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Predictions in the Multiverse

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Predictions in the Multiverse

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Introduction

The measure problem

Vacuum structure & Observer distribution

The String Landscape

String Theory probably contains at least 10^{hundreds} long-lived metastable vacua with three large spatial dimensions. At low energies (less than the compactification scale), these vacua have different effective laws of physics: different particles, forces, density perturbations,...

Eternal Inflation

Many vacua have positive vacuum energy and so expand exponentially, like de Sitter space. Even if the universe starts out in just one of these vacua, other vacua will be produced, at a fixed rate, by Coleman tunneling: a bubble forms and expands almost at the speed of light. Because of the causal structure of de Sitter space, the bubble will not fully consume its parent vacuum. Thus, the global exponential expansion of spacetime continues eternally.

The Multiverse

In this way, all the vacua in the string landscape are produced, over and over, as bubbles (or “pockets”) in different regions of spacetime. Each bubble contains an infinite open FRW universe, separated from other regions by an expanding membrane or domain wall. The whole spacetime is called the Multiverse of string theory.

Probabilities

The probability for observing a certain value of x is proportional to the number of times this value is observed in the multiverse.

$$\frac{p_1}{p_2} = \frac{\langle N_1 \rangle}{\langle N_2 \rangle} \ ,$$

where $\langle N_I \rangle$ is the expected number of times this outcome is measured by someone in the multiverse.

Estimating $\langle N_I \rangle$ requires understanding

- the vacuum structure of the string landscape,
- cosmological dynamics and the distribution of observers,
- and the solution of the measure problem.

Introduction

The measure problem

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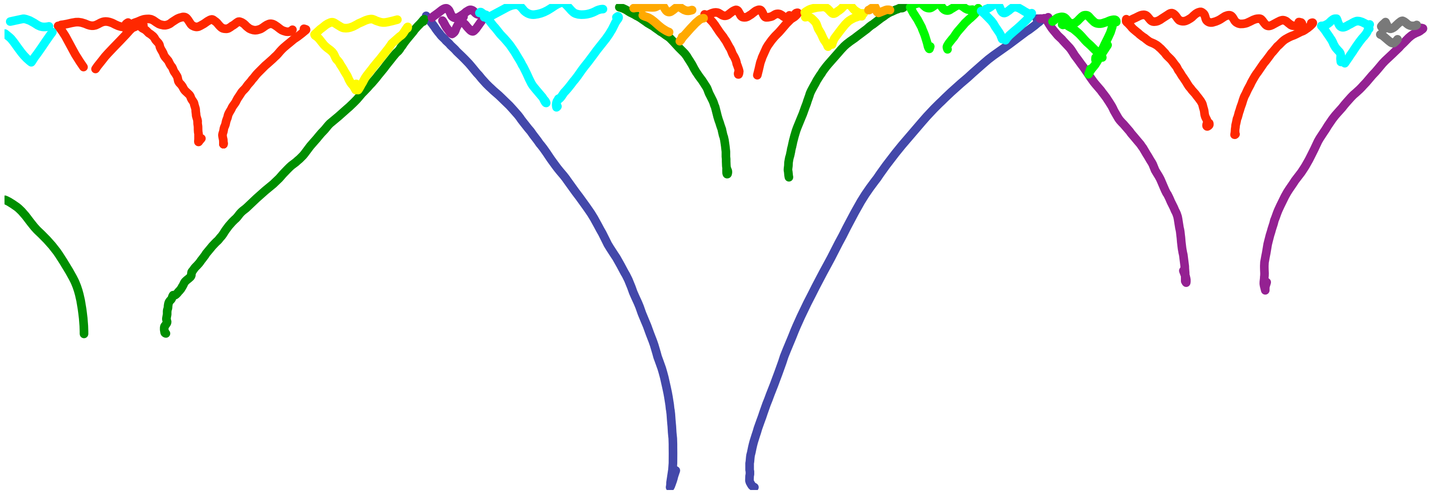
The measure problem



- Finite universe
- + at least one false vacuum with $\Lambda > 0$
- + QFT + gravity
- = Infinite universe [Guth & Weinberg]
- Infinitely many bubbles (pocket universes)
- Each contains infinitely many observers (if any)

