Strings and Cosmology

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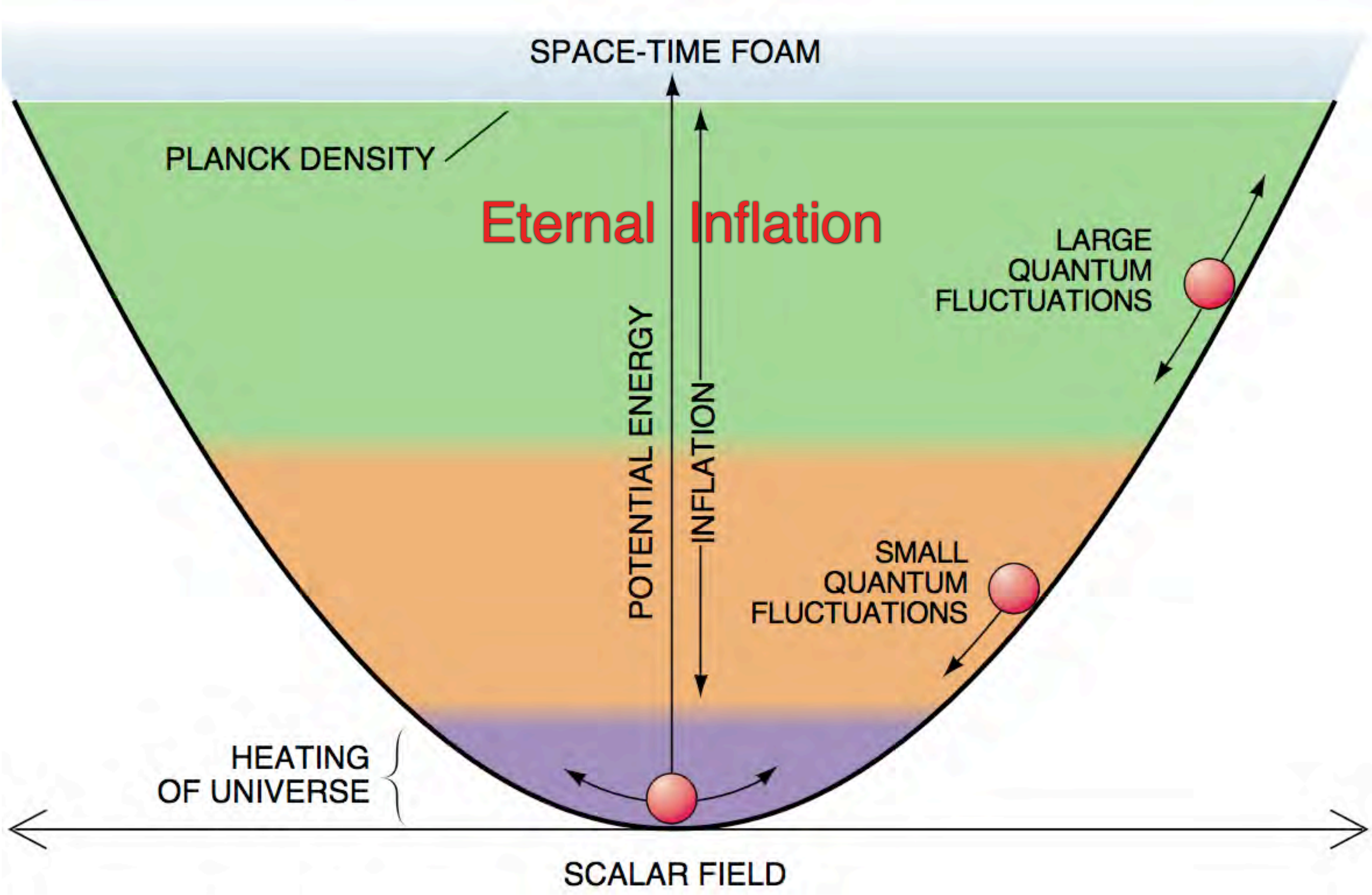
Contents:

1. Inflation and dark energy in
    - i) supergravity
    - ii) string theory
2. Testing string theory with CMB
3. Landscape and beyond

