Holographic probabilities in the string landscape

OR

The entropic principle

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RB, B. Freivogel & M. Lippert, hep-th/0603105

RB, hep-th/0605263

RB, B. Freivogel & I. Yang, hep-th/0606114

RB & I. Yang, in progress

RB, R. Harnik, G. Kribs, G. Perez & M. Porrati, in progress

Holographic

Λ

Entropic

LANDSCAPE

I. Survey long-lived vacua

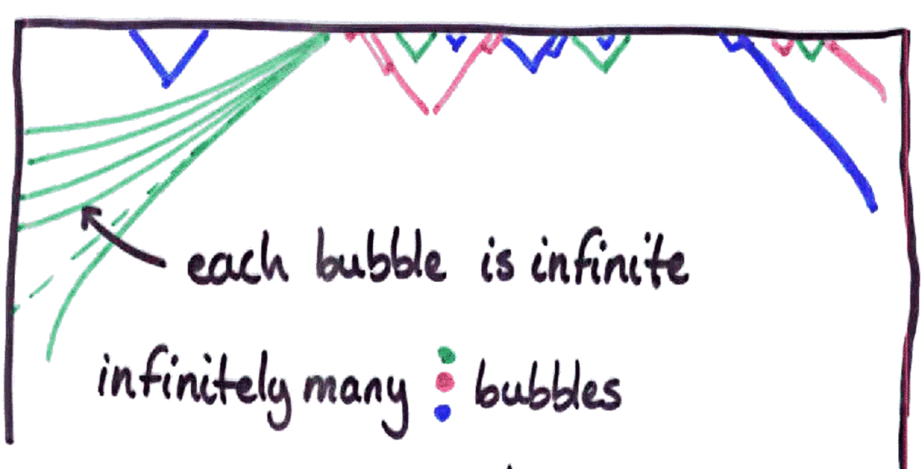
II. Probabilities in Eternal Inflation

III. Anthropic selection

↓

PREDICTIONS

II. Eternal Inflation: Global Structure



each bubble is infinite

infinitely many bubbles

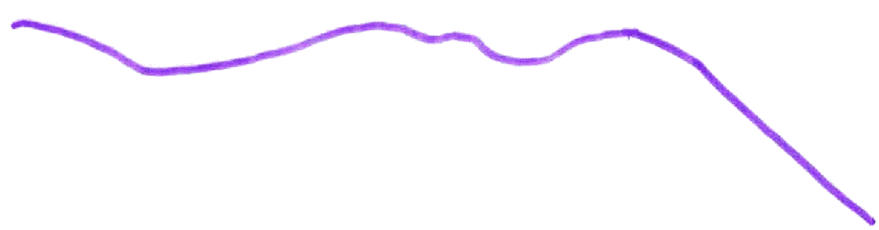
⇒ need regulator !

At finite time, compare...

Garriga & Vilenkin gr-qc/0102090
Garriga et al. hep-th/0509184
Easther et al. astro-ph/0511233

- total volume of bubbles
- number of bubbles
- ...

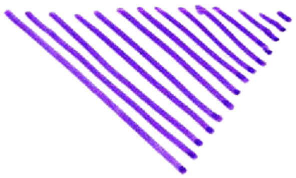
?



No preferred global time

→ get any answer you want!

[Linde et al., gr-qc/9601005]

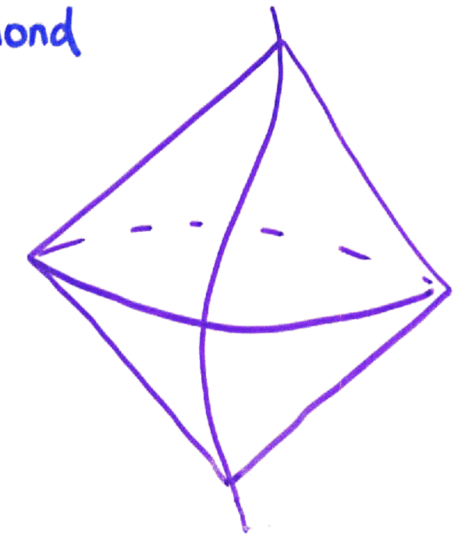


Global ("bird's eye") view leads to ambiguities and pathologies.

