Axions: Diversity beats Simplicity

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Work with R. Kappl and M. Winkler, (1) arXiv:1503.01777, (2) to appear 1511.0XXXX

Useful Axions

Axions can play a role for

- the strong CP problem in QCD (Peccei, Quinn, 1977)
- the mechanism of inflation (Freese, Frieman, Olinto, 1990)
- the source of quintessence (Frieman, Hill, Stebbins, Waga, 1995)

Axions are abundant in string theory constructions

- there is an opportunity for multi-axion systems
- that seems to be helpful for the consistency of axionic models
- two is better than one

Vielfalt statt Einfalt: Diversity beats Simplicity

Outline

Concentrate here (CosPA 2015) on inflation

- axionic inflation
- Planck satellite and BICEP2 data
- high scale inflation and trans-Planckian excursions
- the alignment of axions and its stability
- the question of low scale Susy

Other application of multi-axion systems

- axionic domain walls for QCD axion (Choi, Kim, 1985)
- alignment of quintessential axions (Kaloper, Sorbo, 2006)

The Quest for Flatness

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

- 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)

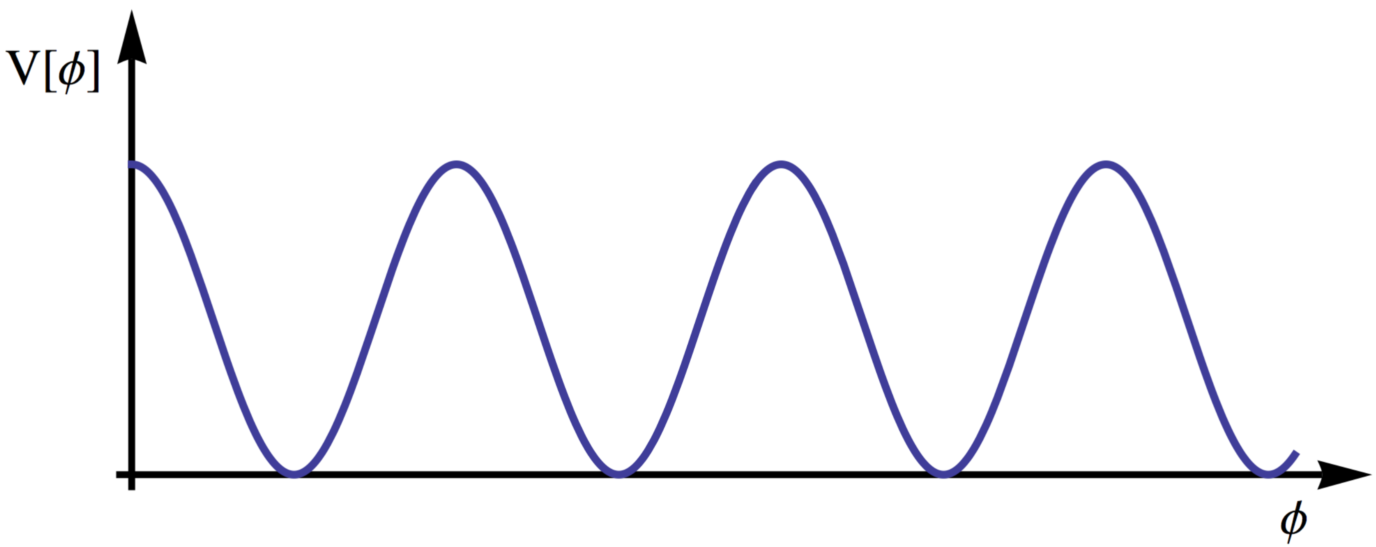
Motivated by the QCD axion

(Freese, Frieman, Olinto, 1990)

The Axion Potential

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

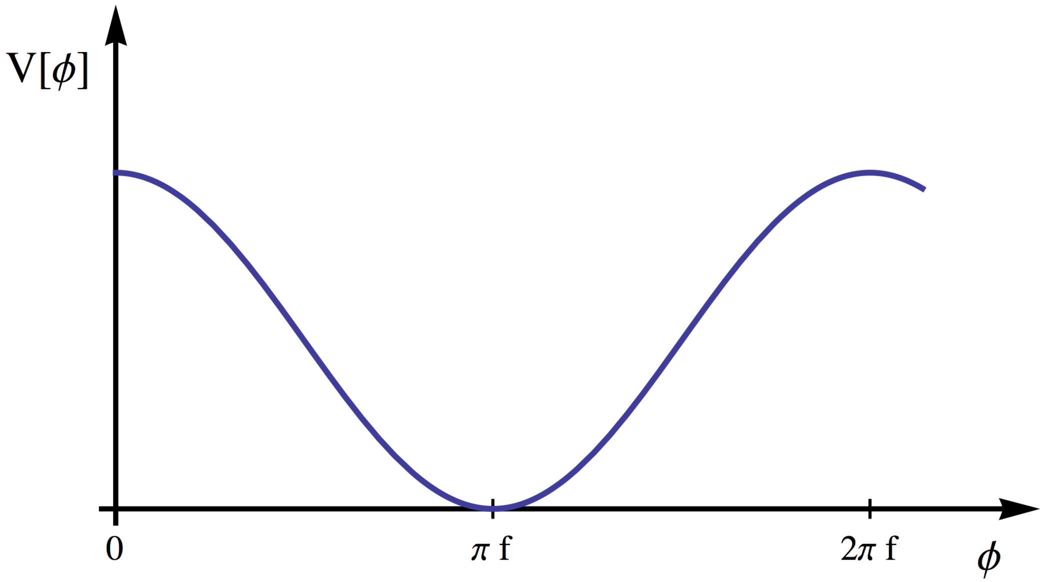
Nonperturbative effects break this symmetry to a remnant discrete shift symmetry



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

The Axion Potential

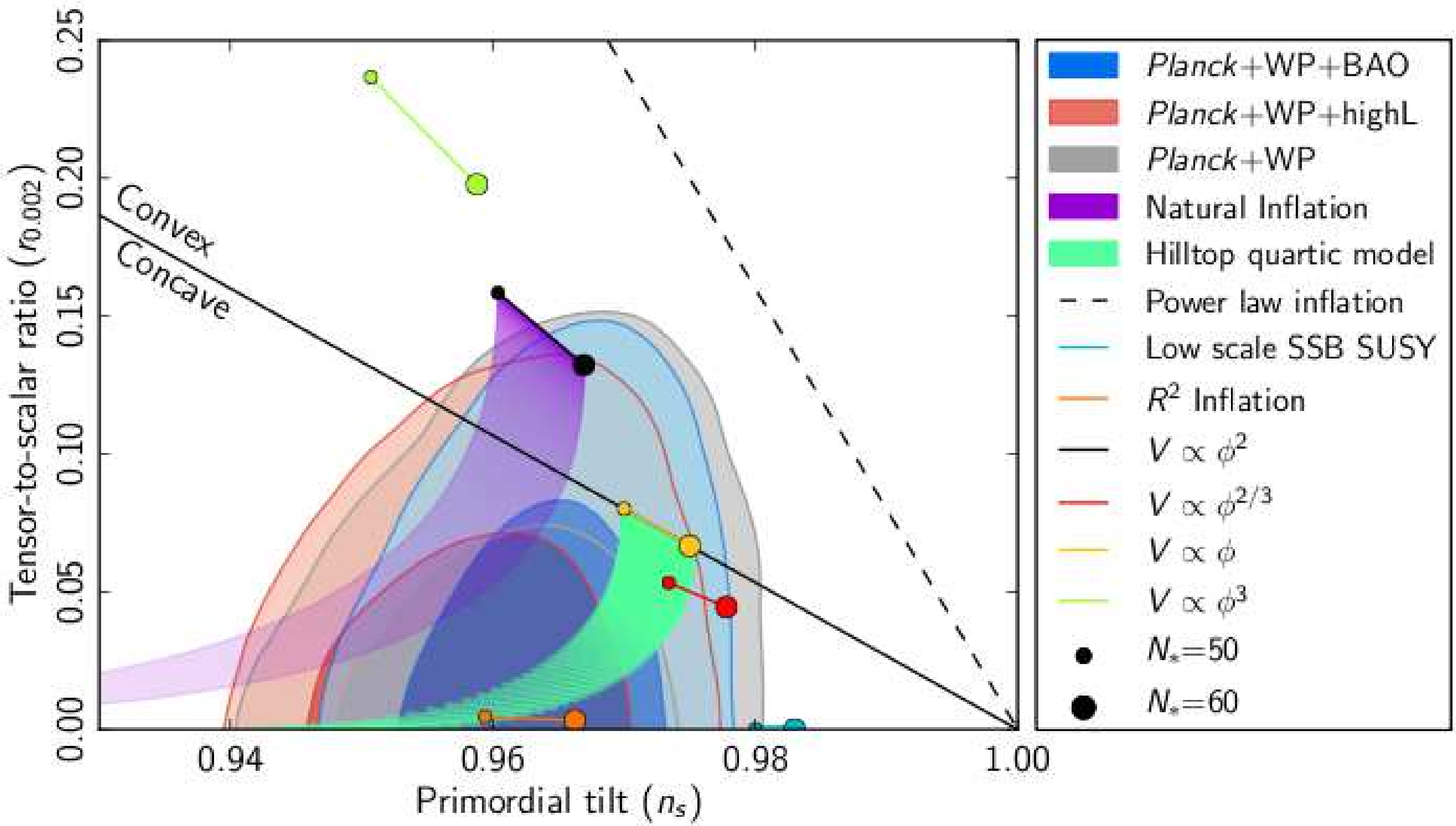
Discrete shift symmetry identifies $\phi = \phi + 2\pi n f$



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

ϕ confined to one fundamental domain

Planck results (Spring 2013)



BICEP2 (Spring 2014)

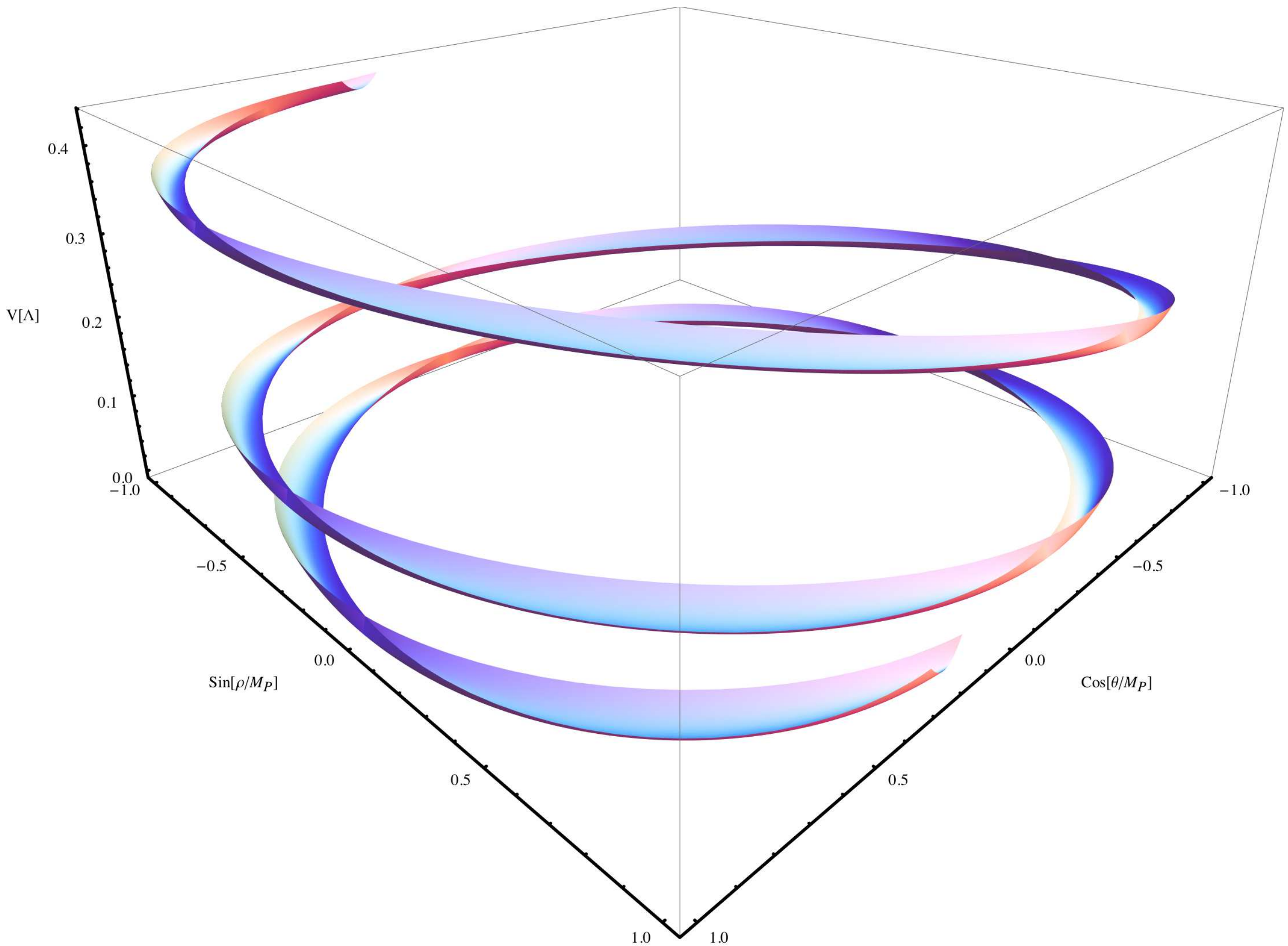
Tentatively large tensor modes of order $r \sim 0.1$ had been announced by the BICEP collaboration

