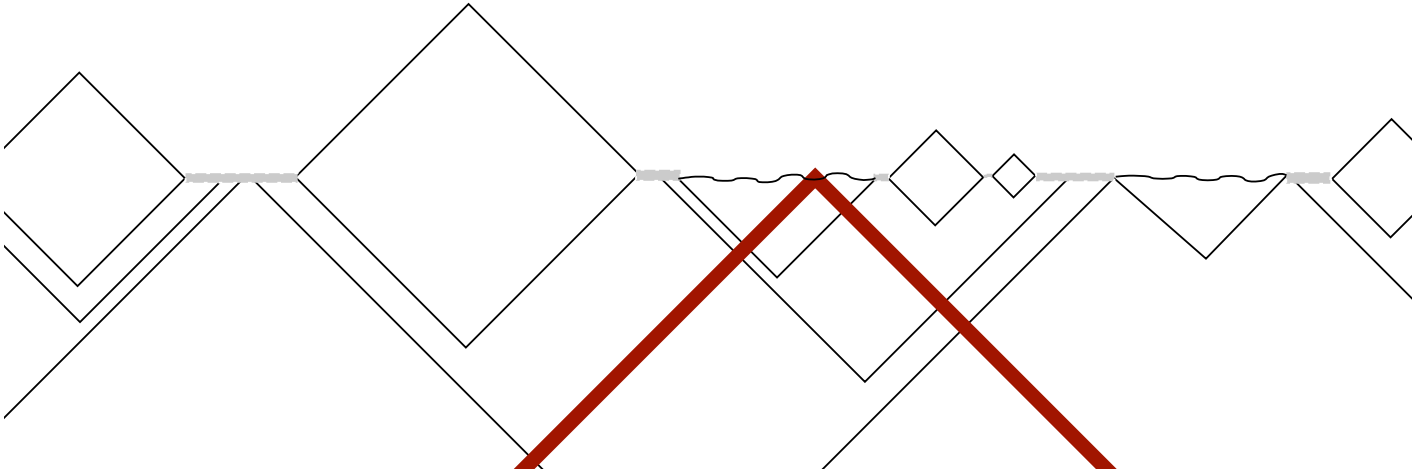
- If black hole evaporation is unitary, then globally it would lead to quantum xeroxing, which conflicts with the linearity of quantum mechanics
- But no observer can see both copies
- Physics need only describe experiments that can actually be performed, so we lose nothing by restricting to a causal patch

Causal Patch Cut-off



- Restrict to the causal past of the future endpoint of a geodesic.
- First example of a “local” measure: keep neighborhood of worldline.
- Roughly, in vacua with $\Lambda > 0$, count events inside the cosmological horizon.

Causal Patch Cut-off



- Restrict to the causal past of the future endpoint of a geodesic.
- First example of a “local” measure: keep neighborhood of worldline.
- Roughly, in vacua with $\Lambda > 0$, count events inside the cosmological horizon.
- What value of Λ is most likely to be observed, according to this measure?

Predicting the cosmological constant

- Consider all observers living around the time $t_{\rm obs}$ after the nucleation of their pocket universe.
- We are a member of this class of observers, so any conclusions will apply to us, but will be more general in that they include observers in very different vacua, with possibly very different particle physics and cosmology.
- What is the probability distribution over observed Λ?

Predicting the cosmological constant

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Because of de Sitter expansion, the number of observers inside the diamond becomes exponentially dilute after $t_\Lambda \sim \Lambda^{-1/2}$:

$$n_{\rm obs} \sim \exp(-3t_{\rm obs}/t_\Lambda) \ ,$$

so there are very few observers that see $\Lambda \gg t_{\rm obs}^{-2}$.

