Cosmological Predictions in the Landscape

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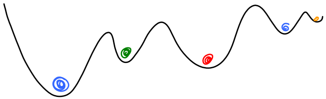
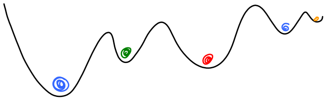
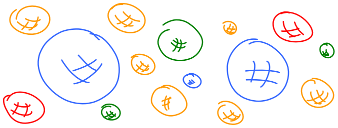
Landscape statistics



Raw landscape statistics is not enough. There are additional selection effects:

Landscape statistics





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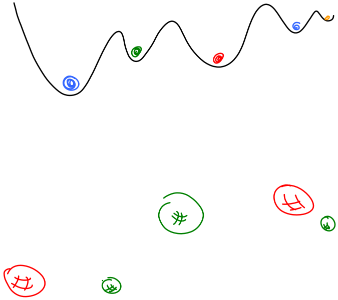
1. Cosmological dynamics can enhance or suppress the probability of vacua

Landscape statistics



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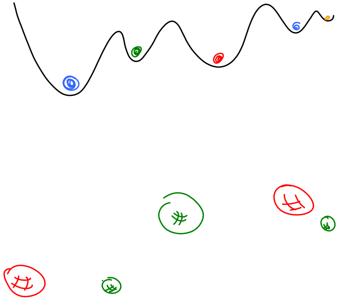
2. Anthropic selection (e.g., $\Lambda \ll 1$)

Landscape statistics



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2. Anthropic selection (e.g., $\Lambda \ll 1$)

Quantifying these effects involves several challenges, including the measure problem in eternal inflation

References

1980's and 90's:

- Linde *et al.*
- Vilenkin *et al.*
- Weinberg *et al.*
- many others

For recent work, see e.g.

- Schwartz-Perlov & Vilenkin: hep-th/0601162
- Vilenkin: hep-th/0611271
- Linde: 0705.1160
- Clifton, Shenker & Sivanandam: 0706.3201

The causal diamond approach

- In this talk I will present the causal diamond approach

RB: hep-th/0605263
RB, Freivogel & Yang: hep-th/0606114
RB, Harnik, Kribs & Perez: hep-th/0702115
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- I will show that it is
  - highly predictive
  - in good agreement with observation

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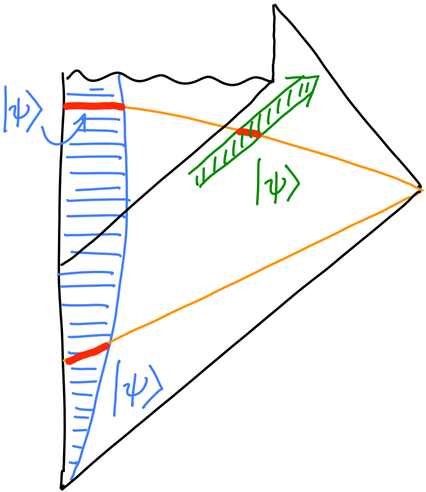
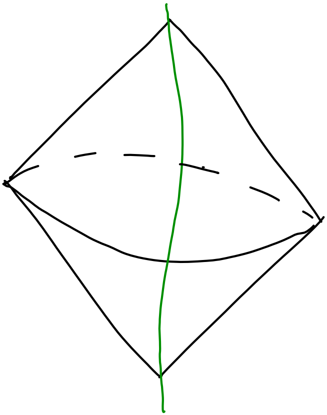
- I will show that it is
  - highly predictive
  - in good agreement with observation
- The approach follows naturally from results in black hole physics.

The xeroxing paradox



- In black hole evaporation, unitarity appears to require $|\psi\rangle \to |\psi\rangle \times |\psi\rangle$
- Xeroxing conflicts with the linearity of quantum mechanics
- But no-one can see both copies of $|\psi\rangle$

The causal diamond



- Restrict to spacetime region accessible to a single worldline: causal diamond
- Describe any such region but not more
- This restriction impacts predictions in the landscape through both cosmological and anthropic selection effects
- I will present one example for each

