# Eternal Inflation in Stringy Landscape

# and A-word

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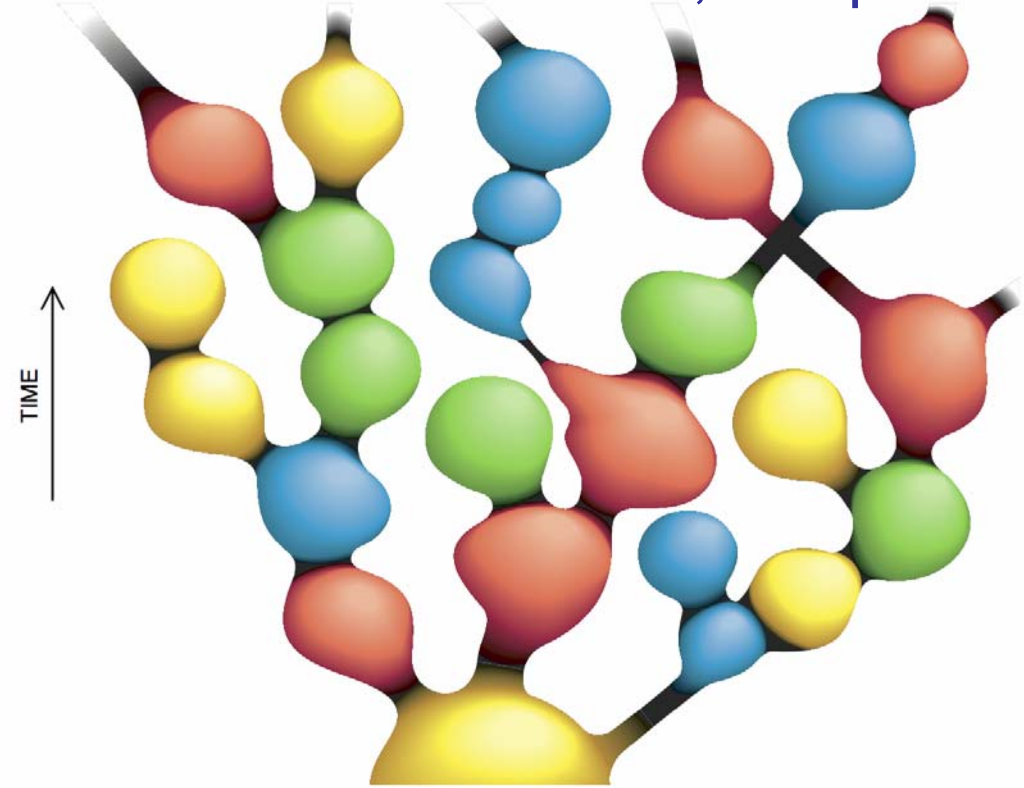
# Inflationary Multiverse

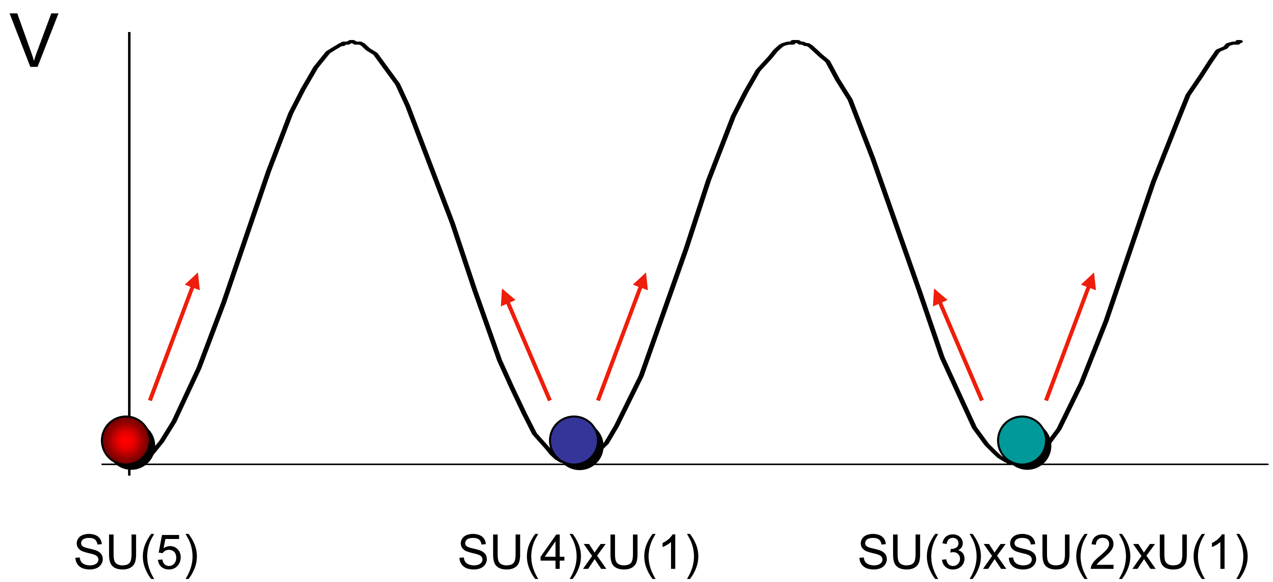
For a long time, people believed in the cosmological principle, which asserted that the universe is everywhere the same.

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.