- 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. (Banks, Dine, Fox, Gorbatov, 2003)

Solution



Helical motion of one axion in the potential of a second one

Aligned axions

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

(Kim, Nilles, Peloso, 2004)

- top-down approach favours a multi-axion picture
- we require $f \leq M_{\mathrm{P}}$ for the individual axions
- diversity beats simplicity

The alignment prolongs the fundamental domain of the aligned axion to super-Planckian values, as the axionic inflaton spirals down in the potential of the second axion

Alternative mechanisms, like e.g. ”Axion Monodromy" give a similar qualitative picture (McAllister, Siverstein, Westphal, 2008)

The KNP set-up

We consider two axions

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

with potential

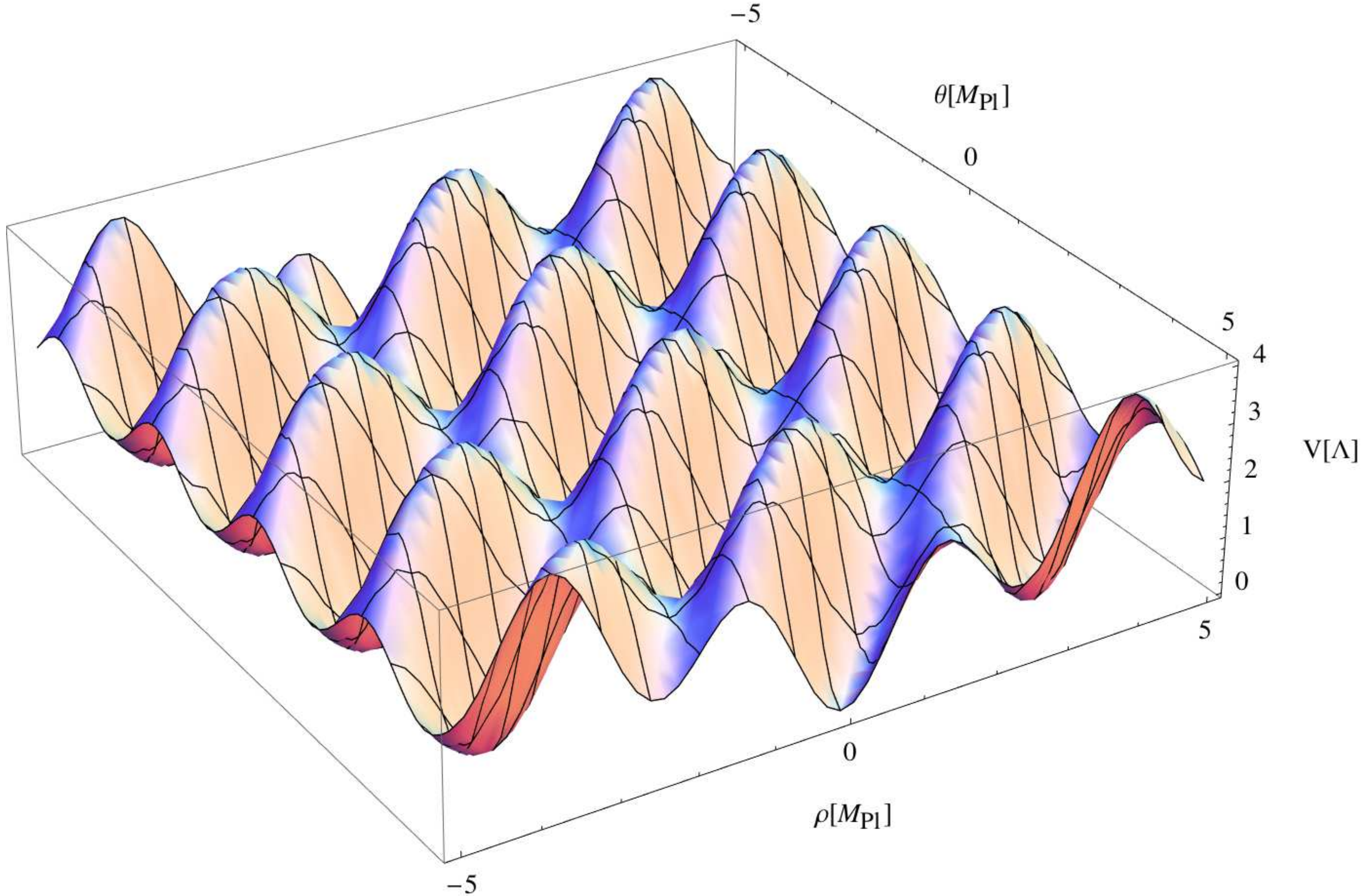
$$V(\theta, \rho) = \Lambda^4 \left(2 - \cos\left(\frac{\theta}{f_1} + \frac{\rho}{g_1}\right) - \cos\left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right)$$

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

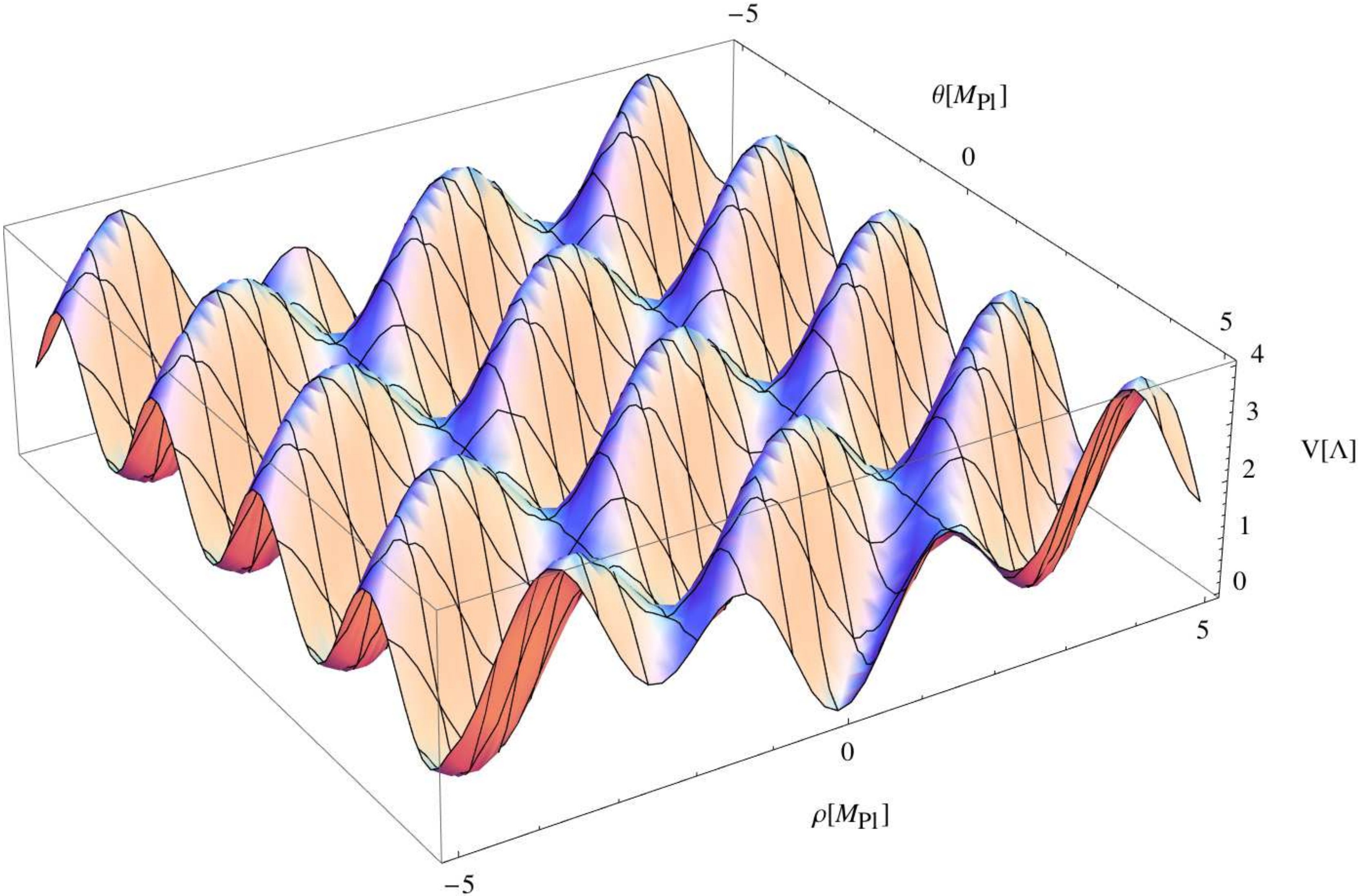
Alignment parameter defined through $\alpha = g_2 - \frac{f_2}{f_1} g_1$

