Inflationary cosmology

Andrei Linde

Problems of the Big Bang theory:

What was before the Big Bang?

Why is our universe so **homogeneous** ?

Why is it **isotropic** ?

Why its parts started expanding simultaneously?

Why is it **flat**? Why parallel lines do not intersect?

Why is the universe so **large and heavy**? Why does it contain so many particles and has such a **large entropy**?

Example: Total mass of the Universe

The total energy of radiation in the universe now is greater than **10^{53} g**. The total number of photons in the universe practically did not change during its evolution, but the energy of each photon decreased as the temperature of the universe T.

The standard description of the universe becomes possible at the Planck time, when T was 10^{32} times greater than now. Therefore at that time the energy of radiation was greater than $10^{53} \times 10^{32}$ = **10^{85} g**

So before the Big Bang there was NOTHING, and then suddenly we got A HUGE AMOUNT OF ENERGY

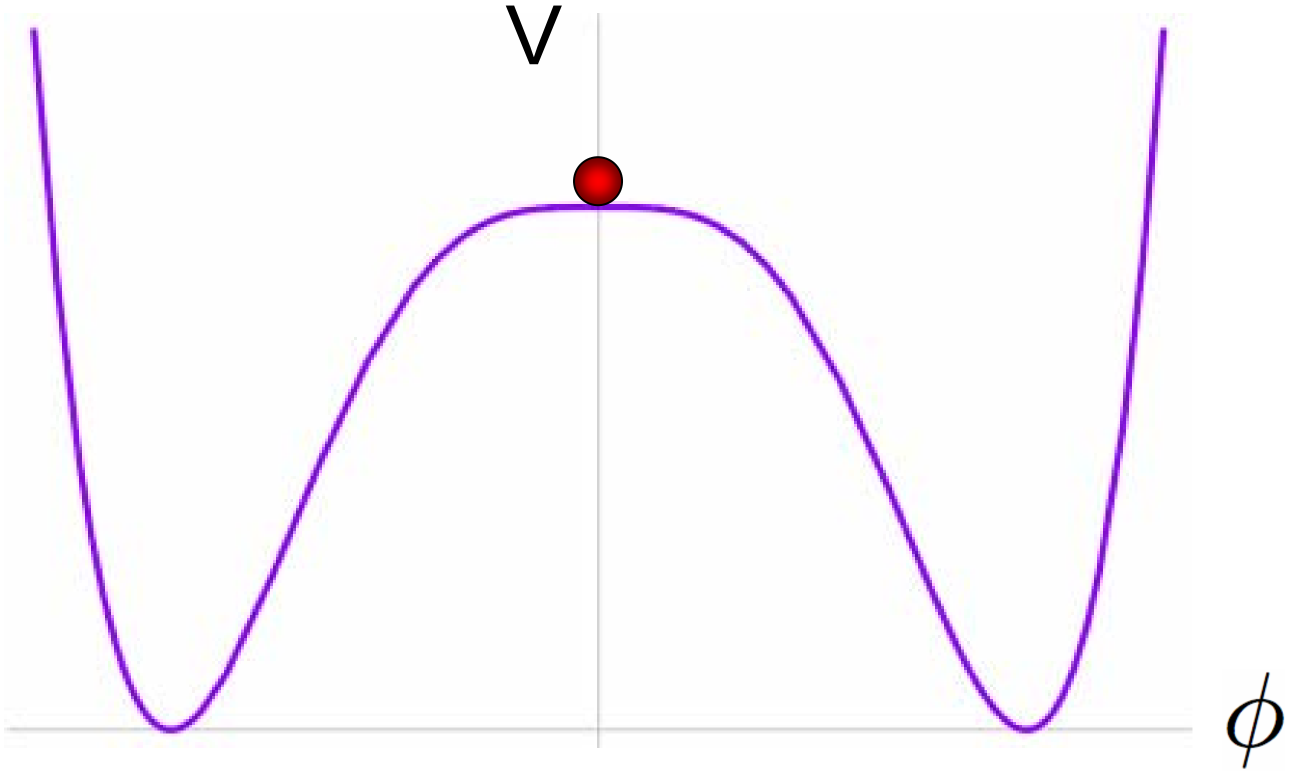
Where did it come from?

Inflationary theory

solves many problems of the old Big Bang theory, and explains how the universe could be created from <u>less than one milligram of matter</u>

