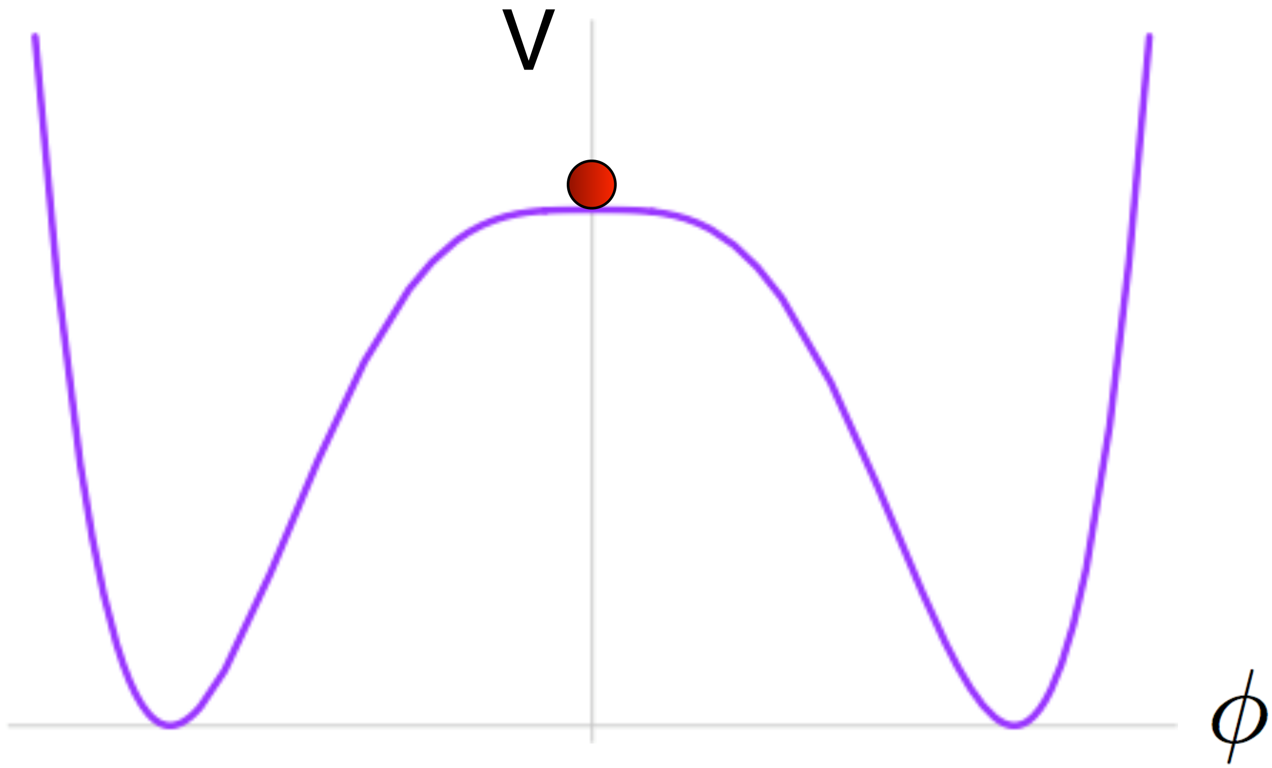
Aspects of Inflationary Theory

Andrei Linde

New Inflation

1981 - 1982

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

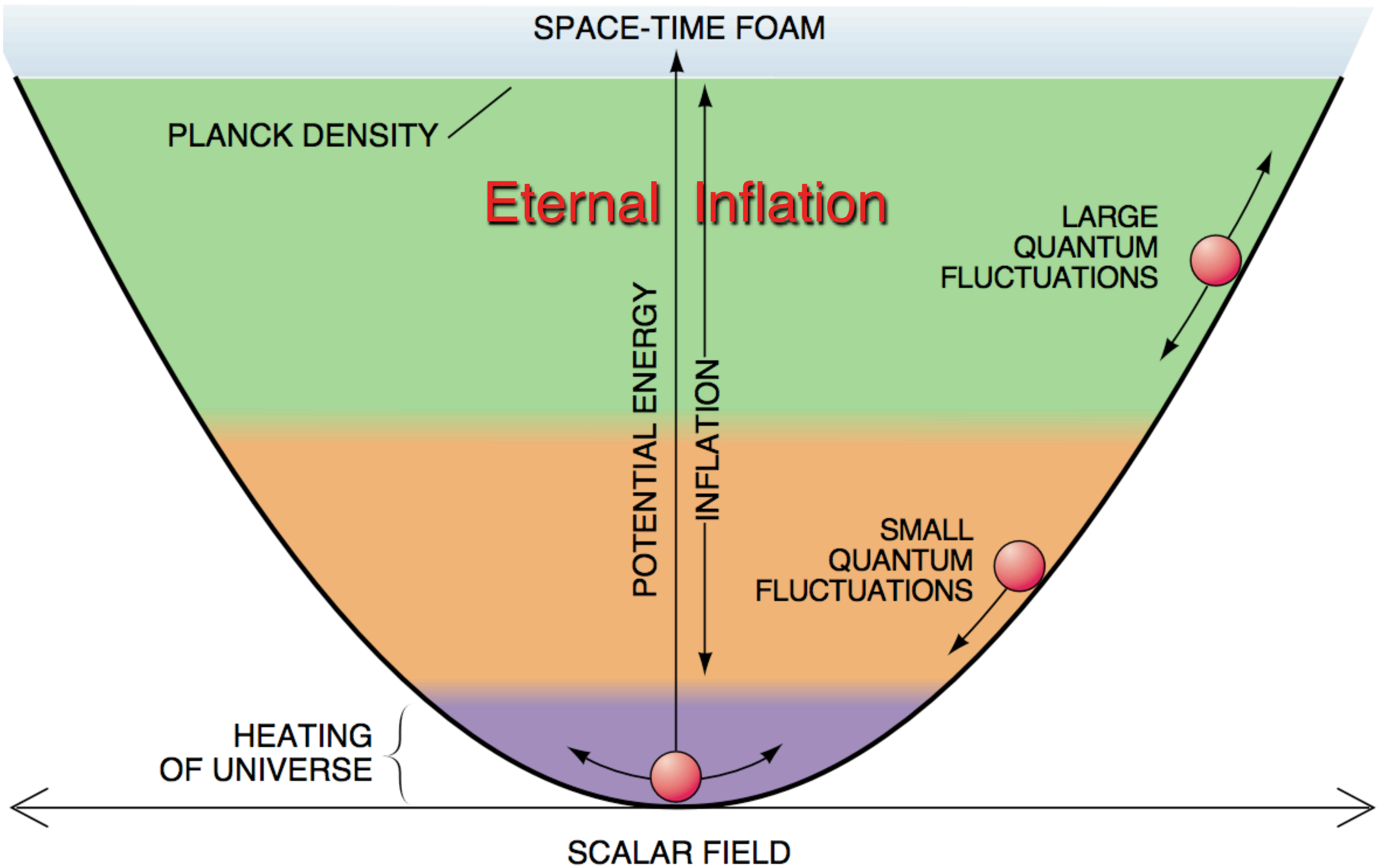



INFLATIONARY
UNIVERSE

Chaotic Inflation

1983

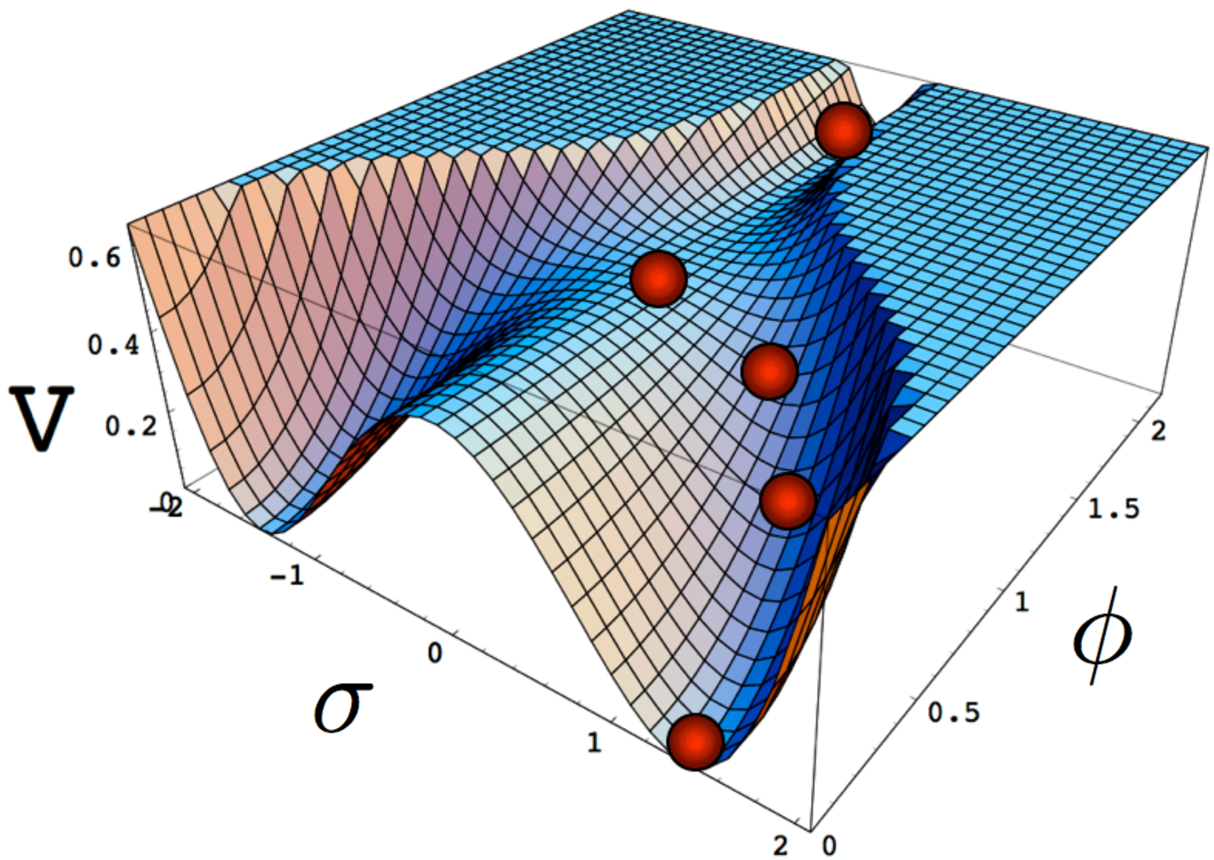
$$V(\phi) = \frac{m^2}{2}\phi^2$$



Hybrid Inflation

1991, 1994

