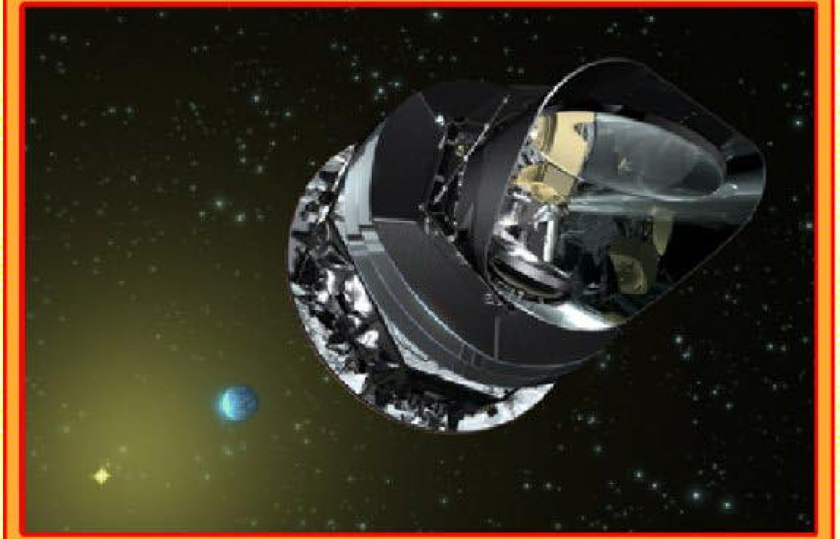
The Abdus Salam
International Centre
for Theoretical Physics

ETERNAL INFLATION AND ITS IMPLICATIONS

— Alan Guth —

Massachusetts Institute of Technology



Abdus Salam Lectures 2018: Lecture 2
Budinich Lecture Hall
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Outline

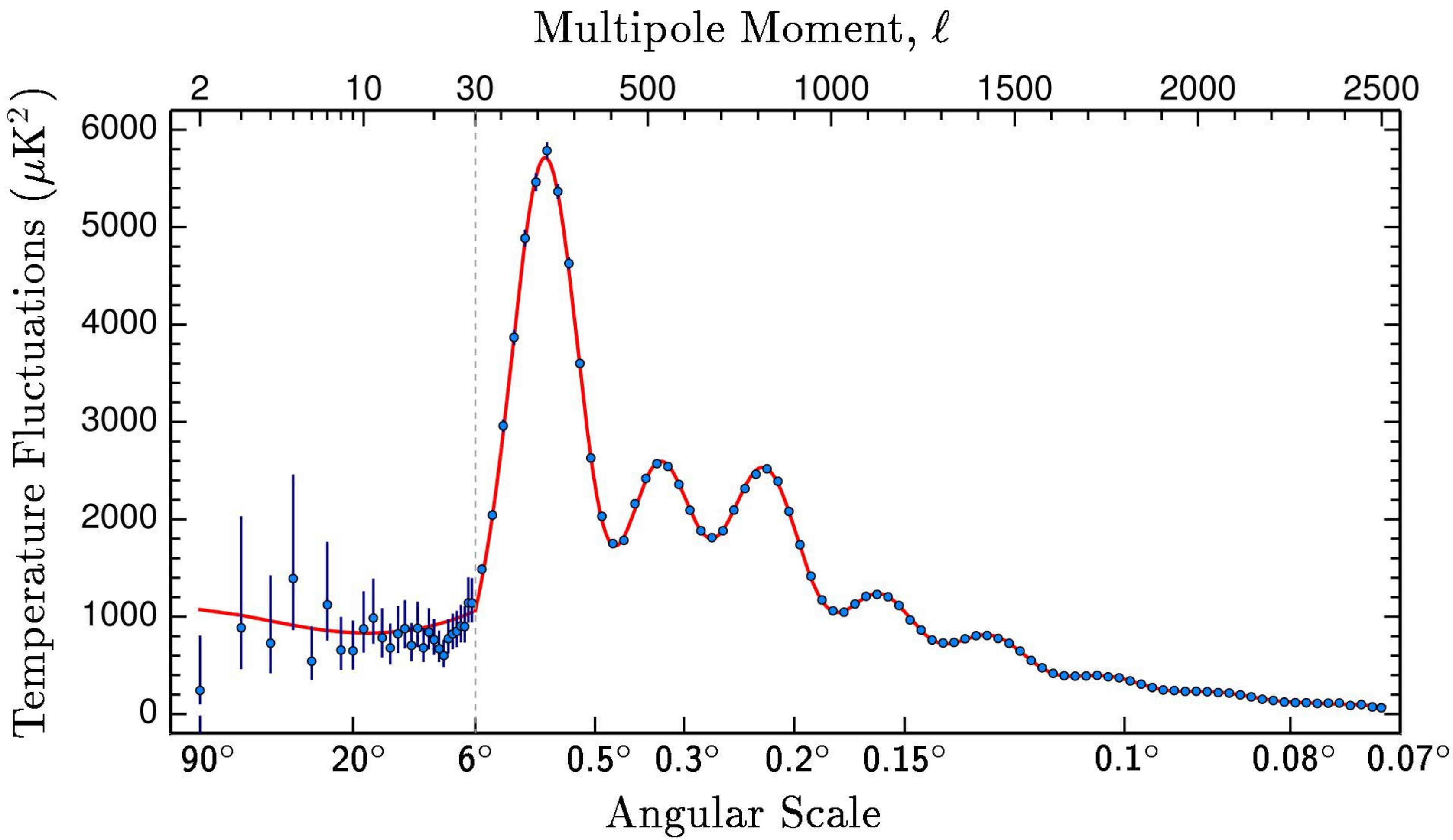
1) Almost all models of inflation lead to eternal inflation.

