The Boltzmann Brain Problem

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The paradox requires few equations to state.

1. A powerful consistency check for theories of [redacted] measure on multiverse.
2. A strong motivation to describe one causal patch in cosmology
3. May provide predictions about Landscape.

Page:

Focus on finite piece of <u>our</u> reheating surface. Follow this piece (comoving coords) into the future.

① At time ~ H^{-1}, see a finite # of ordinary observers.

② If our vacuum inflates eternally, the physical volume grows with time.

③ de Sitter is thermal ⇒ see thermal fluctuations. $V_4 = \infty$

<u>Conclusion:</u> Count finite # of ordinary observers, ∞ Boltzmann Brains.

Page's conclusion: Our vacuum is not eternally inflating: lifetime < Hubble time.
But lifetime is exponential!

<u>Note</u>: Could simply ask:
Given everything we observe, are we more likely to be ordinary observers or BB's?

<u>Answer</u>: 100% BB's.
(Conflicts w/ observation: Dyson, Kleban, Susskind)

<u>Our Comment</u>: A given comoving volume falls out of causal contact in de Sitter.

Who gave Page permission to count all of these BB's?

- Answer seems crazy
- Answer is infinite
- Does not correspond to operational question.

Analogous to BH information paradox.

Suggestion: Restrict to one causal patch.

Back up:
Why count observers in just one vacuum if eternal inflation is occuring?

Experimental evidence:

(a) Bousso, Harnik, Kribs, Perez:
Postdict Λ by counting # of obs in causal patch → works beautifully

(b) Weinberg et al:
weight vacua by collapsed baryon fraction.

Measures:

Vilenkin:

① Solve rate equations to determine bubble abundances

② Count observers within each bubble (regulate by restricting to finite comoving volume).

① is finite; ② is infinite if any dS vacua which can fit BB's eternally inflate!

Bousso:

1. Initial cond's
2. Solve different rate eq'ns
3. Count observers in one causal patch.

Question: In one causal patch, are there more OO's or BB's?

Causal patch desc of dS is thermal $T = \frac{1}{R}$

Typically, one photon per horizon volume. Time to make a BB: $t_{BB} = R e^{S_{BB}} = R e^{\frac{M}{T}}$

Lifetime: $e^{S_{inst}}$

Two regimes: Decay can be a field theory process, or our Λ may be important. In latter case (above "Great Divide"), lifetime $\sim e^{S_{dS}}$

In our vacuum, # of Earths: $t_{BE} = e^{\frac{M_e}{T}} = e^{M_e R}$

$$N_{BE} = \frac{e^{10^{120}}}{e^{10^{92}}} \sim e^{10^{120}}$$

$$\boxed{N_{OE} \sim \frac{1}{\Lambda} \sim 10^{120}}$$

BB's exist in $G_N \to 0$ limit.

$$t_{BB} = \frac{R}{c} e^{S_{BB}}$$

$$\text{or } t_{BB} = \frac{R}{c} e^{\frac{ER}{c\hbar}}$$

$$t_{decay} \sim e^{\left(\frac{R}{l_p}\right)^2}$$

If any BB's are made, a doubly exponential # are made. In Bousso measure, no other exponentials.

<u>Prediction</u>: In landscape, $t_{decay} < e^{S_{BB}}$

Is this crazy?
Look at KKLT decay times. SUSY by $\overline{D3}$ in warped throat.

Long throat: Mild SUSY, but brane-flux annihilation occurs near tip
Insensitive to warping.
Short throat: Strong SUSY, destabilize fluxes in bulk of CY

$$t_{decay} \sim e^{\frac{m_{pl}^2}{M_{3/2}^2}} \quad \text{(CDGKL)}$$

Do there exist vacua with small Λ where decay time ~ recurrence time?

<u>Aside:</u> $\exists$ completely stable ~~SUSic~~ AdS vacua?

<u>Basic Assumption</u>: It makes sense to ask: "What are observers likely to observe?"

- Necessary to Weinberg arg.
- Allows us to ask if we are likely to be BBs.

Conclusions:

- Computing decay times in landscape provides information about measures if we consider BB problem.

Vilenkin et al: $t < H^{-1}$

Bousso: $t < e^{S_{BB}}$

- BB problem encourages us to focus on one causal patch in cosmology
- If we assume counting obs in one causal patch makes sense (based on evidence), nontrivial prediction about Landscape