PREDICTIONS IN THE LANDSCAPE

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IN MEMORY OF ANDREW CHAMBLIN

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Holographic

Entropic

LANDSCAPE

I. Survey long-lived vacua

II. Probabilities in Eternal Inflation

III. Anthropic selection

PREDICTIONS

Rees

Weinberg

Sakharov

Linde

Page

GARRIGA

Lim

VILENKIN

Dyson

Kleban

Hertog

Susskind

Banks

Hawking

Winitzki

Vanchurin

Easther

Mezhlumian

Martin

Tegmark

Schwartz-Perlov

Watari

Hall

Feldstein

Aguirre

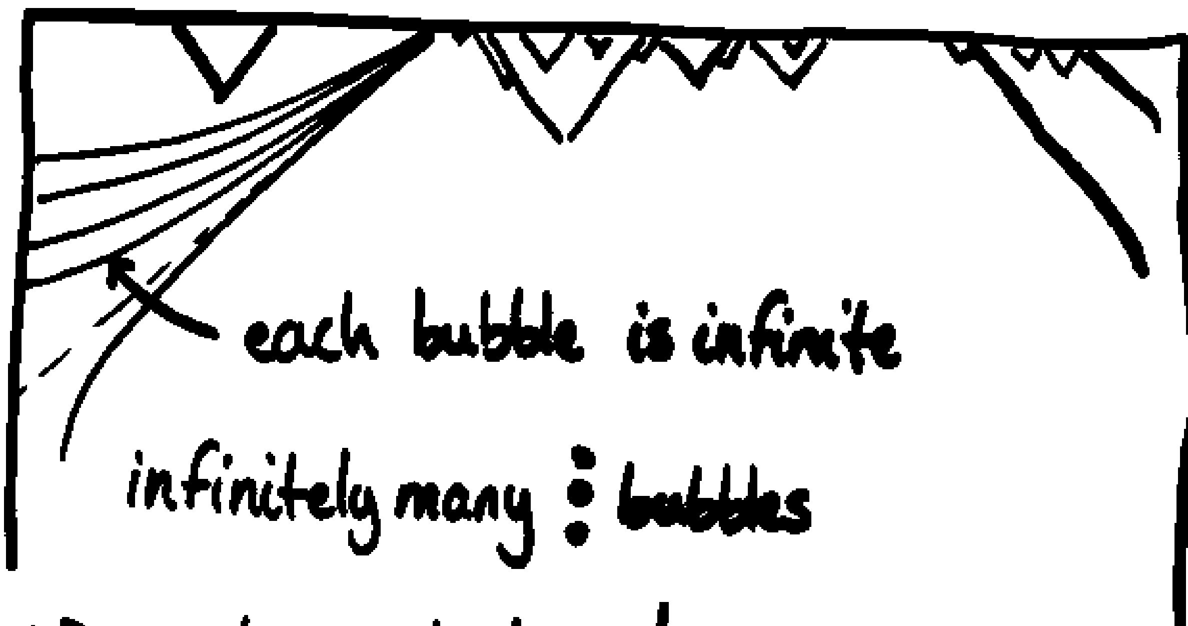
Johnson

Gibbons

Turok

II.

Eternal Inflation: Global Structure



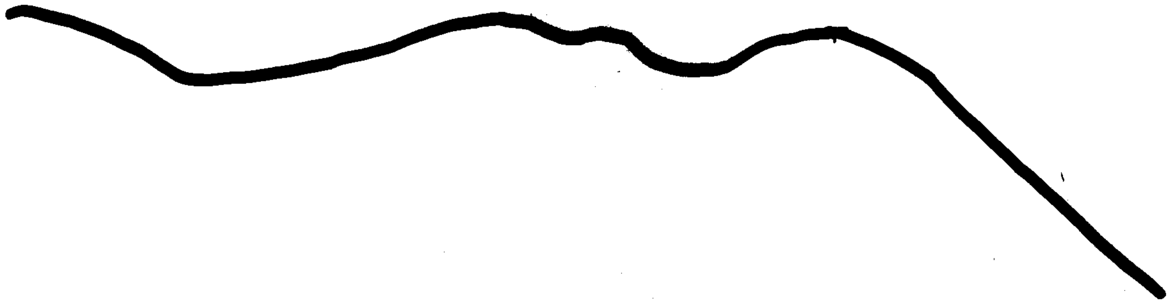
$\Rightarrow$ need regulator!

