The State of the Multiverse: The String Landscape, the Cosmological Constant, and the Arrow of Time

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Stephen Hawking: 70th Birthday Conference
Cambridge, 6 January 2011

RB & Polchinski, hep-th/0004134; RB, arXiv:1112.3341

The Cosmological Constant Problem

The Landscape of String Theory

Cosmology: Eternal inflation and the Multiverse

The Observed Arrow of Time

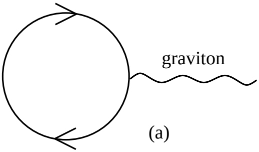
The Arrow of Time in Monovacuous Theories

A Landscape with Two Vacua

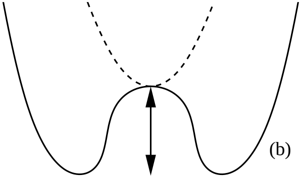
A Landscape with Four Vacua

The String Landscape

Magnitude of contributions to the vacuum energy



(a)



(b)

- Vacuum fluctuations:
  SUSY cutoff: → 10^{-64}; Planck scale cutoff: → 1
- Effective potentials for scalars:
  Electroweak symmetry breaking lowers Λ by approximately $(200\text{ GeV})^4 \approx 10^{-67}$.

The cosmological constant problem

- Each known contribution is much larger than 10^{-121} (the observational upper bound on $|\Lambda|$ known for decades)
- 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?

Recent observations

Supernovae/CMB/
Large Scale Structure:

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

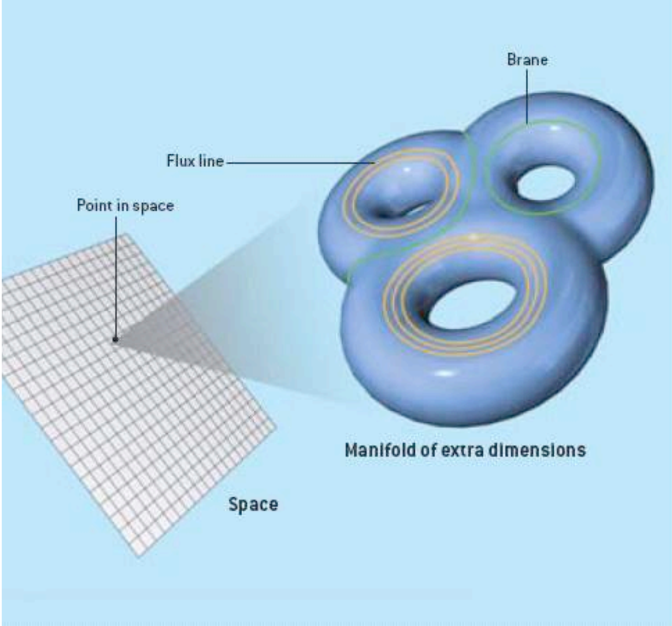
Recent observations

Supernovae/CMB/
Large Scale Structure:

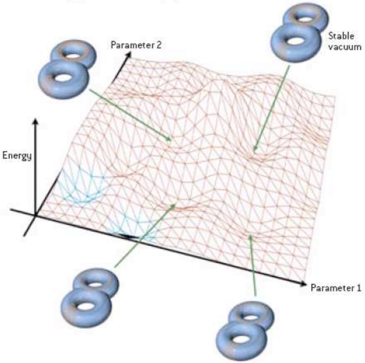
$$\Lambda \approx 0.4 \times 10^{-121} \neq 0$$

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

Many ways to make empty space



Topology and combinatorics

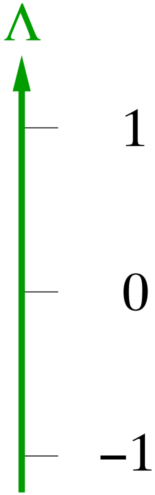


RB & Polchinski (2000)

- A six-dimensional manifold contains hundreds of topological cycles. (Say, 500.)
- Suppose each cycle can hold 0 to 9 units of flux
- Then there will be 10^{500} different configurations.
- This picture is (so far) supported by detailed constructions [Kachru, Kallosh, Linde & Trivedi 2003; Denef and Douglas 2004; . . .]