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



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:

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

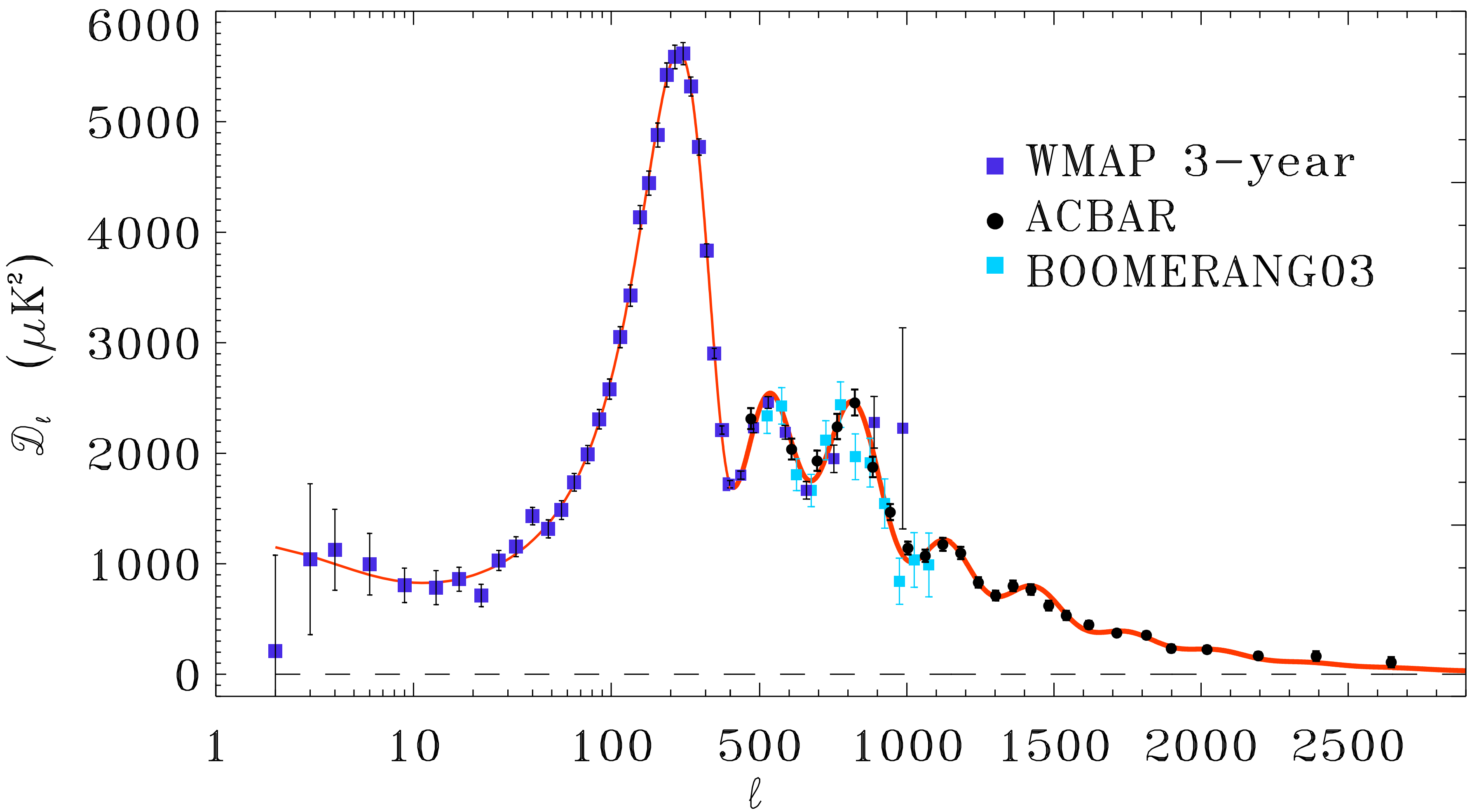
2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1+ O(10^{-1})$. Spectral index n_s slightly differs from 1. (This is an important prediction, similar to asymptotic freedom in QCD.)