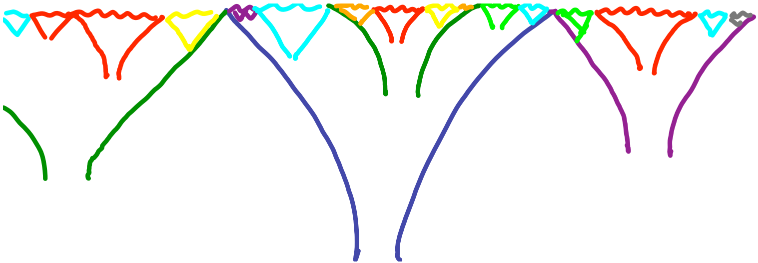
Cosmological Selection Effects

Anthropic (or Entropic) Selection Effects

The basic question

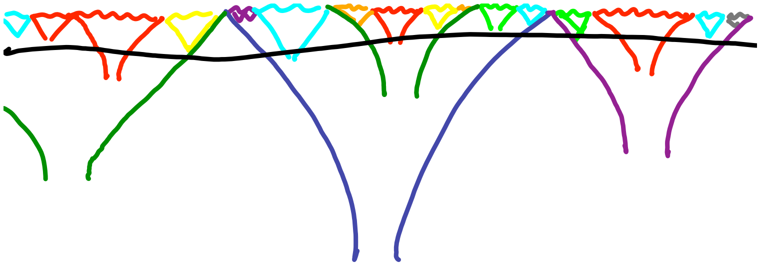
What is the probability for vacuum X to be produced?

Eternal inflation



- Globally, the Universe is eternally inflating
- Each vacuum is produced infinitely many times

Eternal inflation



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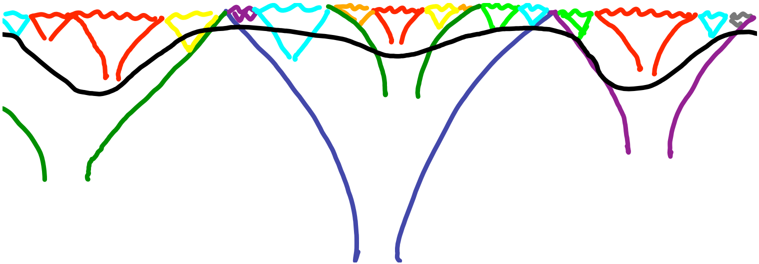
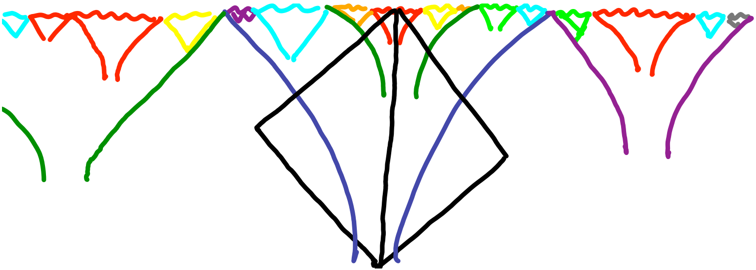
Eternal inflation



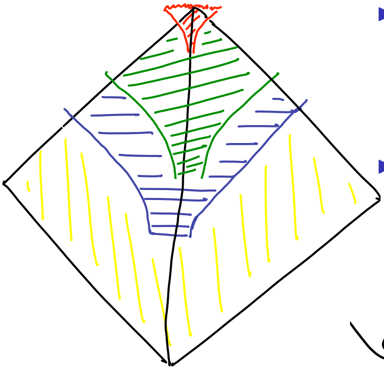
- Globally, the Universe is eternally inflating
- Each vacuum is produced infinitely many times
- Need cutoff to define probabilities
- Ambiguities [Linde, Vilenkin]
- Many simple choices ruled out by paradoxes

Causal diamond cosmology

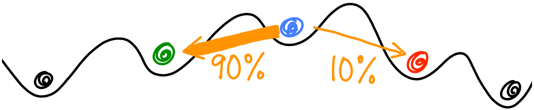


- For a single worldline, inflation eventually ends in a "terminal vacuum" ($\Lambda \leq 0$)
- Reducing to the causal diamond eliminates almost all of the global spacetime

Causal diamond cosmology



- The causal diamond will contain a sequence of vacua corresponding to a particular decay chain through the landscape
- The probability of X to be part of this chain is well-defined and easily computed from branching ratios, η_{AB}



