The Multiverse of String Theory

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Introduction

The (Old) Cosmological Constant Problem

Why the cosmological constant problem is hard

Recent observations

The Landscape of String Theory

Landscape Statistics

Cosmology: Eternal inflation and the Multiverse

The Measure Problem

Definition

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Calling these regions different “universes” is a matter of linguistic convenience. This situation is very similar to a piece of glass separating two different local environments, such as air and water. It does not mean that the fundamental laws of physics are different: everything is made of quarks, electrons, and photons.

Why consider Multiverse theories?

We see only a finite portion of global spacetime. In this "visible universe", environmental properties vary from place to place, and from time to time.

A theory of cosmology must allow at least for the observed amount of variation.

We cannot exclude observationally that more radical variations occur on larger scales. Therefore, we cannot reject a theory that gives rise to such additional variations (a "multiverse theory") just because it does.

Don't buy generic multiverses

"The" multiverse is not a theory.

A multiverse may be the dynamical consequence of a theory; whether or not it is, must be computed from the theory.

To make testable predictions in a multiverse theory, we need to compute

- the relative abundance of regions exhibiting different properties in the multiverse
- the relative abundance of observers in these regions

It is impossible to compute these quantities in the absence of a specific underlying theory.

Thus, it makes no sense to argue about whether "the" multiverse is right or wrong. I will discuss the multiverse arising from string theory.

Statistical predictions in physics

Many theories make “only” statistical predictions.

Even if such a theory allows for some observed phenomenon, we may reject the theory if the phenomenon is extremely unlikely. Examples: air collecting in corner of room; die shows 6 a million times,...

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What “extremely unlikely” means is a pragmatic question. We have never rejected any theory with 100% confidence. And we never will, since the universe only allows for a finite number of experiments, of any type.

Statistical predictions in a multiverse theory

Therefore, to rule out a theory that gives rise to a multiverse, it is not necessary to show that some feature of our observed local environment is strictly impossible in this theory.

It is sufficient to show that this feature is extremely unlikely to be observed.

Conditioning on observers

Our location in the visible universe is highly atypical. For example, most places are devoid of matter.

In the multiverse, we cannot expect to be in a typical place, any more than we would in the visible universe.

But as in any other theory, we should expect that our observations are typical among all observations.

What is an observer?

We do not need a general answer to this question in order to test a multiverse theory.

For example, we can condition on observers that are in some way like us. (Example follows.)

If our observations are extremely atypical even in this restricted ensemble, then the theory is ruled out.

Why consider string theory?

- It may be the correct fundamental theory (theory of everything)
- The particular kind of multiverse that string theory gives rise to can explain the small weight of empty space (cosmological constant problem, dark energy problem)
- It may explain many more things, none of which I will have time to discuss

  (see, e.g. [Freivogel 2008]: axionic dark matter)

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}.

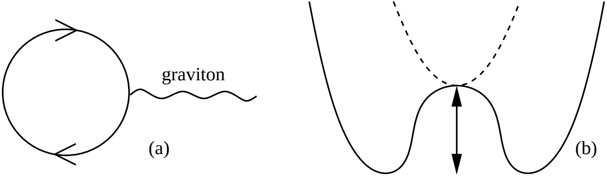
Quantum contributions to Λ

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?

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}

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 $\Lambda = 0$.