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

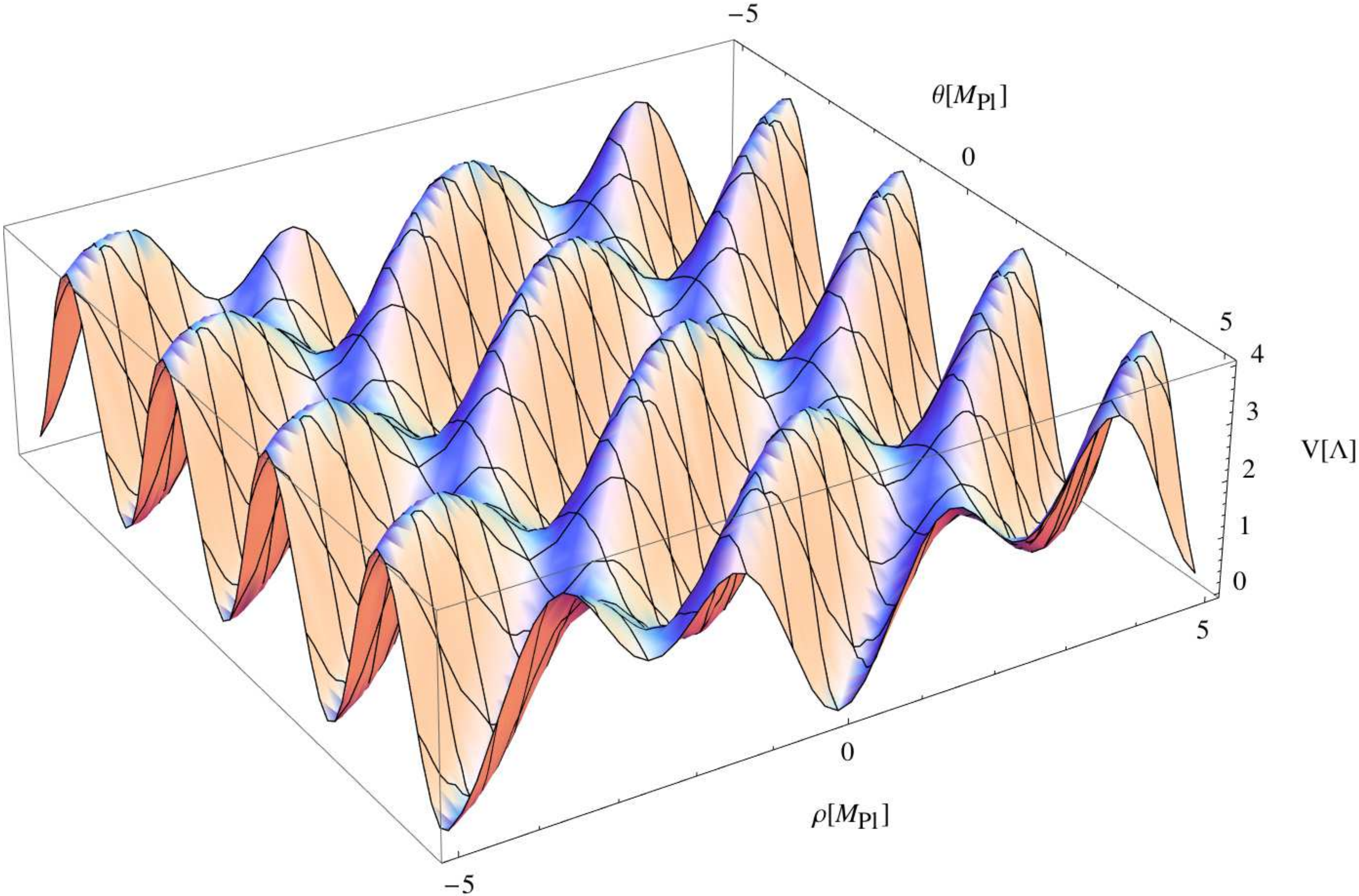
Potential for $\alpha = 1.0$



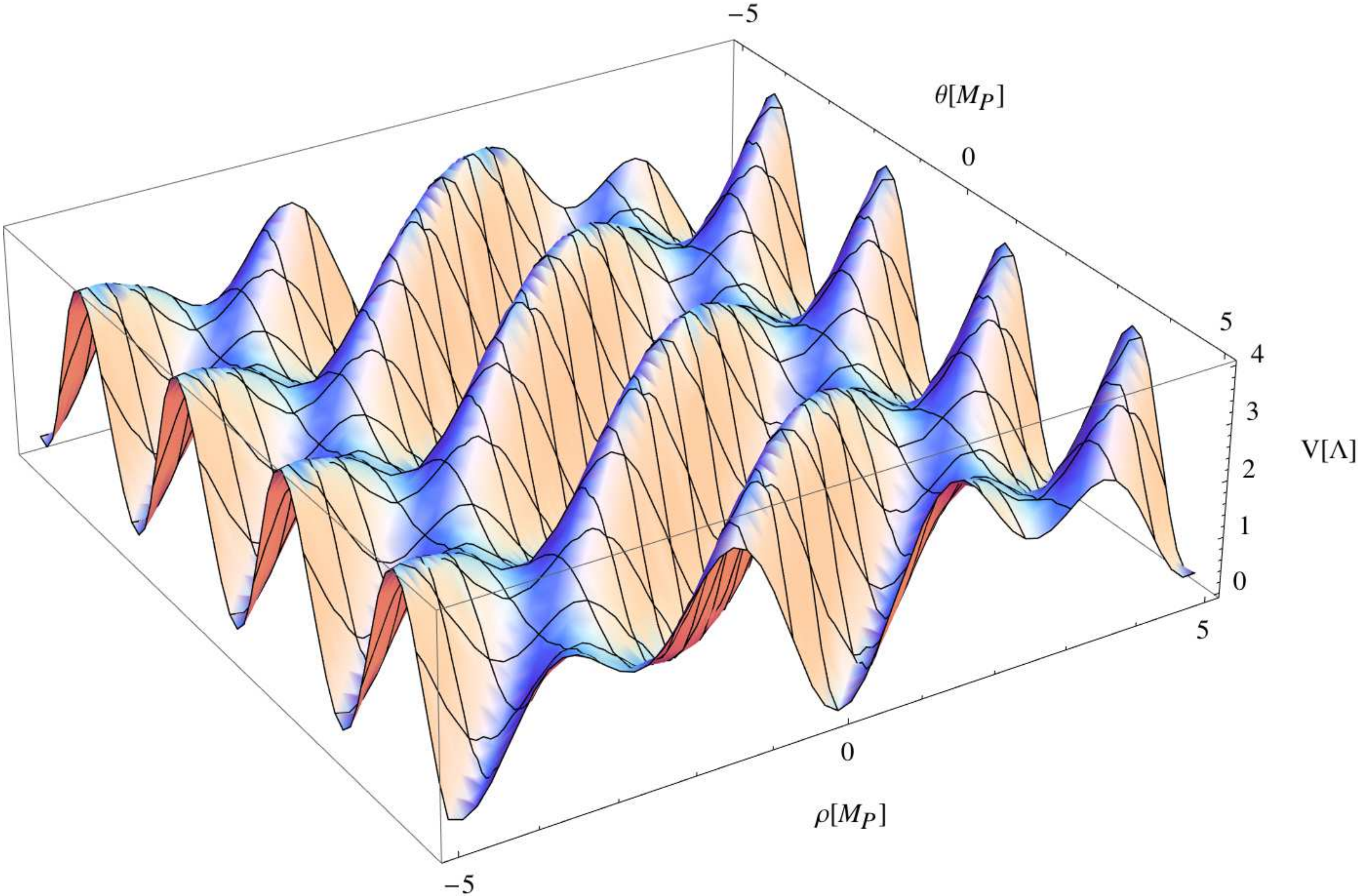
Potential for $\alpha = 0.8$



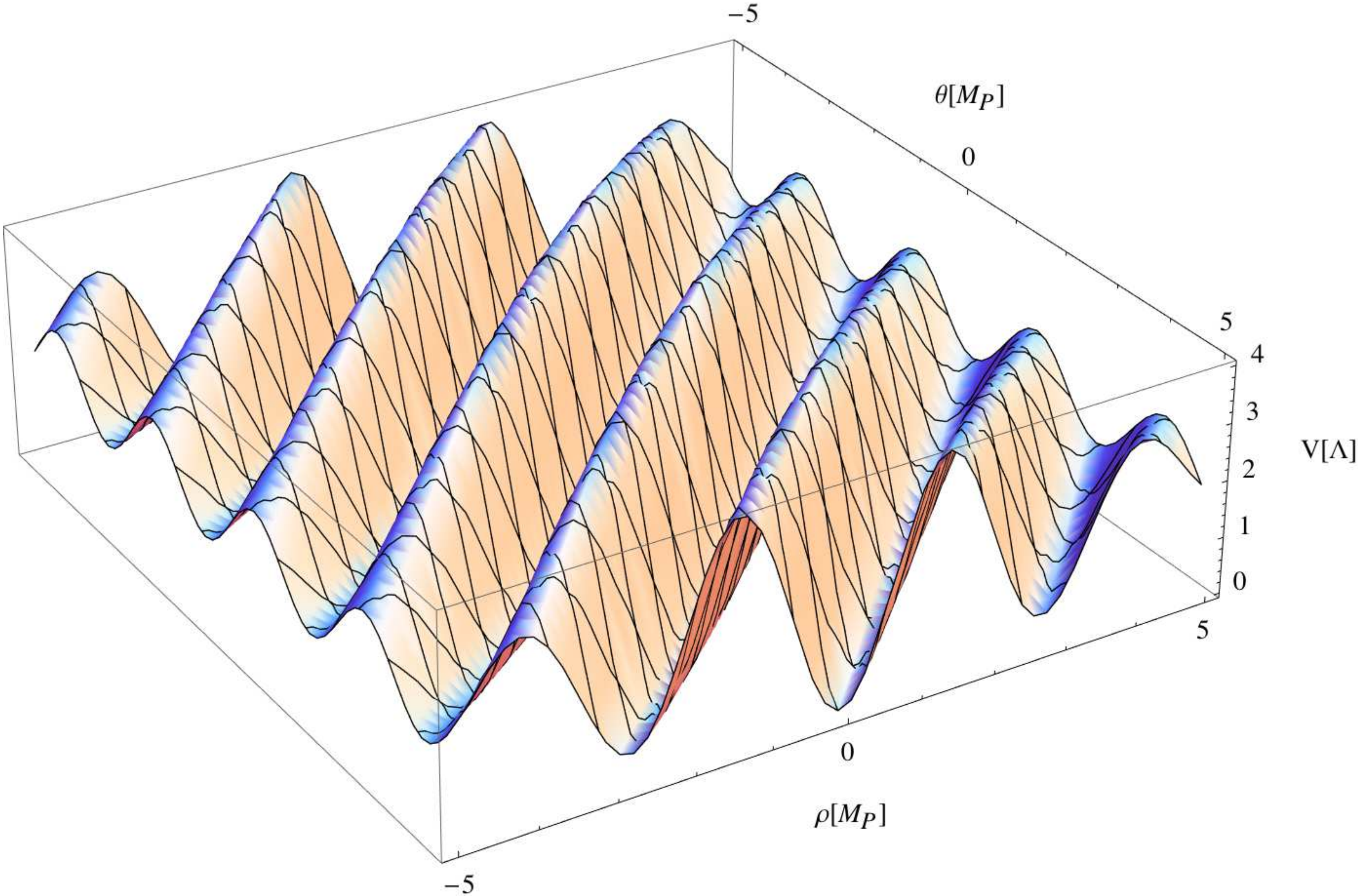
Potential for $\alpha = 0.5$



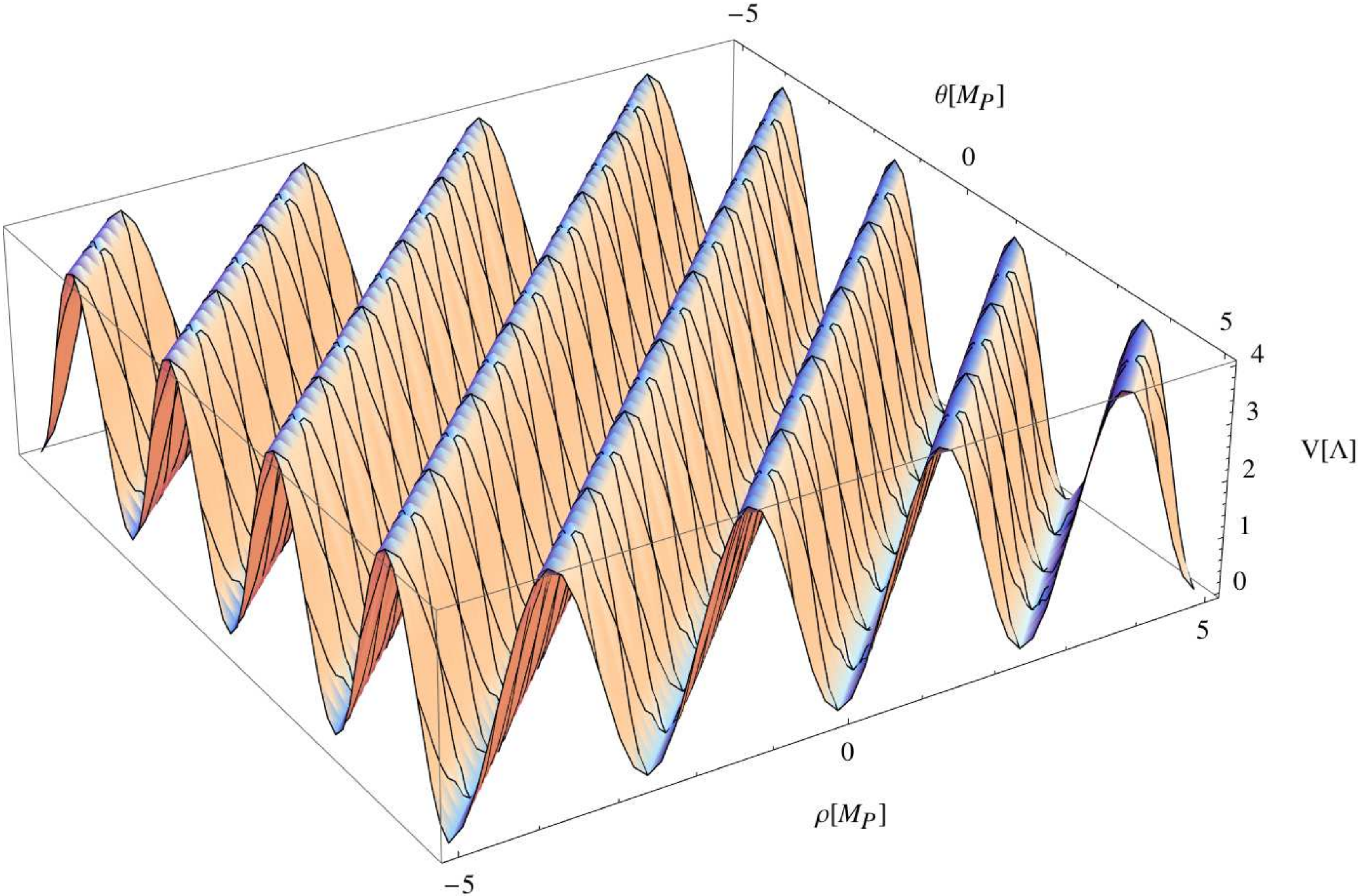
Potential for $\alpha = 0.3$



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

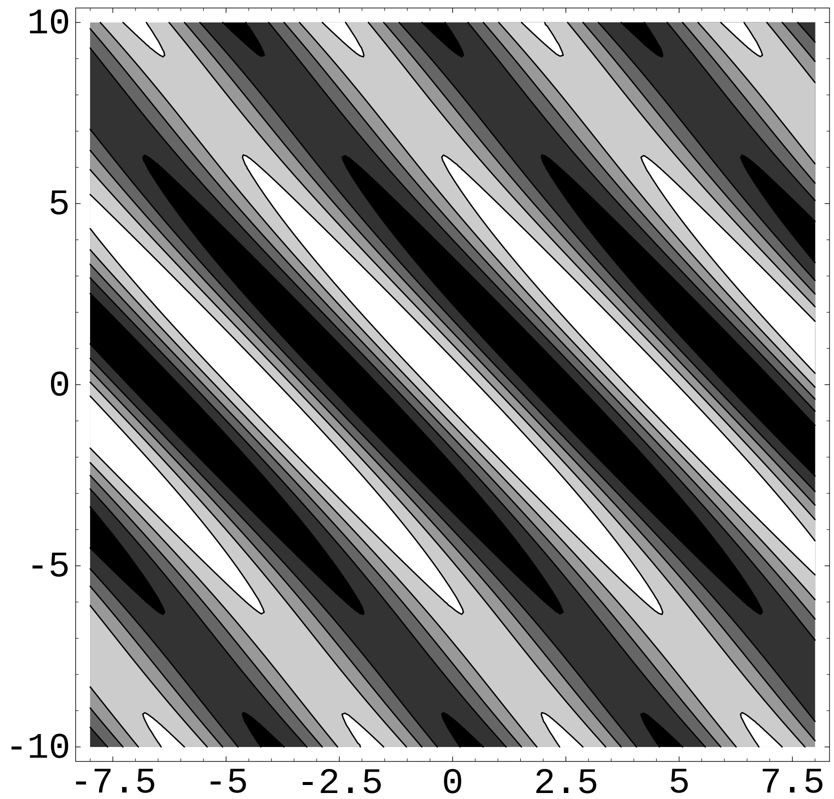
Lightest axion ξ has potential

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

