High Scale Natural Inflation and Low Energy Supersymmetry

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Outline

- Flatness of the inflationary potential
- Natural (axionic) inflation
- Planck satellite data
- the question of potentially large tensor modes
- the scale of supersymmetry breakdown

Large tensor modes

- require trans-Planckian excursion of inflaton field.
- What is the role of the axion decay constant?

(Kappl, Krippendorf, Nilles, 2014; Kim, Nilles, Peloso, 2004)

March Fever

Following the BICEP2 announcement March 2014 there has been some activity concerning the alignment mechanism of KNP.

Choi, Kim, Yun
Higaki, Takahashi,
Tye, Wong,; McDonald; Harigaya, Ibe
Bachlechner, Dias, Frazer, McAllister
Ben-Dayan, Pedro, Westphal
Long, McAllister, McGuirk
Kim; Dine, Draper, Monteux;
Choi, Kyae; Maity, Saha
Higaki, Kobayashi, Seto, Yamaguchi
Li, Li, Nanopoulos
Gao, Li, Shukla ....

The Quest for Flatness

The mechanism of inflation requires a “flat” potential. We consider

- symmetry reason for flatness of potential
- slightly broken symmetry to move the inflaton

The obvious candidate is axionic inflation

- axion has only derivative couplings to all orders in perturbation theory
- broken by non-perturbative effects (instantons)

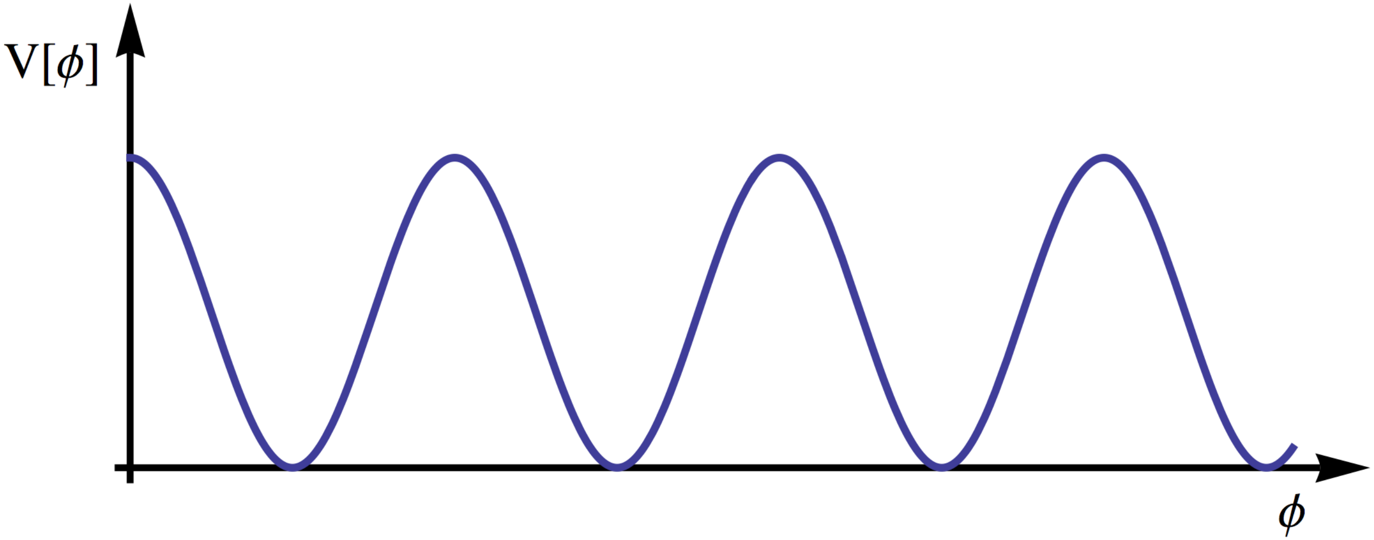
Motivated by the QCD axion

(Freese, Frieman, Olinto, 1990)

The Axion Potential

The axion exhibits a shift symmetry $\phi \to \phi + c$

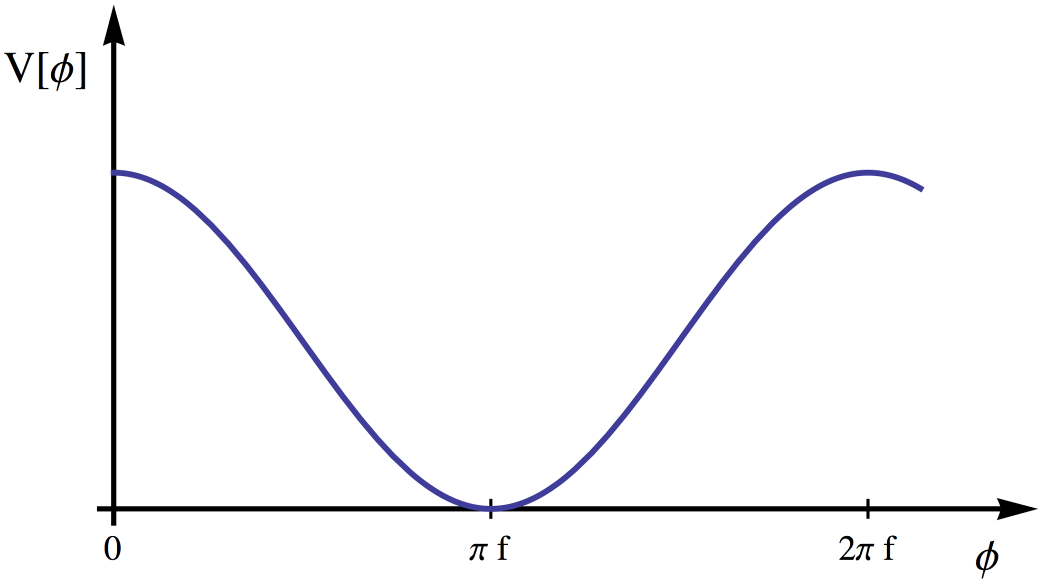
Nonperturbative effects break this symmetry to a remnant discrete shift symmetry



$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{2\pi\phi}{f}\right)\right]$$

The Axion Potential

Discrete shift symmetry identifies $\phi = \phi + 2\pi n f$

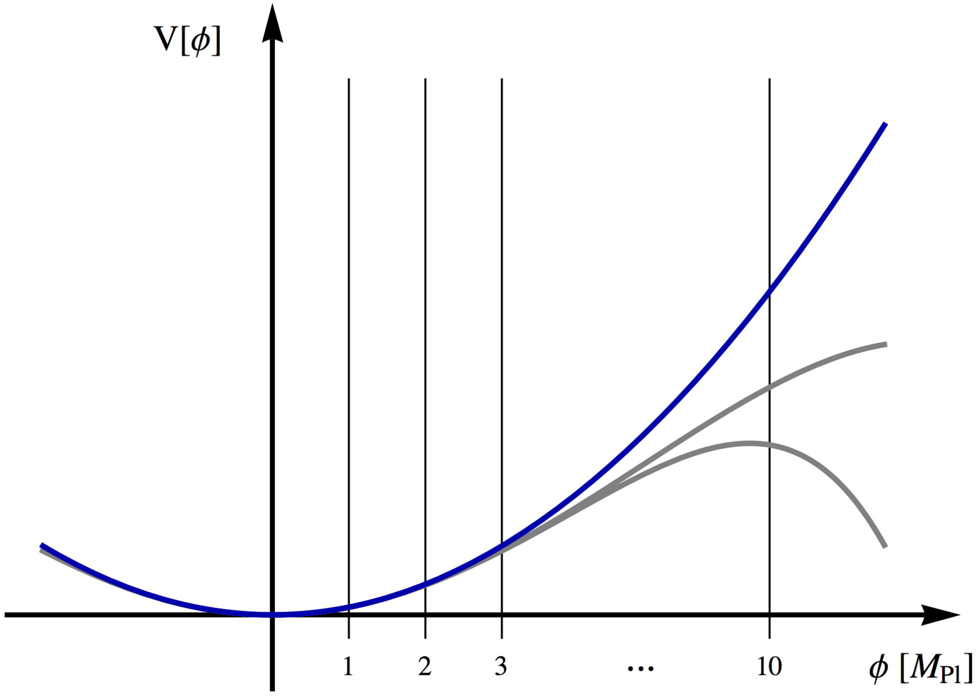


$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{2\pi\phi}{f}\right)\right]$$

ϕ confined to one fundamental domain

“Gravitational backreaction”

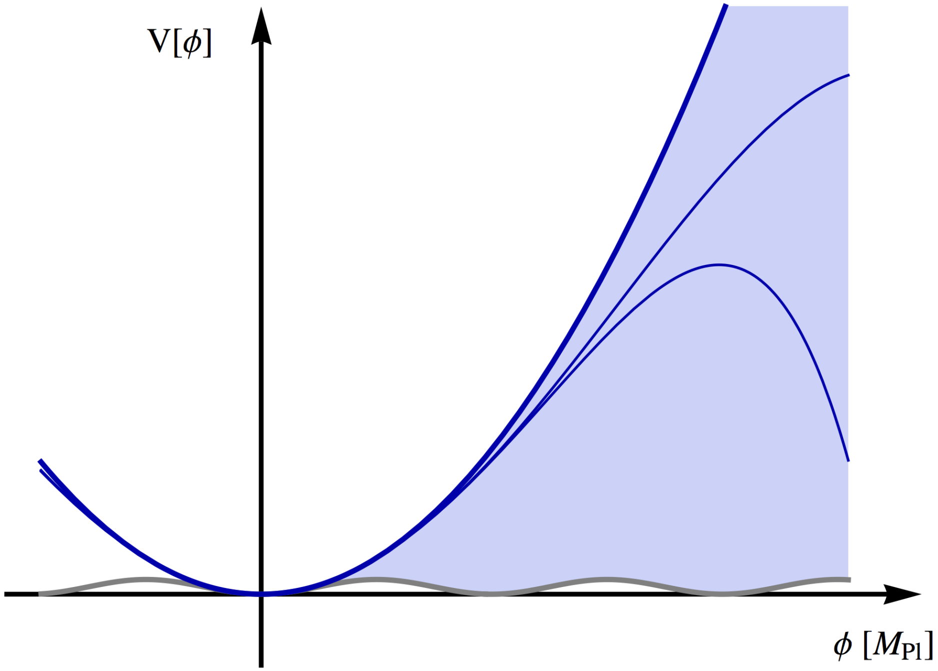
leads to uncertainties at trans-Planckian field values



