Title: Eternal Inflation and it's Implications

Date: Jul 12, 2011 09:50 AM

URL: http://pirsa.org/11070034

Abstract: TBA

ETERNAL INFLATION AND ITS IMPLICATIONS

— Alan Guth —

Massachusetts Institute of Technology

Challenges for Early Universe Cosmology

Perimeter Institute
Waterloo, Ontario
July 12, 2011

Outline

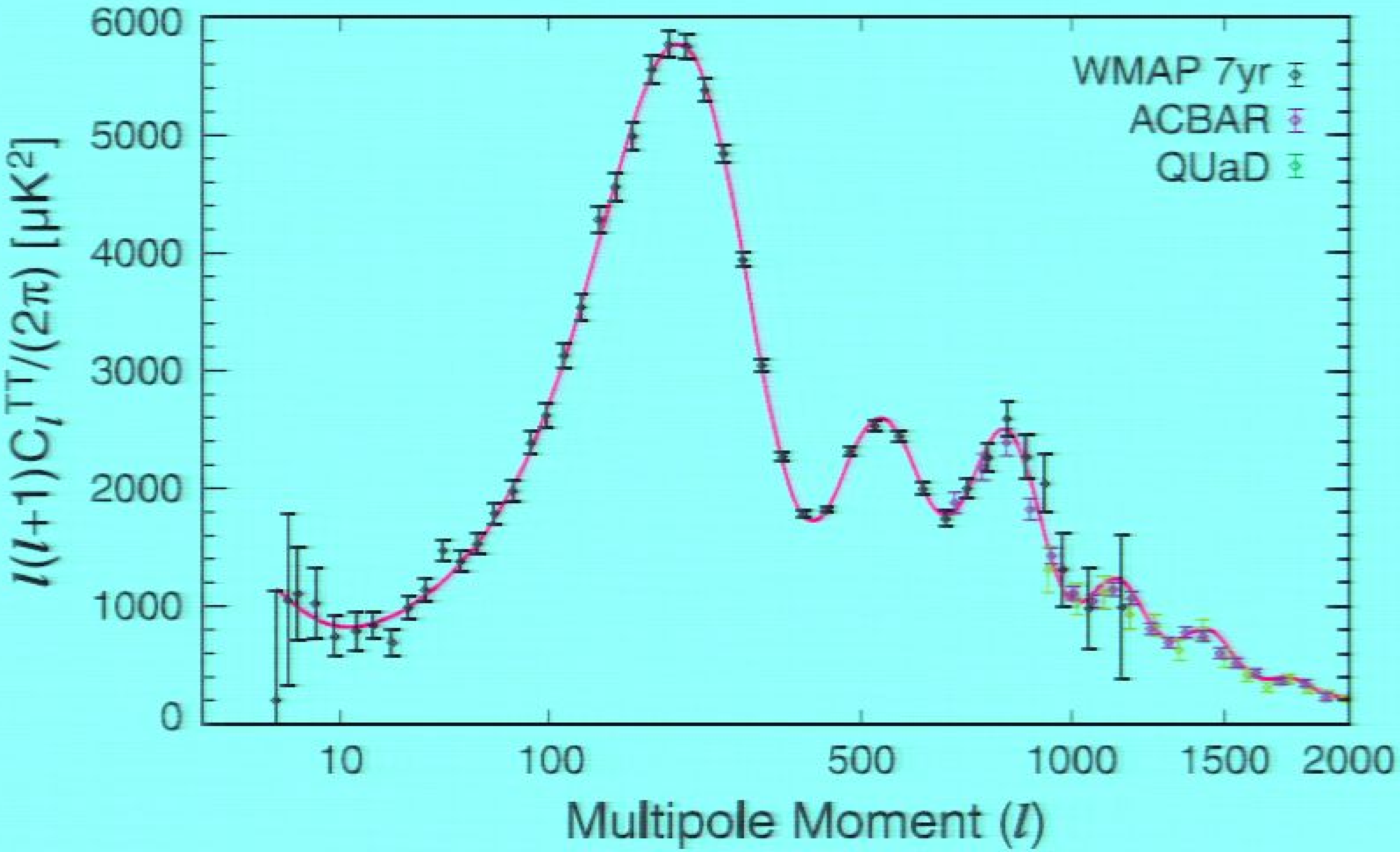
1) Almost all models of inflation lead to eternal inflation.