# Example: SUSY landscape

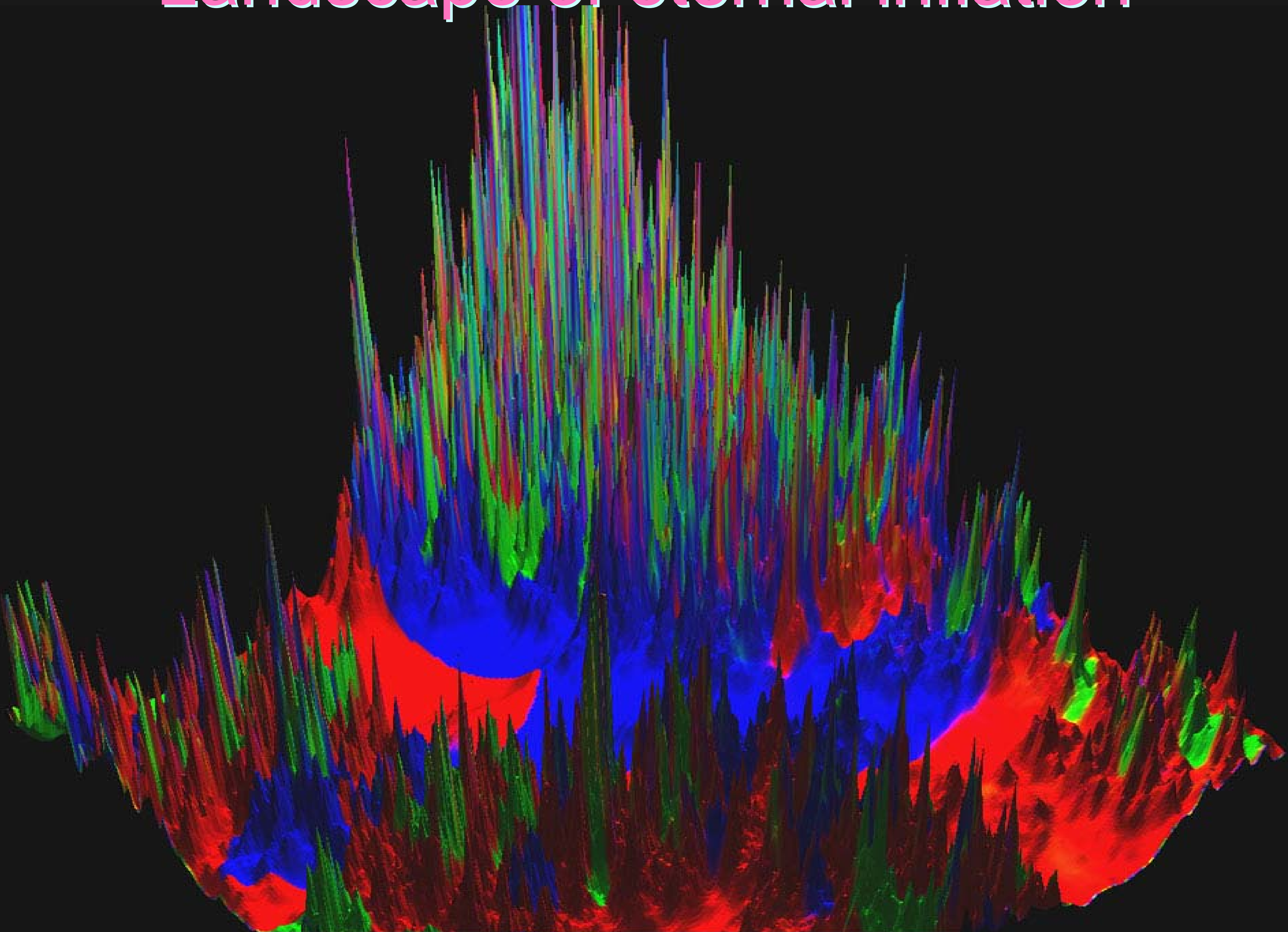
## Supersymmetric SU(5)




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



# Lesson of Inflation:

Do not be afraid to consider such trivial facts as a large size, flatness and homogeneity of the universe as observational data

# Anthropic Principle:

Do not be afraid to consider trivial facts of our own life as observational data

# Simple rules:

If we find that neutrino have masses, study those theories that allow it. With each new experiment we will know better which theories should we use.

If our universe is flat and contains perturbations with a flat spectrum, study those theories where this can happen.

If we find that our life is carbon-based, study only those theories, or those parts of the universe, which allow carbon-based life. Not life in general, not atoms in general, not any kind of silicon-based life, but life as we see it.

We should not try to find all parameters that allow our life to exist. We should consider all our experimental results, including the fact of our existence, and see whether their combination looks surprising. If so, we need a theory to explain it. If the combination of the facts is not surprising, we do not need a theory to explain them.

# Example: Why do we live in a 4D space?

**Ehrenfest, 1917**: Stable planetary and atomic systems are possible only in 4D space. Indeed, for D > 4 planetary system are unstable, whereas for D < 4 there is NO gravity forces between stars and planets.

We may still try to invent a theory which explains why our universe must be 4D. But the fact that our universe is 4D is not surprising, so we do not need to do it. It may be more productive to concentrate on many problems that do not have an anthropic solution.