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

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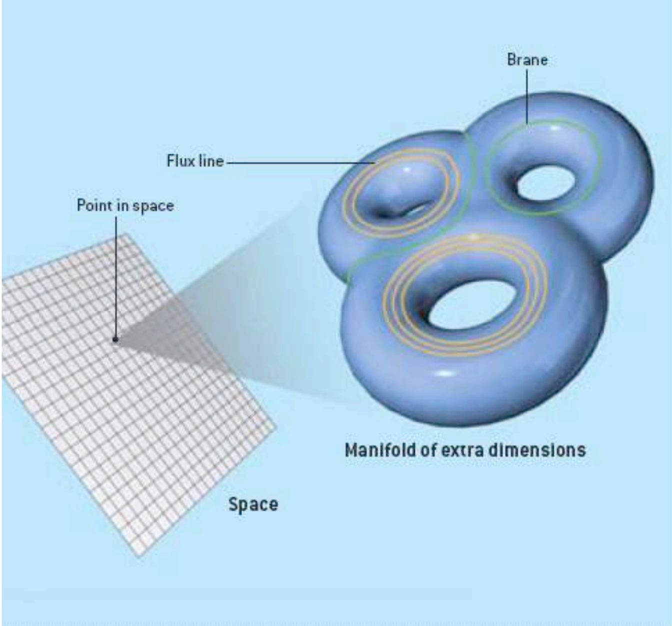
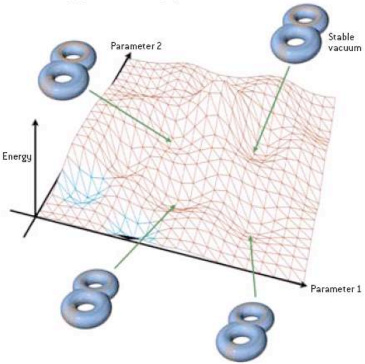
- String theory: Unique theory, no adjustable parameters, many metastable solutions
- Combine D-branes and their associated fluxes, to tie up 6 extra dimensions

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

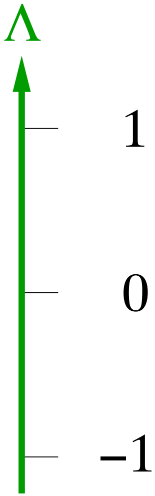
To make predictions and test the landscape of string theory, we face three challenges:

- Landscape statistics
- Cosmological dynamics
- Measure problem

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

The spectrum of Λ

- In each vacuum, Λ receives many different large contributions



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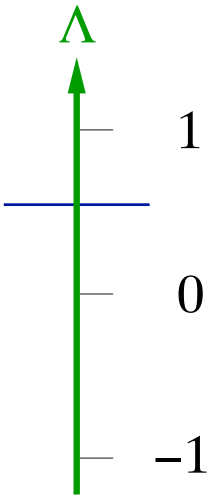
- → random variable with values between about -1 and 1



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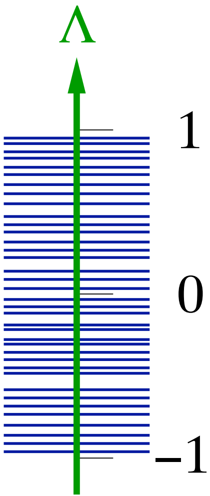

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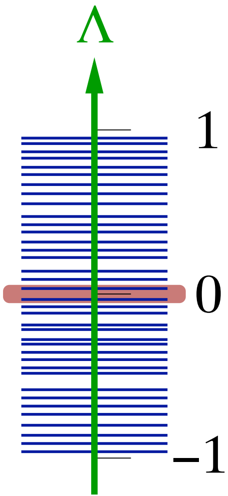

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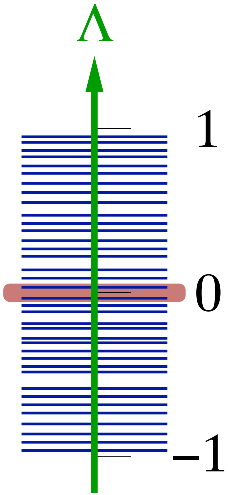

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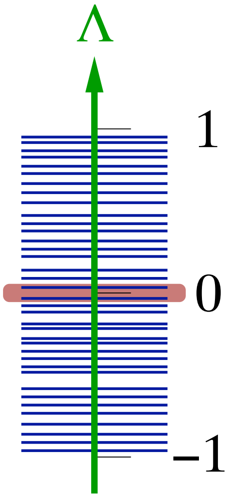
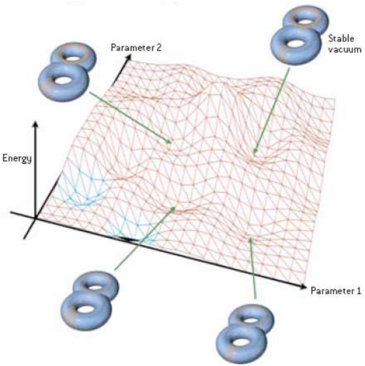
- But will those special vacua actually exist somewhere in the universe?
- And why should we find ourselves in such a rare vacuum?

