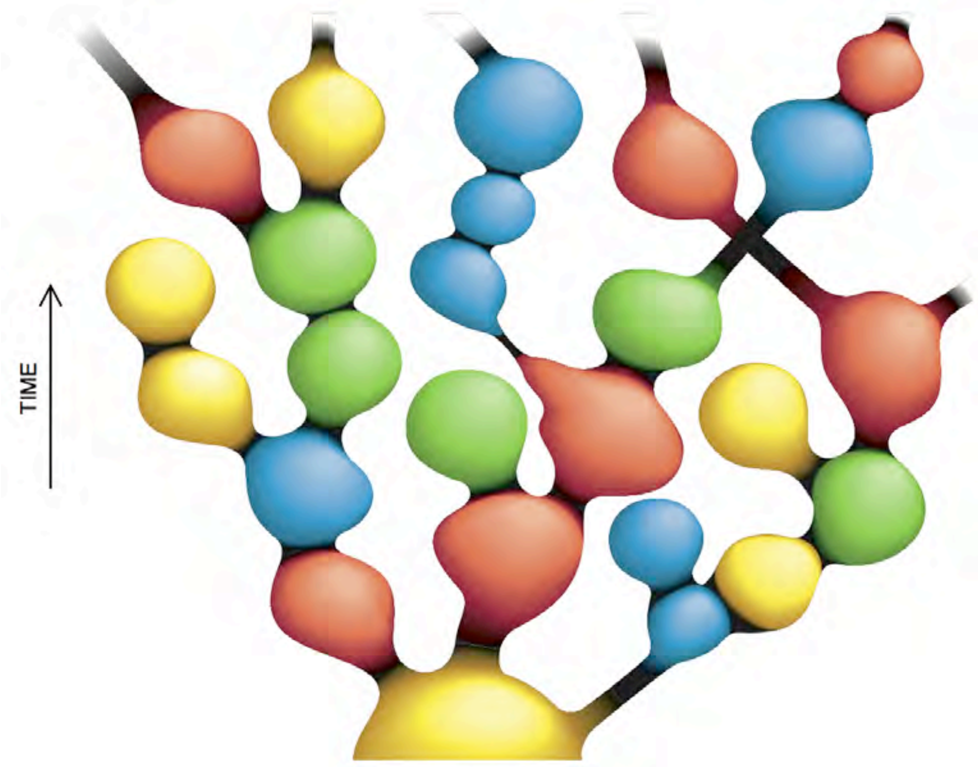
Eternal Inflation and String Theory Landscape

Andrei Linde

Inflationary Multiverse

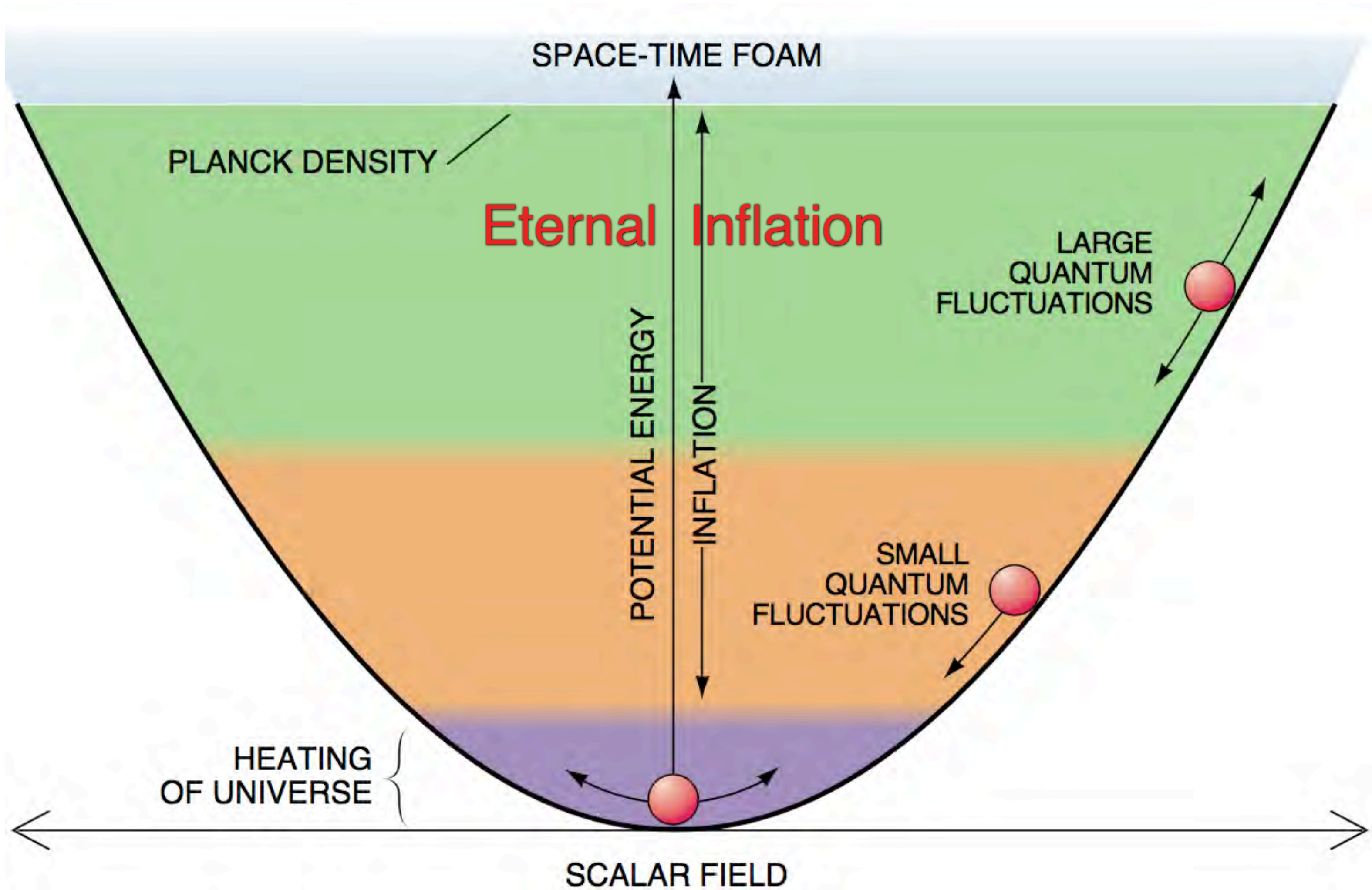
For a long time, people believed in the cosmological principle, which asserted that the universe is everywhere the same.

This principle is no longer required. Inflationary universe may consist of many parts with different properties depending on the local values of the scalar fields, compactifications, etc.



