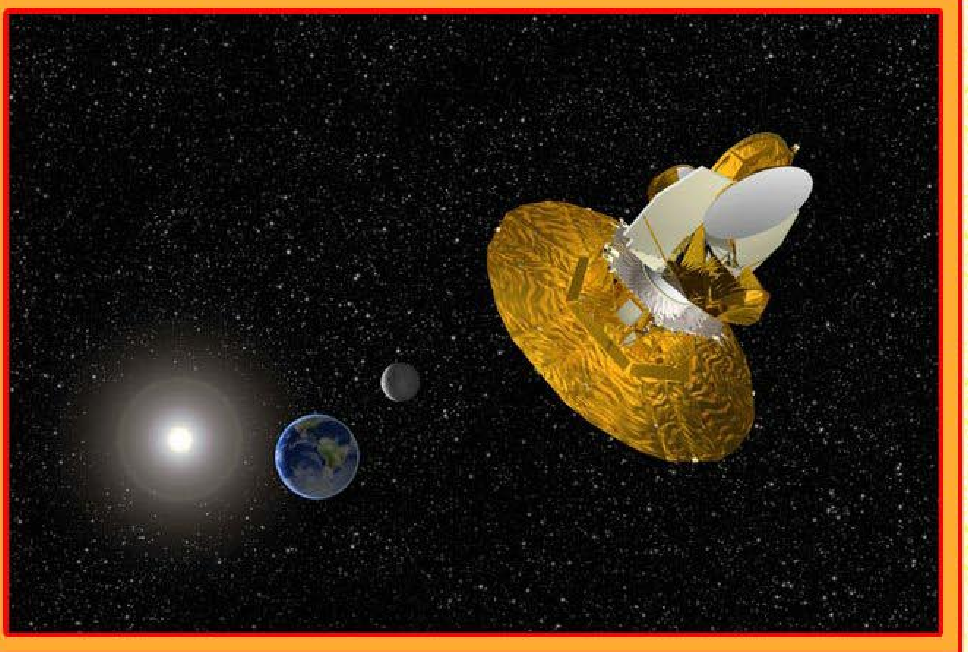
FQXi CONFERENCES
FQXi INTERNATIONAL CONFERENCE:
Ponta Delgada, Azores, July 7-12, 2009

THORNY PROBLEMS in COSMOLOGY



— Alan Guth —
Massachusetts Institute of Technology

FQXI International Conference
Ponta Delgada, Azores
July 8, 2009

Thorny Problem #1: DARK ENERGY

In 1998, astronomers discovered that the universe has been accelerating for about the last 5 billion years (out of its 14 billion year history).

IMPLICATION: Inflation is happening today, so the universe today is filled with a repulsive gravity material. (Within general relativity, this requires negative pressure.) The repulsive gravity material, which apparently fills space, is called the

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SIMPLEST EXPLANATION: Dark energy = vacuum energy, also known as a cosmological constant.

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The NIGHTMARE of DARK ENERGY

- ☆ The quantum vacuum is far from empty, so a nonzero energy density is no problem.
- ☆ In quantum field theory, the energy density of quantum fluctuations diverges.
- ☆ A plausible cutoff for the fluctuations is the Planck scale, $E_p \approx 10^{19}$ GeV, the scale of quantum gravity.
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It is too large by 120 orders of magnitude!

Thorny Problem #2: DEFINING PROBABILITIES IN AN ETERNALLY INFLATING UNIVERSE

For starters, do we live in a multiverse?

Vocabulary problem: if "universe" means everything that exists, there can exist only one.

Current usage: "Our universe" refers to the region of space that evolved from the same big bang that we did. It is sometimes called a "pocket universe." If there are similar regions, they are other pocket universes. The set of all pocket universes is called the **multiverse.**

Do we live in a multiverse, cont.:

Viewpoint: to some, postulating the existence of other (pocket) universes is a wild leap of speculation.

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To others, postulating that there is only one pocket universe is a wild leap of speculation. I.e., if there is a physical explanation (as opposed to supernatural explanation) of the origin of our pocket universe, how could it possibly happen only once?