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

CMB and Inflation

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

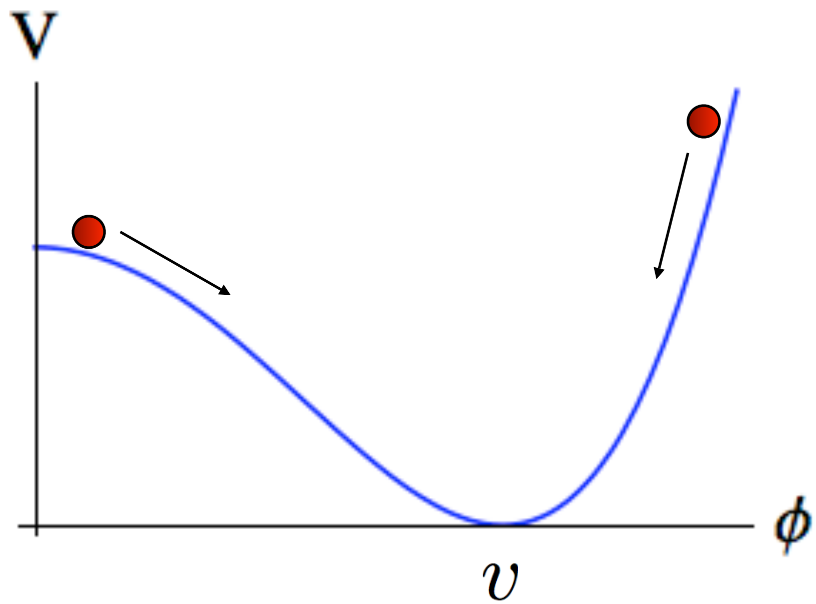
Red line - predictions of inflationary theory

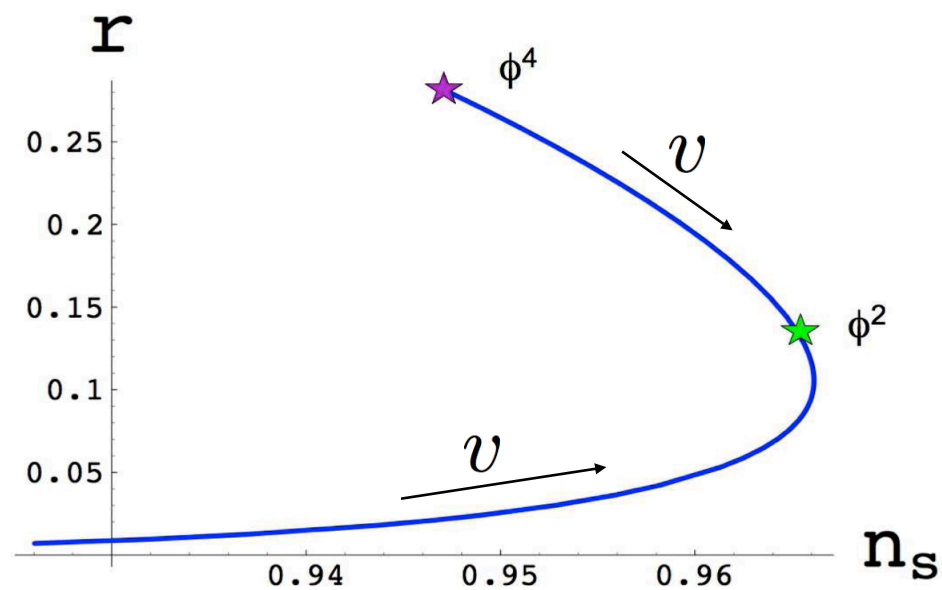


Tensor modes:

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

Kallosh, A.L. 2007





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

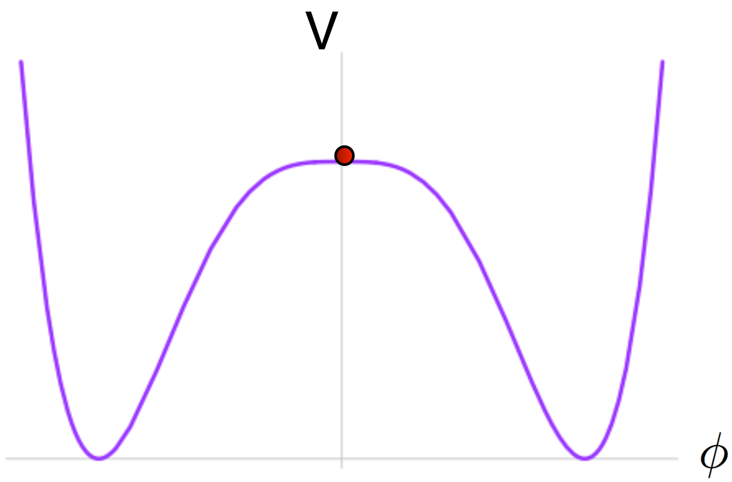
All well studied versions of inflation in string theory predict r << 0.01, but larger r might be possible.

Can we have large nongaussianity ?

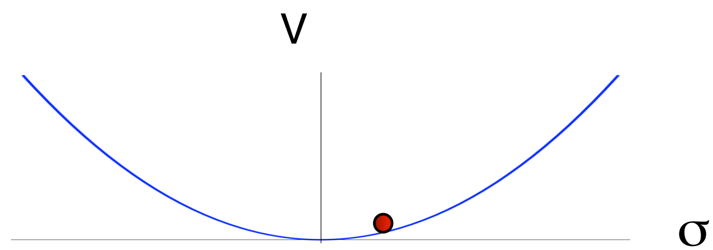
A.L., Mukhanov, 1996,

Lyth, Wands, Ungarelli, 2002

Lyth, Wands, Sasaki and collaborators - many papers up to 2007



Inflaton



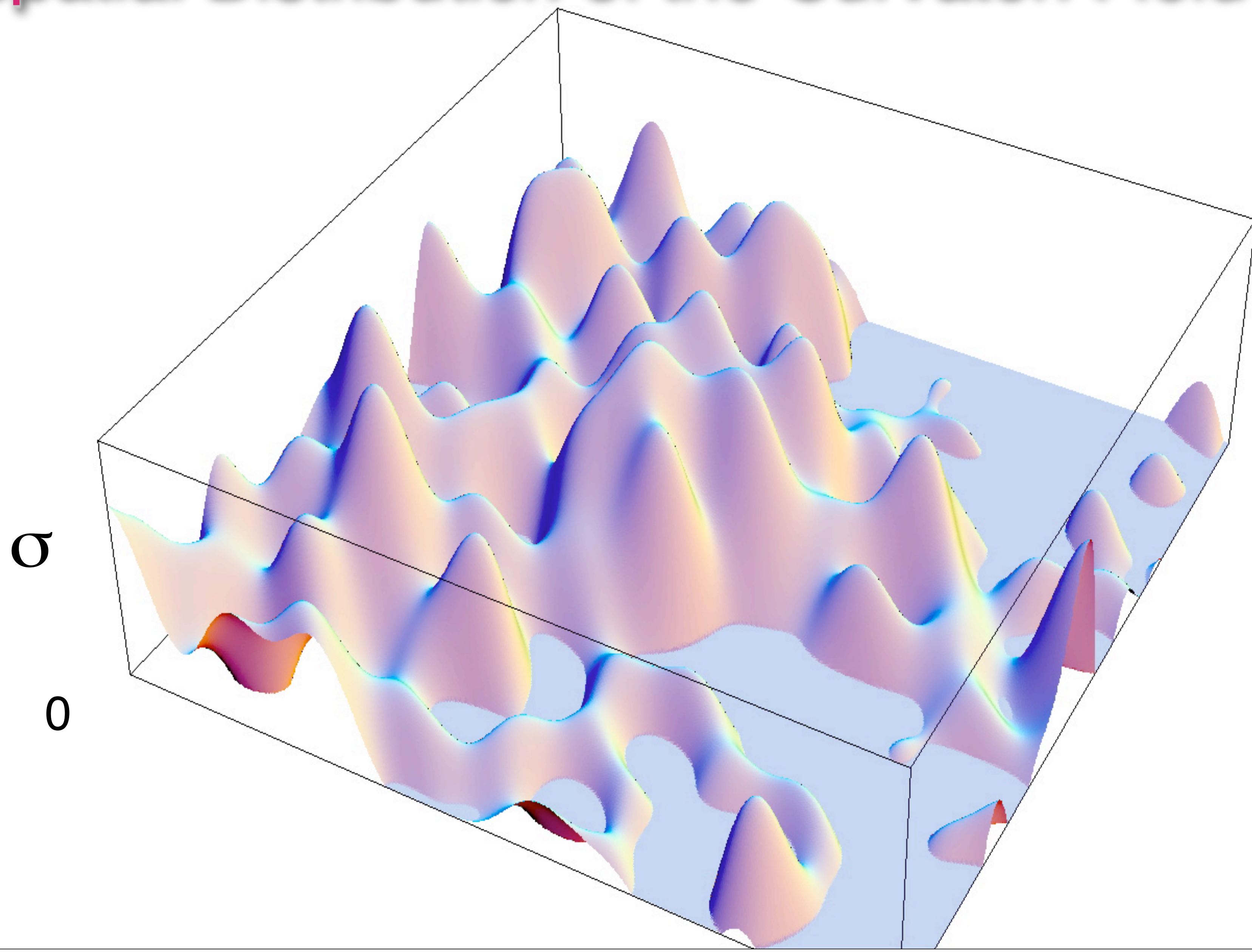
Curvaton

Isocurvature perturbations → adiabatic perturbations

$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$

σ is determined by quantum fluctuations, so the amplitude of perturbations is different in different places