Chaotic Inflation

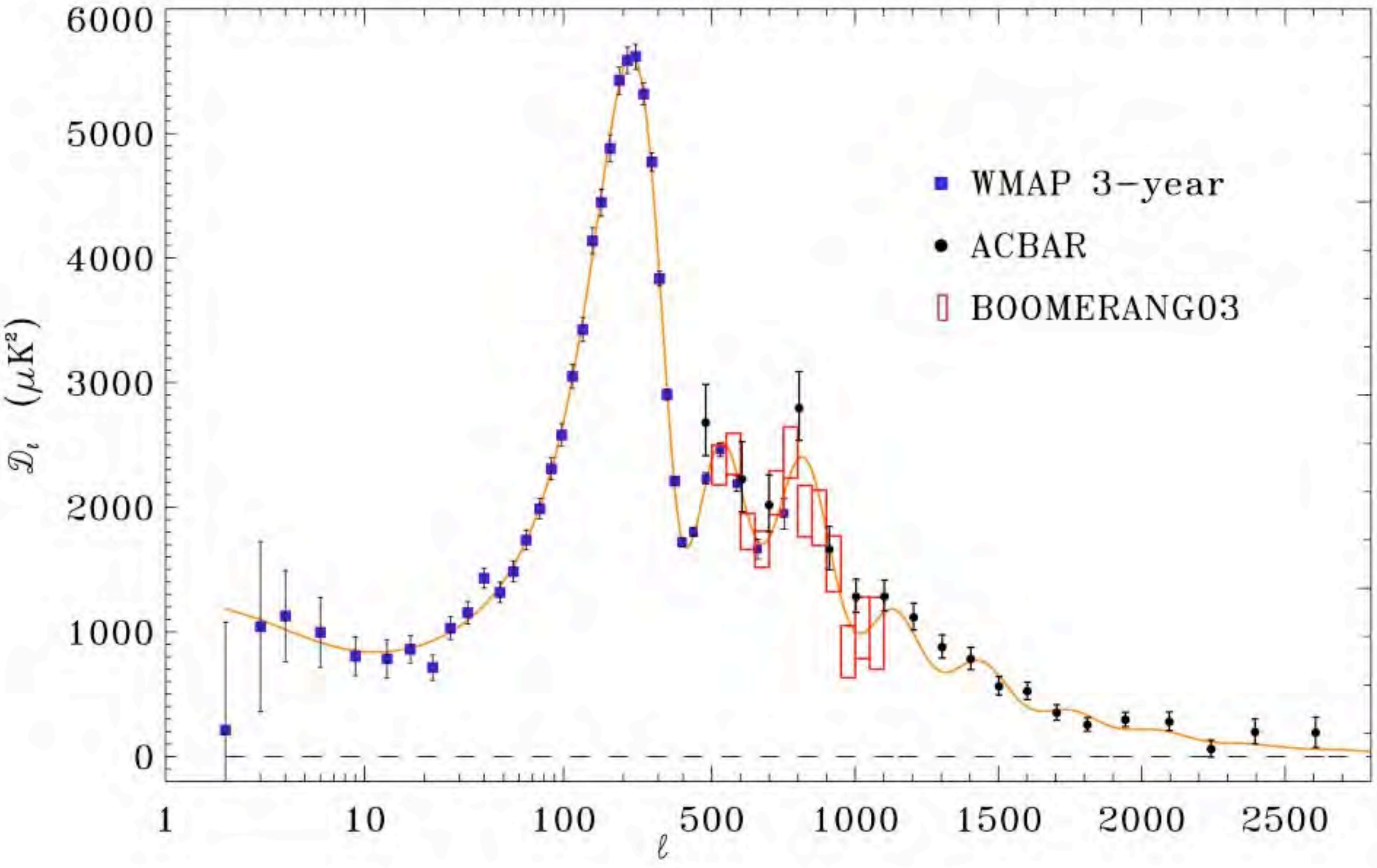
$$V(\phi) = \frac{m^2}{2}\phi^2$$



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:

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

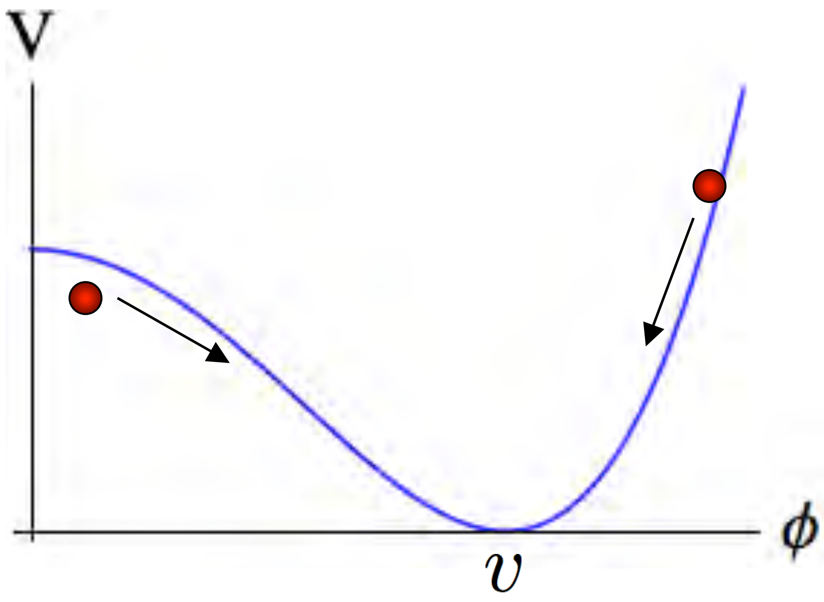
2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-1})$. Spectral index n_s slightly differs from 1. (This is an important prediction, similar to asymptotic freedom in QCD.)

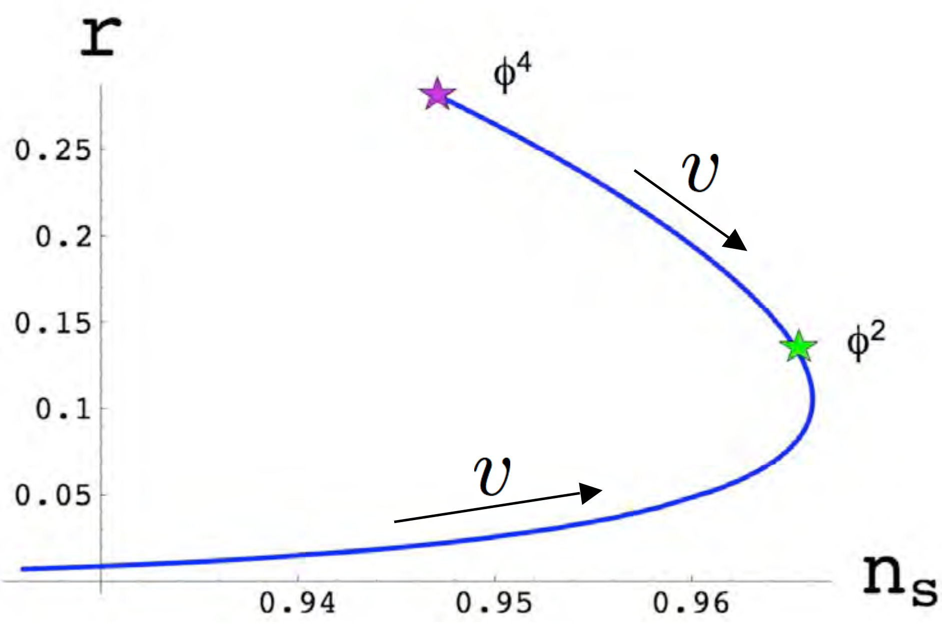
Observations: perturbations are gaussian and adiabatic, with flat spectrum: $n_s = 0.95 \pm 0.02$

Tensor modes: r =T/S

$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

Kallosh, A.L. 2007





If r > 0.1, we may find tensor modes before 2011

If r ~ 0.01, it may require another 10 years or so

In all known inflationary models based on string theory

$r << 0.01$

Chaotic inflation in supergravity

Main problem:

$$V(\phi) = e^{K}\left(K^{-1}_{\Phi\bar{\Phi}}\,|D_\Phi W|^2 - 3|W|^2\right)$$

Canonical Kahler potential is $K = \Phi\bar{\Phi}$

Therefore the potential blows up at large |φ|, and slow-roll inflation is impossible:

$$V \sim e^{|\Phi|^2}$$

Too steep, no inflation…

A solution: shift symmetry

Kawasaki, Yamaguchi, Yanagida 2000

Equally good Kahler potential $K = \frac{1}{2}(\Phi + \bar{\Phi})^2 + X\bar{X}$

and superpotential $W = m\Phi X$

The potential is very curved with respect to X and Re Φ, so these fields vanish.

But Kahler potential does not depend on

$$\phi = \sqrt{2}\ \mathrm{Im}\,\Phi = (\Phi - \bar{\Phi})/\sqrt{2}$$

The potential of this field has the simplest form, without any exponential terms:

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

PNGB inflation in supergravity

Kallosh 2007

Shift symmetry $$K = \frac{1}{2}(\Phi + \bar{\Phi})^2$$

KKLT-type superpotental $$W = W_0 + Be^{-b\Phi}$$

The potential after the KKLT-type uplifting has a minimum at some value of the radial variable $x = (\Phi + \bar{\Phi})/\sqrt{2}$. The radial direction x is very steep. At the minimum with respect to x, the potential is that of the natural inflation:

$$V = V_0 + V_1(1 - \cos b\phi)$$

Here $\phi = (\Phi - \bar{\Phi})/\sqrt{2}$ is the PNGB (axion) field

For b << 1, this model describes “natural inflation” proposed by Freese, Freiman and Olinto in 1990. Just as with the chaotic inflation, it took 17 years to implement this scenario in supergravity. It may take even longer to implement it in string theory.