Do we live in a multiverse, cont.:

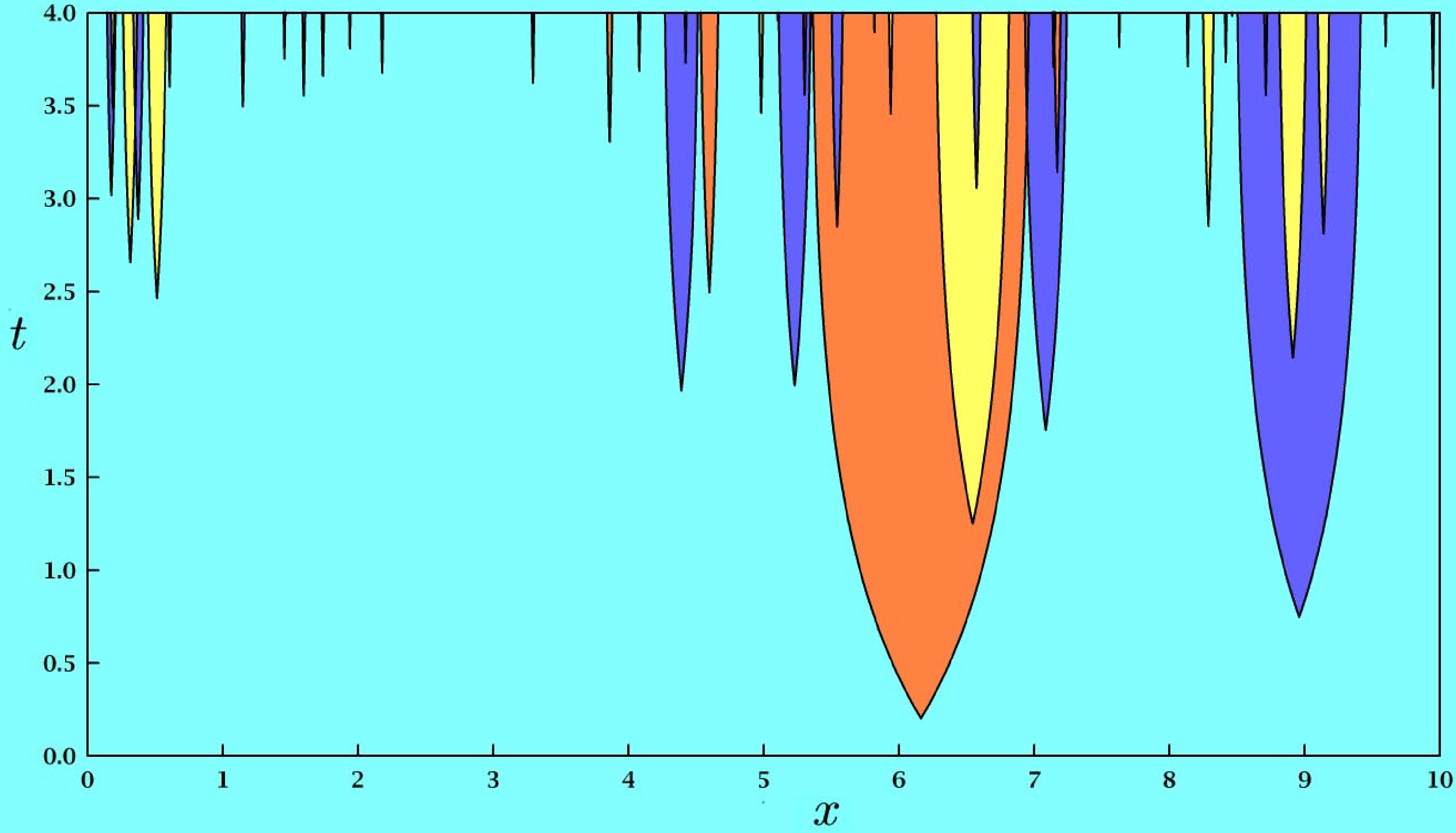
Three strong winds blowing in the direction of the multiverse:

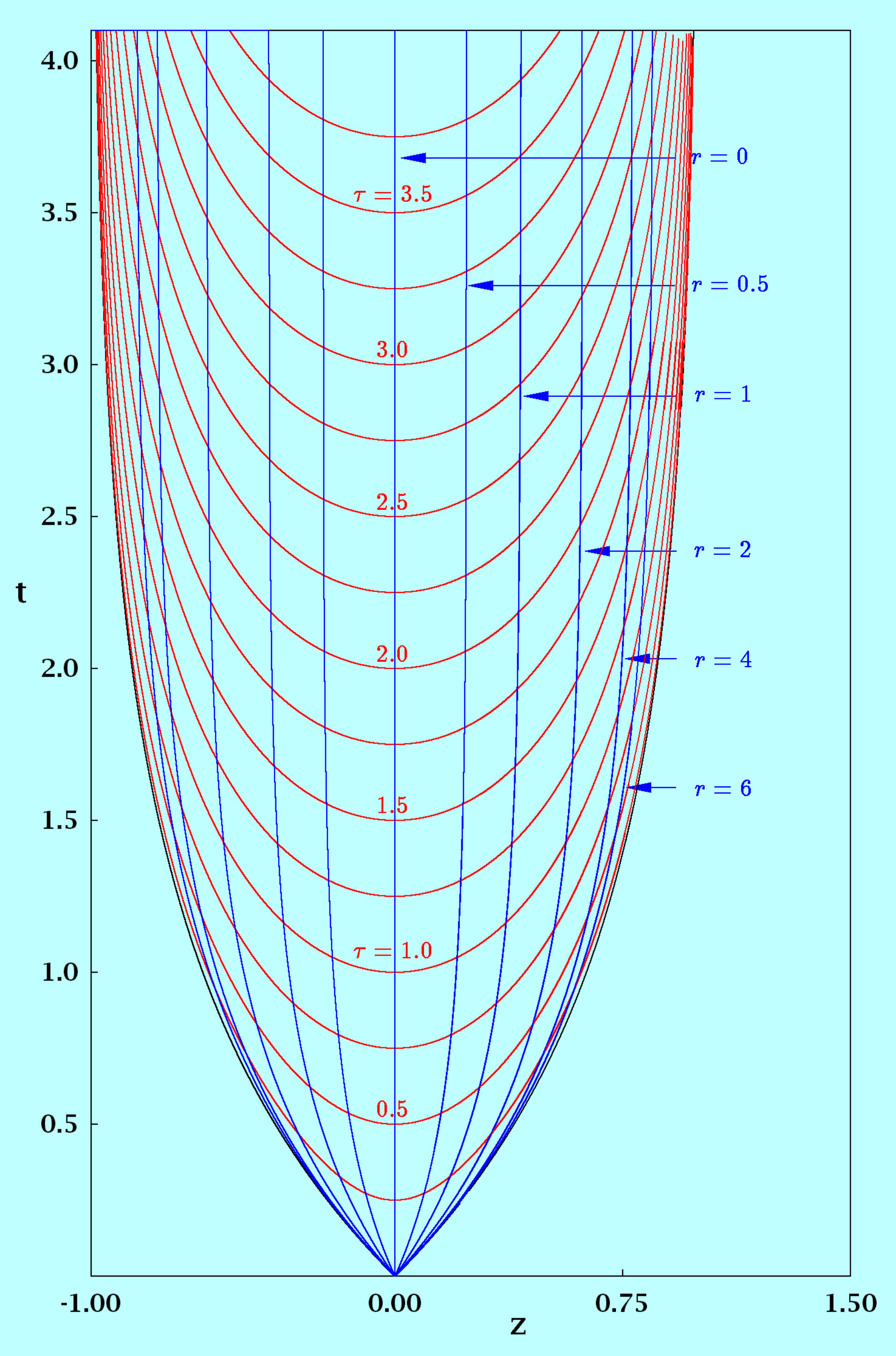
1) **Theoretical Cosmology:** Almost all versions of inflation lead to eternal inflation; once inflation starts, it never stops.

2) **String Theory:** String theorists are convinced that there is no unique vacuum. Instead, there are at least $\sim 10^{500}$ long-lived metastable states, any one of which can serve as the substrate for a pocket universe.

3) **Observational Cosmology:** The cosmological constant Λ. The most plausible known explanation for small Λ is the anthropic one, using the multiverse. That is, the set of string theory vacua is expected to include many with Λ as small as what we observe, eternal inflation can populate these vacua, and life is expected to form only where Λ is small.

Bubble Nucleation in an Eternally Inflating Universe





Even a single bubble, formed by tunneling, has equal-time surfaces that are INFINITE.

Coleman & De Luccia open-universe bubble, with $\Lambda_{\text{bubble}} = \Lambda_{\text{background}}$. I.e., bubble does not affect the metric.

The diagram shows the RW open universe coordinates on the background of the flat coordinate system for the parent spacetime.