Only one causally connected region is accessible to an observer.

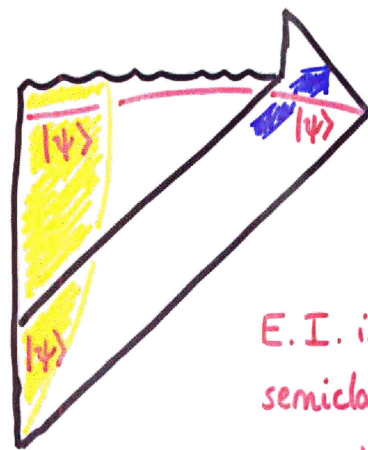
Along any generic worldline, inflation eventually ends.*)

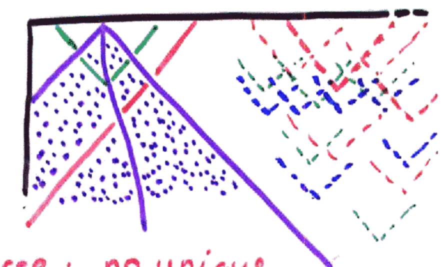
→ use Causal Diamond as a regulator to define probabilities



Also motivated by

- Occam
- Unitarity in black hole evaporation

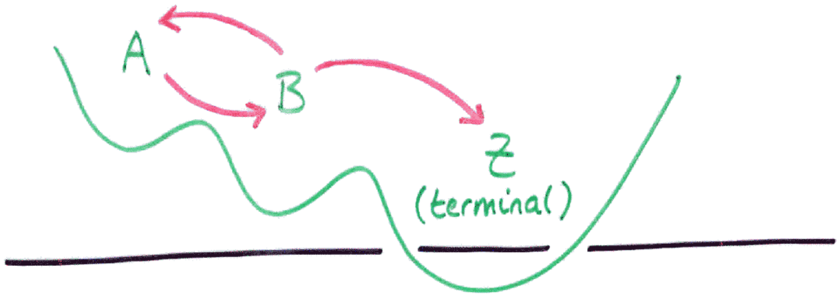




E.I. is worse: no unique semiclassical geometry outside causal diamond

Use a single worldline to compute probabilities

Consider a landscape,



start in A.

K_{ij} = probability per unit time for worldline in vacuum j to enter vacuum i

$$= \begin{pmatrix} 0 & * & 0 \\ * & 0 & 0 \\ 0 & * & 0 \end{pmatrix}$$

Worldline will end up in Z with probability $\to 1$ as $t \to \infty$.

How about:

$p(i) \propto$ expected amount of time the worldline will spend in i on its way through the landscape?

No! Exponentially long lifetime does not make a vacuum more likely to be observed. Mostly "dead time", spent in empty, thermalized de Sitter space.

Observers arise while the universe is <u>out of equilibrium</u>: between bubble nucleation and thermalization. ($\to$ III)

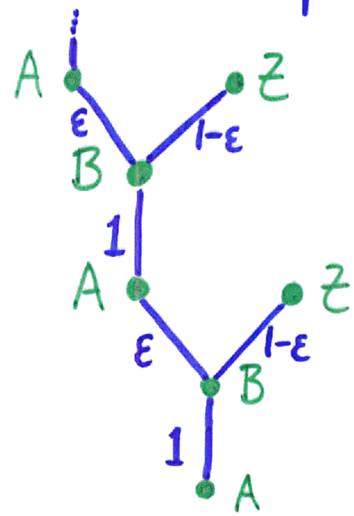
$\Downarrow$

$p(i) \propto$ expected number of times the worldline will <u>enter</u> i on its way through the landscape.