$$V(\phi) = m^2\phi^2 + \sum c_n \frac{\phi^n}{M_{\rm Planck}^{n-4}}$$

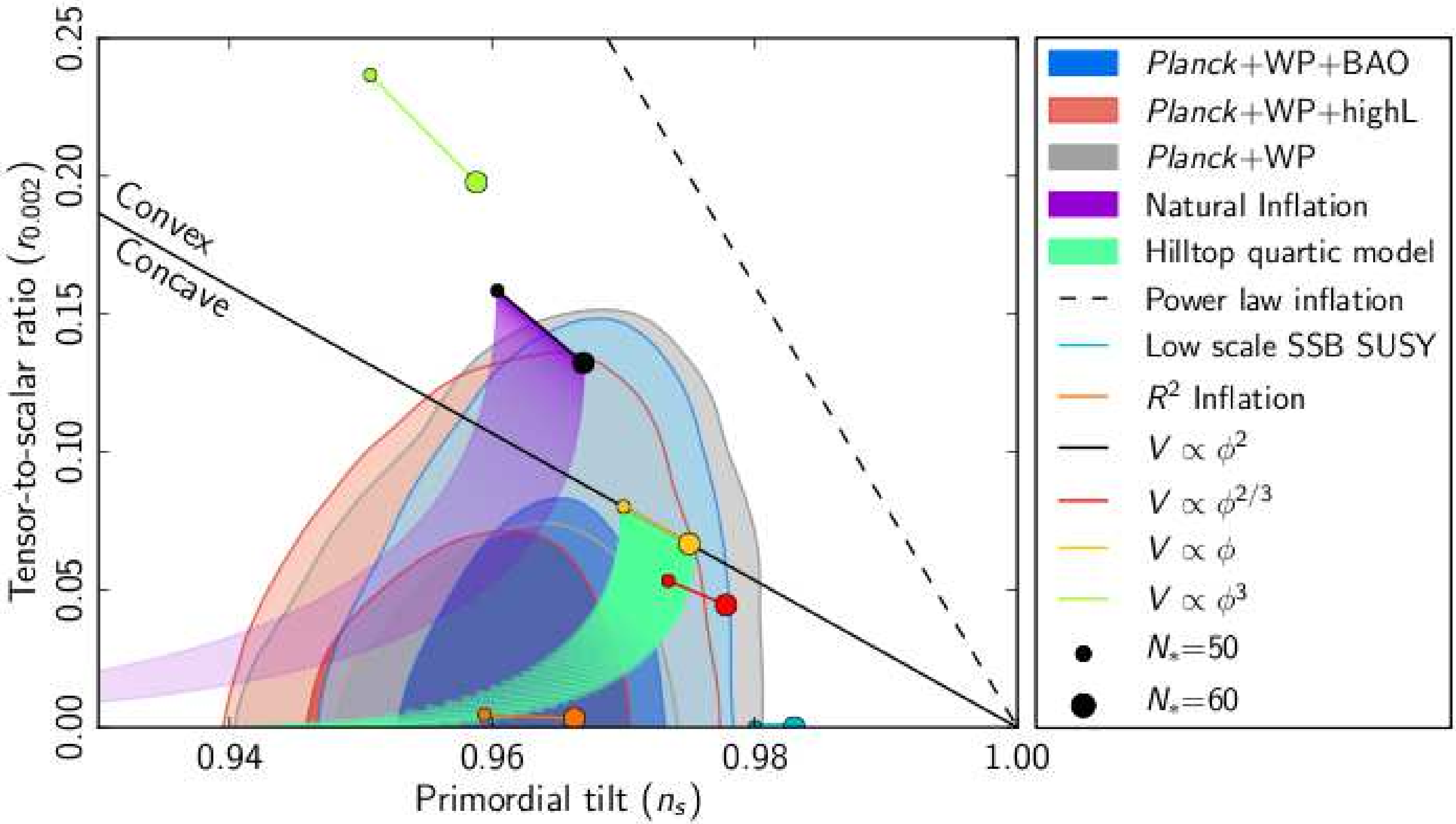
The power of shift symmetry

The discrete shift symmetry controls these corrections



$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{2\pi\phi}{f}\right)\right] + \sum c_n \frac{\phi^n}{M_{\rm Planck}^{n-4}}$$

Planck results (Spring 2013)



BICEP2 (Spring 2014)

Tentatively large tensor modes of order $r \sim 0.1$ had been announced by the BICEP collaboration

- large tensor modes brings us to scales of physics close to the Planck scale and the so-called “Lyth bound”
- potential $V(\phi)$ of order of GUT scale few $\times 10^{16}$ GeV
- trans-Planckian excursions of the inflaton field
- For a quadratic potential $V(\phi) \sim m^2\phi^2$ it implies $\Delta\phi \sim 15 M_{\rm P}$ to obtain 60 e-folds of inflation

Axionic inflation, on the other hand, seems to require the decay constant to be limited: $f \leq M_{\rm P}$.

So this might be problematic.

Solution

A way out is the consideration of two (or more) fields.

(Kim, Nilles, Peloso, 2004)

- we still want to consider symmetries that keep gravitational corrections under control
- discrete (gauge) symmetries are abundant in explicit string theory constructions (Lebedev et al., 2008; Kappl et al. 2009)
- these are candidates for axionic symmetries
- embedding natural inflation in supergravity requires in any case more fields, as e.g. a so-called stabilizer field

(Kawasaki, Yamaguchi, Yanagida, 2001)

Still: we require $f \leq M_{\rm P}$ for the individual axions

The KNP set-up

We consider two axions

$$\mathcal{L}(\theta,\rho) = (\partial\theta)^2 + (\partial\rho)^2 - V(\rho,\theta)$$

with potential

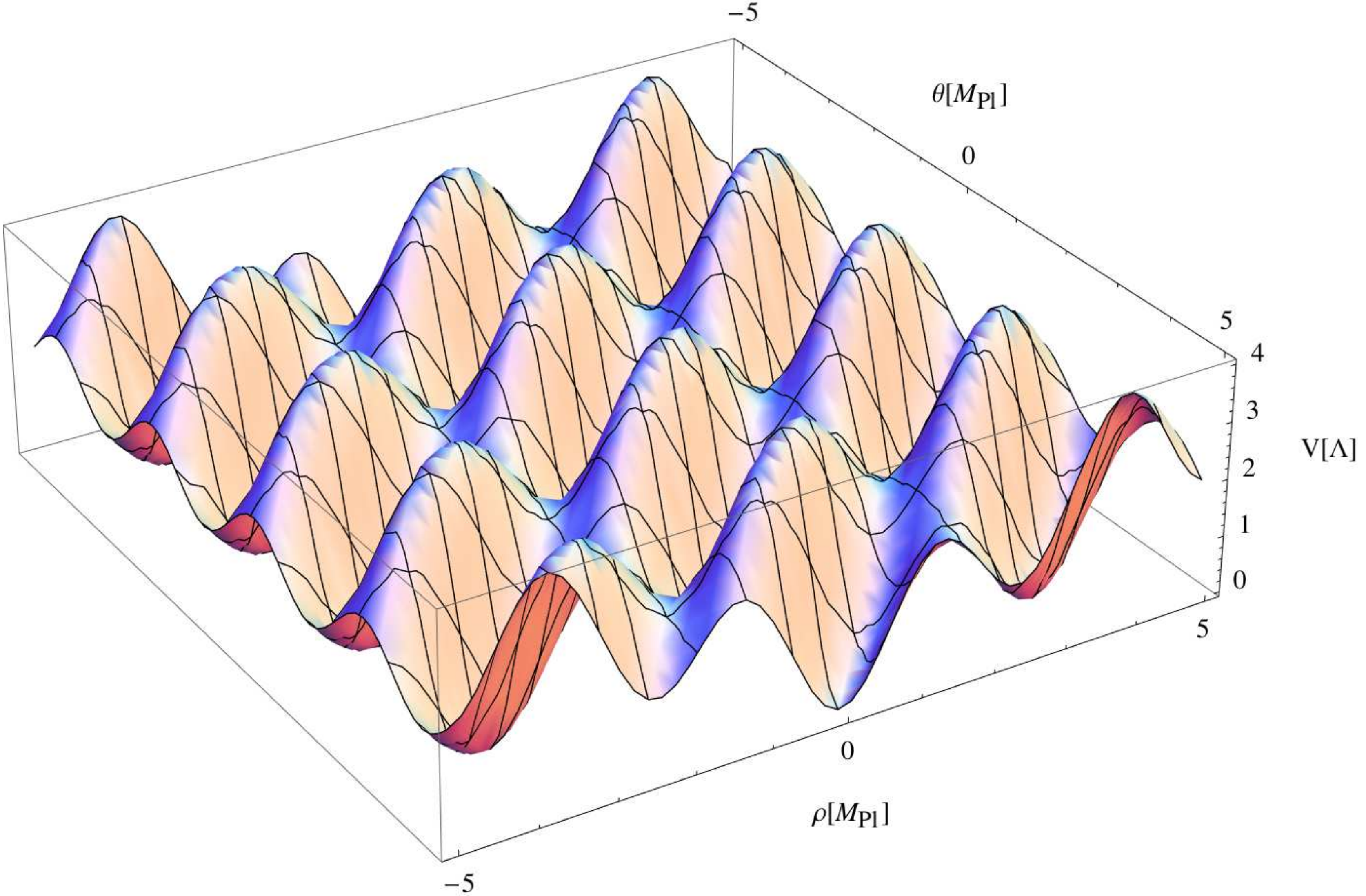
$$V(\theta,\rho) = \Lambda^4 \left(2 - \cos\left(\frac{\theta}{f_1} + \frac{\rho}{g_1}\right) - \cos\left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right)$$