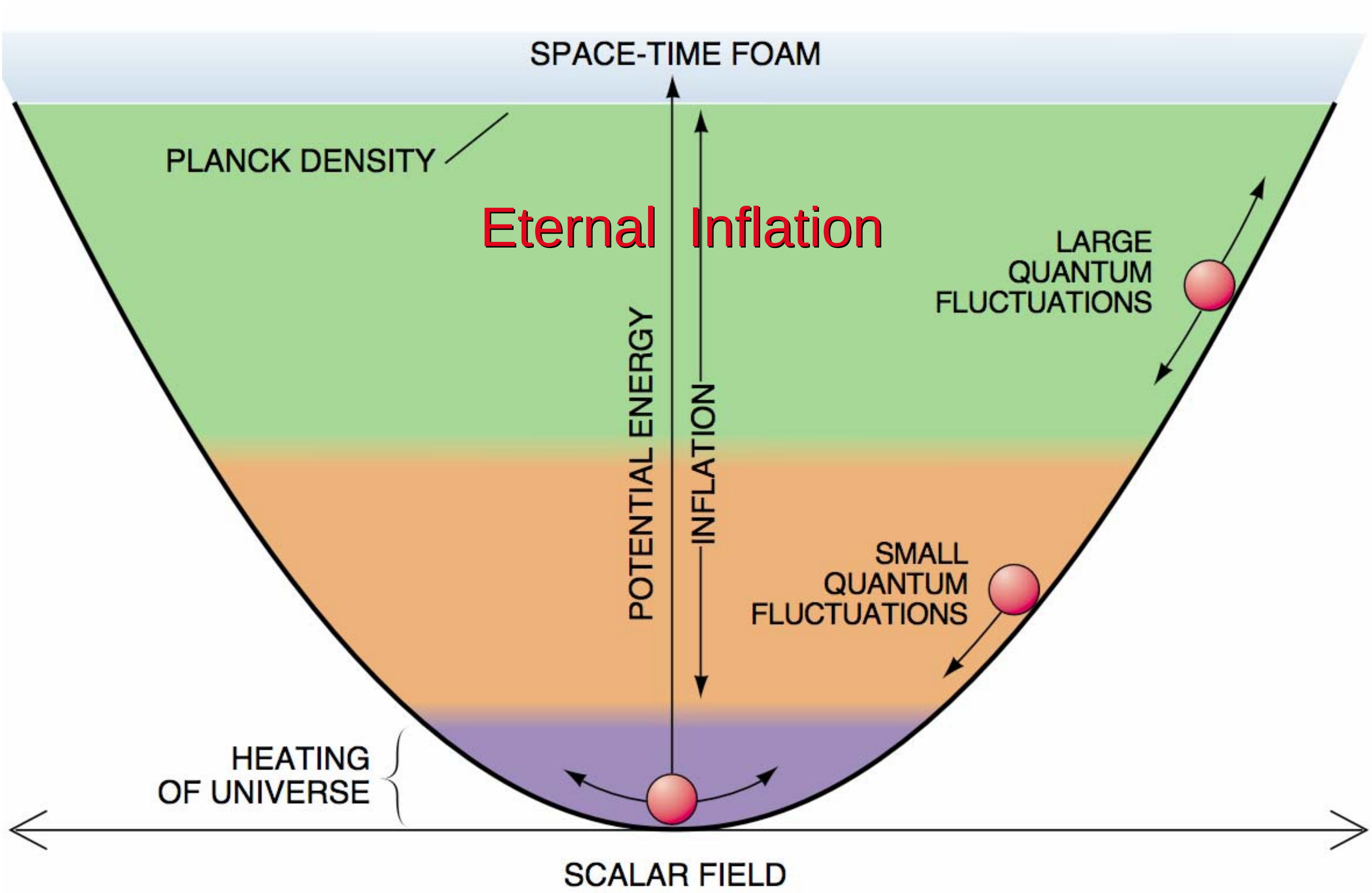
New Inflation

$$V = g^4 \left(\phi^4 \ln \phi - \phi^4/4 + 1/4 \right)$$



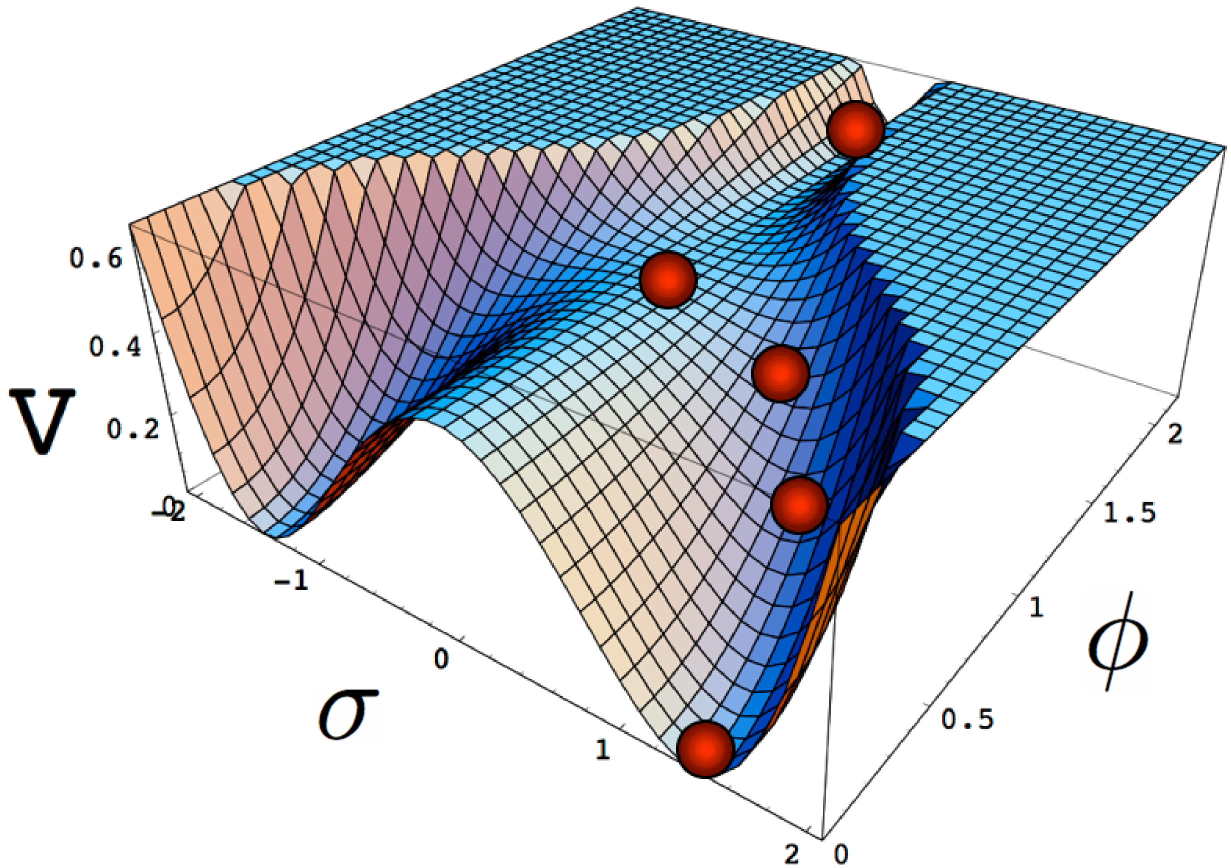
Chaotic Inflation

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



Hybrid Inflation

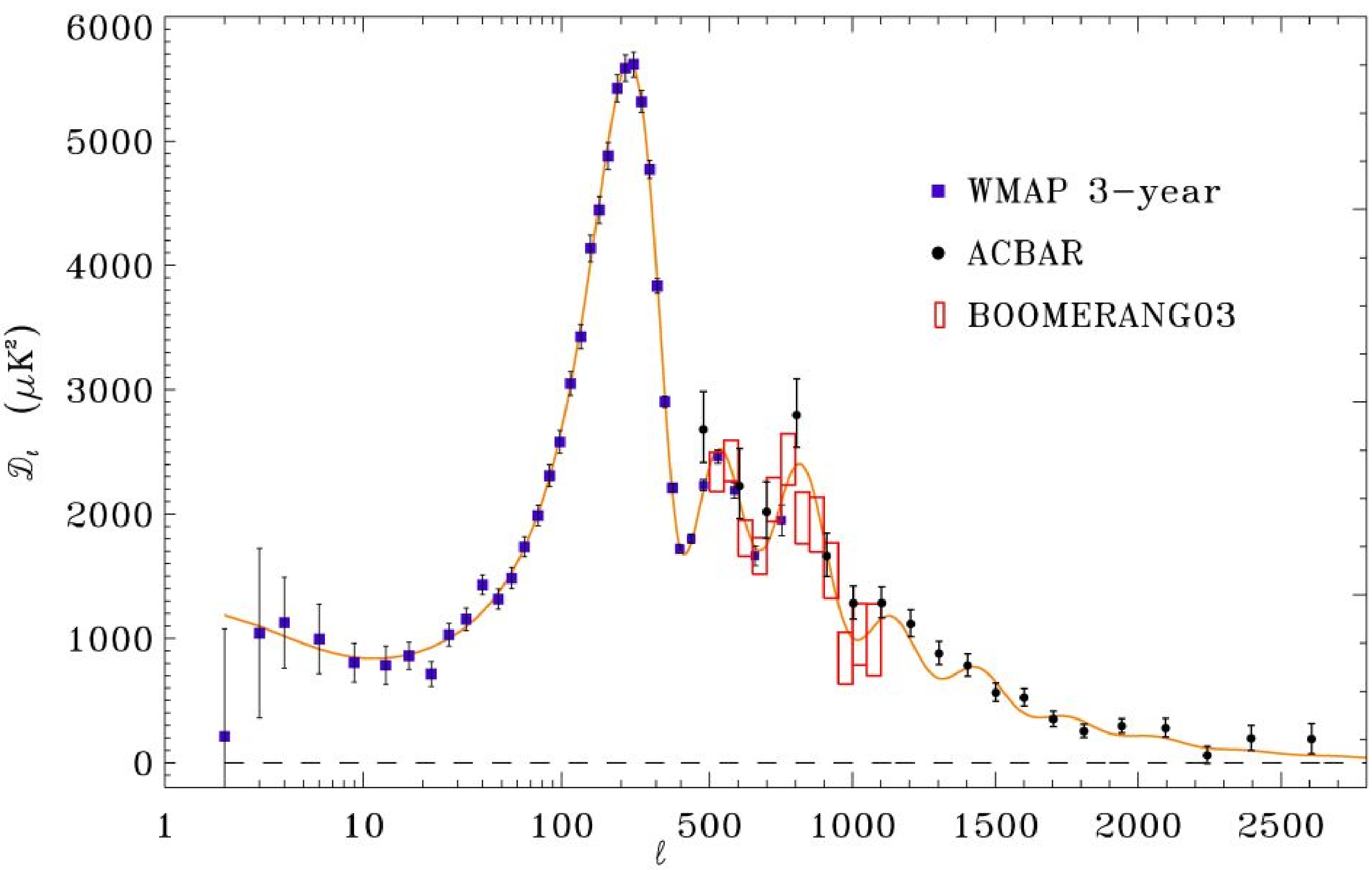
$$V(\sigma, \phi) = \frac{1}{4\lambda}(M^2 - \lambda\sigma^2)^2 + \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\sigma^2$$



CMB and Inflation

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

Pink 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: the universe is homogeneous, isotropic and flat, $\Omega = 1 + O(10^{-2})$

2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-1})$

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

Potential problems:

1) Suppression of anisotropy at low ℓ

Not a real problem (a talk by Lyman Page), but even if it were a problem, all proposed solutions are based on inflationary cosmology.