Eternal Chaotic Inflation

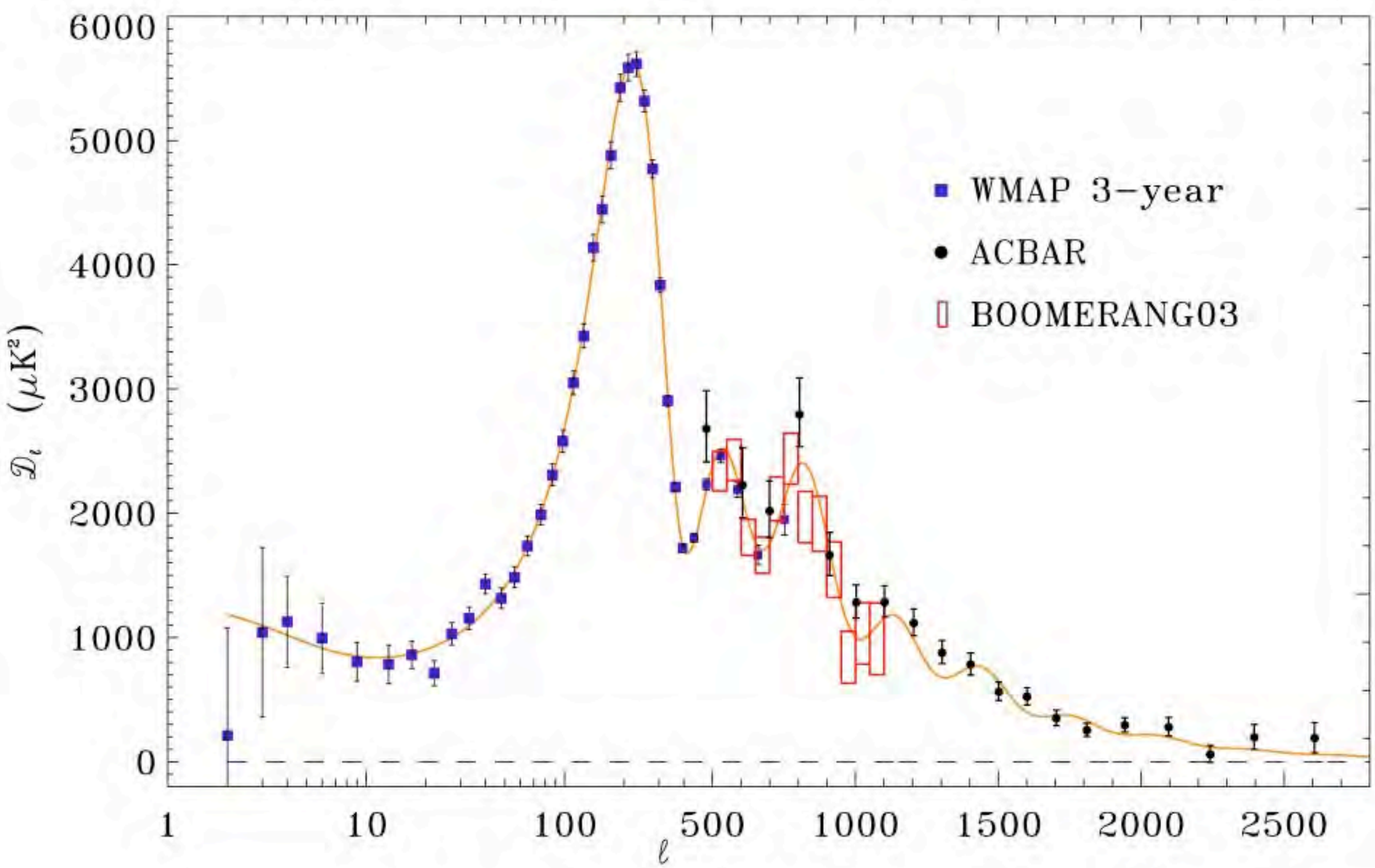
$$V(\phi) = \frac{m^2}{2}\phi^2$$



CMB and Inflation

Blue and black dots - experimental results (WMAP, ACBAR)

Brown line - predictions of inflationary theory



Predictions of Inflation:

1) The universe should be homogeneous, isotropic and flat,

$\Omega = 1 + O(10^{-4})$ [$\Omega = \rho/\rho_0$]

Observations: it is homogeneous, isotropic and flat:

$$\Omega_{\rm total} = 1.003 \pm 0.01$$

2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-1})$. Spectral index n_s slightly differs from 1. (This is an important prediction, similar to asymptotic freedom in QCD.)

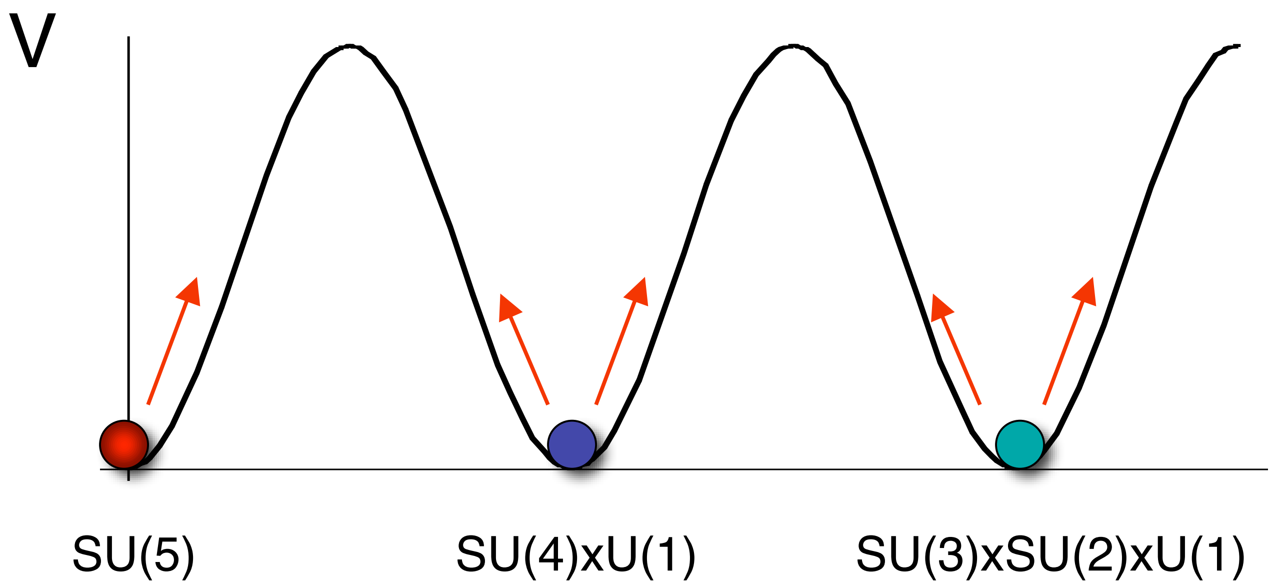
Observations: perturbations are gaussian and adiabatic, with flat spectrum: $n_s = 0.95 \pm 0.02$

Thus, so far the news are rather good. Many new experiments are under way. More about present and future cosmological observations and their implications for inflationary universe and string theory - in the talks by Licia Verde and Renata Kallosh.