This potential has a flat direction if $\frac{f_1}{g_1} = \frac{f_2}{g_2}$

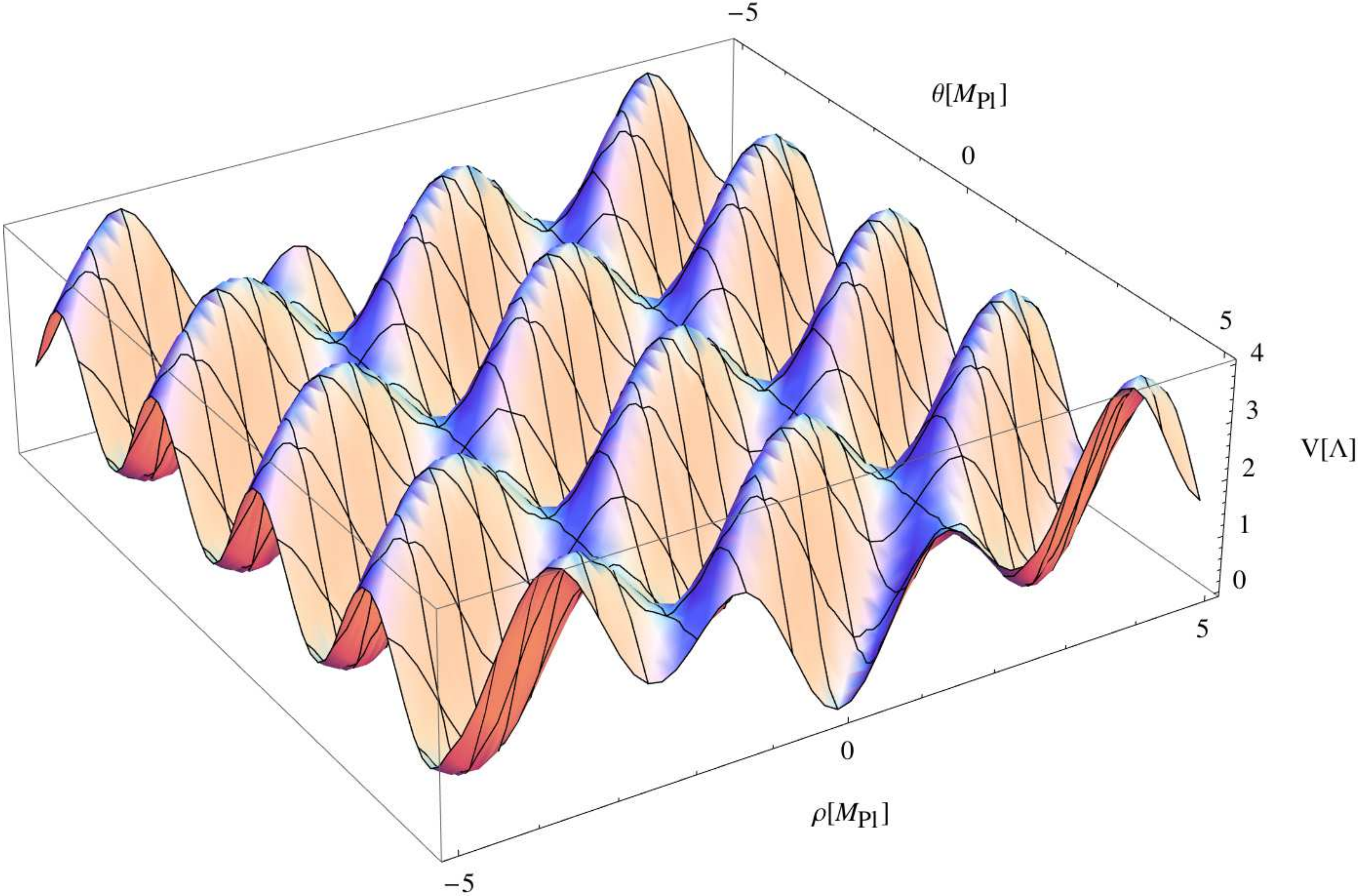
Alignment parameter defined through $\alpha = g_2 - \frac{f_2}{f_1} g_1$

For $\alpha = 0$ we have a massless field ξ.