2) Eternal inflation has a number of benefits:

- ☆ Possible explanation for small vacuum energy density.
- ☆ Independence of initial conditions.
- ☆ 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.

Spectrum of CMB Ripples



Planck Collaboration, 2015

Inflation — the Mechanism (Scalar Fields)

- All fundamental particles are viewed as quantum excitations of a field. (Example: photons are quantum excitations of the electromagnetic field.)
- Scalar fields are like the electric or magnetic fields, but simpler: electric fields point in some direction, but a scalar field is just a number defined at each point of space.
- Scalar fields in physics:

  The Higgs field of the standard model of particle physics (particle discovered at CERN, 2012), is a scalar field.

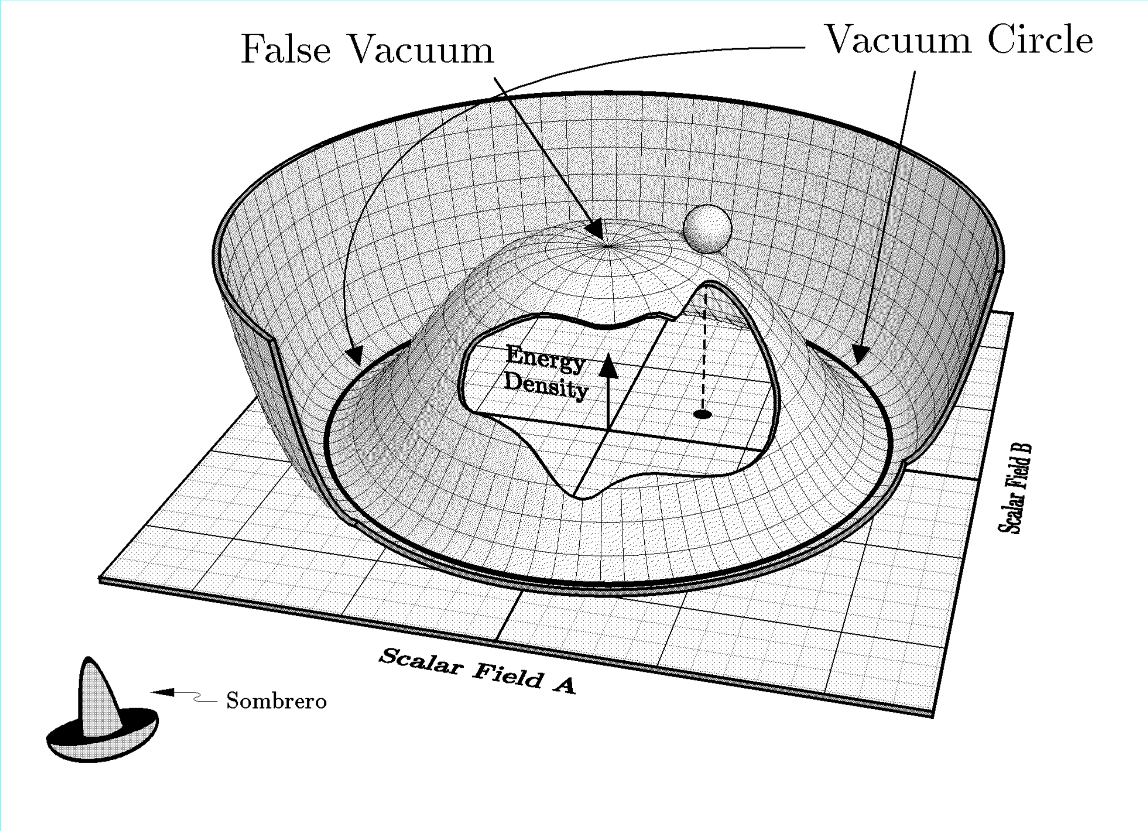
  Grand unified theories require scalar fields.

