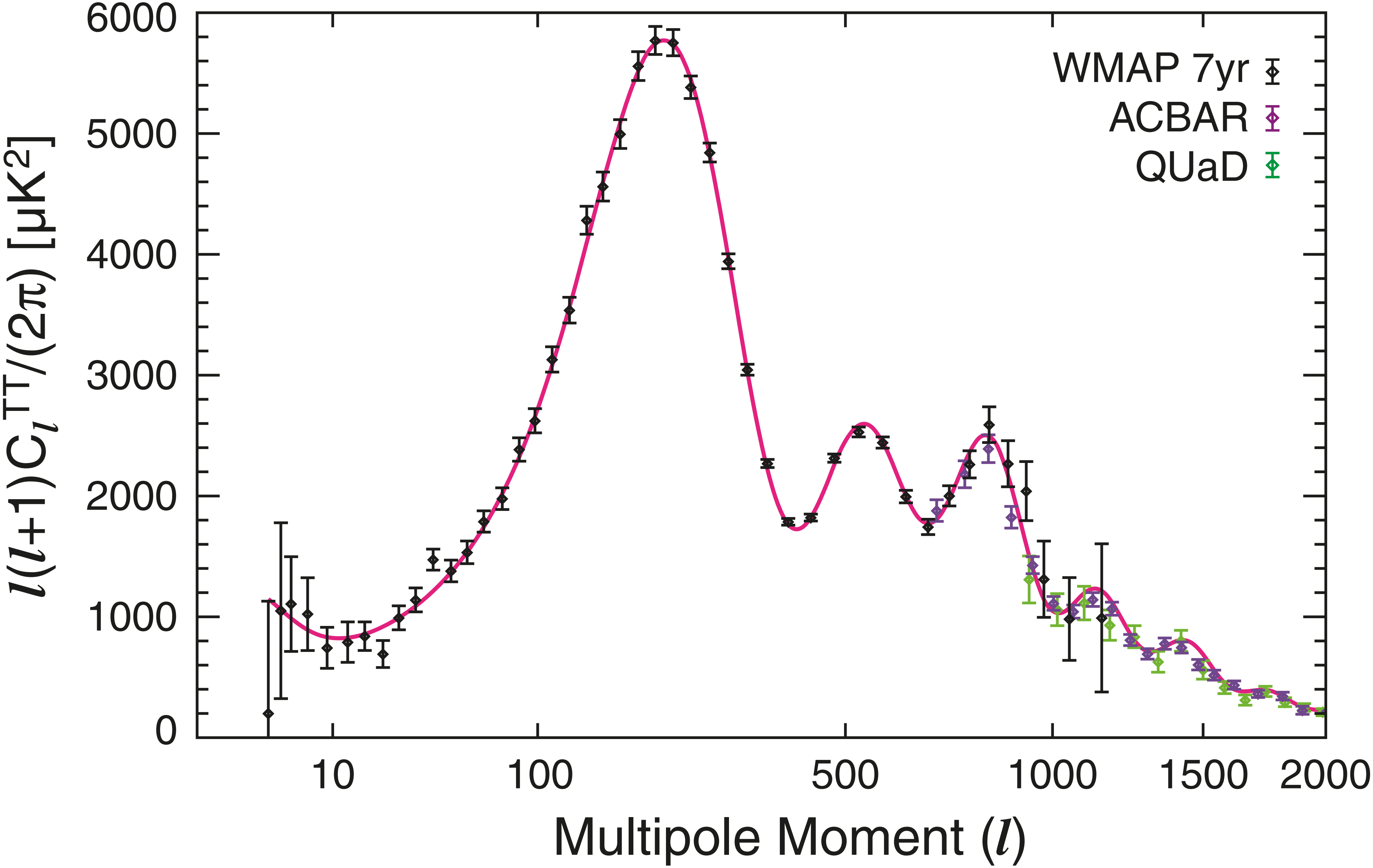
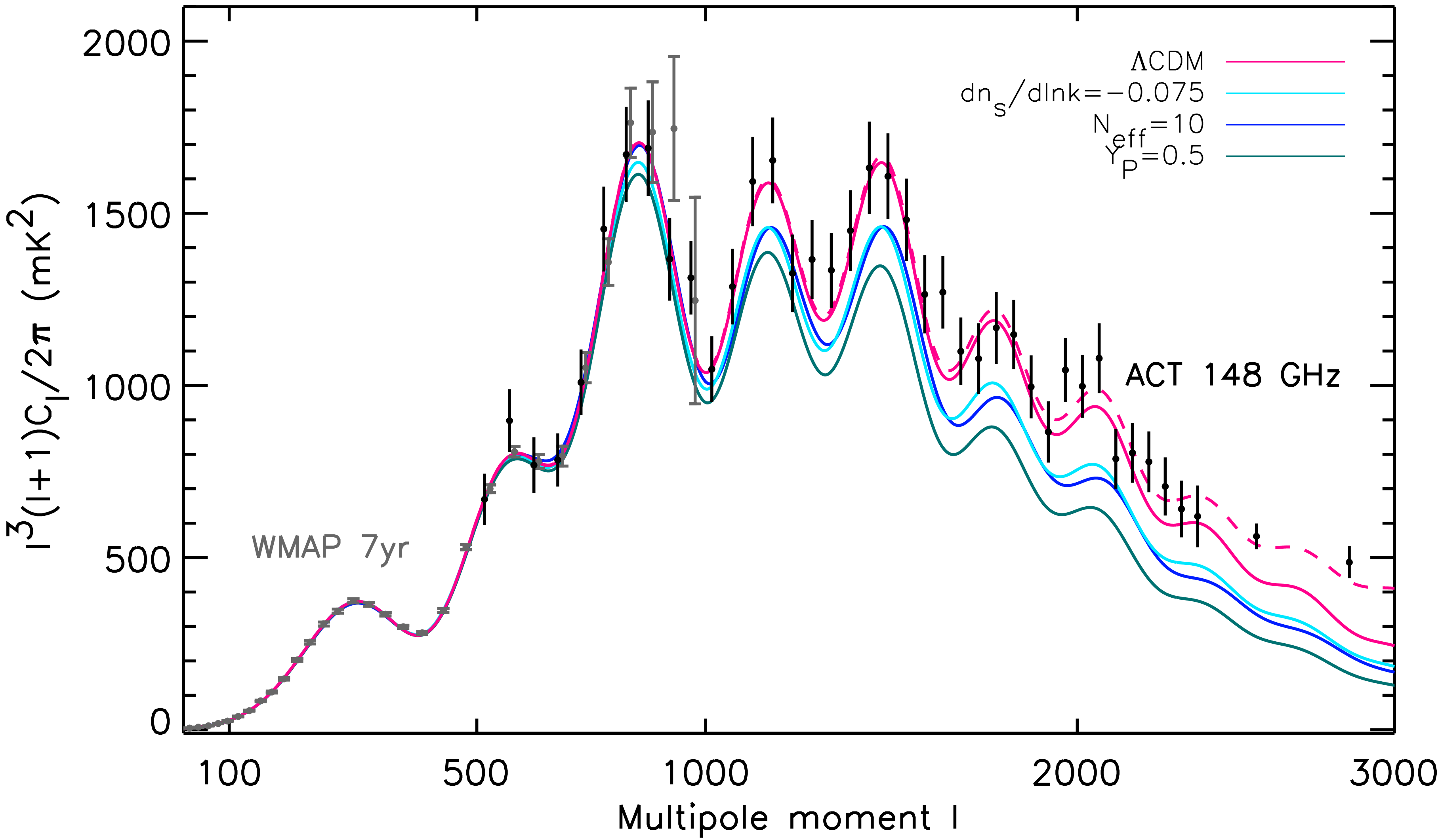
Chaotic Inflation in Supergravity