## For example, there is no anthropic replacement of inflation

It was never easy to discuss anthropic principle, even with friends…

But recently the concept of the string theory landscape came to the rescue

# String Theory Landscape

# Inflation and Cosmological Constant

**Three crucial 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). All of us considered it obvious that we cannot live in the universe with

[redacted]

2) **Derivation of the anthropic constraint** [redacted]

Weinberg 1987, Martel, Shapiro, Weinberg 1997, Vilenkin, Garriga 1999…

# Inflation and Cosmological Constant

## 3) String theory landscape

### Multiplicity of (unstable) vacua:

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

Bousso, Polchinski 2000; Feng, March-Russell, Sethi, Wilczek 2000

### Vacuum stabilization:

KKLT 2003, Susskind 2003, Douglas 2003,…

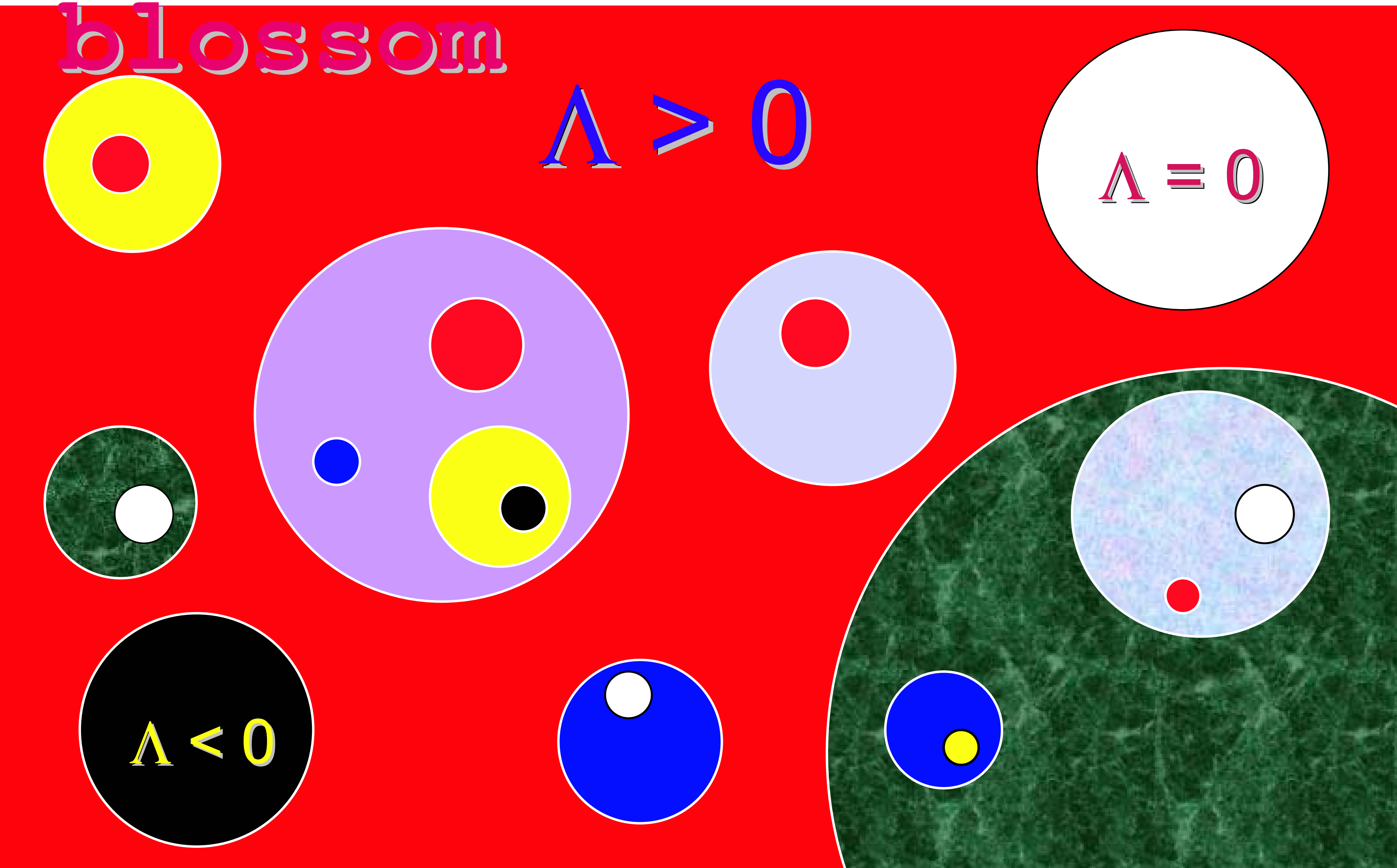
perhaps $10^{1000}$ metastable dS vacuum states - still counting…

# Probabilities in the Landscape

We must find all possible vacua (statistics), and all possible continuous parameters (out-of-equilibrium cosmological dynamics).

We must also find a way to compare the probability to live in each of these states.