At <u>finite time</u>, compare...

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

- total volume of $\vdots$ bubbles
- number of $\vdots$ bubbles
- ...

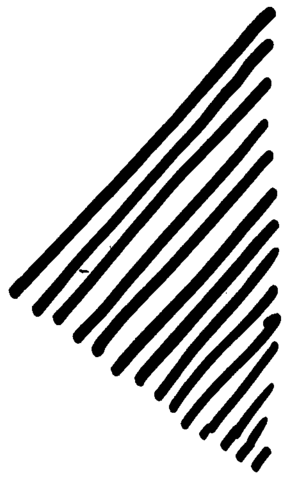
?



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.

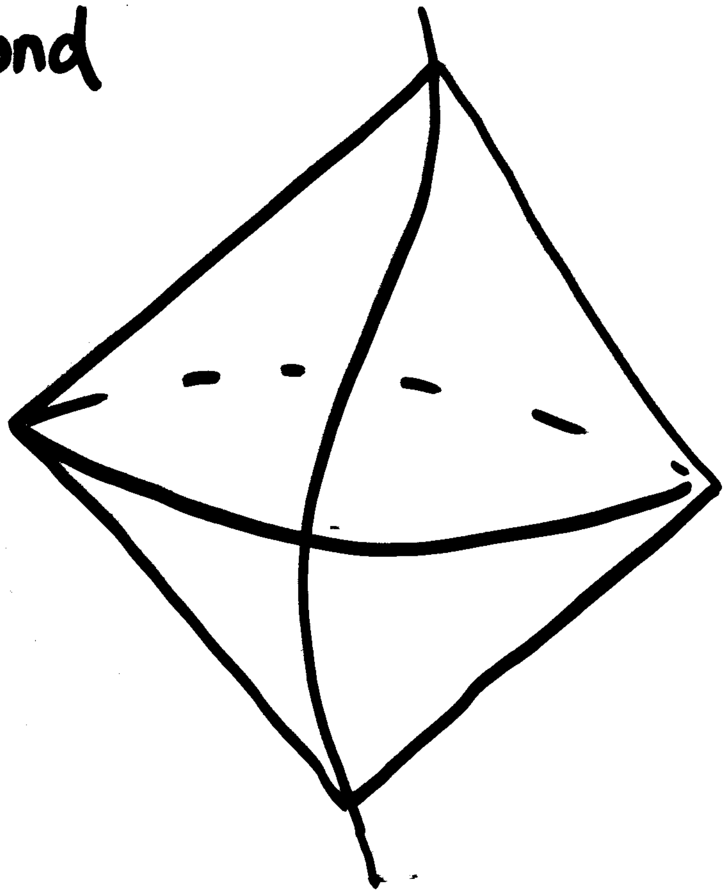
Only one causally connected region is accessible to an observer.

Along any generic worldline, inflation eventually ends.*)