Andrei Linde

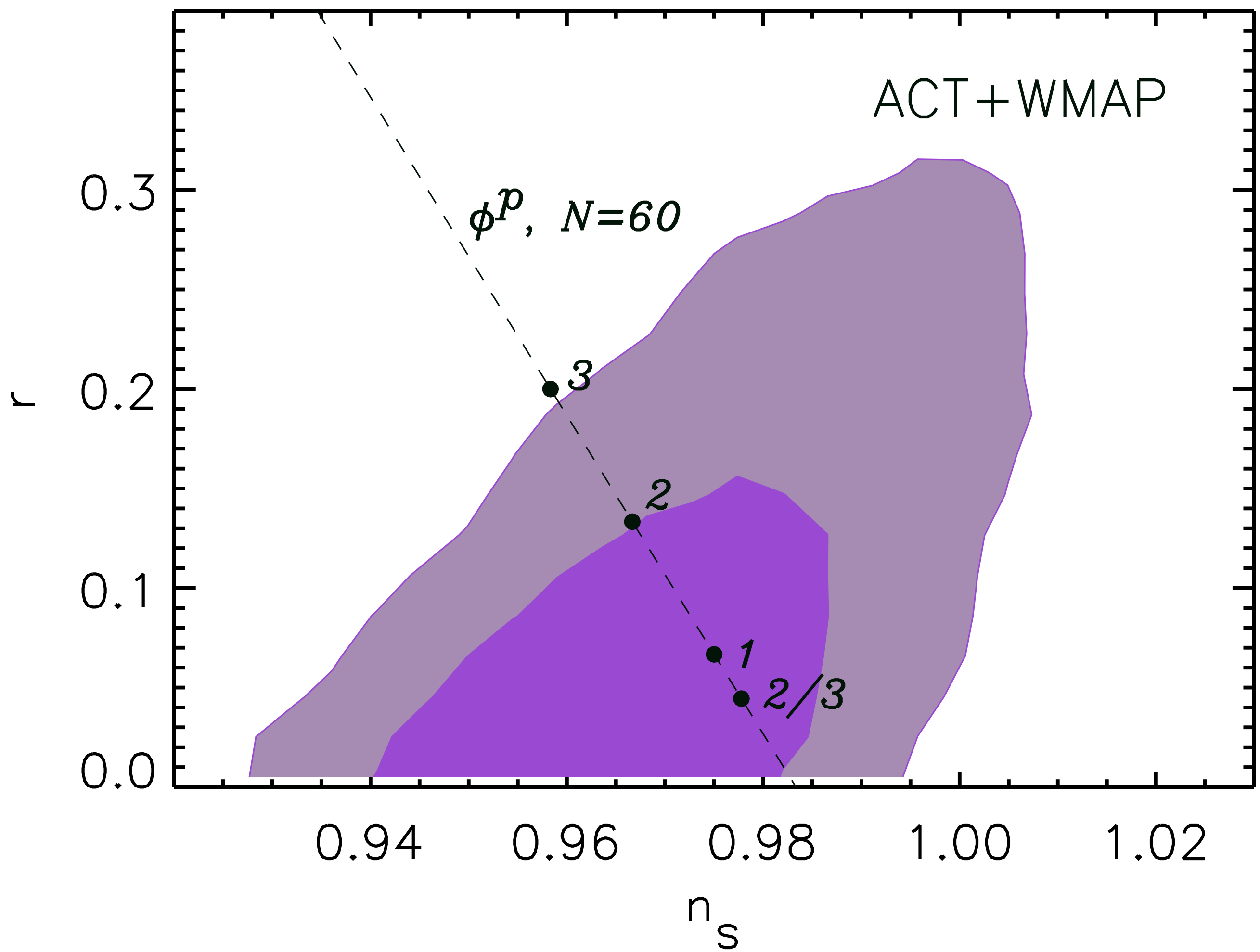
WMAP7 + Acbar + QUaD



WMAP7 + Atacama



WMAP7 + Atacama



Harrison-Zeldovich n_s = 1 excluded at 99.7% CL (3 sigma)

Our goal is to develop a theoretical framework which would give us maximal flexibility to describe upcoming observational data in the context of supergravity/string theory motivated models:

1) Functional freedom in the choice of the potential, to adjust n_s and r.
2) The possibility to go beyond the single-field models to describe a possible non-gaussianity, to tune f_{NL}.
3) Solving the cosmological moduli problem and the gravitino problem

Based on:

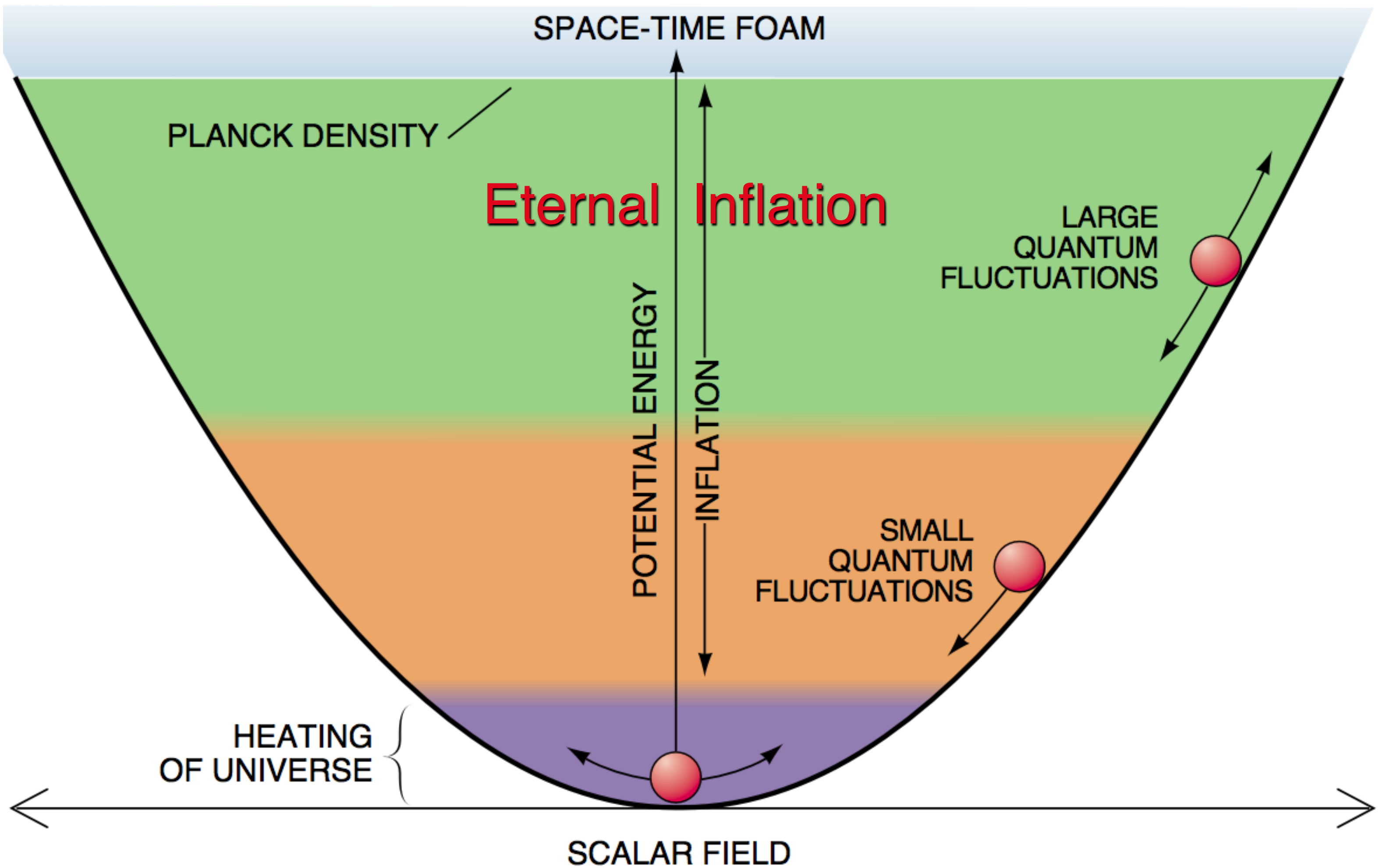
Kallosh, A.L., 1008.3375
Kallosh, A.L. and Rube, 1011.5945
Demozzi, A.L. and Mukhanov, 1012.0549
Kallosh, A.L., Olive, Rube, 1106.6025

Chaotic Inflation

1983

A.L.

