Axion Monodromies

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Outline

- The success of the inflationary Universe
- Flatness of the potential and symmetries
- Natural (axionic) inflation
- Planck satellite data
- BICEP2 observation of a (potential) large tensor mode

But large tensor modes

- require trans-Planckian excursion of inflaton field.
- How to control the axion decay constant?

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

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)

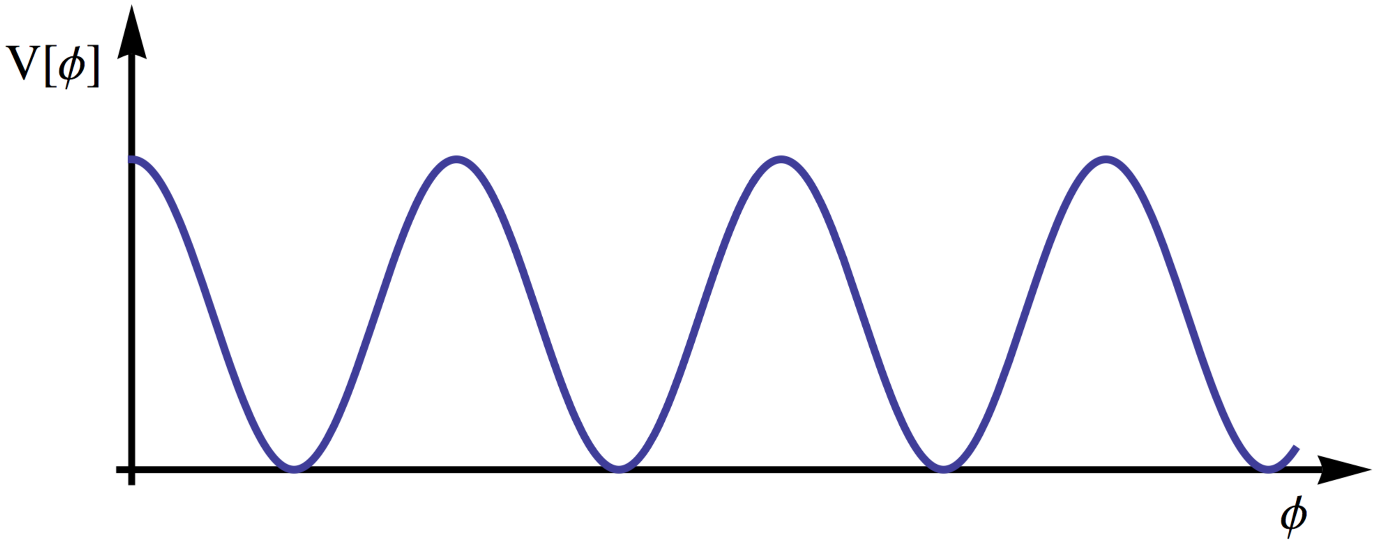
Motivated by the QCD axion

(Freese, Frieman, Olinto, 1990)

The Axion Potential

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

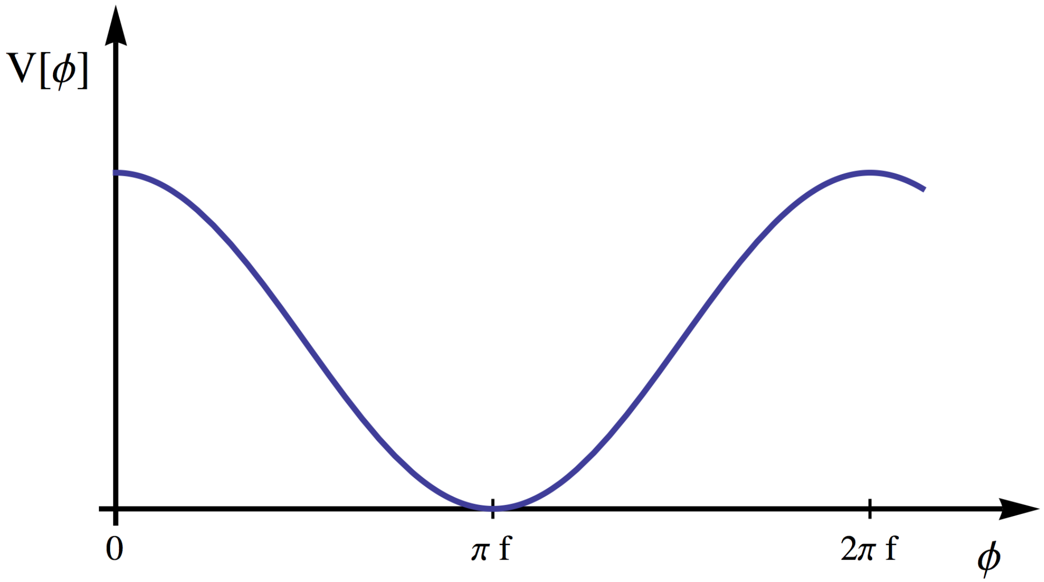
Nonperturbative effects break this symmetry to a remnant discrete shift symmetry



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

The Axion Potential

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

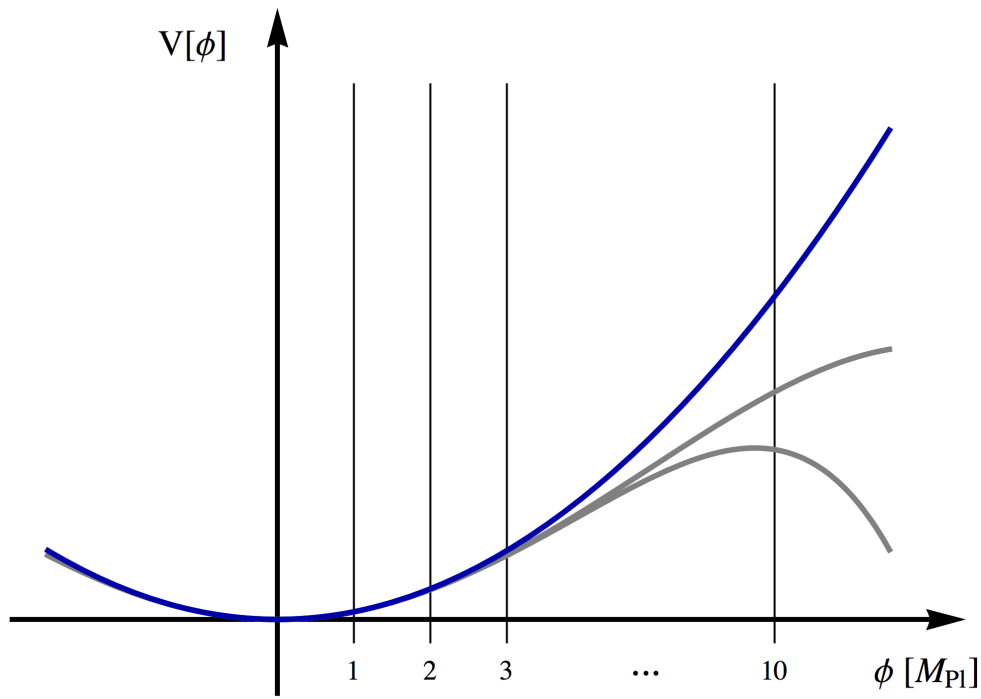


$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{2\pi\phi}{f}\right)\right]$$

ϕ confined to one fundamental domain

“Gravitational backreaction”

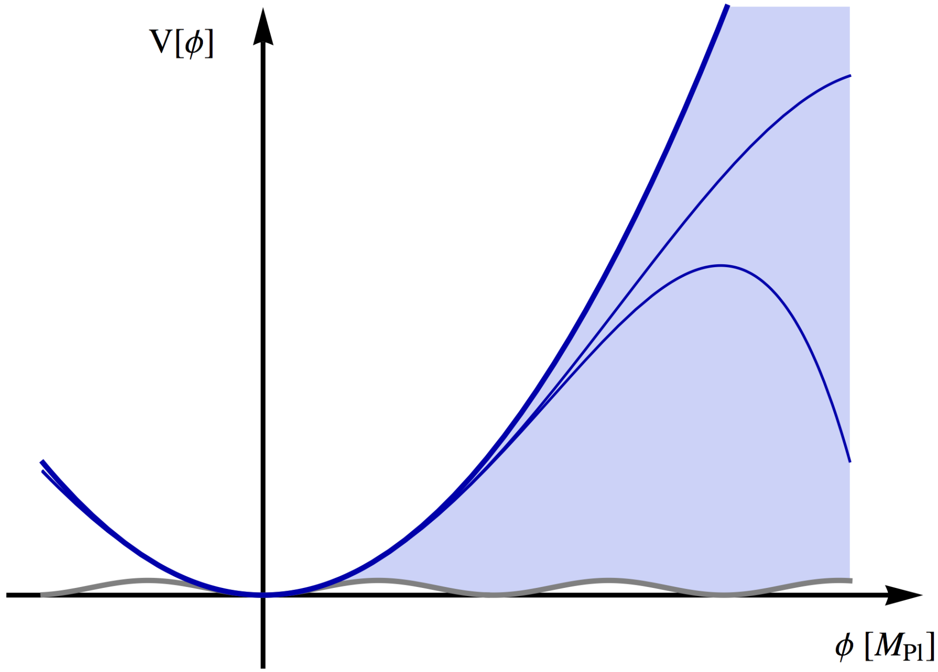
leads to uncertainties at trans-Planckian field values



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

The power of shift symmetry

The discrete shift symmetry controls these corrections



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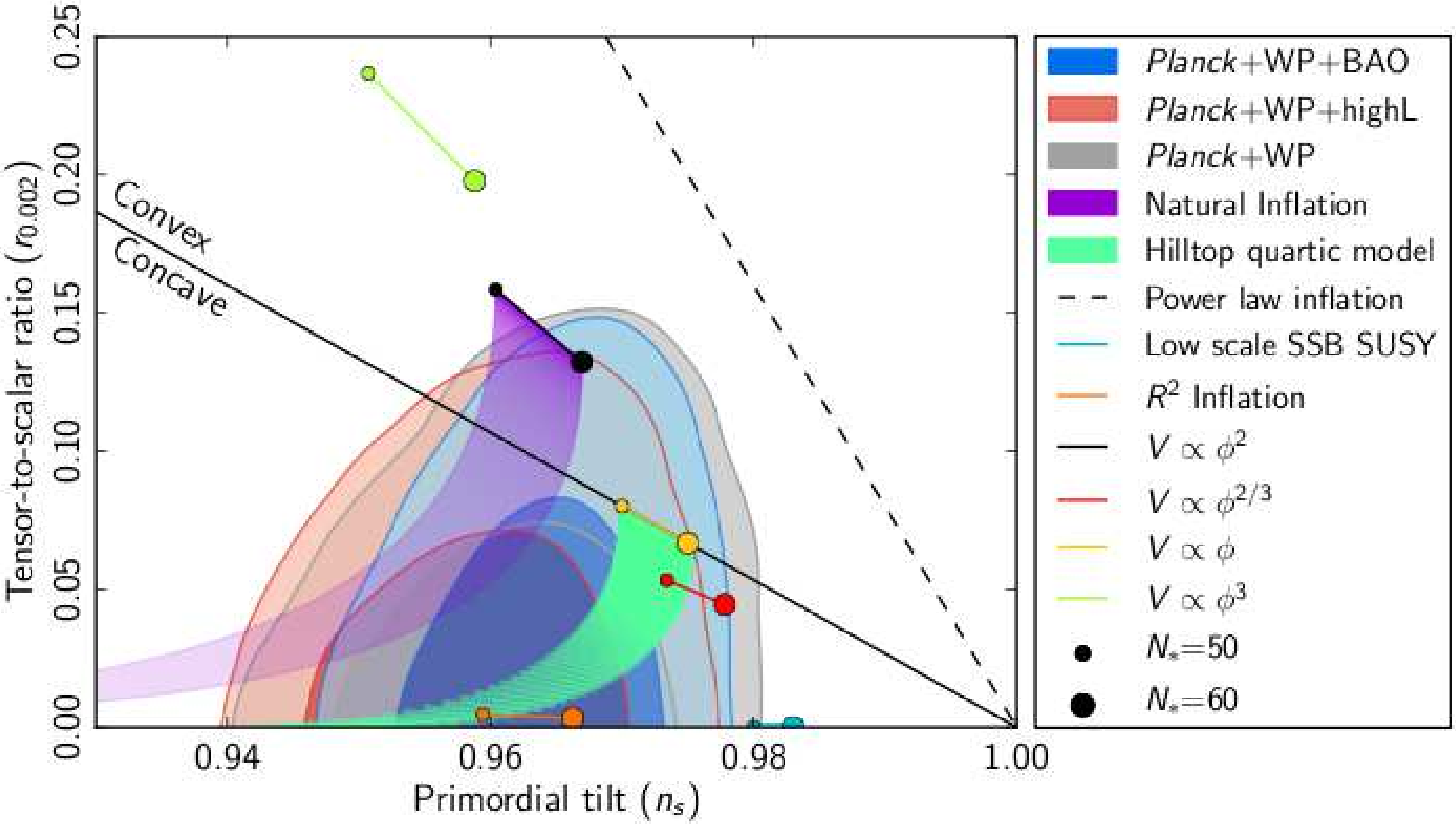
Planck results