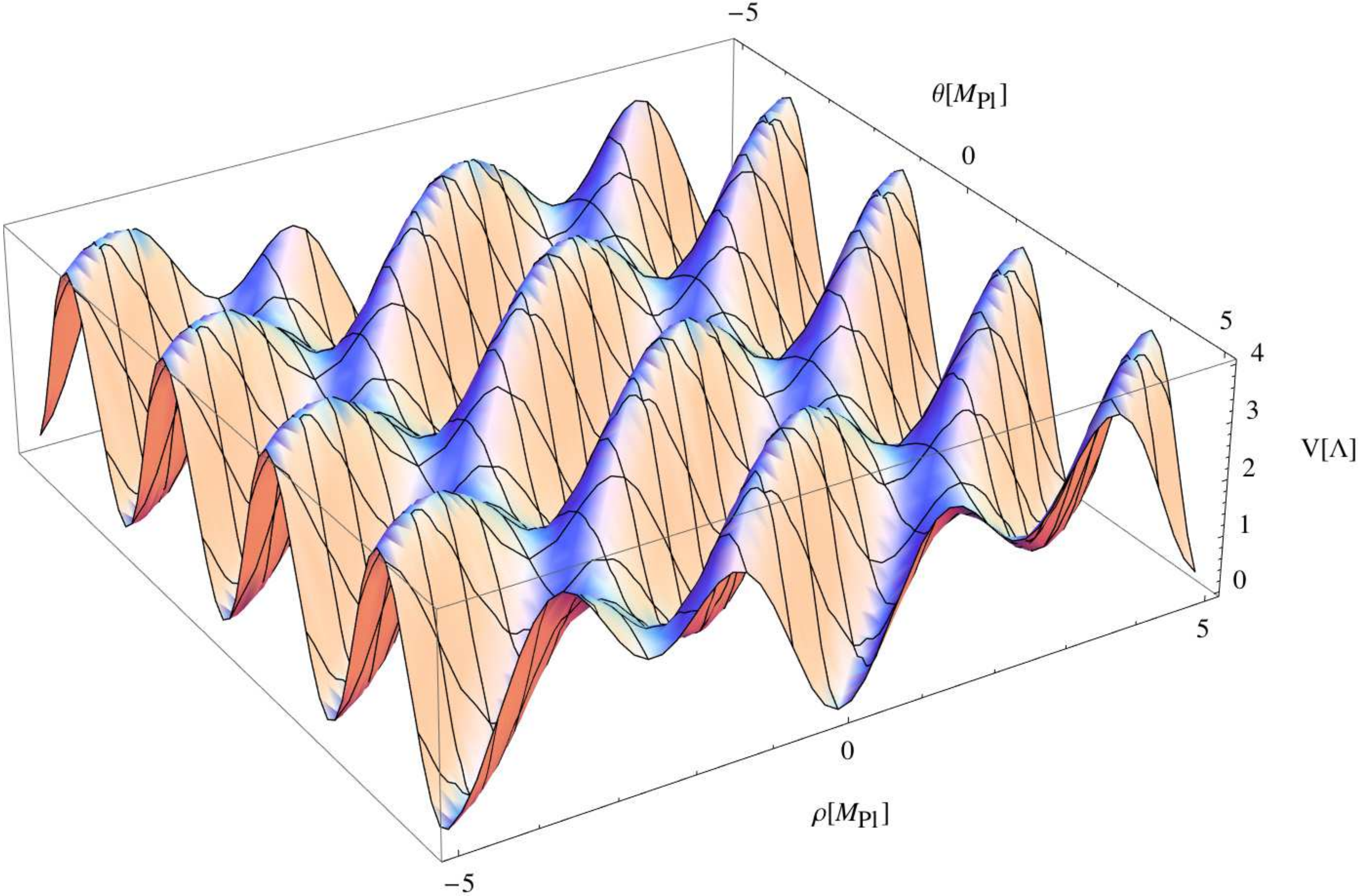
Potential for $\alpha = 1.0$



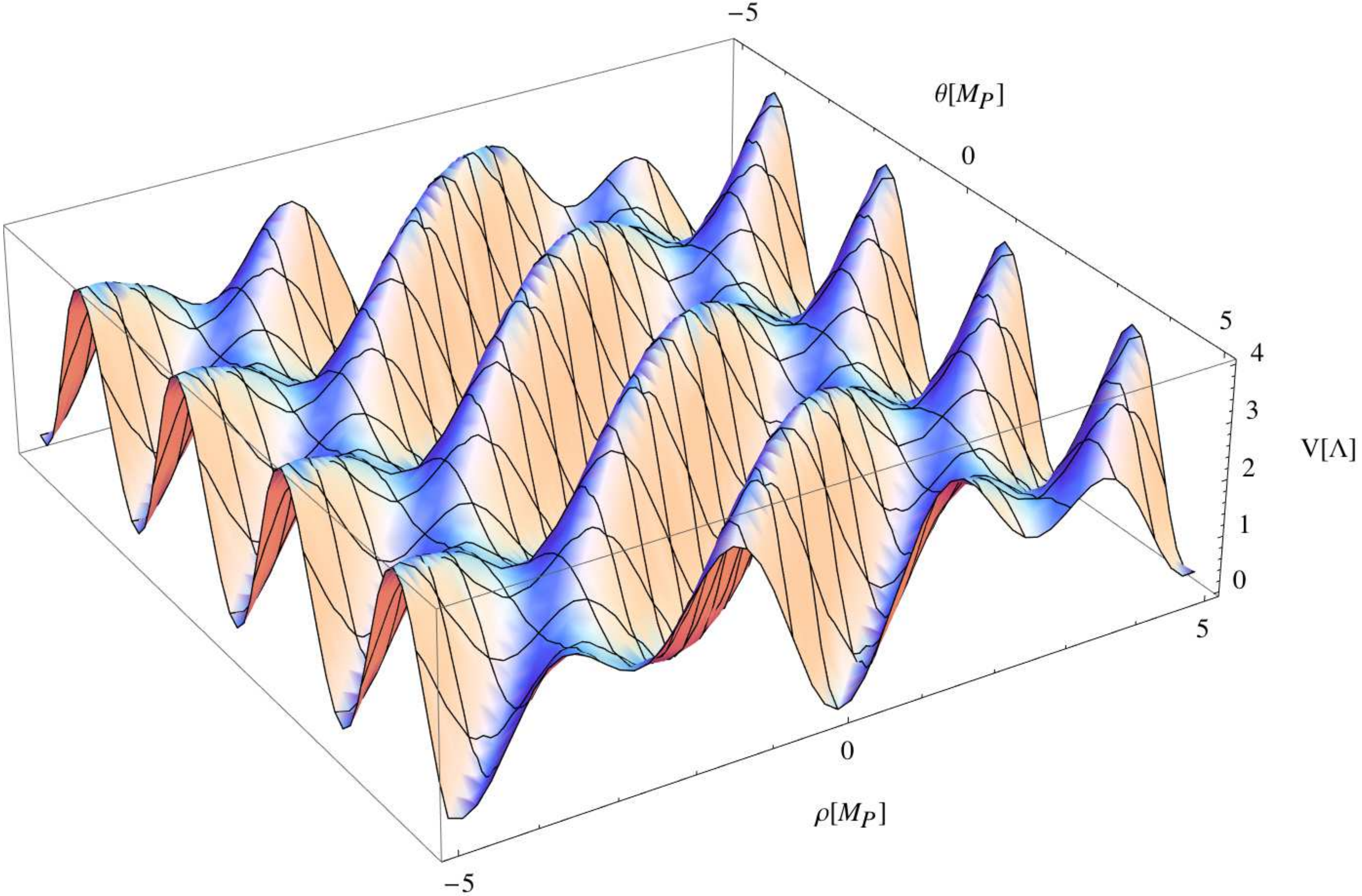
Potential for $\alpha = 0.8$



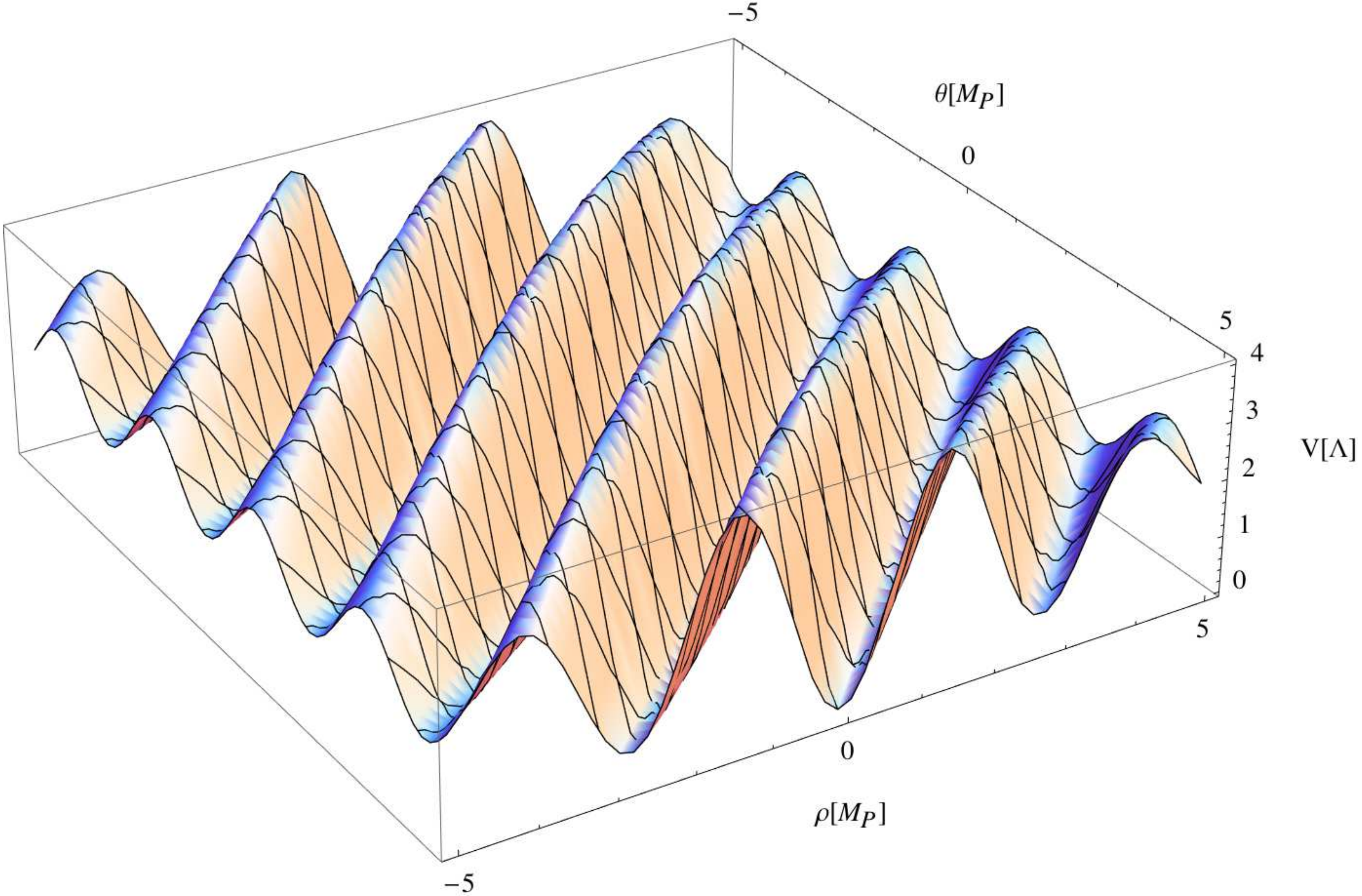
Potential for $\alpha = 0.5$



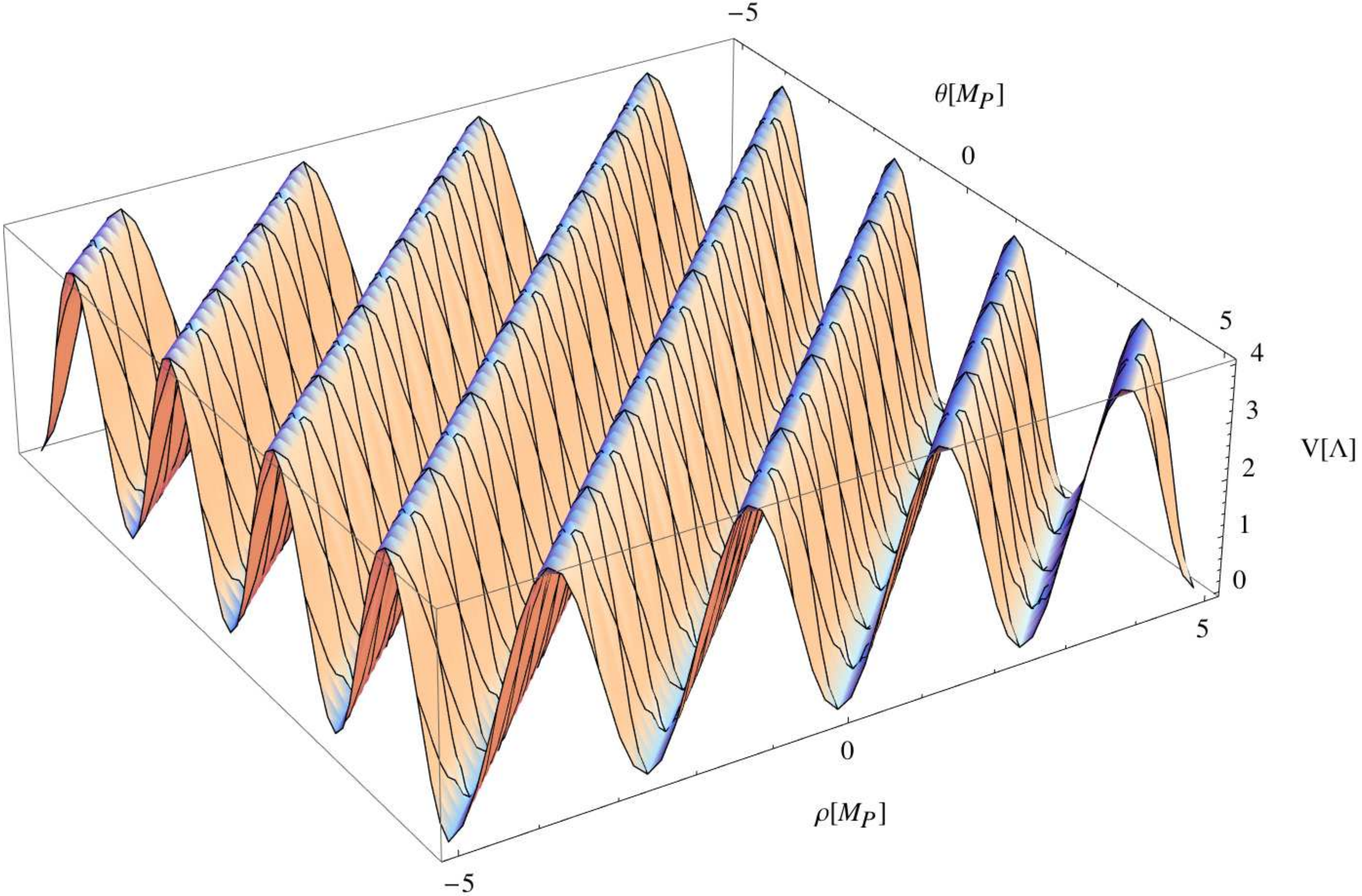
Potential for $\alpha = 0.3$



Potential for $\alpha = 0.1$



Potential for $\alpha = 0$



The lightest axion

Mass eigenstates are denoted by (ξ, ψ). The mass eigenvalues are

$$\lambda_{1/2} = F \pm \sqrt{F^2 + \frac{2g_1g_2f_1f_2 - f_2^2g_1^2 - f_1^2g_2^2}{f_1^2f_2^2f_1^2g_2^2}}$$

with $$F = \frac{g_1^2g_2^2(f_1^2+f_2^2)+f_1^2f_2^2(g_1^2+g_2^2)}{2f_1^2f_2^2g_1^2g_2^2}$$