If one fine-tunes $V_0 \sim 10^{-120}$ in the potential

$$V = V_0 + V_1(1 - \cos b\phi)$$

one can describe the cosmological constant (CC).

If, in addition, one fine-tunes $V_1 \sim 10^{-120}$, one can describe the dark energy. Thus, dark energy typically requires an additional fine-tuning as compared to CC, which does not make it particularly attractive.

Inflation in String Theory

The volume stabilization problem:

A potential of the theory obtained by compactification in string theory of type IIB:

$$V(X,Y,\phi) \sim e^{\sqrt{2}X-\sqrt{6}Y}\ V(\phi)$$

X and Y are canonically normalized field corresponding to the dilaton field and to the volume of the compactified space; ϕ is the field driving inflation

The potential with respect to X and Y is very steep, these fields rapidly run down, and the potential energy V vanishes. We must stabilize these fields.

Dilaton stabilization: Giddings, Kachru, Polchinski 2001

Volume stabilization: **KKLT construction**

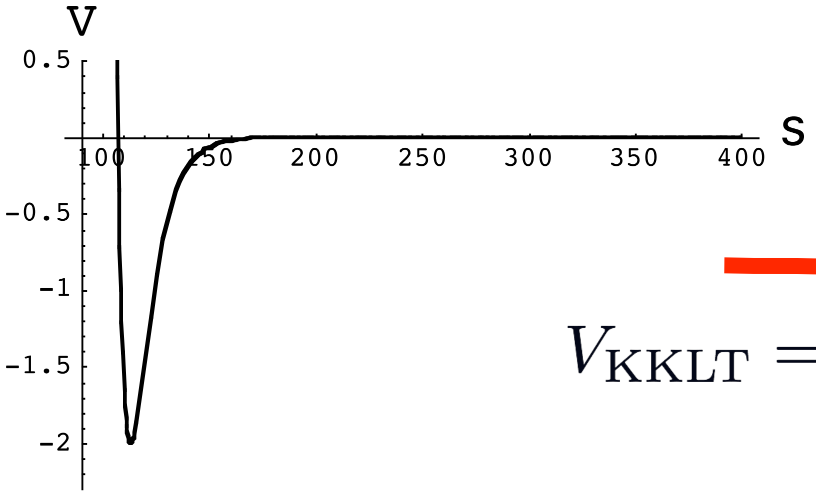
Kachru, Kallosh, A.L., Trivedi 2003

Basic steps of the KKLT scenario:

1) Start with a theory with runaway potential discussed above

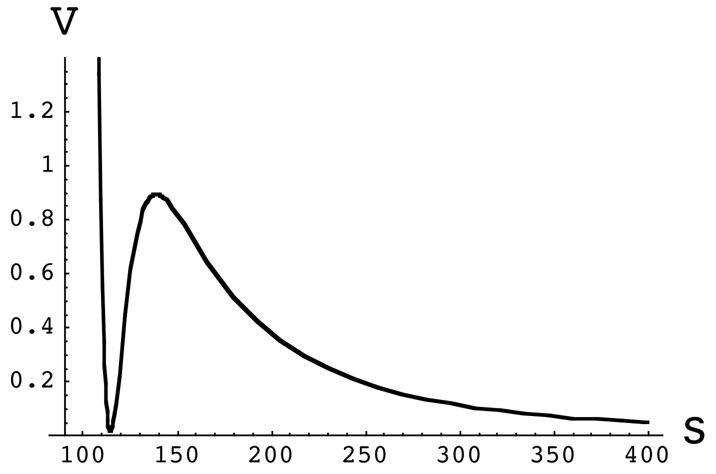
2) Bend this potential down due to nonperturbative quantum effects

3) Uplift the minimum to the state with a positive vacuum energy by adding a positive energy of an anti-D3 brane in warped Calabi-Yau space



AdS minimum

$$V_{\mathrm{KKLT}} = V_{\mathrm{AdS}} + \frac{D}{\sigma^2}$$



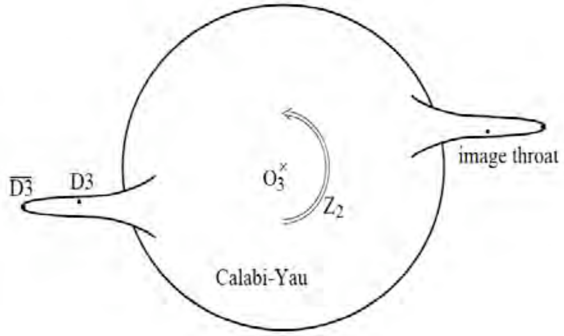
Metastable dS minimum

Two types of string inflation models:

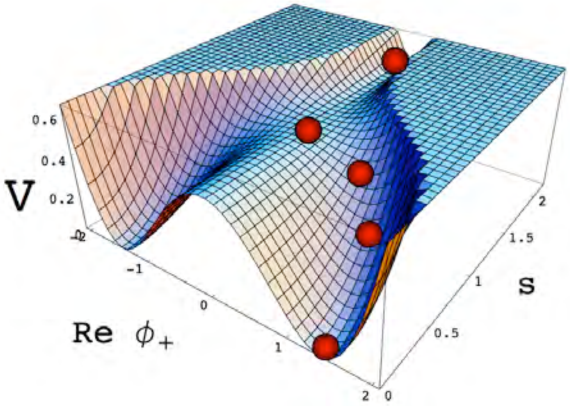
Modular Inflation. The simplest class of models. They use only the fields that are already present in the KKLT model.

Brane inflation. The inflaton field corresponds to the distance between branes in Calabi-Yau space. Historically, this was the first class of string inflation models.