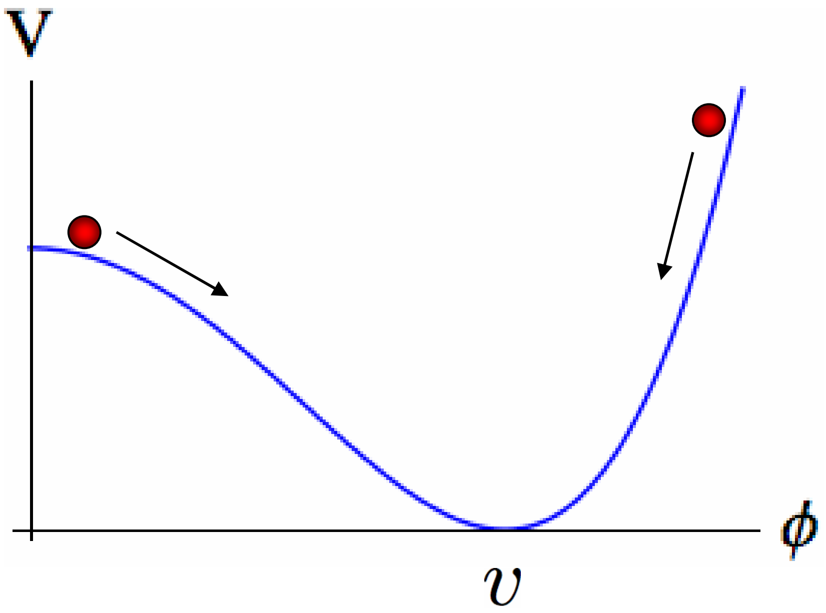
2) Correlations between $\ell = 2$ and $\ell = 3$

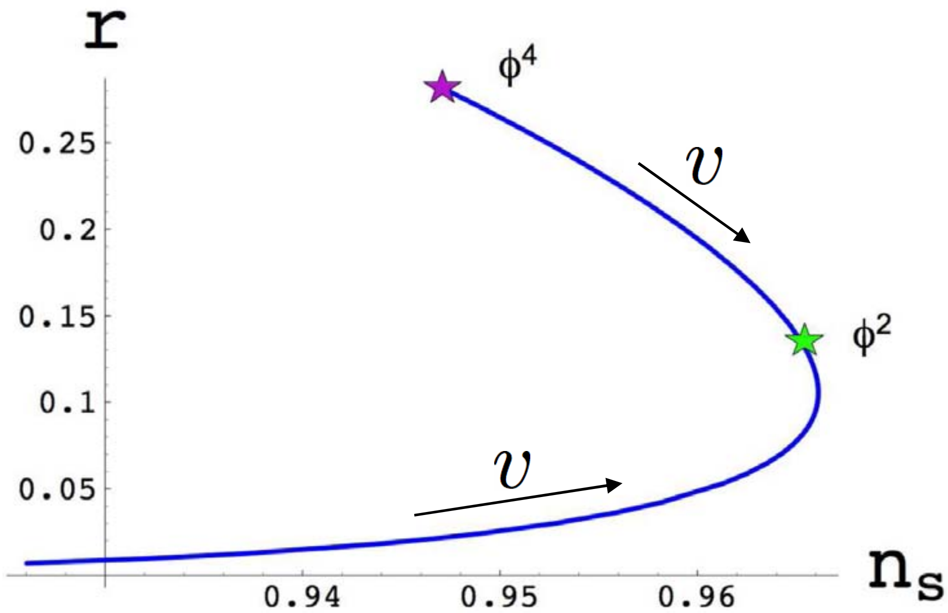
So far, all proposed solutions are based on inflationary cosmology, with some additional ingredients. For example, one may consider effects due to domain walls formed after inflation, corresponding to spontaneous symmetry breaking on MeV scale (few walls per horizon).

Tensor modes:

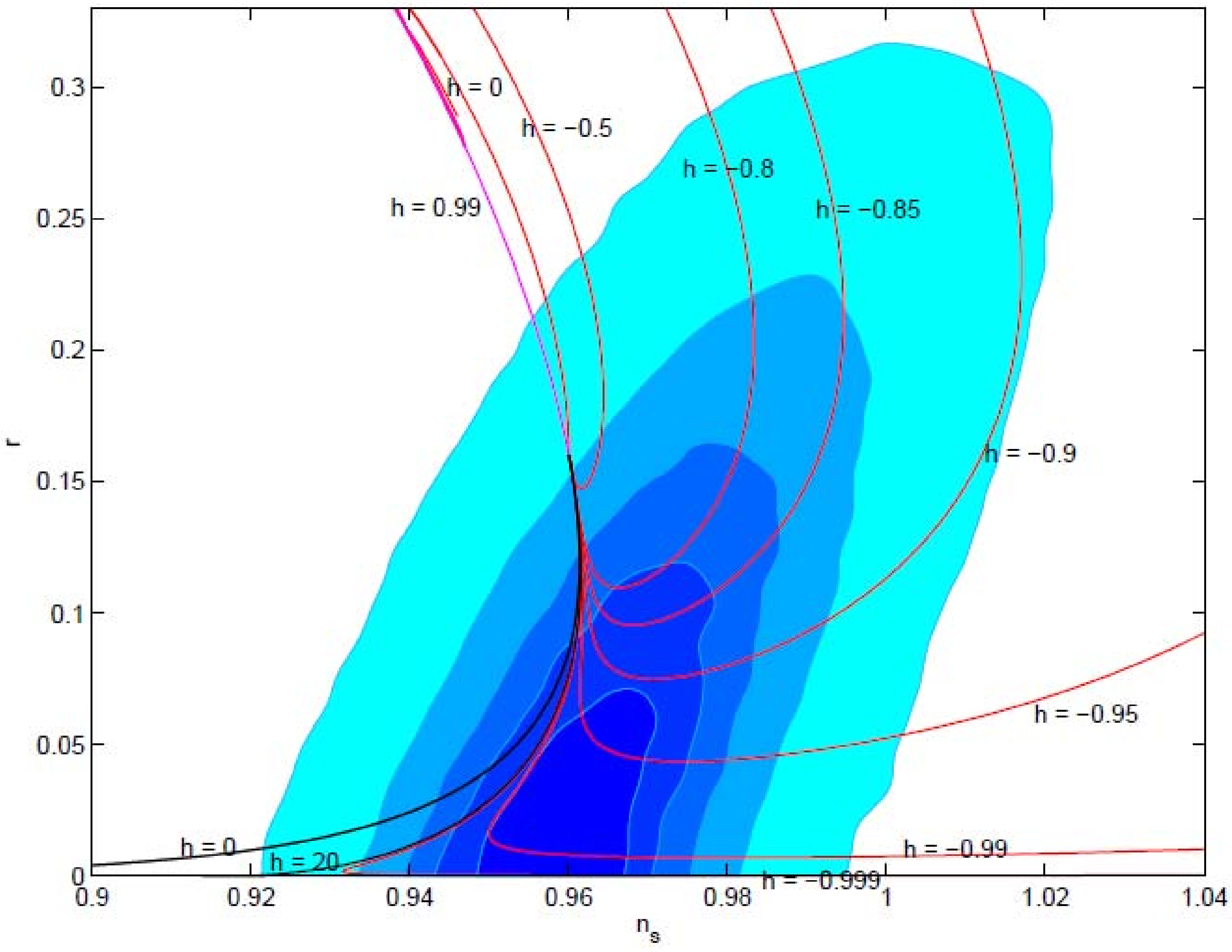
$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

Kallosh, A.L. 2007





It <u>does</u> make sense to look for tensor modes even if none are found at the level r ~ 0.1 (Planck)



Destri, de Vega, Sanchez, 2007

Possible values of r and n_s for chaotic inflation with a potential including terms ϕ^2, ϕ^3, ϕ^4 for N = 50. The color-filled areas correspond to various confidence levels according to the WMAP3 and SDSS data.

Alternatives: Ekpyrotic/cyclic scenario

Singularity problem remains unsolved after many years of attempts and optimistic announcements.

Recent developments: “New ekpyrotic scenario” based on the ghost condensate theory with the curvaton heart.

Even the authors of the ghost condensate theory dislike it: violation of the null energy condition, absence of the ultraviolet completion, problems with black hole thermodynamics, etc.

But there are other problems. For example, generation of density perturbations with flat spectrum requires an additional field. At the stage of collapse, classical inhomogeneities of this field must be incredibly small, smaller that its quantum fluctuations. Otherwise classical irregularities will be amplified, and dominate density perturbations.

This is a severe homogeneity problem, much worse than in the standard Big Bang theory.

Other alternatives: String gas cosmology

Brandenberger, Vafa, Nayeri 2005-2006

Many loose ends and unproven assumptions (e.g. stabilization of the dilaton and of extra dimensions). Flatness problem is not solved. The class of models studied there differs from the only class of stringy models (KKLT) where stabilization of all moduli was achieved.