Now we will discuss inflationary multiverse

Example: SUSY landscape

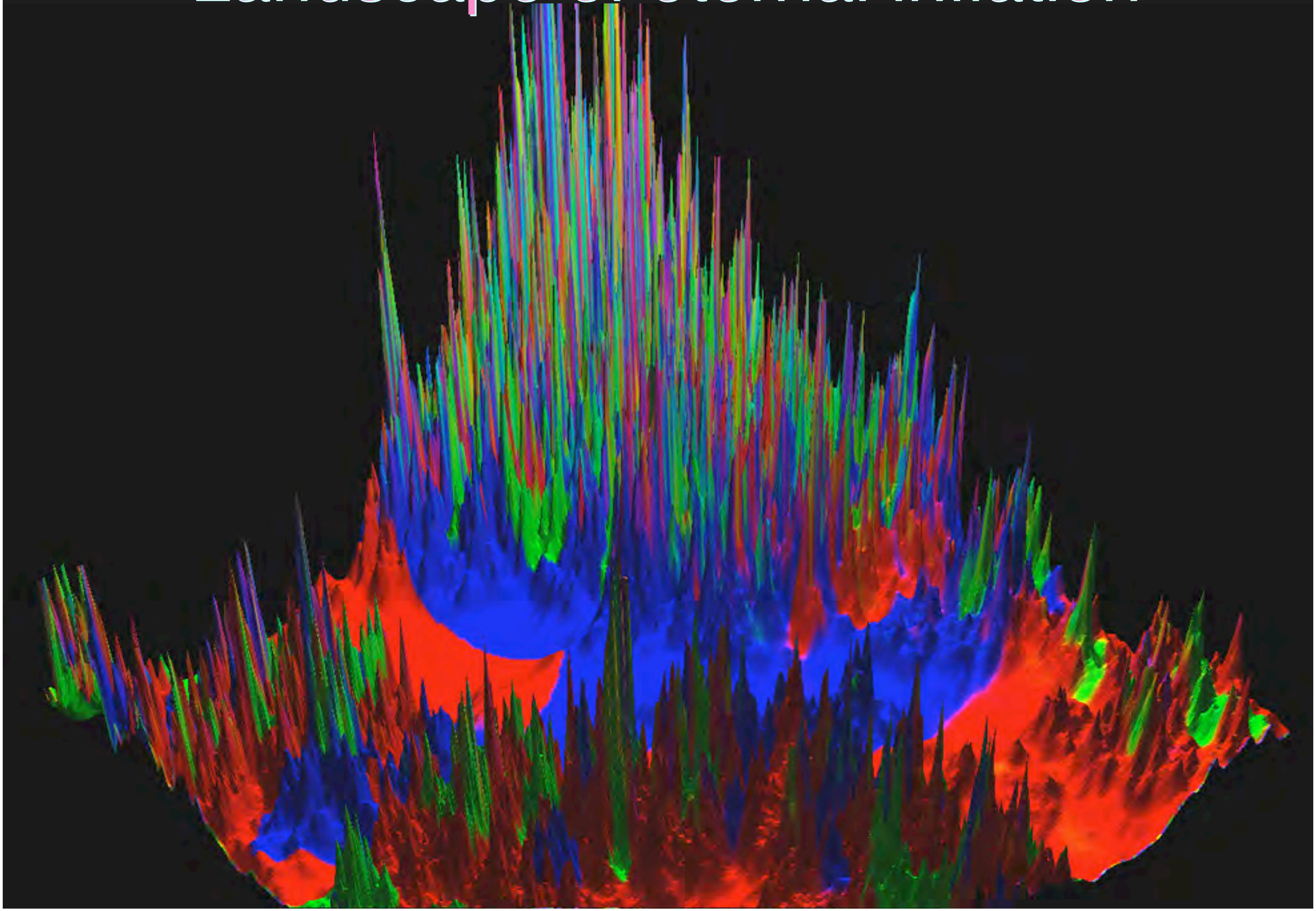
Supersymmetric SU(5)



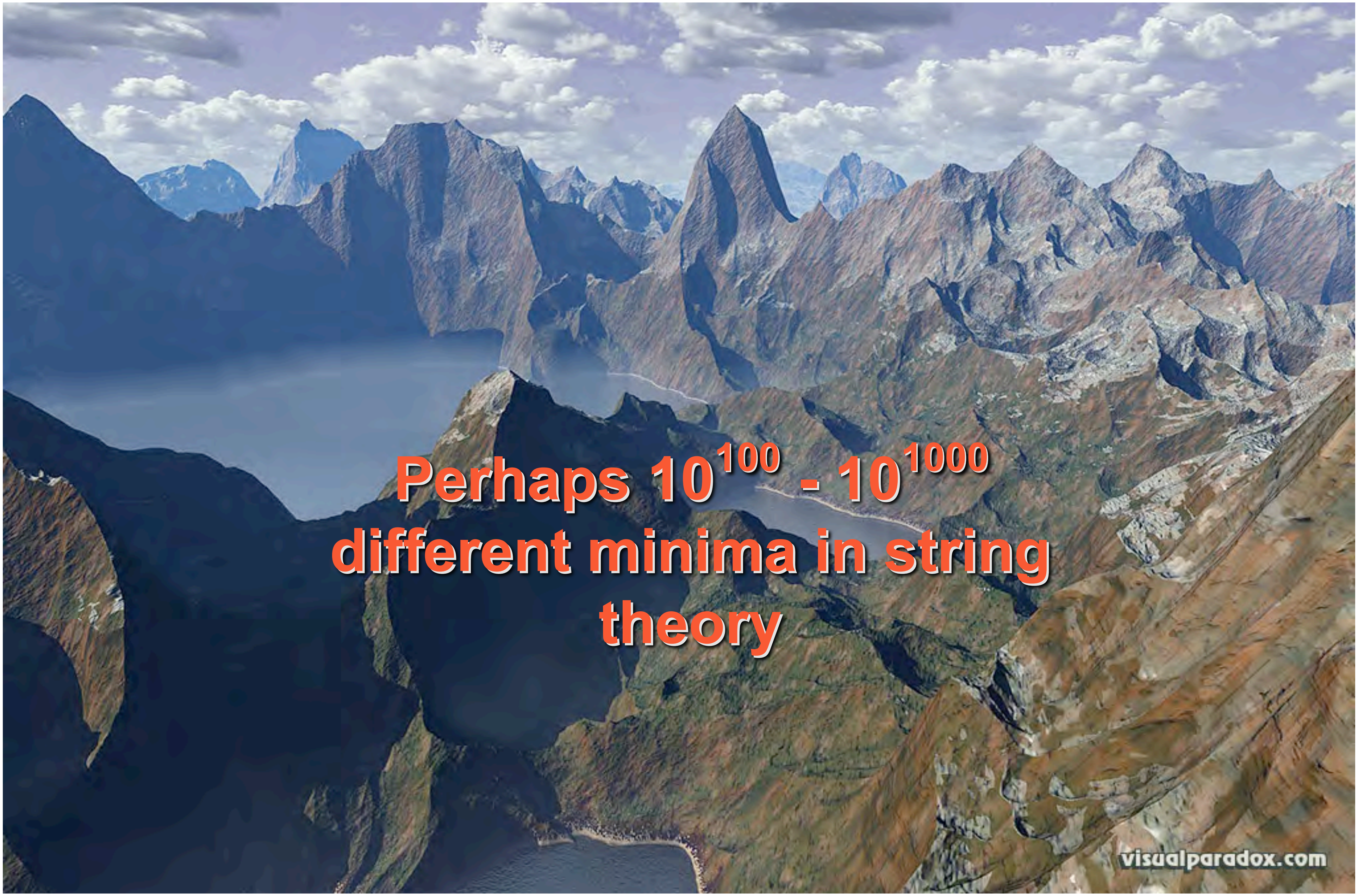
Weinberg 1982: Supersymmetry forbids tunneling from SU(5) to SU(3)xSU(2)XU(1). This implied that we cannot break SU(5) symmetry.

A.L. 1983: Inflation solves this problem. Inflationary fluctuations bring us to each of the three minima. Inflation make each of the parts of the universe exponentially big. We can live only in the SU(3)xSU(2)xU(1) minimum.