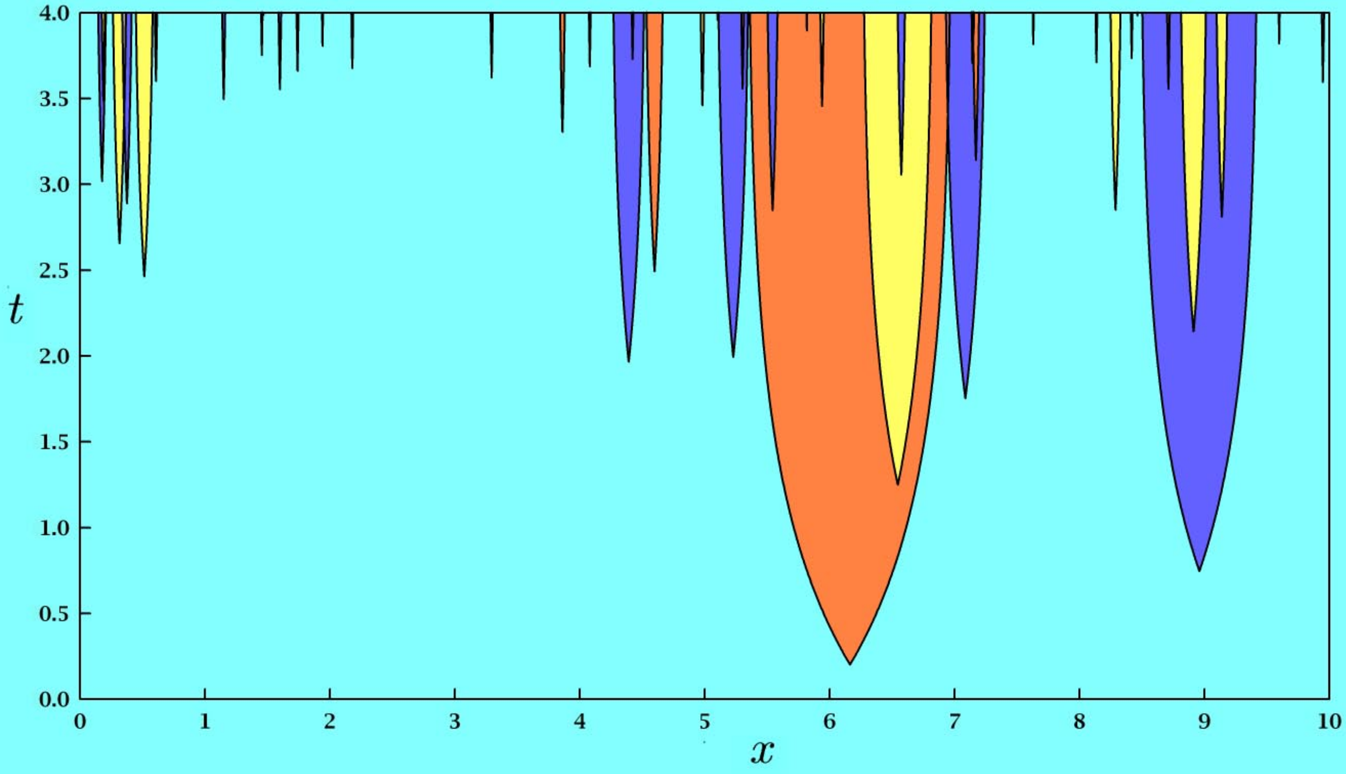
Need for a Measure

- ☆ Anything that can happen will happen — an infinite number of times!
- ☆ To separate the probable from the improbable, we need to compare infinities.
- ☆ Probabilities can be defined by introducing a cutoff, but in this case the answers can depend strongly on the type of cutoff.

A Simple Strategy

- Choose a finite spacetime volume V_4, calculate the desired ratio of events in the finite volume, and then take the limit as $V_4 \to \infty$.
- Failure: the resulting answer depends crucially on the method for choosing and enlarging the spacetime volume.