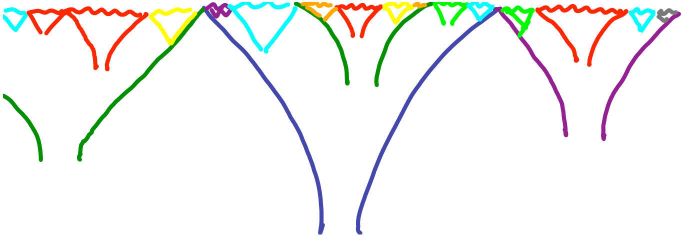


Metastability and eternal inflation



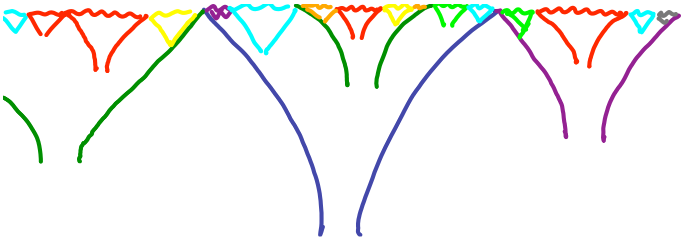
- Fluxes can decay spontaneously (Schwinger process)
- $\rightarrow$ landscape vacua are metastable
- First order phase transition
- Bubble of new vacuum forms locally.

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

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

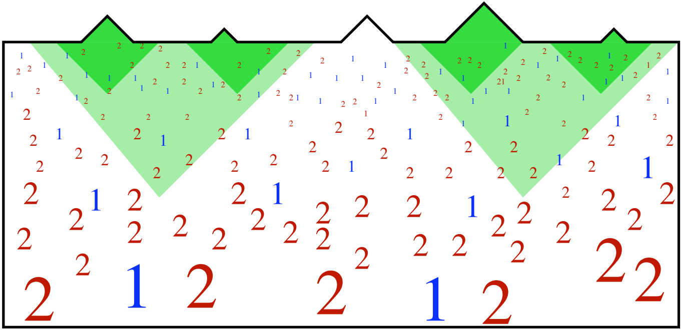
Connecting with standard cosmology

- 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 (R.B. & Polchinski, 2000)

The string multiverse is special

- This way of solving the cosmological constant problem does not work in any old multiverse
- In a multiverse arising from an (ad-hoc) one-dimensional quantum field theory landscape, most observers see a much larger cosmological constant (Abbott; Brown & Teitelboim, 1980s)
- This is a simple example of how not all multiverses are the same: some are ruled out while others are not.

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; arises in any theory that gives rise to eternal inflation

Build quantitative models subject to usual criteria:

- simple, well-defined, predictive
- not in conflict with observation

Measures

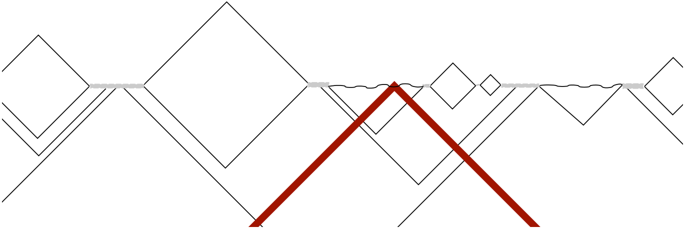
A small number of measures survive for which

- no “really bad” problems are known, and
- whose predictions are compatible with observed cosmological and particle physics parameters

Causal Patch measure

Example: Causal Patch cut-off [RB 2006]: Restrict to the causal past of the future endpoint of a geodesic.