Landscape of eternal inflation

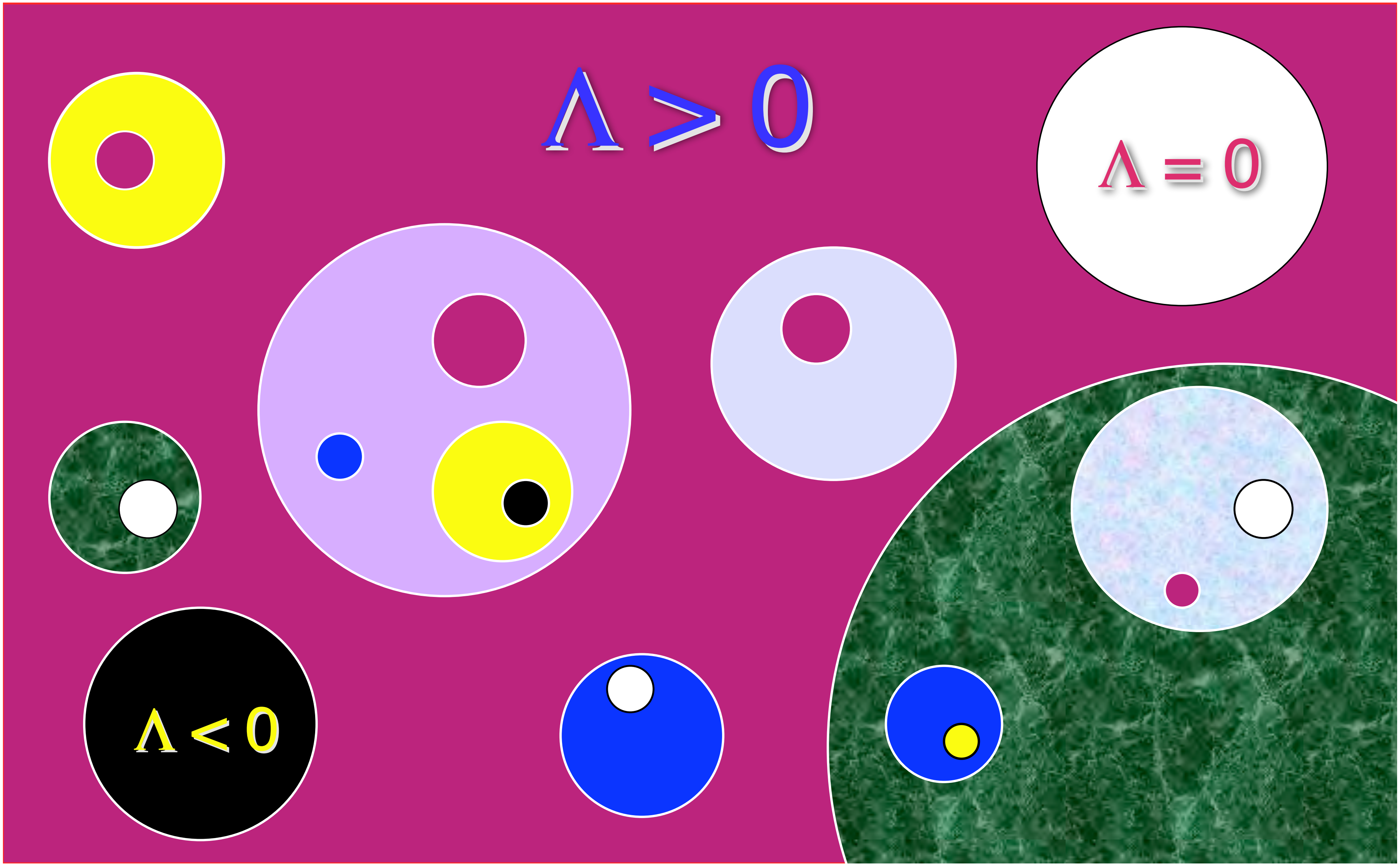


String Theory Landscape



String Theory Multiverse

and eternal old inflation



Discrete and continuous parameters

Properties of our world (local part of the universe) depend on 10^{1000} **discrete parameters** (topological numbers, quantized fluxes, etc.), which describe our vacuum state.

Beyond the landscape: Our world may depend on **a continuous set of parameters,** which took different values during the cosmological evolution far away from the vacuum state.

EXAMPLES:

a) Axion field could take different values during inflation, which should affect the local value of the density of dark matter.

b) Affleck-Dine fields could take different values in different parts of the universe, thus affecting the local value of the baryon asymmetry of the universe.

Inflation and Cosmological Constant

4 steps in finding the anthropic solution of the CC problem:

1) **Anthropic solutions of the CC problem** using **inflation and fluxes** of antisymmetric tensor fields (A.L. 1984), **multiplicity of KK vacua** (Sakharov 1984), and **slowly evolving scalar field** (Banks 1984, A.L. 1986). We considered it obvious that we cannot live in the universe with

$$|\Lambda| \gg 10^{-120} M_p^4$$

but the proof was needed for positive Λ.

2) **Derivation of the anthropic constraint** $|\Lambda| \lesssim 10^{-120} M_p^4$

Weinberg 1987; Martel, Shapiro, Weinberg 1997, …

Inflation and Cosmological Constant

3) String theory landscape

Multiplicity of (unstable) vacua:

Lerche, Lust and Schellekens 1987: 10^{1500} vacuum states

Duff, 1986, 1987; Bousso, Polchinski 2000

Vacuum stabilization and statistics:

KKLT 2003, Susskind 2003, Douglas 2003,…

perhaps 10^{1000} metastable dS vacuum states - still counting…

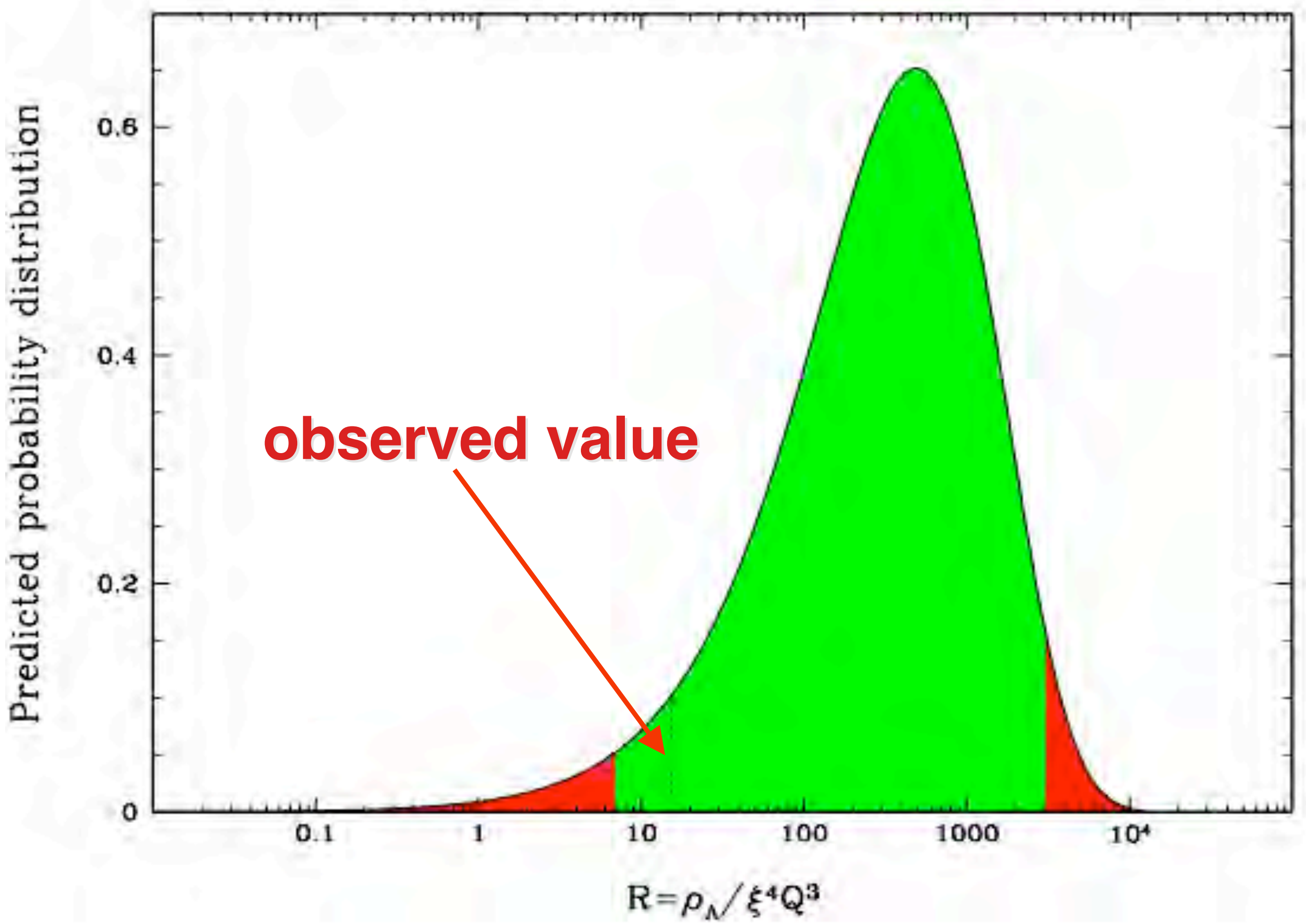
4) Counting probabilities in an eternally inflating universe

(more about it later)

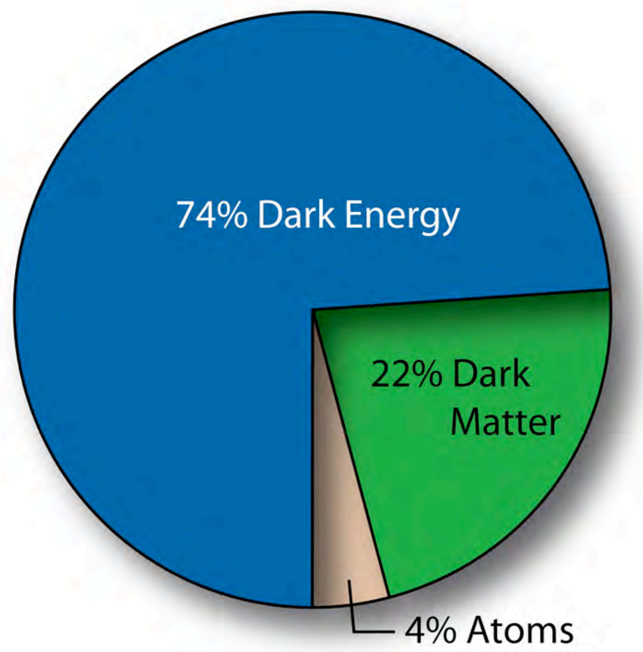
Anthropic constraints on Λ

Aguirre, Rees, Tegmark, and Wilczek, astro-ph/0511774

(an attempt to improve it will be discussed by Bousso)



Dark Energy (Cosmological Constant) is about 74% of the cosmic pie



Dark Matter constitutes another 22% of the pie. Why there is 5 times more dark matter than ordinary matter?

Example: Dark matter in the axion field

Old lore: If the axion mass is smaller than 10^{-5} eV, the amount of dark matter in the axion field contradicts observations, for a typical initial value of the axion field.

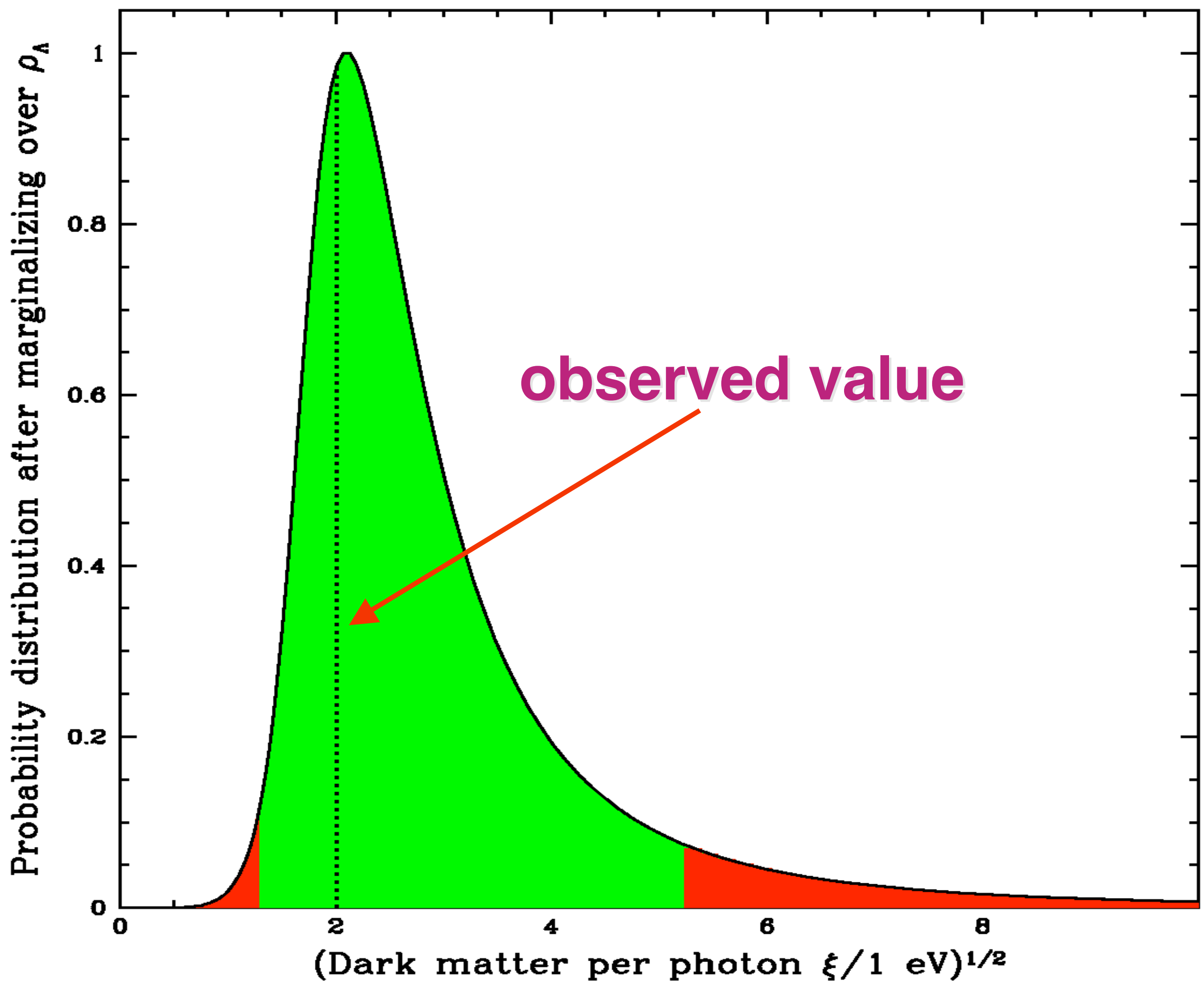
Can we give a scientific definition of "typical" ?