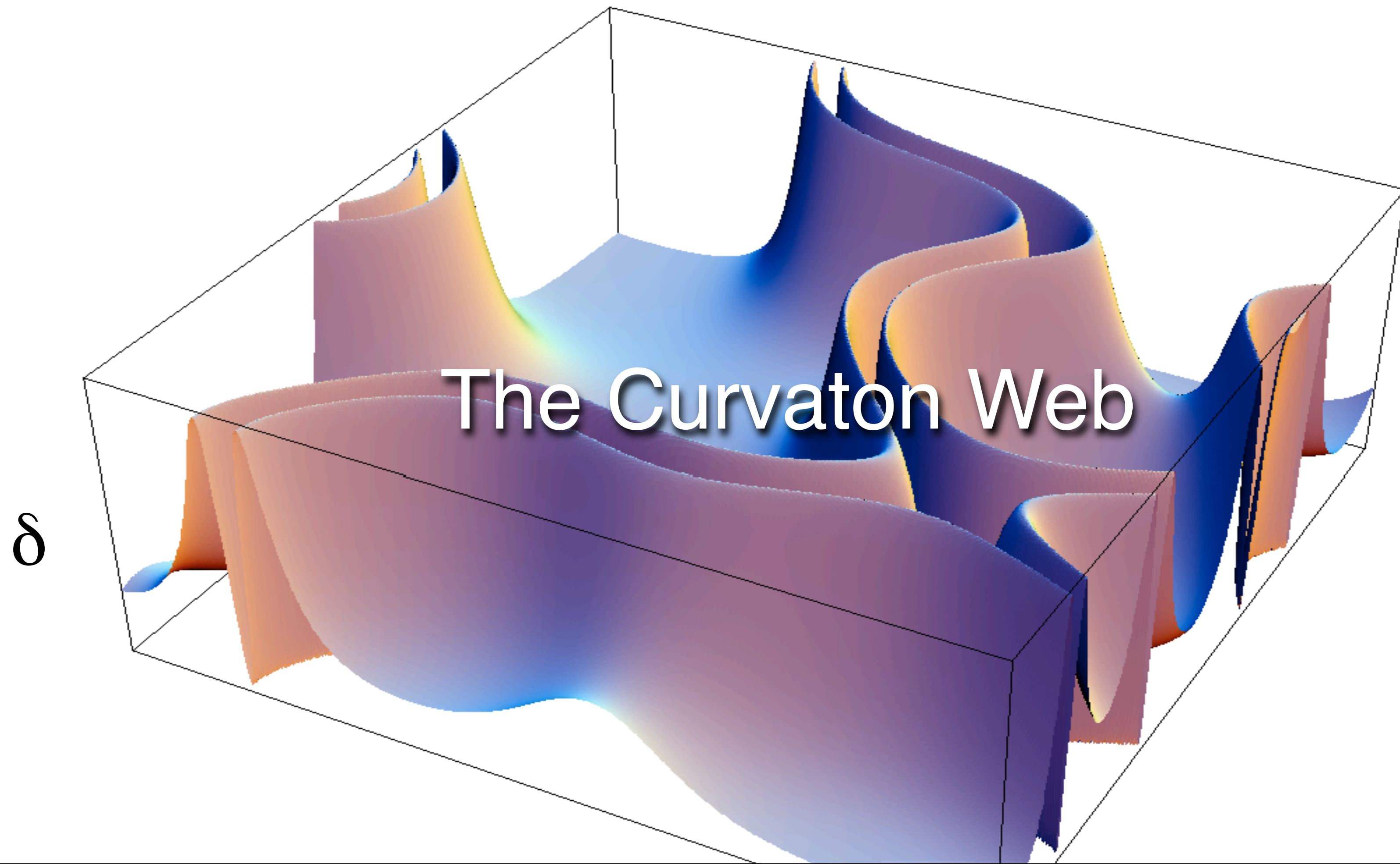
Spatial Distribution of the Curvaton Field



The Curvaton Web and Nongaussianity

Usually we assume that the amplitude of inflationary perturbations is constant, $\delta \sim 10^{-5}$ everywhere. However, in the curvaton scenario δ can be different in different parts of the universe. This is a clear sign of nongaussianity.

A.L., Mukhanov, astro-ph/0511736



Alternatives?

Ekpyrotic/cyclic scenario

Original version (Khoury, Ovrut, Steinhardt and Turok 2001) did not work (no explanation of the large size, mass and entropy; the homogeneity problem even worse than in the standard Big Bang, instead of the Big Bang they had Big Crunch, etc.).

It was replaced by cyclic scenario (Steinhardt and Turok 2002) which is based on a set of conjectures about what happens when the universe goes through the singularity and re-emerges.

Despite many optimistic announcements, the singularity problem in 4-dimensional space-time, as well as several other problems of the cyclic scenario, remains unsolved.

Recent developments: "New ekpyrotic scenario" based on the ghost condensate theory and the curvaton mechanism.

Creminelly and Senatore, 2007, Buchbinder, Khoury, Ovrut 2007

Even the authors of the ghost condensate theory dislike it: violation of the null energy condition, absence of the ultraviolet completion, difficulty to embed it in string theory, violation of the second law of thermodynamics, problems with black hole physics.

The main problem: the ghost condensate theory contains terms with higher derivatives, which lead to new ekpyrotic ghosts, particles with negative energy. As a result, the vacuum state of the ghost condensate theory and of the new ekpyrotic scenario suffers from a **catastrophic vacuum instability.**

For ekpyrotic: Kallosh, Kang, Linde and Mukhanov, arXiv:0712.2040

For ghost condensate: Aref'eva and Volovich, hep-th/0612098

The New Ekpyrotic Ghosts

New Ekpyrotic Lagrangian:

$$L = \sqrt{g}\left[M^4 P(X) - \frac{1}{2}\left(\frac{\Box\phi}{M'}\right)^2 - V(\phi)\right]$$

Dispersion relation:

$$\omega^2 = P_{,X}\, k^2 + \frac{(\omega^2 - k^2)^2}{m_g^2}$$

Two classes of solutions, for small $P_{,X}$:

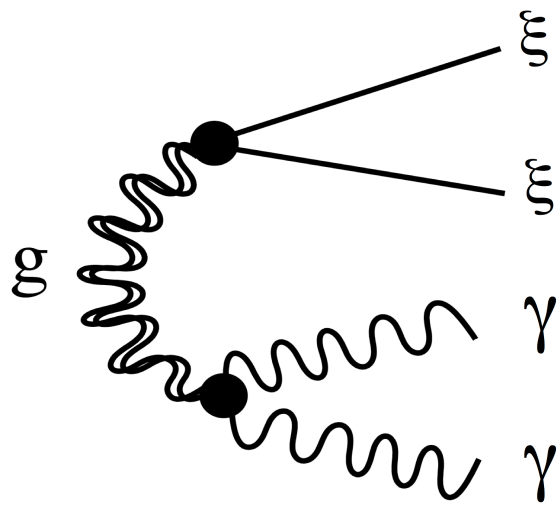
$$\omega = \pm\, \omega_i \;, \quad \omega_1 = \frac{1}{2}\left(\sqrt{m_g^2 + 4k^2} - m_g\right), \quad \omega_2 = \frac{1}{2}\left(\sqrt{m_g^2 + 4k^2} + m_g\right)$$

Hamiltonian describes normal particles with positive energy $+\,\omega_1$

and ekpyrotic ghosts with negative energy $-\,\omega_2$

$$H_{quant} = \int \frac{d^3k}{(2\pi)^3}\left(\omega_1 a_k^\dagger a_k - \underline{\omega_2 c_k^\dagger c_k}\right)$$

Vacuum in the new ekpyrotic scenario instantly decays due to emission of pairs of ghosts and normal particles.