Only care about <u>relative</u> decay probability

$$\eta_{ia} = \frac{\kappa_{ia}}{\sum_j \kappa_{ja}} = \begin{pmatrix} 0 & \varepsilon & 0 \\ 1 & 0 & 0 \\ 0 & 1-\varepsilon & 0 \end{pmatrix}$$

Compute using tree:

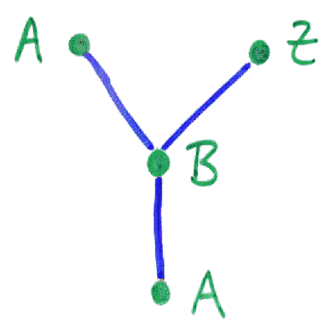


$$P(A) = \frac{\varepsilon}{1-\varepsilon} \qquad p(A) = \frac{\varepsilon}{2}$$

$$P(B) = \frac{1}{1-\varepsilon} \qquad p(B) = \frac{1}{2}$$

$$P(Z) = \frac{1}{\frac{2}{1-\varepsilon}} \qquad p(Z) = \frac{1-\varepsilon}{2}$$

Get same answer from "pruned tree":



General matrix equation:

$$\boxed{(\mathbb{1} - \eta S)\vec{P} = \eta \vec{P}^{(0)}}$$

non-terminal (cyclic) landscape:

$$(\mathbb{1} - \eta)\vec{P} = 0$$

terminal landscape:

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

[In this special case, agrees with Garriga et al. hep-th/0509184; see Vanchurin & Vilenkin, hep-th/0605015]

- can depend on initial conditions
- can be applied to (toy models of the) string landscape [RB & I. Yang, in progress]
- "deterministic" approximation ⇒ in BP model, prefer to shed light fluxes ⇒ predict they will be off in our vacuum
- some thinning-out of discretuum but much less than in a measure that depends on K_{ij} directly

Schwarz-Perlov & Vilenkin

III.

Anthropic selection ⟶

Entropic weighting

- Have probability for vacuum to be produced
- Want probability for vacuum to be observed

structure formation

galaxy cooling

long-lived stars

nucleosynthesis/chemistry

⋮

$\nearrow$ $\exists$ observers $\rightarrow \omega = 1$

$\searrow$ $\nexists$ observers $\rightarrow \omega = 0$

too specific

too crude

Since $\mathrm{vol}(i) = \infty$ for all vacua in the global view, it is hard to be more quantitative.

But without a more nuanced weighting, it is questionable whether successful predictions (e.g., Weinberg: $0 \neq \Lambda \lesssim 10^{-120}$) survive in the real landscape, where everything varies.

# of vacua with $0 < \Lambda < \Lambda_* \propto \Lambda_*$

$\Rightarrow$ strong preference for large Λ

(can be arranged by increasing Q, η_b, ...)

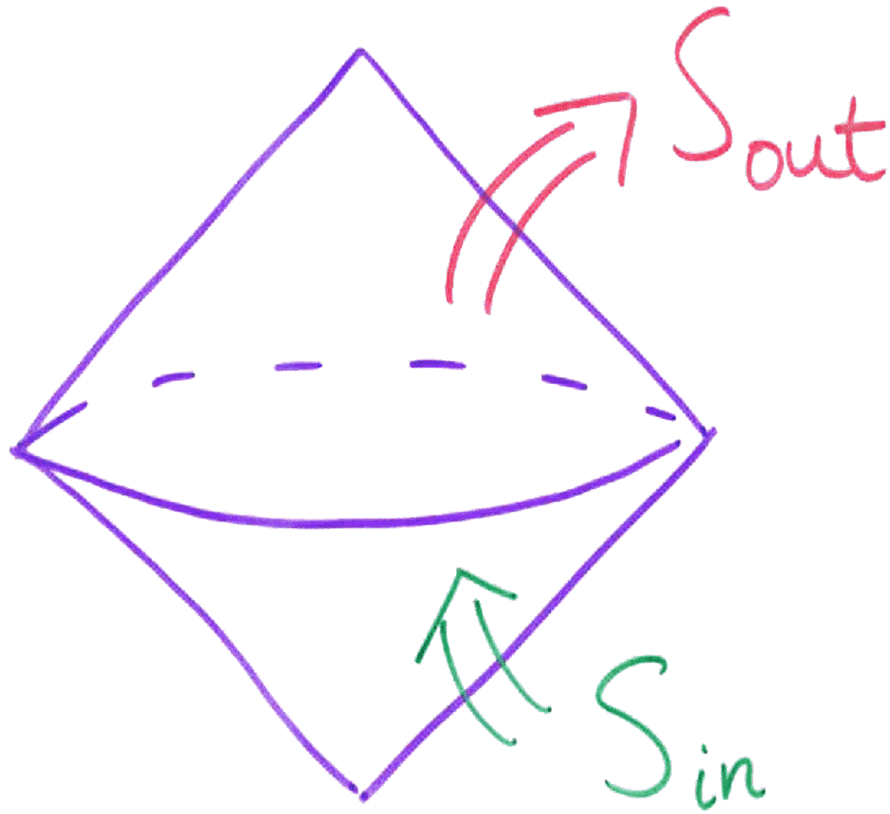
The holographic cutoff makes vol (i) finite  and admits a weighting which mitigates these problems.