Anthropic argument: Inflationary fluctuations make the amount of the axion dark matter a CONTINUOUS RANDOM PARAMETER. We can live only in those parts of the universe where the initial value of the axion field was sufficiently small (A.L. 1988).

Recently this possibility was analyzed by Aguirre, Rees, Tegmark, and Wilczek.

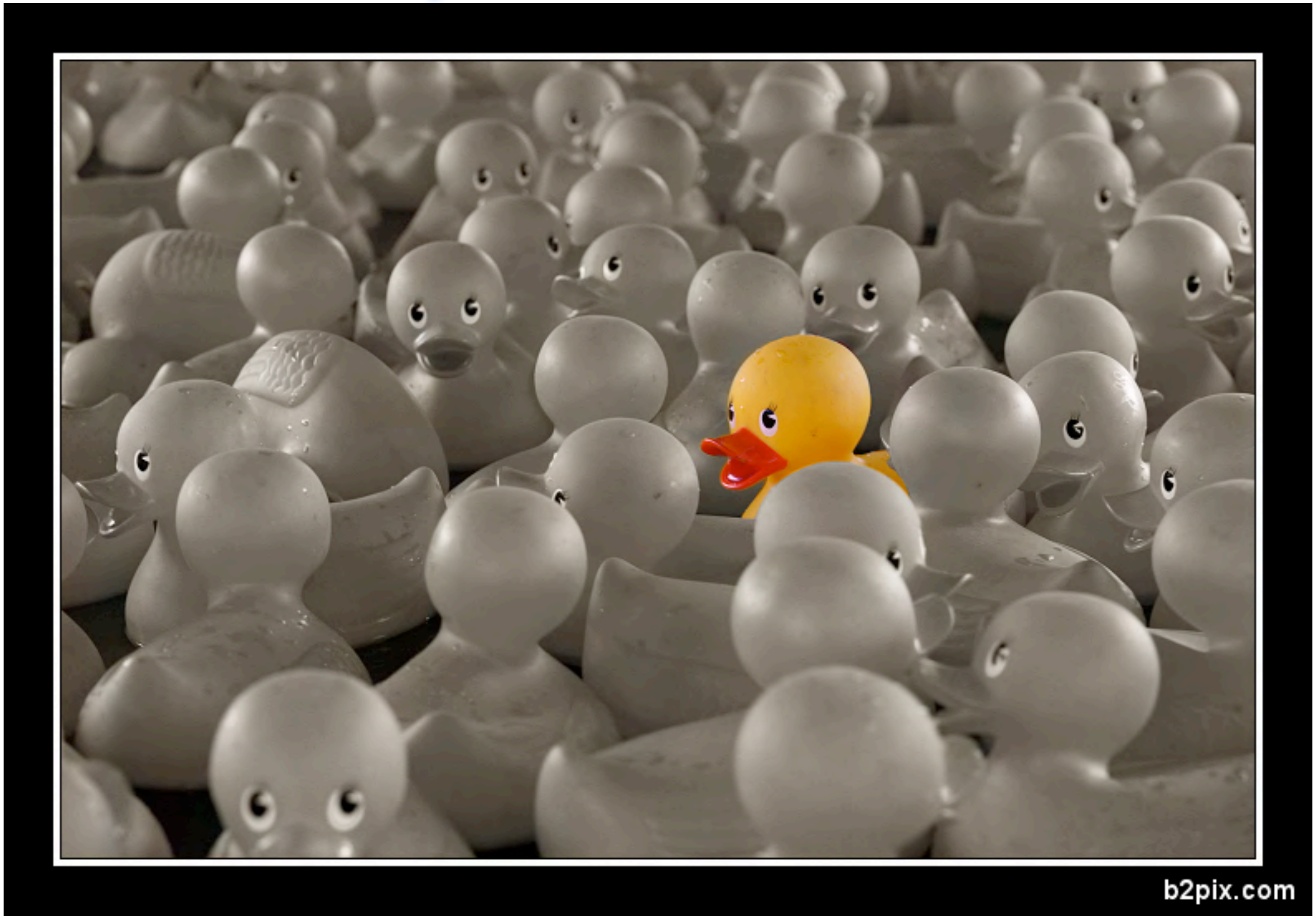
Anthropic Constraints on Axion Dark Matter

Aguirre, Rees, Tegmark, and Wilczek, astro-ph/0511774



The situation with Dark Matter is even better than with the CC !

What is so special about our world?



Problem: Eternal inflation creates infinitely many different parts of the universe, so we must compare infinities

Two different approaches:

1. Study events at a given point, ignoring growth of volume

Starobinsky 1986, Garriga, Vilenkin 1998, Bousso 2006, A.L. 2006

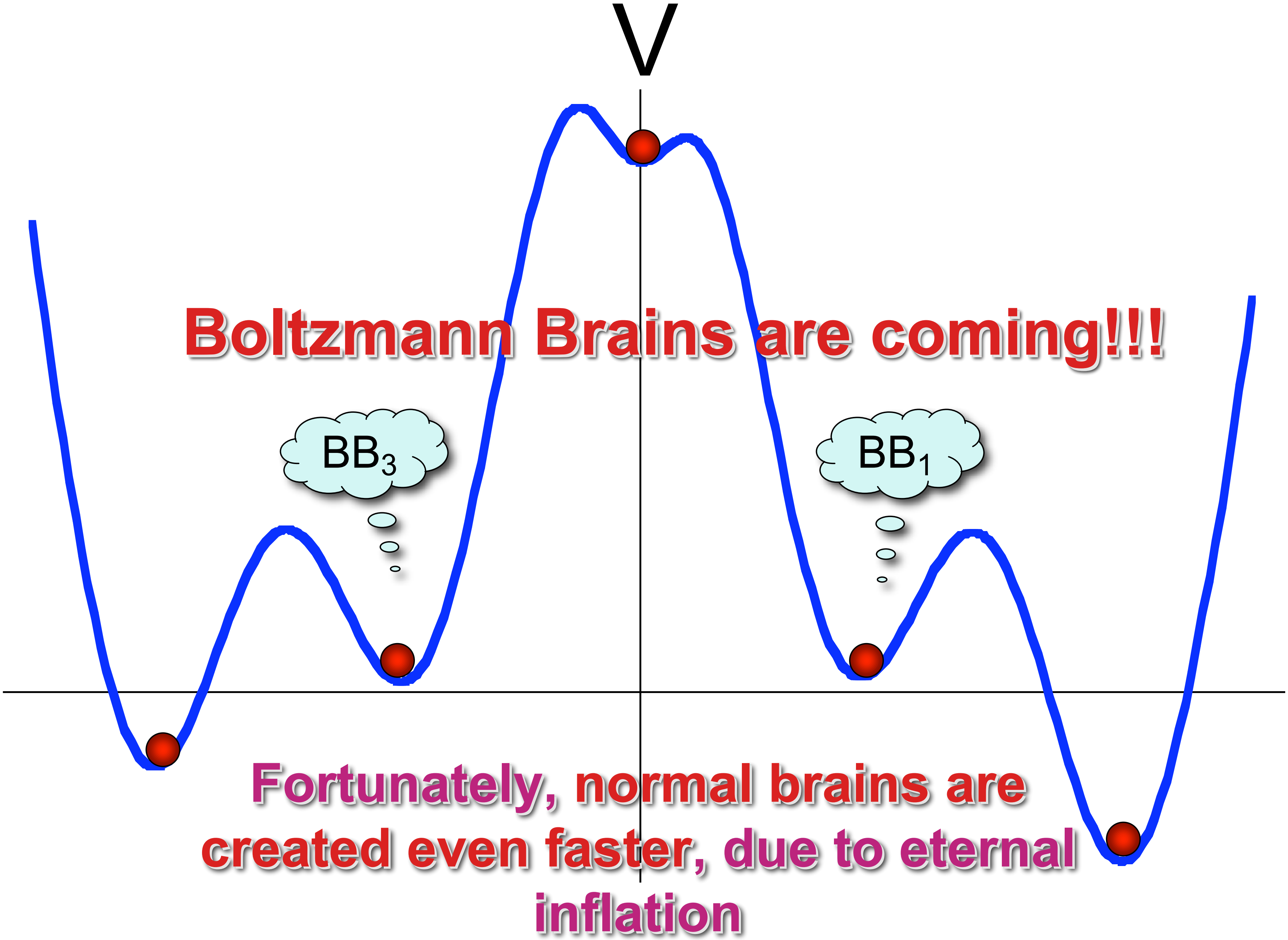
No problems with infinities, but the results depend on initial conditions. It is not clear whether these methods are appropriate for description of eternal inflation, where the exponential growth of volume is crucial.