Even if one ignores all of these issues, the perturbations generated in these models are very non-flat:

Instead of $n_s = 1$ one finds $n_s = 5$

Kaloper, Kofman, Linde, Mukhanov 2006, hep-th/0608200

Brandenberger et al, 2006

Towards realistic string cosmology

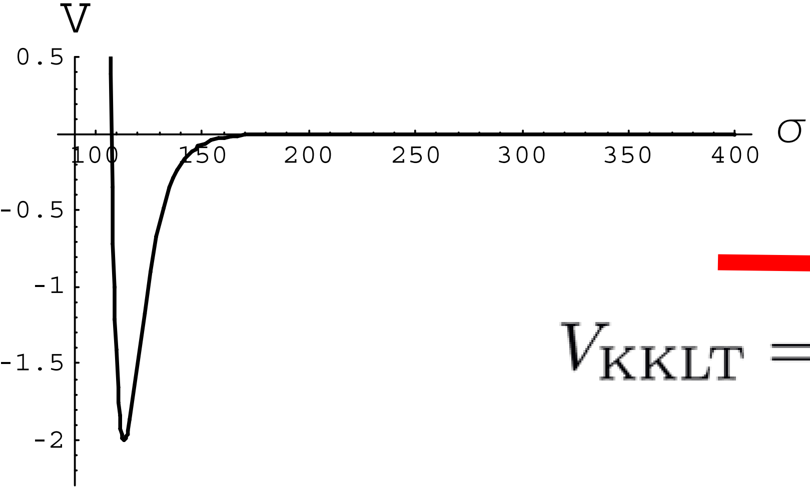
Dilaton stabilization: Giddings, Kachru, Polchinski 2001

Volume Stabilization: Kachru, Kallosh, A.L., Trivedi 2003

Basic steps of the KKLT scenario:

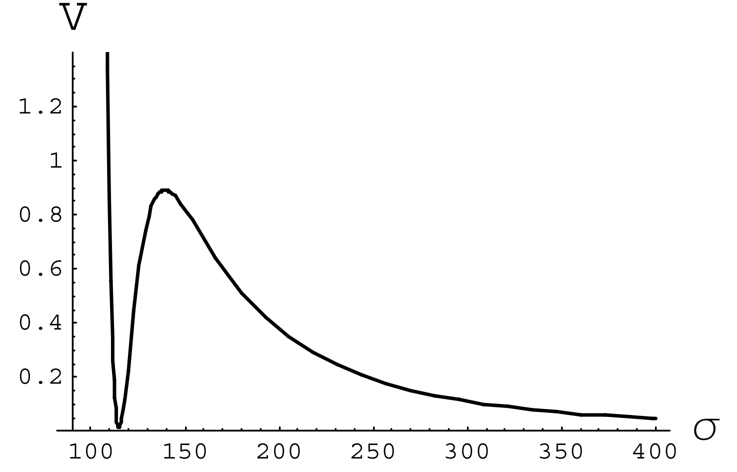
1) Bend the volume modulus potential down due to nonperturbative quantum effects

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



AdS minimum

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



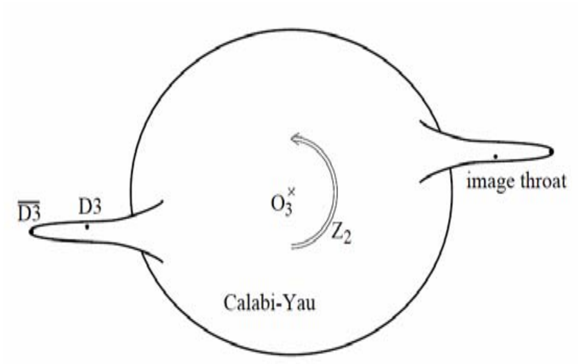
Metastable dS minimum

Two types of string inflation models:

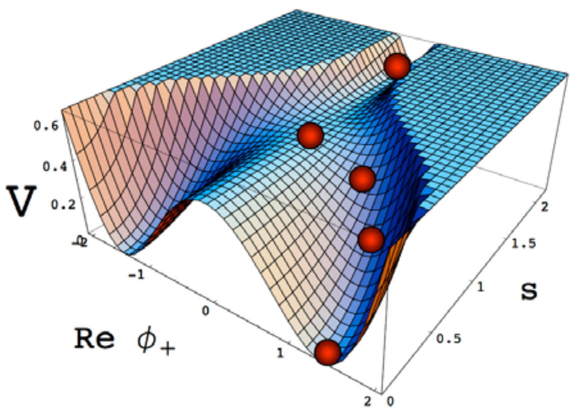
Modular Inflation. The simplest class of models. They use only the fields that are already present in the KKLT model.

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.

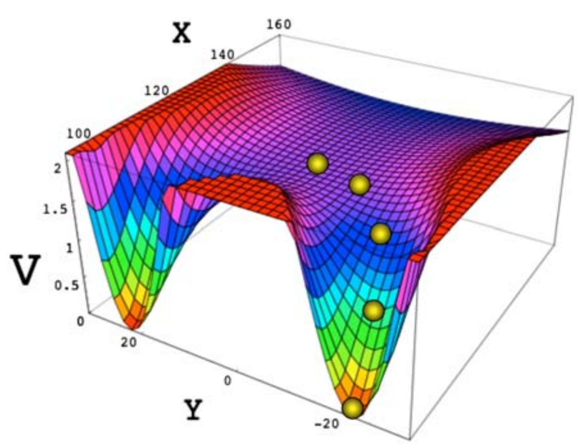
Inflation in string theory



KKLMMT brane-anti-brane inflation



D3/D7 brane inflation



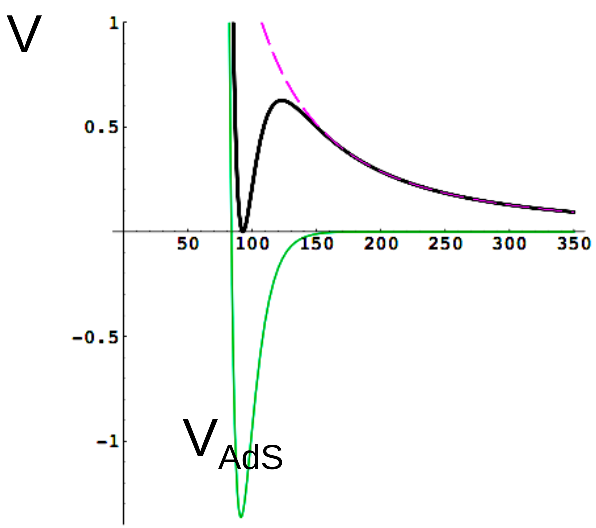
Racetrack modular inflation

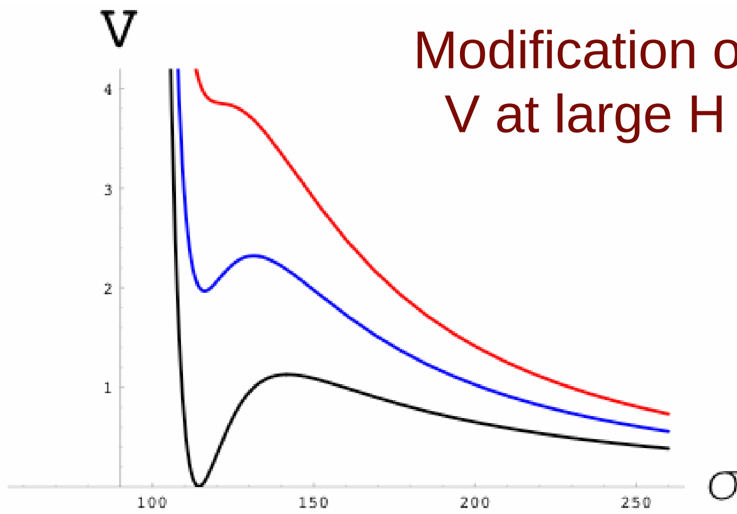
DBI inflation (non-minimal kinetic terms)