News from BICEP2

Tentatively large tensor mode $r = 0.2^{+0.07}_{-0.05}$

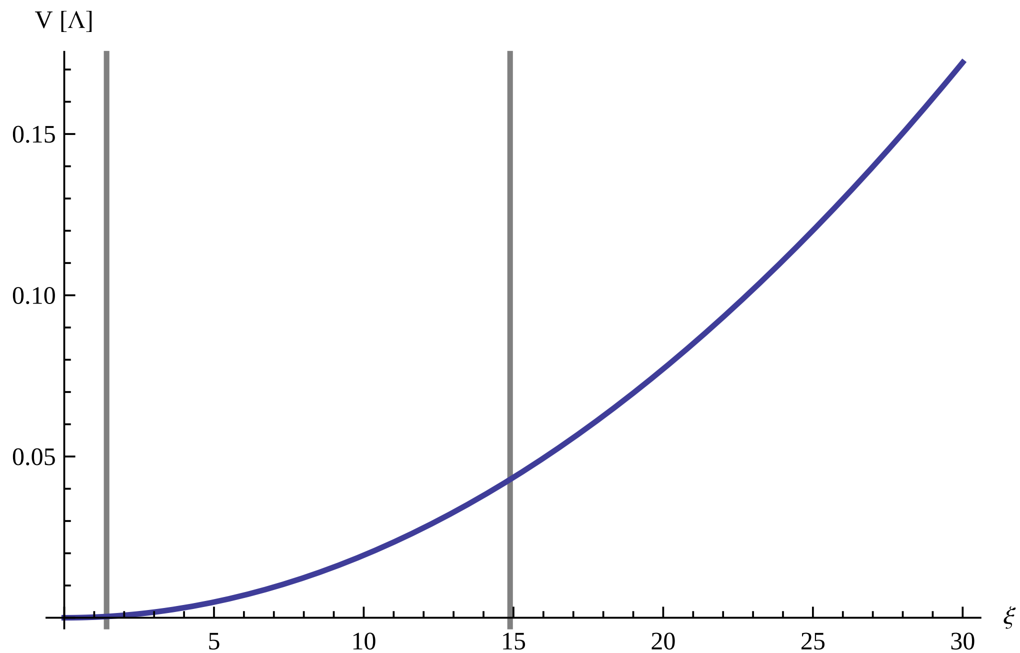
(after dust reduction $r = 0.16^{+0.06}_{-0.05}$)

- this is large compared to the expectation from the Planck satellite (although consistent)
- 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 $V(\phi) \sim m^2\phi^2$

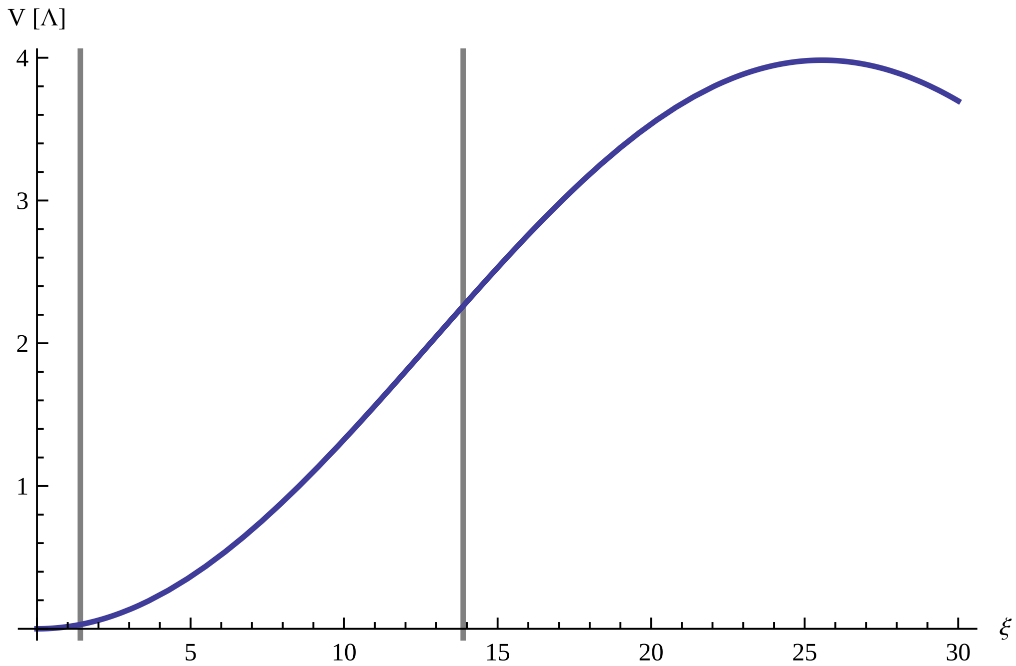
- it implies $\triangle\phi \sim 15 M_{\mathrm{P}}$ to obtain 60 e-folds of inflation

Range of inflaton field



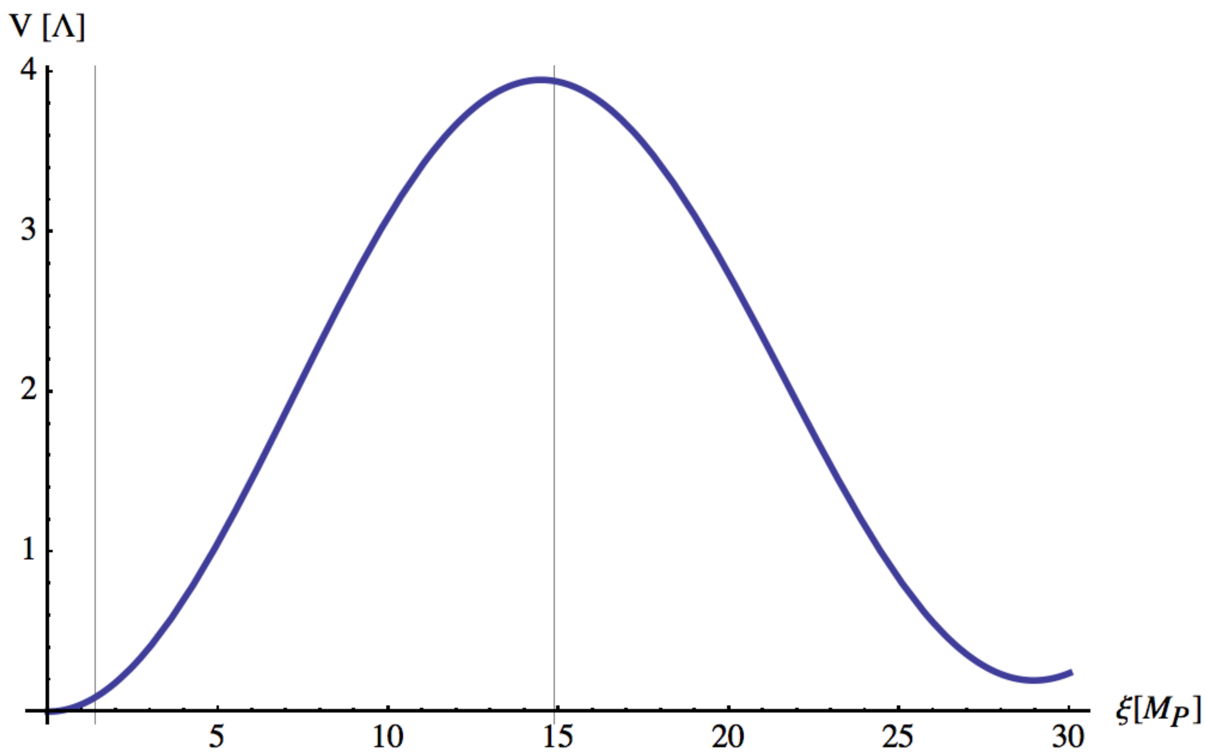
For the axionic potential this implies a rather large value of the axion decay constant $\pi f \gg M_{\mathrm{P}}$

Range of inflaton field



This "trans-Planckian" problem is common to all (single field) models, and in particular to axionic inflation. It is a problem of potential gravitational backreaction.

Range of inflaton field



A decay constant $\pi f \gg M_{\rm P}$ does not necessarily seem to make sense. Needs strong coupling and/or small radii.