# Let $10^{1000}$ flowers blossom

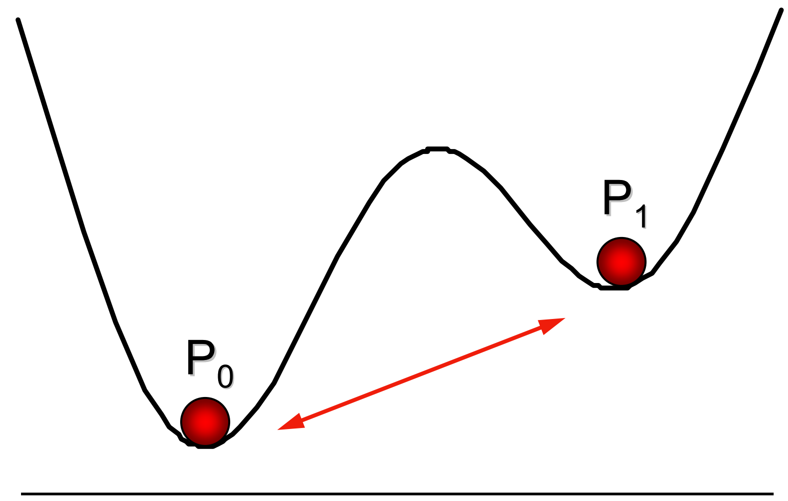


# Example: Two dS vacua

$$P_0\, e^{-S_0+B} = P_1\, e^{-S_1+B}$$

$$S = \frac{1}{V}$$ is dS entropy

$$\frac{P_1}{P_0} = e^{S_1-S_0} = e^{\Delta S}$$



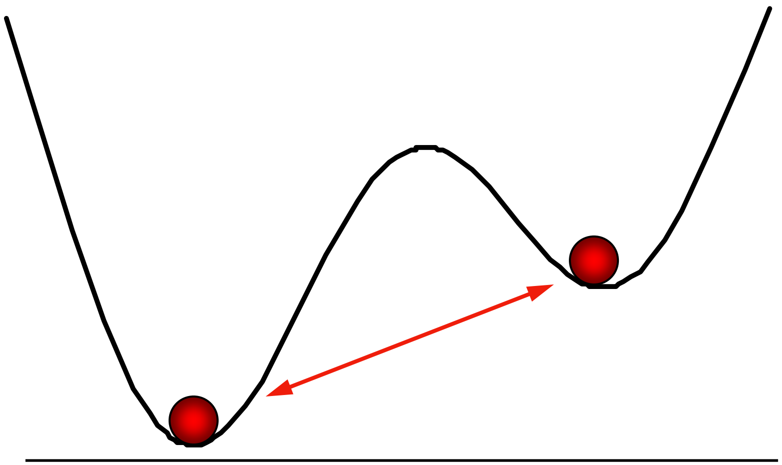

$P_i$ is the probability to find a given point in the vacuum $dS_i$

This is the square of the Hartle-Hawking wave function, which tells that the fraction of the comoving volume of the universe with the cosmological constant $V_i = \Lambda$ is proportional to

$$P = e^{\frac{1}{\Lambda}}$$

In this context the HH wave function describes the ground state of the universe, it has no relation to creation of the universe "from nothing", and it does not require any modifications recently discussed in the literature.

## In this scenario we should live in the lowest of all dS spaces compatible with the existence of our life

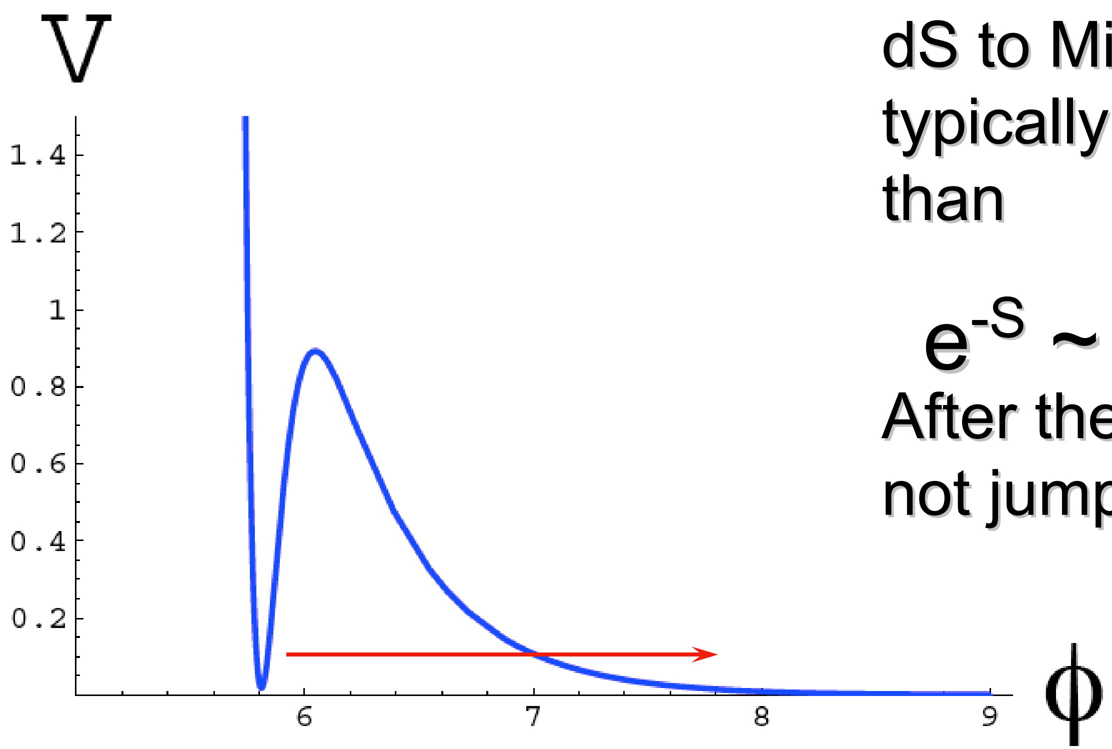


However, this would also mean that instead of inflation we would have eternal recycling of dead dS spaces. This would disagree with observations.

Dyson, Goheer, Kleban, Susskind 2002

Fortunately, this problem disappears in the KKLT scenario because of metastability of dS vacua.