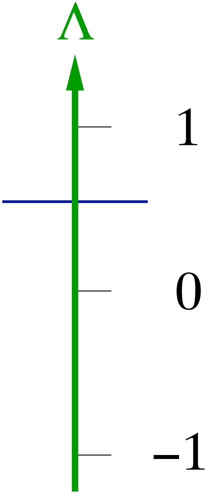
The spectrum of Λ

- In each vacuum, Λ receives many different large contributions



The spectrum of Λ

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



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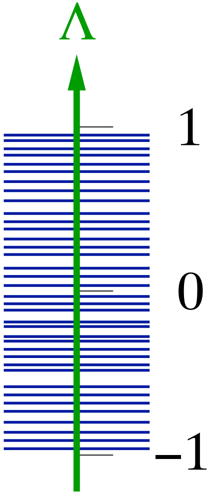
- With 10^{500} vacua, Λ has a dense spectrum [RB & Polchinski 2000]



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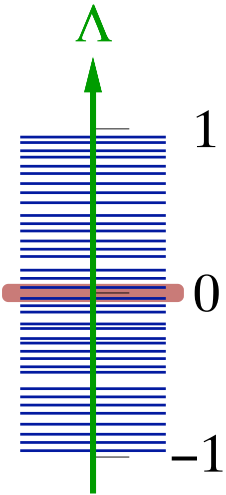

The spectrum of Λ

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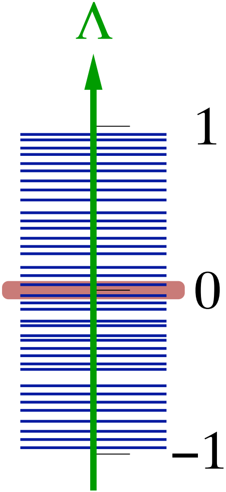
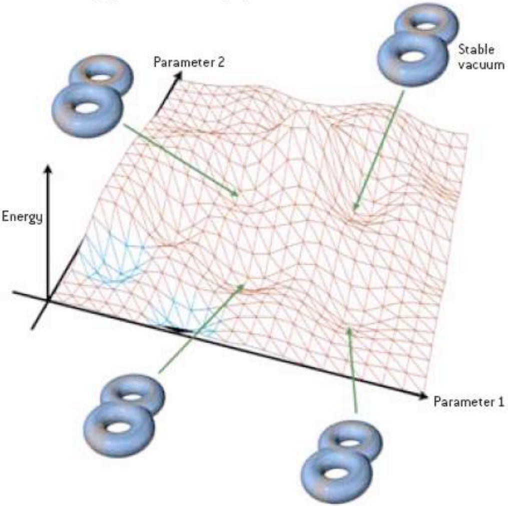
- Many vacua with $|\Lambda| \lesssim 10^{-121}$
- *But will those special vacua actually exist somewhere in the universe?*

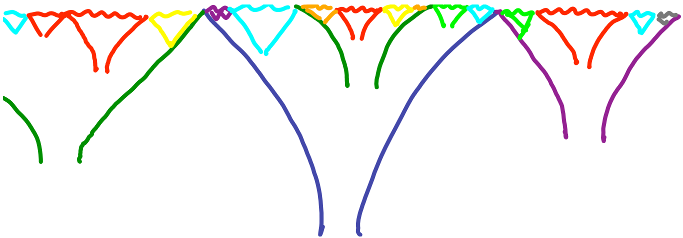


Metastability and eternal inflation



Fluxes can decay spontaneously (Schwinger process)

Metastability and eternal inflation



- Bubble expands to eat up the parent vacuum
- But for $\Lambda > 0$, the parent vacuum expands even faster

Guth & Weinberg (1982)

- So the parent vacuum can decay again somewhere else
- $\rightarrow$ Eternal inflation, infinitely many pocket universes

Our place in the multiverse

- Eternal inflation ensures that vacua with $\Lambda \ll 1$ are cosmologically produced RB & Polchinski 2000
- *But why do we find ourselves in such a special place in the Multiverse?*

Our 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.

Quantitative analysis: $\Lambda \sim t_{\rm gal}^{-2}$ Weinberg 1987

$\ldots$ [...]