Cline, Jeon and Moore, 2003

"But ghosts have disastrous consequences for the viability of the theory. In order to regulate the rate of vacuum decay one must invoke explicit Lorentz breaking at some low scale. In any case there is no sense in which a theory with ghosts can be thought as an effective theory, since the ghost instability is present all the way to the UV cut-off of the theory."

Buchbinder, Khoury, Ovrut 2007

Other alternatives: String gas cosmology

Brandenberger, Vafa, Nayeri, 4 papers in 2005-2006

Many loose ends and unproven assumptions (e.g. stabilization of the dilaton and of extra dimensions without using fluxes). Flatness/entropy problem is not solved. This class of models differs from the only known class of stringy models (KKLT-type construction) 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, A.L., Mukhanov 2006, hep-th/0608200

Brandenberger et al, 2006

Other problems with similar speculative constructions were recently discussed by Kaloper and Watson, arXiv:0712.1820

Inflation in String Theory

Moduli 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.

Moduli stabilization for noncritical strings: Silverstein et al 2001

Dilaton stabilization: Giddings, Kachru, Polchinski 2001

Volume stabilization: **KKLT construction**

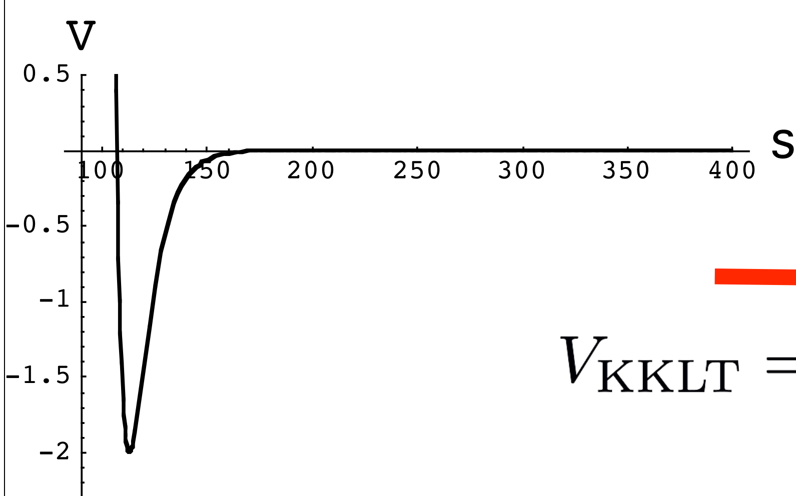
Kachru, Kallosh, A.L., Trivedi 2003

Basic steps of the KKLT scenario:

1) Start with a theory with runaway potential discussed above

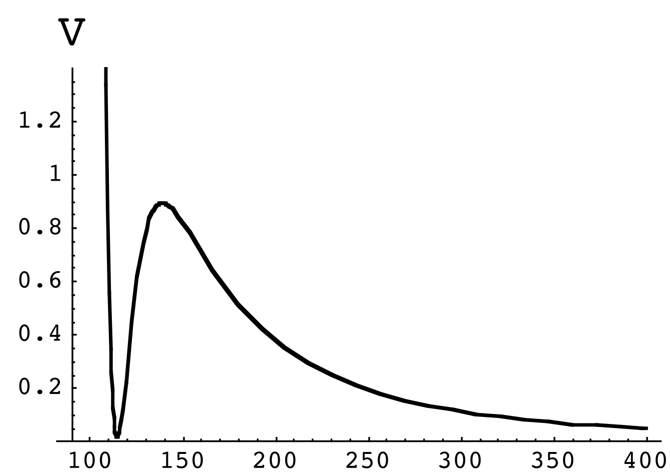
2) Bend this potential down due to nonperturbative quantum effects

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

Moduli stabilization allows to describe a metastable cosmological constant in string theory.

Despite numerous attempts, we still do not have any reasonable model of a dynamical dark energy (quintessence).

When we learned how to stabilize stringy vacua, we learned how to do it in **MANY** different ways, which is the basis of the string landscape scenario.

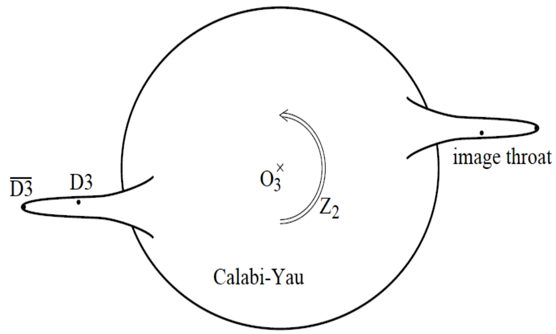

Perhaps 10^{1000} different uplifted vacua
Lerche, Lust, Schellekens 1987
Bousso, Polchinski 2000; Susskind 2003; Douglas, Denef 2003

Two types of string inflation models:

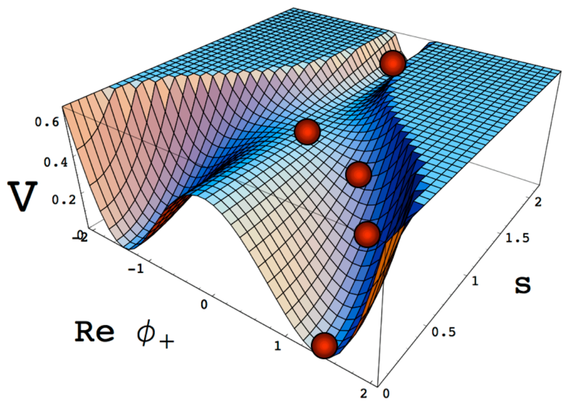
Modular Inflation. The simplest class of models. They use only the fields that are already present in the KKLT model.

Brane inflation. The inflaton field corresponds to the distance between branes in Calabi-Yau space.

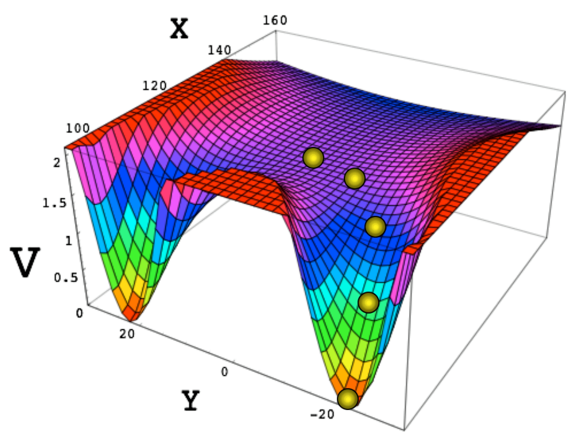
Inflation in string theory



KKLMMT brane-anti-brane inflation



D3/D7 brane inflation



Racetrack modular inflation

DBI inflation (non-minimal kinetic terms)

Wanted ...