leading effectively to a one-axion system

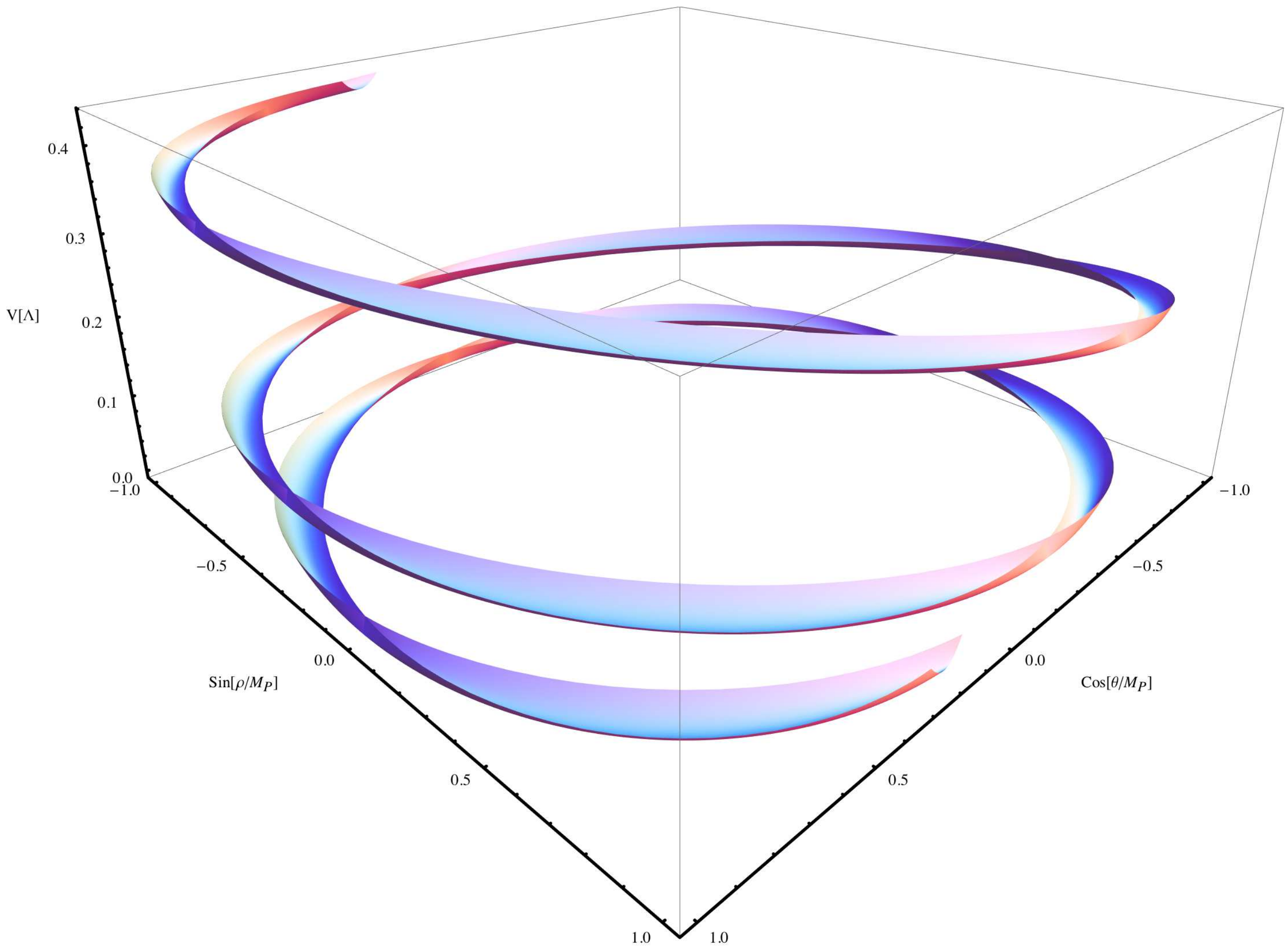
$$V(\xi) = \Lambda^4\left[1 - \cos\left(\frac{\xi}{\tilde{f}}\right)\right] \quad \text{with} \quad \tilde{f} = \frac{f_2g_1\sqrt{(f_1^2+f_2^2)(f_1^2+g_1^2)}}{f_1^2\alpha}$$

Axion landscape of KNP model



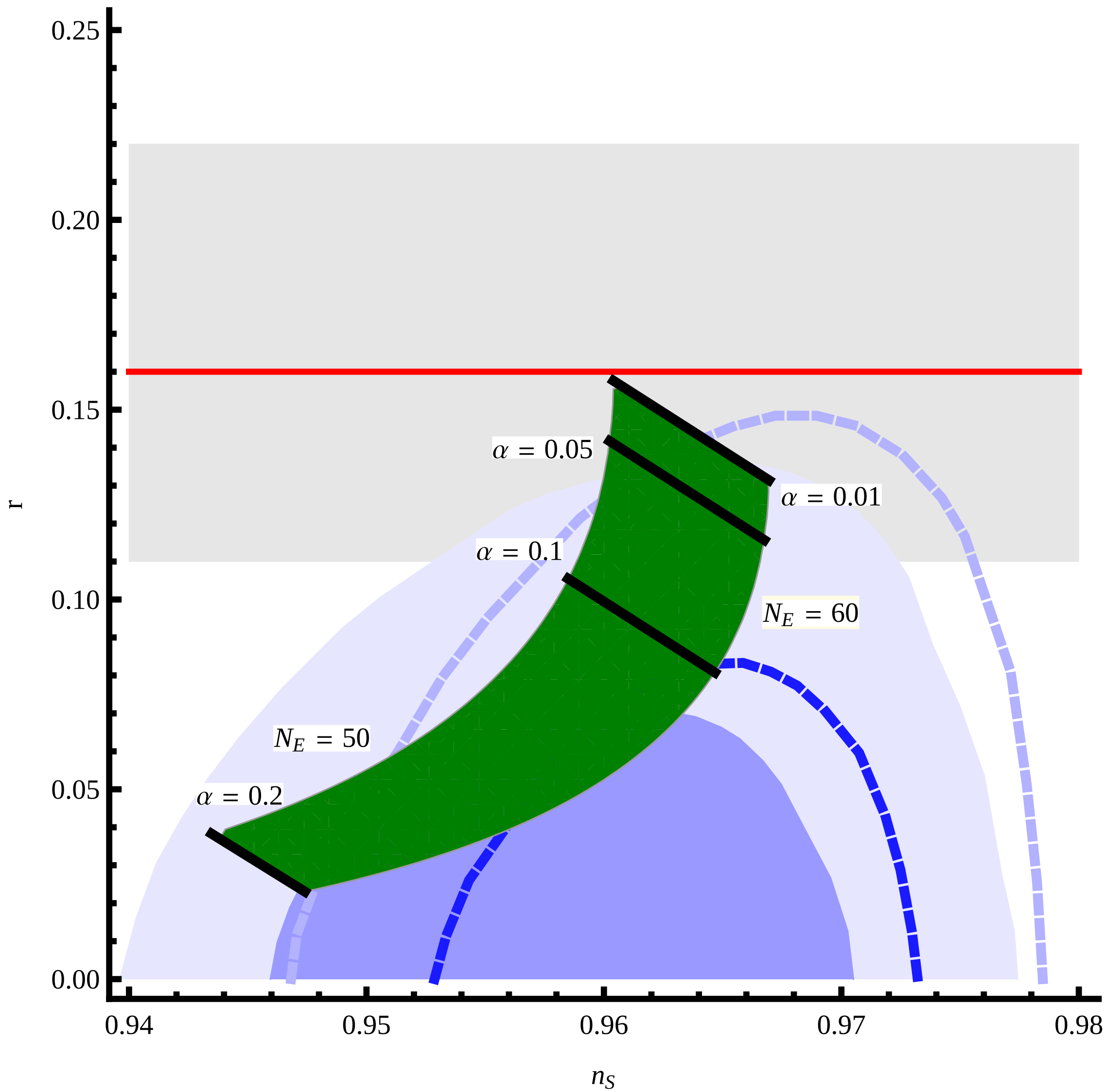
The field ξ rolls within the valley of ψ. The motion of ξ corresponds to a motion of θ and ρ over many cycles. The system is still controlled by discrete symmetries.