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



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

Kahler potential $\mathcal{K} = S\bar{S} - \frac{1}{2}(\Phi - \bar{\Phi})^2$

and superpotential $W = mS\Phi$

The potential is very curved with respect to S and Im Φ, so these fields vanish. But Kahler potential does not depend on

$$\phi = \sqrt{2}\,\mathrm{Re}\ \Phi = (\Phi + \bar{\Phi})/\sqrt{2}$$

The potential of this field has the simplest form, as in chaotic inflation, without any exponential terms:

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

Higher order quantum corrections do not change this result

More general models

Kallosh, A.L. 1008.3375, Kallosh, A.L., Rube,1011.5945

$$W = S\, f(\Phi)$$

The Kahler potential is any function of the type

$$\mathcal{K}((\Phi - \bar{\Phi})^2,\, S\bar{S})$$

The potential as a function of the real part of Φ at S = 0 is

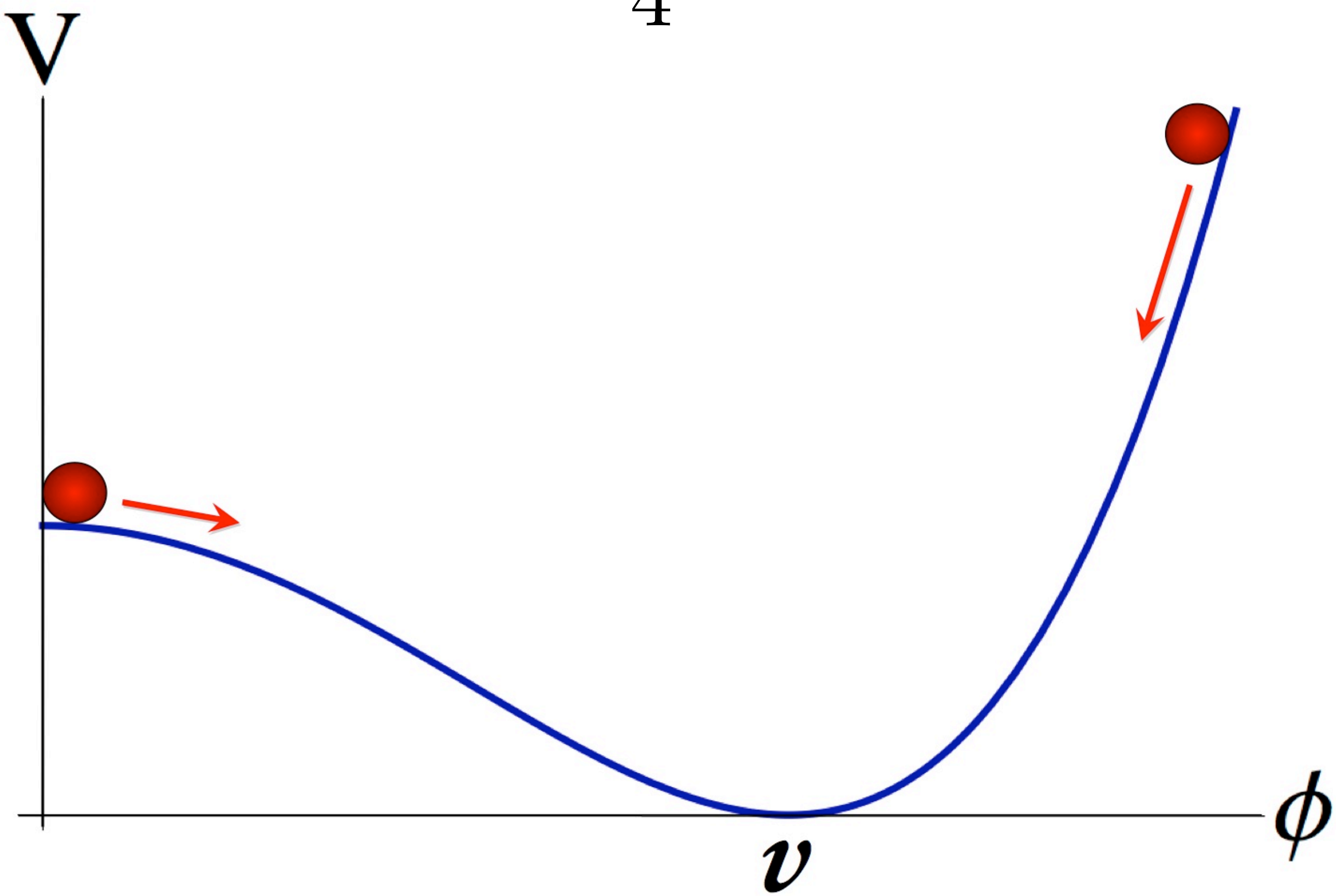
$$V = |f(\Phi)|^2$$

FUNCTIONAL FREEDOM in choosing inflationary potential

Example: $W = -\lambda S(\Phi^2 - v^2/2)$

During inflation $S = 0, \ \mathrm{Im}\,\Phi = 0, \ \mathrm{Re}\,\Phi = \sqrt{2}\,\phi$

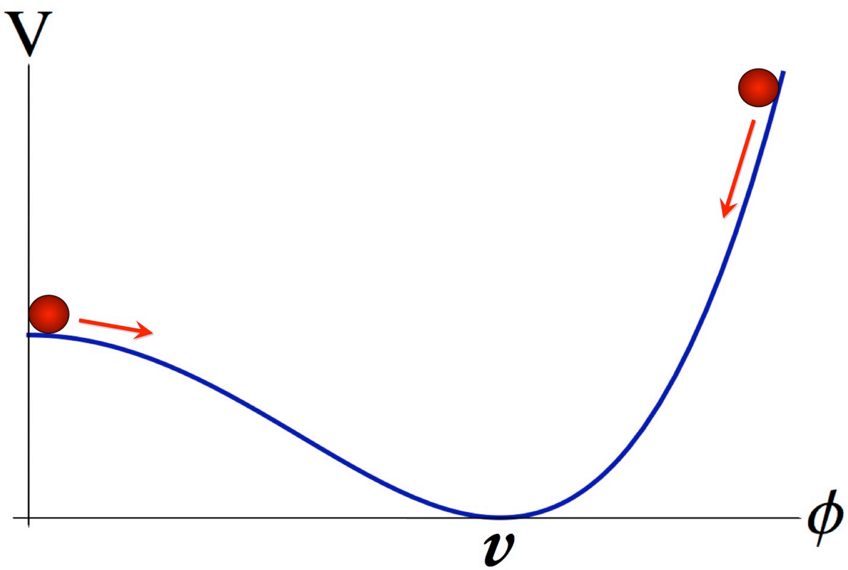
$$V(\phi) = \frac{\lambda^2}{4}(\phi^2 - v^2)^2$$