→ use Causal Diamond

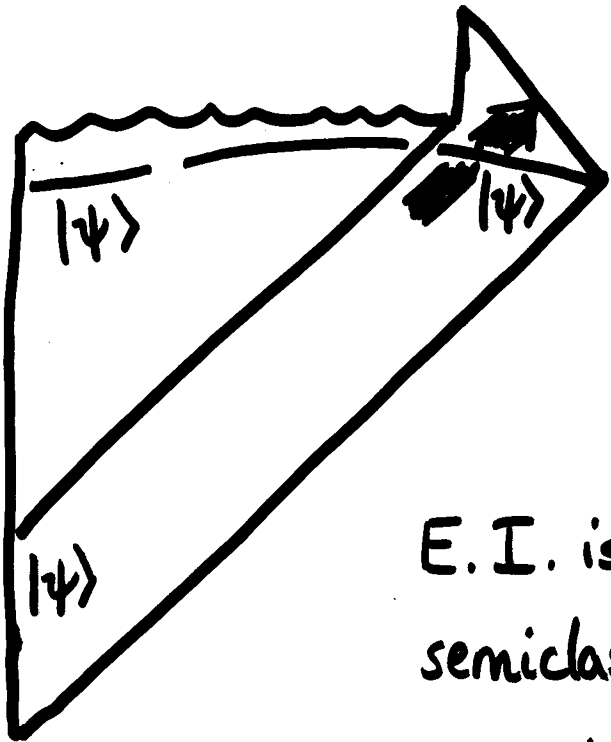
as a regulator to

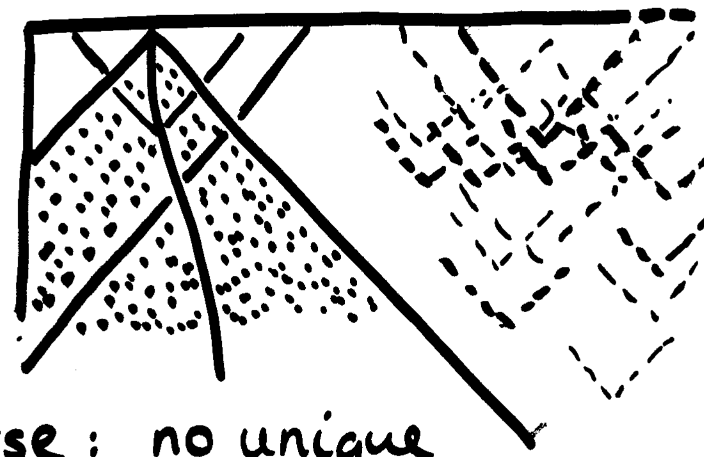
define probabilities



Also motivated by

- Occam
- Unitarity in black hole evaporation

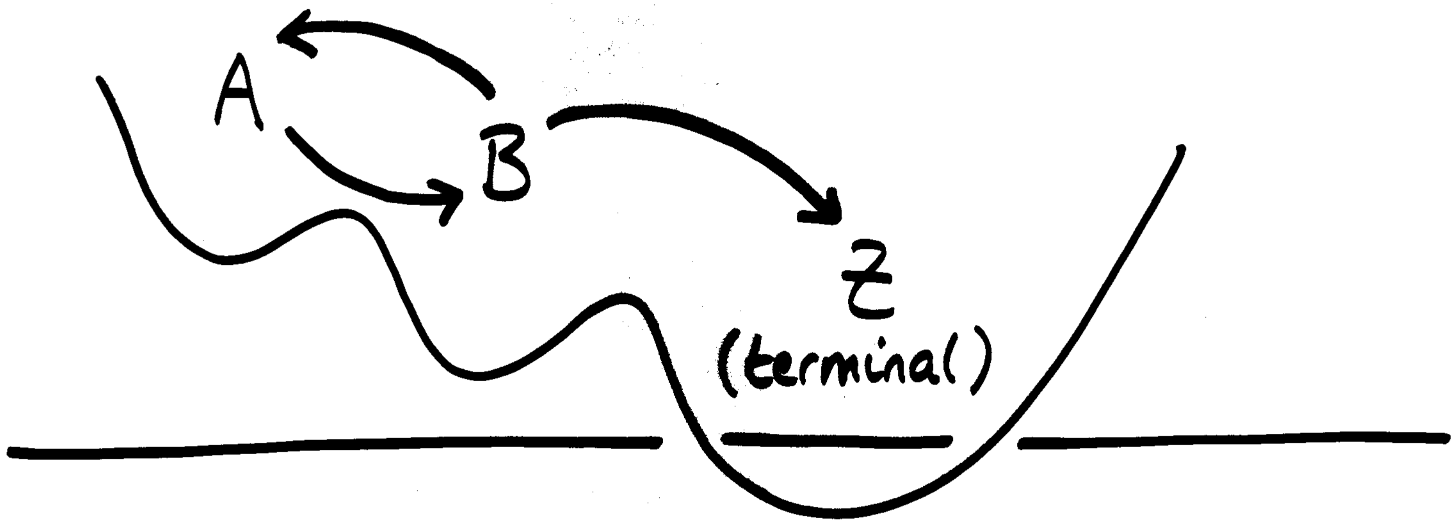




E.I. is worse: no unique semiclassical geometry outside causal diamond

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

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

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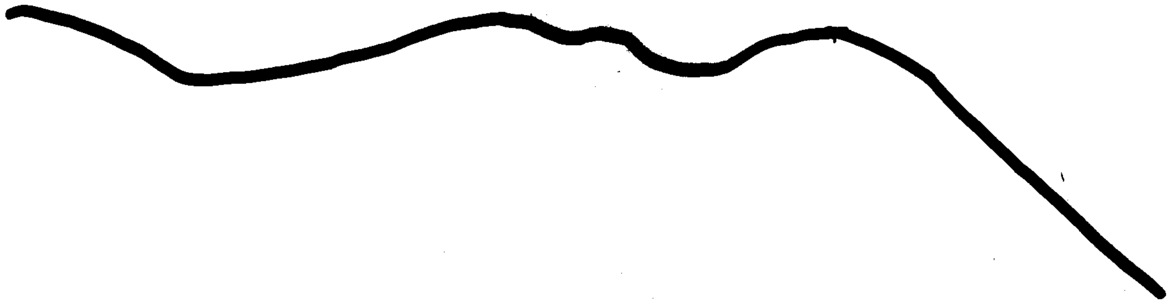