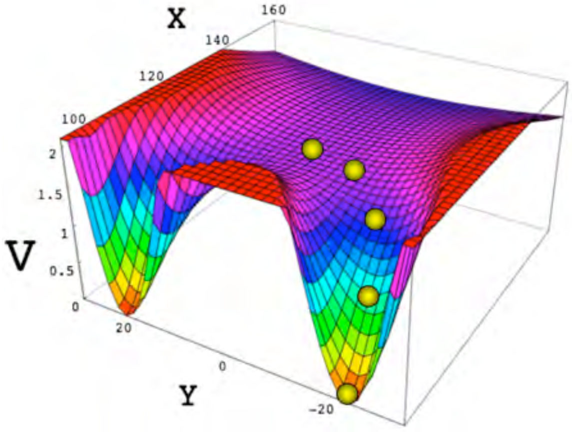
Inflation in string theory



KKLMMT brane-anti-brane inflation



D3/D7 brane inflation



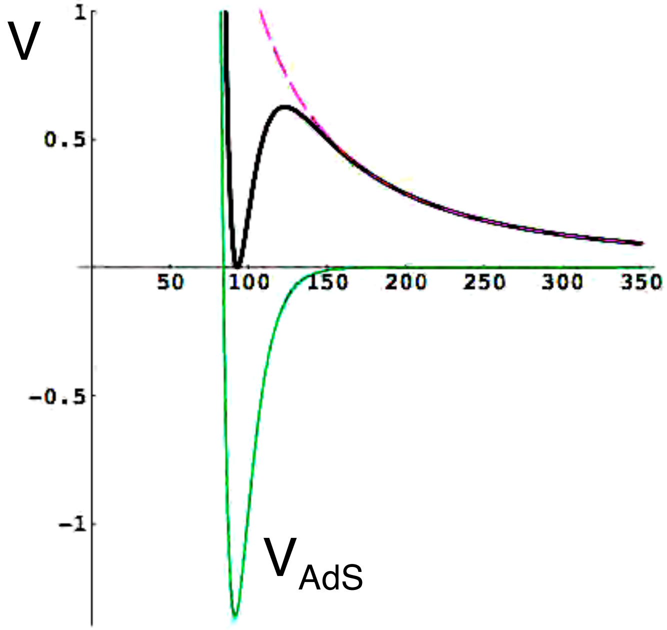
Racetrack modular inflation

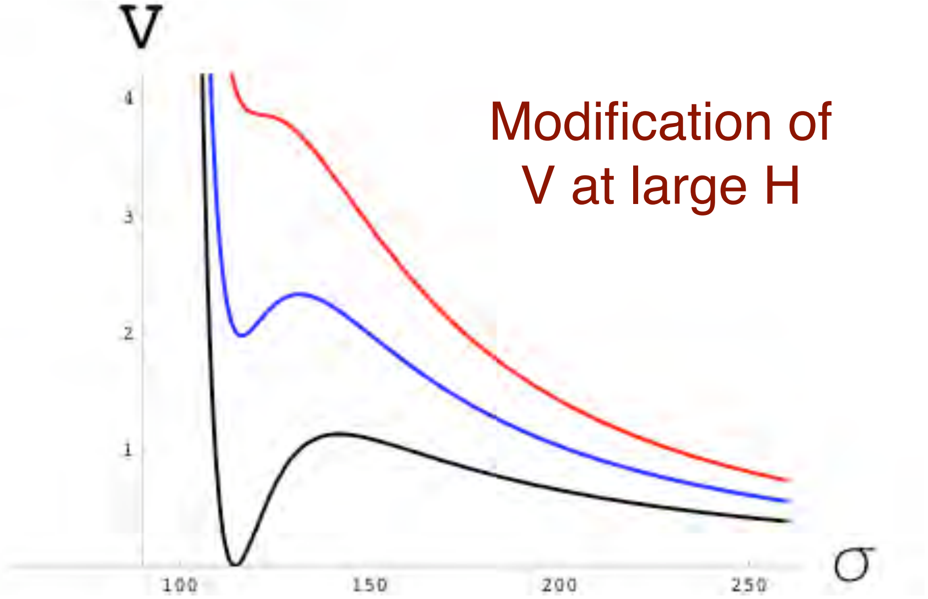
DBI inflation (non-minimal kinetic terms)

String Cosmology and the Gravitino Mass

Kallosh, A.L. 2004

The height of the KKLT barrier is smaller than $|V_{AdS}| = m^2_{3/2}$. The inflationary potential V_{infl} cannot be much higher than the height of the barrier. Inflationary Hubble constant is given by $H^2 = V_{infl}/3 < m^2_{3/2}$.





Modification of V at large H

Constraint on the Hubble constant in this class of models:

$$H < m_{3/2}$$

$$V(\phi) = e^K \left(K^{-1}_{\Phi\bar{\Phi}} \, |D_\Phi W|^2 - 3|W|^2 \right)$$

In the AdS minimum in the KKLT construction $D_\Phi W = 0$

Therefore

$$V_{\rm AdS} = -3\, e^K |W^2| = -3\, m^2_{3/2}$$

$$3H^2 = V_{\rm inflation} \leq V_{\rm barrier} \sim |V_{\rm AdS}| = 3m^2_{3/2}$$

$$H \leq m_{3/2}$$

Tensor Modes and GRAVITINO

$$r \sim 10^8 H^2$$

for inflationary perturbations

$$H \leq M_{3/2}$$

$$r \leq 10^8 M_{3/2}^2$$

Kallosh, A.L. 2007

$$r \sim 10^{-2} \longrightarrow M_{3/2} \sim 10^{13} GeV$$

superheavy gravitino

$$M_{3/2} \sim 1 TeV \longrightarrow r \sim 10^{-24}$$

unobservable

A discovery or non-discovery of tensor modes would be a crucial test for string theory and particle phenomenology

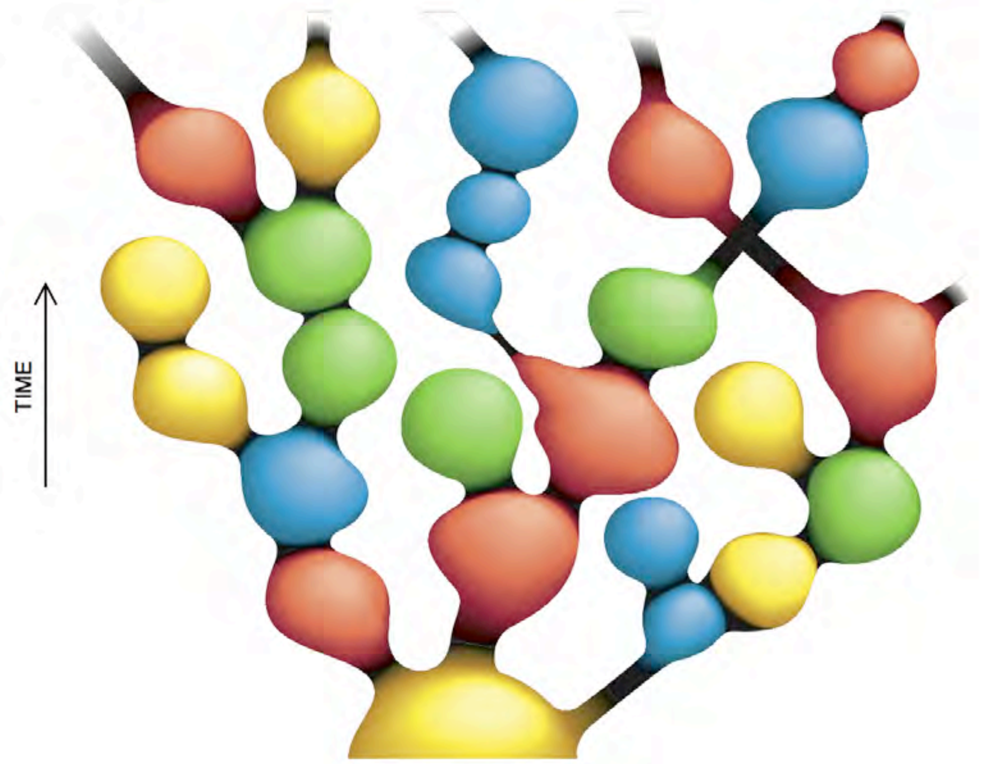
If one suppresses the scale of inflation by 100 orders of magnitude (!), one will obtain dark energy (quintessence).