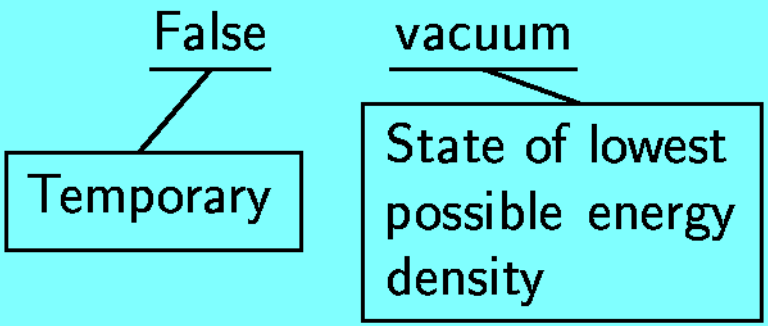
  String theory is well-approximated by field theories for energies well below the Planck scale (10^{19} GeV), with many scalar fields.

THE FALSE VACUUM

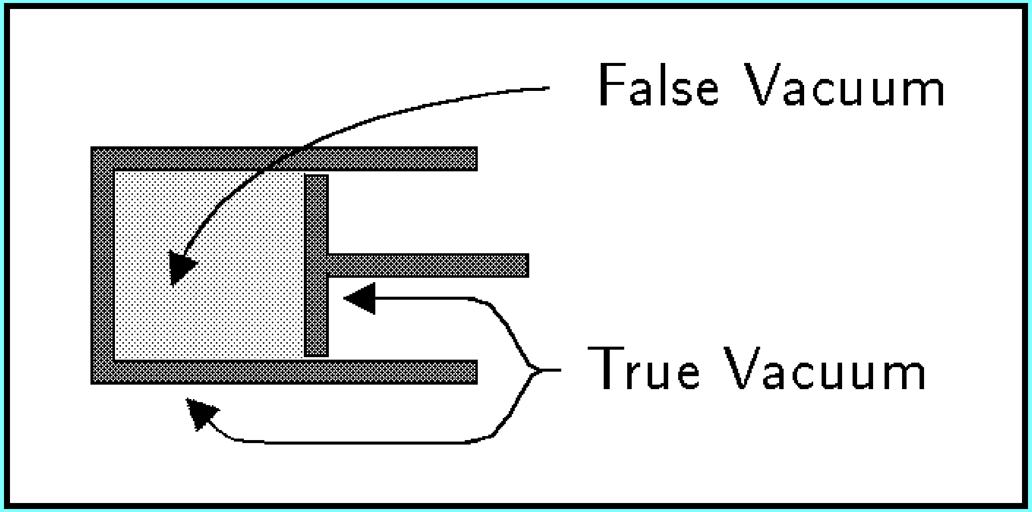
False Vacuum = region of space within which scalar field has the value of zero.