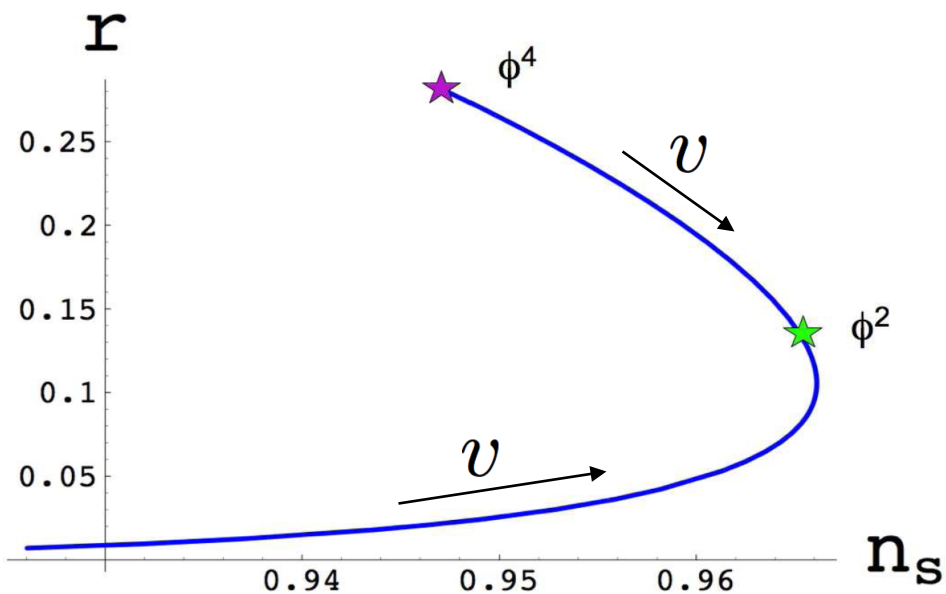


Tensor modes:

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

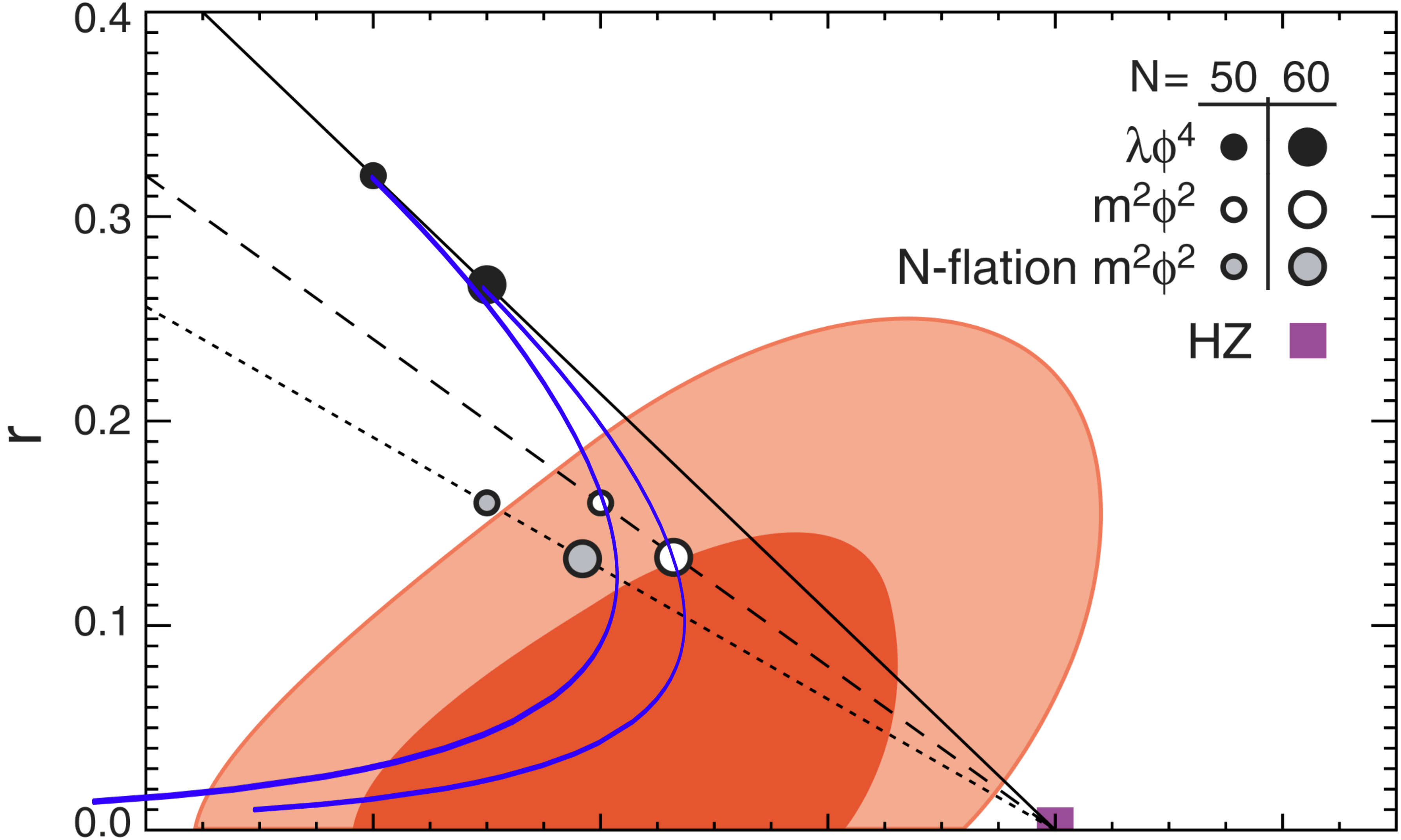
Kallosh, A.L. 2007





Observers are optimistic now about measuring r at the level approaching r ~ 0.01 after 2011-2012 (BICEP2, other experiments)

Chaotic Inflation



Blue lines – chaotic inflation with the simplest spontaneous symmetry breaking potential $-m^2\phi^2 + \lambda\phi^4$ for N = 50 and N = 60

Supersymmetry and non-gaussianity

Demozzi, A.L., Mukhanov, 1012.0549

$-10 < f_{NL}^{local} < 74$

Consider a generalized model of Kawasaki, Yamaguchi, Yanagida:

$$W = mS\Phi$$

$$\mathcal{K} = S\bar{S} - \frac{1}{2}(\Phi - \bar{\Phi})^2 - \zeta(S\bar{S})^2$$

added for stabilization

In this scenario, the “stabilizer” field S has mass:

$$m_s^2 = m^2 + 12\zeta H^2$$

During inflation,

$$\phi \gg 1, \qquad H^2 = m^2\phi^2/6 \gg m^2$$

For $12\zeta \gg 1$ the mass of the field S is much greater than H, and this field is firmly stabilized at S = 0.