Monodromic Axion Motion



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

The “effective” one-axion system



UV-Completion

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

UV-Completion

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
- potential protection through supersymmetry

The Quest for 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 point towards high scale Susy!

Stabilizer fields

Toy model: quadratic inflation in supergravity

$$W = \frac{1}{2} m \rho^2 , \quad K = \frac{(\bar{\rho} + \rho)^2}{4}$$

where the inflaton corresponds to Im(ρ)

Problem: Potential is unbounded from below because of the supergravitational term $-3|W|^2$

Solution: introduce a stabilizer field X

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

(Kawasaki, Yamaguchi, Yanagida, 2000)

Susy and Natural Inflation

Axionic inflation with a stabilizer field X.

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

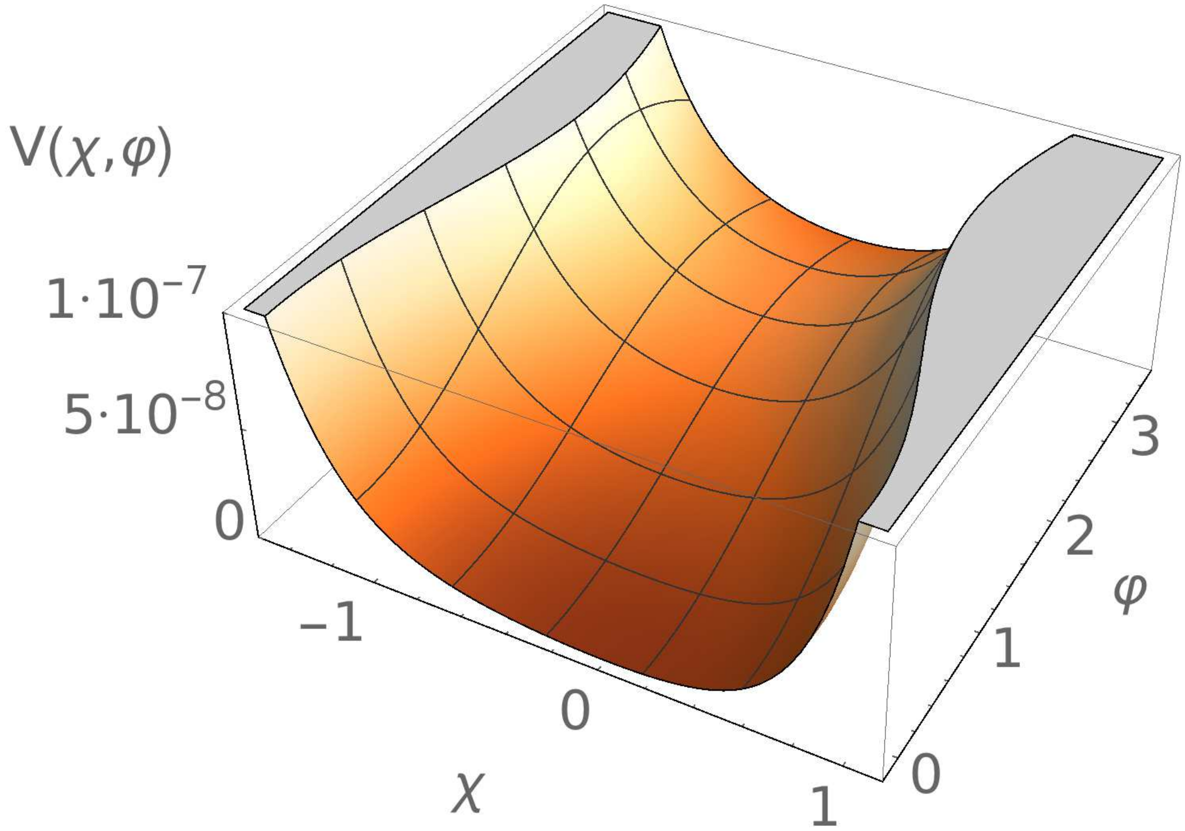
Supersymmetric ground state at $X = 0, \rho = \rho_0 = -\log(\lambda)/a$

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

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.

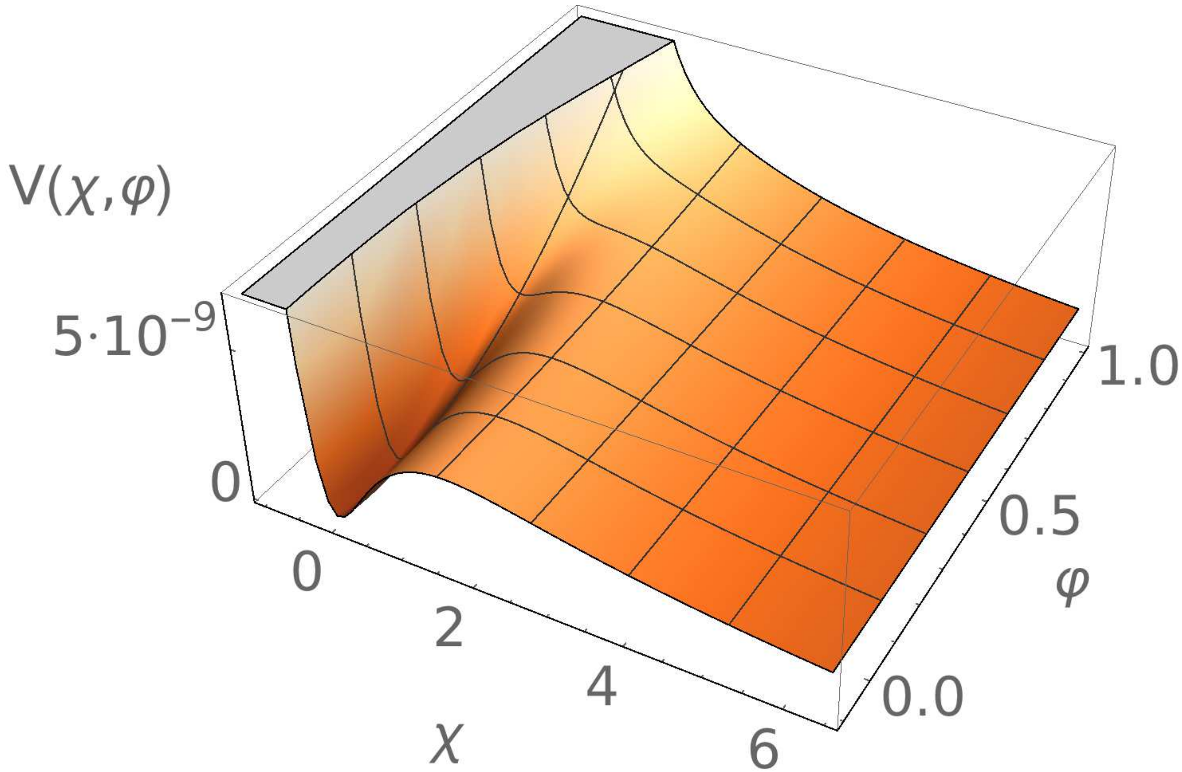
Challenge: we typically have $K = -\log(\rho + \bar{\rho})$ leading to

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

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.

We need more fields to stabilise the system.

A 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, gauge- and world-sheet-instantons (e.g. with magnetised D-branes in toroidal/orbifold compactification)

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

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

(Kappl, Nilles, Winkler(1), 2015; Ruehle, Wieck, 2015)

A Benchmark Model

Again we need more fields.

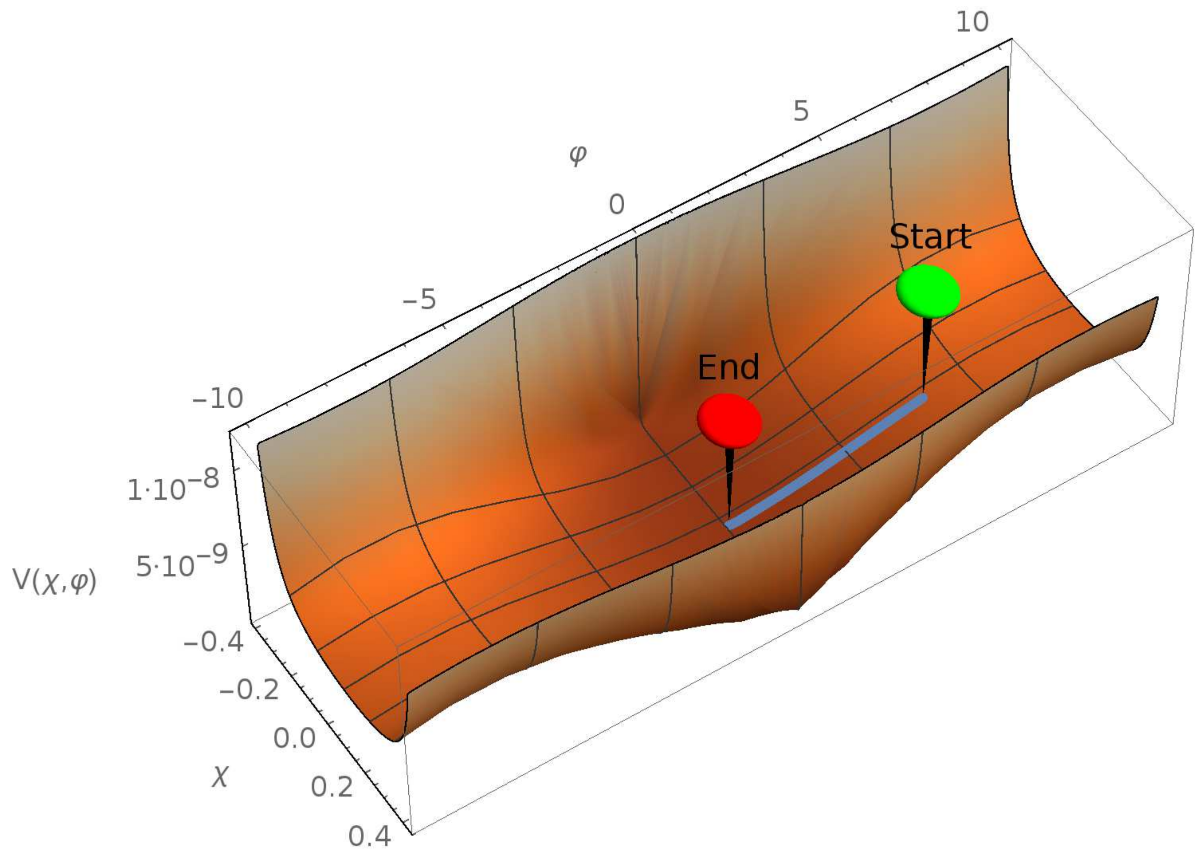
$$W = \sum_{i=1}^{2} m_i^2 X_i \left(e^{-a_i\rho_1 - b_i\rho_2} - \lambda_i\right)$$