# KKLT potential always has a Minkowski minimum (Dine-Seiberg vacuum)



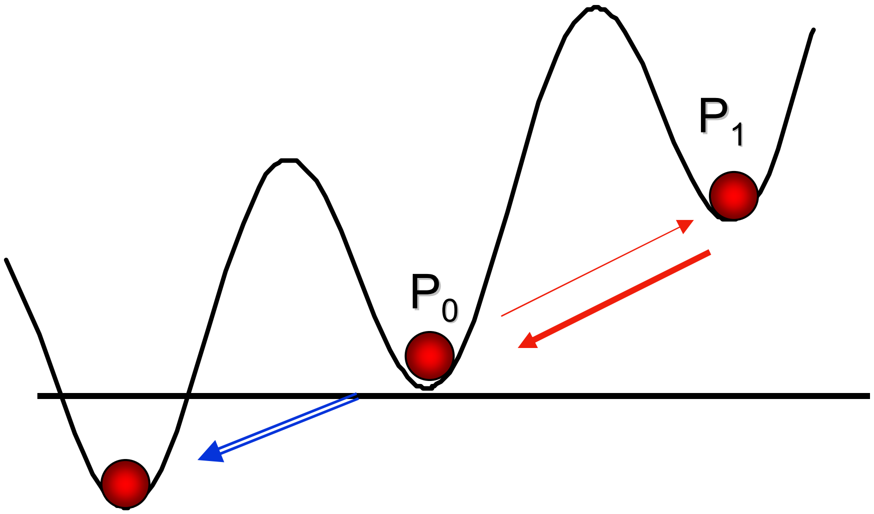

Probability of tunneling from dS to Minkowski space typically is somewhat greater than

$$e^{-S} \sim e^{-1/\Lambda} \sim e^{-10^{120}}$$

After the tunneling, the field does not jump back - no recycling.

Now we will study decay from dS to the collapsing vacua with negative vacuum energy.

# Two dS vacua and AdS sink




Parts of dS space tunneling to space with negative V rapidly collapse and drop out of equilibrium (one-way road to hell). Therefore instead of detailed balance equations, one has flow equations:

$$\frac{dP_0}{dt} = -P_0\, e^{-C_0} - P_0\, e^{-S_0+B} + P_1\, e^{-S_1+B} \ ,$$

$$\frac{dP_1}{dt} = P_0\, e^{-S_0+B} - P_1\, e^{-S_1+B} \ .$$

Ceresole, Dall'Agata, Giryavets, Kallosh, A.L., hep-th/0605266

# Tunneling to the sink

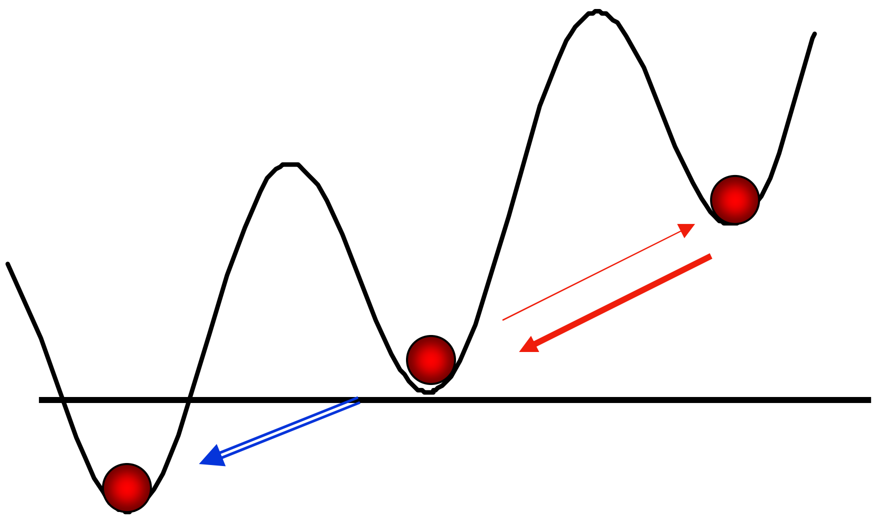
In the class of the KKLT models that we explored, the probability of the tunneling to the collapsing space with negative vacuum energy is related to SUSY breaking after the AdS uplifting, and is of the order

$$\Gamma \sim e^{-\frac{1}{|V_{AdS}|}} \sim e^{-m_{3/2}^{-2}} \gg e^{-\frac{1}{\Lambda}}$$

In the simplest SUSY models, the rate of a decay to a sink is ~ $e^{10^{120}}$ times greater than the probability to jump from our vacuum to a higher dS vacuum.

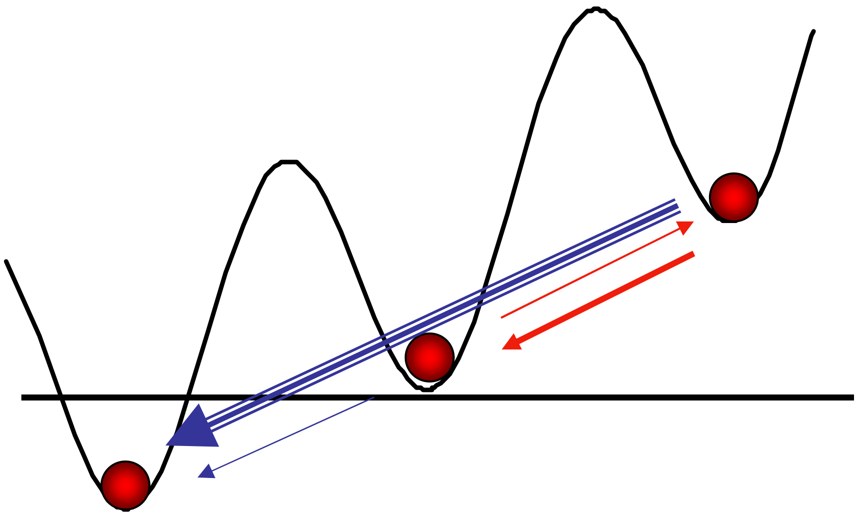
That is why our part of the universe was produced by inflation rather than by recycling of dead dS spaces: Only ~ $e^{-10^{120}}$ of all points produced by inflation are recycled; all others go to the sink.

# Narrow sink



If the decay to the sink is slower than the decay of the upper dS vacuum to the lower dS vacuum, then the probability distribution is given by the Hartle-Hawking expression, despite the vacuum instability and the general probability flow down.