STRING COSMOLOGY AND 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

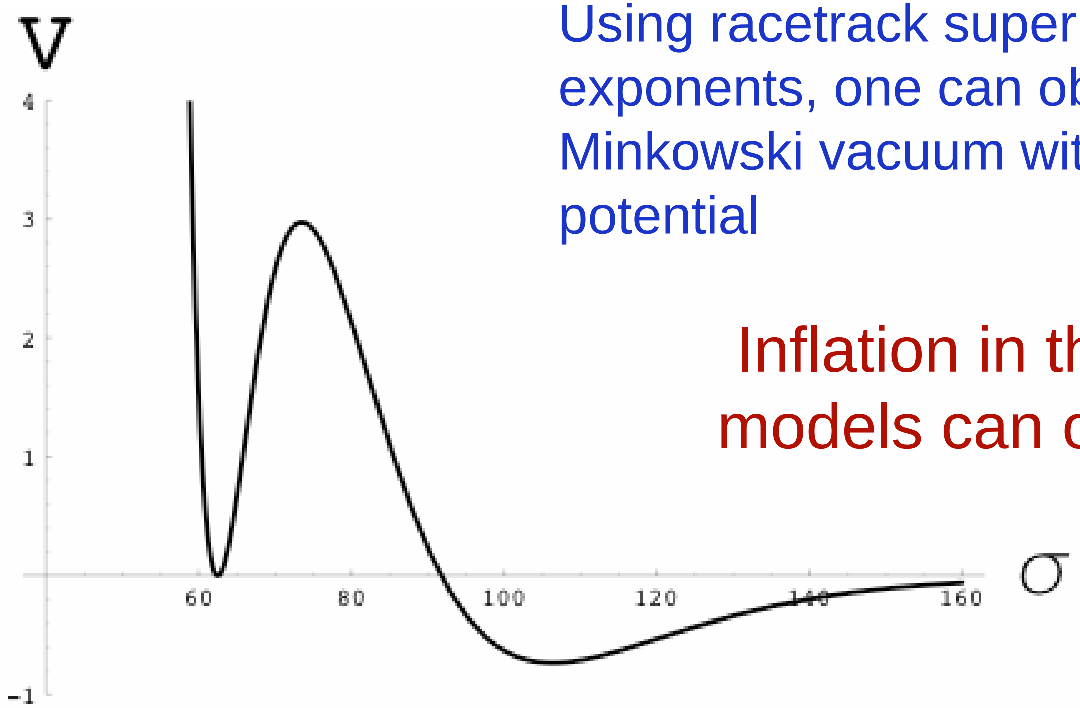
$$V_{\mathrm{AdS}} = -3\, e^K |W^2| = -3\, m^2_{3/2}$$

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

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

KL model

Kallosh, A.L. hep-th/0411011

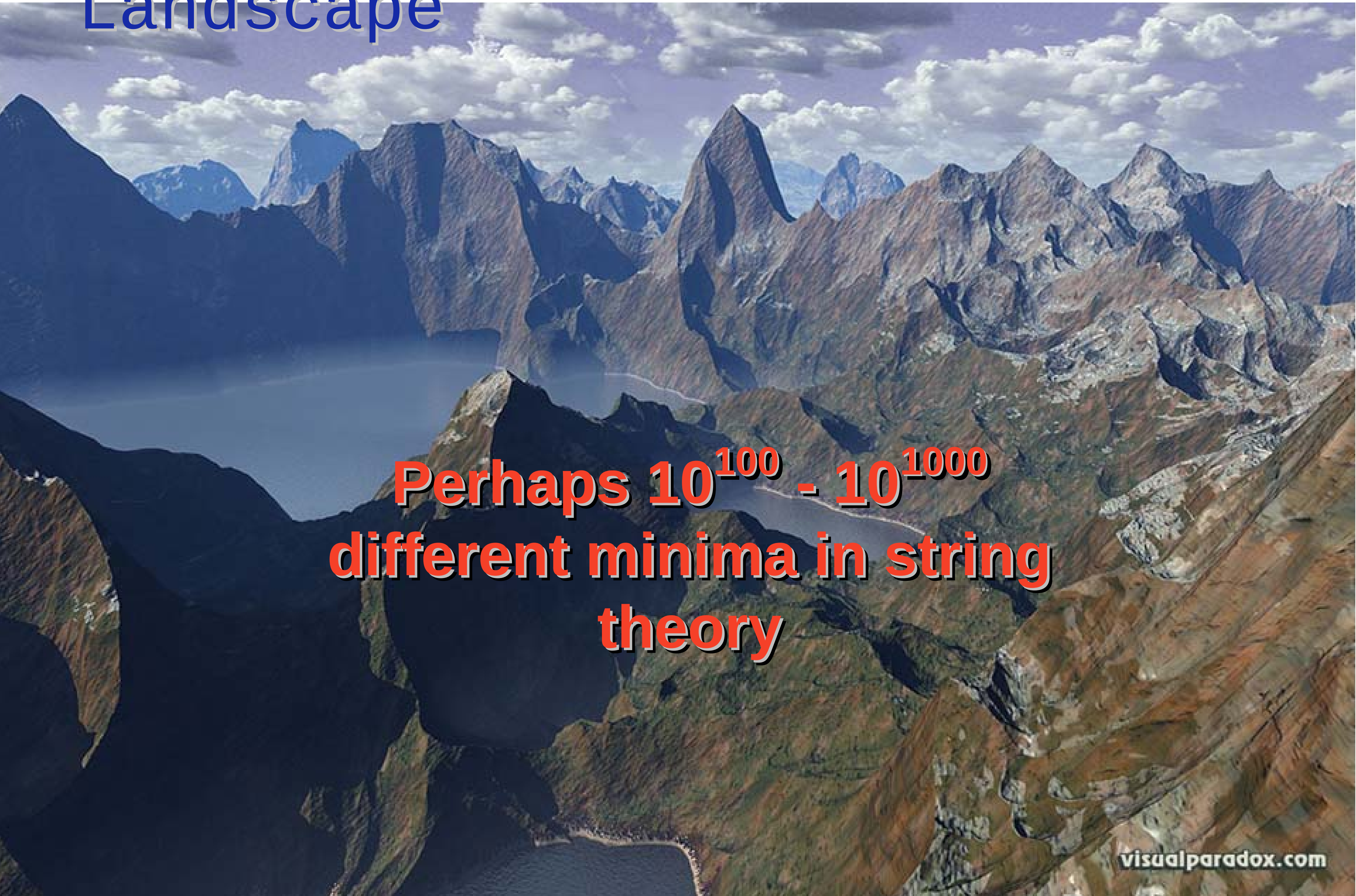


Using racetrack superpotential with two exponents, one can obtain a supersymmetric Minkowski vacuum without any uplifting of the potential

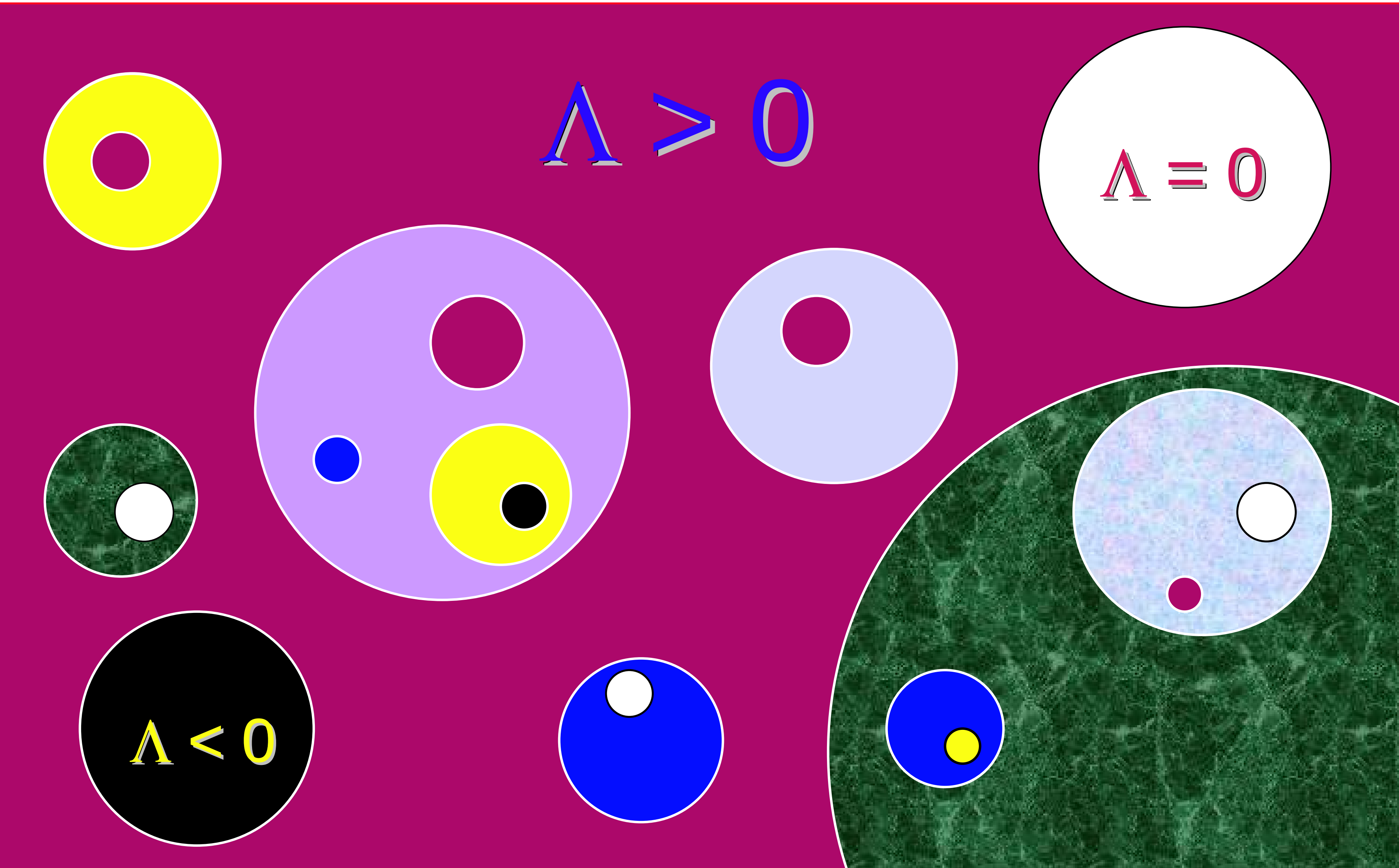
Inflation in this class of KKLT models can occur at $H >> m_{3/2}$