But for $12\zeta \ll 1$ the mass of the field S is much smaller than H, and therefore its perturbations are also generated, in addition to the standard inflaton perturbations. This is the basis of the curvaton mechanism, which may lead to a significant non-gaussianity of inflationary perturbations.

$$S = \sigma\, e^{i\theta}/\sqrt{2}$$

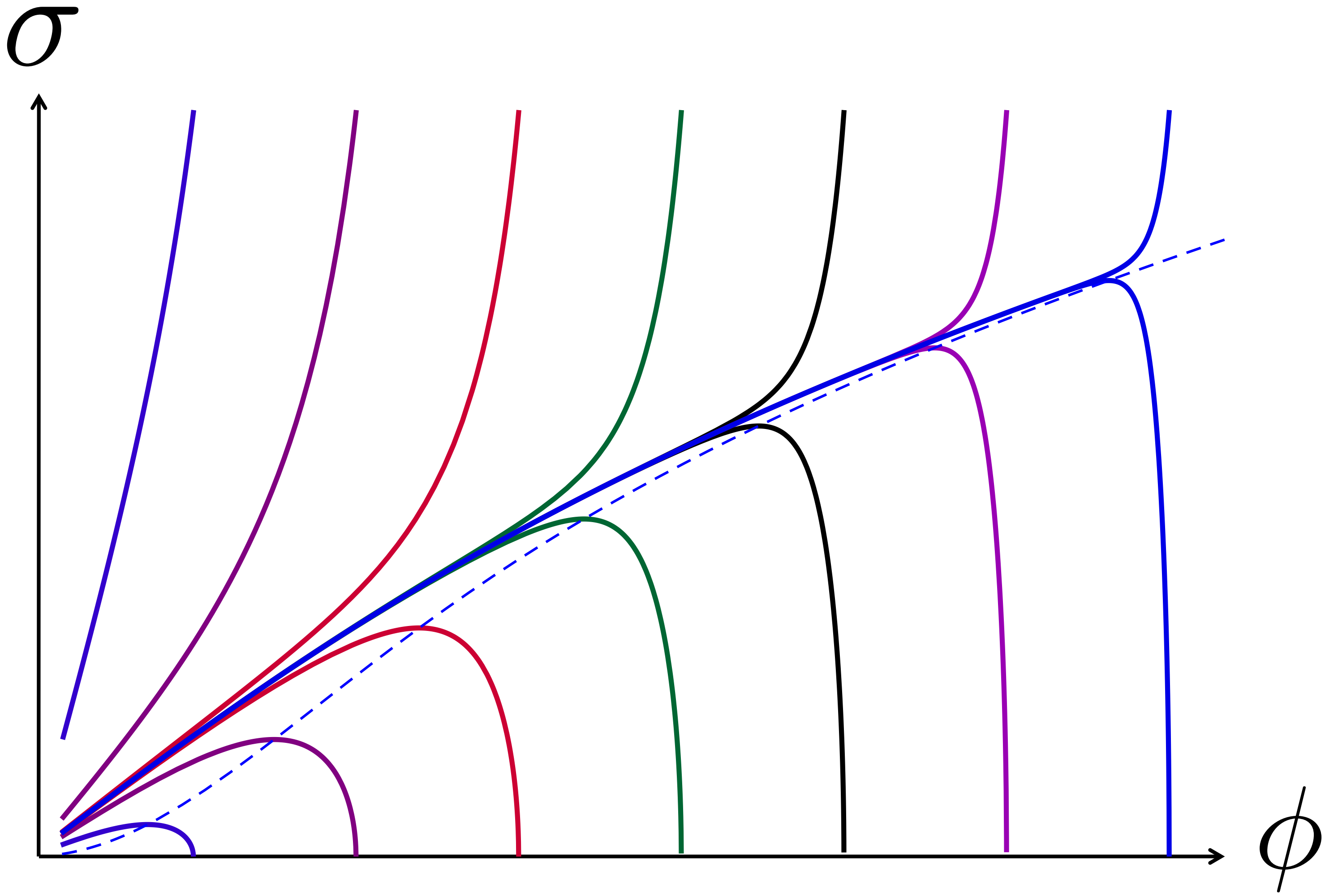
$$\frac{\delta\rho_\sigma}{\rho} \sim \frac{2r\delta\sigma}{\sigma}$$

$$r = \rho_\sigma/\rho$$

$$r\frac{\delta\sigma}{\sigma} \sim 7 \times 10^{-5}$$

$$f_{\rm NL} = \frac{5}{4r}$$

Attractor solution for the average amplitude of fluctuations of the curvaton field, does not depend on initial conditions