Reason for Difficulty



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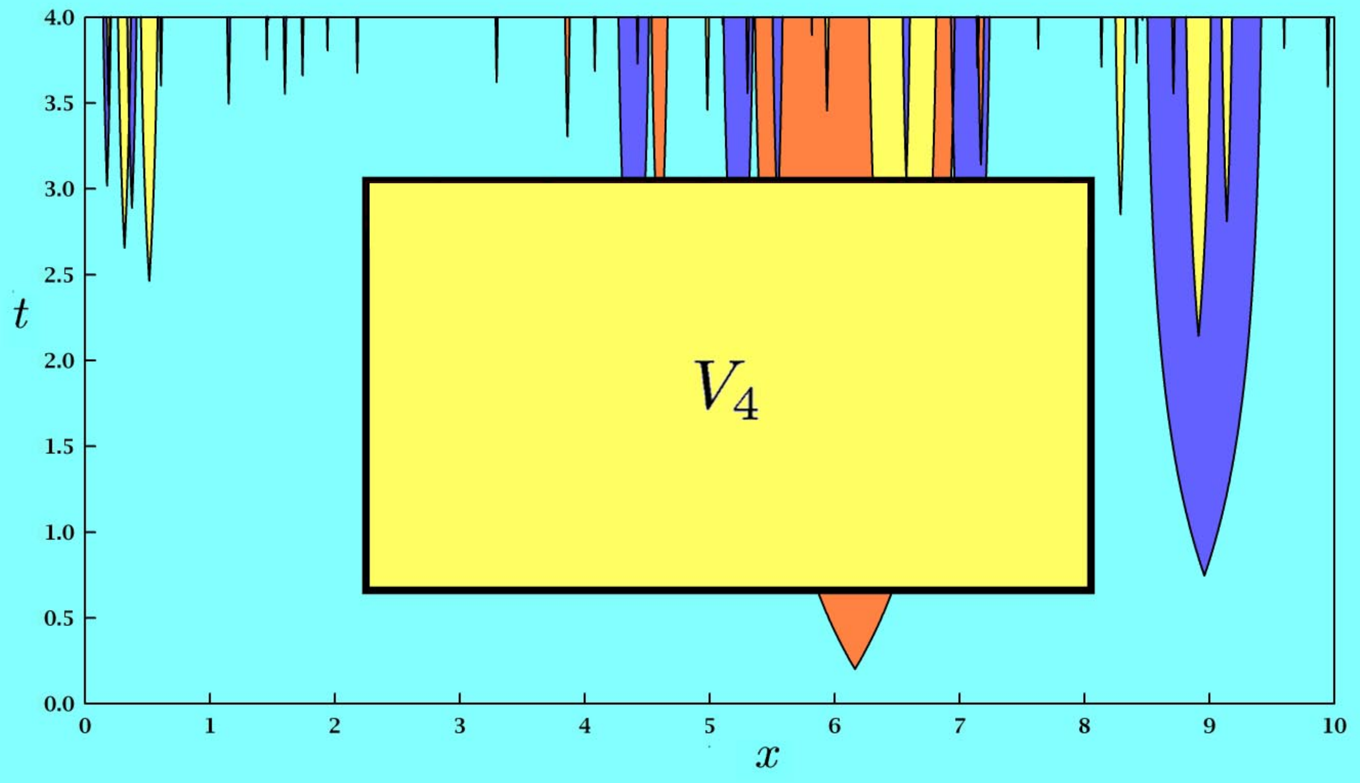

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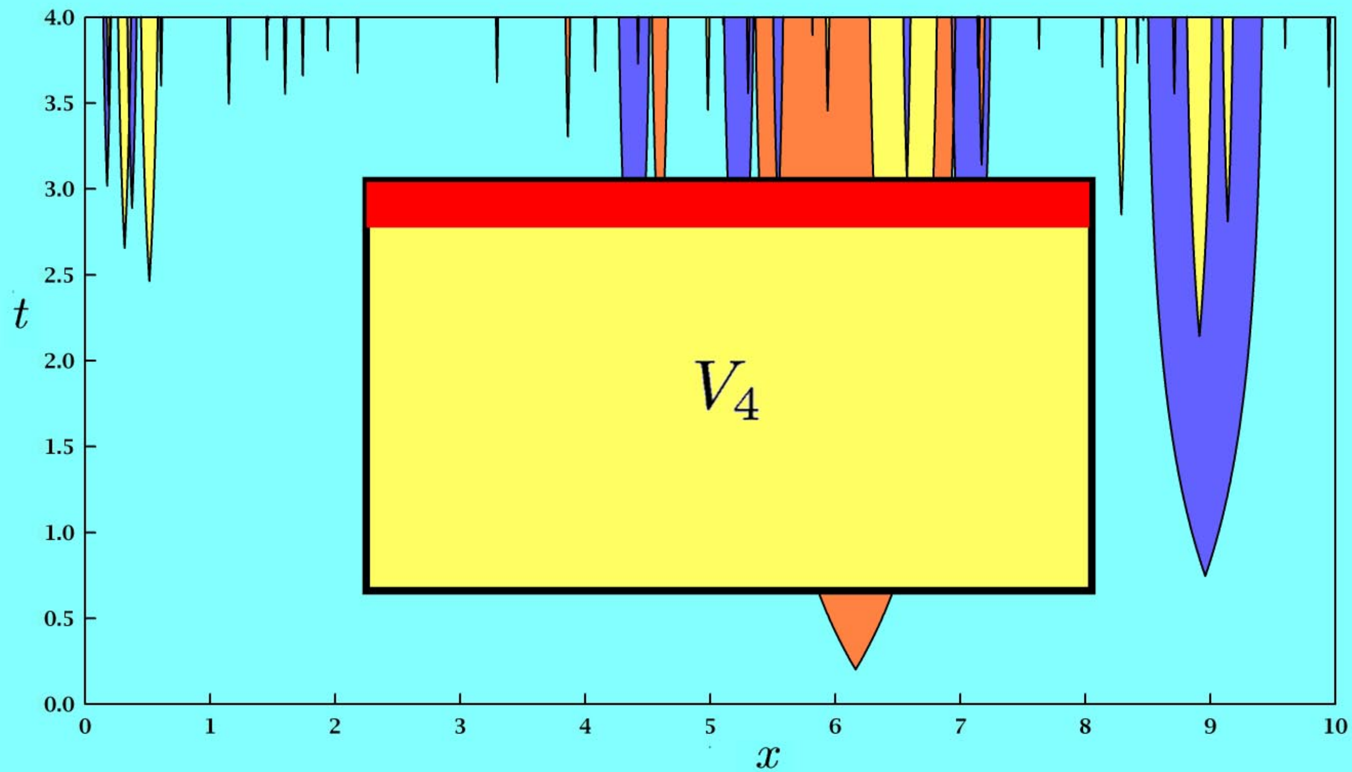