Small mass of gravitino, no correlation with the height of the barrier and with the Hubble constant during inflation

String Theory Landscape



Let 10^{1000} flowers blossom



Probabilities in the Landscape

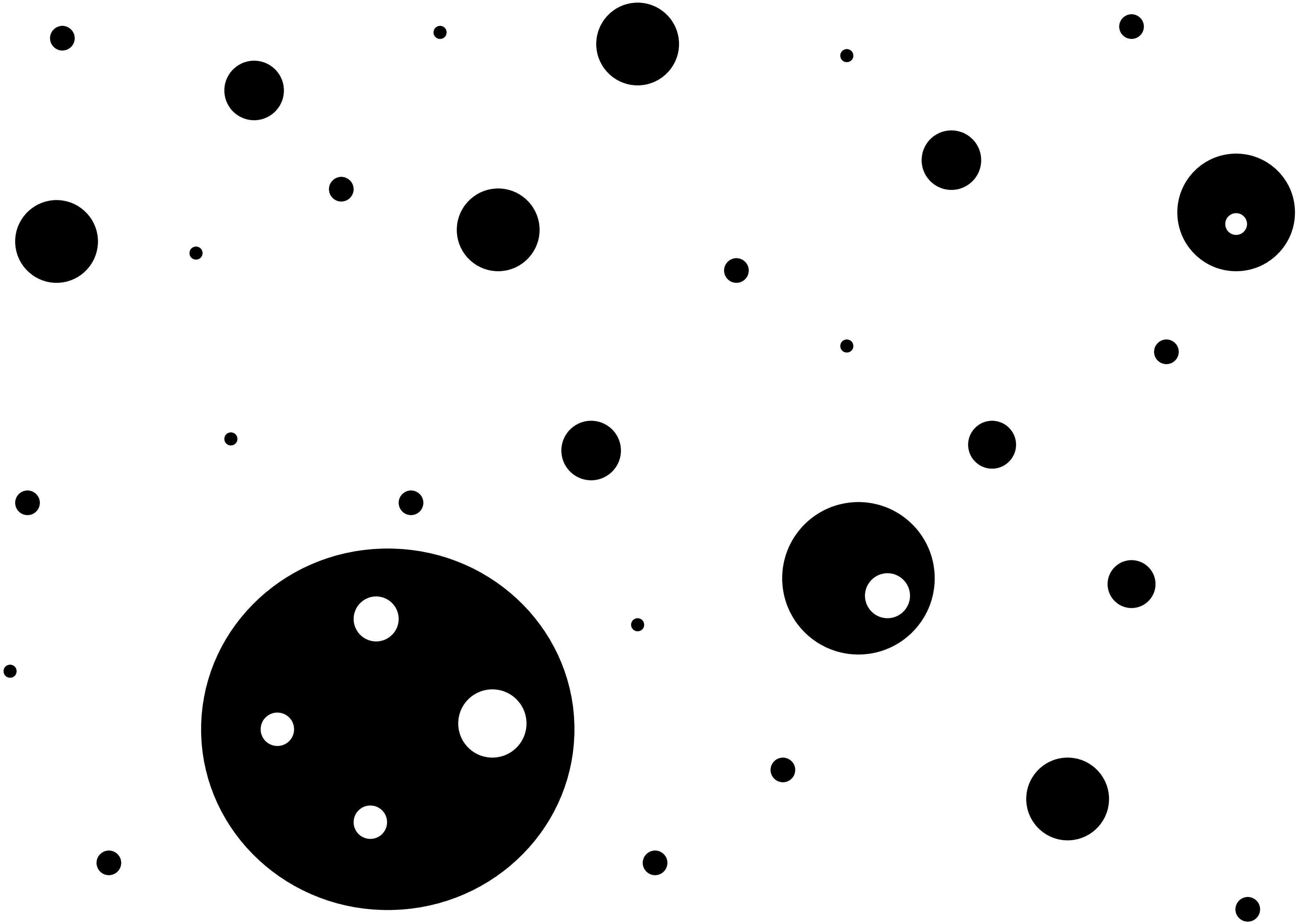
We must find all possible vacua (statistics), and all possible continuous parameters (out-of-equilibrium cosmological dynamics).