One can easily get large non-gaussianity

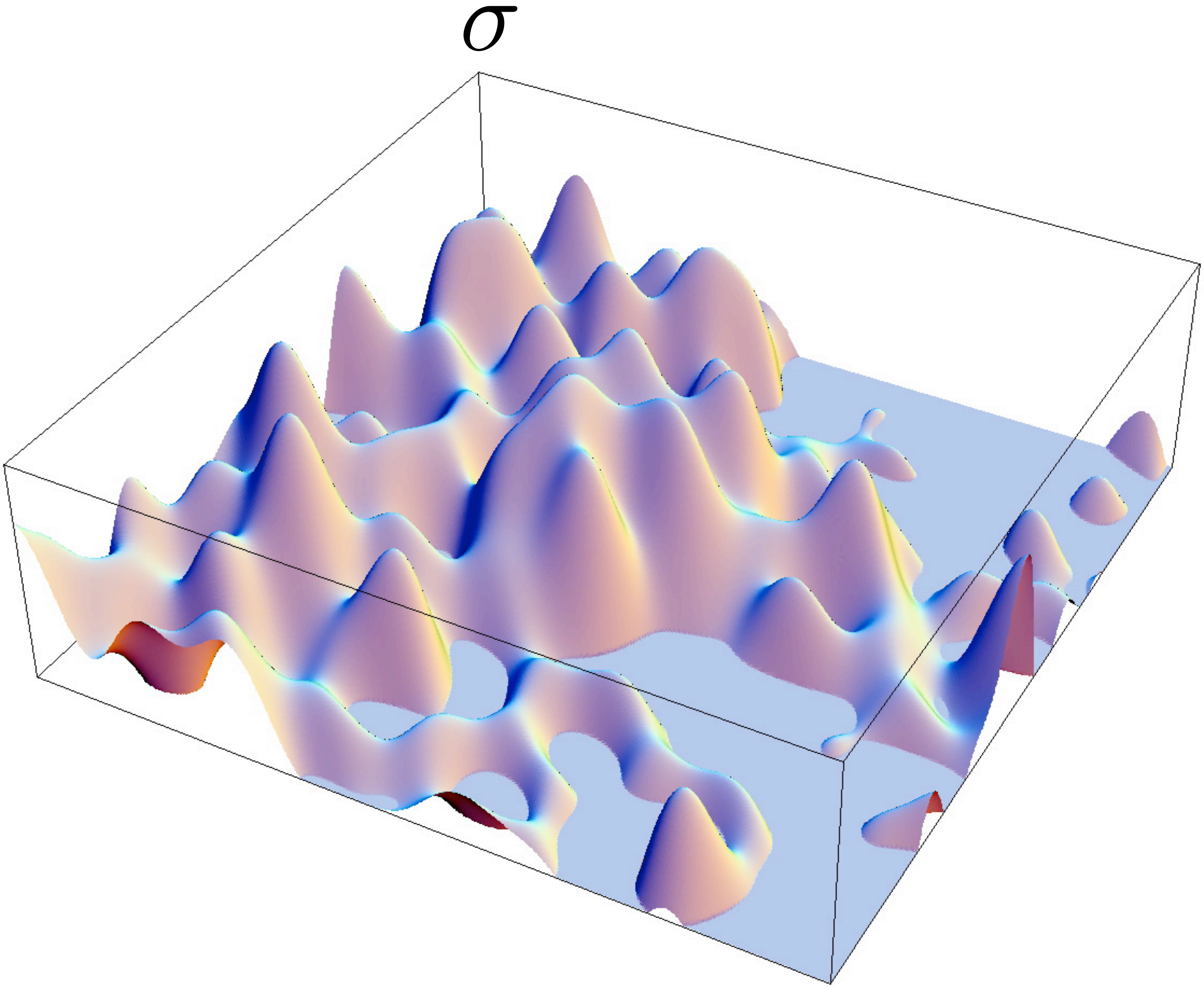
$$f_{\rm NL} \sim 10 - 10^2$$

Moreover, locally measured value of non-gaussianity can be even much greater

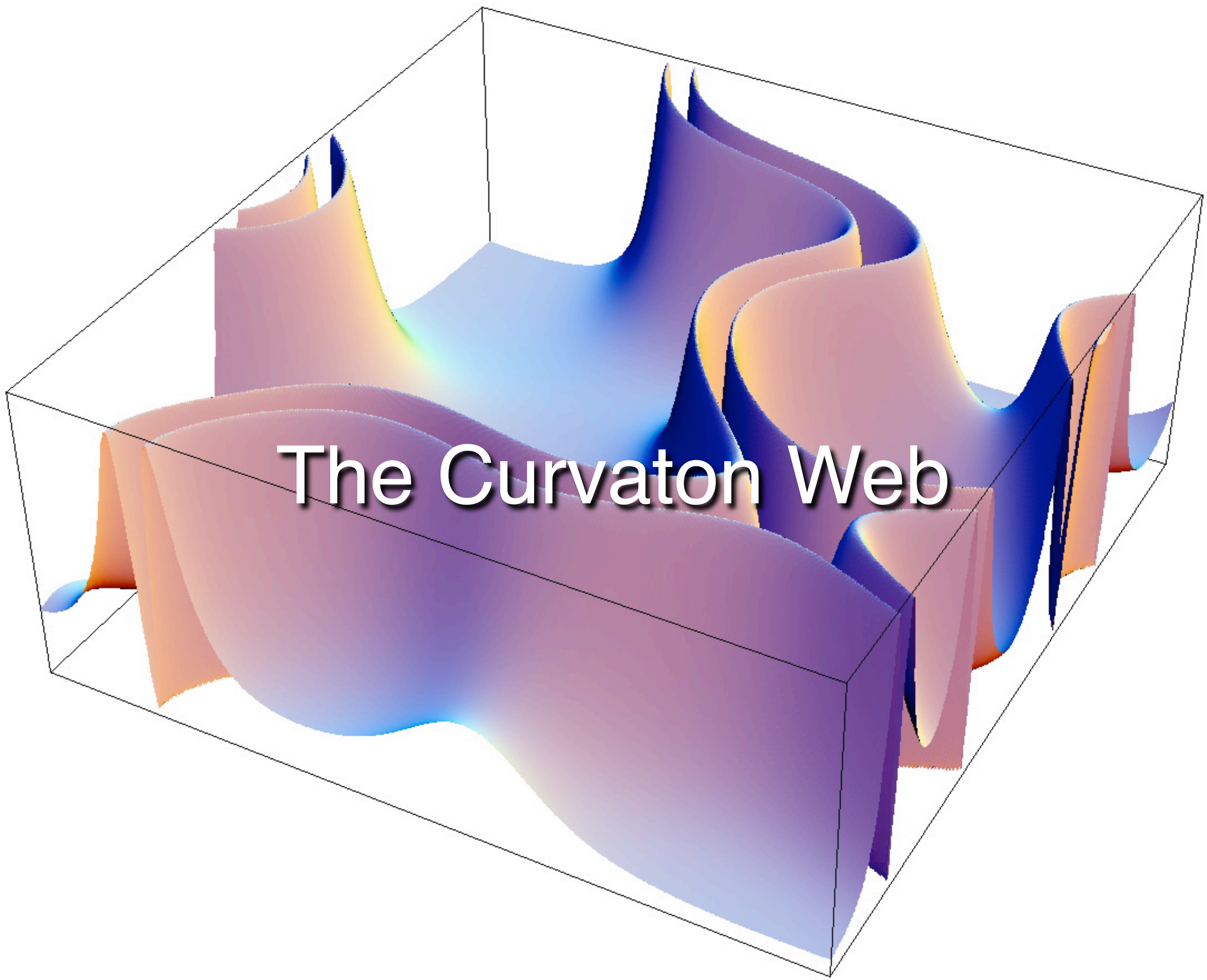
$$\frac{\delta\rho(\sigma)}{\rho} = \frac{\delta\rho(\bar\sigma)}{\rho} \cdot \frac{\sigma}{\bar\sigma}$$

$$f_{\rm NL}(\sigma) = f_{\rm NL}(\bar\sigma) \cdot \frac{\bar\sigma^2}{\sigma^2}$$

Even though the fraction of the volume of the universe with a small value of the curvaton field is not large, the non-gaussianity in such parts of the universe can be huge.


σ

$$\frac{\delta\rho_\sigma}{\rho} \sim \frac{2r\delta\sigma}{\sigma}$$



Nongaussianity has topology-related features

For the real curvaton field S, one finds domain walls corresponding to the maxima of the amplitude of perturbations of metric

For a complex field, we will have string-like configurations

For a field with O(3) symmetry we may have separate localized regions with high amplitude of density perturbations

Non-gaussianity disappears if all fields except the inflaton are firmly stabilized during inflation. This is achieved by a proper choice of the Kahler potential.

Supersymmetry breaking after inflation

Kallosh, A.L., Olive, Rube, 1106.6025

$$W = S\, f(\Phi) \qquad \mathcal{K}((\Phi - \bar{\Phi})^2,\, S\bar{S})$$

In this class of models one can get a theory with ANY type of inflationary potential of the real part of the field Φ

$$V = |f(\Phi)|^2$$

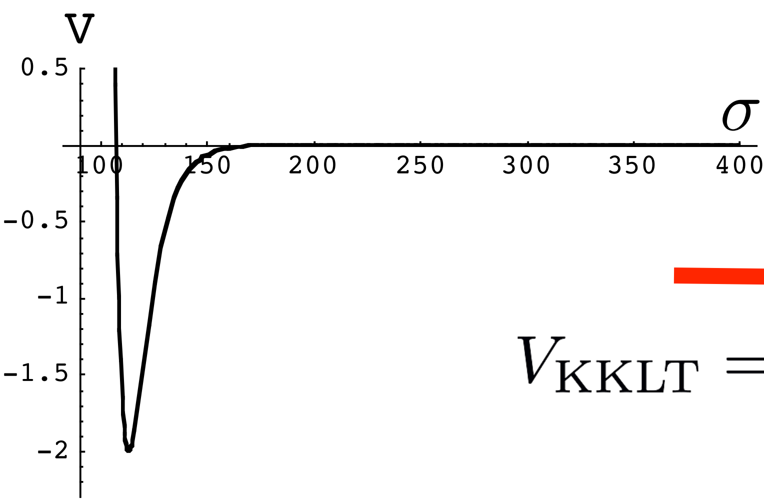
To have SUSY breaking on TeV scale one can add to this model a hidden sector with light Polonyi-type fields. But this leads to the cosmological moduli problem, which plagues SUGRA cosmology for the last 30 years.

In string theory, **SUSY breaking is a part of the KKLT construction**. Do we need to add Polonyi fields? Can we avoid the moduli problem?