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
- that could control the gravitational back-reaction
- axions are abundant in string theory

Still: we need $f \leq M_{\mathrm{P}}$ 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

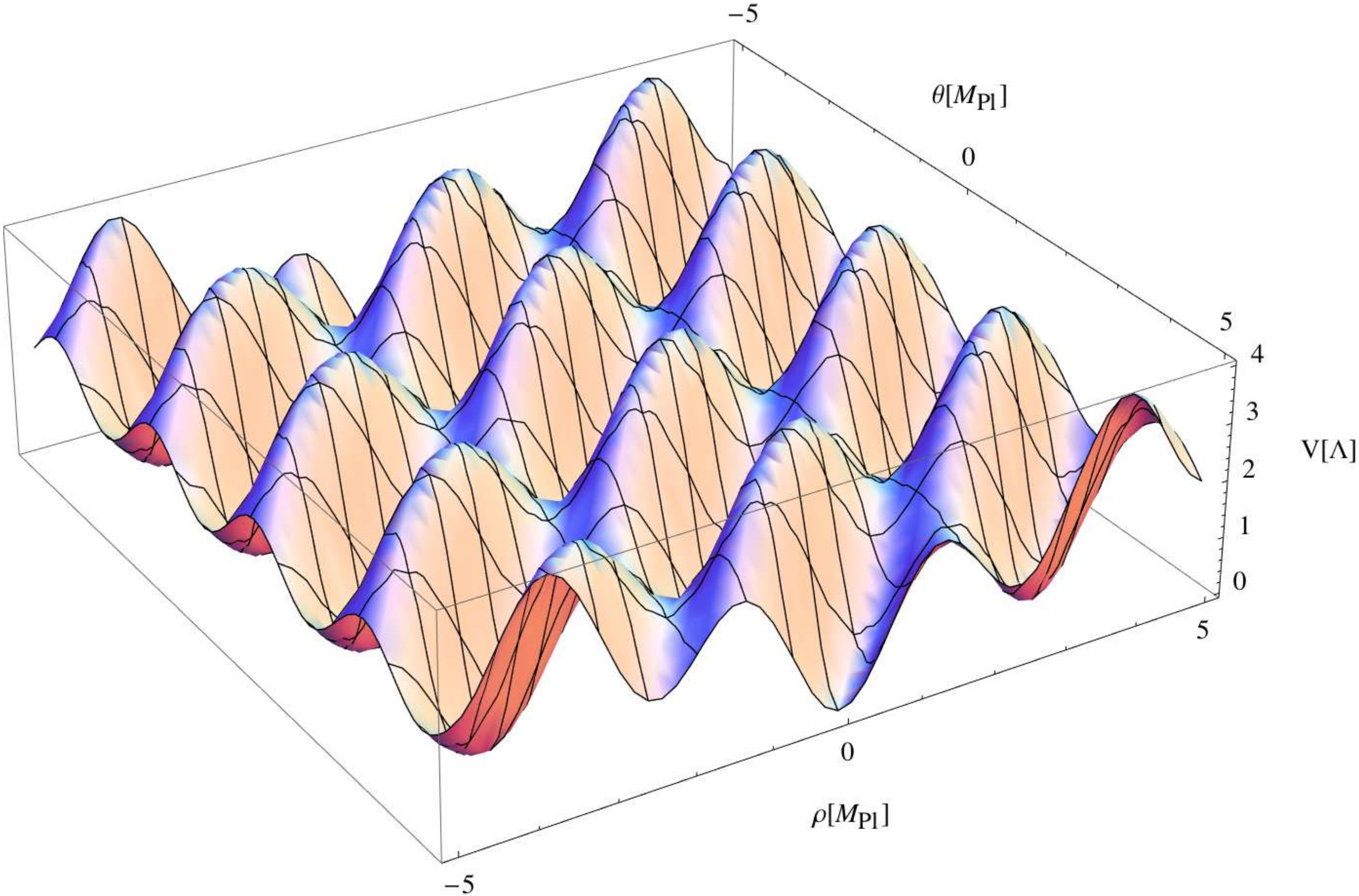
$$V(\theta,\rho) = \Lambda^4\left(2 - \cos\left(\frac{\theta}{f_1} + \frac{\rho}{g_1}\right) - \cos\left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right)$$

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

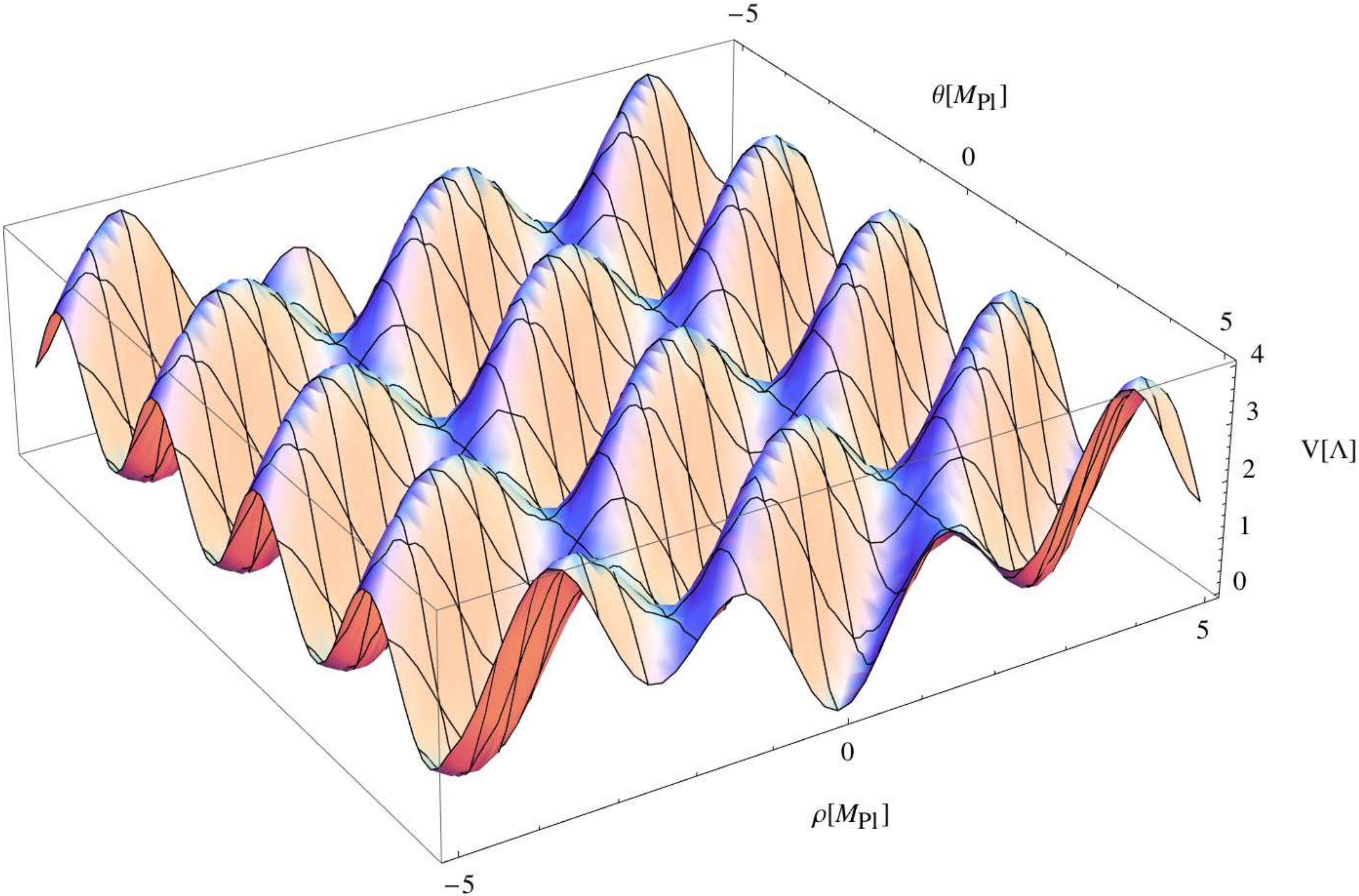
Alignment parameter defined through $\alpha = g_2 - \frac{f_2}{f_1}g_1$