2) Eternal inflation has a number of benefits: independence of initial conditions; possible explanation for small vacuum energy density; avoidance of a thermal equilibrium phase.

3) Eternal inflation has a key outstanding problem: the measure problem — how to define probabilities for what an observer will see.

Alan Guth
Massachusetts Institute of Technology

WMAP 7-YEAR FLUCTUATION SPECTRUM



Alan Guth
Massachusetts Institute of Technology

Eternal Inflation

- Essentially all models of inflation lead to (future) eternal inflation.
- Crude explanation: inflating false vacuum is metastable, but decay rate $\ll$ expansion rate. Therefore the volume of false vacuum increases exponentially with time.
- Once inflation starts, it never stops. The inflating region never disappears, but pieces of it undergo decay and produce "pocket universes" ad infinitum.

Alan Guth
Massachusetts Institute of Technology

Eternal Inflation In Our Pocket

- Our own universe appears to have $\Lambda > 0$, so it is entering a period of inflation.
- If our vacuum is stable, then our visible universe will become eternal. Life will die out, but in the infinite de Sitter region that will follow, tunnelings that create new pocket universes will occur. Upward tunnelings as well as downward tunnelings are possible. Eternal inflation will follow.
- If our vacuum is metastable, it has to have a decay rate $\lambda \sim H^4$ to prevent eternal inflation.

Alan Guth
Massachusetts Institute of Technology

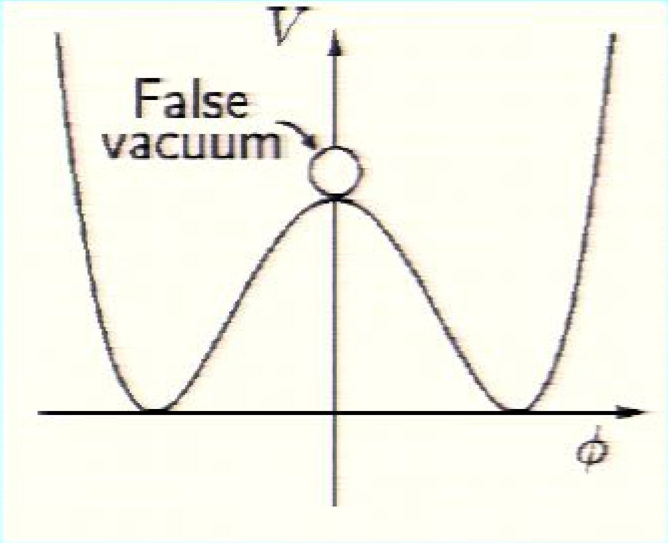
Mechanism of Eternal Inflation: Small Field (New) Inflation

1) False vacuum is metastable, and decays exponentially.

2) Volume of false vacuum inflates exponentially.

3) Rate of inflation $\gg$ rate of decay.