Observers require free energy

Must be able to increase entropy

Estimate potential complexity of a vacuum by how much it allows the entropy to increase within one causal diamond : $\Delta S \sim \frac{F}{T}$

Expect this to capture, e.g., structure formation.



$$\Delta S = S_{out} - S_{in}$$

Test this idea on our data point.

(Ignore horizon entropy.)

In our universe, the main contribution to ΔS since reheating comes from stellar burning ! $(10^5 n_b)$

This requires not only structure formation but galaxy formation (cooling $\rightarrow \Delta S$) and long-lived stars.

In our vacuum, ΔS captures anthropic requirements usually put in by hand.

$\rightarrow$ entropic weighting may estimate (at least crudely) the observer content of very different vacua.

"Entropic Principle"

Application: What happens to the Weinberg bound when everything scans?

Still hard to estimate ΔS in detail but expect, on average, a simple dependence on Λ; and expect $\omega = f(\Delta S)$, f monotonic.

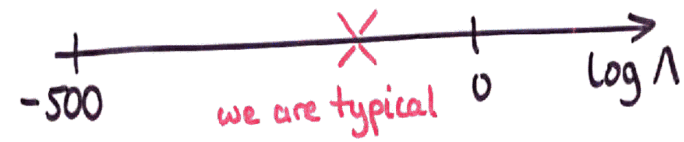
Suppose that $\langle \Delta S \rangle \propto S_{max} \approx \Lambda^{-3/4}$;

$$\omega(\Lambda) \propto \Lambda^{\beta}.$$

$\beta < -1$: smallest Λ preferred. 10^{-123} is data point for measuring size of landscape

$\beta = -1$: Flat distribution in $\log \Lambda$

$$p(\Lambda_1 < \Lambda < \Lambda_2) \sim \log \frac{\Lambda_2}{\Lambda_1}$$

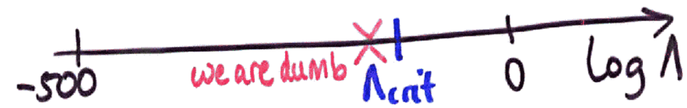


$\beta > -1$: for example, $\omega = \begin{cases} 0, & \Delta S < S_{crit} \\ \Delta S, & \Delta S > S_{crit} \end{cases}$

Then with $\Delta S \propto \Lambda^{-3/4}$, get

$$p(\Lambda < \Lambda_*) = \begin{cases} 0, & \Lambda_* > \Lambda_{crit} \\ \Lambda_*^{1/4}, & \Lambda_* < \Lambda_{crit} \end{cases}$$

Still need cutoff, but expect it to be much less sharp: $\Lambda^{1/4}$ vs. Λ^{1}.



More work needed to estimate $w(\Delta S)$ and especially $w(\Lambda)$.

Meanwhile: What w will not depend on:

exponentially large, hard to control factors like

- lifetime of vacuum (beyond $\Lambda^{-1/2}$)
- inflationary volume expansion (need only enough to suppress curvature domination until Λ dominates)

Still solve coincidence problem.

SUMMARY

-  Holographic cutoff yields well-defined probabilities in eternal inflation. Simple matrix equation
- "Entropic Principle": Weight vacua by $f(\Delta S)$. Appears to capture some anthropic requirements & generalizes to other vacua; prior-free.
- Probabilities & weights effectively thin out the discretuum, but less than if they depended on κ_{ij}, and more predictive. (Example: no light fluxes.)