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

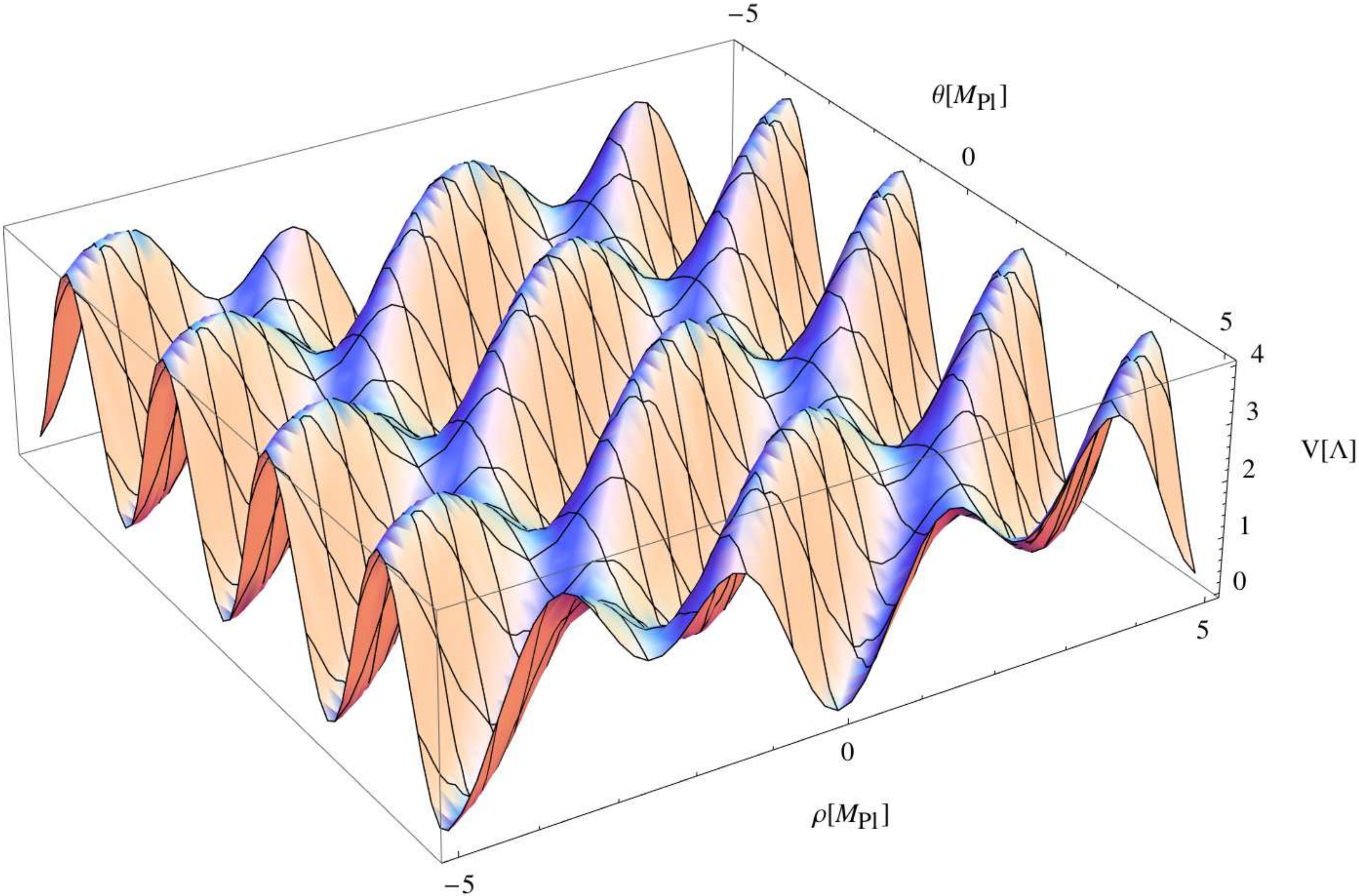
Potential for $\alpha = 1.0$



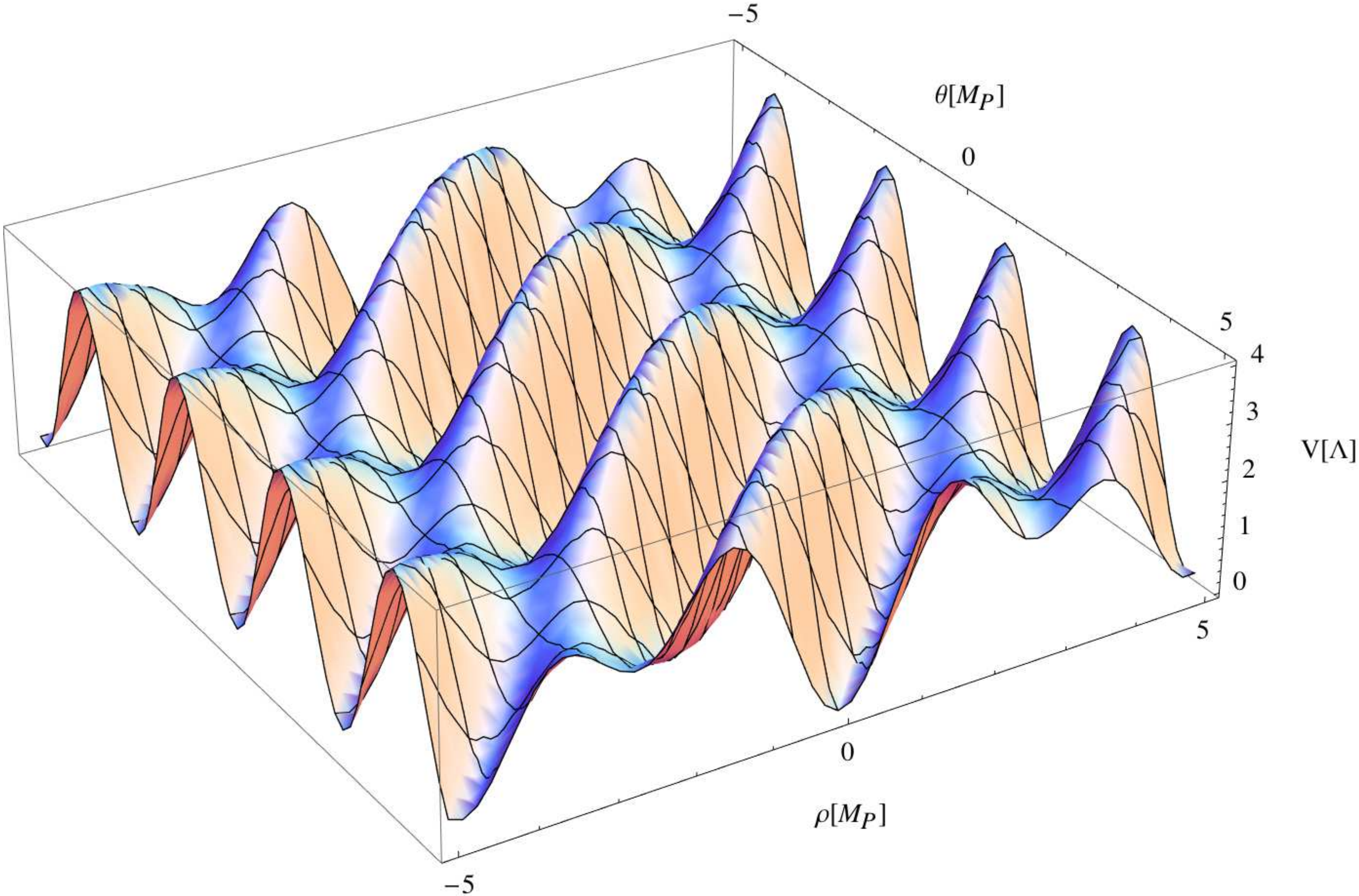
Potential for $\alpha = 0.8$



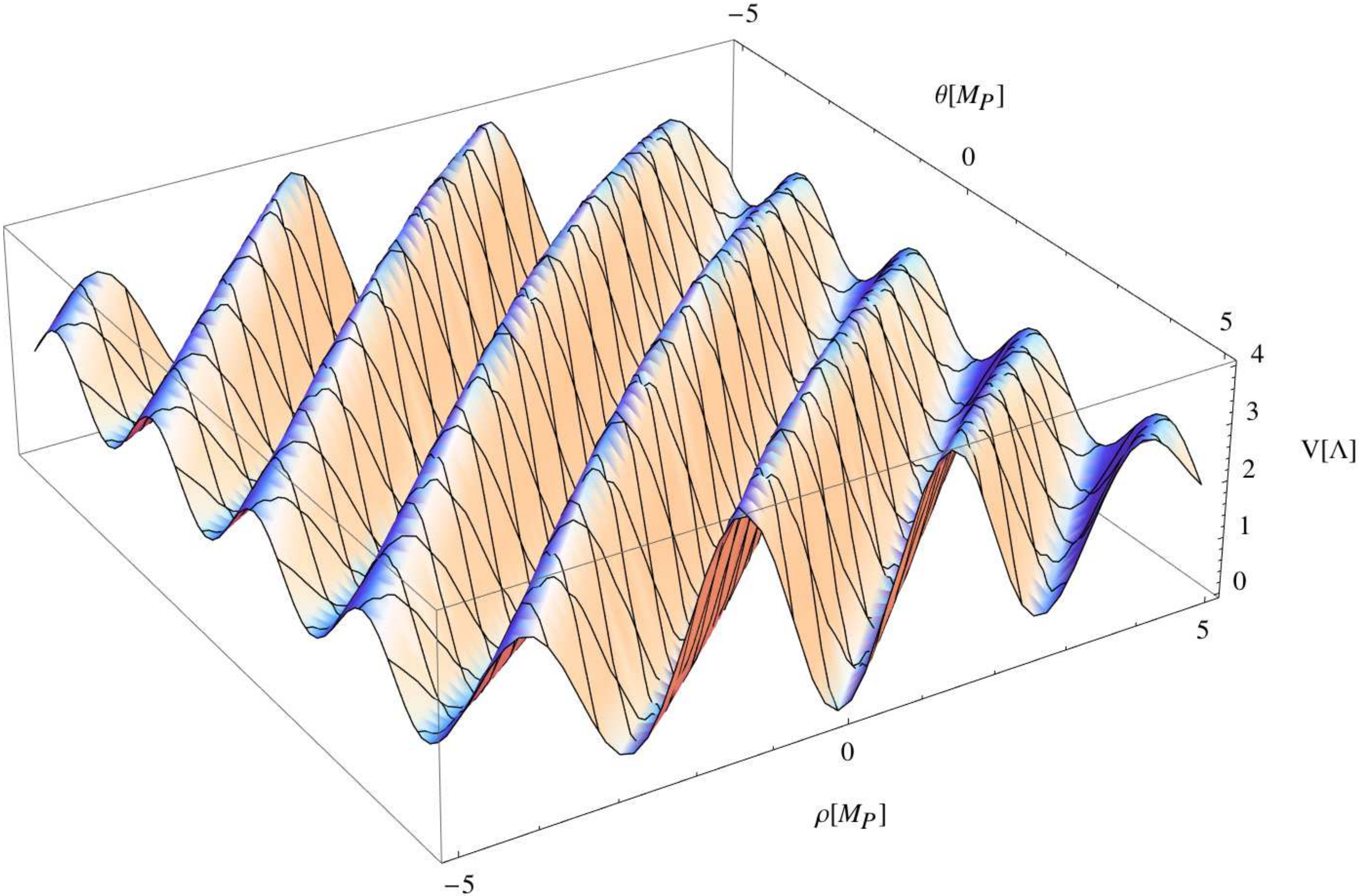
Potential for $\alpha = 0.5$



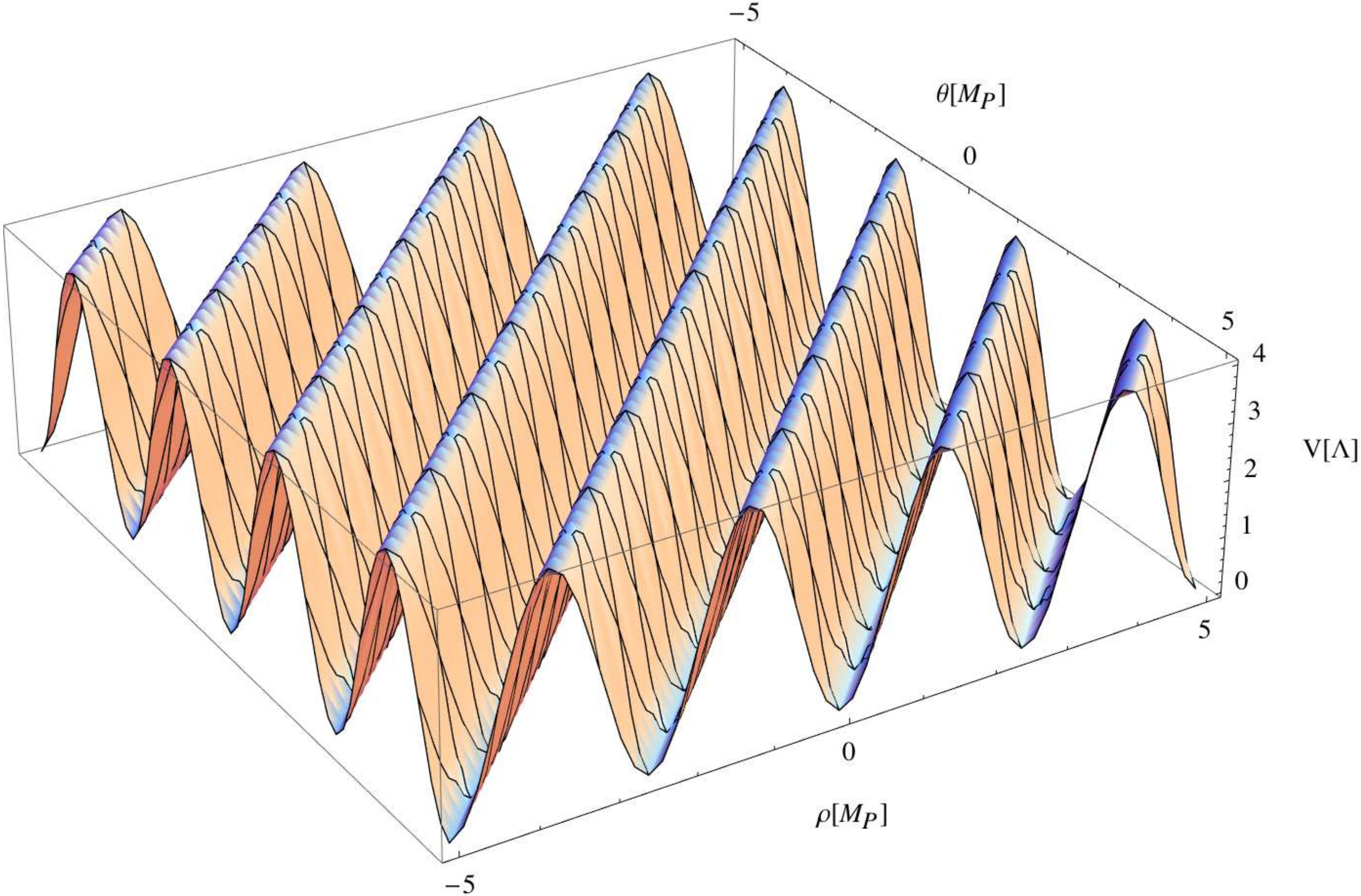
Potential for $\alpha = 0.3$



Potential for $\alpha = 0.1$



Potential for $\alpha = 0$



The lightest axion

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

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

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