2. Take into account growth of volume

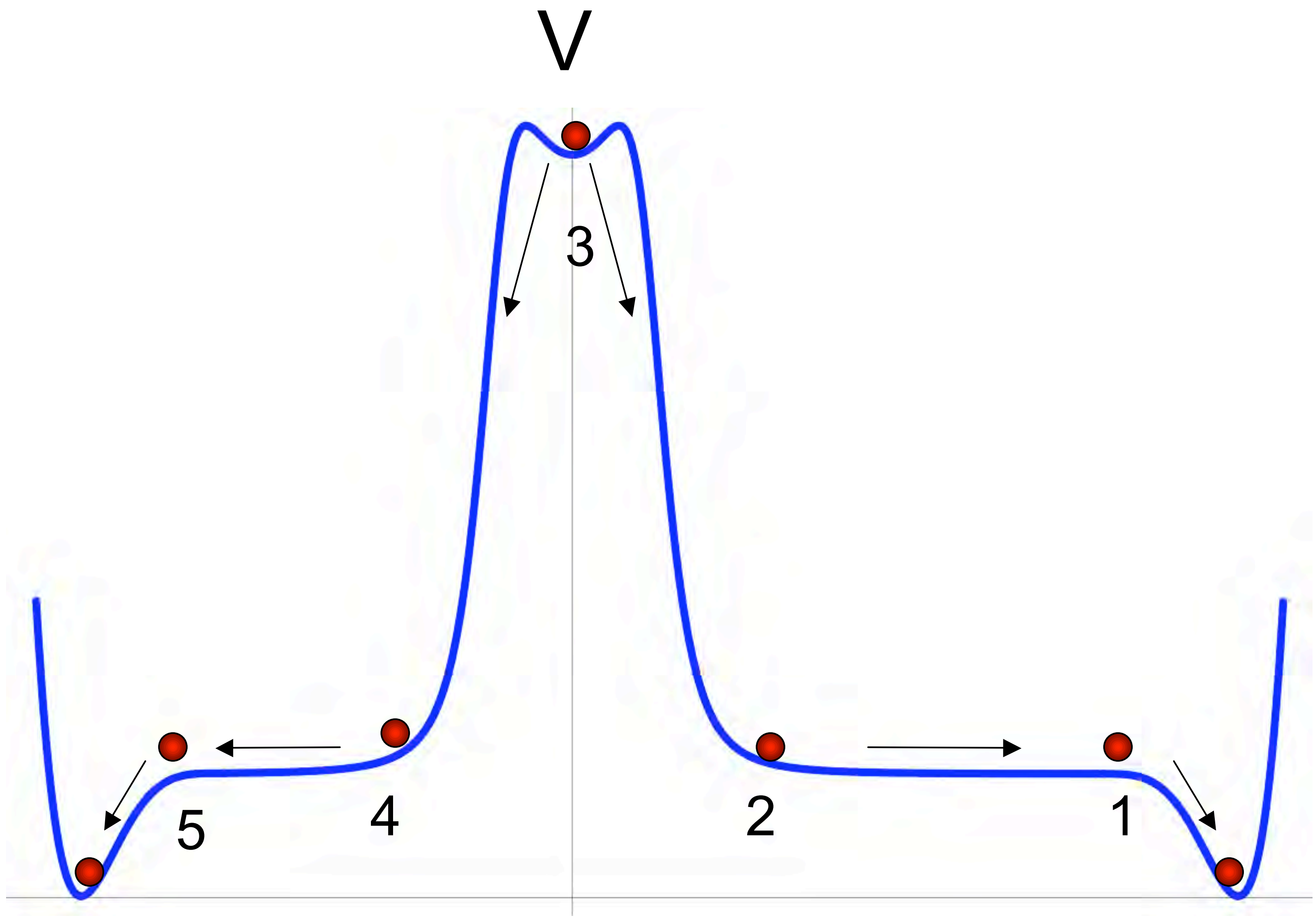
A.L. 1986; A.L., D.Linde, Mezhlumian, Garcia-Bellido 1994;

Garriga, Schwarz-Perlov, Vilenkin, Winitzki 2005; A.L. 2007

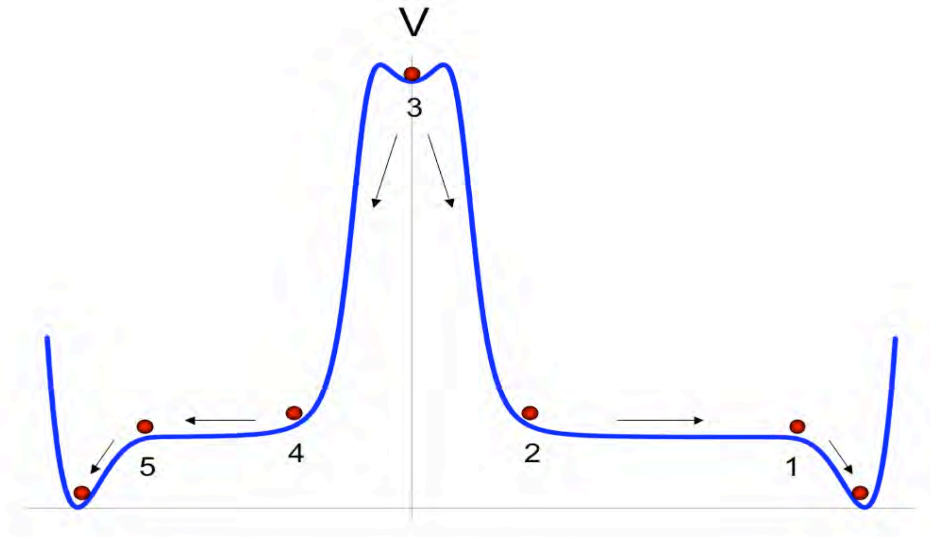
No dependence on initial conditions, but we are still learning how to do it properly. I will review some recent progress.