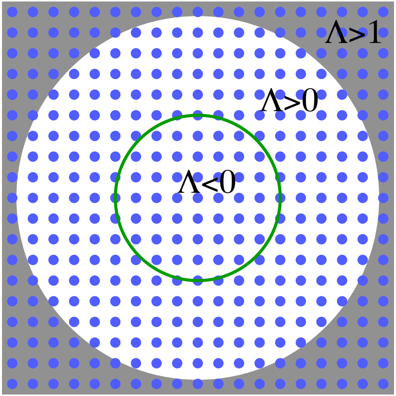
Probability of vacua in the causal diamond

- The probability vector **P** satisfies [RB: hep-th/0605263]

$$(1-\eta)\mathbf{P} = \eta\mathbf{P}^{(0)}$$

- Equivalently, probabilities can be estimated by generating Monte Carlo decay chains. This is more practical for a large landscape.
- Let us apply this prescription to a toy landscape with $10^{100's}$ of vacua. [RB & Yang: hep-th/0703206]

BP model



- $J = 250$ fluxes: $n_1, \ldots, n_J$
- membrane charges $\sim 1/30$: $q_1 < \ldots < q_J$
- $\Lambda - \Lambda_{\text{bare}} = \frac{1}{2} \sum n_i^2 q_i^2$
- $\Delta\Lambda \ll 10^{-123}$

Statistical questions

- How many vacua have $\Lambda \sim 10^{-123}$?
- What are their typical values of fluxes?

Let us ask these questions first for the “raw landscape”, and then with cosmological dynamics taken into account.

Raw landscape statistics: Method

Consider a canonical ensemble of vacua, with β dual to Λ.

- Flux probabilities:

$$p_i(n) \propto \exp\left(-\beta \frac{n^2 q_i^2}{2}\right)$$

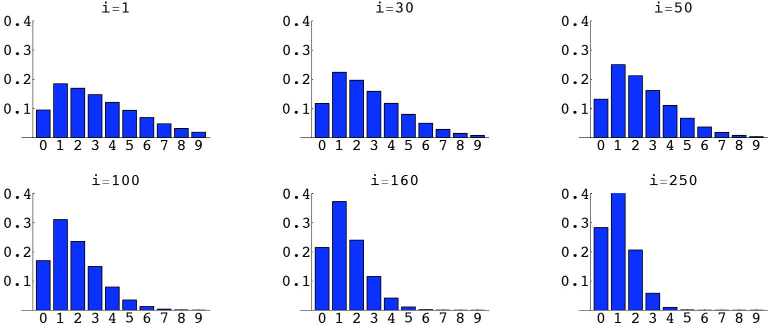
- Shannon entropy:

$$S = -\sum_{i,n} p_i(n) \log p_i(n)$$

- Number of vacua in the ensemble:

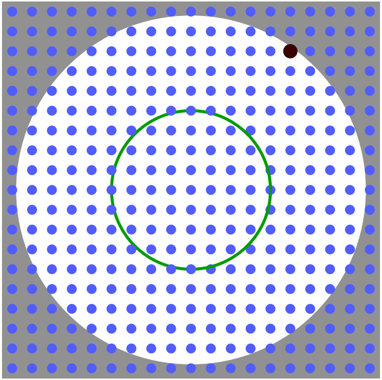
$$\mathcal{N} = \exp(S)$$

Raw landscape statistics: Results



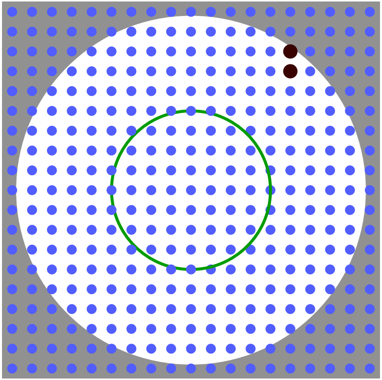
$p_i(n) \rightarrow \mathcal{N} \rightarrow 10^{121}$ vacua with $\Lambda \sim 10^{-123}$

Cosmological selection: Method



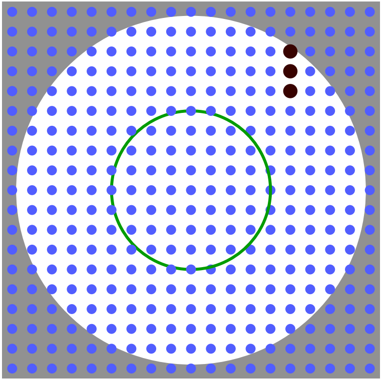
1. Generate initial conditions
   - Assume no strong preference for small or negative Λ
   - Start with random vacuum, $\Lambda \sim O(1)$.
   - True randomness is hard; use canonical ensemble