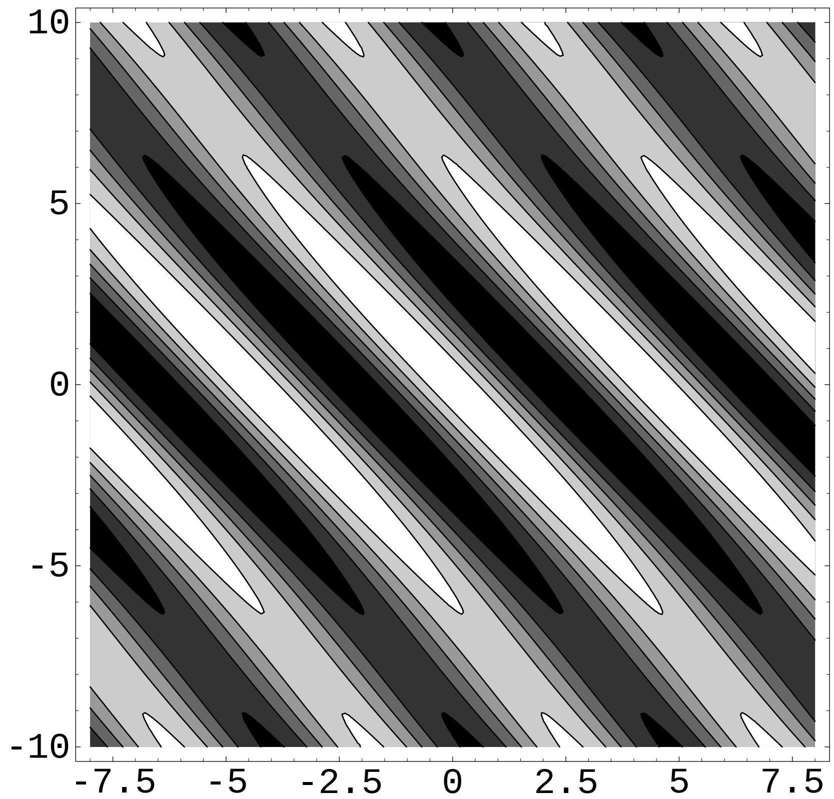
Lightest axion ξ has potential

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

leading effectively to a one-axion system

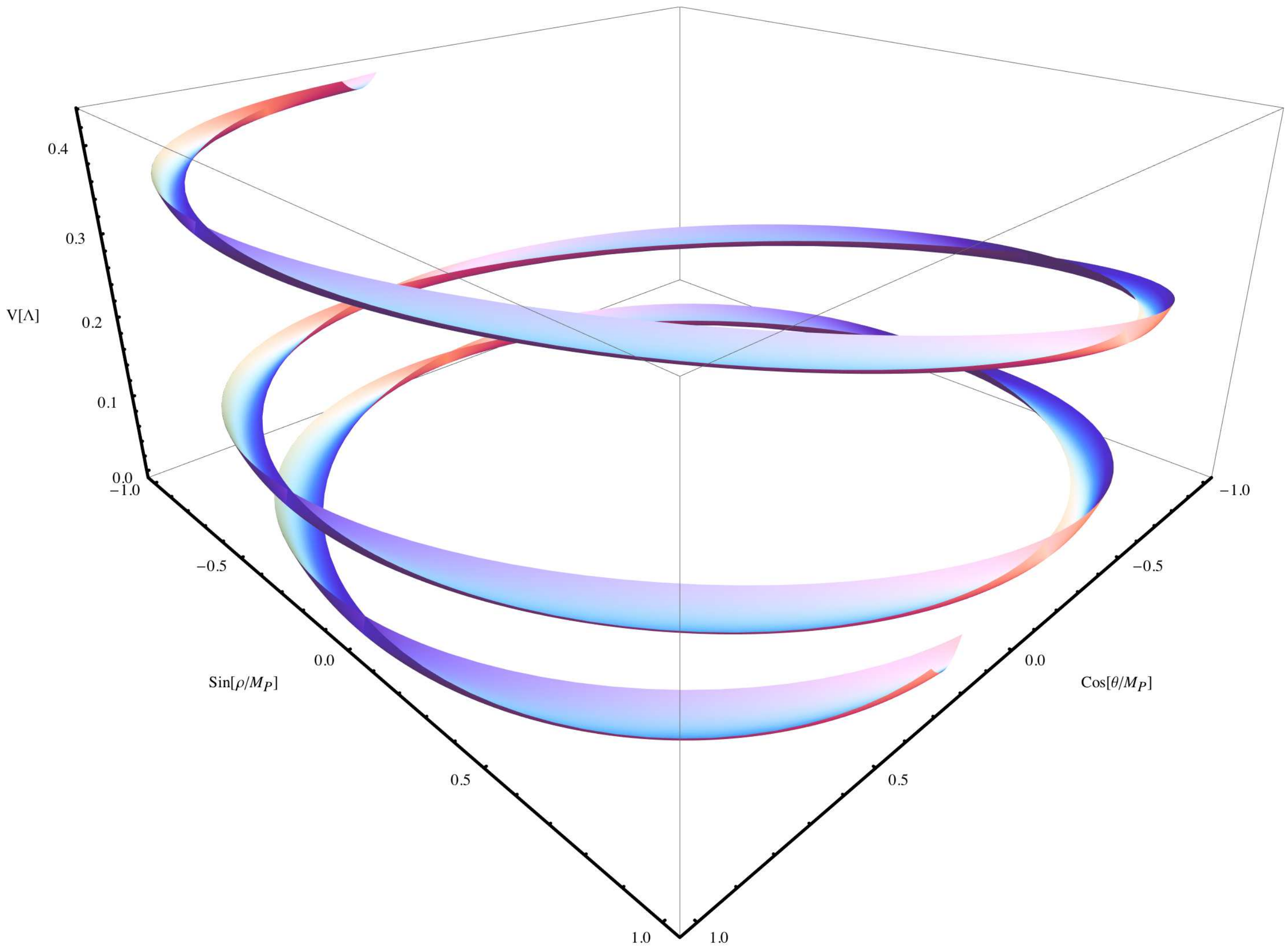
$$V(\xi) = \Lambda^4 \left[1 - \cos\left(\frac{\xi}{\tilde{f}}\right)\right] \quad \text{with} \quad \tilde{f} = \frac{f_2 g_1 \sqrt{(f_1^2 + f_2^2)(f_1^2 + g_1^2)}}{f_1^2 \alpha}$$

Axion landscape of KNP model



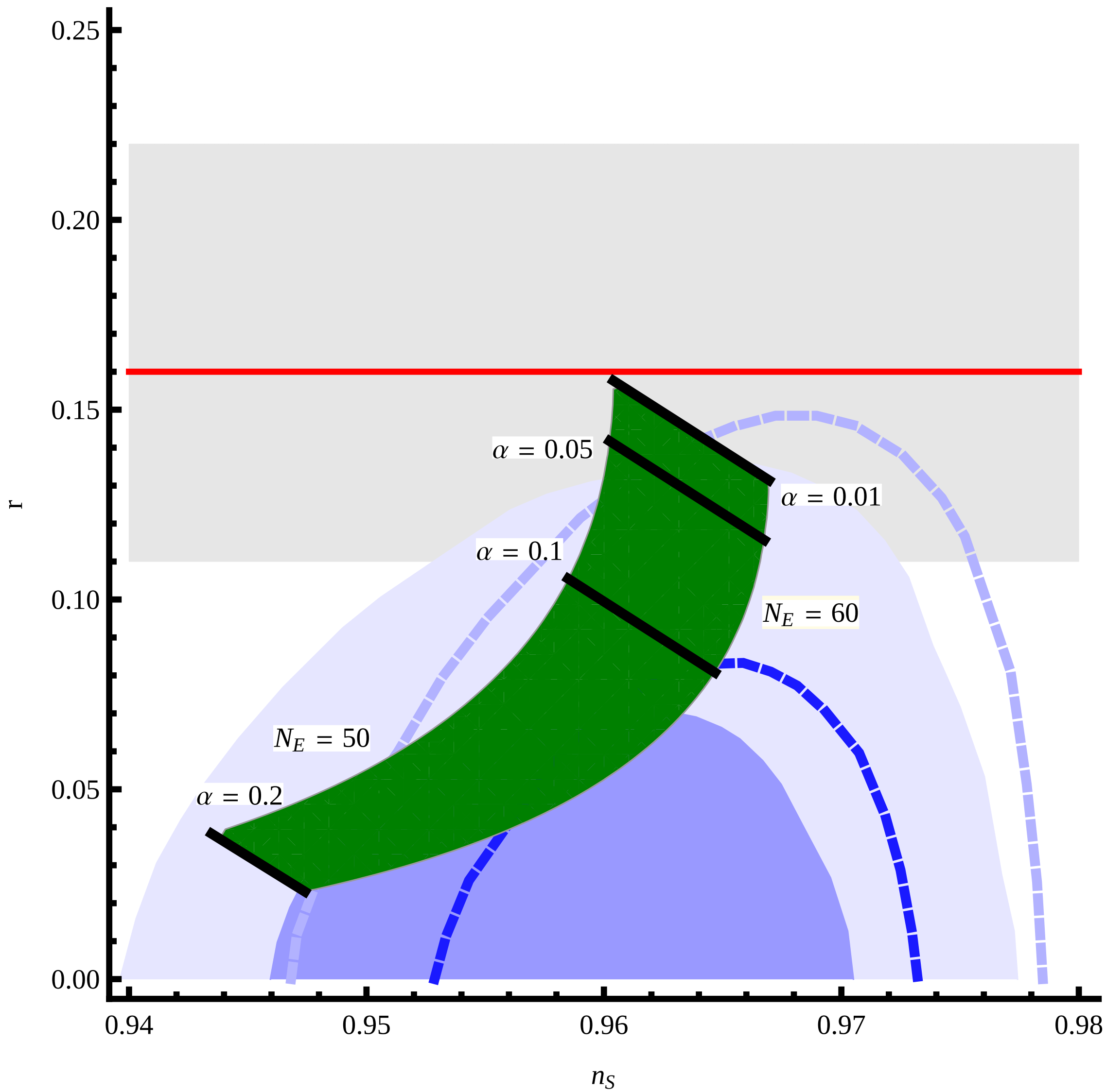
The field ξ rolls within the valley of ψ. The motion of ξ corresponds to a motion of θ and ρ over many cycles. The system is still controlled by discrete symmetries.