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Therefore,

$$\frac{dp}{d\log\Lambda} \propto \frac{d\tilde{p}}{d\log\Lambda} n_{\rm obs} \propto \Lambda \exp(-\sqrt{3\Lambda}\, t_{\rm obs})$$

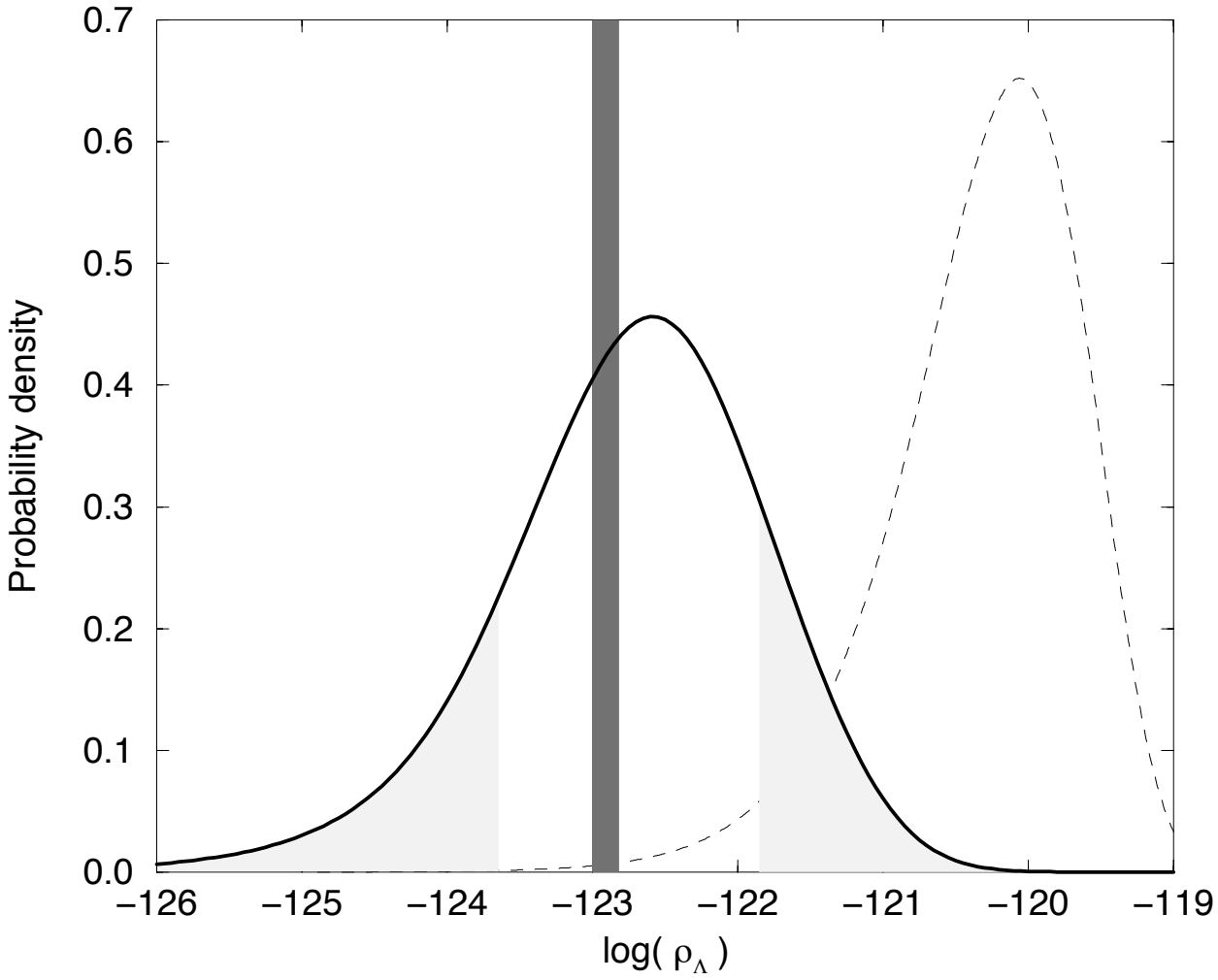
Predicting the cosmological constant

Therefore, the string landscape + causal patch measure predict

$$\Lambda \sim t_{\rm obs}^{-2}$$

- Solves the coincidence problem directly.
- Agrees better with observation than $\Lambda \sim t_{\rm gal}^{-2}$ [Weinberg '87]
  (especially if $\delta\rho/\rho$ is also allowed to scan)
- More general: Holds for all observers, whether or not they live on galaxies [RB & Harnik '10]