- a simple and in that sense ‘explicit’ toy model of modular inflation:

- with no need for extra fields beyond the volume modulus

- with no extra terms beyond tree-level flux & non-perturbative effects

- such a model may then be explicitly realized within existing KKLT construction, *remaining question is fine-tuning in its parameter space*

A toy model of SUGRA inflation:

Holman, Ramond, Ross, 1984

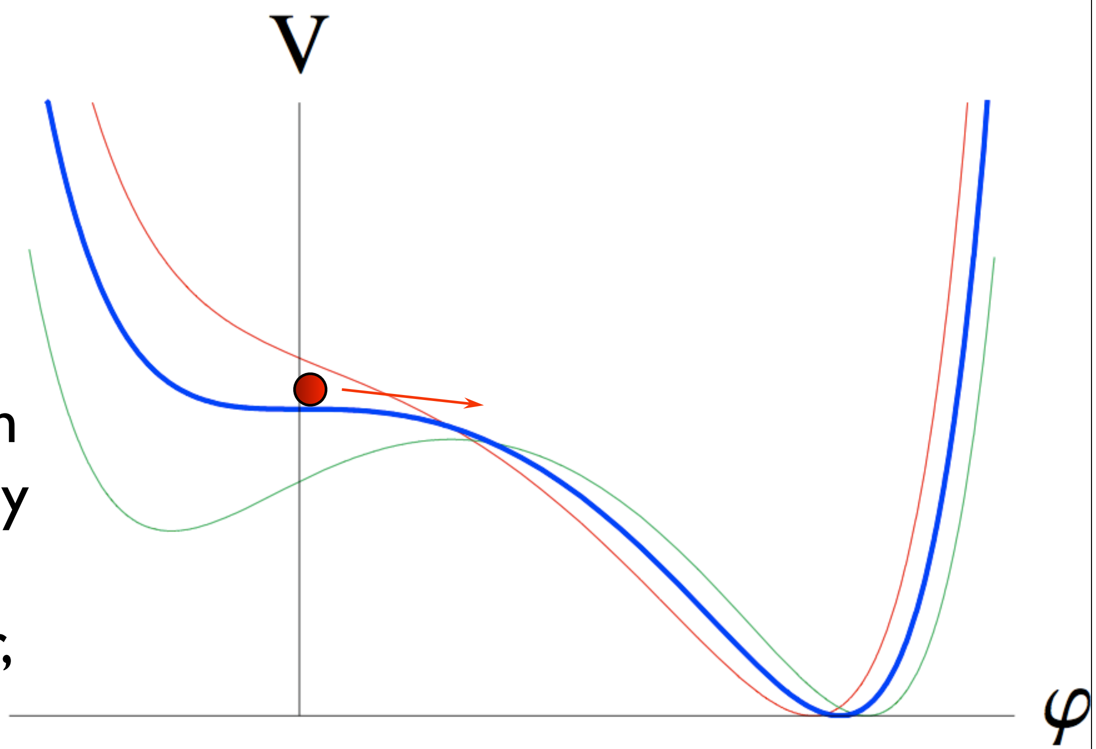
Superpotential: $$W = c\,(\Phi - \Phi_0)^2$$

Kahler potential: $$K = \Phi\bar{\Phi}$$

Inflation occurs for $\Phi_0 = 1$

Requires fine-tuning, but it is simple, and it works

Recently similar potentials with an inflection point were used by Allahverdi, Enqvist, Garcia-Bellido, Jokinen and Mazumdar, and also by Baumann et al

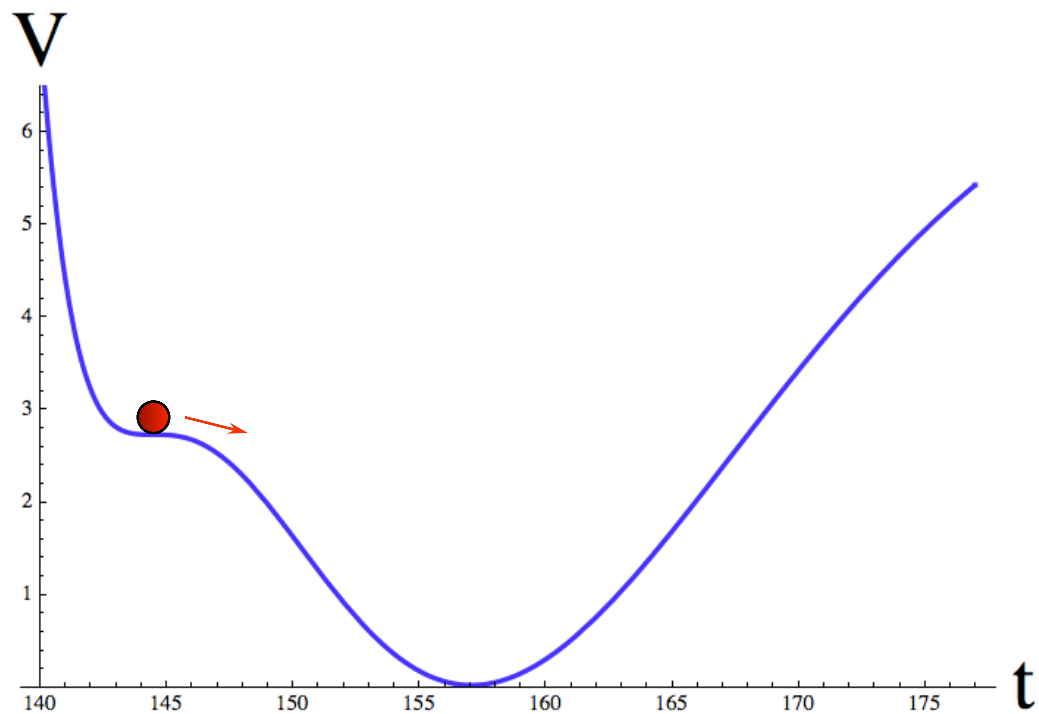


A toy model of string inflation:

A.L., Westphal, 2007

Superpotential: $$W = W_0 + A\, e^{-aT} + B\, e^{-bT}$$

Kahler potential: $$K = -3 \log(T + T^*)$$



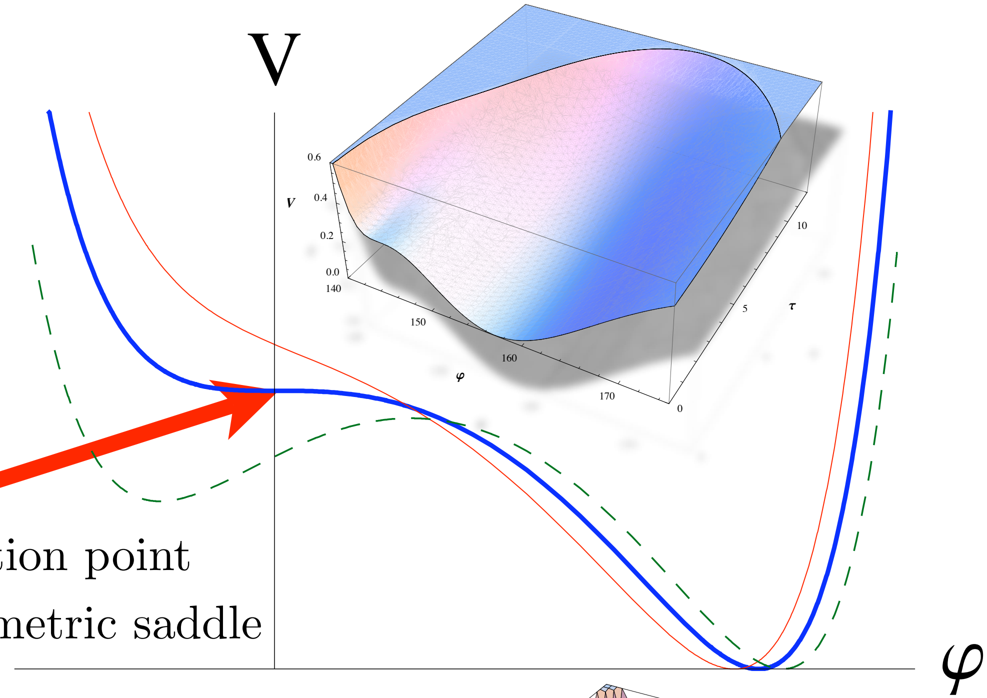
Volume modulus inflation

Requires fine-tuning, but works without any need to study complicated brane dynamics