Cosmological selection: Method



2. Generate Monte Carlo decay chain
   - Use branching ratios computed from instantons
   - Restrict to single-flux decays

Cosmological selection: Method



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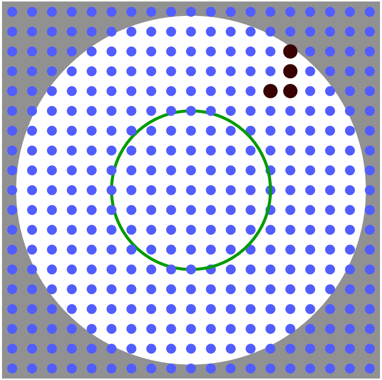

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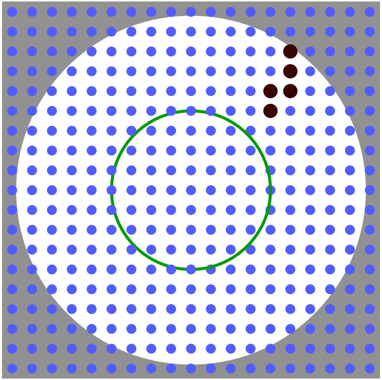

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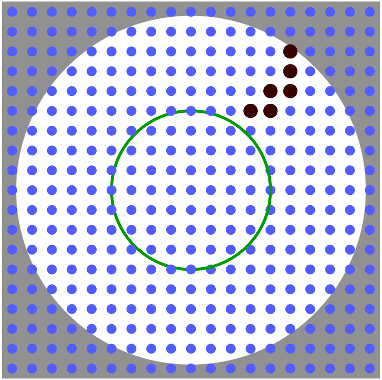

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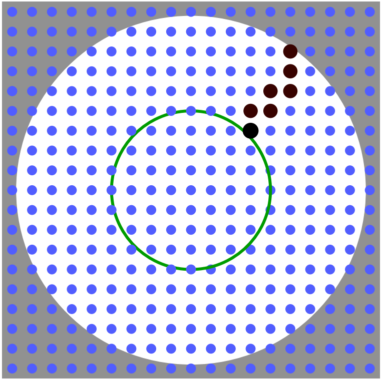
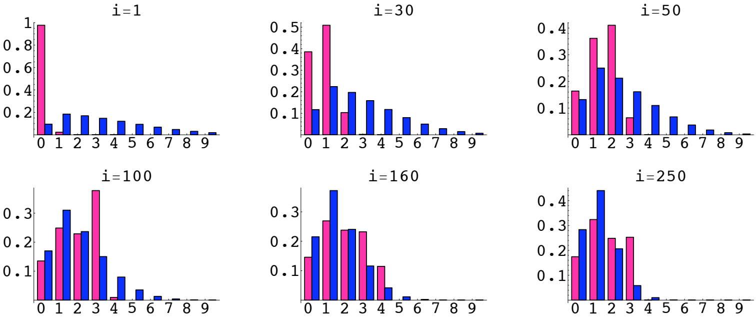


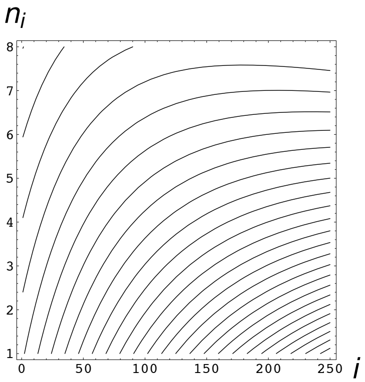
3. Record final flux configuration $(n_1, \ldots, n_J)$
   - Good statistics for each flux after a few thousand runs
   - Obtain flux probabilities $p_i(n)$

Cosmological selection: Results



- Sharp contrasts with raw landscape, e.g.:
  - first 30 fluxes all ≤ 2
  - no fluxes > 4
- Hundreds of predictions, many with probability near 1
- Only 10^{80} vacua with $\Lambda \sim 10^{-123}$ (1 in 10^{41} selected)