The measure problem

- Everything that can happen will happen, infinitely many times
- Can't do statistics on infinities $\rightarrow$ crisis of predictivity
- Robust problem; precedes landscape [Linde et al., Vilenkin et al., ... 1990s]
- E.g., should we expect to live in a collision region?
- With multiple vacua, which low energy properties should we find?
- Need a cutoff or regularization procedure

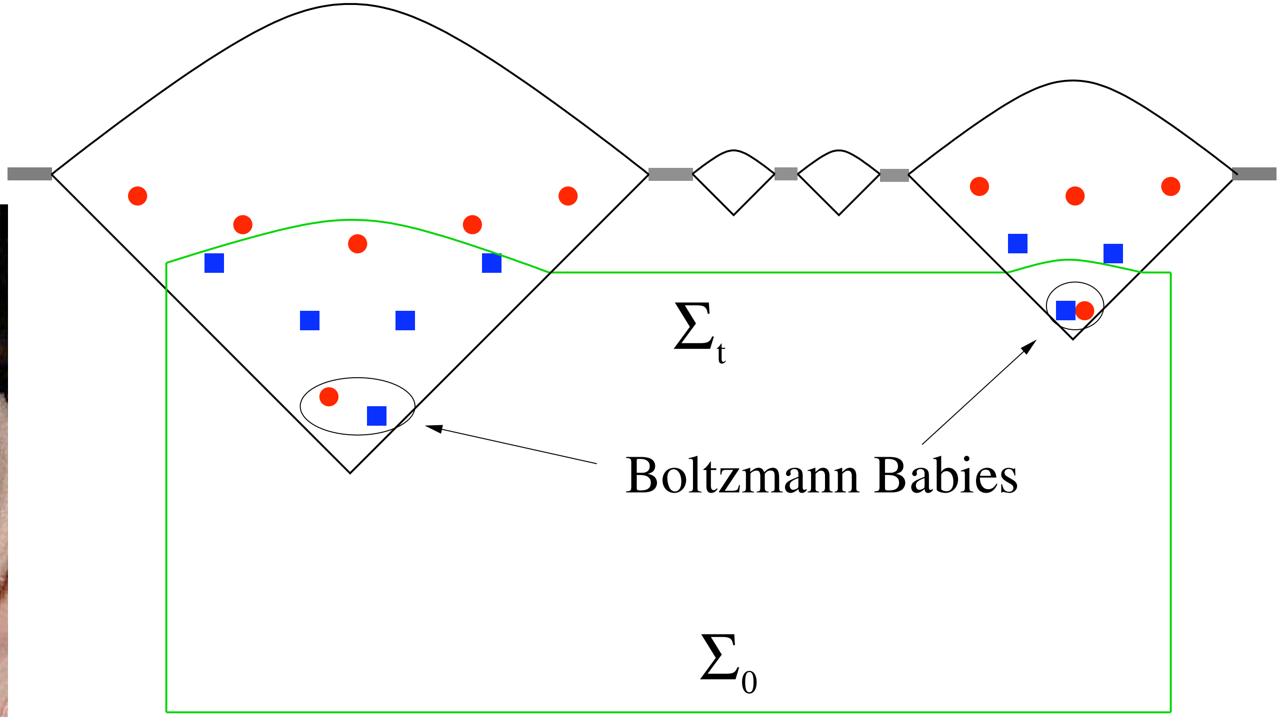
Two approaches

- Phenomenological
- Fundamental

Phenomenological approach

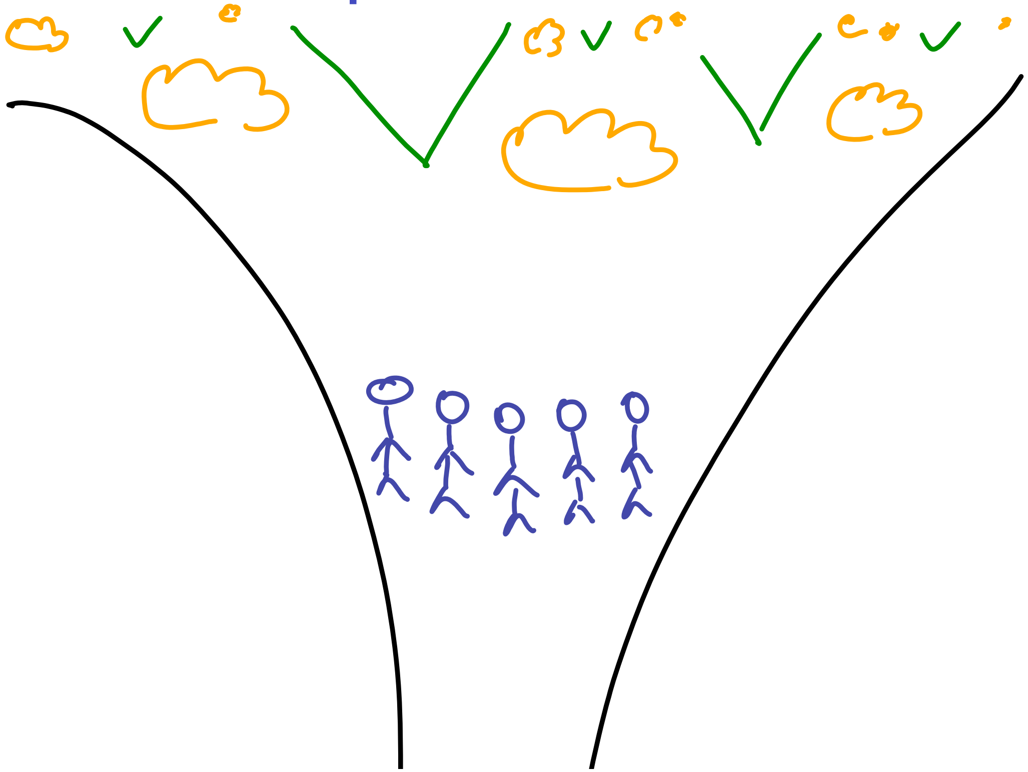
- Treat this as any other scientific problem
- Build quantitative models subject to usual criteria:
  - simple
  - well-defined
  - predictive
  - not in conflict with observation
- Proceed by elimination

Really bad contradiction, example 1: Too hot



- Proper time cutoff; take ratios as $t \to \infty$.
- Most observations made prior to t are made in recently formed bubbles.
- Nearly all observers live earlier than we do ("Youngness Paradox") [García-Bellido; Guth; Linde; Mezhlumian; Tegmark; RB, Freivogel & Yang]
- $p(T_{\rm CMB} \leq 3\text{ K}) = \exp(-10^{60}) \to$ Ruled out

Really bad contradiction, example 2: Too cold



- Cutoff: observers-per-comoving-volume (or per baryon, ...)
- Infinitely many observers arise per comoving volume, from thermal fluctuations at late times, in empty de Sitter space
- "Oldness Paradox", or Boltzmann brain problem [Dyson, Kleban & Susskind 2002; Page 2006; RB & Freivogel 2006; RB, Freivogel & Yang 2008; DeSimone *et al.* 2008, . . .]
- $p(T_{\text{CMB}} \geq 2\text{ K}) \approx 0 \rightarrow$ Ruled out

These examples show that certain measure proposals can be ruled out

- at high level of confidence ($> 10^{60}\sigma$)
- even though we have just one data point