Monodromic Axion Motion



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

The “effective” one-axion system



α versus r

The alignment parameter can be determined experimentally

- $r \sim 0.1$ requires $\alpha \sim 0.1$
- large $r > 0.1$ corresponds to smallish α and might require a fine-tuning
- $r > 0.16$ is not possible within the scheme

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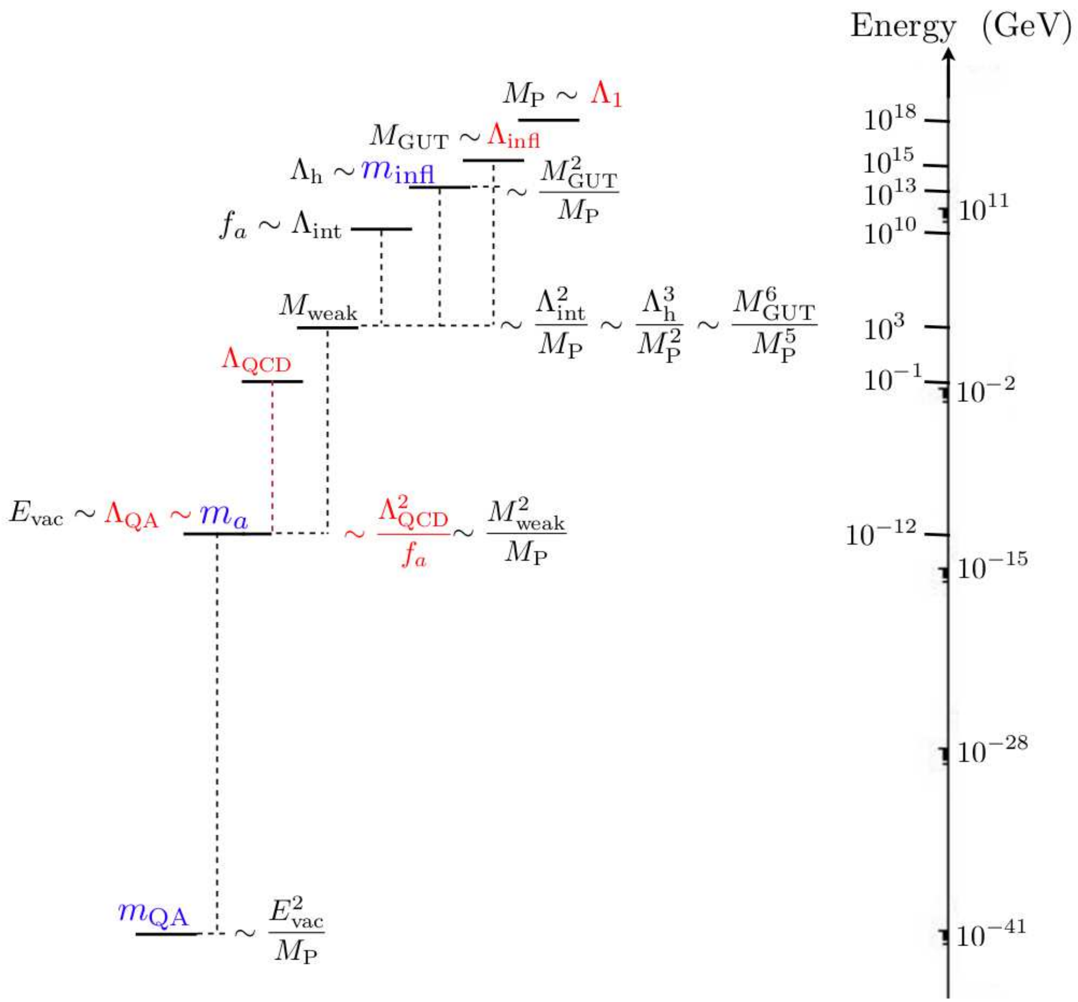
So let us wait till the "dust settles". Large r has to deal with

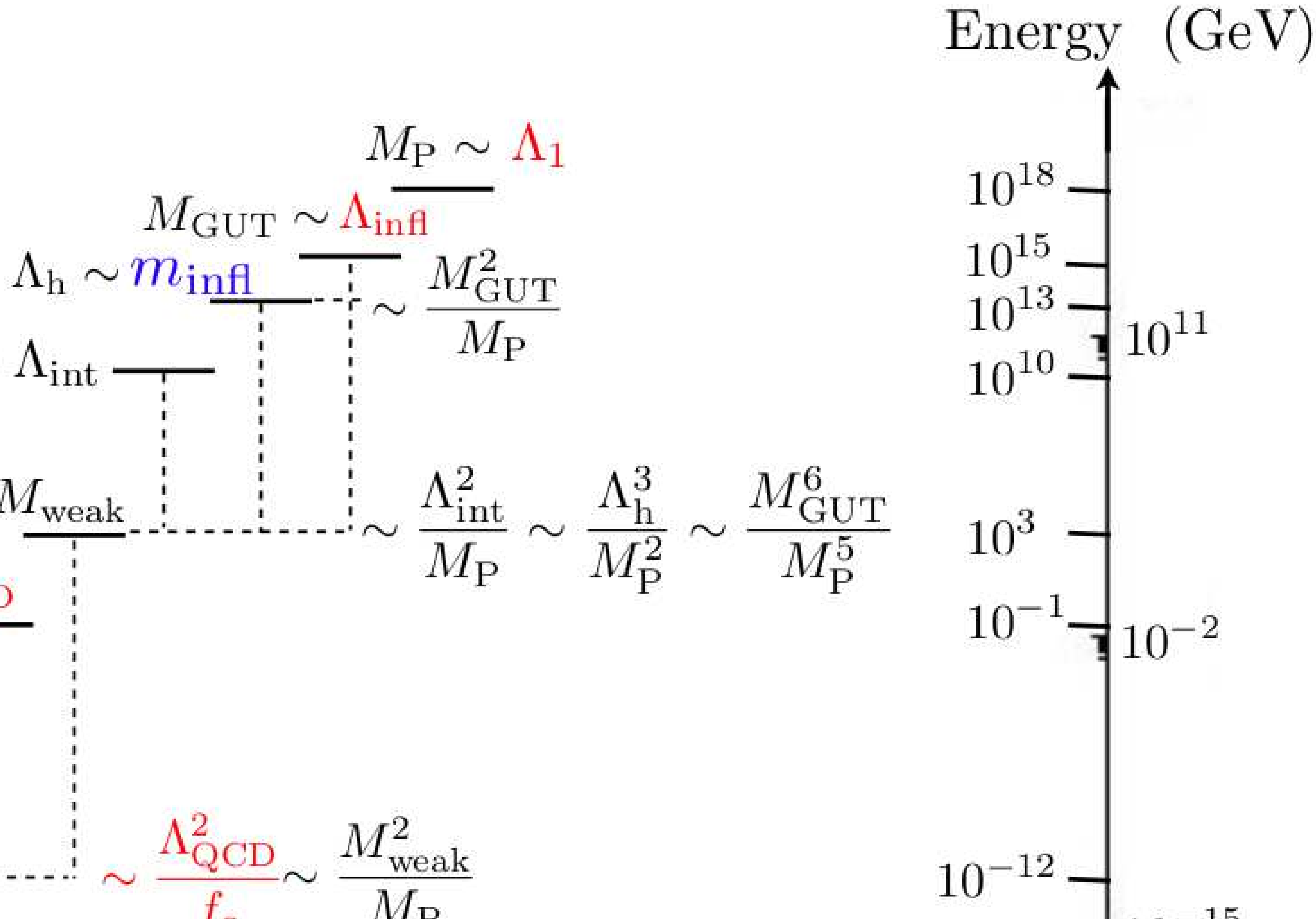
- a certain tuning of parameters
- or the consideration of more than two axions

(Czerny, Higaki, Takahashi 2014; Choi, Kim, Yun, 2014)

The scales of axions



(Chatzistavrakidis, Erfani, Nilles, Zavala, 2012)


Energy (GeV)
10^{18}
10^{15}
10^{13}
10^{11}
10^{10}
10^{3}
10^{-1}
10^{-2}
10^{-12}
$M_{\rm P} \sim \Lambda_1$
$M_{\rm GUT} \sim \Lambda_{\rm infl}$
$\Lambda_{\rm h} \sim m_{\rm infl}$
$\sim \frac{M_{\rm GUT}^2}{M_{\rm P}}$
$\Lambda_{\rm int}$
$M_{\rm weak}$
$\sim \frac{\Lambda_{\rm int}^2}{M_{\rm P}} \sim \frac{\Lambda_{\rm h}^3}{M_{\rm P}^2} \sim \frac{M_{\rm GUT}^6}{M_{\rm P}^5}$
$\sim \frac{\Lambda_{\rm QCD}^2}{f_a} \sim \frac{M_{\rm weak}^2}{M_{\rm P}}$

Does this fit into 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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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

Explicit realizations

The original KNP paper considered heterotic b_2 axions

- with gauge instantons of $SU(n) \times SU(m)$
(require pretty large n, m depending on value of α)
- TypeII theories have more flexibility
(b_2, c_2 and c_4 axions and various stacks of D7-branes)

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  (b_2, c_2 and c_4 axions and various stacks of D7-branes)

Recently there have been model building attempts with

- multiply wrapped or magnetized D7-branes
- still seem to require large ranks and windings

(Long, McAllister, McGuirk, 2014)

There are reasons for optimism. But new ideas welcome?

Variants of the KNP-scenario

"N-flation" (Dimopoulos, Kachru, McGreevy, Wacker, 2005)

- postulates N non-interactive axions to obtain
- an effective axion scale $f_{\text{eff}} \sim \sqrt{N} f_i$
- a realistic scenario requires $N \geq 1000$

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Many fields lead to a rescaling of Planck mass $M_{\text{Pl}} \to \sqrt{N} M_{\text{Pl}}$ (and the problem remains unsolved)

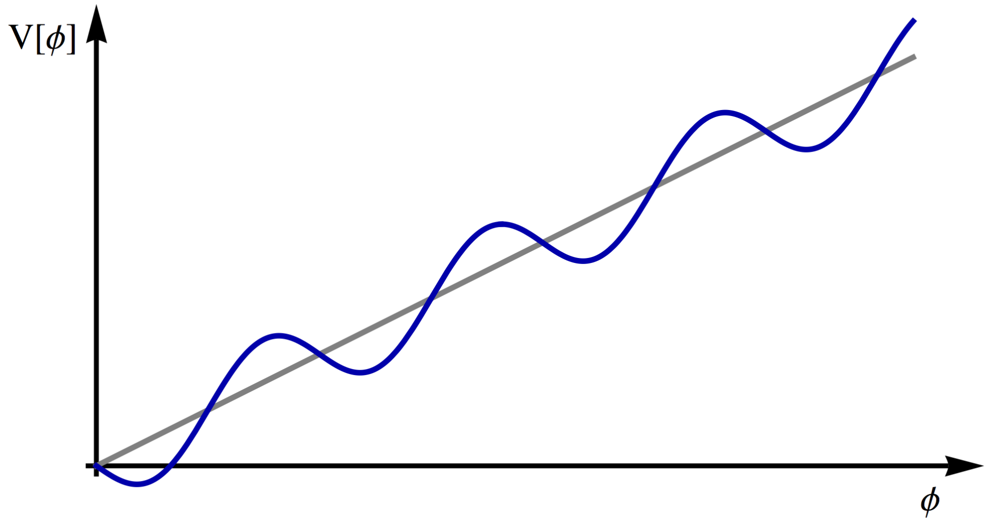
The way out is alignment à la KNP !

In aligned multi-axion systems you gain a factor $\sqrt{N!}$

(Choi, Kim, Yun; Czerny, Higaki, Takahashi; Bachlechner et al., 2014)

So-called “Axion Monodromy”

One adds a background (brane) that breaks the axionic symmetry (McAllister, Silverstein, Westphal, 2008)



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

The discrete shift symmetry is broken explicitely.