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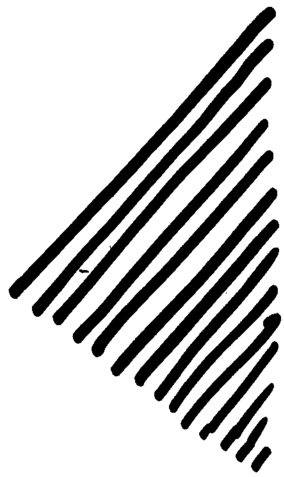

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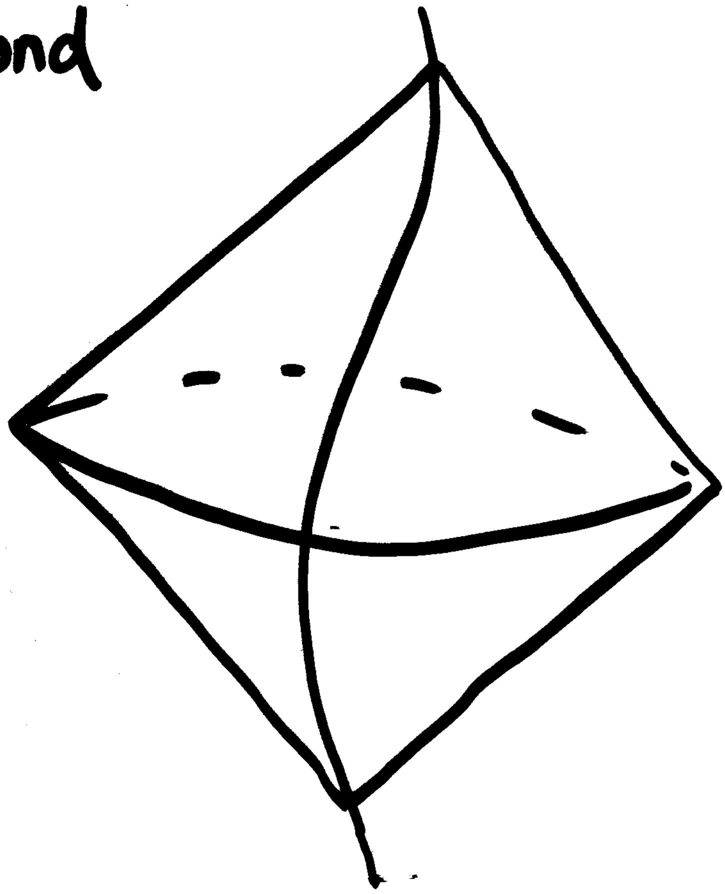

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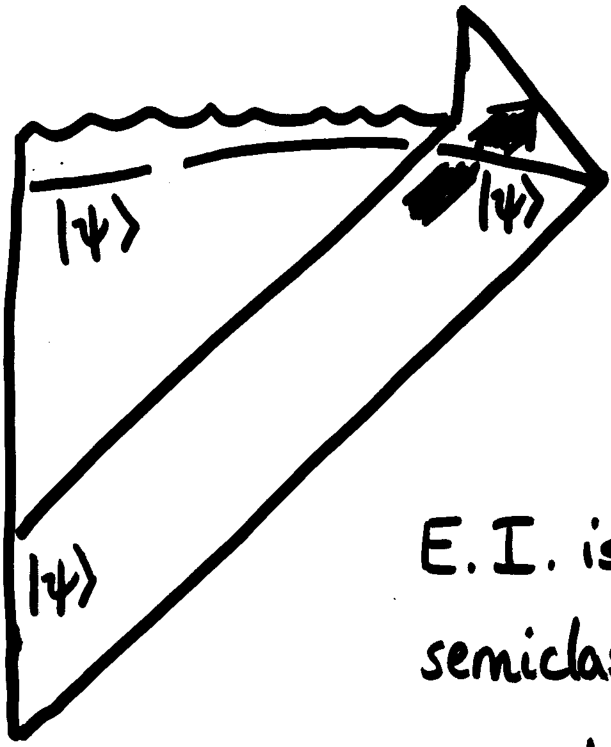