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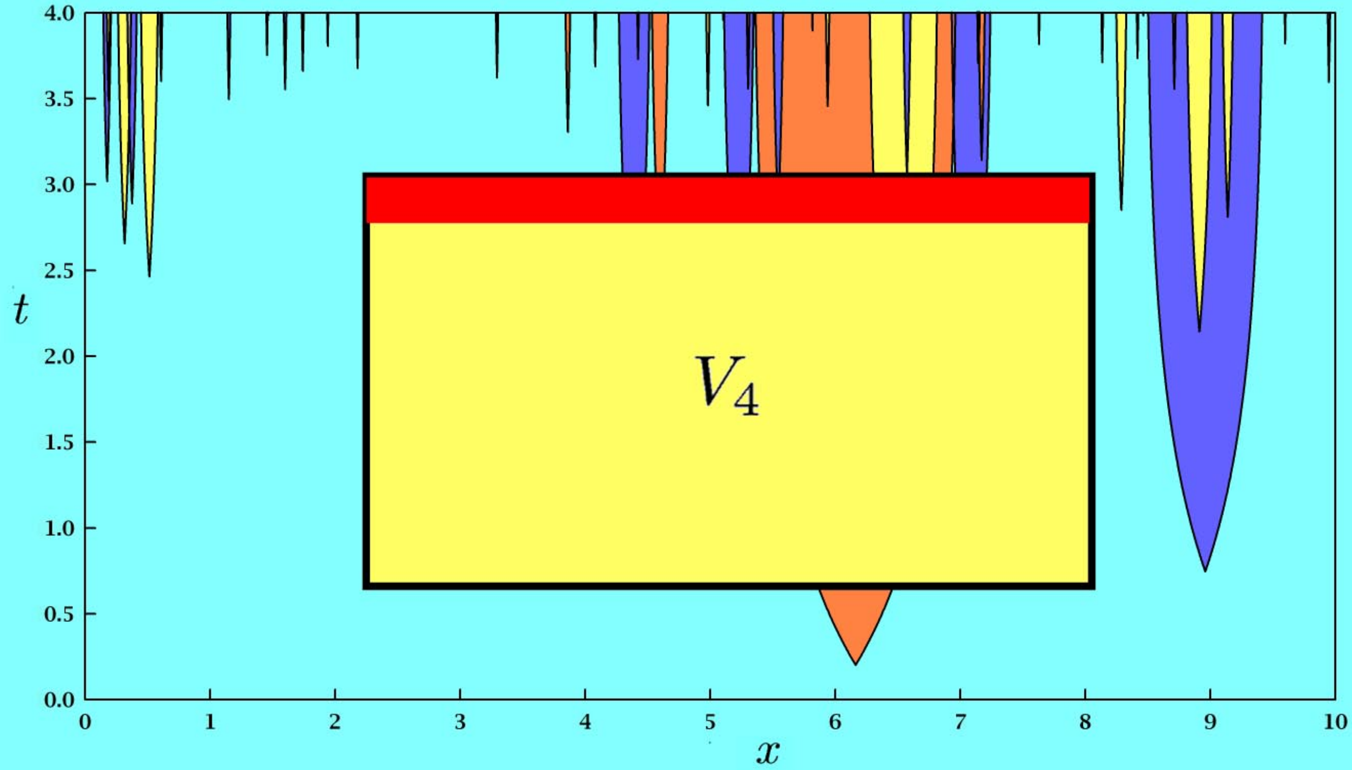
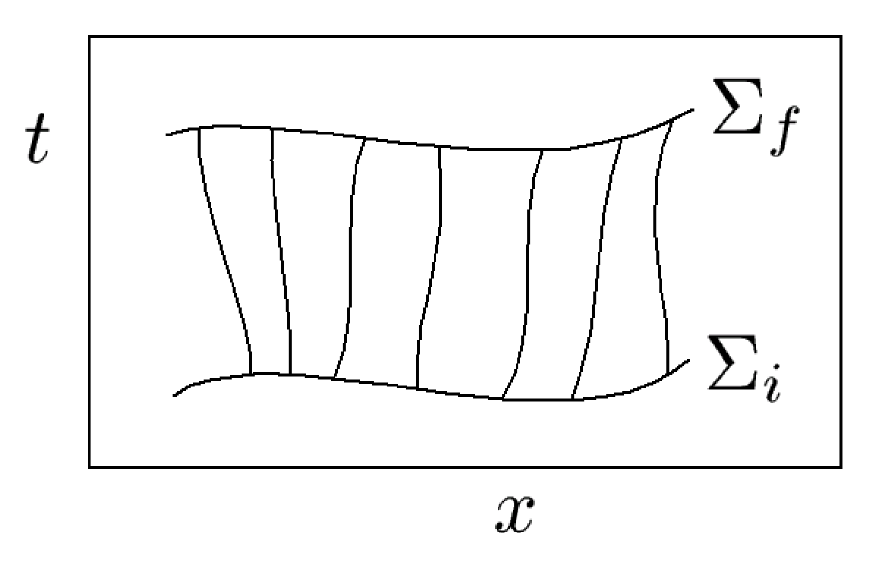