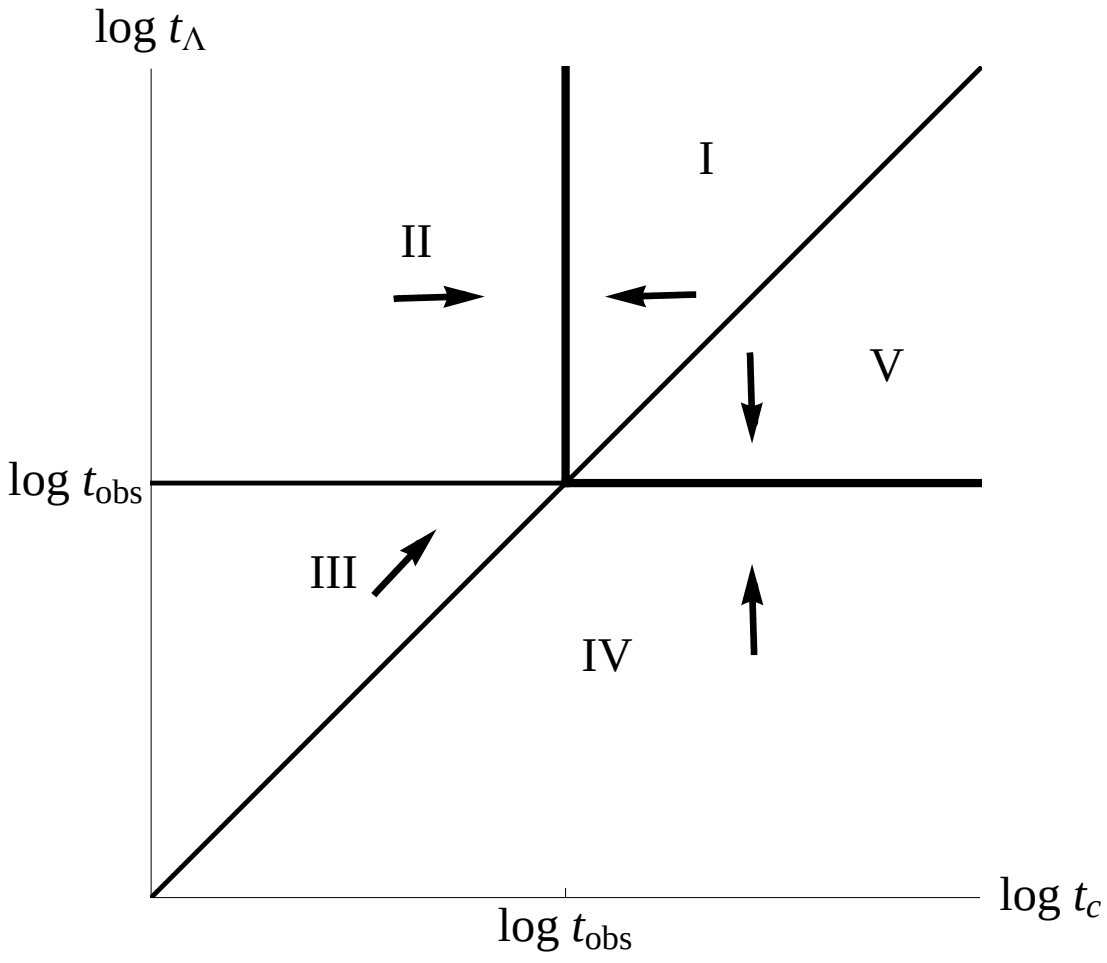
The probability distribution over Λ



solid line: prediction; *vertical bar:* observed value

[RB, Harnik, Kribs & Perez '07]

The probability distribution over Λ and N_e



Geometric effects dominate; no specific anthropic assumptions required $\rightarrow$ $t_\Lambda \sim t_c \sim t_{\rm obs} \sim \bar{\mathcal{N}}$

[RB, Freivogel, Leichenauer & Rosenhaus '10]