With two axions and stabilizer fields we can achieve

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

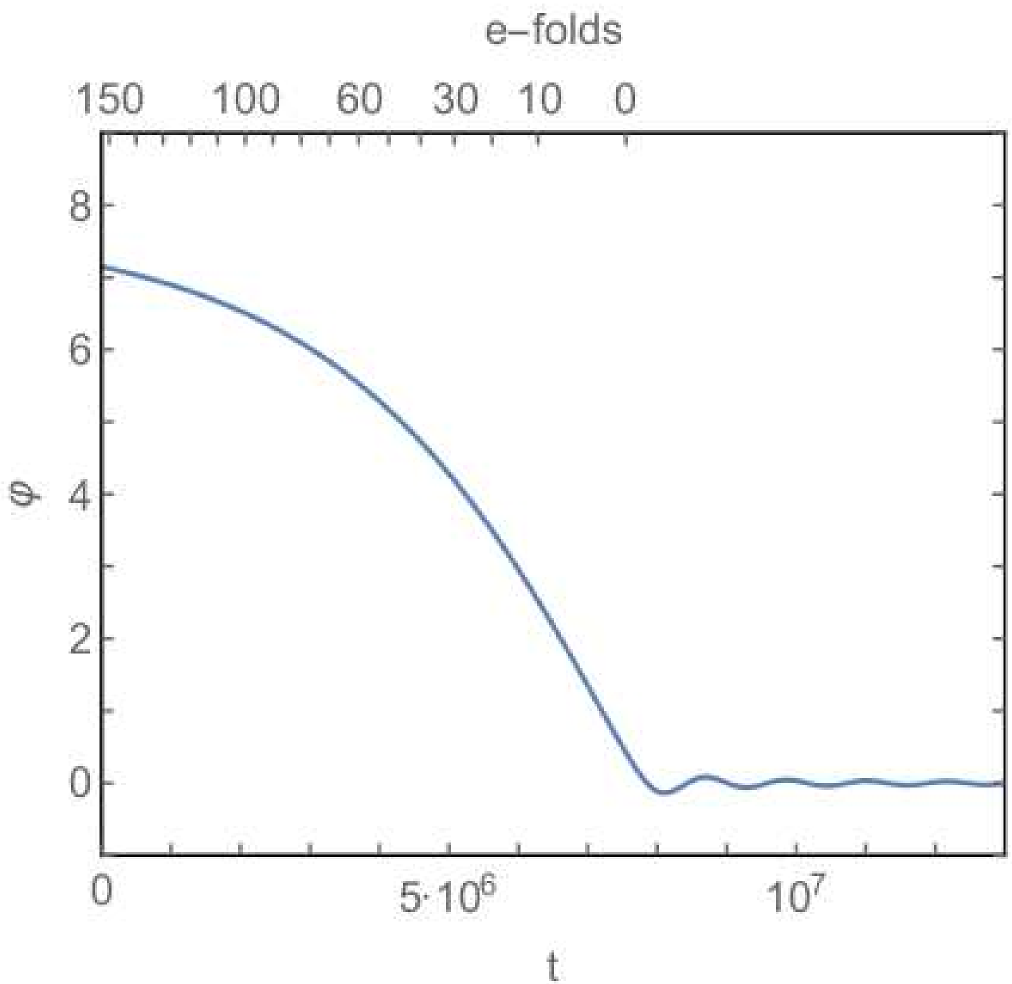
$$V = \frac{\lambda_1^2 m_1^4 \, e^{-\delta\chi} \left[\cosh(\delta\chi) - \cos(\delta\varphi)\right]}{2(\rho_{1,0} + b_2\chi)(\rho_{2,0} - a_2\chi)}$$

Aligned Axion with Trapped Saxion

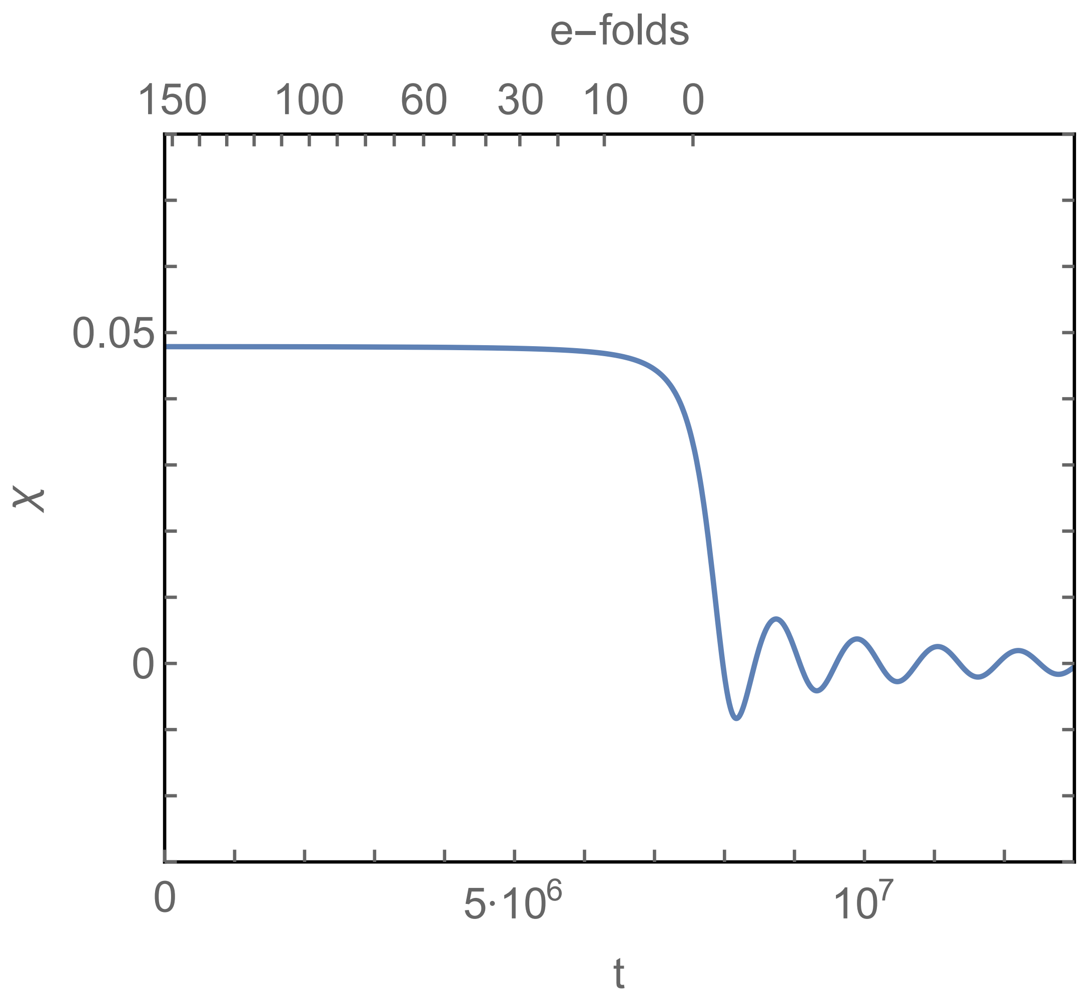


The valley is narrow (observe difference of scales)

Evolution of Axion



Evolution of Saxion



The saxion stays close to zero

Comparison with observations

In the extreme case, again, we have an effective one-axion system 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

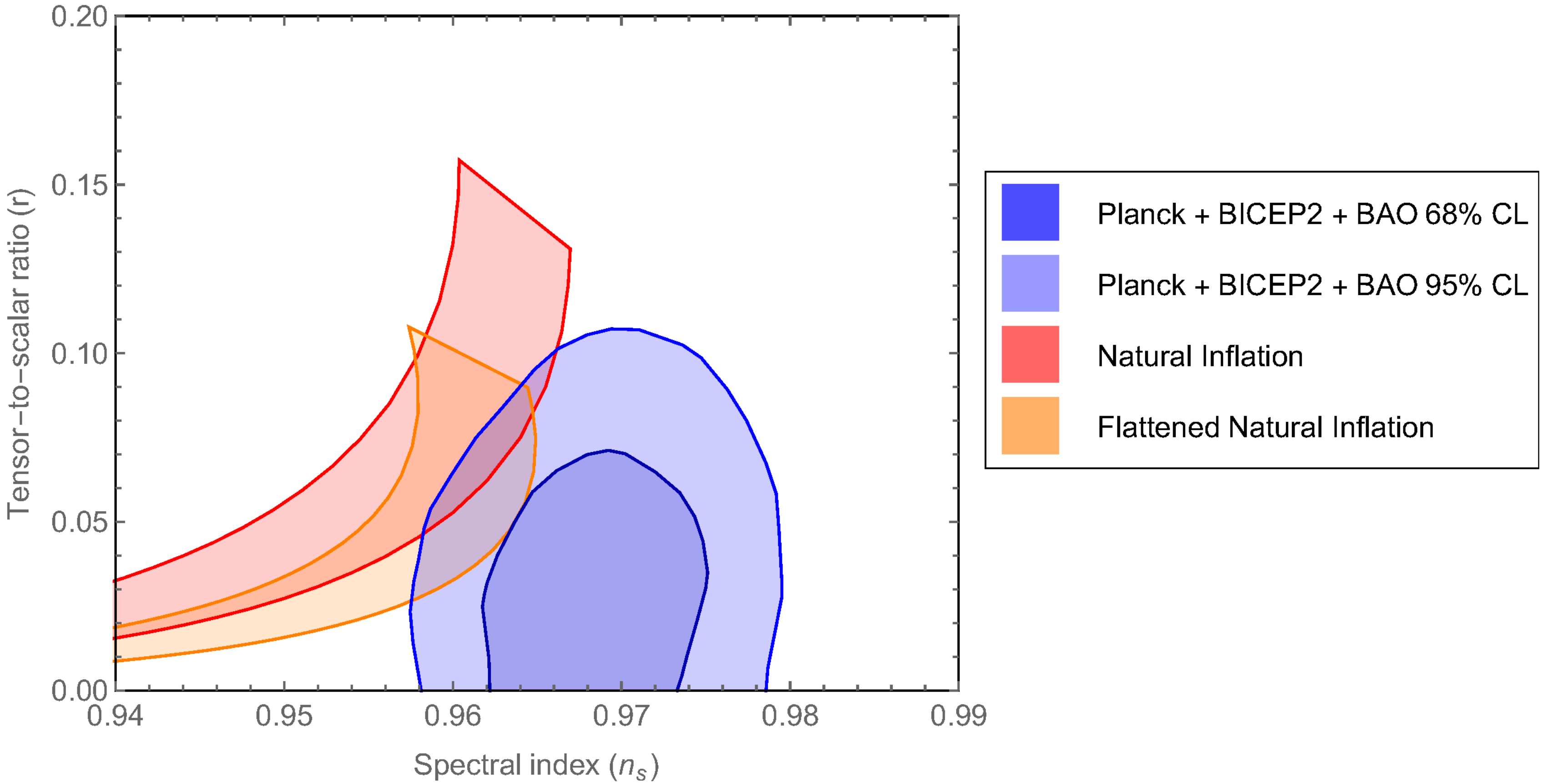
Comparison with data leads to an effective axion scale

$$f_{\rm eff} \geq \text{few} \times \text{M}_{\text{Planck}}$$

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; Kappl, Nilles, Winkler(2), 2015)

$n_s - r$ plane



(Kappl, Nilles, Winkler(1), 2015)

Axionic inflation and supersymmetry

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

- additional fields and a specific form of moduli stabilization.

The alignment of axions

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

A satisfactory and consistent scheme require more fields:

Diversity beats Simplicity

Stability

We have a very flat direction and within the effective QFT we are at the "edge of control"

- is inflation perturbed by other effects?
- is there an upper limit on f_{eff}?

Remember that in case of a single axion we had limits

- $f_{\mathrm{eff}} \leq M_{\mathrm{string}}$ (Banks, Dine, Fox, Gorbatov, 2003)
- derived from dualities in string theory

In the multi-axion case these arguments are not directly applicable, but the question of trans-Planckian values should be tested in a given model

Weak Gravity Conjecture (WGC)

It is based on prejudice about black hole properties and is formulated to constrain $U(1)$ gauge interactions

(Arkani-Hamed, Motl, Nicolis, Vafa, 2006)

- give limits on mass to charge ratio $q/m > 1$
- “convex hull” restrictions in multi-field case

But our “knowledge” on black hole properties (no-hair conjecture and information paradox) has changed recently

- fuzzballs, (Mathur, 2009-2015)
- brick- and fire-walls (Almheiri, Marolf, Polchinski, Sully, 2012)

The motivation for the WGC might not be valid any longer.