Origin of cosmological selection effects



- Large fluxes, and those associated with small-charge membranes, are particularly unstable
- They decay early in the chain, and will not be observed

General lessons

- Cosmological selection thins out the landscape,
- suppressing large classes of vacua and
- leading to strong predictions
- Some models can be ruled out by cosmological selection
- No “staggering” problem

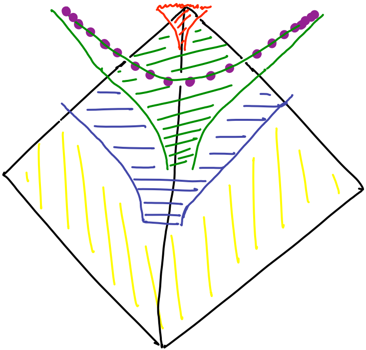
Cosmological Selection Effects

Anthropic (or Entropic) Selection Effects

The basic question

What is the probability for vacuum X to be observed?

Observers in the causal diamond



- Weight each vacuum by the number of observers, or observations, it contains
- In the causal diamond, this number is finite
- But what is an observer/observation?
- Trade "observers" for a better defined quantity, ΔS.

The Causal Entropic Principle

- Observation requires free energy; must produce entropy
- Conjecture that on average, $N_{\text{observers}} \propto \Delta S$
- Let $\Delta S(X)$ be the matter entropy produced inside the causal diamond, in vacuum X, since reheating
- Weight by ΔS:

$$\mathcal{P}_X \propto P_X \Delta S$$

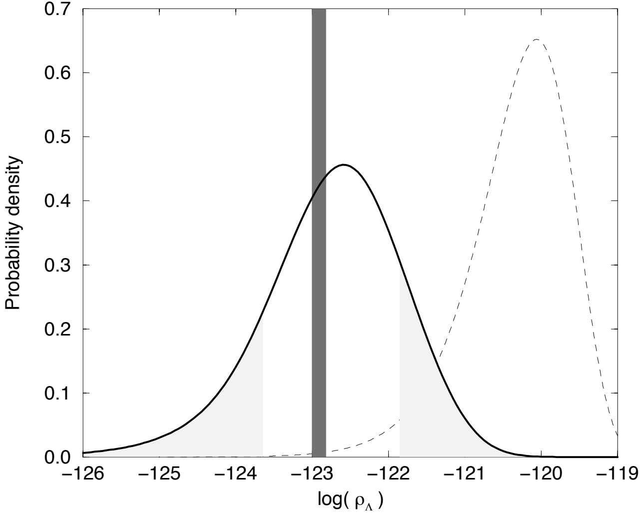
A statistical question

- What is the probability distribution for Λ?
  - Restrict to the subset of the string landscape with low energy physics identical to ours
  - Only Λ varies
- By entropic weighting,

$$\frac{d\mathcal{P}}{d\log\Lambda} \propto \Lambda\, \Delta S(\Lambda)$$

- Computing $\Delta S(\Lambda)$ is an astrophysics problem

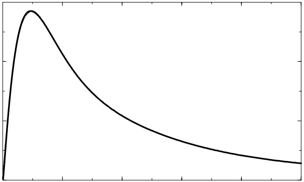
Main result: The probability distribution for Λ



Our Λ is typical under this distribution [BHKP: hep-th/0702115]

Origin of this distribution

- Λ wants to be large by raw statistics
- But Λ should not dominate too early, or it will expel all matter (and free energy) from the diamond
- The preferred Λ starts dominating around the time when entropy production peaks
- This solves the coincidence problem
- With our low energy physics, entropy production peaks at $\sim 10^{10}$ yr.



- This explains why $\Lambda \sim 10^{-123}$

Including more variables

- Galaxy formation plays no role in suppressing large Λ
- This bodes well for cases with variable $\delta\rho/\rho$, ...
- ΔS is dominated by IR from dust heated by starlight
- So, in vacua similar to ours, ΔS is sensitive to the existence of galaxies, stars, and heavy elements
- This suggests that ΔS will be a good proxy for $N_{\text{observers}}$

Summary

- The causal diamond provides a well-motivated regulator for eternal inflation

- Cosmological selection thins out the BP landscape
- Many predictions, some counter to landscape statistics

- Observed Λ is in good agreement with anthropic weighting in the causal diamond
- Weighting by entropy production is equally successful and universally defined