# Generic probability leaks



In general, however, the probability leaks from dS to a collapsing space or to a Minkowski space may occur from all dS vacua, and the resulting probability distribution may differ dramatically from the Hartle-Hawking distribution.

In particular, if there is a strong probability leak from the upper dS vacua, then the probability to live there is exponentially small, and it does not depend on their vacuum energy. In some other cases, the probability to live in the lower dS vacuum is exponentially smaller than in the upper ones (inverted probability distribution).

# Conclusion:

In the string landscape scenario we do not study the ground state of the universe, as we did before. Instead of that, we study the universe with many holes in the ground.

Instead of studying static probabilities, like in a pond with still water, we study probability currents, like in a river dividing into many streams.

In other words, in addition to exploring vacuum statistics, we also explore vacuum dynamics.

## The main conclusion:

# IT IS SCIENCE

**It is unusual, it is complicated, it has many unsolved problems, one may like it or hate it, but we must learn how to live in a free world where many different possibilities are available**

# Two types of questions:

What is a **typical history** of a given point in an eternally inflating universe? (That is what we studied so far.)

What is a **typical population** ? (Volume-weighted distributions)

# Example:

1) What is a typical age when any particular scientist makes his best discoveries?

2) What is the average age of scientists making greatest discoveries?

**Both questions make sense, but the answers are significantly different because of the exponentially growing population of scientists.**

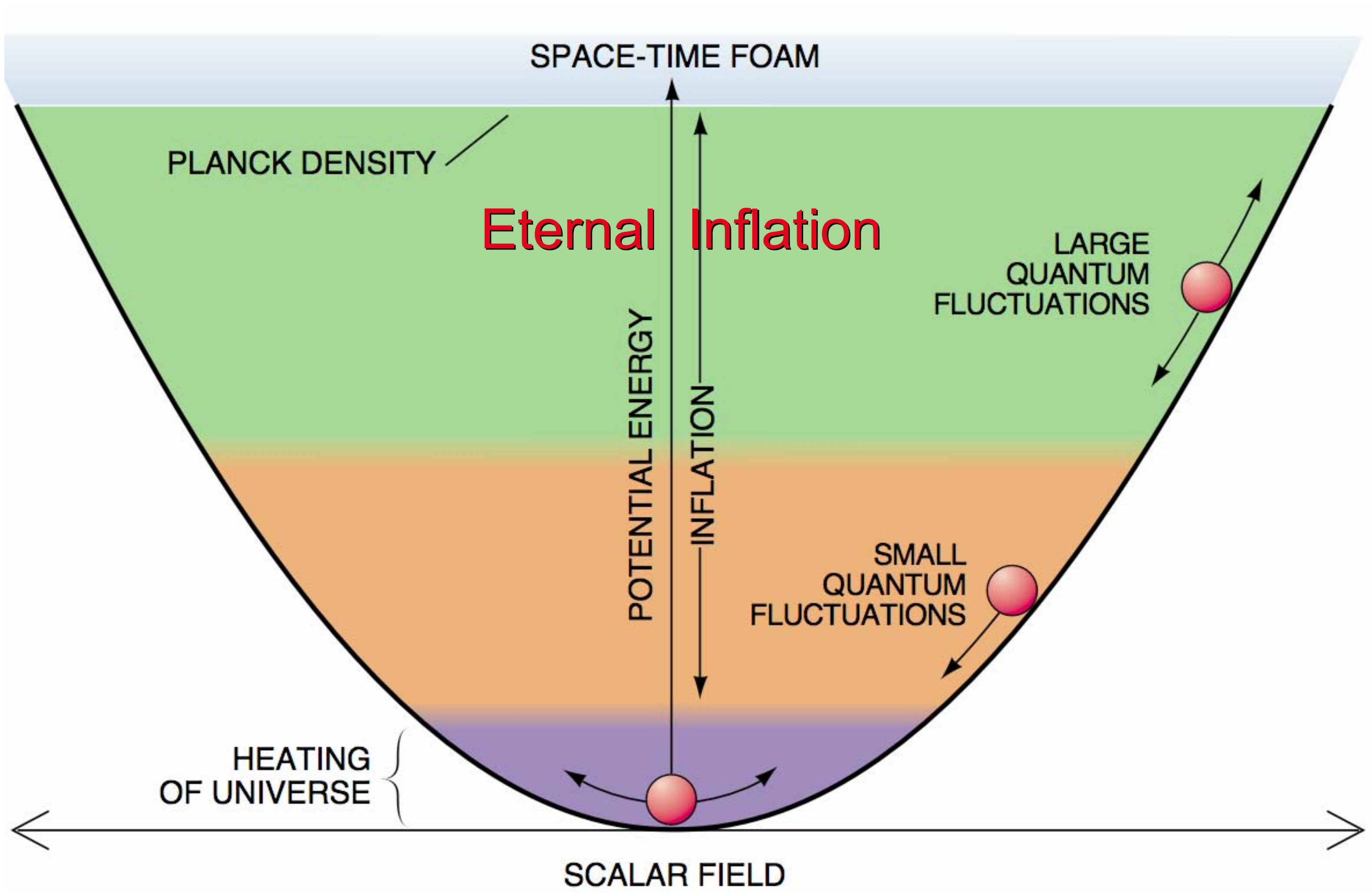
Similarly, in the context of inflationary cosmology one may study a typical behavior at a given point, or an average behavior per unit volume.

Pointilists (like Seurat, Pissaro, and some of our friends) see no point in studying volume. Meanwhile inflation is all about the exponential growth of volume. All physically relevant points, such as baryons, galaxies, and observers, were created AFTER inflation, and their number was proportional to volume.