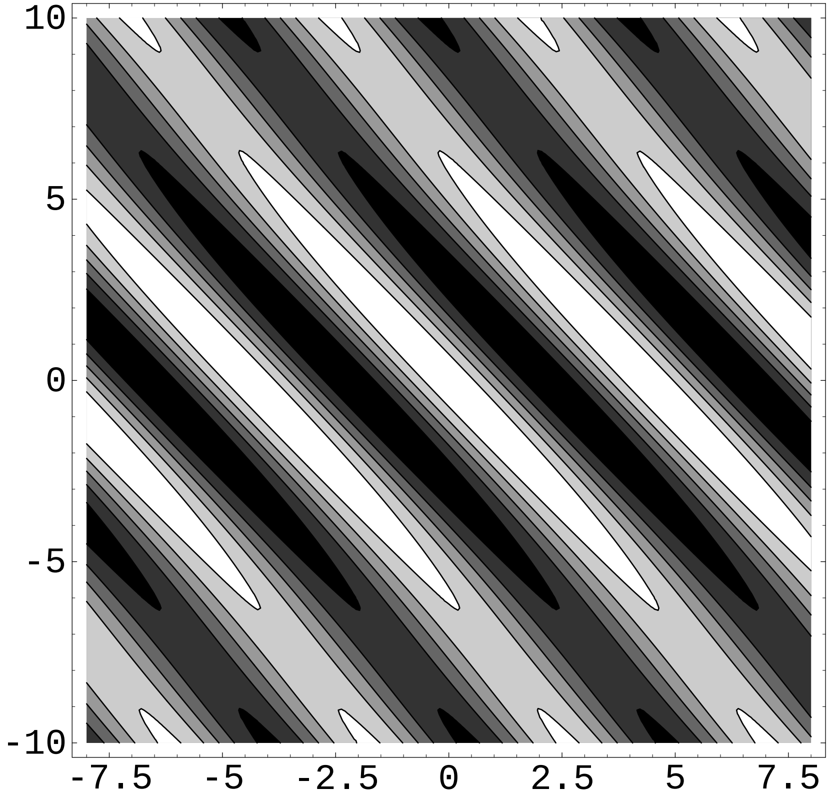
Lightest axion ξ has potential

$$V(\xi) = \Lambda^4\left[2 - \cos\left(m_1(f_i, g_1, \alpha)\xi\right) - \cos\left(m_2(f_i, g_1, \alpha)\xi\right)\right]$$

leading effectively to a one-axion system

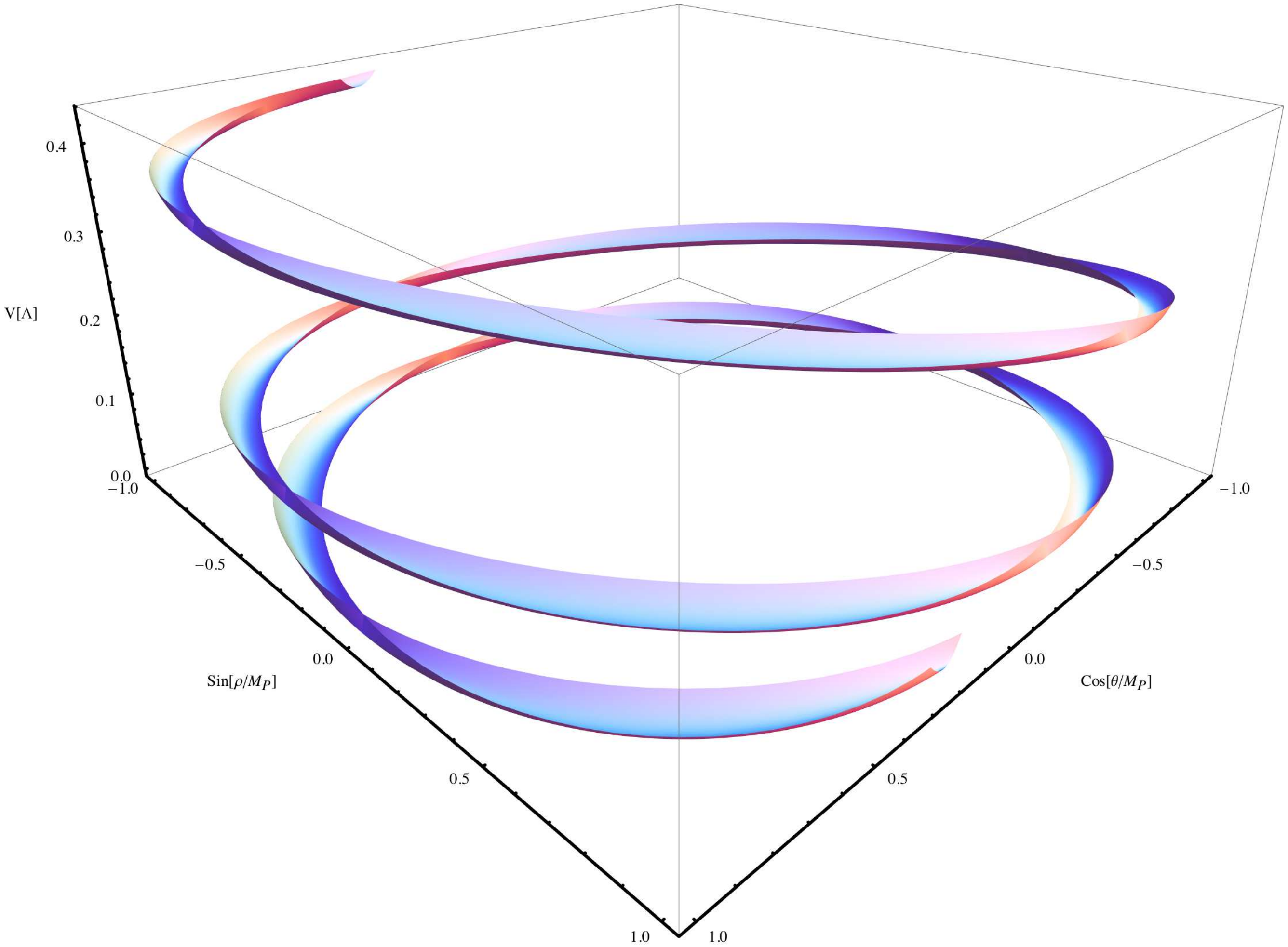
$$V(\xi) = \Lambda^4\left[1 - \cos\left(\frac{\xi}{\tilde{f}}\right)\right]$$ with $$\tilde{f} = \frac{f_2g_1\sqrt{(f_1^2+f_2^2)(f_1^2+g_1^2)}}{f_1^2\alpha}$$

Axion landscape of KNP model



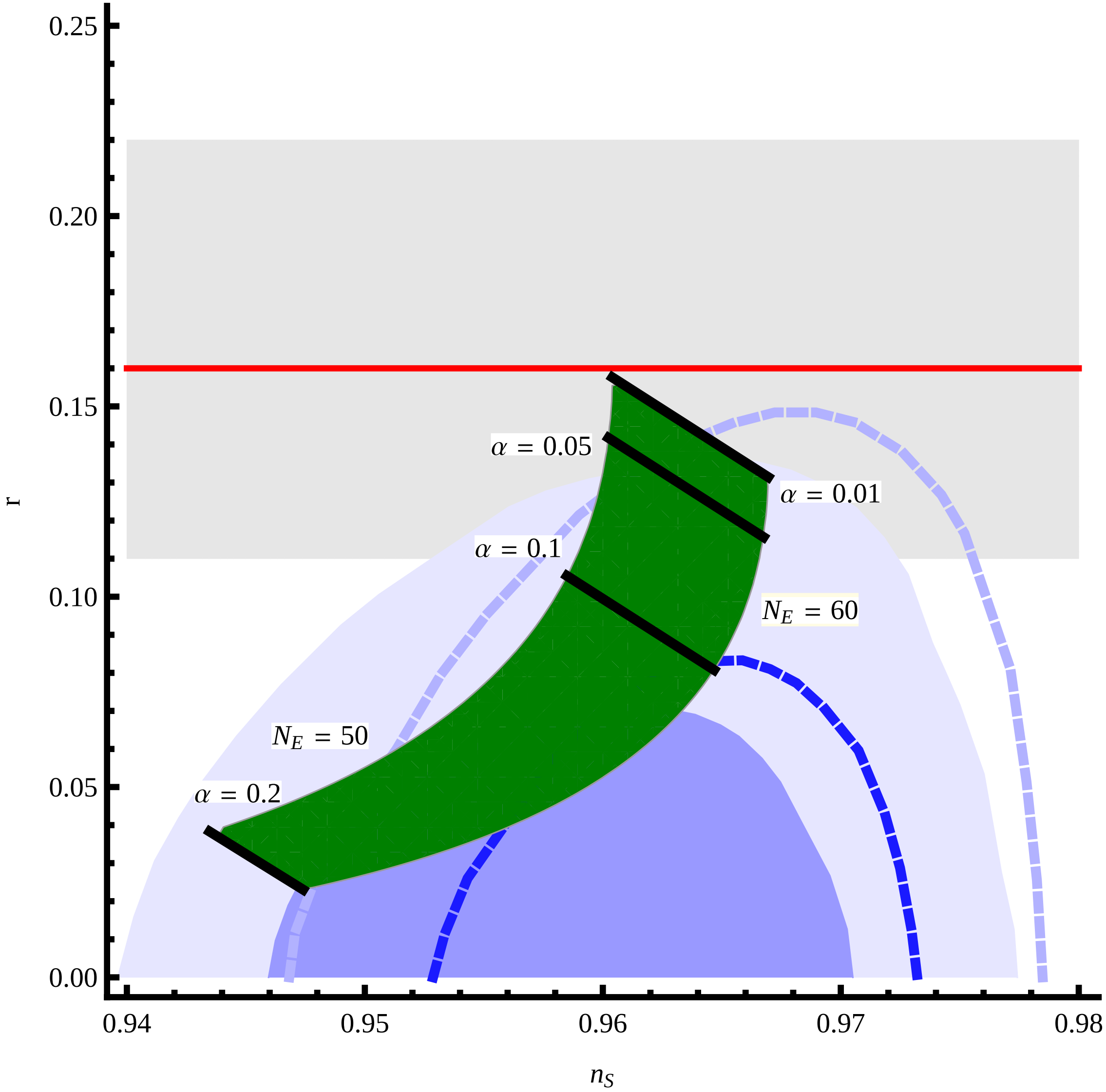
The field ξ rolls within the valley of ψ. The motion of ξ corresponds to a motion of θ and ρ over many cycles. The system is still controlled by discrete symmetries.