$\Lambda \sim t_{\rm obs}^{-2}$ RB, Harnik, Kribs & Perez 2007

RB, Freivogel, Leichenauer & Rosenhaus 2011

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 (“Large Step Size”)
- → The decay of our parent vacuum released enough energy to allow for subsequent nucleosynthesis and other features of standard cosmology RB & Polchinski 2000

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 [Abbott 1985, Brown & Teitelboim 1987]
- (This is a theory that leads to a multiverse *and* has been falsified!)

String Theory is special

- Topology of extra dimensions, D-branes, Fluxes generate high-dimensional parameter space
- which generates discretuum of vacua without fine-tuning
- while preserving Large Step Size, thus circumventing the empty universe problem

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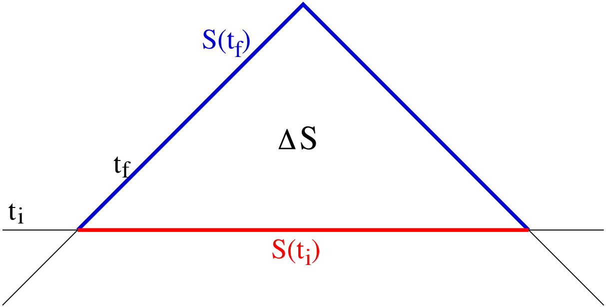
Definition

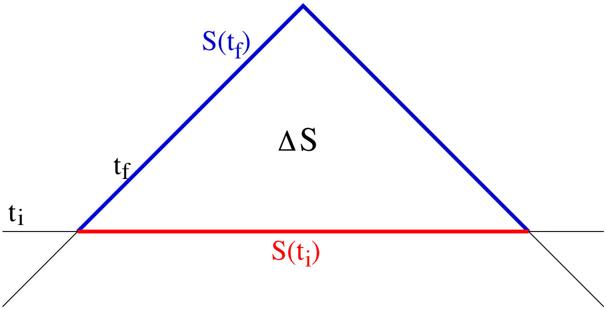


The observed arrow of time is the entropy

$$\Delta S \equiv S(t_f) - S(t_i)$$

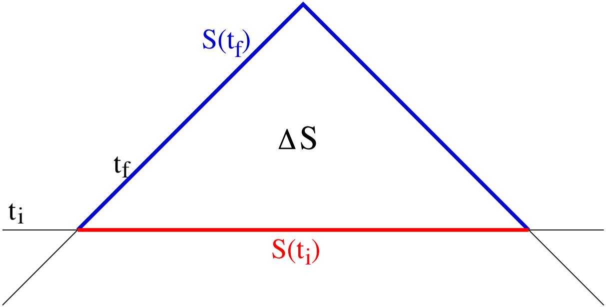
produced in our past light-cone since the time t_i.

Definition



E.g., with $t_i = t_{\rm BBN} = 3$ min, one finds $\Delta S \sim 10^{103}$. This is dominated by the supermassive black holes that formed since nucleosynthesis.

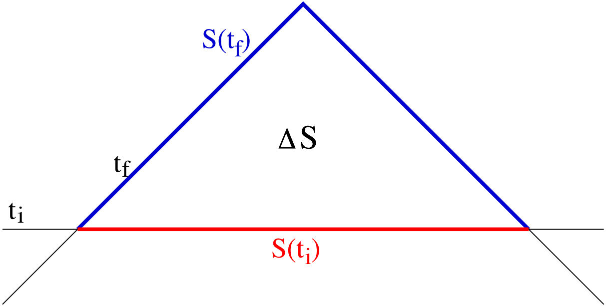
Definition



Ordinary matter entropy contributes only 10^{86}, from the cosmic infrared background produced by galactic dust

RB, Harnik, Kribs & Perez 2007

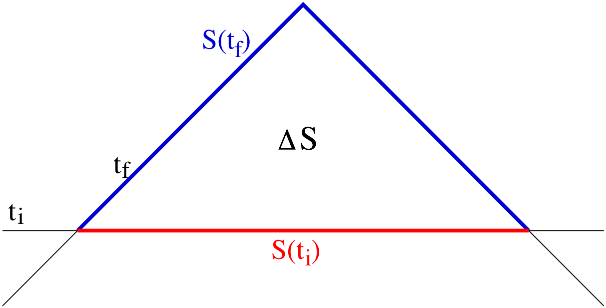
Definition



The exact value of ΔS will not be important.