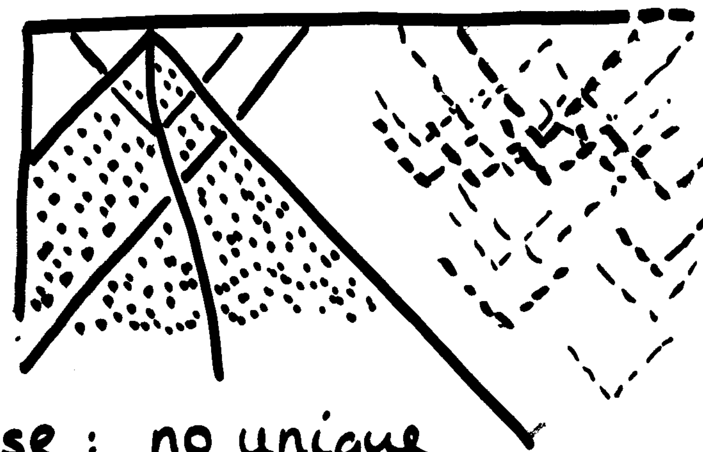

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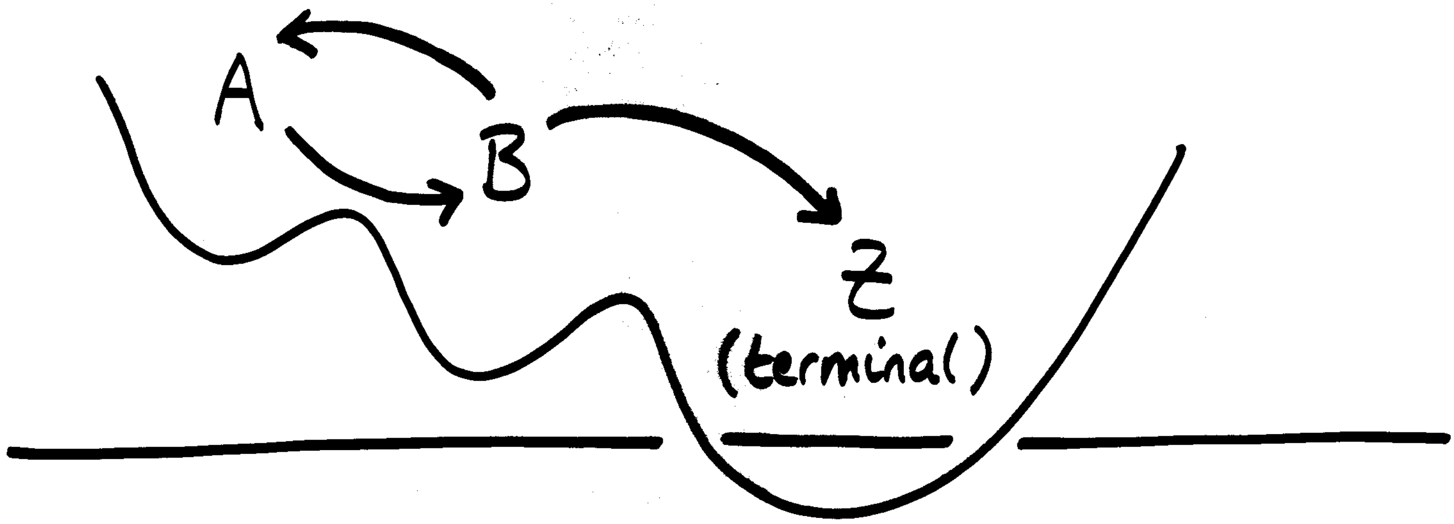

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III.