Here I will illustrate the difference by studying the simplest model of chaotic inflation.

# Naturalness (?) of chaotic inflation

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



Chaotic inflation requires $\phi > M_p$. This condition can be easily satisfied in the scalar field theory plus gravity, but it is difficult to construct inflationary models with $\phi > M_p$ in supergravity and string theory. It took almost 20 years to construct a natural version of chaotic inflation in SUGRA. In string theory we started doing it only 3 years ago, with limited success.

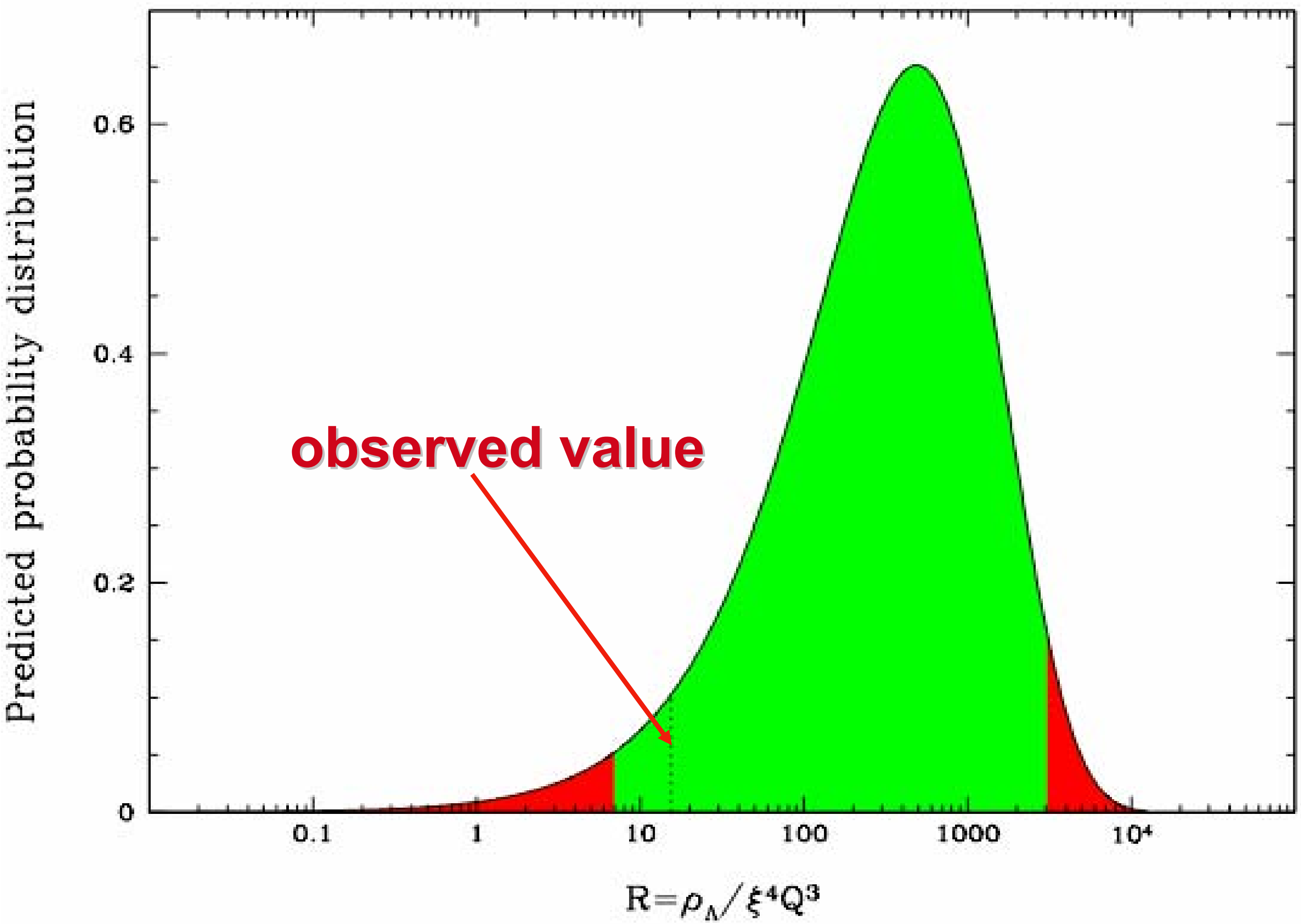
**HOWEVER…**

Let us imagine that just one out of $10^{1000}$ of string theory vacua allows existence of the field $\phi \sim 100$, in units of $M_p$. The volume produced during chaotic inflation in this universe is proportional to $e^{\phi^2} \sim 10^{10000}$.

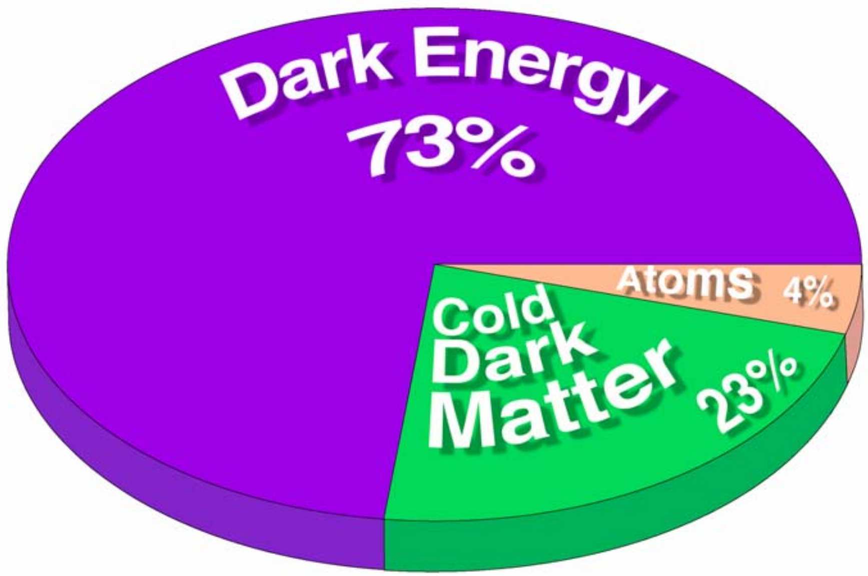
Therefore a part of the universe in such an improbable and “unnatural” state will have more volume (and contain more observers like us) than all other string theory vacua combined.