If V_4 is specified in comoving coordinates, the volume is always dominated by the final time surface, due to the exponential expansion. So the method of selecting the surface is always crucial.

Search for a Recipe

- ☆ The problem is ~25 years old. Very frustrating! Even if the evolution of the multiverse is fully described, predictions are still impossible.
- ☆ Is there a fundamental principle to define probabilities? **Not yet.** There is some hope offered by Garriga and Vilenkin's *Holographic Multiverse* (0809.4257 hep-th).
- ☆ Current Status: try out ideas and reject those that conflict with observation or known physics.

Example 1: Proper Time Cutoff



1) Choose initial finite spacelike hypersurface Σ_i.

2) Construct family of timelike fiducial geodesics normal to it, projected into the future.

3) Cut off the fiducial geodesics on a final hypersurface Σ_f, defined by proper time $\tau = \tau_c$.

4) Calculate desired ratios, and then let $\tau_c \to \infty$.

☆ If the region includes an eternal worldline, then it can be argued that the limit exists, and is independent of the initial hypersurface.

☆ Strongly favors large amounts of inflation. The fastest inflating state, and its decay products, will dominate.

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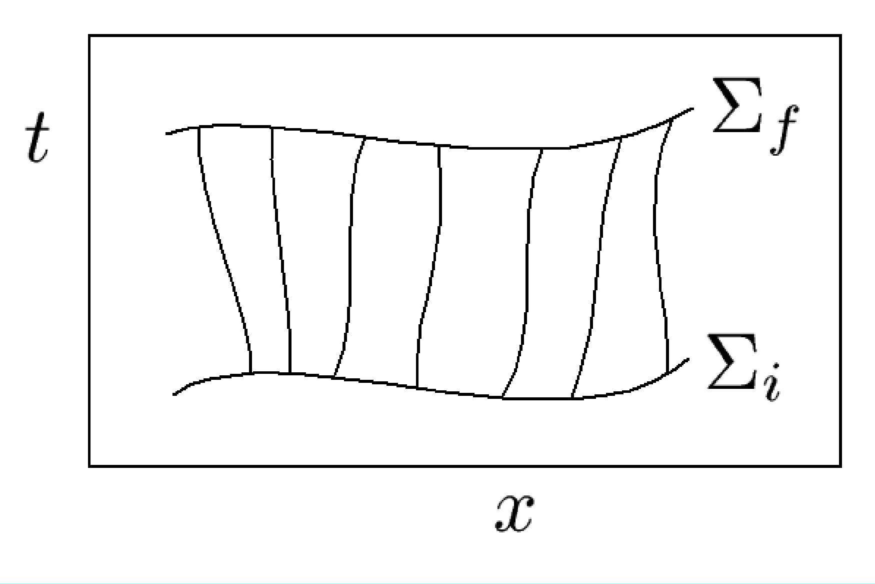
Example 2: Scale-Factor Cutoff Measure

☆ Same method as proper time cutoff, but use scale-factor time $t_{\rm sf}$ instead of proper time τ.



$$dt_{\rm sf} = \frac{1}{3}\, u^{\mu}_{;\mu}\, d\tau \ ,$$

or equivalently

$$\rho \propto e^{-3t_{\rm sf}} \ ,$$

where ρ = density of fiducial worldlines.

☆ Since volumes grow as $e^{3t_{\rm sf}}$, regardless of inflation, large amounts of inflation are not favored. Instead, the state with the slowest decay rate is favored — called the dominant vacuum. It, and its "decay products," will dominate the volume. "Decay" includes tunneling to a high energy false vacuum.