No natural models of quintessence so far, whereas the cosmological constant is nearly unavoidable: It appears in 10^{1000} vacua in string theory landscape.

Inflationary Multiverse

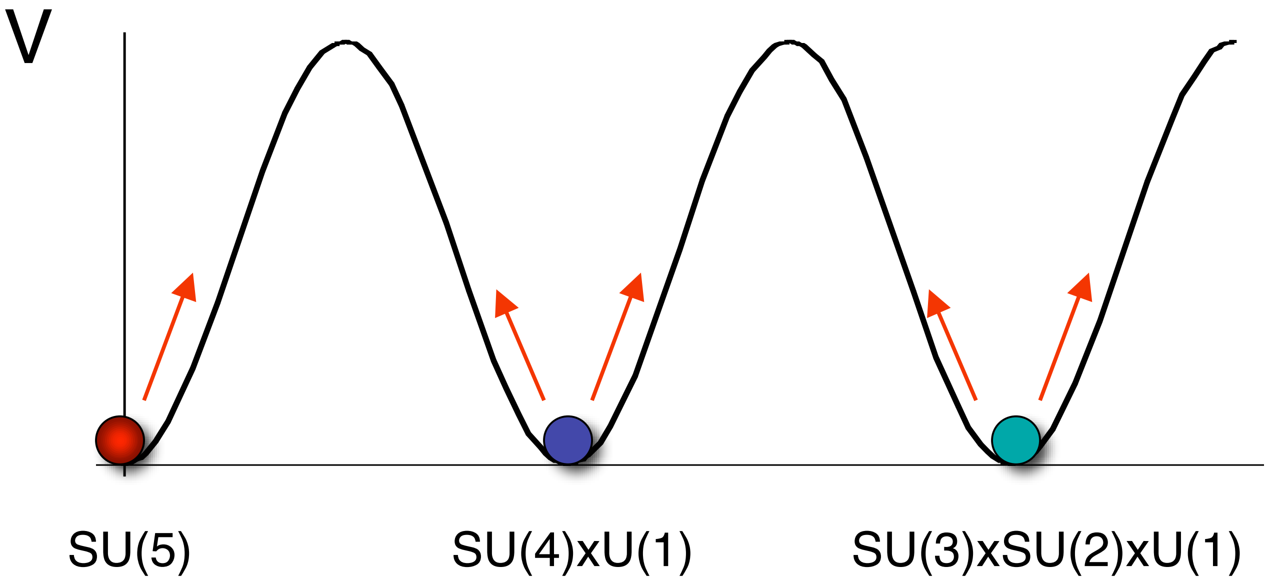
For a long time, people believed in the cosmological principle, which asserted that the universe is everywhere the same.

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

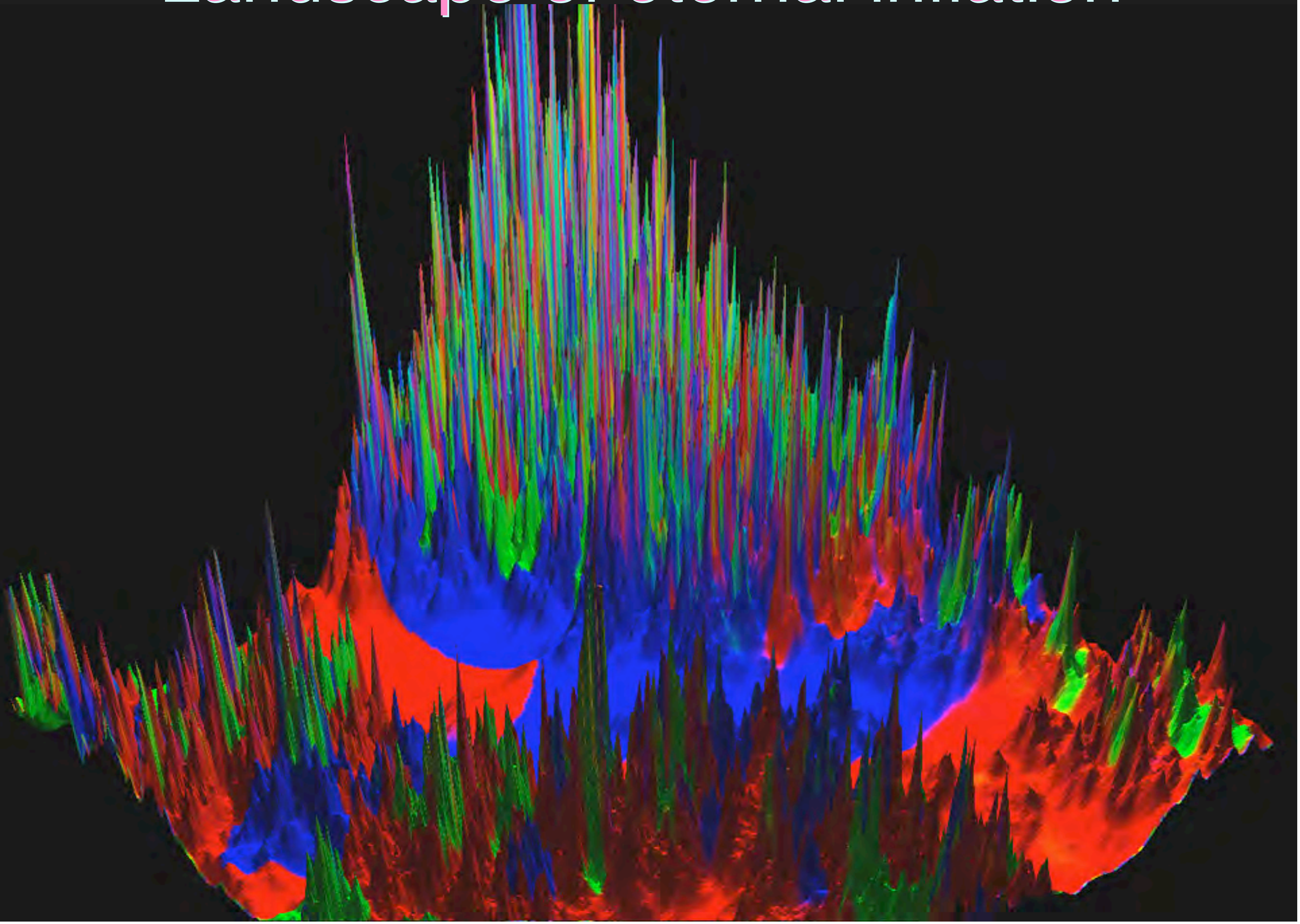
Supersymmetric SU(5)