# Latest anthropic constraints on $\Lambda$

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



**Dark Energy** (Cosmological Constant) is about 73% of the cosmic pie




What's about **Dark Matter**, another 23% of the pie? Why there is 5 times more dark matter than ordinary matter?

# Example: Dark matter in the axion field

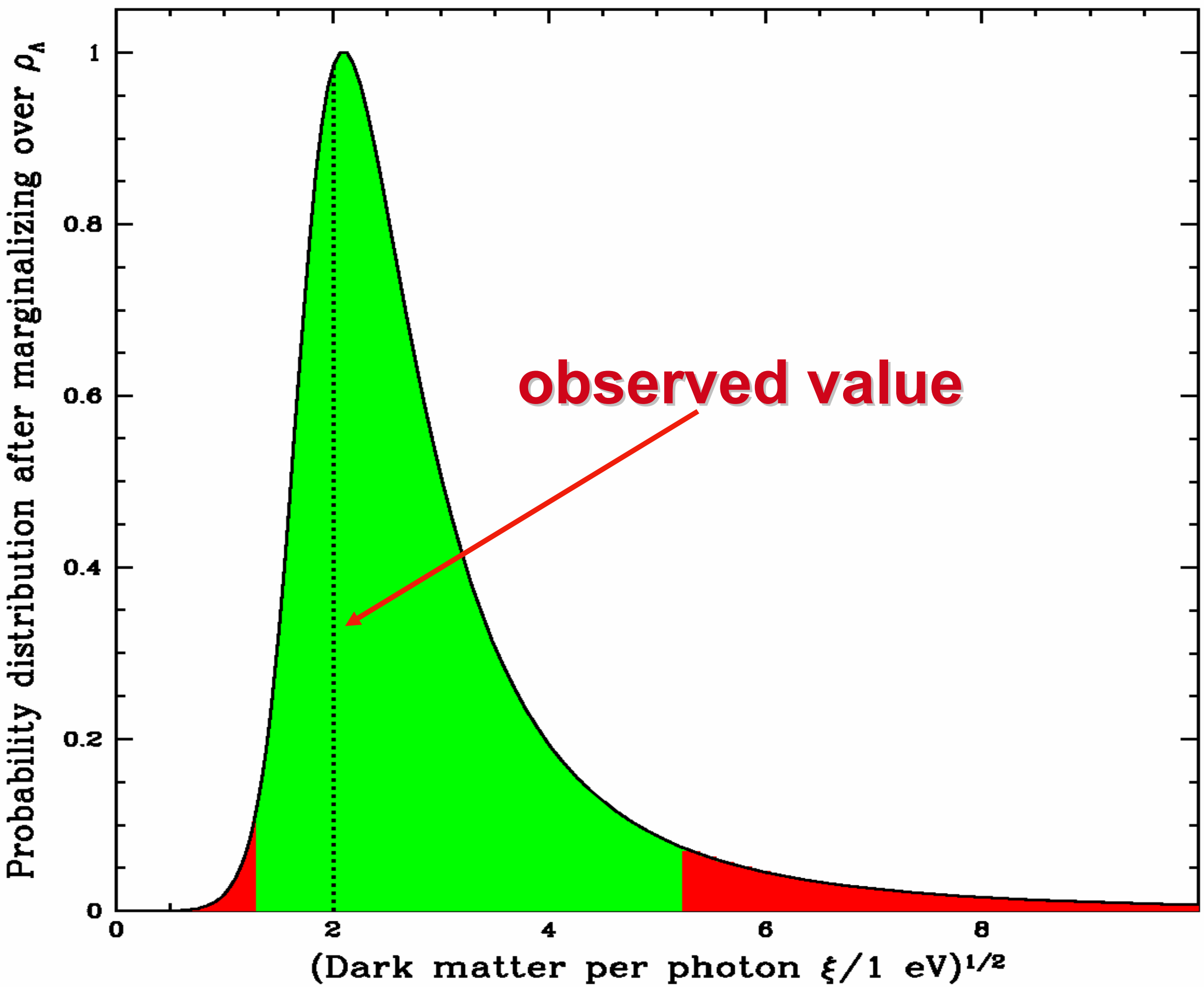
**Standard lore:** If the axion mass is smaller than $10^{-5}$ eV, the amount of dark matter in the axion field contradicts observations, for a typical initial value of the axion field.

**Anthropic argument:** Due to inflationary fluctuations, the amount of the axion dark matter is 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.

# Latest anthropic constraints on Dark Matter

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




**The situation with Dark Matter is similar to the situation with CC !**

# Split Supersymmetry

Arkani-Hamed, Dimopoulos, 2005

The amplitude of spontaneous symmetry breaking can be explained anthropically. This allows a new SUSY phenomenology, to be tested at LHC.

Exciting possibility: Testing anthropic principle on a collider…