Current approaches tend to break up the probability for vacuum i to be observed:

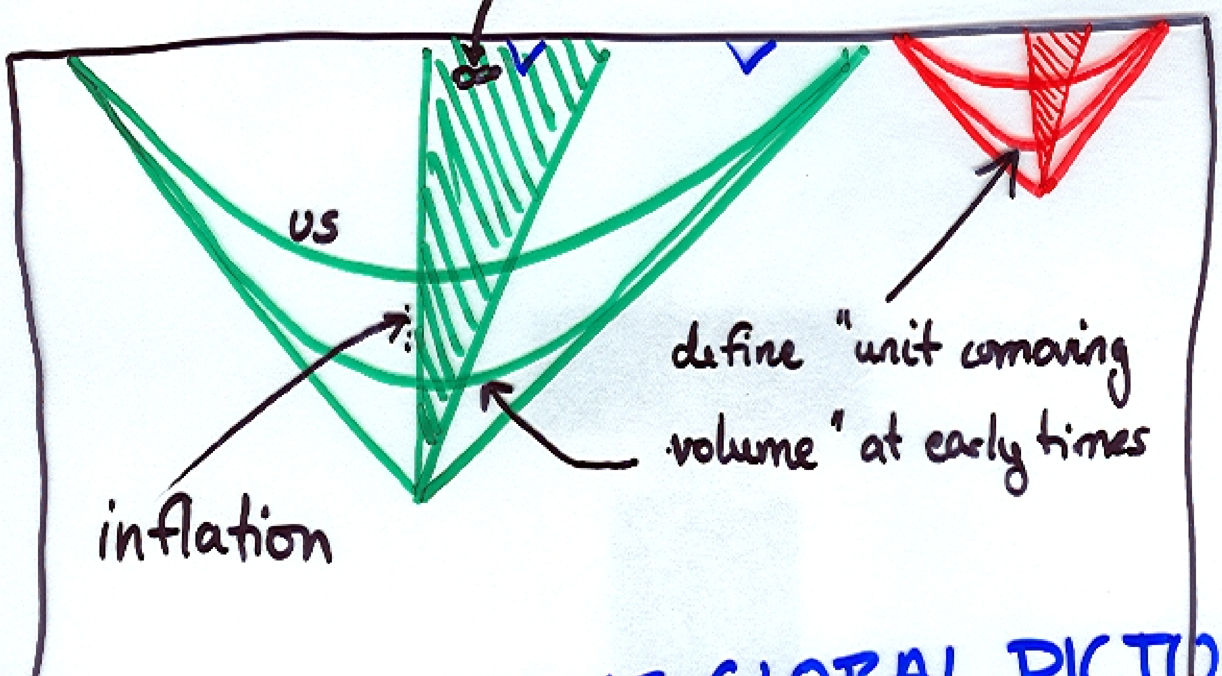
$$\Pi_i = p_i \, \omega_i$$

p_i : probability for i-bubble to be produced

ω_i : usually taken to be proportional to the number of observers expected in the i-bubble. This is <u>infinite</u> in the <u>global</u> picture (or zero). →

Define $\omega_i = \dfrac{N_{obs}}{\text{unit comoving volume}}$

(Vilenkin)



PROBLEMS OF THE GLOBAL PICTURE:

1) How to <u>define</u> "observer" and <u>estimate</u> their formation rate in unfamiliar vacua?

2) ω_i is exponentially sensitive to the duration of slow-roll inflation in the i-bubble

$\longrightarrow$ expect $\frac{\delta\rho}{\rho} \longrightarrow \begin{cases} 0 \\ 1 \end{cases}$ or [Feldstein, Watari & Hall], [Vilenkin]

3) The overwhelming majority of observers are not like us. [Page] [RB, Freivogel]

The holographic cutoff makes vol (i)

Finite  and admits

a weighting which mitigates

problem # 1. Solves #2 (see later), #3*).