The point is that it is large: the early universe was in a very special state, even more special than the current state, by a superexponential factor such as $\exp(10^{103})$.

Claim



Whether or not a theory predicts an arrow of time depends primarily on its vacuum structure.

In particular, low-entropy initial conditions are not necessary, and/or not sufficient, for an arrow of time, depending on the vacuum structure.

Negative Cosmological Constant

Consider a flat or open FRW universe with $\Lambda < 0$ that begins with a big bang and radiation domination. It will end in a big crunch on a timescale of order $|\Lambda|^{-1/2}$.

There are at least two necessary conditions for an arrow of time:
low initial entropy, and small $|\Lambda|$.

Negative Cosmological Constant

- Since $S(t_i)$ is non-negative, an arrow of time requires the existence of a past light-cone with $S(t_f) > 10^{103}$
- The covariant entropy bound [RB 1999] implies

$$S(t_f) \lesssim \Lambda^{-2}$$

RB, Freivogel & Leichenauer 2010

- Thus, the theory predicts the observed arrow of time only if $|\Lambda| \lesssim 10^{-52}$

Negative Cosmological Constant

- The rate for large downward fluctuations of the entropy is $\exp(-10^{103})$, and time is short, so the Second Law rules
- Thus, the entropy at the big bang must satisfy $S(0) \leq S(t_i) \leq S(t_f) - 10^{103}$.
- The theory predicts an arrow of time only if initial conditions select for a state of low coarse-grained entropy (compared to some later state)

Negative Cosmological Constant

There are other necessary conditions, such as

- absence of large positive spatial curvature
- existence of a matter-dominated era
- …

Negative Cosmological Constant

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- …

In any case, this model conflicts with observation ($\Lambda > 0$).

Positive Cosmological Constant

Consider a flat or open FRW universe with $\Lambda > 0$ that begins with a big bang and radiation domination.

In this model, an arrow of time is not predicted, even if the initial entropy and the vacuum energy are both small.

Dyson, Kleban & Susskind 2002

Guth's talk, yesterday

Positive Cosmological Constant

- After a finite period of duration $t_\Lambda \sim \Lambda^{-1/2}$ after the big bang, vacuum energy dominates. At late times, the universe becomes empty de Sitter space.
- The cosmological event horizon and its interior, the “causal patch”, satisfy analogues of the laws of black hole thermodynamics [Gibbons & Hawking 1977]
- de Sitter space is a thermal state with temperature

$$T \sim \Lambda^{1/2} \; .$$

- What happens at early times in the causal patch is irrelevant, since an infinite number of observers (including states such as ours) are thermally produced at late times.

Positive Cosmological Constant

- Consider two coarse-grained states with equal energy but different entropy $S_2 > S_1$.
- Boltzmann:

$$p_i \sim \exp(S_i - E_i/T)$$

- Hence, state 2 will be produced more frequently, by a factor

$$\exp(S_2 - S_1) \; .$$

Positive Cosmological Constant

- Let state 1=the observed universe, and state 2=the observed universe but with a CMB temperature of 4 K and a slightly smaller number of protons.
- Each state contains the same number of observers, but state 2 is produced more frequently by a factor $\exp(10^{88})$.
- Other states with yet more entropy (and lower energy) are still more strongly preferred.

Positive Cosmological Constant

- The most probable state is empty de Sitter space (with $S = 3\pi/\Lambda$ and $E = 0$), but this will not be observed.
- The most probable state with observers contains only one observer, otherwise empty de Sitter space (a “Boltzmann brain”).
- A state such as ours, far from maximum entropy, has probability ≈ 0.
- The theory predicts that the vast majority of observers see a small arrow of time, corresponding to their own decay back to equilibrium (i.e., to empty de Sitter space).

Positive Cosmological Constant

- This result is due to Dyson, Kleban, and Susskind [2002].
- It assumes that stable de Sitter space is a finite-entropy quantum system with unitary, ergodic evolution.
- It implies that stable de Sitter space is experimentally ruled out because it conflicts with our observation of a large arrow of time.
- They concluded that the observed positive vacuum energy must be metastable.