V
Boltzmann Brains are coming!!!
BB_3
BB_1
Fortunately, normal brains are
created even faster, due to eternal
inflation

Problems with probabilities



Time can be measured in the number of oscillations ($\beta = 1$) or in the number of e-foldings of inflation ($\beta = 0$). The universe expands as $e^{H^\beta t}$



$$P_3(t) \sim P_3(0)\ e^{3H_3^\beta t}, \quad P_4 = P_3(0)\ \Gamma_{34} e^{3H_3^\beta t}, \quad P_2 = P_3(0)\ \Gamma_{32} e^{3H_3^\beta t}$$

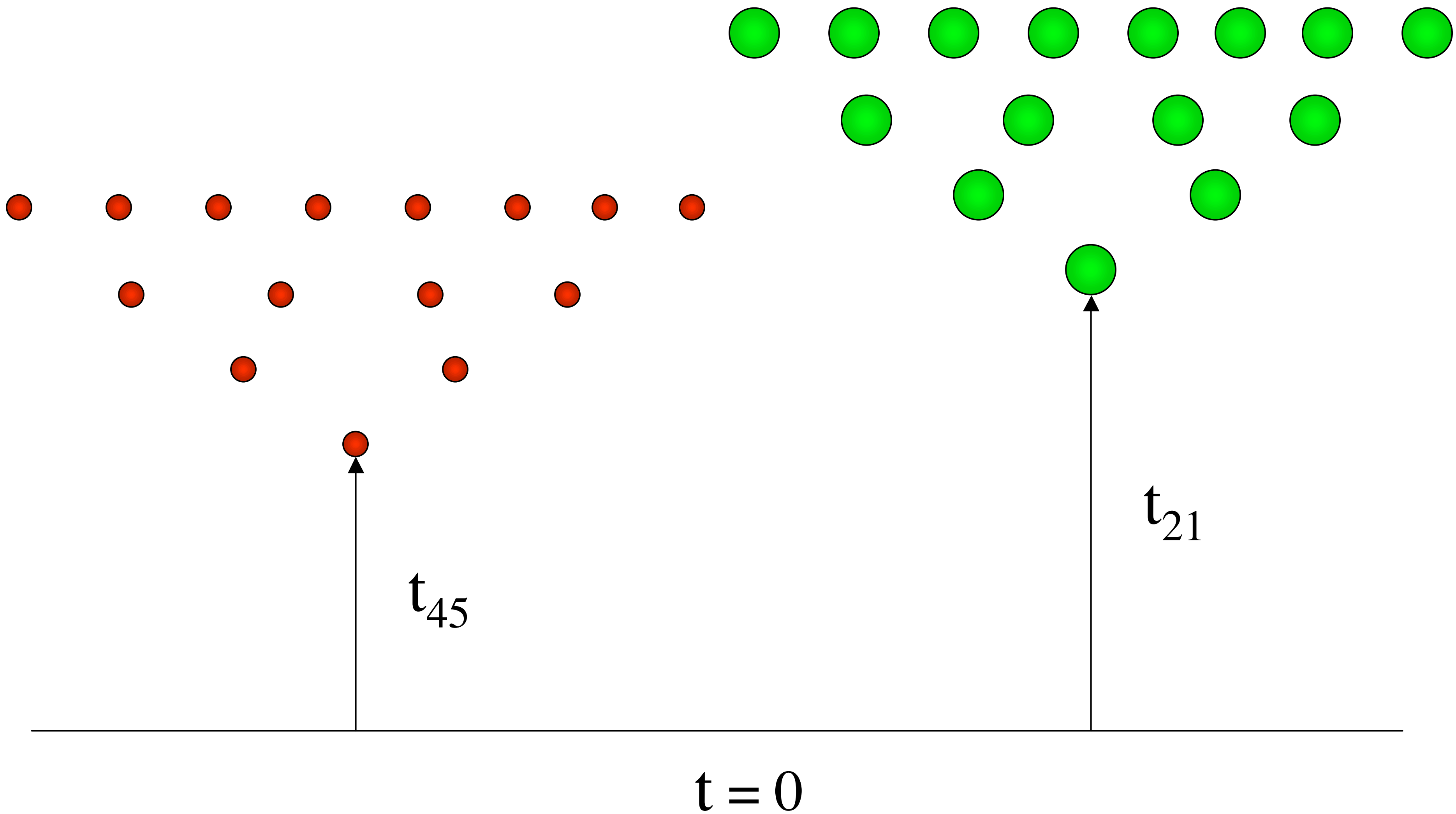
$$P(\phi_1, t) = P_3(0)\ \Gamma_{32}\ e^{3N_{21}}\ e^{3H_3^\beta (t - t_{21})}$$

$$P(\phi_5, t) = P_3(0)\ \Gamma_{34}\ e^{3N_{45}}\ e^{3H_3^\beta (t - t_{45})}$$

e^{3N} is the growth of volume during inflation

$$\frac{P(\phi_1, t)}{P(\phi_5, t)} = \frac{\Gamma_{32}\ e^{3N_{21}}}{\Gamma_{34}\ e^{3N_{45}}}\, e^{3H_3^\beta \Delta t}, \quad \Delta t = t_{45} - t_{21}$$

Unfortunately, the result depends on the time parametrization.



We should compare the “trees of bubbles” not at the time when the trees were seeded, but at the time when the bubbles appear

A possible solution of this problem:

If we want to compare apples to apples, instead of the trunks of the trees, we need to reset the time to the moment when the stationary regime of exponential growth begins. In this case we obtain the gauge-invariant result

$$\frac{P(\phi_1, t)}{P(\phi_5, t)} = \frac{\Gamma_{32}\ e^{3N_{21}}}{\Gamma_{34}\ e^{3N_{45}}}$$

As expected, the probability is proportional to the rate of tunneling and to the growth of volume during inflation.

A.L., arXiv:0705.1160

This result agrees with the expectation that the probability to be born in a part of the universe which experienced inflation can be very large, because of the exponential growth of volume during inflation.

Applications: Probabilities and the solution of the CC problem in the BP landscape

Clifton, Shenker, Sivanandam, arXiv:0706:3201

The main source of volume of new bubbles is the tunneling from the fastest growing dS vacua with large vacuum energy towards the anthropic sphere with $|\Lambda| \lesssim 10^{-120} M_p^4$.

If the tunneling occurs sequentially, between the nearby vacua, the process typically moves us to a minor fraction of the anthropic sphere with one of the fluxes being much greater than all others. This allows sharp predictions. One of the predictions - vacuum decay few billion years from now.

However, if the tunneling with large jumps is possible due to nucleation of large stacks of branes (which seems plausible during the tunneling from the high energy dS vacua), then the probability distribution on the anthropic sphere becomes rather uniform, no doomsday.

The cosmological constant problem is solved in this scenario in either case (small or large jumps): the probability distribution for the CC is flat and smooth near the anthropic sphere.

The predictions of other features of our world, including stability/instability of our vacuum, depend on the properties of the landscape, on the possibility of the nucleation of large stacks of branes, on the proper choice of the probability measure, and on the duration of the slow-roll stage of inflation.