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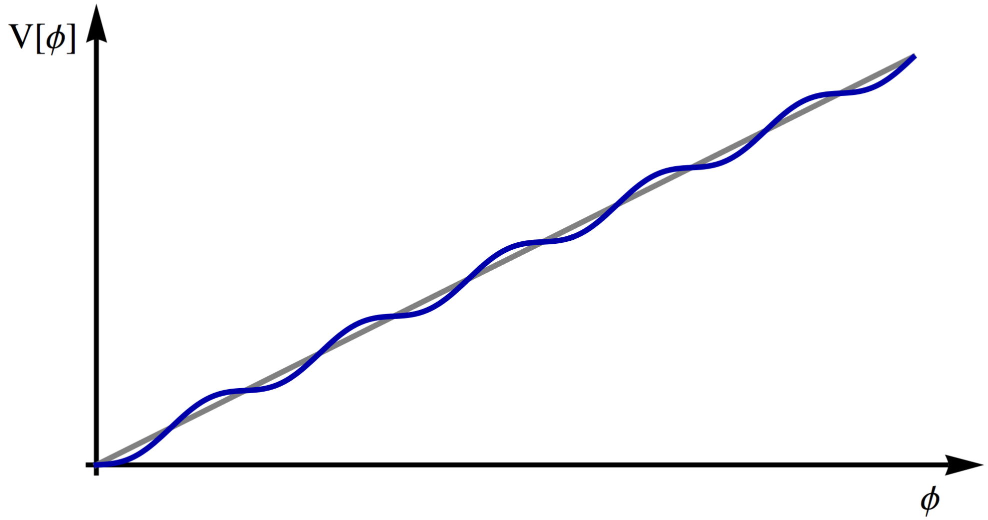
The “axionic potential” has to be suppressed



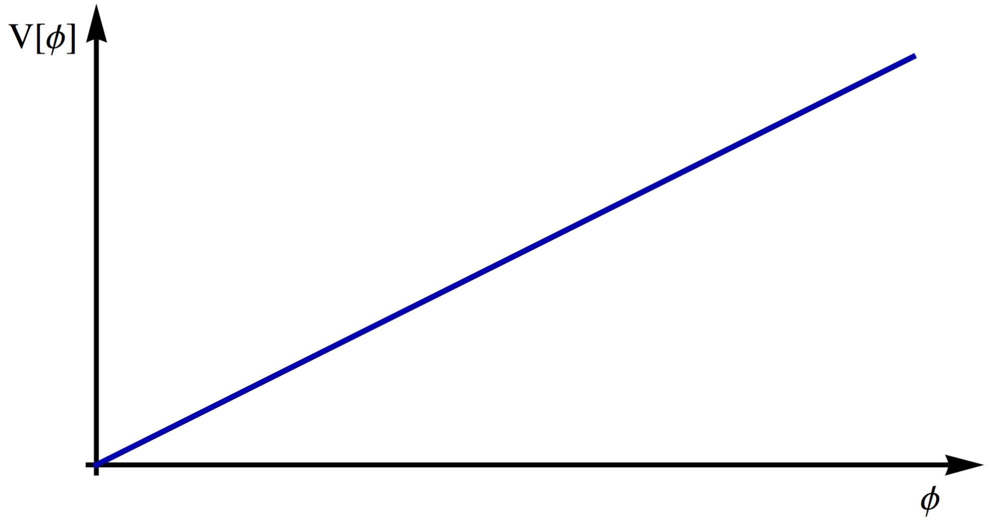
$$V(\phi) = \mu^{4-p}\phi^p + \Lambda^4 \left[1 - \cos\left(\frac{2\pi\phi}{f}\right)\right]$$

Symmetry protection is lost. Have to worry about gravitational backreaction of branes.

The original discrete symmetry becomes irrelevant

The “homeopathic axion”

The “axionic potential” is completely suppressed



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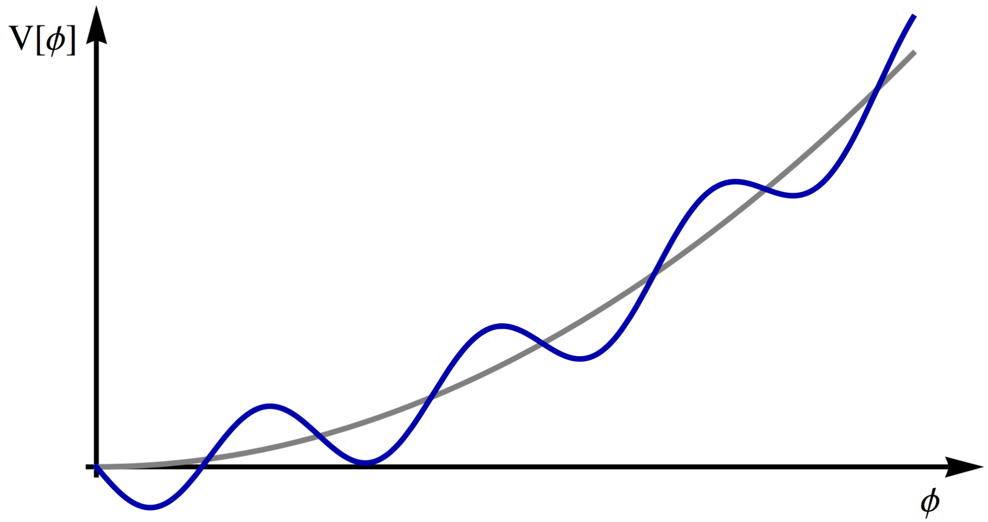
The original problem remains unsolved....

“Axion Monodromy”

One adds a background (brane) that breaks the axionic symmetry (quadratic potential)



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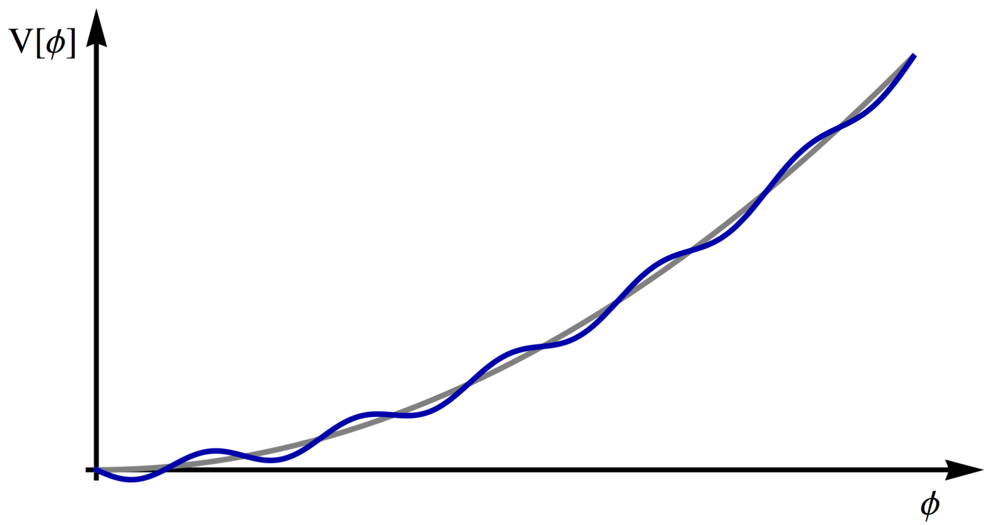

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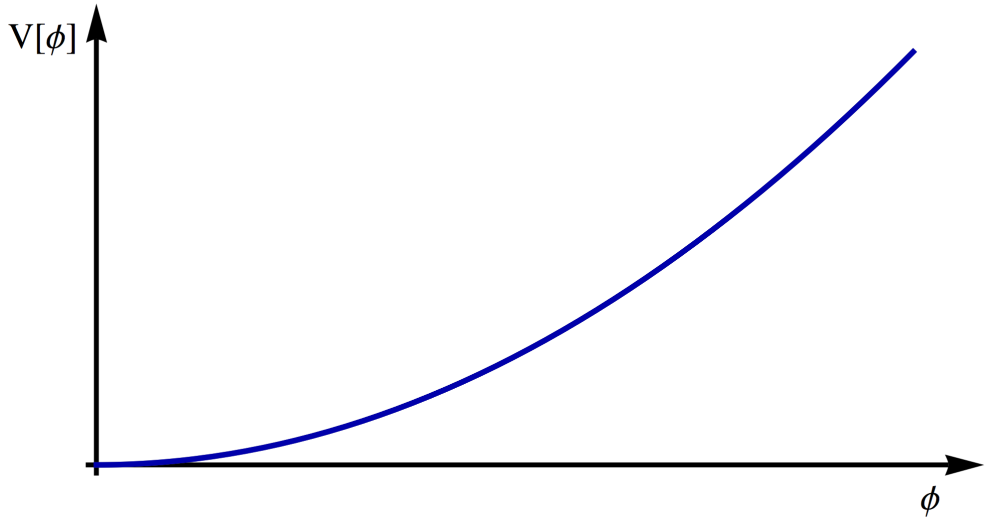

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The original problem remains unsolved....

Backreaction in Axion Monodromy

Once the (discrete) axionic symmetry is broken one has to worry about the brane backreaction

- “For the backreaction to be a small correction, the geometry must be arranged to respect an additional approximate symmetry....”
- “The original axion shift symmetry, on its own, does not suffice to guarantee a flat potential”

(Baumann, McAllister, arXiv: 1404.2601)

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(Baumann, McAllister, arXiv: 1404.2601)

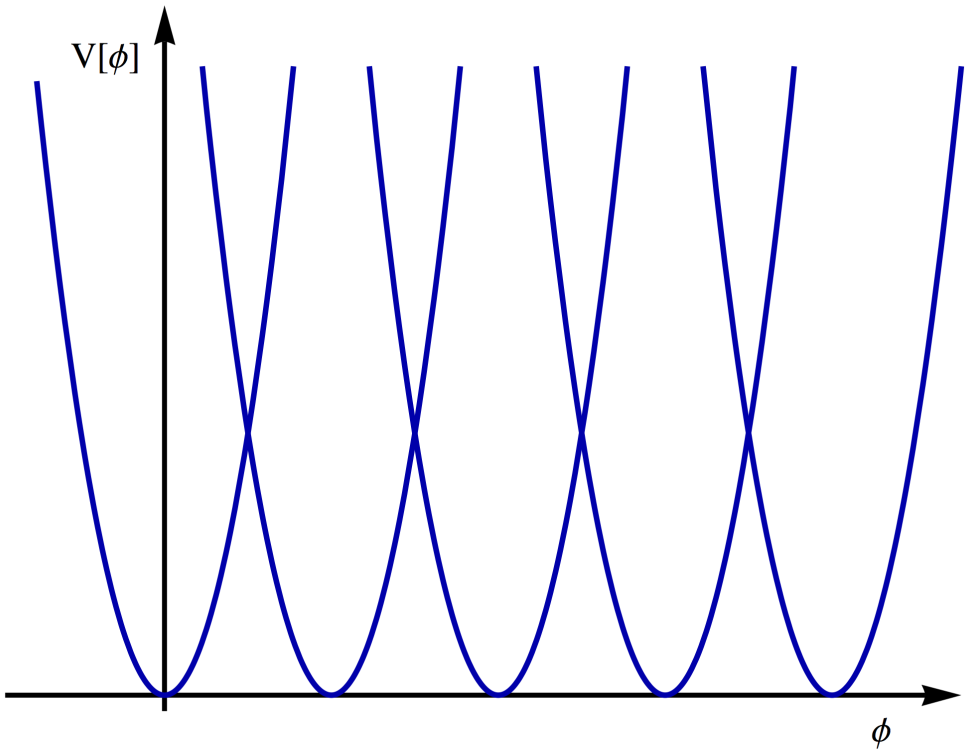
New ideas beyond the (homeopathic) “Axion Monodromy” are needed to solve the problem.

An attempt could be “Massive Wilson Line Monodromy” ?