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



String Theory Landscape

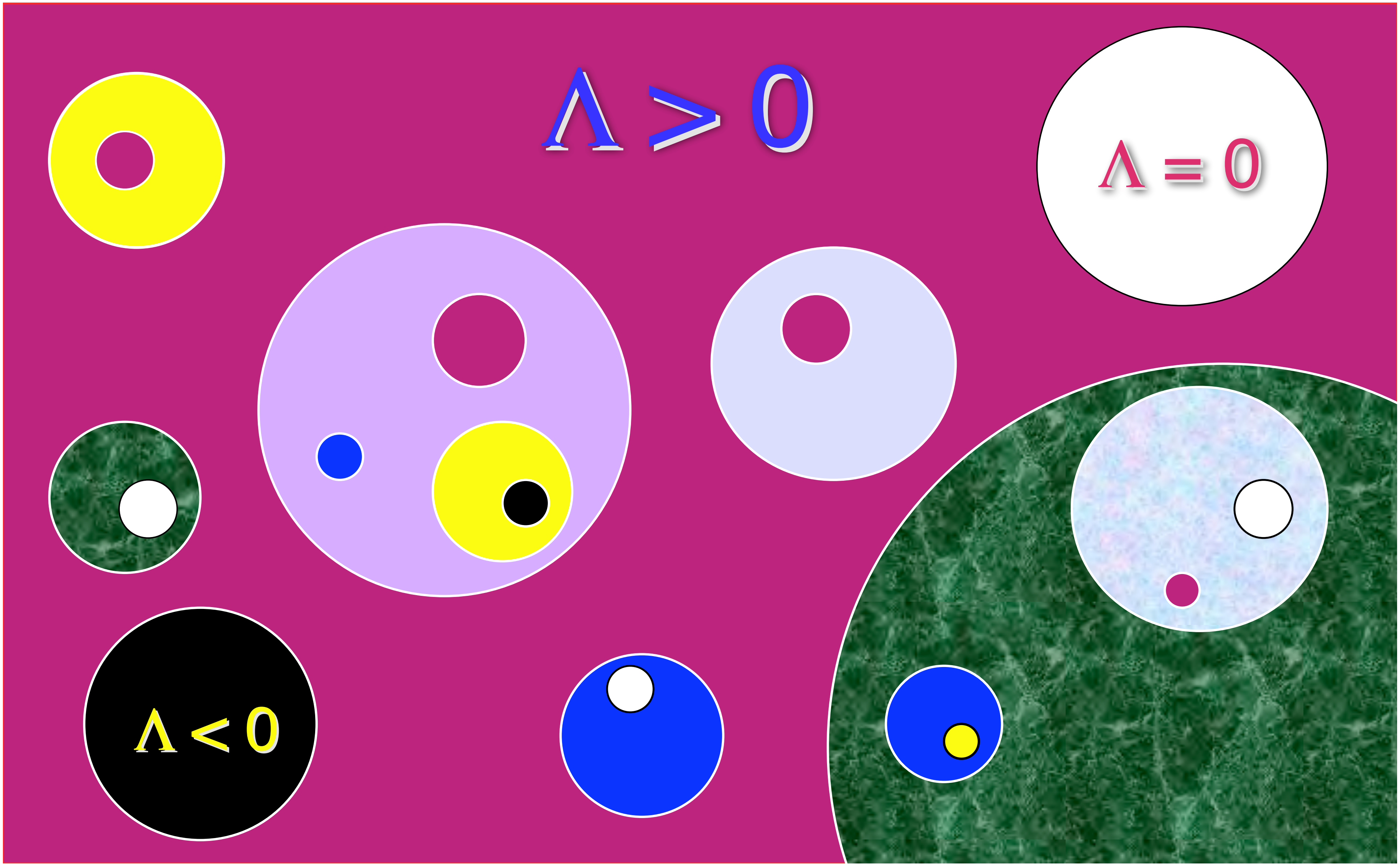
Perhaps 10^{1000} different uplifted worlds