- and without knowing much about cosmological dynamics and vacuum statistics of the landscape

Two approaches

- Phenomenological
- Fundamental [$\rightarrow$ Yang's talk]

Recently, some tentative signs of convergence:

- There is a small class of closely related measures for which no "really bad" problems are known[1], and which appear to give reasonable predictions for cosmological and particle physics parameters. (There is no argument for uniqueness however.)
- This class includes two measures that are, in different ways, motivated by holography:
  The causal patch cut-off [RB 2006], and
  the light-cone time cut-off; [Garriga & Vilenkin '08; RB '09]

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[1] . . . if the lifetimes of de Sitter vacua in the landscape satisfy a certain interesting constraint [Freivogel and Lippert 2008; Lippert's talk]

Two types of geometric cut-offs

- Global time cut-off:
  keep spacetime prior to time t
  E.g., light-cone time, scale factor time
- Local cut-off:
  keep spacetime region near some worldline
  E.g., Causal patch, fat geodesic

Recently, some exact global-local dualities were discovered which imply the equivalence of certain pairs of measures. [RB, Freivogel & Yang, 2008]

In particular, the causal patch cut-off is equivalent to the light-cone time cut-off. RB & Yang, 2009; Yang's talk

Outlook

It would be nice to have a fundamental derivation of the correct measure. Approaches include

- Giving a preferred status to the census taker or $\Lambda = 0$ regions; $D - 2$ dimensional theory on the rim of the hat [Freivogel & Susskind 2004; Freivogel *et al.* 2006; Freivogel & Kleban 2009]
- Dual theory living on the future boundary (or on the fractal subset formed by the endpoints of eternal geodesics) [Garriga & Vilenkin 2008, 2009]

Also: $\rightarrow$ talks by Kleban, Senatore, Villadoro, ...