First example of a “local” measure: keep neighborhood of worldline.
Variations: Causal Diamond cut-off, Apparent Horizon cut-off



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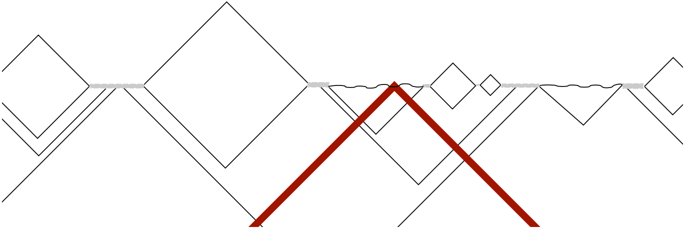


Roughly, in vacua with $\Lambda > 0$, count observers inside the cosmological horizon. What value of Λ do we predict?

Predicting the cosmological constant

Consider a vacuum with observers living around the time $t_{\rm obs}$. What is the probability distribution over observed Λ?

Landscape statistics: Most vacua have large Λ,

$$\frac{d\tilde{p}}{d\log\Lambda} \propto \Lambda$$

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 $\Lambda \gg t_{\rm obs}^{-2}$. 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

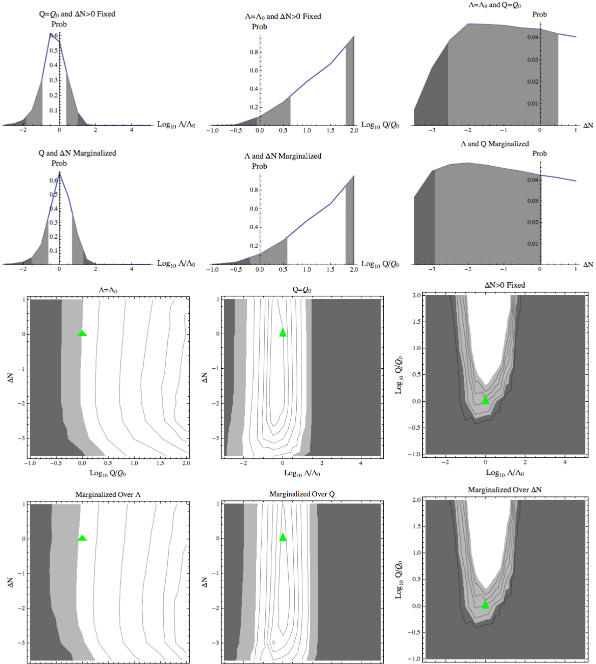
Therefore, the string landscape + causal diamond measure predicts

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

[RB, Harnik, Kribs & Perez 2007]

- Solves the coincidence problem directly.
- Agrees better with observation than $\Lambda \sim t_{\rm gal}^{-2}$ [Weinberg 1987] (especially if $\delta\rho/\rho$ is also allowed to scan)
- More general: Holds for all observers, whether or not they live on galaxies

[RB & Leichenauer 2008, 2009]



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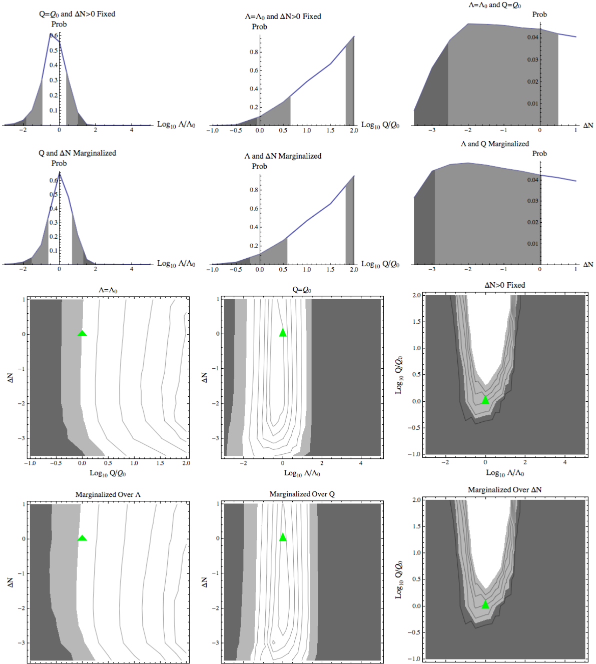