Consider a metastable de Sitter vacuum

Goal: a model with $\Lambda > 0$ that predicts an arrow of time.

The causal patch measure

I will use the causal patch measure [RB 2006]:

$$\frac{p_I}{p_J} = \frac{\langle N_I \rangle}{\langle N_J \rangle} ,$$

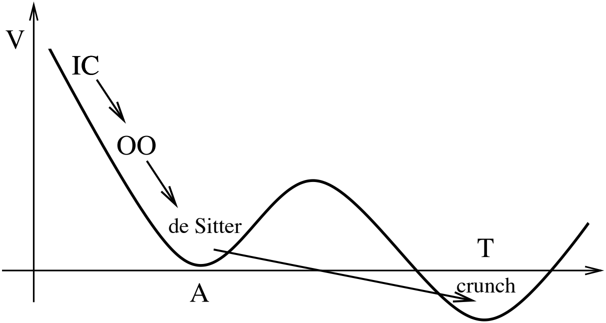
where N_I is the expected number of times events of type I happen within the event horizon (the past of a maximally extended geodesic).

Without a measure, N_I and N_J would both diverge.

This particular regulator is motivated by the resolution of the xeroxing paradox in unitary black hole evolution.

For the arrow of time analysis, several other measures give the same results.

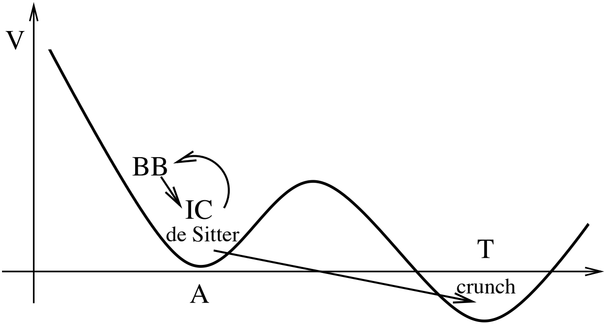
A theory with an arrow of time



If initial conditions are low-entropy, and
if vacuum *A* decays faster than it produces Boltzmann brains
($\Gamma_{BB,A} < \Gamma_A$),
then an arrow of time is predicted.

(See, however, [Page 2006].)

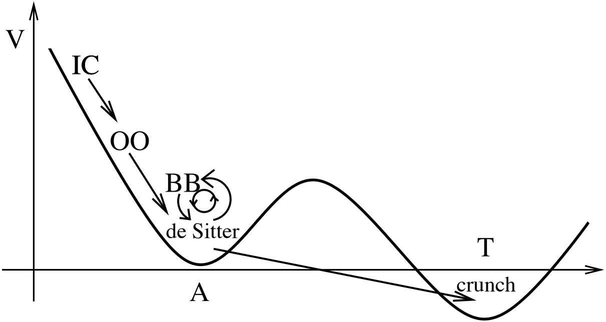
A theory without an arrow of time



Q: What if initial conditions have high entropy?

A: $N_{\mathrm{BB}} \sim \Gamma_{BB,A} \ggg N_{\mathrm{OO}} \sim \Gamma_{OO,A}$

A theory without an arrow of time



Q: What if $\Gamma_{BB,A} < \Gamma_A$?

A: $N_{\mathrm{BB}} \sim \Gamma_A^{-1} \ggg N_{\mathrm{OO}}$

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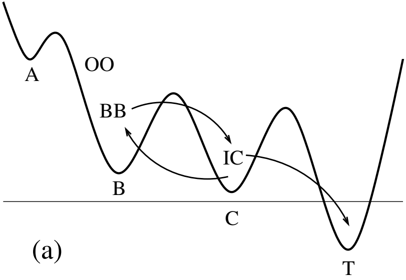
Goal

Goal: a model with $\Lambda > 0$ that predicts an arrow of time, despite initial conditions with higher entropy than the observed universe:

$$S(0) \gg S(t_f)$$

We will see that this model has features that are shared by the string landscape.