Meanwhile . . .

. . . we can hope to make some progress by making predictions from the surviving measures and comparing to observation.

This means we need to overcome or get around our limited understanding of

- Vacuum structure
- Observer distribution

Introduction

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Vacuum structure & Observer distribution

Vacuum structure

For many parameters of interest, we do not know their statistical distribution in the landscape: ΔN_e (curvature), Q (density perturbations), m_e, α, ...

An important exception is Λ. For $\frac{dp}{d\log\Lambda}$ from different viable measures and various models for observers, see, e.g.,
[RB, Harnik, Kribs & Perez 2007;
Cline, Frey & Holder 2007;
De Simone, Salem, Guth & Vilenkin 2008;
RB, Freivogel & Yang 2008;
Salem 2009 $\rightarrow$ talk;
RB & Leichenauer 2009]

Vacuum structure

Approaches include:

- Estimate or derive a distribution (e.g., [Freivogel, Kleban, Martinez & Susskind])

- Make predictions that have little sensitivity to the landscape distribution. A beautiful recent example is Freivogel's 2008 explanation for the $O(1)$ ratio of axion dark matter to baryonic matter. The trick is that this depends only on the axion vev, which can be understood dynamically.

- Identify catastrophic boundaries and posit a "landscape force" that drives us towards them [Hall & Nomura 2007; RB, Hall & Numura 2009]. This can explain unnatural coincidences—see below.

- Make a best-case assumption. If predictions contradict observation, then the problem is with the measure.

Conditional probabilities

It would be nice to have a general definition of “observer”, but it is not essential. We are allowed to ask conditional questions. For example, we can ask what values of the cosmological constant are measured by observers “like us”, where “like us” can be defined, e.g., as the observers who live near stars like ours, in multiverse regions that have the same low energy particle physics and the same initial conditions in the early universe (aside from the value of Λ).

Catastrophic boundaries

Computing the distribution even of these special observers in different vacua can be difficult.

One approach is to identify catastrophic boundaries, across which observers like us cannot exist (e.g., failure of structure formation). If there is a landscape force or a dynamical force towards such boundaries, then we should find ourselves near them.

The Weinberg prediction

Classic example: Weinberg's prediction of a nonzero cosmological constant [1987]: $\Lambda \sim t_{vir}^{-2}$. The relevant catastrophic boundary was the disruption of large scale structure formation for $\Lambda \gg t_{\mathrm{vir}}^{-2}$.

This prediction could have been falsified. But it was basically successful [SN collaborations, 1998].

Catastrophic boundaries *vs.* the measure

Catastrophic boundaries are never completely sharp. An exponential drop-off can be overrun by super-exponentially large pressures.

An example are the “really bad” measures which predict Boltzmann brains or Boltzmann babies. In both cases, the prediction becomes $\Lambda \gg \Lambda_0$.

Catastrophic boundaries *from* the measure

Conversely, catastrophic boundaries can also arise from the measure. This was perhaps not appreciated until recently.

The causal patch measure and the fat geodesic measure count observers in a certain physical volume. If Λ dominates before $t_{\rm obs}$ then their number will be exponentially suppressed by de Sitter expansion, even if galaxies form.

$\rightarrow$ Predict $\Lambda \sim 1/t_{\rm obs}^2$. This solves the coincidence problem directly. [RB, Harnik, Kribs & Perez 2007; DeSimone *et al.* 2008; RB, Freivogel, Yang 2009]

The technique of catastrophic boundaries can be used to explain multiple coincidences [RB, Nomura & Hall 2009]: If

$$
\begin{aligned}
p_{\bar{\rho}} + p_\Lambda - \frac{1}{2}p_{\rm obs} - \frac{1}{2}p_Q &= -\left[0.19\,^{+0.31}_{-0.14}(1\sigma)\,^{+0.84}_{-0.18}(2\sigma)\right], \\
-p_\Lambda + \frac{1}{2}p_{\rm obs} &= -\left[0.141\,^{+0.233}_{-0.106}(1\sigma)\,^{+0.626}_{-0.136}(2\sigma)\right], \\
-\frac{1}{2}p_{\rm obs} &= -\left[0.76\,^{+1.25}_{-0.57}(1\sigma)\,^{+3.37}_{-0.73}(2\sigma)\right], \\
-\frac{1}{2}p_Q &= -\left[0.12\,^{+0.20}_{-0.09}(1\sigma)\,^{+0.53}_{-0.11}(2\sigma)\right].
\end{aligned}
$$

then

$$
t_{\rm obs} \sim t_\Lambda \sim t_{\rm vir} \sim t_{\rm comp} \sim t_{\rm cool} \sim \frac{\alpha^2}{G_{\rm N} m_e^2 m_p}
$$