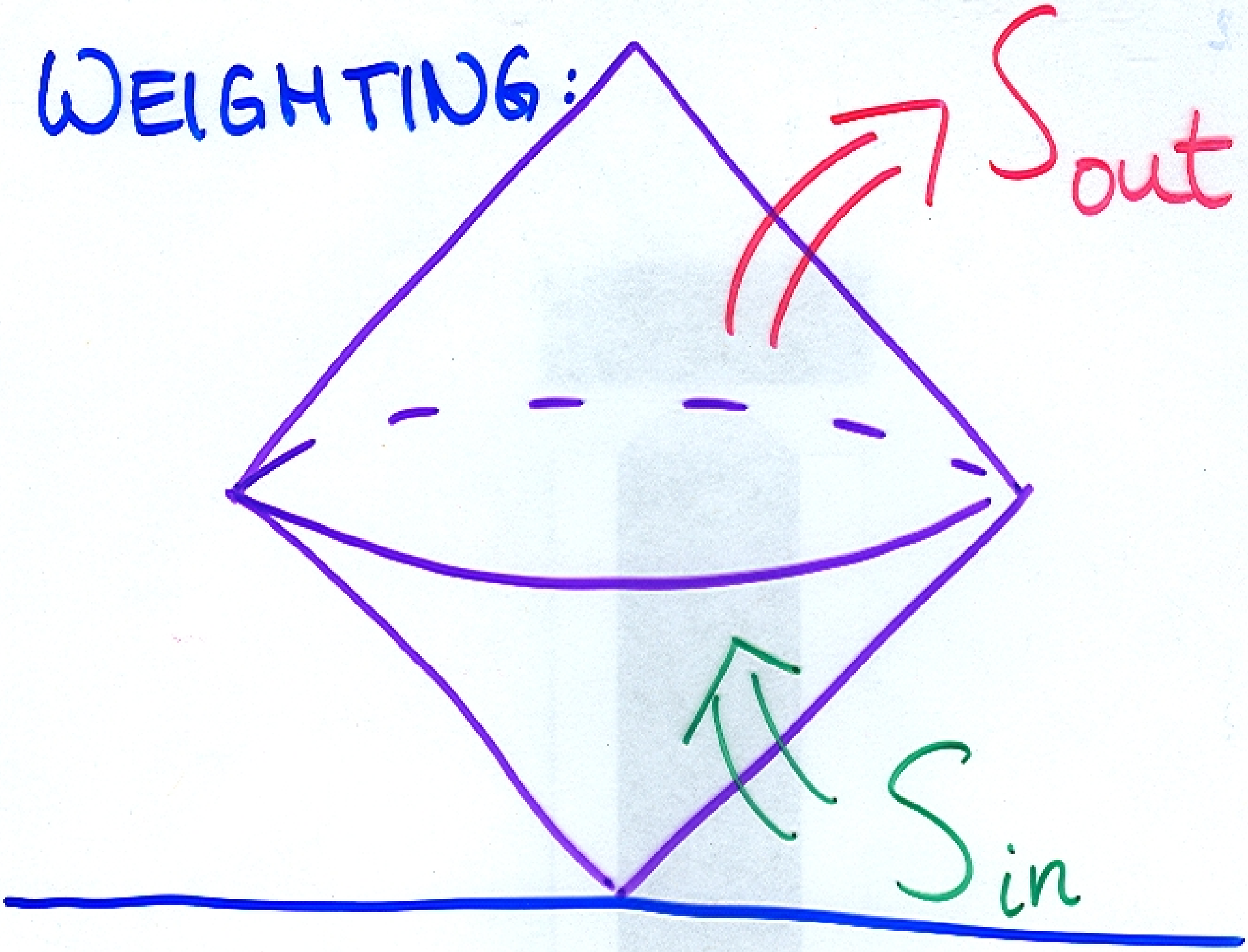
Observers require free energy

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.

THE NOT-SO-ANTHROPIC WEIGHTING:



Define

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

What ΔS will <u>not</u> depend on:

- lifetime of vacuum (beyond $\Lambda^{-1/2}$)
- inflationary volume expansion (beyond suppressing curvature domination until Λ dominates).

Thus the local viewpoint <u>resolves</u> a paradox identified by Feldstein, Hall and Watari: If # of e-folds <u>did</u> enter the weight (as in most proposals) then $\frac{\delta\rho}{\rho}$ would be driven towards an extreme value (0 or 1).

So much for problems #3 and #2.

Before turning to #1 there is a worry.

I did not use explicit anthropic weighting requiring $w_i \to 0$ if no observers, only used $w_i = \Delta S$. Won't we lose the successful pre-/post-dictions of the anthropic principle?

E.g. Λ, $\frac{\delta\rho}{\rho}$, ...

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 <u>structure formation</u> but galaxy formation (cooling $\rightarrow \Delta S$) and long-lived stars.