Monodromic Axion Motion



One axion spirals down in the valley of a second one.

The “effective” one-axion system



UV-Completion (string theory)

Large tensor modes and $\Lambda \sim 10^{16}$GeV lead to theories at the “edge of control” and require a reliable UV-completion

- small radii
- large coupling constants
- light moduli might spoil the picture

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Large tensor modes and $\Lambda \sim 10^{16}$GeV lead to theories at the “edge of control” and require a reliable UV-completion

- small radii
- large coupling constants
- light moduli might spoil the picture

So it is important to find reliable symmetries

- axions are abundant in string theory
- perturbative stability of “shift symmetry”
- broken by nonperturbative effects
- discrete shift symmetry still intact

The potential role of Supersymmetry

So far our discussion did not consider supersymmetry.

- How to incorporate axion inflation in a Susy-framework?
- A possible set-up for natural inflation would be

$$W = W_0 + A \exp(-a\rho); \quad K \sim (\rho + \bar{\rho})^2$$

For a simple form of axionic inflation we have to assume that W_0 dominates in the superpotential

- this implies that Susy is broken at a large scale
- Does high scale inflation require high scale Susy breakdown?

Previous constructions are based on high scale Susy!

Susy and Natural Inflation

The standard way is to introduce a stabilizer field X.

$$W = m^2 X\left(e^{-a\rho} - \lambda\right), \quad K = \frac{(\bar\rho + \rho)^2}{4} + k(|X|^2) - \frac{|X|^4}{\Lambda^2}$$

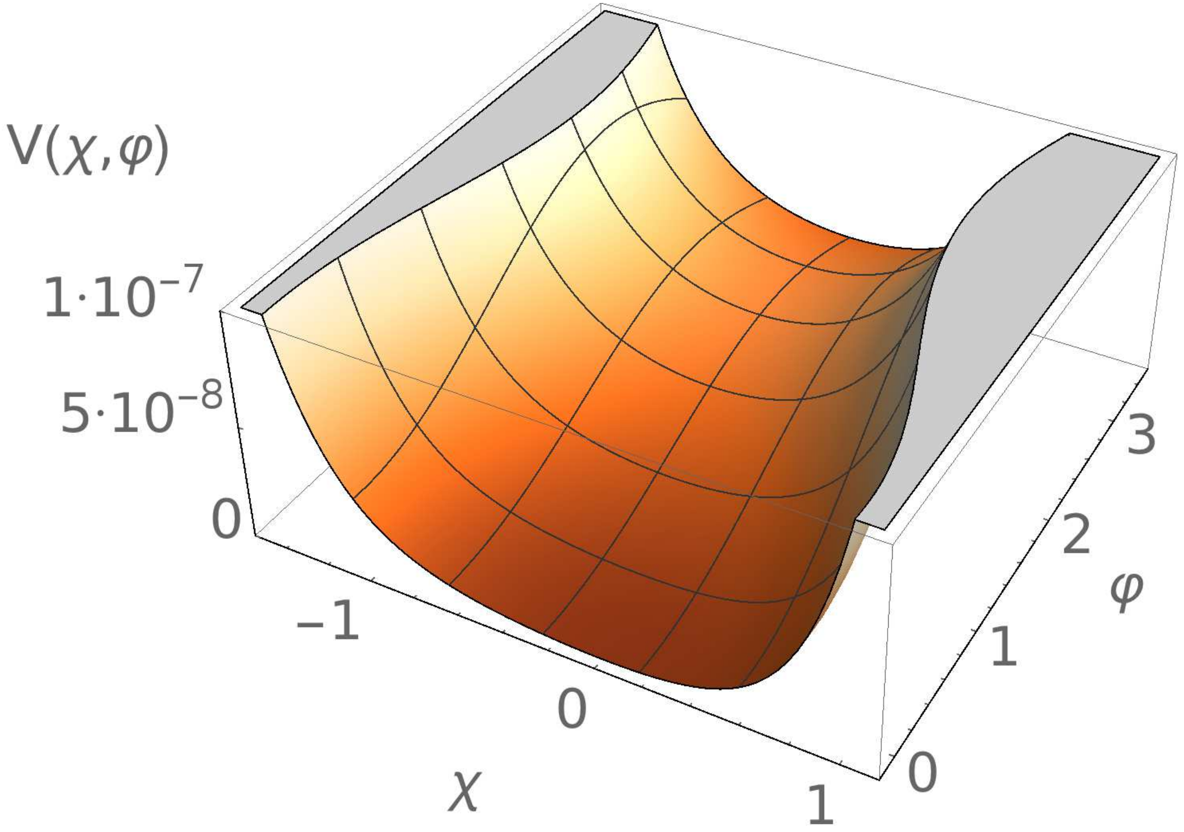
Supersymmetric ground state at $X = 0, \rho = \rho_0 = -\log(\lambda)/a$

$$V = \frac{m^4\, e^{-a(2\rho_0 + \chi)}}{\rho_0 + \chi}\left[\cosh\left(a\chi\right) - \cos\left(a\varphi\right)\right]$$

Susy is restored at the end of inflation.

Conclusion: additional fields help to incorporate Susy.

Trapped Saxion



The axion-saxion valley

Towards string theory

String theory contains many (moduli and matter) fields and stabilizers can be easily incorporated.

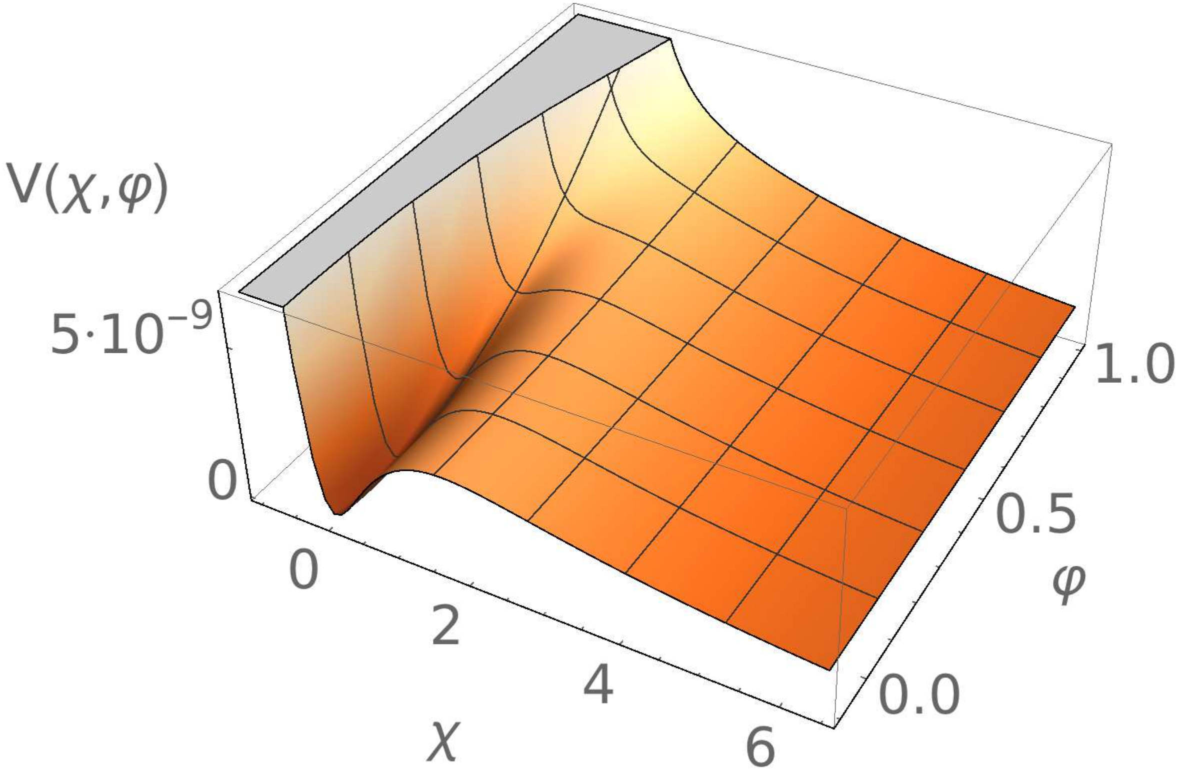
Challenge: we typically have $K = -\log(\rho + \bar{\rho})$ leading to

$$V = \frac{m^4 \, e^{-a(2\rho_0+\chi)}}{\rho_0 + \chi} \left[\cosh\left(a\chi\right) - \cos\left(a\varphi\right)\right] \, .$$

This destabilises the saxion field
(in the presence of low scale supersymmetry).

A successful model has to address the stabilisation of moduli fields.

Unstable Saxion



Potential run-off of saxion

The String Scenario

We have to achieve moduli fixing and trans-Planckian excursion of the inflaton field

- alignment of axions
- stabilisation of saxions and other moduli

This can be done with the help of flux superpotentials as well as gauge- and world-sheet-instantons

$$W = W_{\text{flux}} + \sum_i A_i e^{-2\pi n_i^\beta T_\beta} + \prod_i \phi_i e^{-S_{\text{inst}}(T_\beta)} ,$$

Still we have to make an effort to avoid high scale Susy.