Pitfalls of Measures: Youngness Problem

- Severe problem in the proper time measure.
- Problem: Since the available volume grows $\sim e^{3H\tau}$, where $H^{-1} \approx 10^{-37}$ s (for example), most bubbles in the sample formed within a few Hubble times of the final time cutoff. Older bubbles are **VERY** rare.
- Quantitatively, one can define local Robertson-Walker time τ_p for each spacetime point in any pocket universe. The available spatial volume for a given τ_p obeys

$$V_{\text{proper}-\text{time}}(\tau_p) \propto\!\!\!\!\sim a^3_{\text{pock}}(\tau_p) \times R(\tau_{\text{global}} - \tau_p),$$

where τ_{global} is the proper time-coordinate as measured by the fiducial geodesics, and $R(\tau)$ is the nucleation rate at global proper time τ. Approximately,

$$V_{\text{proper-time}}(\tau_p) \propto\!\!\!\!\sim a^3_{\text{pock}}(\tau_p) \times e^{-3H\tau_p} .$$

- Example of youngness bias: the "coolness" problem (Tegmark, astro-ph/0410281). I.e., the cosmic microwave background should be hotter. If we could have evolved earlier, when $T_{\rm CMB} = 4{\rm K}$, $V(\tau_p)$ would be larger by about $10^{10^{56}}$.
- Scale-factor cutoff measure has only a very mild (and tolerable) youngness bias.

$$V_{\rm scale-factor}(t_{\rm sf}) \underset{\sim}{\propto} a^3_{\rm pock}(t_{\rm sf}) \times R(t_{\rm global} - t_{\rm sf})$$
$$\underset{\sim}{\propto} e^{3t_{\rm sf}} e^{-3t_{\rm sf}}$$
$$\underset{\sim}{\propto} \text{const.}$$

But more precisely $V_{\text{scale-factor}}(t_{\rm sf})$ decreases very slowly with $t_{\rm sf}$, due to the decay of the vacuum within the bubble.

Pitfalls of Measures: Boltzmann Brains

- ☆ Serious problem in pocket-based measures, and in other measures not discussed here.
- ☆ Consider our own pocket universe, and assume that dark energy = vacuum energy. Assume that our vacuum is stable, or that nucleation rate for other bubbles in our vacuum obeys $\lambda \ll H^4$.
- ☆ Then our pocket will be eternal, with infinite de Sitter expansion in the future.
- ☆ De Sitter space has a nonzero Gibbons-Hawking temperature $T_{\rm GH} = H/2\pi$. Thermal fluctuations can produce anything, with $P \sim e^{-M/T_{GH}}$.
- ☆ Brains like ours can nucleate, with a low rate, but with an infinite spacetime volume. They are called Boltzmann brains (BB's).

Boltzmann Brains: A Thought Experiment

1) Observer closes her eyes. (Idealization: all sensory input is shut off.)

2) While the eyes are shut, the brain has access only to its memory and thought processes — i.e., to stored data and programs.

3) For every normal observer, there are an infinite number of BB's with exactly the same data and programs (by random choice).

4) The observer's brain predicts what will happen when she opens her eyes, based on previous knowledge. But the probability is 1 that the brain is really a BB. Prediction: the next observation will have no logical relationship to the world she remembers.

5) Conclusion: our continued observation of a coherent world gives overwhelming evidence that we do ***not*** live in a world with an infinite ratio of BB's to normal observers.

Boltzmann Brains and Scale-Factor Cutoff Measure

- $V_{\text{scale-factor}(t_{\text{sf}})}$ falls off exponentially with pocket proper time τ_p, with a very slow time constant, related to decay rates. The exponential convergence is just what is needed to make the number of BB's finite. It is still not certain whether the number is acceptable, because it depends on estimates of decay rates and BB nucleation rates. It is plausible that the rates are okay.

Complications with Scale-Factor Cutoff Measure

Source: Bousso, Freivogel, & Yang: "Properties of Scale Factor Measure".

The Problem: Structure formation perturbs the RW metric.

Perturbations in the metric from RW are usually irrelevant in cosmology, but not here. Galaxies reverse the cosmological expansion in their neighborhood, causing geodesics to converge. Scale factor time stops increasing! Since observers are assumed to live in galaxies, the counting of observers is significantly perturbed.

There is no problem inventing definitions about how to handle this — but there are many options.

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- ☆ Beware: there are other measures (causal patch measure, Linde's stationary measure, pocket based measures . . .) and other criteria (Q-catastrophe, consistency with local laws of physics, . . .) that I have not talked about.