Lerche, Lust, Schellekens 1987

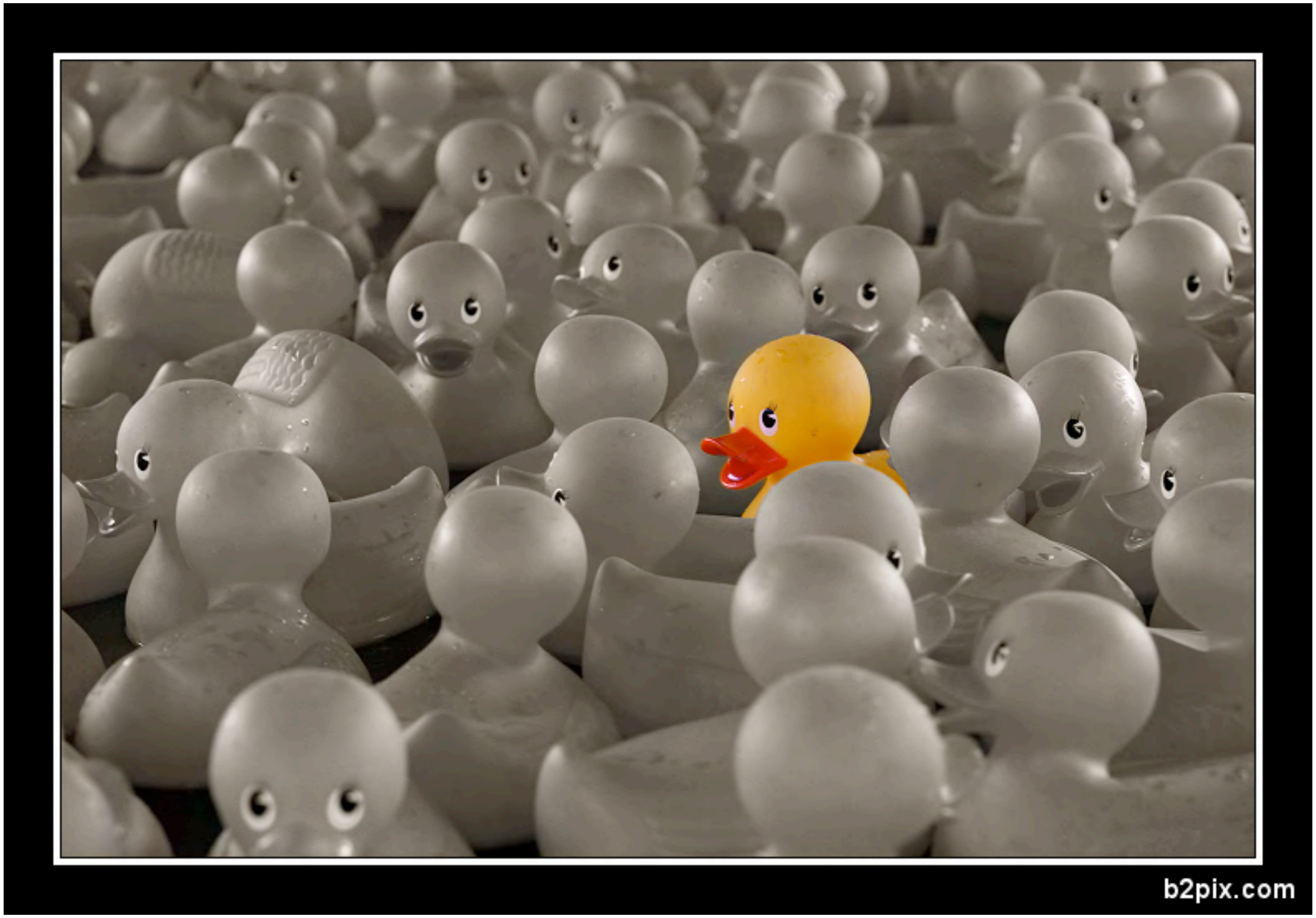
Bousso, Polchinski 2000; Susskind, Douglas, Denef 2003

String Theory Multiverse

and eternal old inflation



What is so special about our world?


b2pix.com

<u>Problem:</u> 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

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

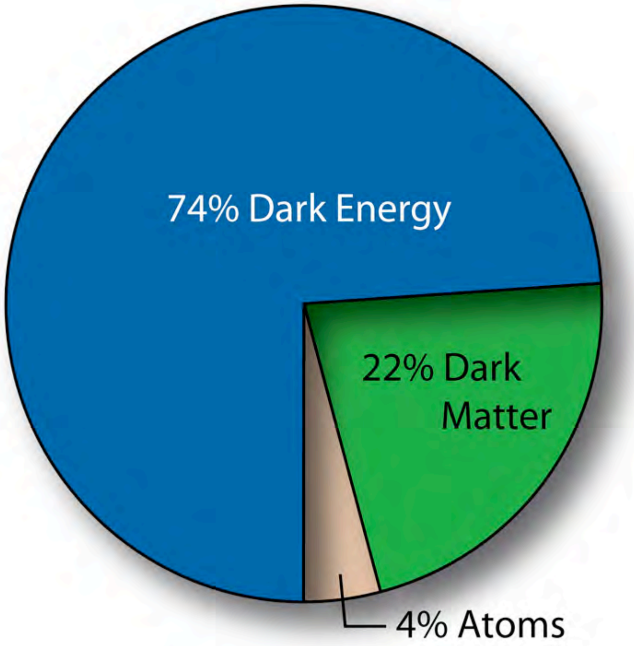
A.L. 1986; A.L., D.Linde, Mezhlumian, Garcia-Bellido 1994;

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

No dependence on initial conditions. We are still learning how to do it properly.

We will consider two examples: Dark matter and the cosmological constant.

Cosmological Constant (Dark Energy) 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.

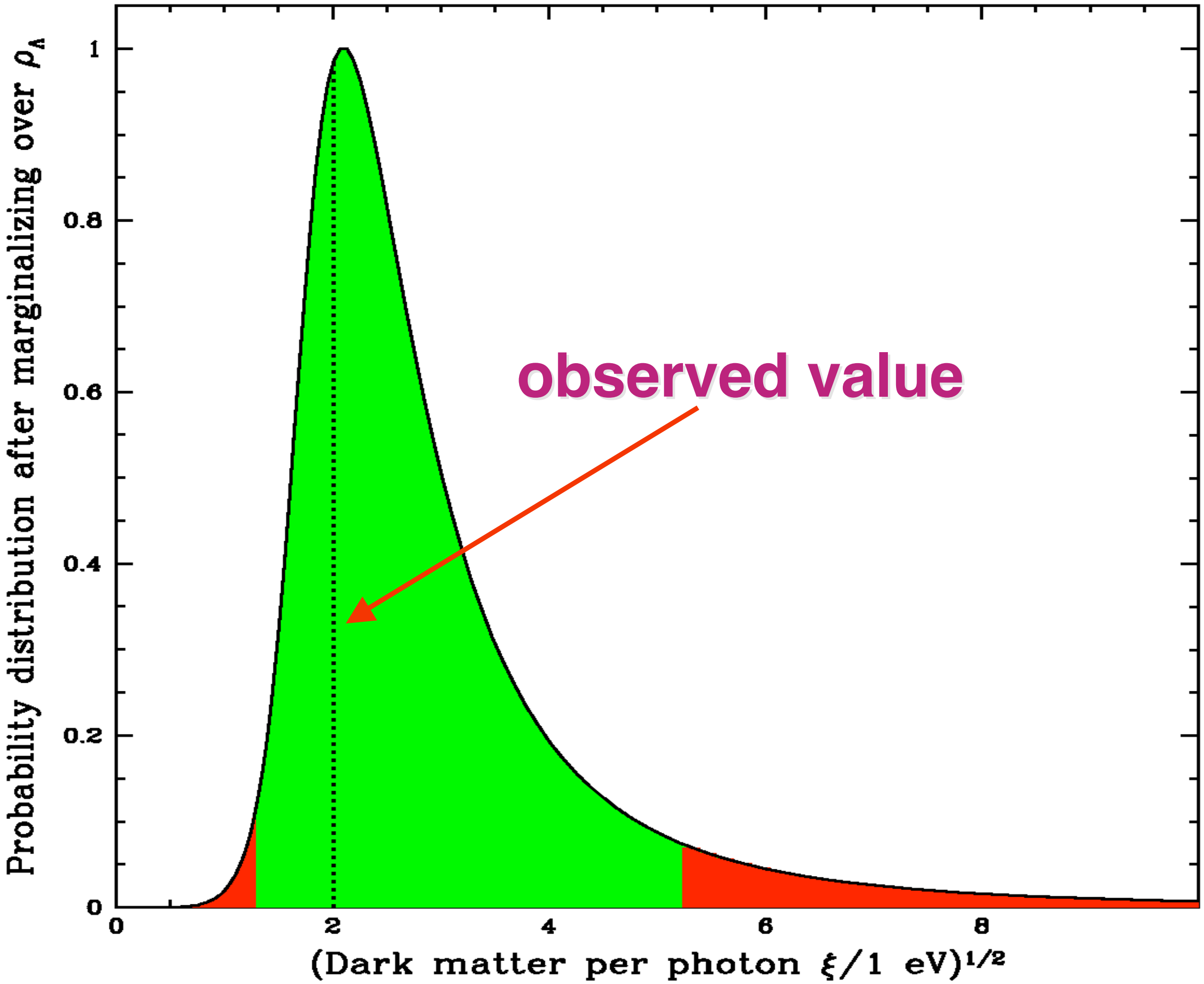
Can we give a scientific definition of "typical" ?