SUSY breaking in KKLT

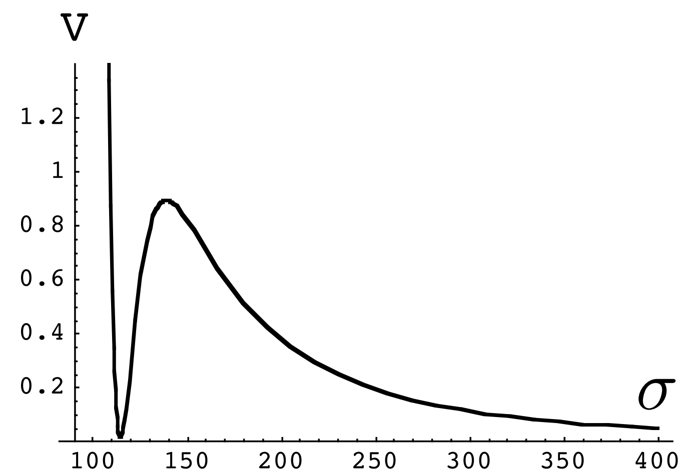
$$W = W_0 + Ae^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho + \bar{\rho})]$$

$$\rho = \sigma + i\alpha$$



Stabilization in a supersymmetric AdS minimum

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



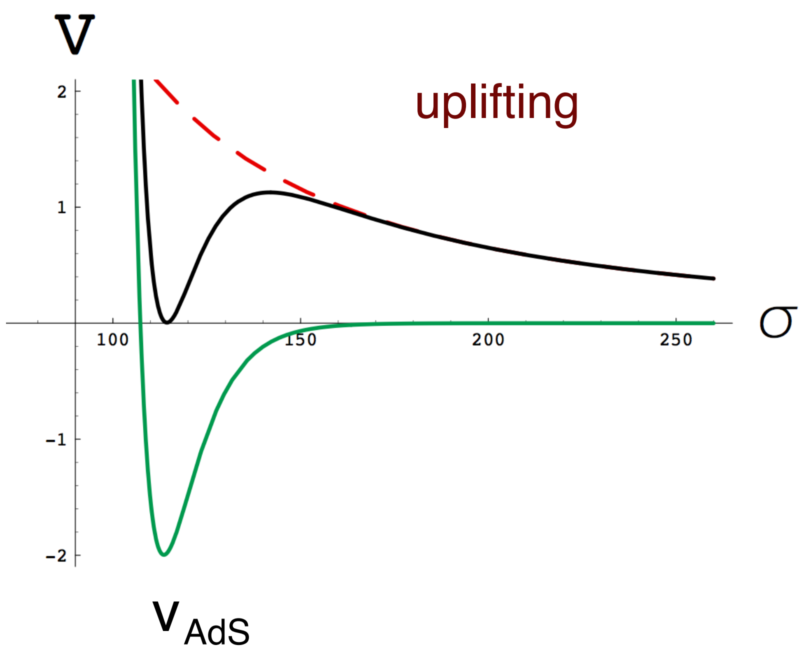
Uplifting to dS breaks SUSY

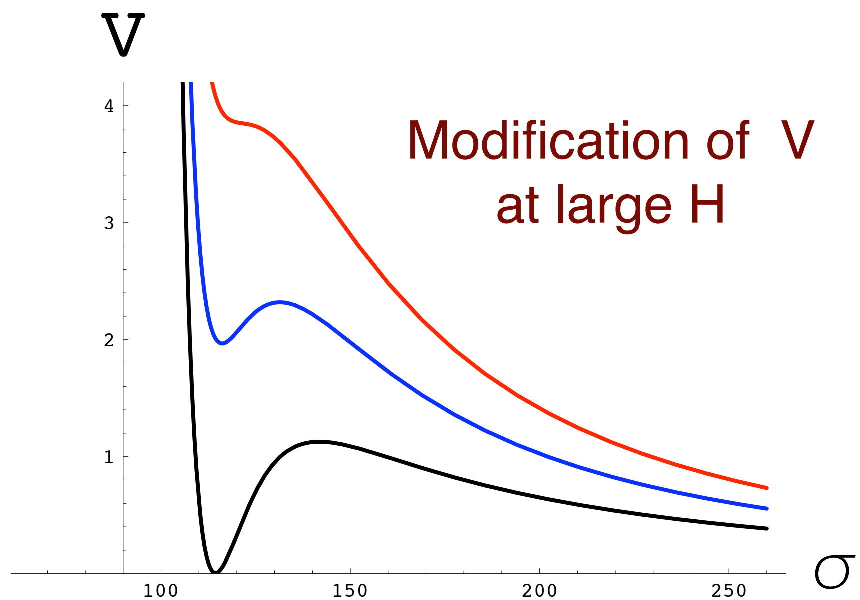
$$m_{3/2}^2 = |V_{\mathrm{AdS}}/3|$$

String Cosmology and the Gravitino Mass

Kallosh, A.L. 2004

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





Constraint on the Hubble constant in this class of models:

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

Tensor modes in CMB and gravitino

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

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

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

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 SUSY phenomenology

Modern versions of string theory

Discovery of SUSY particles at LHC

Discovery of gravity waves

Any 2 of these 3 items are compatible with each other. Can all 3 of them live in peace?

There are several ways to address this issue, see e.g. Kallosh, A.L. 2004; Badziak and M. Olechowski 2008, 2010; Conlon, Kallosh, A.L. and Quevedo 2008; He, Kachru and Westphal 2010. We will describe the first of these approaches.

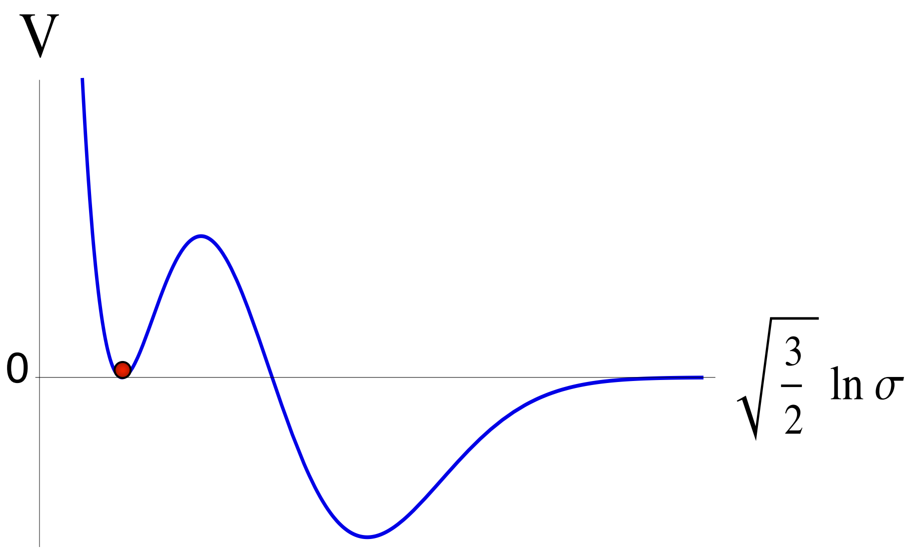
KL model

$$\mathcal{K} = -3\ln[(\rho+\bar\rho)]$$

Kallosh, A.L. 2004

$$W = W_0 + Ae^{-a\rho} - Be^{-b\rho}$$

$$W_0 = -A\left(\frac{a\,A}{b\,B}\right)^{\frac{a}{b-a}} + B\left(\frac{a\,A}{b\,B}\right)^{\frac{b}{b-a}} + \Delta W$$



It has a supersymmetric Minkowski vacuum for $\Delta W = 0$, with a high barrier.

ΔW makes it a supersymmetric AdS.