WGC II

It is conjectured that the WGC (if true) might be applicable to axions (Rudelius, 2015)

- based on a chain of string dualities
- might give an upper limit on decay constants $f_{\rm eff}$

This might lead to a no-go theorem for large axion decay constants, but

- there are loop-holes in the presence of subleading instantons (Brown, Cottrell, Shiu, Soler, 2015)
- computationally we are at the "edge of control"

Needs to be clarified in explicit constructions.

(Kappl, Nilles, Winkler(2), 2015)

Explicit String Constructions

In string theory we do not just get cosine potentials, but have to deal with modular functions (Jacobi theta- and/or Dedekind-functions), as e.g. in the case of

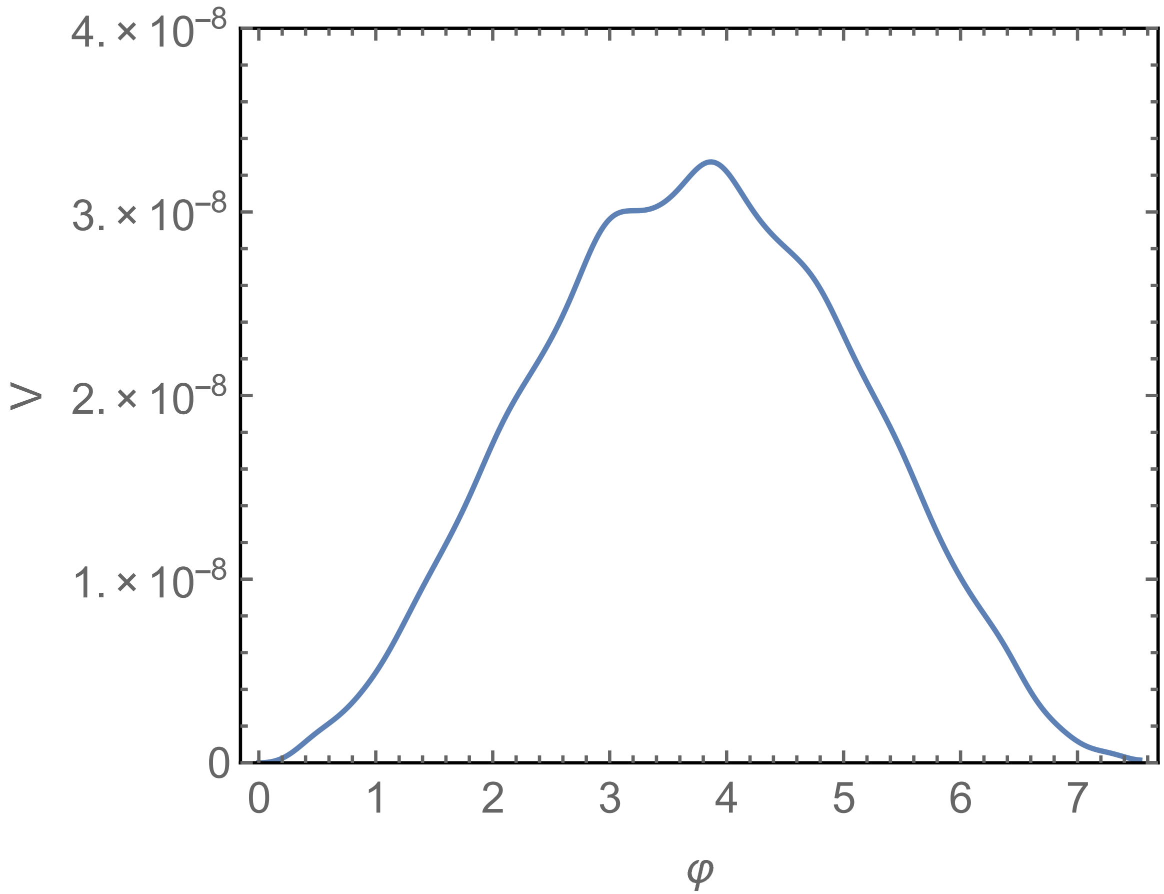
- world sheet instanton effects
- gauge kinetic functions and gaugino condensates

So we might consider instead

$$\eta(T) = e^{-\pi T/12} \times \prod_k \left(1 - e^{-2k\pi T}\right)$$

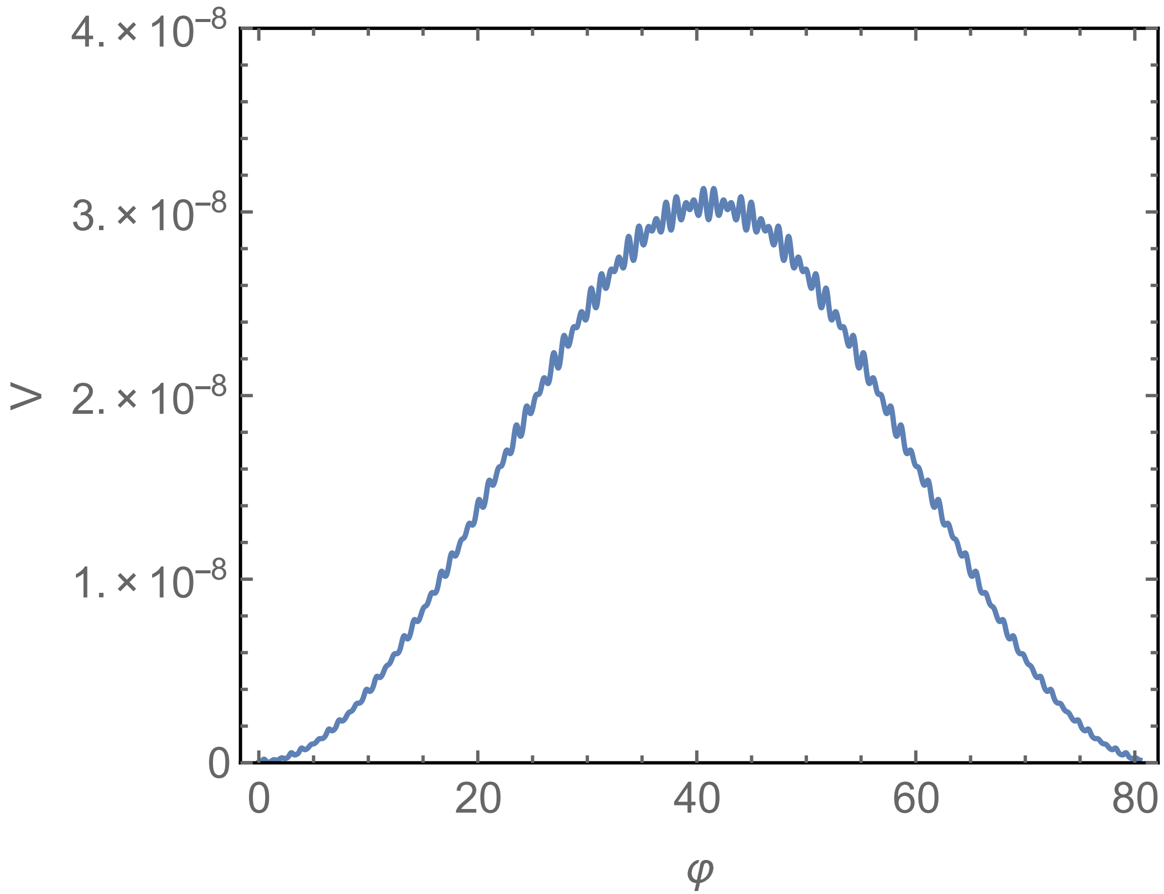
Higher harmonics give wiggles in the potential that perturb the flat direction and might stop inflation

Wiggles



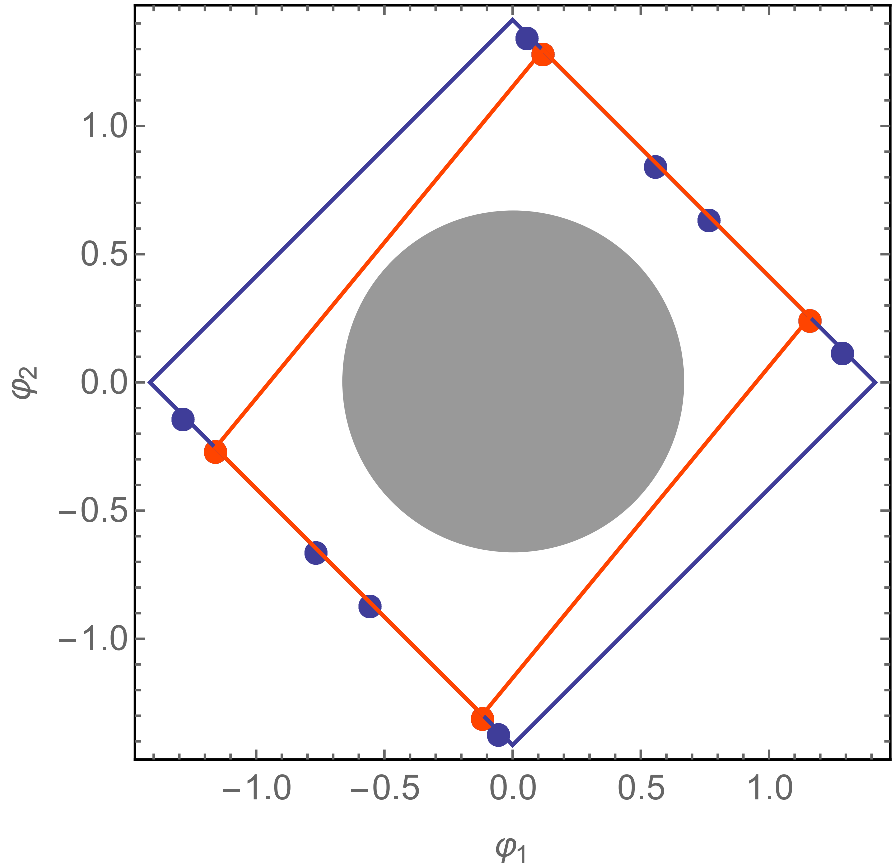
The wiggles in the case of weak alignment

Wiggles



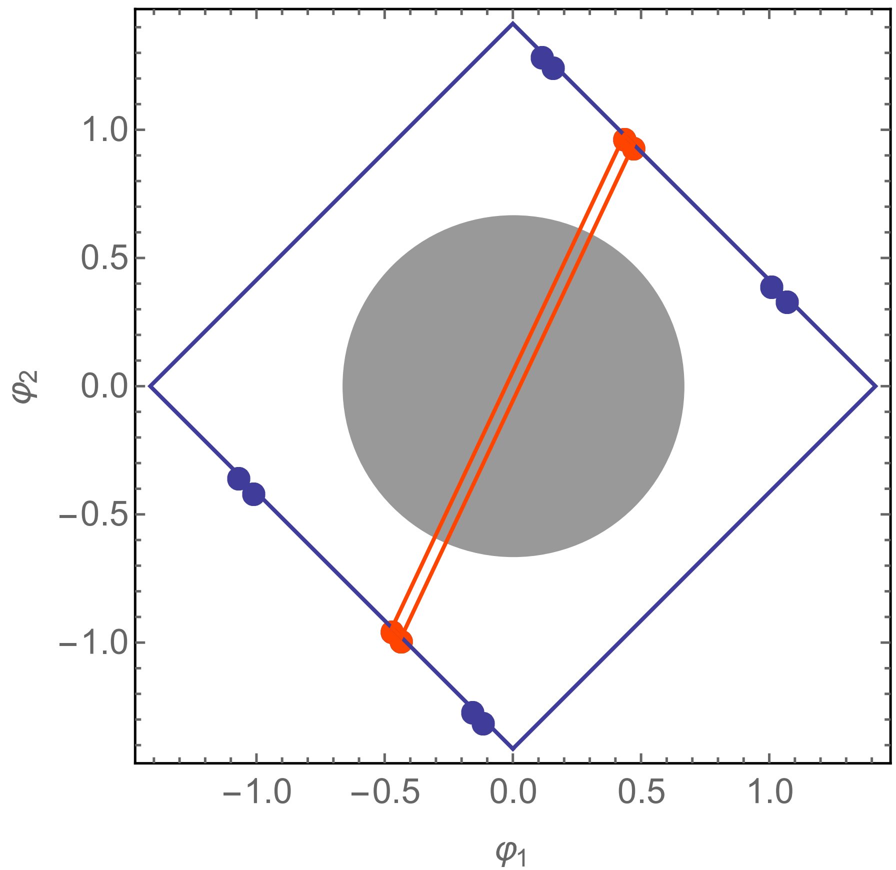
The wiggles in the case of strong alignment