(Kappl, Nilles, Winkler, 2015; Ruehle, Wieck, 2015)

A Benchmark Model

We start with two axions and stabilizer fields

$$W = \sum_{i=1}^{2} m_i^2 X_i \left(e^{-a_i \rho_1 - b_i \rho_2} - \lambda_i\right)$$

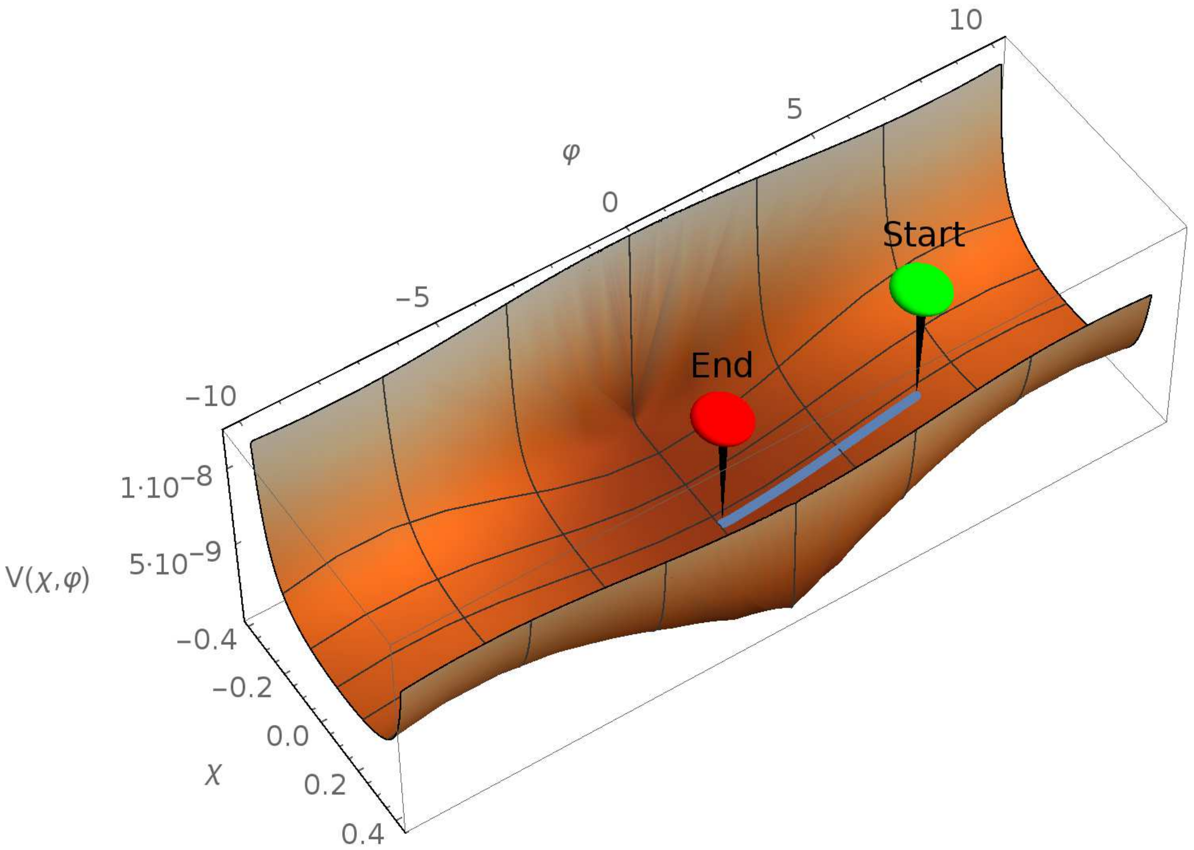
With this we can achieve

- a susy ground state at $X_{1,2} = 0$
- one heavy and one light combination of $\rho_i = \chi_i + i\varphi_i$

$$V = \frac{\lambda_1^2 m_1^4 \, e^{-\delta\chi} \left[\cosh(\delta\chi) - \cos(\delta\varphi)\right]}{2(\rho_{1,0} + b_2 \chi)(\rho_{2,0} - a_2 \chi)}$$

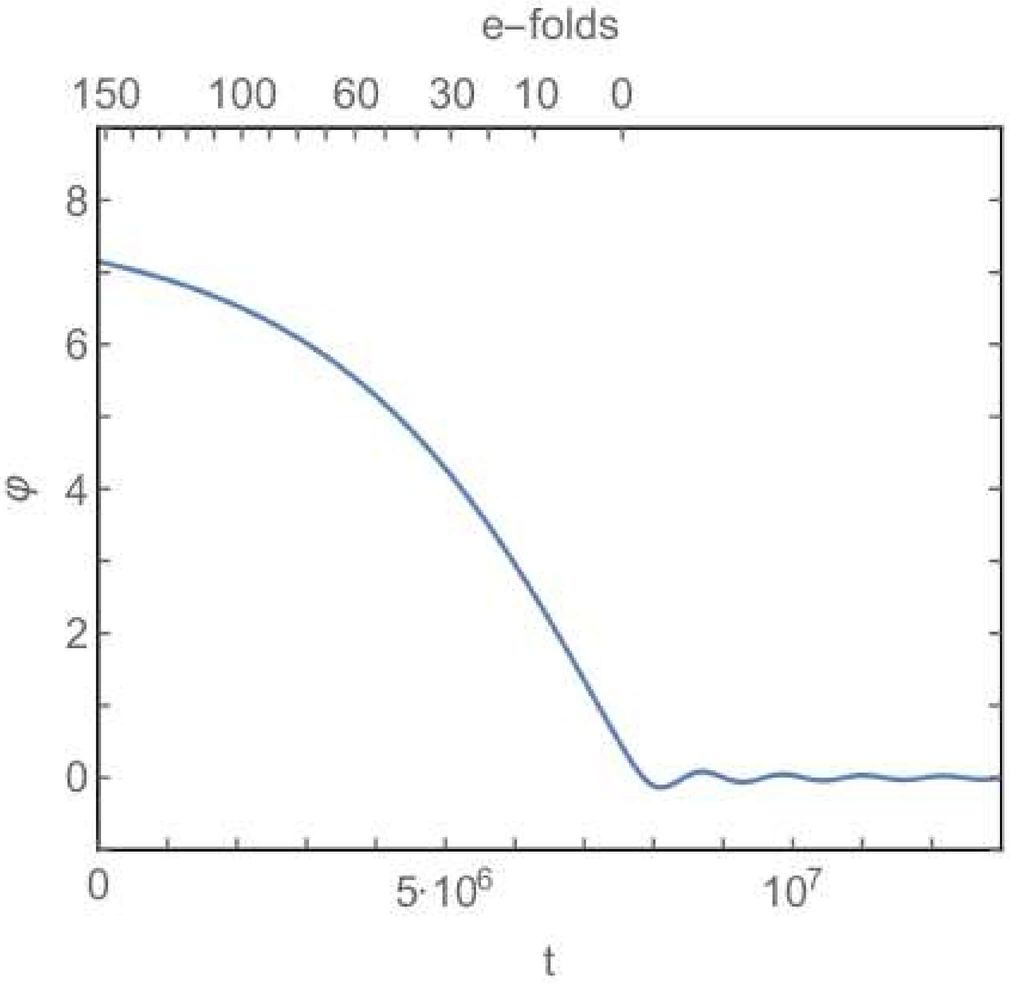
(Kappl, Nilles, Winkler, 2015)

Aligned Axion with Trapped Saxion

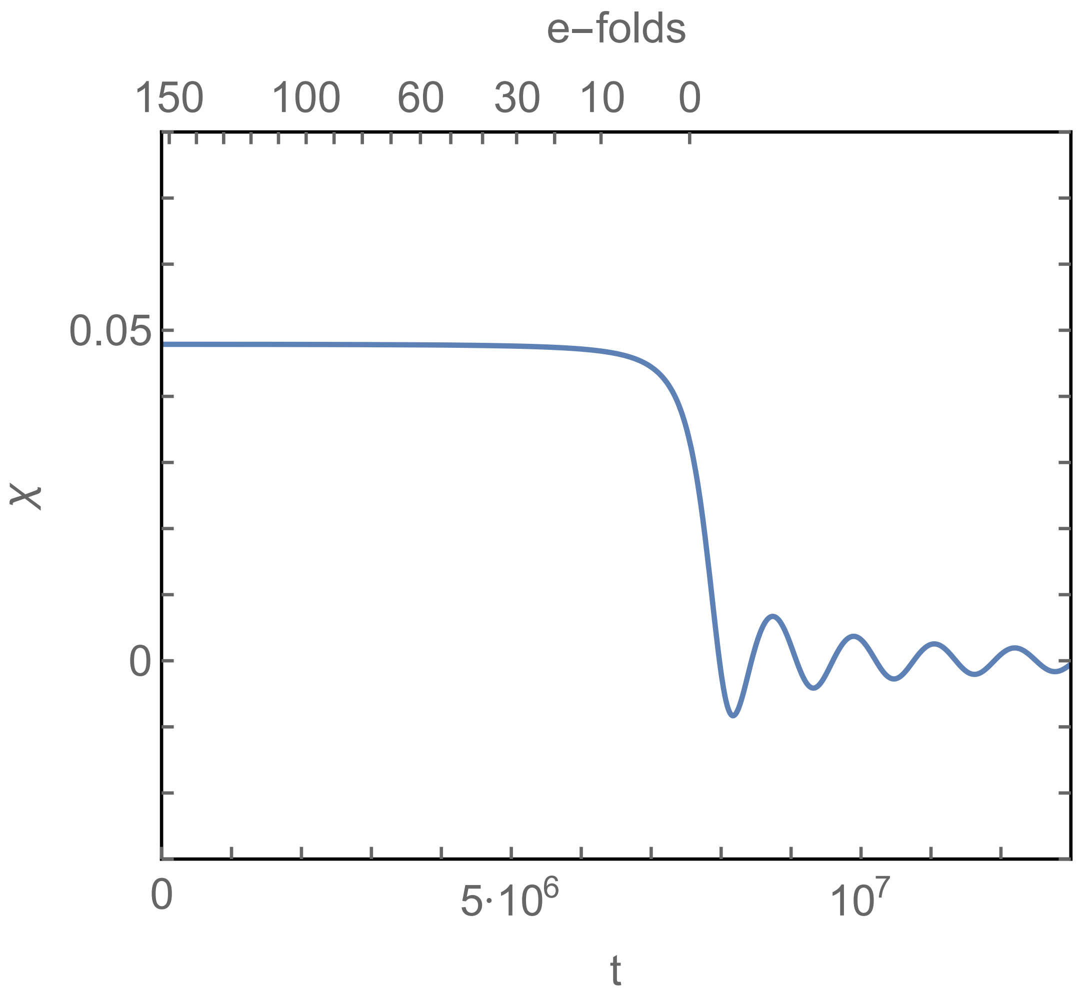


The valley is narrow (observe difference of scales)

Evolution of Axion



Evolution of Saxion



The saxion stays close to zero

Comparison with observations

In the extreme case, again, we have one effective axion with allowed trans-Planckian excursion.