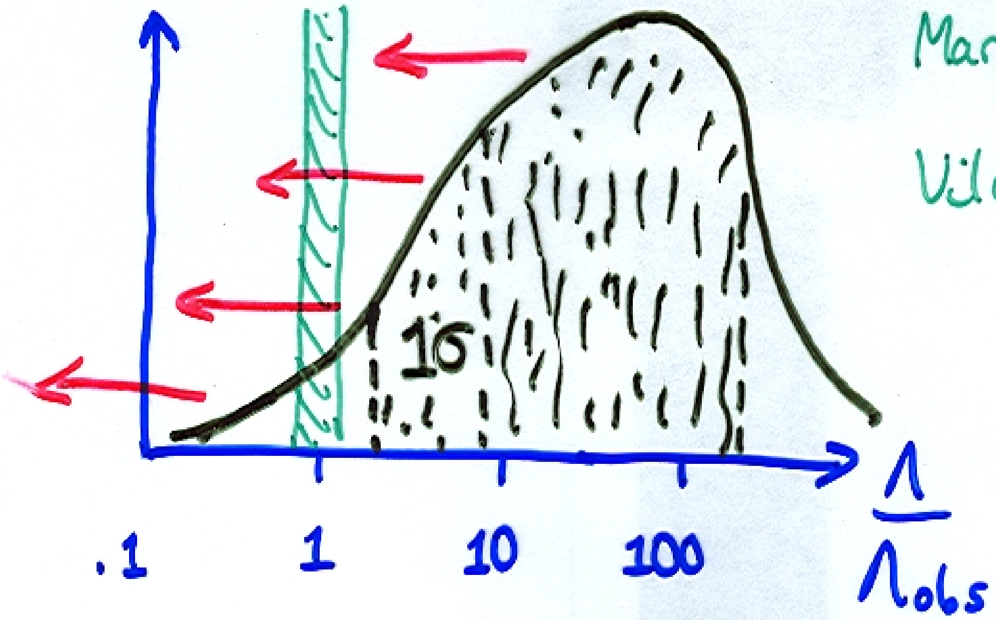
This result is a major success.

① This means that the entropic principle will reproduce the successful predictions of the anthropic principle, which were based on prior measurements:

- $t_\Lambda \gtrsim t_{Galaxies}$ or else $\Delta S \to 0$
- $\frac{\delta\rho}{\rho} \gtrsim 10^{-6}$ or else $\Delta S \to 0$
- coincidence problem: we should live at the time when most of ΔS is produced: ~ 5 Gyr after $t_{Galaxies}$ ✓

Same results from much simpler assumption!

② In some cases, the entropic principle gives better agreement with observation



Martel Shapiro Weinberg

Vilenkin et al.

Extra weight by total mass inside causal diamond, $\Lambda^{-1/2}$, favors smaller Λ and will shift curve to the left!

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

→ entropic weighting may ~~~~ estimate (at least crudely) the observer content of very different vacua.

"Entropic Principle"

(progress on problem # 1.)

Can we predict Λ without priors?

(aka, What happens to the Weinberg bound if everything scans?)

$$p(\Lambda_1 < \Lambda < \Lambda_2) \propto \sum_i \omega_i \quad ; \quad \omega_i = \Delta S_i$$

need statistical averaging; define

$$W(\Lambda)\,\Delta\Lambda = \sum_i \omega_i \quad ; \quad N^{-1} \ll \Delta\Lambda \ll 1 \,.$$

i ← vacua in $\Delta\Lambda$ interval

so that

$$p(\Lambda_1 < \Lambda < \Lambda_2) \propto \int_{\Lambda_1}^{\Lambda_2} d\Lambda \;\; W(\Lambda) \,.$$

How to estimate $\omega(\Lambda)$

$\omega(\Lambda)$ is the average ΔS.

Assumption: Suppose the average ΔS scales with Λ like the maximum ΔS:

$$W(\Lambda) = \alpha \, \Delta S_{max}(\Lambda)$$

We know that $\Delta S_{max} = 3\pi/\Lambda$ (2nd law)

(This can actually be attained:

$$\Delta S \approx \frac{\text{energy burned}}{\text{temperature}} \lesssim \frac{\Lambda^{-1/2}}{\Lambda^{1/2}} = \frac{1}{\Lambda}.)$$

So $\omega(\Lambda)$ scales like $\dfrac{1}{\Lambda}$.

$$\Rightarrow p(\Lambda_1 < \Lambda < \Lambda_2) = \int_{\Lambda_1}^{\Lambda_2} d\Lambda \, \omega(\Lambda)$$

$$\sim \boxed{\log \Lambda_2 - \log \Lambda_1}$$

Use structure of theory, e.g. $N \approx 10^{500}$

$\longrightarrow$ prior-free prediction

$$\boxed{-\log \Lambda \sim O(100)}$$