Two landscapes with four vacua

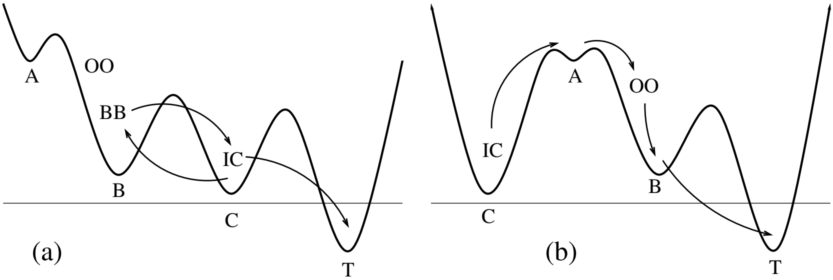


Theory (a) and theory (b) differ only in the ordering of vacua.

Same vacuum energies, same low-energy physics,
same initial conditions.

Observers of any type exist only in B; $\Gamma_{BB,B} < \Gamma_B$.

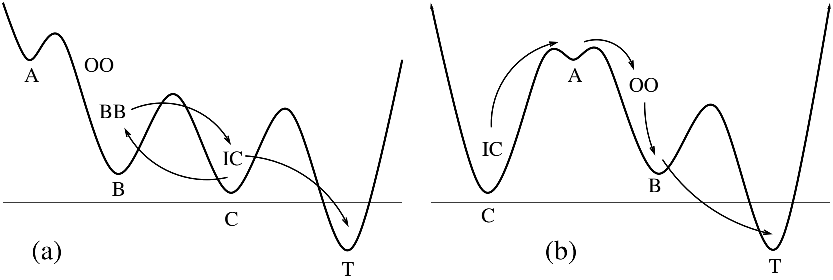
Two landscapes with four vacua



In theory (b), ordinary observers dominate, despite arbitrarily high entropy initial conditions in vacuum *C*. [RB 2011]

Vacuum *A* acts as a bottleneck.

Two landscapes with four vacua

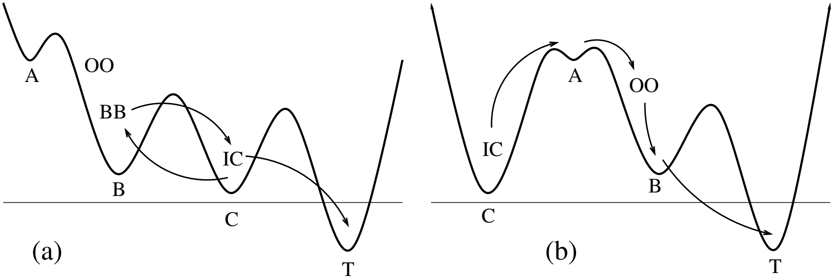


An example of a theory of initial conditions that would select vacuum *C* is the Hartle-Hawking no-boundary proposal [1983].

It selects for the empty de Sitter vacuum of highest entropy, with probability $\exp(3\pi/\Lambda)$.

In the landscape (b), the no-boundary proposal is compatible with the observed arrow of time.

Two landscapes with four vacua



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However, Page 2012, p.c.

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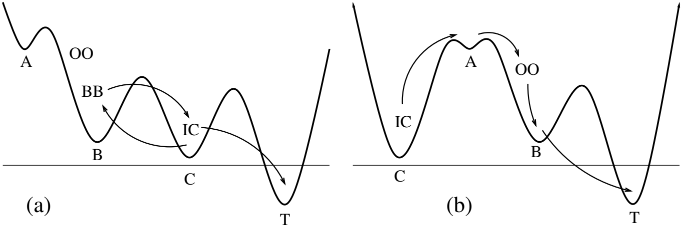

The string landscape shares features with the second model:

- No Fine-Tuning → No observers in initial vacuum
- Even Boltzmann brains require $\Lambda \ll 1$; such vacua must be populated by some decay path
- Large Step Size: vacua with observers will be entered from high-Λ vacua, with enough free energy to produce ordinary observers
- Boltzmann brains are Boltzmann-suppressed

The Arrow of Time in the String Landscape

Assuming $\Gamma_{BB,A} < \Gamma_A$ for all de Sitter vacua,

RB & Freivogel 2006
RB, Freivogel & Yang 2008
De Simone et al. 2008

one can show that

an arrow of time is predicted independently of the initial entropy.

RB 2011

Happy Birthday Stephen!

Happy Birthday Stephen!

Thank you for making our life beautifully difficult.