Key property: For a long time (at least by early universe standards), energy density cannot be lowered.





A fixed energy density implies **NEGATIVE PRESSURE**



- ★ If the piston is pulled, the energy density inside remains constant!
- ★ Therefore the energy increases.
- ★ Therefore work must be done $(-p\,\Delta V)$.
- ★ Therefore pressure must be negative!

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Negative Pressure and Gravity

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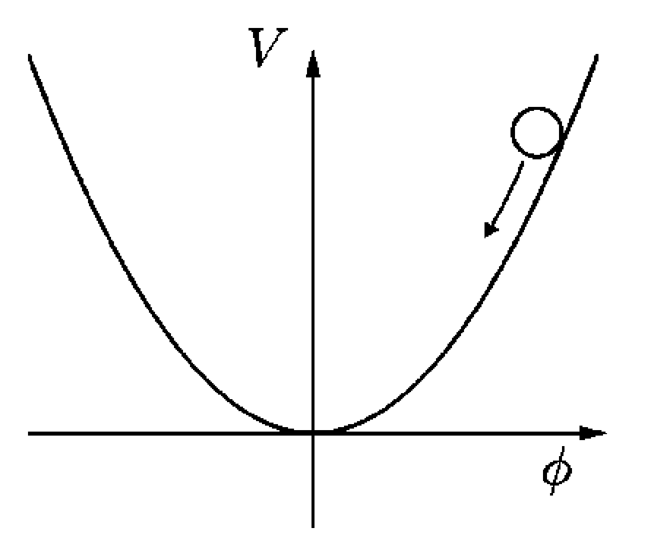
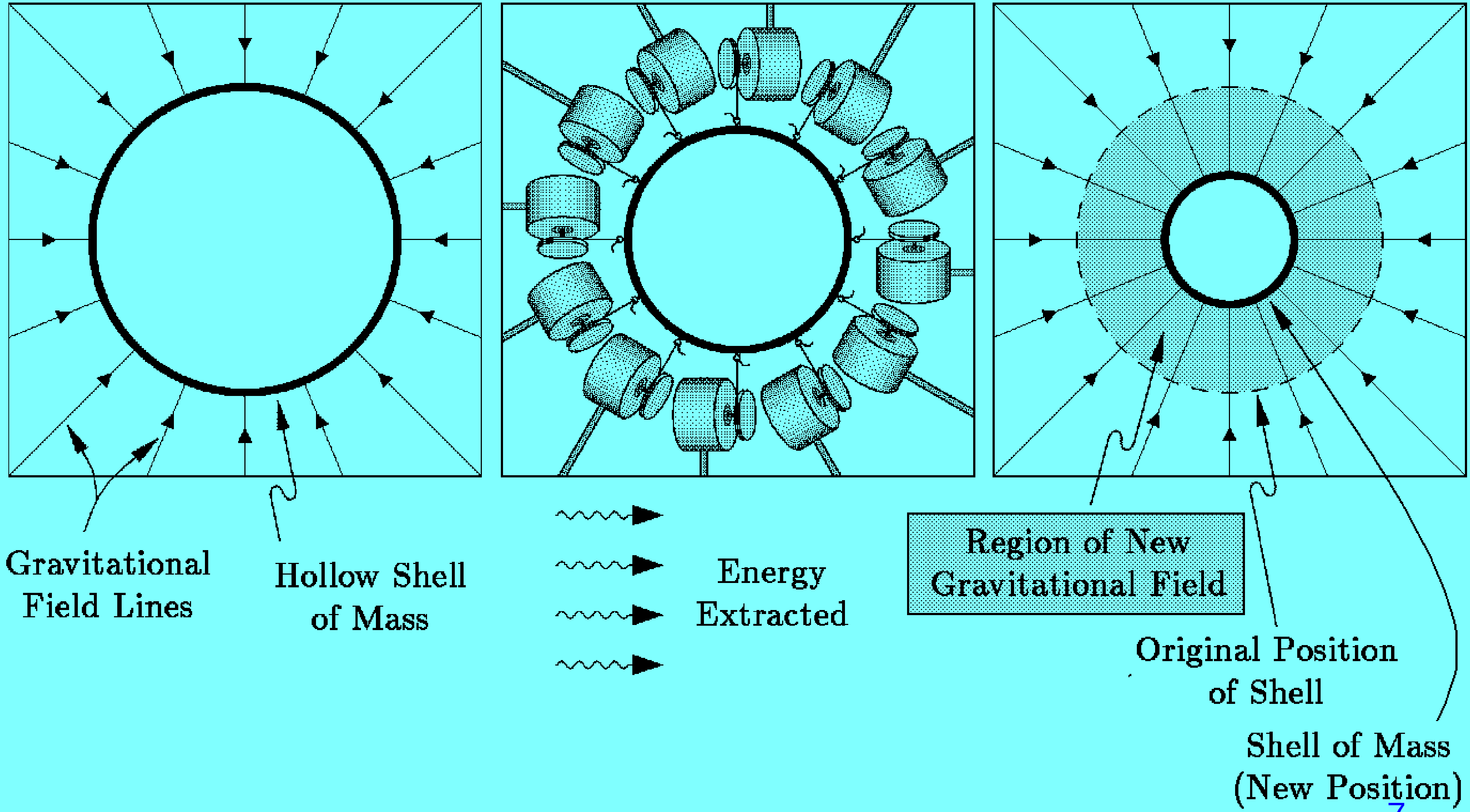
- Positive pressure creates attractive gravity, but negative pressure creates gravitational repulsion.
- Furthermore, a plateau in the potential energy function is not needed:



In Linde's *chaotic inflation*, inflation occurs while the scalar field rolls down a hill.

How to See That the Energy of Gravity is Negative



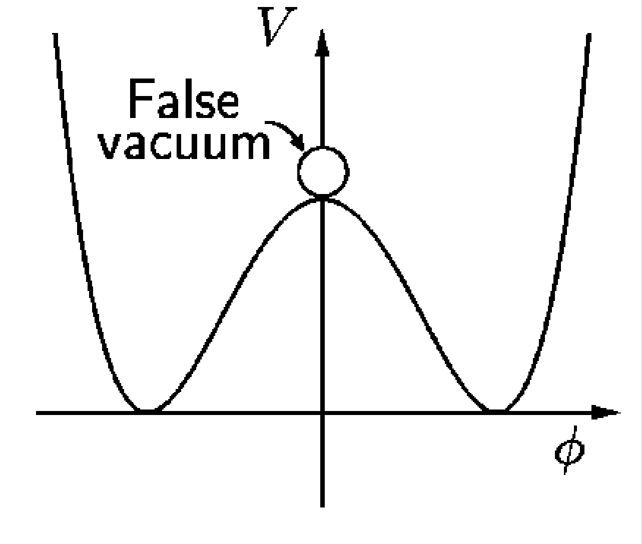
Mechanism of Eternal Inflation: Small Field (New) Inflation

1) False vacuum is metastable, and decays exponentially.

2) Volume of false vacuum inflates exponentially.

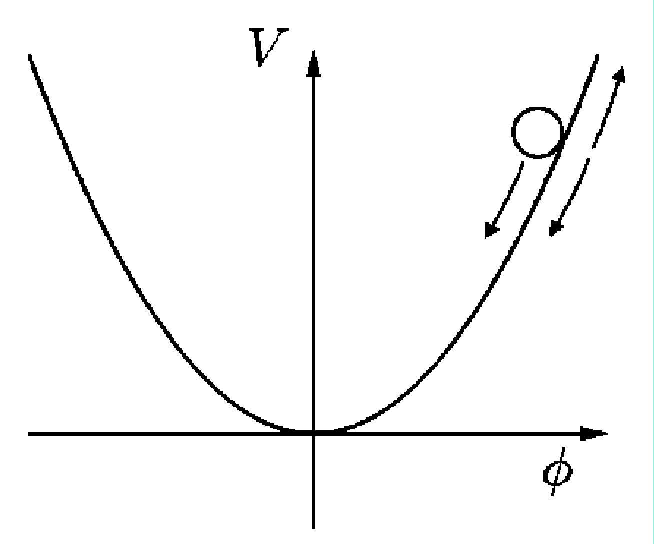
3) Rate of inflation $\gg$ rate of decay.