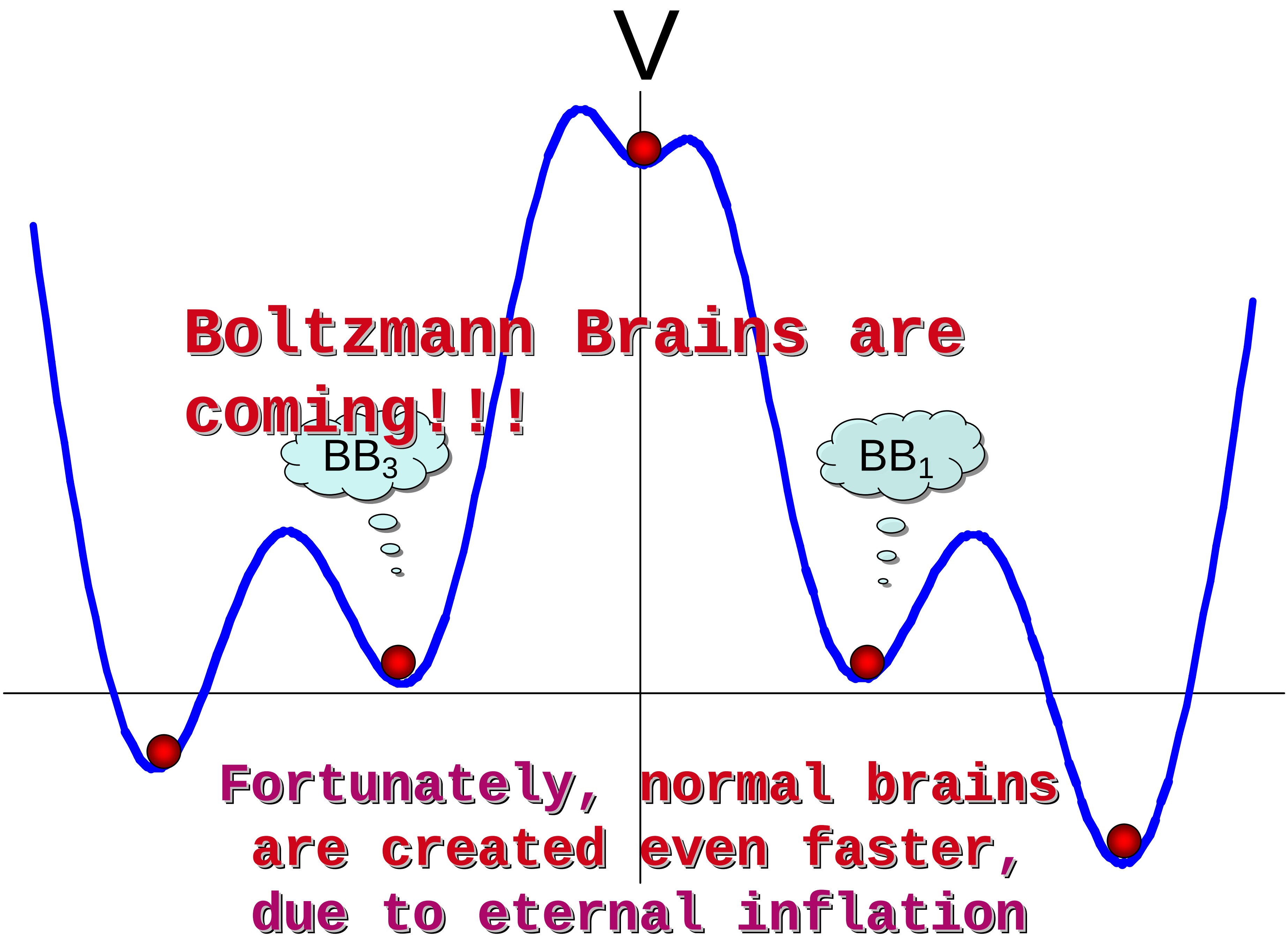
Douglas 2003

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

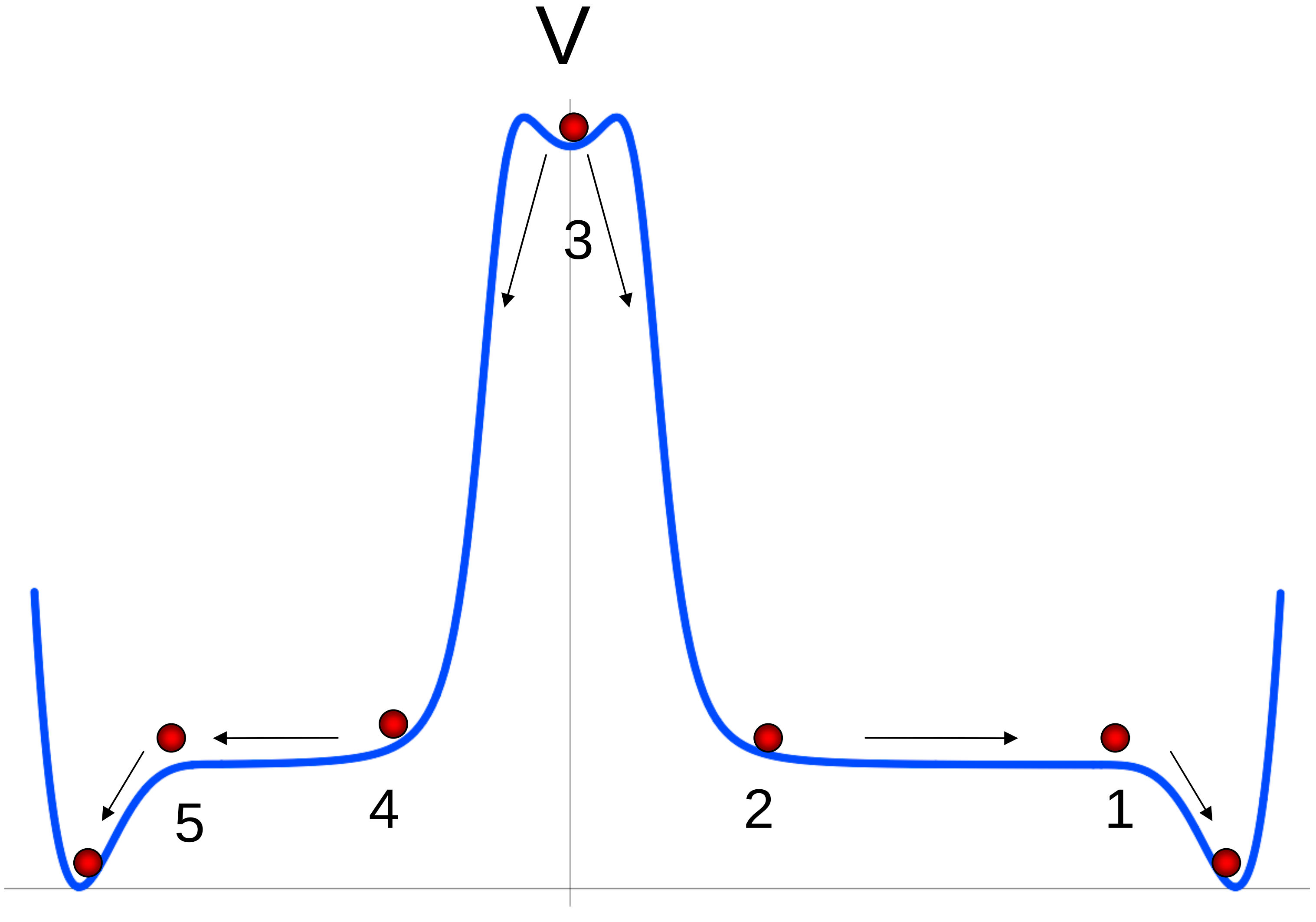
A.Linde, D.Linde, Mezhlumian, Bellido 1994;

Vilenkin 1995; Garriga, Schwarz-Perlov, Vilenkin, Winitzki, 2005

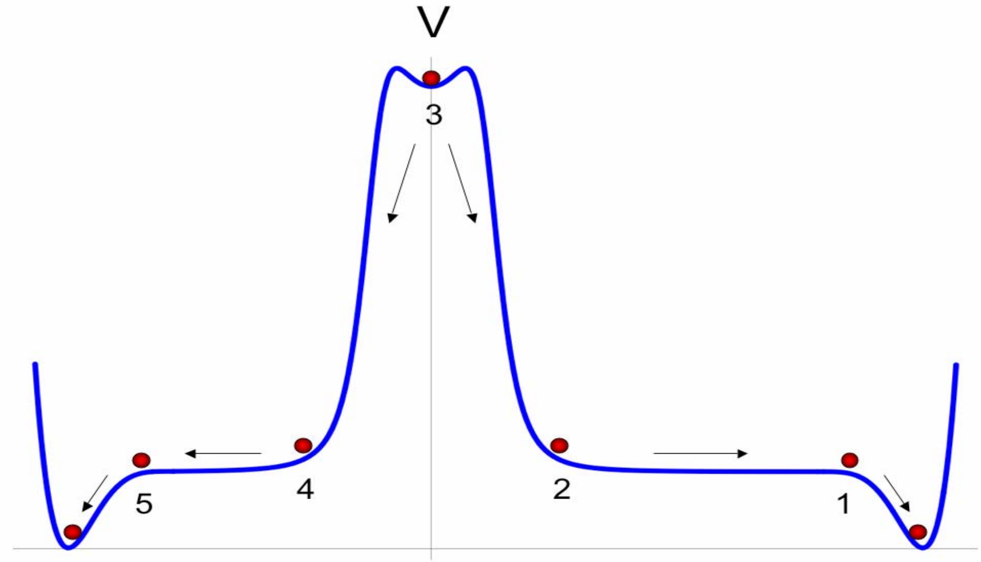



V
Boltzmann Brains are coming!!!
BB_3
BB_1
Fortunately, normal brains are created even faster, due to eternal inflation