(Marchesano, Shiu, Uranga; Hebecker, Kraus, Witkowski, 2014)

The “ignoble approach”

Several branches of quadratic potential from 4-form

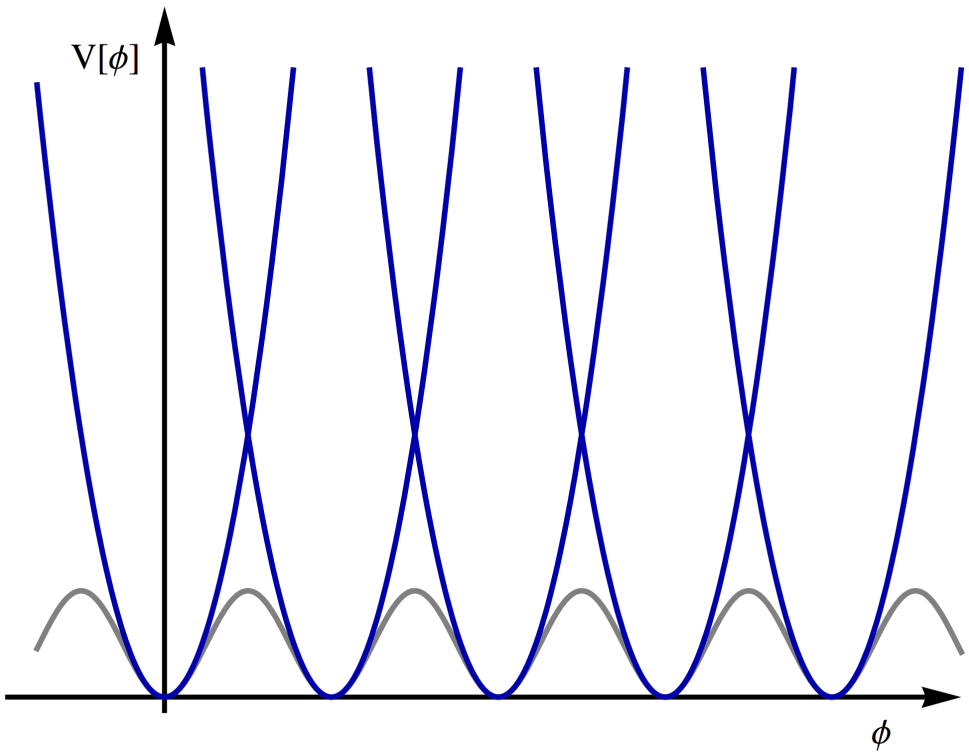


(Kaloper, Lawrence, Sorbo, 2008-2014)

Are there transitions between the branches?

Stability of branches?

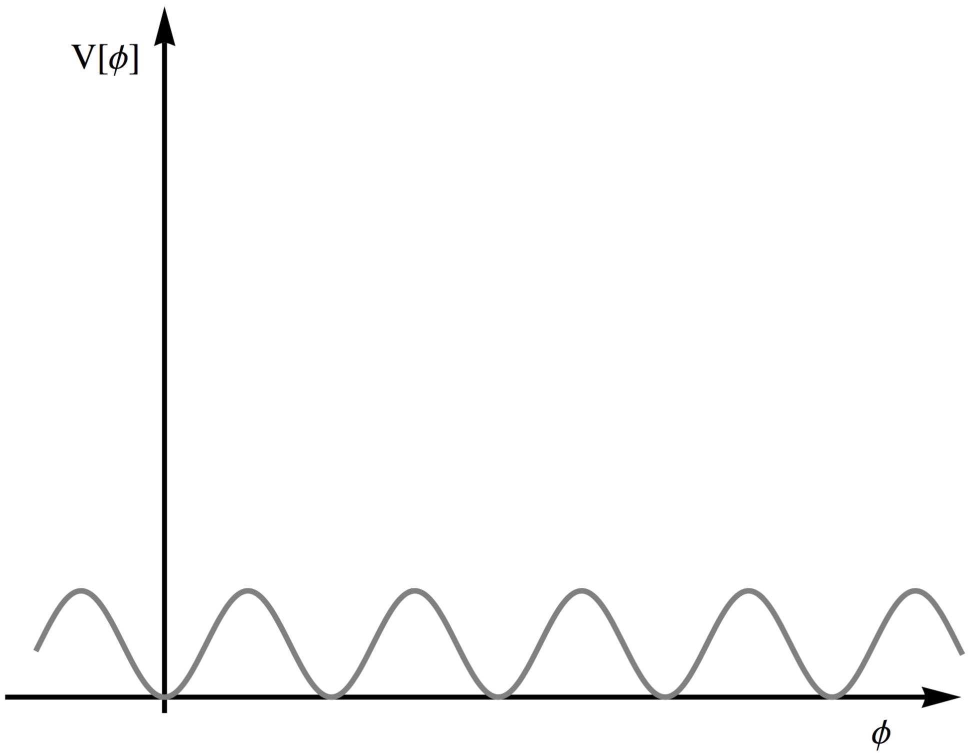
Connection to the original axion potential



The role of the discrete shift symmetry has to be clarified

Stability of branches?

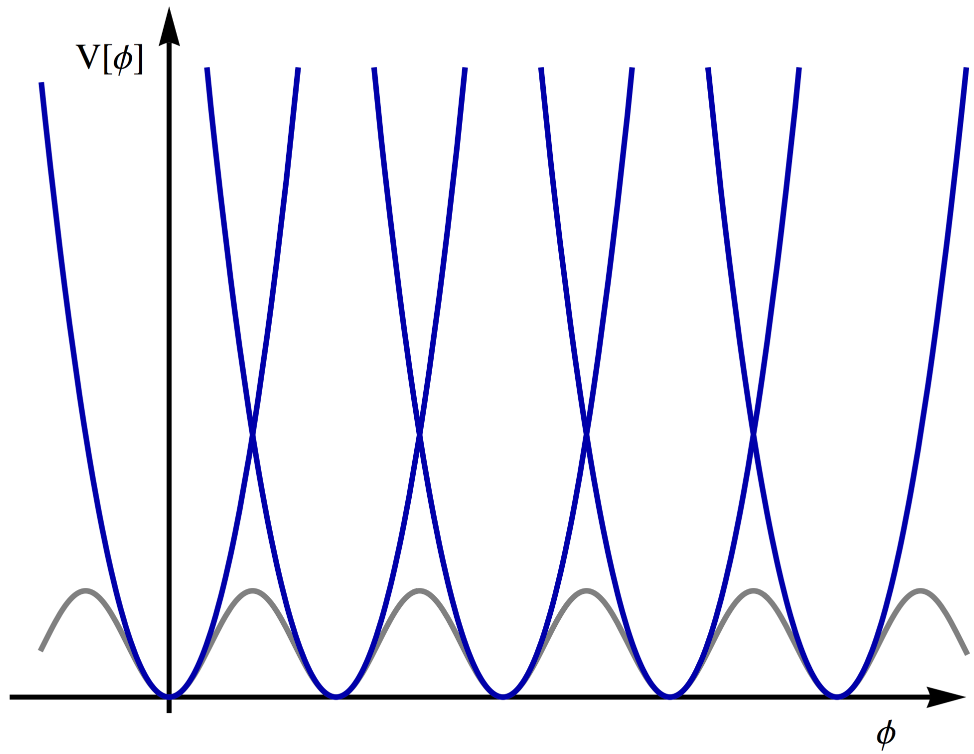
Connection to the original axion potential



The discrete shift symmetry does guarantee stability

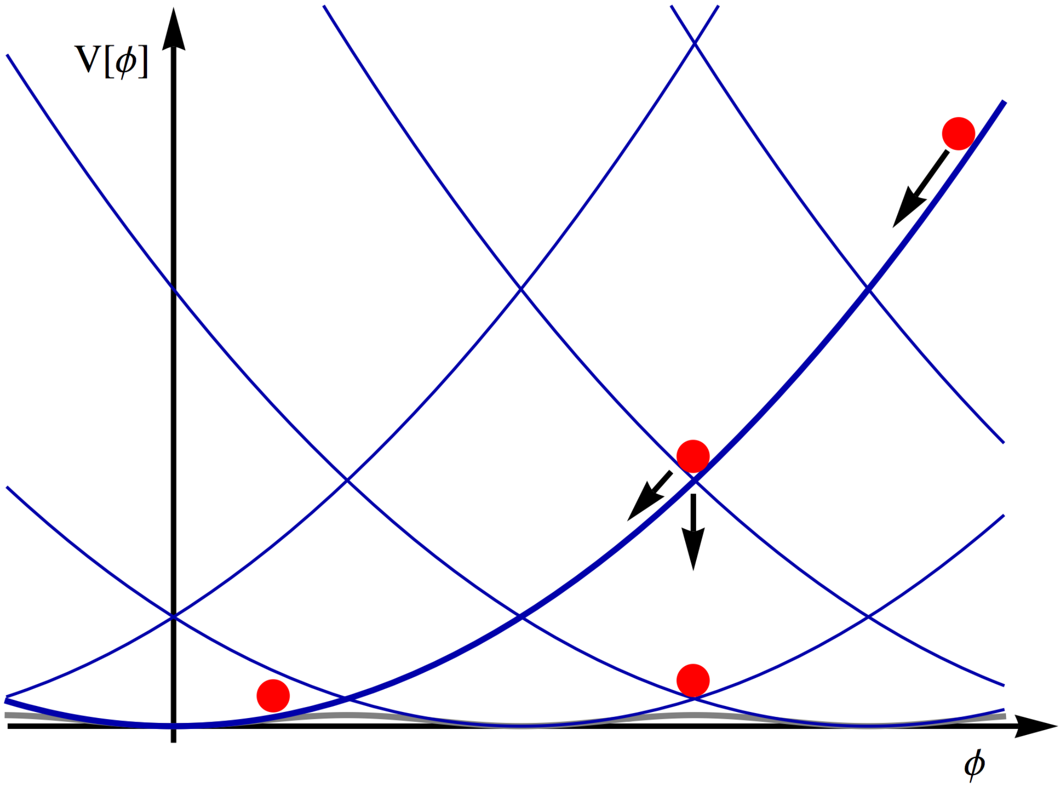
Stability of branches?

Connection to the original axion potential



The shift symmetry by itself does not guarantee stability

Transitions



The discrete shift symmetry is broken.
How to avoid transitions between the branches?

Dante's Inferno

"Dante's Inferno" uses two axions and a background brane

(Berg, Pajer, Sjors, 2009)

- KNP with a brane added or
- "axion monodromy" with an additional axion

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- KNP with a brane added or
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The alignment parameter α

- is tuned by choosing $f_1 \ll f_2$
- have to check backreaction of the brane

Again, the original (discrete) axion shift symmetry is broken and, in itself, might no longer guarantee the "flatness" of the potential (although the breaking could be "milder" here).

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
- sizeable tensor modes need trans-Planckian excursion of the inflaton field

In bottom-up approach one postulates a single axion field

- this leads to problems with trans-Planckian excursions
- and would require a trans-Planckian decay constant

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
- in principle such moduli might hurt, but here they help to solve the problem through monodromic motion

Conclusion

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 a single field have severe problems

- the discrete axionic symmetry has to be destroyed
- control of gravitational backreaction is lost

Conclusion II

The solution is the alignment mechanism of axions

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

The ingredients for a successful model are

- several axion fields
- remnant discrete (gauge) symmetries

Axion fields and discrete symmetries are abundant in string theory. The discrete gauge symmetries control the gravitational back reaction through “monodromy”.

The result is an “effective one-axion” inflaton model.
One axion spirals down down in the valley of a second one.

The spiral axion slide