But the other moduli and matter fields

- can influence the inflationary potential
- and might e.g. lead to a flattening of the potential

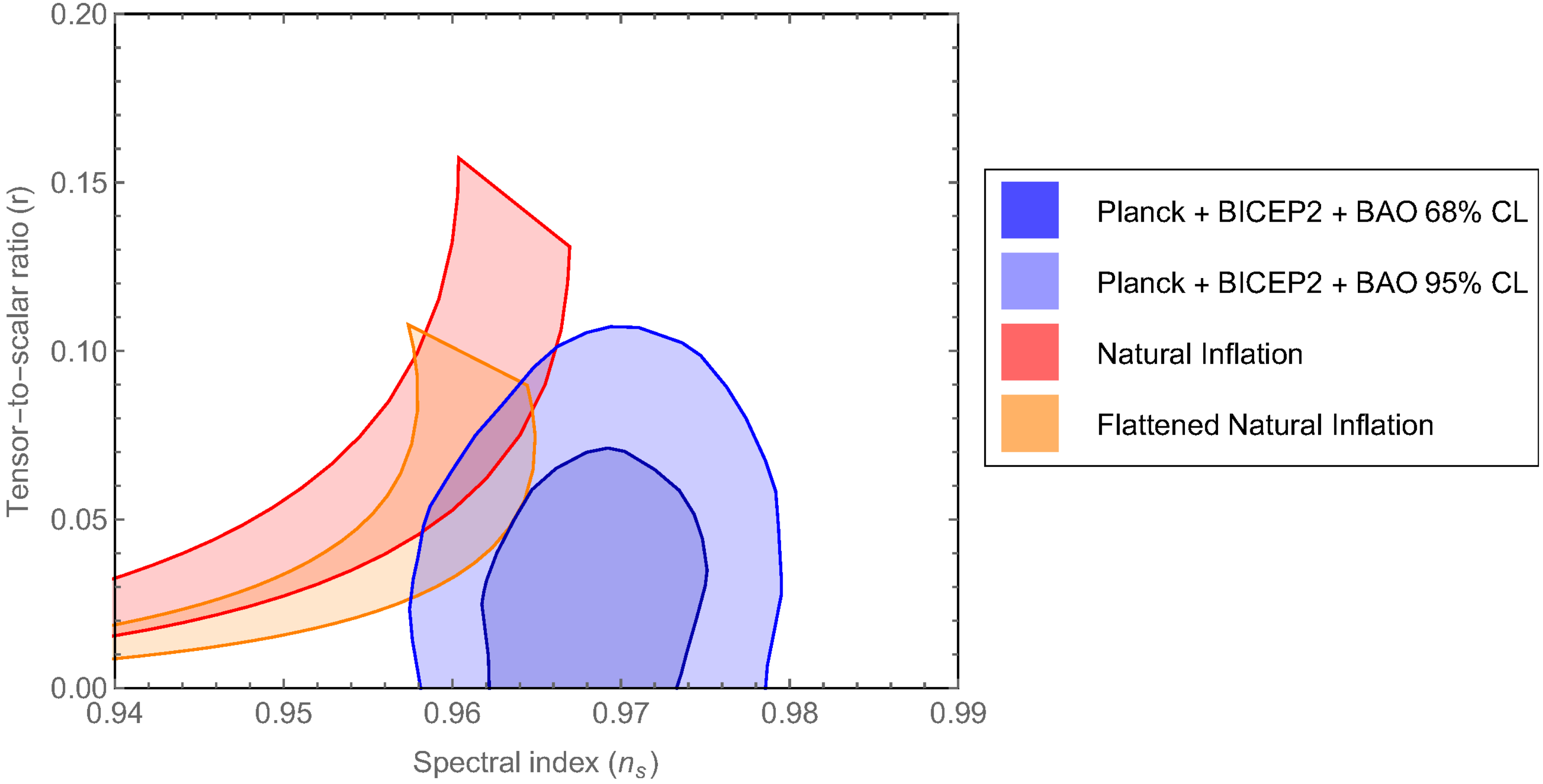
Comparison with data leads to an effective axion scale

$$f_{\text{eff}} \geq 5.8 M_{\text{Planck}}$$

Other limits give a stronger influence of the additional axions and allow a broader range of values in the n_s-r plane

(Peloso, Unal, 2015)

$n_s - r$ **plane**



(Kappl, Nilles, Winkler, 2015)

The quest for supersymmetry

High scale inflation prefers large scale susy breakdown.
The quest for low scale supersymmtery requires

- additional fields and
- a specific form of moduli stabilization.

The alignment of axions

- allows trans-Planckian excursions of the inflation,
- favours the appearance of low energy supersymmetry.

In the simplest case we obtain an effective one-axion system with a “trapped" saxion field.

(Kappl, Nilles, Winkler, 2015)

Bottom-up approach

A successful model of inflation needs a flat potential and this is a challenge (in particular for models with sizeable tensor modes.)

- flatness of potential requires a symmetry
- axionic inflation is the natural candidate

In bottom-up approach one postulates a single axion field

- but already in the framework of supergravity one needs more fields, e.g. the so-called stabilizer field

(Kawasaki, Yamaguchi, Yanagida, 2001)

- we have to go beyond single field inflation

Top-down approach

Possible UV-completions provide new ingredients

- discrete (gauge) symmetries are abundant in the quest to construct realistic models of particle physics
- they typically provide many moduli fields
- axion fields are abundant in string compactifications

No strong motivation to consider just a single axion field

- second axion is just an additional modulus participating in the inflationary system
- additional fields allow a simple implementation of low-scale supersymmetry

Conclusions

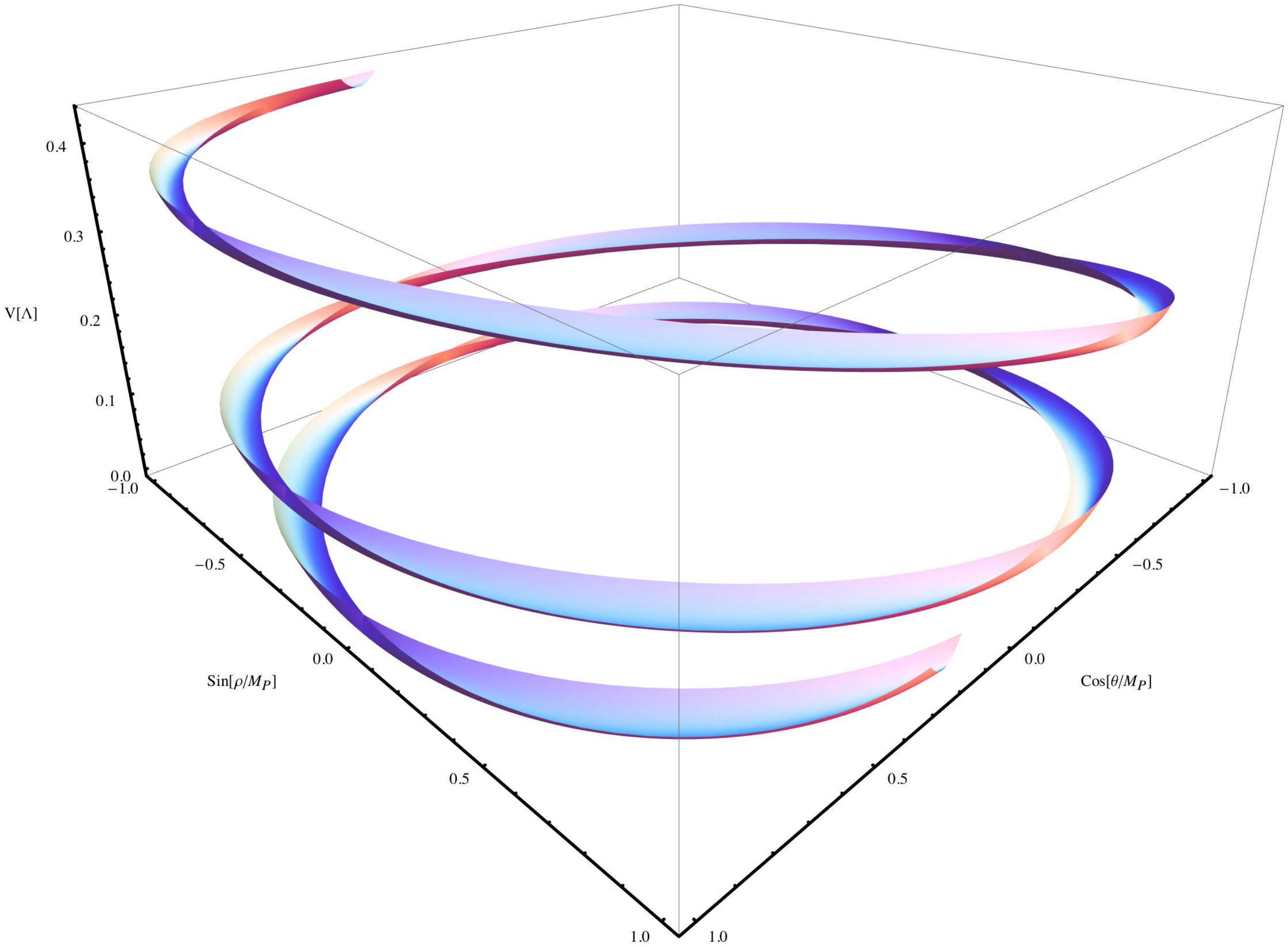
A successful model of inflation needs a flat potential and this is a challenge (in particular for models with sizeable tensor modes.)

- flatness of potential requires a symmetry
- axionic inflation is the natural candidate
- sizeable tensor modes need trans-Planckian excursion of inflaton

Models with several fields

- lead to such trans-Planckian values via alignment
- allow the incorporation of low-scale supersymmetry

The spiral axion slide



The fate of shift symmetries

Shift symmetries have to be broken. This could happen

- explicitly at tree level
- via loop corrections
- via nonperturbative effects

With high tensor modes we are at the “edge of control”.
We can gain control by

- remnant (discrete) symmetries
- specific approximations
  (e.g. large volume or large complex structure limit)
- wishful thinking

Remarks on WGC

The weak gravity conjecture

- is based on arguments from black hole horizons (what about firewalls and fuzzballs?)
- concerns $U(1)$ gauge symmetries (not axions?)
- parametrically large excursions (what about $5\ M_{\text{Planck}}$?)

Lack of computational control for instantons in the relevant region of parameter space

- Loopholes in the presence of sub-leading instanton contributions,
- which are abundant in low scale susy models.