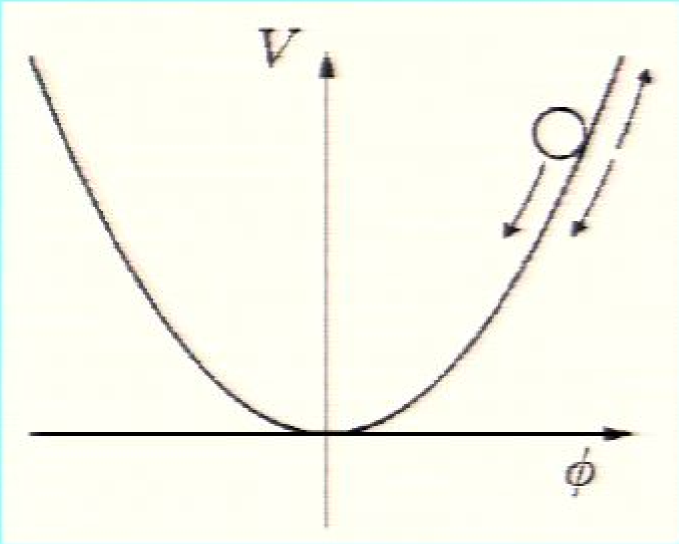
∴ Volume of false vacuum increases with time! (Steinhardt, 1983; Vilenkin, 1983)



Alan Guth
Massachusetts Institute of Technology

Mechanism of Eternal Inflation: Large Field (Chaotic) Inflation

Andrei Linde showed in 1986 that even chaotic inflation can be eternal. One needs to consider quantum fluctuations of ϕ:

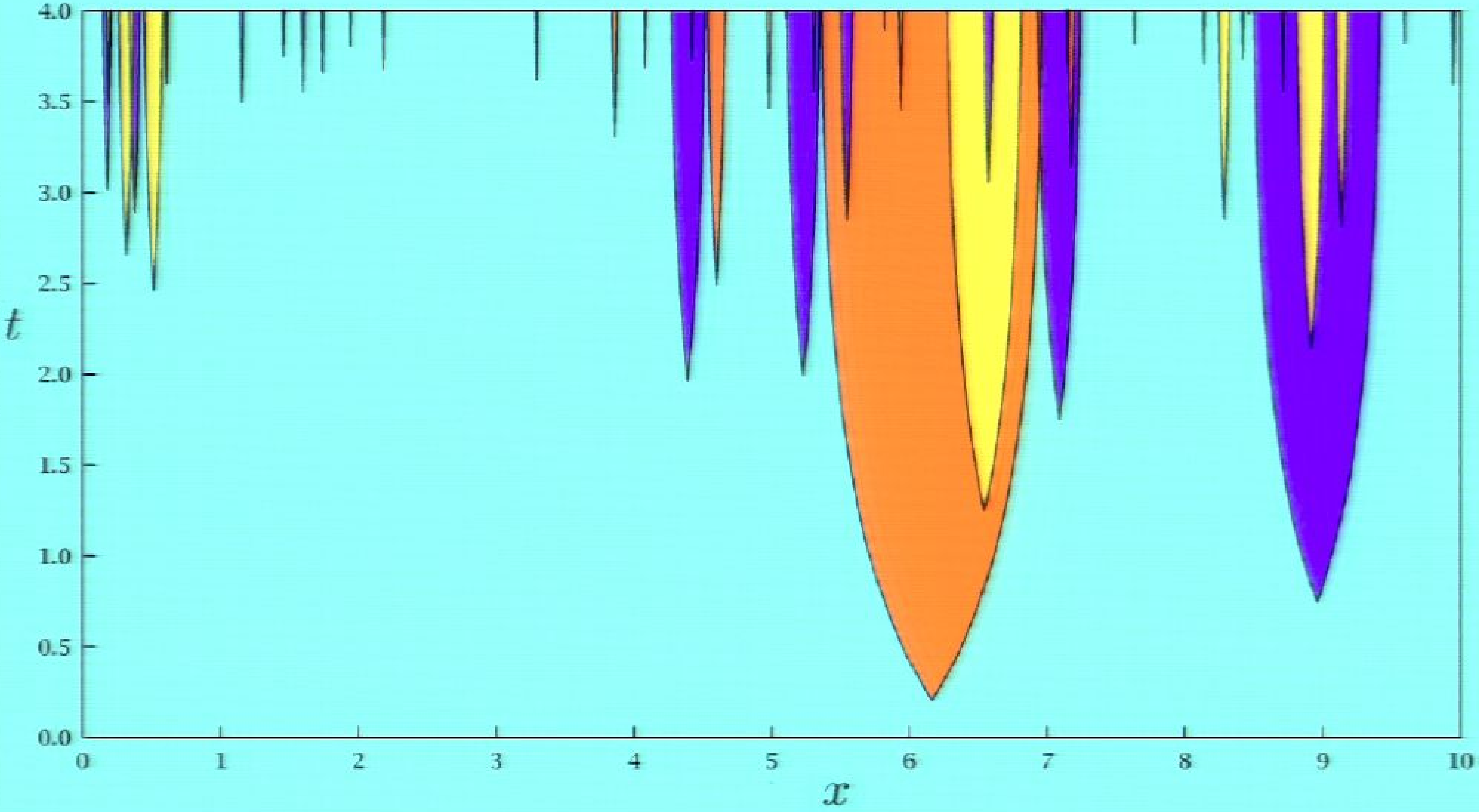


- Simple random walk picture: In each time interval $\Delta t = H^{-1}$, the average field ϕ in each region of size H^{-1} receives a random increment with root mean square $\Delta\phi_{\rm qu} = H/2\pi$. This random increment, either up or down, is superimposed on the downward classical motion.
- Suppose $\phi = \phi_0$ at the start of some time interval $\Delta t = H^{-1}$. During Δt, the volume expands by $e^3 \approx 20$. If the fraction of space in which ϕ increases is $> 1/20$, then volume of region with $\phi > \phi_0$ INCREASES. If so, inflation never ends.

Alan Guth

Massachusetts Institute of Technology

Bubble Nucleation in an Eternally Inflating Universe



Alan Guth
Massachusetts Institute of Technology

Theoretical Benefits of Eternal Inflation

1) Independence of Initial Conditions

With some assumptions, an eternally inflating universe approaches a steady-state equilibrium, so the initial conditions do not affect late-time predictions. (This depends on the measure question, but is true for many proposed measures, including all my favorites.)

Alan Guth
Massachusetts Institute of Technology

2) Possible Explanation for Small Vacuum Energy Density

- ☆ The vacuum energy density is at least 120 orders of magnitude smaller than expected, and there is no known, accepted, dynamical explanation.
- ☆ But string theory strongly suggests that there are at least $\sim 10^{500}$ long-lived vacuum-like states, so we expect many of these to have vacuum energy densities as small as what we observe.
- ☆ If eternal inflation populates these vacua, and selection effects cause life to predominantly form in these vacua, then the small vacuum energy density is explained. That is, maybe almost all living things see a small vacuum energy density, even if it is very rare in the multiverse. [Refs: Weinberg, 1987; Martel, Shapiro, and Weinberg, 1998.]

Alan Guth
Massachusetts Institute of Technology

3) Avoidance of Thermal Equilibrium Phase

☆ I am not aware of any papers that make this argument (in full).

☆ *Need to avoid thermal equilibrium:*

- Suppose, for example, that reality can be described by some quantum system with a maximum possible entropy. Then the system will reach thermal equilibrium and undergo Poincaré recurrences *forever*, and all microstates will occur and re-occur with equal probability.
- Life (including observers like us) will continue to occur in the thermal equilibrium phase, but with overwhelming probability the worlds that they will observe will look nothing like ours. Boltzmann brains.
- We think that the world we see looks the way it does because of its big-bang history. But in thermal equilibrium, probabilities are determined **ONLY** by state counting. For example, a state that looks just like our world except that $T_{\text{CMB}} = 10$ K would have more microstates, and would be much more likely than 2.7 K. [Ref: Dyson, Kleban, & Susskind (2002).]

Alan Guth
Massachusetts Institute of Technology

3) Avoidance of Thermal Equilibrium Phase, Cont.

- ☆ If the semiclassical global picture of eternal inflation is valid, then new pocket universes are constantly being created and new regions of phase space are constantly being explored. Poincaré recurrences do not happen.
- ☆ For this to happen, the available classical phase space must be infinite, or the quantum mechanical Hilbert space must be infinite-dimensional.