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).

This possibility was analyzed by Aguirre, Rees, Tegmark, and Wilczek.

Anthropic Constraints on Axion Dark Matter

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



observed value

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

One of the arguments in favor of light supersymmetric particles to be discovered at LHC is the possibility to explain the abundance of dark matter.

As we see now, the same goal can be achieved by axions violating the naïve bound $m_a > 10^{-5}$ eV.

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) <u>String theory landscape</u>

Multiplicity of (unstable) vacua:

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

Duff, 1986, 1987; Bousso, Polchinski 2000

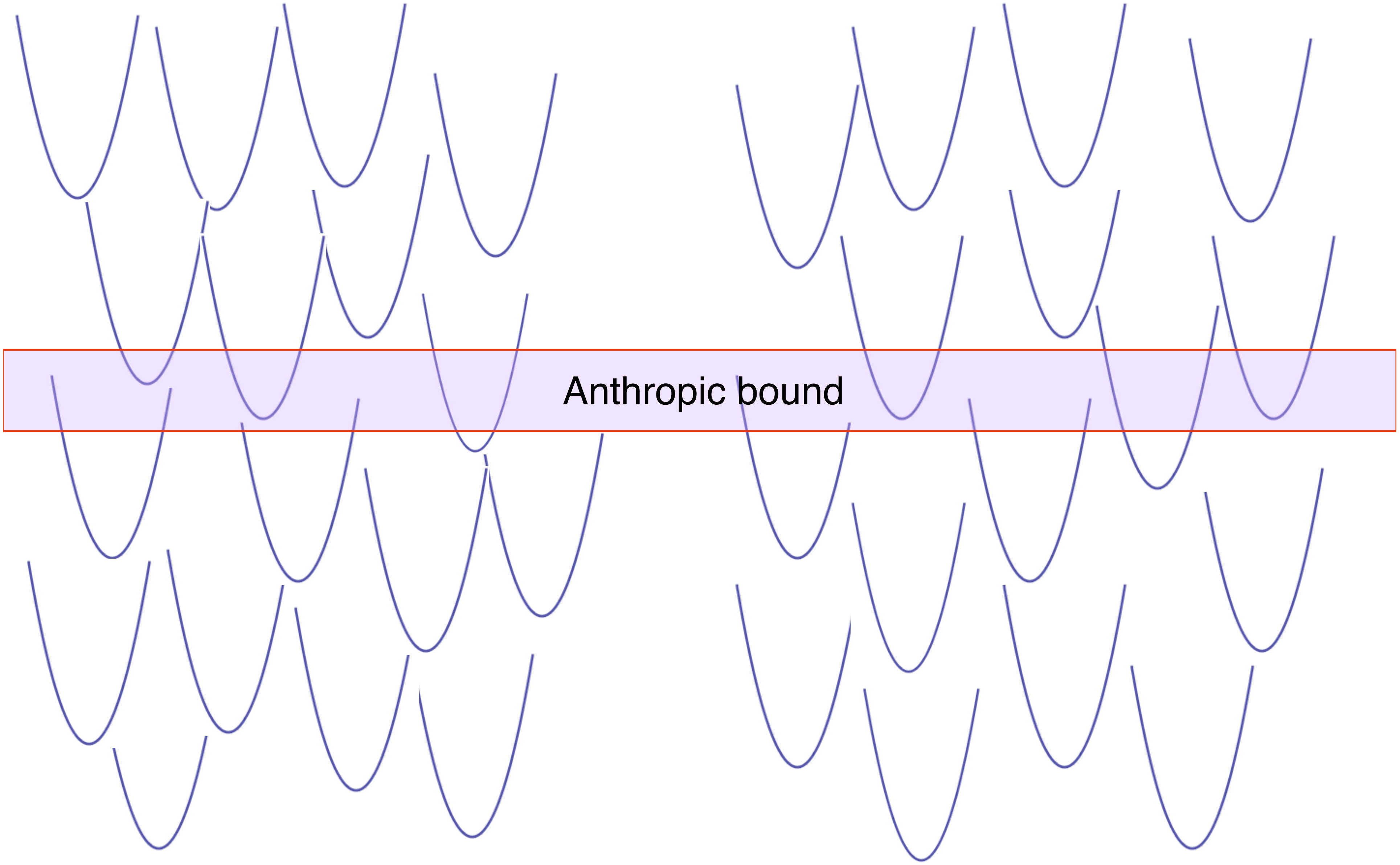
Vacuum stabilization and statistics:

KKLT 2003, Susskind 2003, Douglas 2003,…

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

4) <u>Counting probabilities in an eternally inflating universe</u> (more about it later)

Anthropic constraints on Λ: The main idea



Before quantum corrections

After quantum corrections

Volume-weighted probabilities and the landscape

Clifton, Shenker, Sivanandam, arXiv:0706:3201

Assumption: Volume-weighted probability measure, A.L., arXiv:0705.1160.

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.

This model shows in a more detailed way how one can solve the CC problem in the string landscape scenario.

It also demonstrates that the observable properties of our world and its fate may depend on the mechanism of the population of the landscape during eternal inflation.

Conclusions:

There is an ongoing progress in implementing inflation in supergravity and string theory.

String theory can describe the cosmological constant, but quintessence does not come easy.

CMB can help us to test string theory. If inflationary tensor modes are discovered, we may need to develop a new class of stringy models, or phenomenological models with superheavy gravitino.

One may like or dislike the present stage of the development of science. However, it seems that we have only two possibilities:

We must either propose something better than inflationary cosmology and string theory in its present form, or learn how to use the theory of an inflationary multiverse and the string landscape scenario to make probabilistic predictions.