Analytical treatment by expansion around saddle point

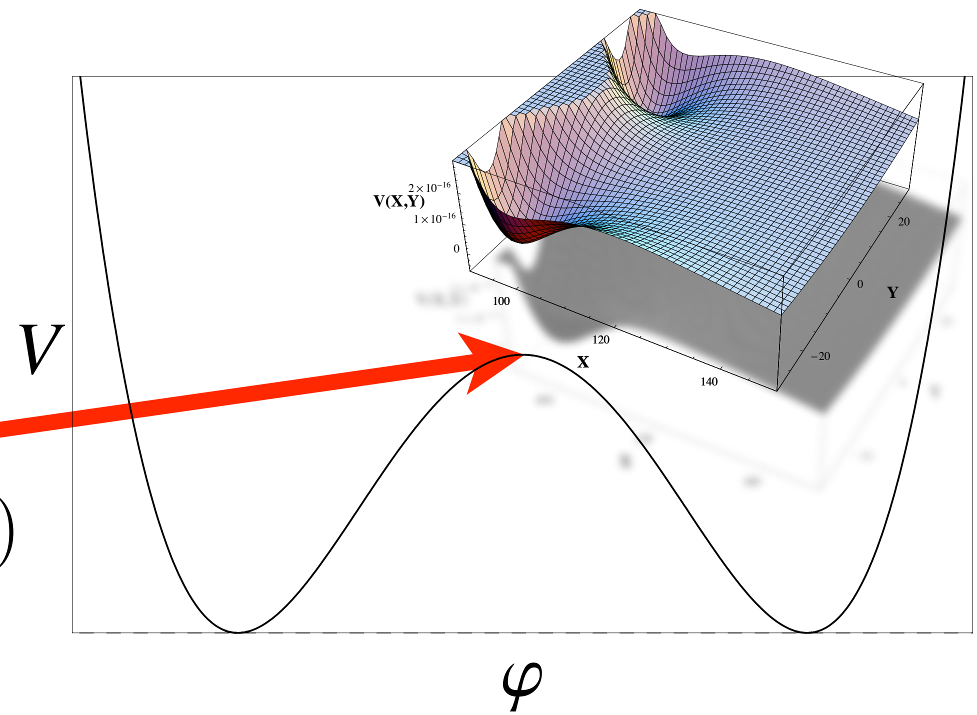
$$V = \begin{cases} V_0\left(1 - \lambda_1\varphi - \frac{\lambda_3}{3}\varphi^3\right) & \text{inflection point} \\ V_0\left(1 + \frac{\eta(0)}{2}\varphi^2 - \frac{\lambda_3}{3}\varphi^3\right) & \text{asymmetric saddle} \end{cases}$$

$$\lambda_1 \sim \sqrt{\epsilon(0)} < 0 \quad , \quad \eta(0) < 0$$



$$V = V_0\left(1 + \frac{\eta(0)}{2}\varphi^2 + \frac{\lambda_4}{4}\varphi^4\right)$$

$$\eta(0) < 0$$



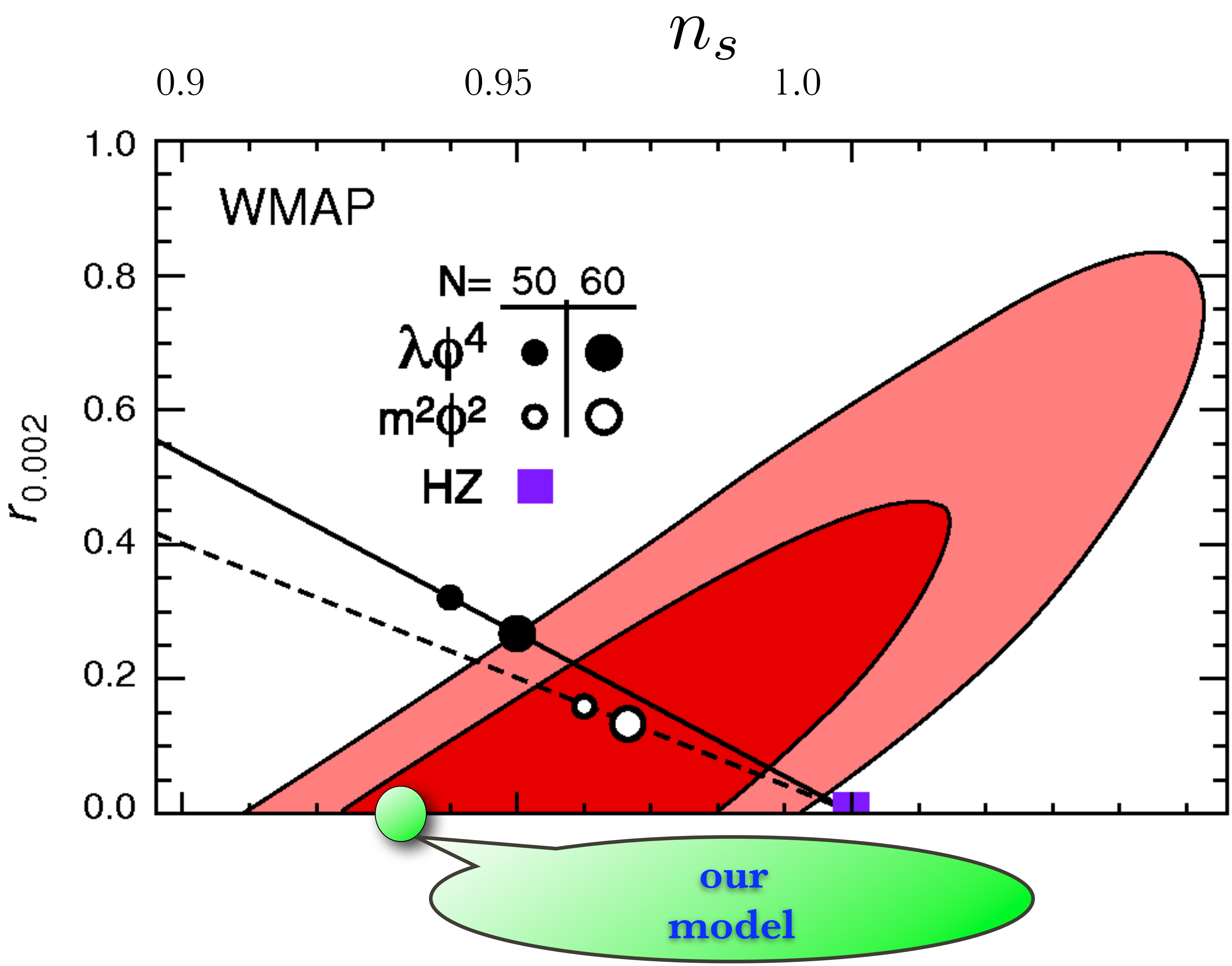
Is fine-tuning natural?