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 $e^{H^\beta t}$



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

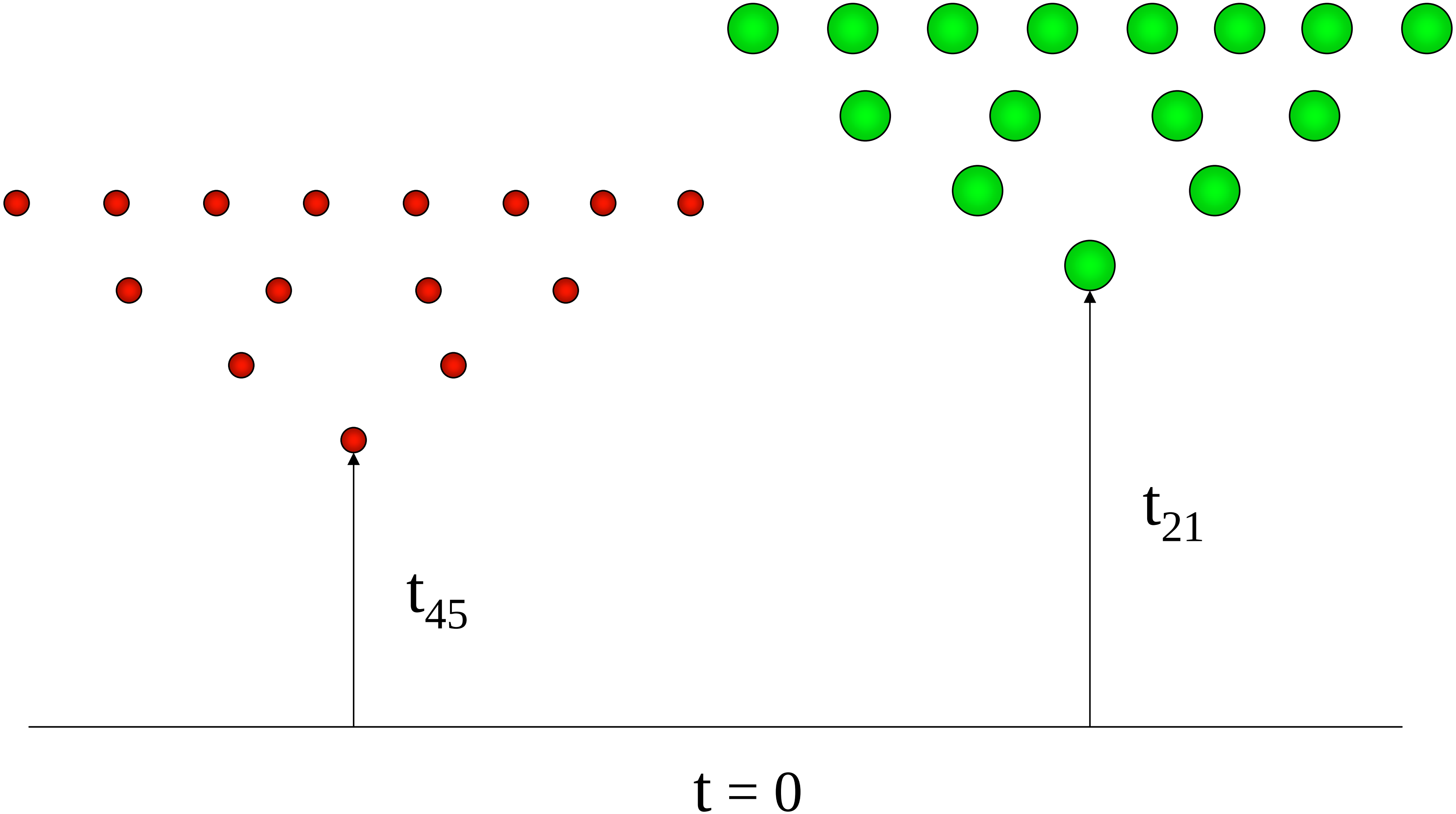
$$P(\phi_1, t) = P_3(0)\ \Gamma_{32}\ e^{3N_{21}}\ e^{3H_3^\beta (t - t_{21})}$$

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

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

The answer depends on the time parametrization.

This is suspicious…



We should compare the “trees of bubbles” not at the time when they were seeded, but at the time when they began to grow

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.

Conclusion

Long inflation creates lots of space populated by many observers like us. Even in the situations where inflation could seem improbable, the probability that we were born in an inflationary universe can be very large due to the exponential growth of volume during inflation.

A possible application: Chaotic inflation

$$V_0 + \frac{m^2}{2}\phi^2 + \frac{\lambda_n}{n}\phi^n + \frac{\xi}{2}R\phi^2$$

Naively, one could expect that each coefficient in this sum is O(1).
However, $|V_0| < 10^{-120}$, otherwise we would not be around.

A.L. 1984, Weinberg 1987

For a quadratic potential, one should have $m \sim 10^{-5}$ to account for the smallness of the amplitude of density perturbations $\delta_H \sim 10^{-5}$

Is there any reason for all other parameters to be small?
Specifically, we must have

$$\lambda_n \ll m^2 \qquad \xi \ll 1$$

A simple argument:

Suppose that the upper bound on the inflaton field is given by the condition that the potential energy is smaller than Planckian, $V < 1$. In addition, the effective gravitational constant should not blow up. In this case

$$\phi^2 < \min\{m^{-2}, \lambda_n{}^{-\frac{2}{n}}, \xi^{-1}\}$$

In these models the total growth of volume of the universe during inflation (ignoring eternal inflation, which will not affect the final conclusion) is

$$e^{\phi^2} < \exp\left[\min\{m^{-2}, \lambda_n{}^{-\frac{2}{n}}, \xi^{-1}\}\right]$$

For a purely quadratic model, the volume is proportional to

$$e^{1/m^2} \sim e^{10^{10}}$$

But for the theory $\lambda\phi^4, \quad \lambda \sim m^{-2}$ the volume is much smaller:

$$e^{\lambda^{-1/2}} \sim e^{1/m} \sim e^{10^5}$$

The greatest growth by a factor of $e^{10^{10}}$ occurs for

$$\lambda_n \ll m^n \qquad \xi \ll m^2$$

But in this case at the end of inflation, when

$$\phi \sim 1 \qquad R \sim m^2$$

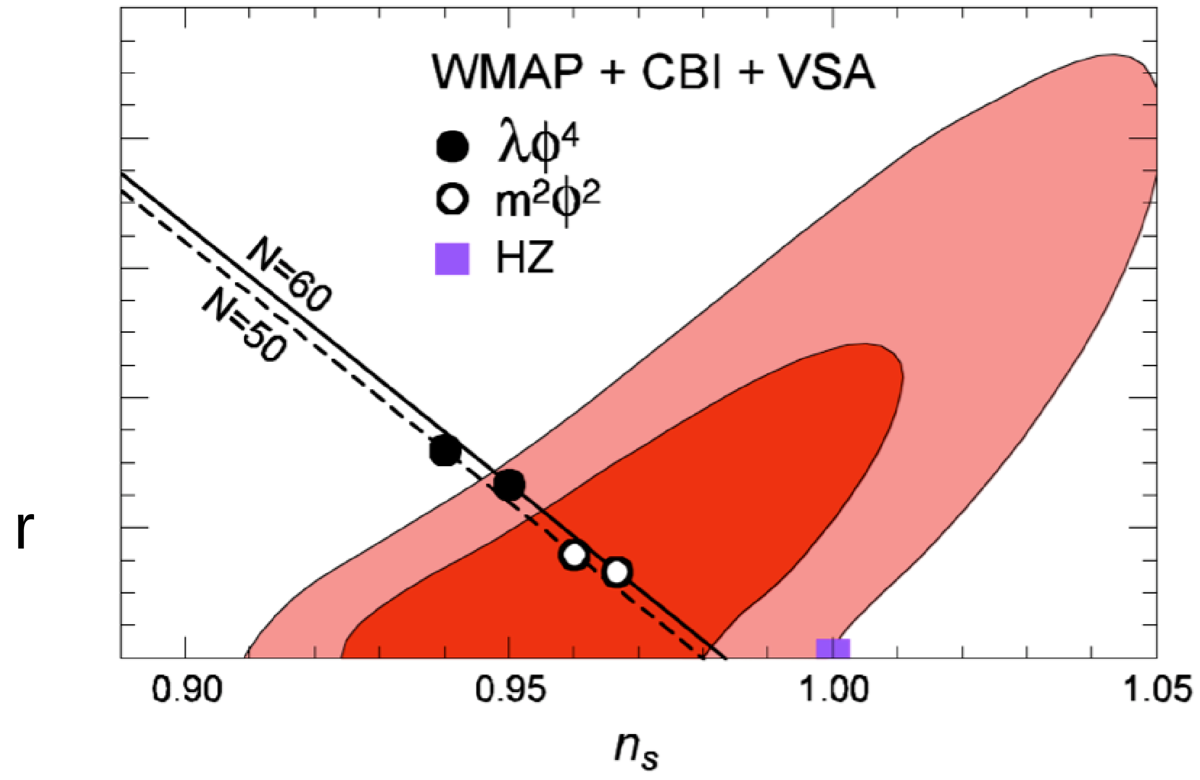
one has

$$\begin{aligned} V &= V_0 + \frac{m^2}{2}\phi^2 + O(m^n) + O(m^4) \\ &\approx V_0 + \frac{m^2}{2}\phi^2 \end{aligned}$$

Thus, if we have a choice of inflationary parameters (which is a big IF), then the simplest chaotic inflation scenario with a quadratic potential is the best.

This may explain why chaotic inflation is so simple: A power-law fine-tuning of the parameters gives us an exponential growth of volume, which is maximal for a purely quadratic potential

$$V = V_0 + \frac{m^2}{2}\phi^2$$



This should not be considered as a prediction, since we do not know yet how to obtain such a model in string theory. However, the fact that the simplest inflationary model has such an advantage is unexpected and very intriguing.