Weak alignment



The convex hull restrictions are trivially satisfied

Strong alignment



Subleading terms satisfy the restrictions

Modulated natural Inflation

It seems plausible that under some circumstances the wiggles become important and

- spoil the flat direction
- provide un upper limit on decay constant f_{eff}

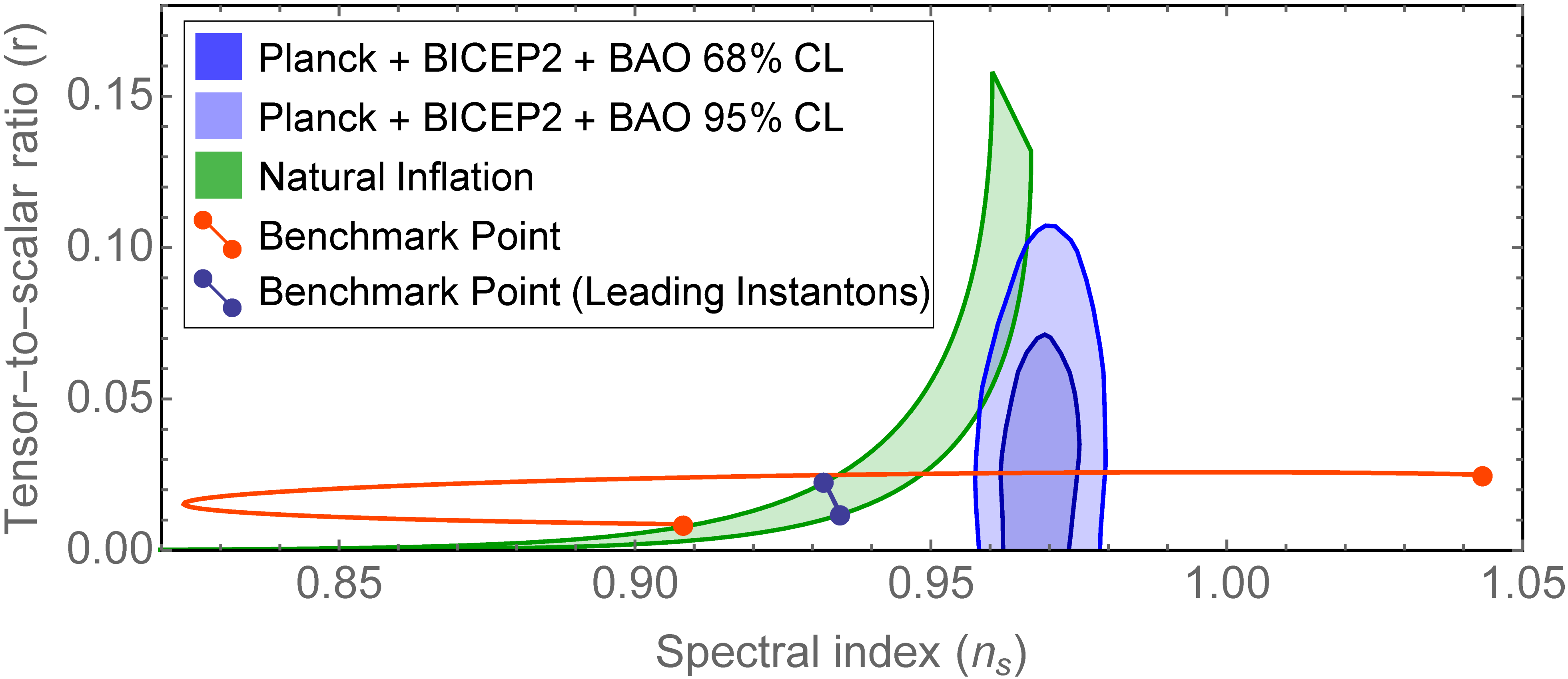
Explicit calculation are necessary to clarify the situation

- might be beyond our present capabilities
- observational confirmation is extremely important

Restrictions from WGC are satisfied here both in the aligned and non-aligned case.

WGC appears as a "red herring" (Kappl, Nilles, Winkler(2), 2015)

Modulated natural inflation

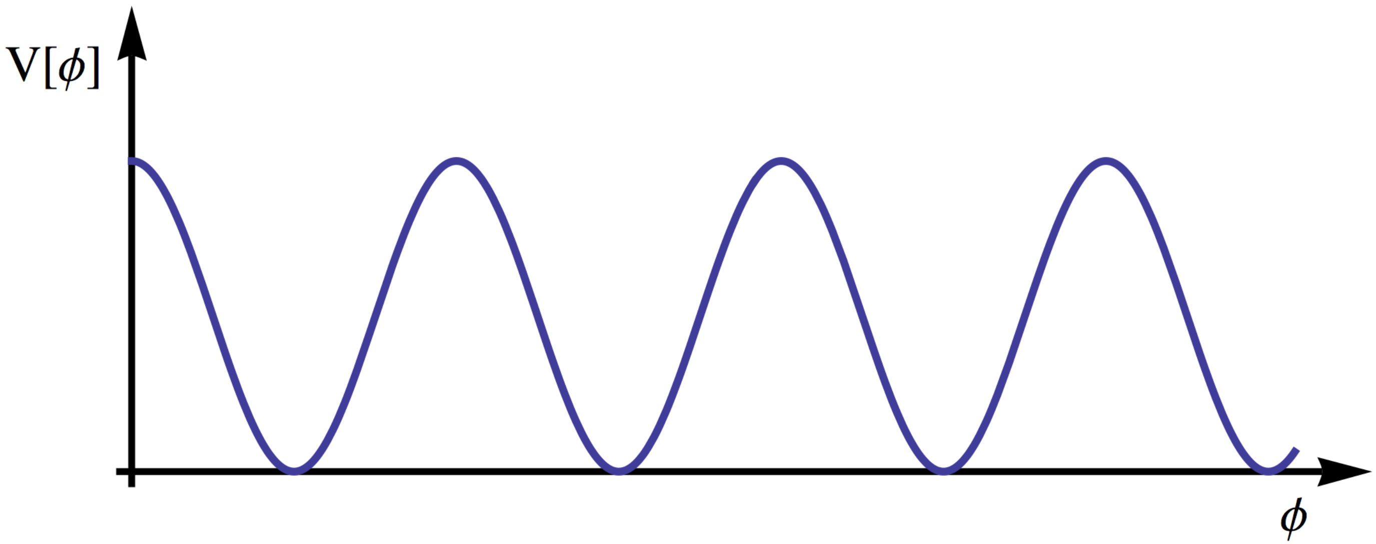


The scalar index shows a large variation

(Abe, Kobayashi, Otsuka, 2015; Kappl, Nilles, Winkler(2), 2015)

QCD axion and axionic domain walls

In general we have $a = a + 2\pi N f_a$ for $V \sim \cos(Na/f_a)$,



leading to N nontrivial degenerate vacua separated by maxima of the potential.

During the cosmic evolution this might lead to the production of potentially harmful axionic domain walls.

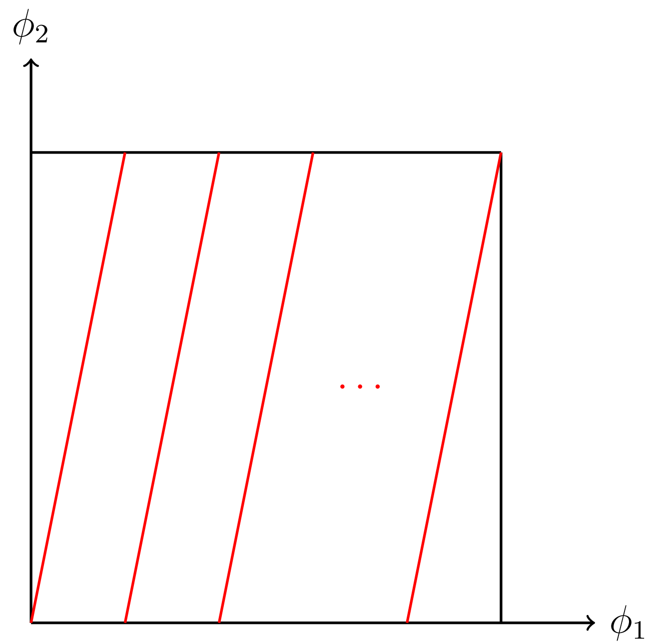
Two-Axion-model (by Kiwoon Choi)

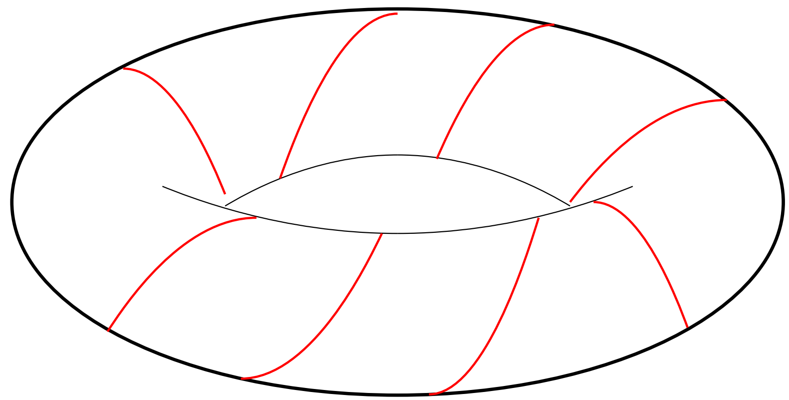
Consider a system with two axions

$$V \sim \Lambda_1^4 \cos\left(\frac{a_1}{f_1} + N\frac{a_2}{f_2}\right) + m\Lambda_2^3 \cos\left(\frac{a_2}{f_2}\right)$$

- For fixed a_1 there are N nontrivial vacua and potentially $N_{\rm DW} = N$ domain walls
- for $m = 0$ there is a Goldstone direction,
- and thus a continuous unique vacuum with effective domain wall number $N_{\rm DW} = 1$ (Choi, Kim, 1985)
- the Goldstone mode develops an axionic potential in the case $m \neq 0$

The axionic vacuum





(Choi, Kim, Yun, 2014)

- There is continuous unique vacuum with effective domain wall number is $N_{\rm DW} = 1$ (Choi, Kim, 1985)
- the Goldstone mode develops an axionic potential in the case $m \neq 0$

Quintessential axion alignment

Axions could be the source for dynamical dark energy

- in contrast to scalar quintessence, the axion has only derivative couplings and does not lead to a “fifth force"
- we need a slow roll field with $\Lambda \sim 0.003$ eV
- to act as dark energy today we need $f_a \geq M_{\rm Planck}$
- the quintaxion mass is $m_a \sim \Lambda^2/M_{\rm Planck} \sim 10^{-33}$ eV

Again we need a trans-Planckian decay constant for a consistent description of the present stage of the universe

- the problem can be solved via aligned axions à la KNP

(Kaloper, Sorbo, 2006)

Bottom-up approach

Axions can help with the solution of various problems

- natural inflation
- the strong CP-problem
- pseudoscalar quintessence

In bottom-up approach one aims at a minimal model and thus postulates a single axion field

But there are some remaining problems:

- trans-Planckian decay constants and
- axionic domain walls

require a non-minimal particle content.

Top-down approach

Possible UV-completions provide new ingredients

- there are typically many moduli fields
- axion fields are abundant in string compactifications

No strong motivation to consider just a single axion field.
Additional fields are needed for

- trans-Planckian values for inflation and quintessence
- domain wall problem of QCD axion
- a simple implementation of low-scale supersymmetry

Vielfalt statt Einfalt - Diversity beats Simplicity