Alan Guth
Massachusetts Institute of Technology

3) Avoidance of Thermal Equilibrium Phase

☆ I am not aware of any papers that make this argument (in full).

☆ *Need to avoid thermal equilibrium:*

- Suppose, for example, that reality can be described by some quantum system with a maximum possible entropy. Then the system will reach thermal equilibrium and undergo Poincaré recurrences *forever*, and all microstates will occur and re-occur with equal probability.
- Life (including observers like us) will continue to occur in the thermal equilibrium phase, but with overwhelming probability the worlds that they will observe will look nothing like ours. Boltzmann brains.
- We think that the world we see looks the way it does because of its big-bang history. But in thermal equilibrium, probabilities are determined **ONLY** by state counting. For example, a state that looks just like our world except that $T_{\text{CMB}} = 10$ K would have more microstates, and would be much more likely than 2.7 K. [Ref: Dyson, Kleban, & Susskind (2002).]

Alan Guth
Massachusetts Institute of Technology

3) Avoidance of Thermal Equilibrium Phase, Cont.

☆ If the semiclassical global picture of eternal inflation is valid, then new pocket universes are constantly being created and new regions of phase space are constantly being explored. Poincaré recurrences do not happen.

☆ For this to happen, the available classical phase space must be infinite, or the quantum mechanical Hilbert space must be infinite-dimensional.

Alan Guth
Massachusetts Institute of Technology

Infinite vs. Finite Phase Space

Can Hamiltonian evolution, consistent with Liouville's theorem, lead to fine-tuning of parameters?

For finite phase space, NO:

> Time evolution merely pushes the probability distribution around in phase space. What is rare at one time is rare at all times.

BUT: if available phase space is infinite, the answer is YES!!

Alan Guth
Massachusetts Institute of Technology

3) Avoidance of Thermal Equilibrium Phase, Cont.

- ☆ If the semiclassical global picture of eternal inflation is valid, then new pocket universes are constantly being created and new regions of phase space are constantly being explored. Poincaré recurrences do not happen.

- ☆ For this to happen, the available classical phase space must be infinite, or the quantum mechanical Hilbert space must be infinite-dimensional.

Alan Guth
Massachusetts Institute of Technology

Infinite vs. Finite Phase Space

Can Hamiltonian evolution, consistent with Liouville's theorem, lead to fine-tuning of parameters?

For finite phase space, NO:

> Time evolution merely pushes the probability distribution around in phase space. What is rare at one time is rare at all times.

BUT: if available phase space is infinite, the answer is YES!!

Alan Guth
Massachusetts Institute of Technology

Can Hamiltonian evolution, consistent with Liouville's theorem, lead to fine-tuning of parameters?

Example (due to Larry Guth):

$$H = \tan^{-1}(-pq) \ .$$

(Time independent, bounded from below.)

$$\dot{p} = \frac{p}{p^2q^2+1} \qquad \dot{q} = -\frac{q}{p^2q^2+1} \ .$$

For any normalizable initial probability distribution, for any $\epsilon > 0$, and for any $\delta > 0$, there exists a T such that

$$t > T \quad \Longrightarrow \quad P(|q| < \delta) > 1 - \epsilon \ .$$

Alan Guth
Massachusetts Institute of Technology

Theoretical Problem of Eternal Inflation — The Definition of Probabilities

- Anything that can happen will happen — an infinite number of times!
- To separate the probable from the improbable, we need to compare infinities.
- Example of ambiguity: what fraction of the positive integers are odd? Normal answer: 1/2. BUT, consider listing the integers as 1, 3, 2, 5, 7, 4, 9, 11, 6 , . . . , always writing two odds and then the next even. Each positive integer appears once and only once, yet it looks like 2/3 of the integers are odd!
- Probabilities can be defined by introducing a cutoff, but in this case the answers can depend strongly on the type of cutoff.