$\therefore$ Volume of false vacuum increases with time! (Steinhardt, 1983; Vilenkin, 1983)



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 $\Delta\phi_{\text{qu}} = H/2\pi$. 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.

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 exponentially expanding 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. Otherwise the volume will continue expanding forever despite the decays. Tunneling events in our own pocket universe will create an infinite number of others.

Theoretical Benefits of Eternal Inflation

1) Explaining the Very Small Vacuum Energy Density

DARK ENERGY
Key Mystery of the Universe

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IN ANY CASE, it was dark energy which caused $\Omega \approx 0.2$–0.3 to change to $\Omega = 0.999$

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. All wavelengths contribute, and there is no shortest wavelength.
- ☆ A plausible cutoff for the fluctuations is the Planck length, $\sim 10^{-33}$ cm, the scale of quantum gravity.
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It is too large by 120 orders of magnitude! **WHOOPS!**

The String Theory Landscape

- Since the inception of string theory, theorists have sought to find the vacuum of string theory — with no success.
- Since about 2000, most string theorists have come to believe that there is no unique vacuum.
- Instead, there are perhaps 10^{500} or more long-lived metastable states, any one of which could serve as a substrate for a pocket universe. This is the landscape!
- Eternal inflation can presumably produce an infinite number of pocket universes of every type, populating the landscape.
- Although string theory would govern everywhere, each type of vacuum would have its own low-energy physics — its own "standard model," its own "constants" of nature, and its own vacuum energy density.

The Landscape and Environmental Selection AKA: The Anthropic Principle

☆ If the landscape has 10^{500} vacua, and a fraction 10^{-120} have small vacuum energy densities like our universe, then we expect about

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- But how could we explain why we are living in such a fantastically unusual type of vacuum?
- Possible answer: maybe it is a selection effect. I.e., maybe life only forms where the vacuum energy density is unusually small.

- As early as 1987, Steve Weinberg pointed out that the vacuum energy density might be explained in the same way.
- Maybe the vacuum energy density ***IS*** huge in most pocket universes. Nonetheless, we need to remember that vacuum energy causes the expansion of the universe to accelerate. If large and negative, the universe quickly collapses. If large and positive, the universe flies apart before galaxies can form. It is plausible, therefore, that life can arise only if the vacuum energy density is very near zero.
- In 1998 Martel, Shapiro, and Weinberg made a serious calculation of the effect of the vacuum energy density on galaxy formation. They found that to within a factor of order 5, they could "explain" why the vacuum energy density is as small as what we measure.

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- But I would advocate that selection-effect explanations be thought of as the explanation of last resort — the best evidence for a selection-effect explanation is the absence of any other.

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- For the vacuum energy density, because it seems so hard to explain any other way, it seems like it is time to strongly consider the selection-effect explanation.
- It is even hard to deny that, as of now, the selection-effect explanation is by far the most plausible that is known.

Attractive Features of Eternal Inflation

2) Independence of Initial Conditions

With some (plausible) 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, to be discussed shortly, but is true for many proposed measures, including all my favorites.)

3) Avoidance of Thermal Equilibrium Phase

☆ *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).]

c) Avoidance of Thermal Equilibrium Phase, Cont.