Observer distribution 2.0

Assume observers arise near stars with O(Gyr) time delay.

Model the star formation rate as a function of time, in a three-parameter multiverse $(\Lambda, \Delta N_e, Q)$
[RB & Leichenauer 2008].

With standard assumptions for prior distributions, compute probability distributions over these parameters, for various measures and observer models
[RB & Leichenauer to appear].

The entropic principle

Assume that entropy production traces observers, at least on average:

$$N_{\rm obs} \propto \Delta S \; ,$$

where ΔS is the matter entropy produced inside the causal diamond since reheating.

In our universe, the peak entropy production time is at about $t_{\rm peak} \sim 3$ Gyr. Thus, ΔS is a successful predictor of the observed value of $\Lambda \sim t_{\rm peak}^{-2} \sim 10^{-123}$
[RB, Harnik, Kribs & Perez 2007]

Generalized to predict multiple parameters $(\Lambda, \Delta N_e, Q)$ [Cline, Frey & Holder 2007; Bozek, Albrecht & Phillips 2009; RB & Leichenauer 2009]

The entropic principle

In our universe, ΔS is dominated by the infrared radiation emitted by dust heated by starlight. Thus, ΔS be much smaller in a vacuum that fails to contain

- heavy elements
- stars
- galaxies

Such vacua will be suppressed if we weight by ΔS.

ΔS appears to "know" about anthropic criteria; yet, it remains well-defined in much less familiar vacua, whose observer content would be hard to guess.

Beyond vacua "mostly like ours"

[RB & Harnik to appear]

$$\Delta S \sim \frac{M}{T}$$

where M is the free energy inside the causal diamond at the time t_{peak} when most entropy is produced, and
T is the energy of a typical radiation particle (in our universe, photons emitted by dust)

In this formula it is irrelevant how the entropy is produced and what particles carry it. It can be applied to all vacua in the landscape.

Naively, the entropic principle predicts that the temperature should be as low as possible.

Predicting the temperature of dust

However, if $T < t_{\rm peak}^{-1/2}$ then the radiation cannot be thermal; the photons cannot be a dilute gas. Then the above formula breaks down; the entropy production is maximal for $T \sim t_{\rm peak}^{-1/2}$.

Thus, weighting by ΔS predicts that the temperature should not be much larger than

$$T_{\rm min} \sim t_{\rm peak}^{-1/2} \sim \Lambda^{1/4} \ .$$

Predicting the temperature of dust

This general prediction does hold in our universe: With $t_{\rm peak} \sim 3$ Gyr, $T_{\rm min} \sim 30$ K; the temperature of galactic dust is around 200 K.

At the limiting value, the free energy is converted into thermal radiation that fills up the whole universe. Thus, the same prediction explains why galaxies nearly fill up the sky, and why the infrared radiation from galaxies appears nearly as a uniform background.

Predicting the temperature of background radiation

Assume a landscape pressure towards large values of T_{CMB}.

But T cannot be smaller than the background temperature. Therefore we expect T_{CMB} to be near the catastrophic boundary $T_{\mathrm{CMB}} \sim T$.

In our universe, this prediction holds up: $T_{\mathrm{CMB}} \sim 8$ K at the time t_{peak}.

Predictions in the Multiverse

To summarize, the entropic principle predicts the triple coincidence

$$T_{\rm CMB} \sim T \sim t_{\rm peak}^{-1/2} \sim \Lambda^{1/4}$$

in the full multiverse, independently of the nature of the observers.

Bonus question

We have learned to explain correlations between scales. To get numbers out, we need at least one input parameter. Can we be more ambitious?

What is the ultimate origin of scales like $\Lambda \sim 10^{123}$—the "ur-hierarchy"?

Anthropic/entropic pressure + Discretuum limit?