Uplifting breaks SUSY

$$m_{3/2} \sim |\Delta W|$$

Thus one can have a high barrier and a tiny gravitino mass

H can be arbitrarily large

This model requires fine-tuning:

$$\Delta W \sim m_{3/2} \sim 10^{-15}$$

This is similar to what we had in the Polonyi model, where we needed to add an extra field Z with the superpotential,

$$\Delta W = \mu(Z + \beta)$$

to fine-tune the cosmological constant to 0 ($\beta = 2 - \sqrt{3}$)
and then to fine-tune the gravitino mass,

$$\Delta W \sim m_{3/2}\,(Z + 2 - \sqrt{3}) \sim 10^{-15}$$

This is the usual price for the SUSY “solution” of the hierarchy problem

Bringing it all together: Chaotic inflation + KL stabilization

Kallosh, A.L., Olive, Rube, 1106.6025

$$K = K_{\text{inf}}((\Phi - \bar{\Phi})^2, S\bar{S}) - 3\log(\rho + \bar{\rho})$$

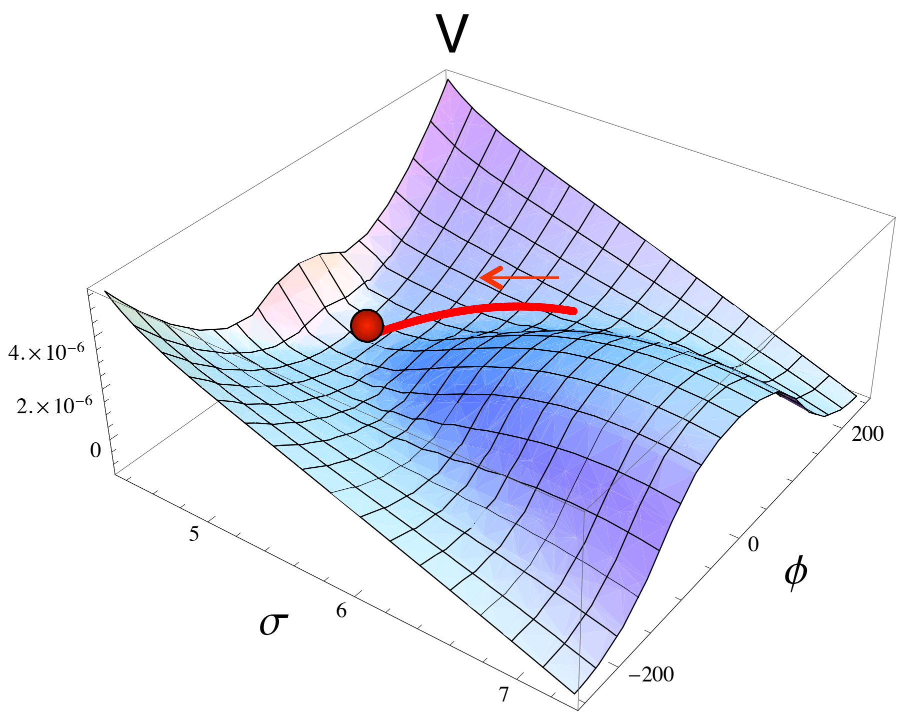
$$W = Sf(\Phi) + W_0 + Ae^{-a\rho} - Be^{-b\rho} + \Delta W$$

Even if one does not ensure stabilization of the S field, inflation is possible, especially if its energy scale is much smaller than the height of the KL barrier

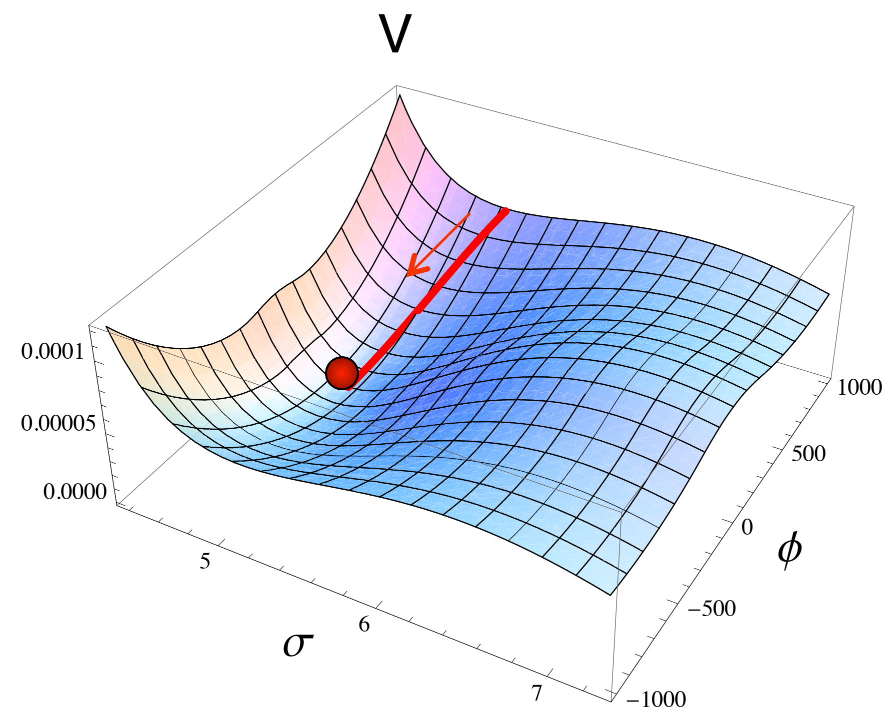
Davis, Postma 2008

However, if one firmly stabilizes S field near S = 0, e.g. by terms S^4 in the Kahler potential, inflation inflation occurs in a much greater range of the values of the inflaton field. The description of inflation decouples from the KL sector, which becomes important only for the low-scale SUSY breaking.

Bringing it all together: Chaotic inflation + KL stabilization



no S stabilization
short inflation
Davis, Postma 2008



S and σ are stabilized
long inflation
Kallosh, A.L., Olive, Rube 2011

Reheating in the theories with flat directions

In the models where $K_{\rm infl} = \Phi\bar{\Phi}$ there is a generic interaction of the inflaton field with all scalars in the observable sector, which results in the decay rate

$$\Gamma \sim 10^{-2}\frac{m_\phi^3}{M_p^2}$$

There is **no such decay** in our models where the Kahler potential does not depend on the inflaton field

Reheating occurs only because of the coupling to gauge fields

$$-\tfrac{1}{4}({\rm Re}\, h_{\alpha\beta})F^\alpha_{\mu\nu}F^{\beta\mu\nu} + \tfrac{i}{4}({\rm Im}\, h_{\alpha\beta})\epsilon^{\mu\nu\rho\sigma}F^\alpha_{\mu\nu}F^{\beta\rho\sigma}$$

This may contain the inflaton coupling to gauge fields

$$-\frac{d\delta_{\alpha\beta}}{4\sqrt{2}}\phi F^\alpha_{\mu\nu}F^{\beta\mu\nu}$$

This interaction results in the decay rate for the inflaton field

$$\Gamma(\phi \to A_\mu A_\mu) \sim 10^{-2} \times d^2 \ \frac{m_\phi^3}{M_p^2}$$

COBE normalization requires

$$m_\phi \sim 6 \times 10^{-6}$$

In this case the reheating temperature, which is proportional to $\Gamma^{1/2}$ is given by

$$T_R \sim d \times 10^9 \ \mathrm{GeV}$$

For d < 0.1, this temperature is low enough to avoid the primordial gravitino problem

Conclusions

A simple class of chaotic inflation models in supergravity is developed. The inflaton potential can have an arbitrary shape determined by the choice of the superpotential $W = Sf(\Phi)$. This allows to describe observations with any values of n_s and r.

Depending on the choice of the Kahler potential, these models may describe a single-field inflation with gaussian perturbations of metric, or a curvaton scenario with large non-gaussianity. This provides additional flexibility to fit observational data.

One can unify this scenario with the KL model of moduli stabilization in string theory, which may help us to describe small scale SUSY breaking and solve the cosmological moduli problem

There is a natural suppression of the decay rate of the inflaton field in this class of models, which helps to solve the primordial gravitino problem in this scenario.