Measure problem: Theoretical developments

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
- UV/IR relation in AdS/CFT $\longrightarrow$ light-cone time cut-off [Garriga & Vilenkin '08; RB '09]

These cut-offs look very different, so which gives the right probabilities?

Dualities

They give exactly the same probabilities!

Recently, some global-local dualities were discovered which imply the equivalence of certain pairs of cut-offs:

- Fat geodesic (local) $\longleftrightarrow$ scale factor time (global) [RB, Freivogel & Yang, 2008]
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with the initial conditions for the local cut-off given by the longest-lived metastable vacuum in the landscape.

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Calling it a duck

"When I see a bird that
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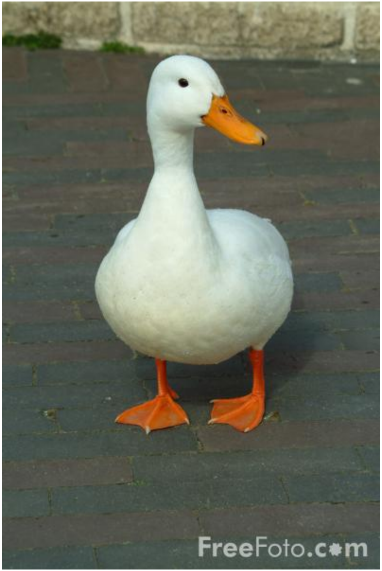

Why “dark energy” is vacuum energy

- 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 $\Lambda = 0$).
- All we can do is 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?

⟶

Not calling it a duck

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

$\longrightarrow$

- Why is this unicorn wearing a duck suit?

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- Why is this unicorn wearing a duck suit?
- Why have we never seen a unicorn without a duck suit?

Not calling it a duck

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

$\longrightarrow$

- 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

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

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- Whether Λ is very small, or zero,
  either way we must explain why it is not huge

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Anthropic weighting

- Eternal inflation makes sure that vacua with tiny Λ are cosmologically produced
- Still need to explain why we find ourselves in such a special place in the Multiverse
- However, the real question (Weinberg, 1987) is: Is the Λ we see special among observed values (in the Multiverse)?
- Typical regions have $\Lambda \sim 1$ and admit only structures of Planck size, with a few quantum states. They do not contain observers, so they will not be observed.
- This argument shows quite generally that the landscape predicts an "unnatural" value, $\Lambda \ll 1$. It does not, however, allow us to derive its magnitude.

Anthropic weighting

Are we putting humans first, the laws of Nature second?

Conditioning on observers is used, here,

- *not* to select fundamental parameters of the theory
- *nor* to select initial conditions of the universe
- but to identify the regions that will be observed in the multiverse

This should not be controversial. The scientific question is whether the multiverse is actually realized in Nature or not. String theory suggests that it is, and to probe it further, we need to extract predictions, which will be biased (though far from determined) by the locations of observers.

Anthropic weighting

But how do we define what "observers" are? Sidestep this thorny issue by asking smart questions:

- Not everything is anthropic. Many properties of vacua don't affect life, and others may simply occur in all or none of the vacua.
- Restrict to observers like us and/or vacua that differ from ours only through a few parameters. If our observations are highly atypical among this restricted group, then the landscape is ruled out.
- Identify abstract features correlated with complexity, e.g. entropy production; exploit large numbers

R.B. (2006); R.B., Harnik, Kribs & Perez (2007)

We need not test every consequence of a theory—just enough to rule it out or confirm it.