Growth of volume of the universe during inflation exponentially depends on the degree of fine-tuning of the linear term:

$$a^3 \sim \exp \frac{3\pi}{2\sqrt{\lambda_1 \lambda_3}}$$

for $\lambda_1 > 10^{-10}$

Fine-tuning rewards us by a factor up to e^{10^6}

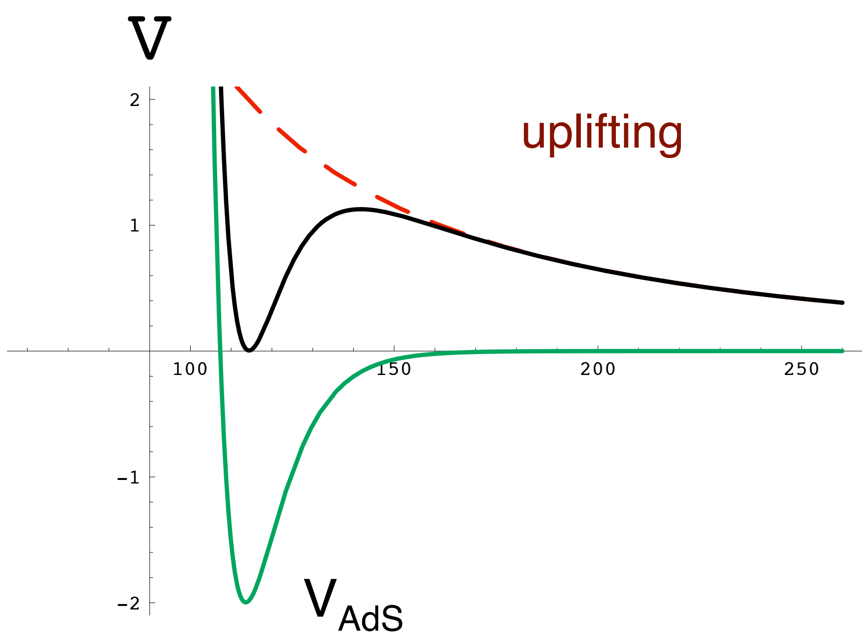


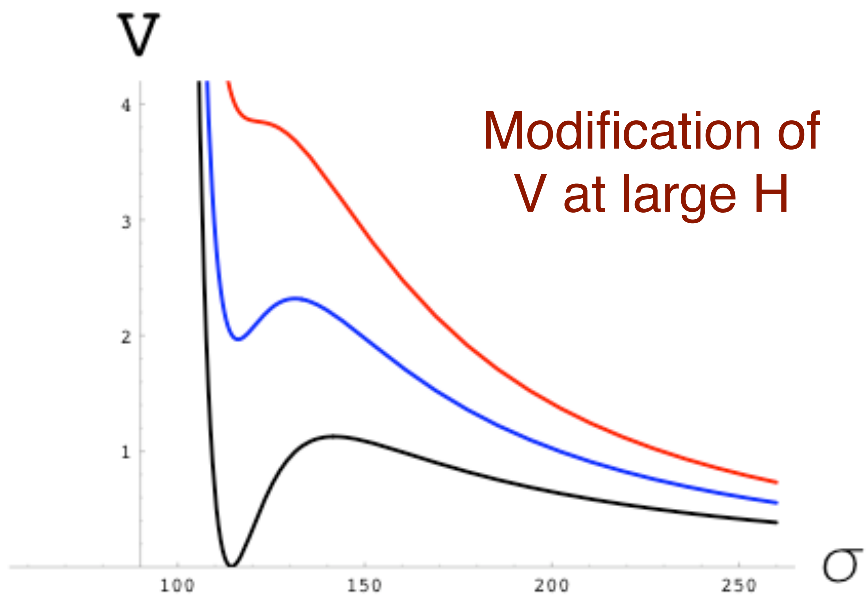
n_s
0.9
0.95
1.0
1.0
0.8
0.6
0.4
0.2
0.0
$r_{0.002}$
WMAP
N= 50 60
λφ⁴
m²φ²
HZ
our model

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 $H^2 = V_{infl}/3 < m^2_{3/2}$.





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

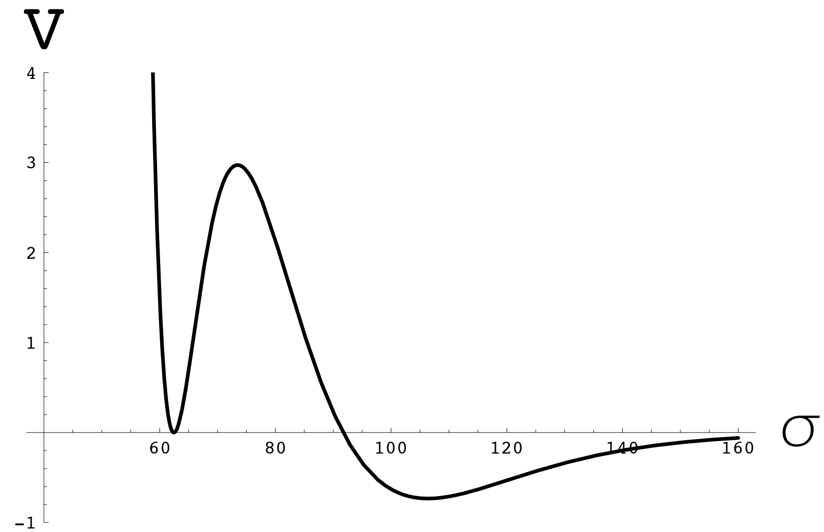
$$V_{\text{AdS}} = -3\, e^K |W^2| = -3\, m^2_{3/2}$$

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

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

Can we avoid these conclusions in more complicated models?

In theories with racetrack superpotential one can have the gravitino mass squared much smaller than the height of the barrier. But this requires fine-tuning (Kallosh, A.L. 2004)



In models with large volume of compactification (Quevedo et al) the situation is even more difficult:

$$H < m_{3/2}^{3/2} < 1\ KeV$$

The price for having the standard “solution” of the hierarchy problem is higher than expected; we are waiting for LHC...

Gravitino mass and gravity waves

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

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

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

Kallosh, A.L. 2007

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

superheavy gravitino

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

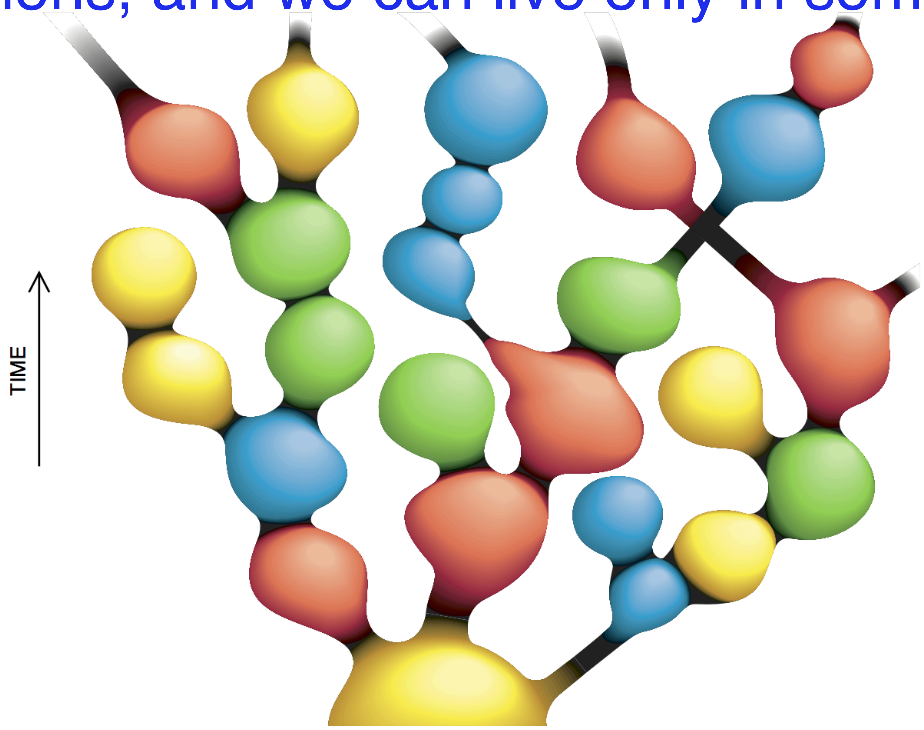
unobservable

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

Inflationary Multiverse

For a long time, people believed that the universe is everywhere the same.

However, back in 1982-1983 we learned that inflationary universe may consist of many parts with different properties depending on the local values of the scalar fields, compactifications, and we can live only in some of them.



Conclusions:

Ideas which were developed 25 years ago are alive and well. Competing models appear and disappear, with a much shorter typical lifetime.

String theory can describe inflation in the early universe, as well as inflation now (i.e. acceleration of the universe due to the cosmological constant), but quintessence does not come easy.

Eternal inflation and string theory joined each other in the context of the string theory landscape. The resulting picture changes the way we look at our place in the world. This is one of the most exciting and mysterious parts of modern science.