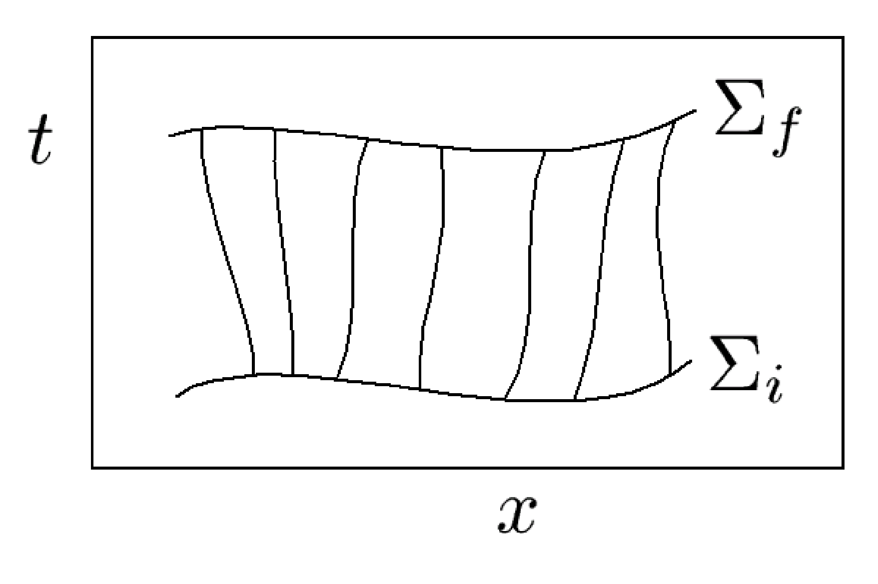
- ☆ If the semiclassical global picture of eternal inflation is valid, then new pocket universes are constantly being created and new regions of phase space are constantly being explored. Poincaré recurrences do not happen.

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

Theoretical Problem of Eternal Inflation: The Measure Problem (Defining 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.

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.

Failure of Proper-Time Cutoff: Youngness Problem

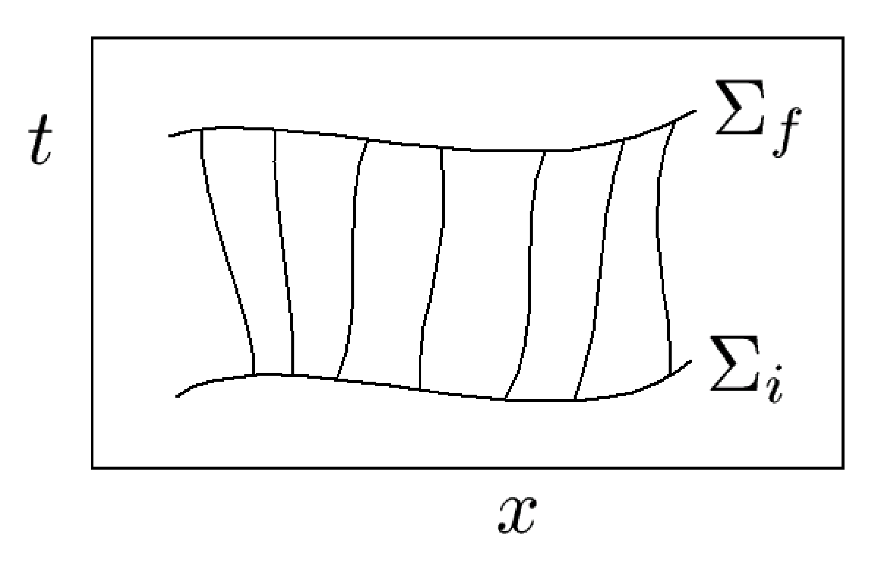
- Problem: Since the available volume grows $\sim e^{3H_{\text{max}}\tau}$, where $H_{\text{max}}^{-1} \approx 10^{-37}$ s (for example), most bubbles in the sample formed within a few Hubble times of the final time cutoff. Older bubbles are **VERY** rare.

- 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 $T_{\text{CMB}} =$ 4K, $V(\tau_{\text{RW}})$ would be larger by about $10^{10^{56}}$.

Example 2: Scale-Factor Cutoff Measure

☆ Same method as proper time cutoff, but use scale-factor time t_{sf} instead of proper time τ. Imagine sprinking initial surface with uniform dust. At later times, local rest-frame density is ρ. Define

$$\rho \propto e^{-3t_{\text{sf}}} \ .$$



☆ Since volumes grow as $e^{3t_{\text{sf}}}$, 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.

Is the Measure Problem a Show-Stopper?

- I don't think so.
- The description of the multiverse itself is not a problem.

  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.

- 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.)

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) **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.

3) **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. This plethora of choices can explain why we see such a small Λ.

Bubble Nucleation in an Eternally Inflating Universe