Alan Guth
Massachusetts Institute of Technology

Theoretical Problem of Eternal Inflation — The Definition of Probabilities

- Anything that can happen will happen — an infinite number of times!
- To separate the probable from the improbable, we need to compare infinities.
- Example of ambiguity: what fraction of the positive integers are odd? Normal answer: $1/2$. BUT, consider listing the integers as $1, 3,\ 2,\ 5, 7,\ 4,\ 9, 11,\ 6\ , \ldots,$ always writing two odds and then the next even. Each positive integer appears once and only once, yet it looks like $2/3$ of the integers are odd!
- Probabilities can be defined by introducing a cutoff, but in this case the answers can depend strongly on the type of cutoff.

Alan Guth
Massachusetts Institute of Technology

The Measure Problem

- ☆ A **measure** is a prescription for defining probabilities in an eternally inflating universe.
- ☆ A measure is a prescription for regularizing $\int d^4x \sqrt{g}$ for the multiverse: how can one say that one type of event is twice as frequent as another type.

Alan Guth
Massachusetts Institute of Technology

Wave Function of the Universe?

- Formalisms such as the wave function of the universe do not settle this question.
- The formalism defines the probabilities of spacelike slices. But, if eternal inflation occurs, typical slices will each have an infinity of observers on them, with an infinite number observing X and an infinite number observing Y.
- The relative probability of observing X or Y remains undefined.

Alan Guth
Massachusetts Institute of Technology

The Measure Problem

- A **measure** is a prescription for defining probabilities in an eternally inflating universe.
- A measure is a prescription for regularizing $\int d^4x \sqrt{g}$ for the multiverse: how can one say that one type of event is twice as frequent as another type.

Alan Guth
Massachusetts Institute of Technology

Is the Measure Problem a Show-Stopper?

- Don't think so.
- The description of the multiverse itself is not a problem (AHG and Vitaly Vanchurin, to appear SOON).

  Can imagine describing multiverse on a lattice that grows exponentially with time.

  The update rule is defined by the laws of physics.

  The infinite system is mathematically well-defined, just like the integers.

  There have been claims that time must end, but Vanchurin and I don't think so.

Alan Guth
Massachusetts Institute of Technology

The Measure Problem

- A **measure** is a prescription for defining probabilities in an eternally inflating universe.
- A measure is a prescription for regularizing $\int d^4x \sqrt{g}$ for the multiverse: how can one say that one type of event is twice as frequent as another type.

Alan Guth
Massachusetts Institute of Technology

Wave Function of the Universe?

- Formalisms such as the wave function of the universe do not settle this question.
- The formalism defines the probabilities of spacelike slices. But, if eternal inflation occurs, typical slices will each have an infinity of observers on them, with an infinite number observing X and an infinite number observing Y.
- The relative probability of observing X or Y remains undefined.

Alan Guth
Massachusetts Institute of Technology

Is the Measure Problem a Show-Stopper?

- Don't think so.
- The description of the multiverse itself is not a problem (AHG and Vitaly Vanchurin, to appear SOON).

  Can imagine describing multiverse on a lattice that grows exponentially with time.

  The update rule is defined by the laws of physics.

  The infinite system is mathematically well-defined, just like the integers.

  There have been claims that time must end, but Vanchurin and I don't think so.

Alan Guth
Massachusetts Institute of Technology

- Multiverse itself is a mathematically well-defined system, which is even well-motivated by what we understand of fundamental physics.
- Measure problem arises only when we try to count events in the multiverse.
- The fact that we don't understand the measure problem is no reason to think eternal inflation is off track.

> Nature is not required to behave in a way that we find easy to understand.

(Arthur Eddington refused to believe that stars could collapse to black holes, because we would not understand where this would lead.)

Alan Guth
Massachusetts Institute of Technology

Three strong winds blowing in the direction of the multiverse— a diverse multiverse where selection effects play an important role.

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

2) **String Theory:** Most 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.