The Quest for Primordial Tensor Modes

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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)
- the relaxion (Graham, Kaplan, Rajendran, 2015)

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

Vielfalt statt Einfalt: Diversity beats Simplicity

The Role of Axions

Concentrate here on (aligned) inflation (Kim, Nilles, Peloso, 2005)

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

Other application of multi-axion systems

- axionic domain walls for QCD axion (Choi, Kim, 1985)
- alignment of quintessential axions (Kaloper, Sorbo, 2006)
- the relaxion mechanism (Choi, Im, 2015)

Window of Opportunity

Measurement of sizeable tensor modes could give precious information on the physics at highest energies.

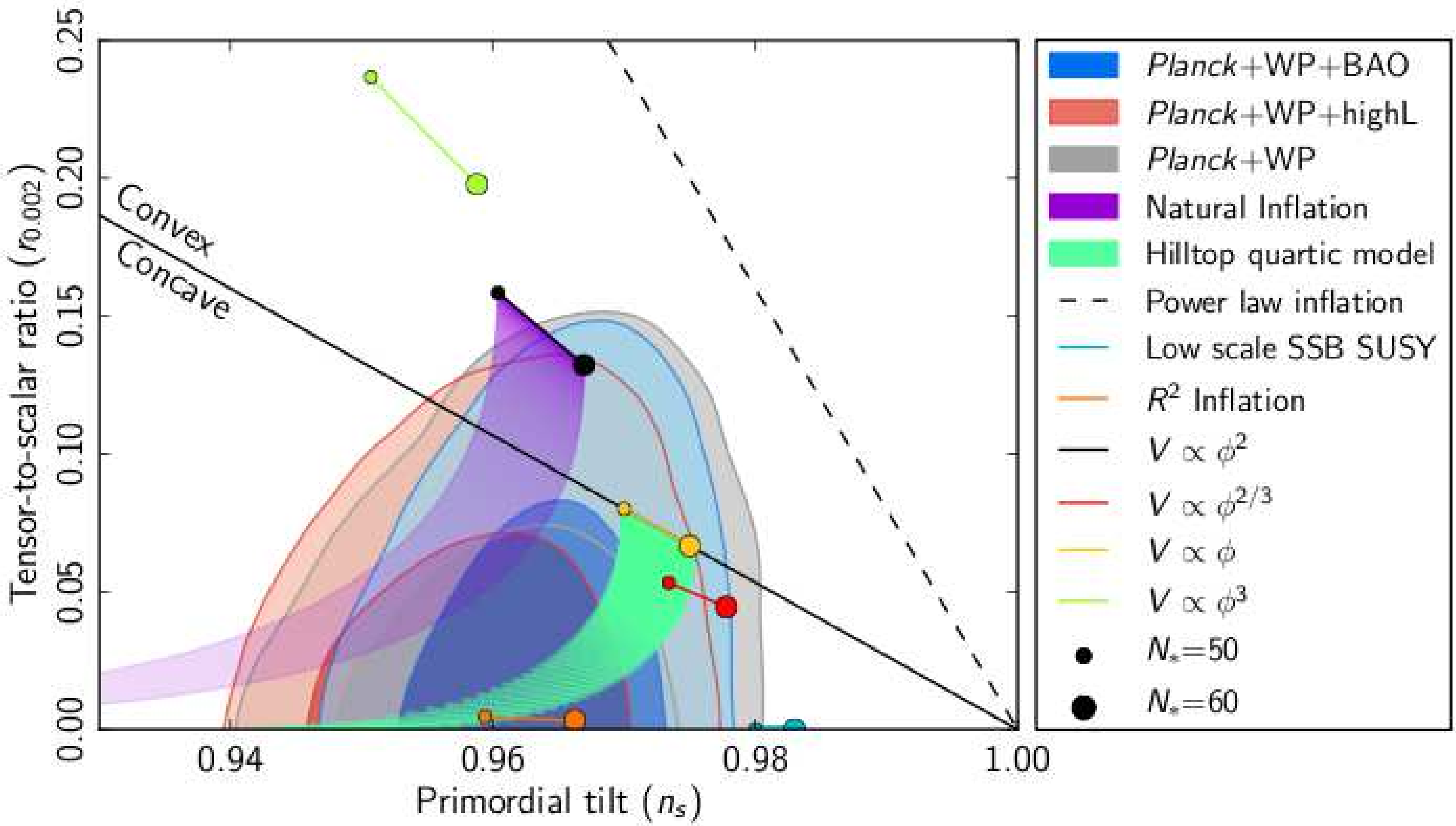
- we might explore physics close to the Planck scale
- get new insight on properties of (quantum) gravity

A theoretical treatment of these sizeable tensor modes could therefore be problematic

- question of trans-Planckian excursions (Lyth bound)
- the question of UV-completion (e.g. string theory)
- the weak gravity conjecture (and variants thereof)

Let us hope that sizeable tensor modes will be found.

Planck results (Spring 2013)



How to get Large Tensor Modes

We consider here two specific cases for large tensor modes

- the mechanism of axionic (natural) inflation

  (Freese, Frieman, Olinto, 1990)

- enhanced tensor modes from extra dimensions

  (Giudice, Kolb, Lesgourgues, Riotto, 2002)

On the way we shall be confronted with some obstacles

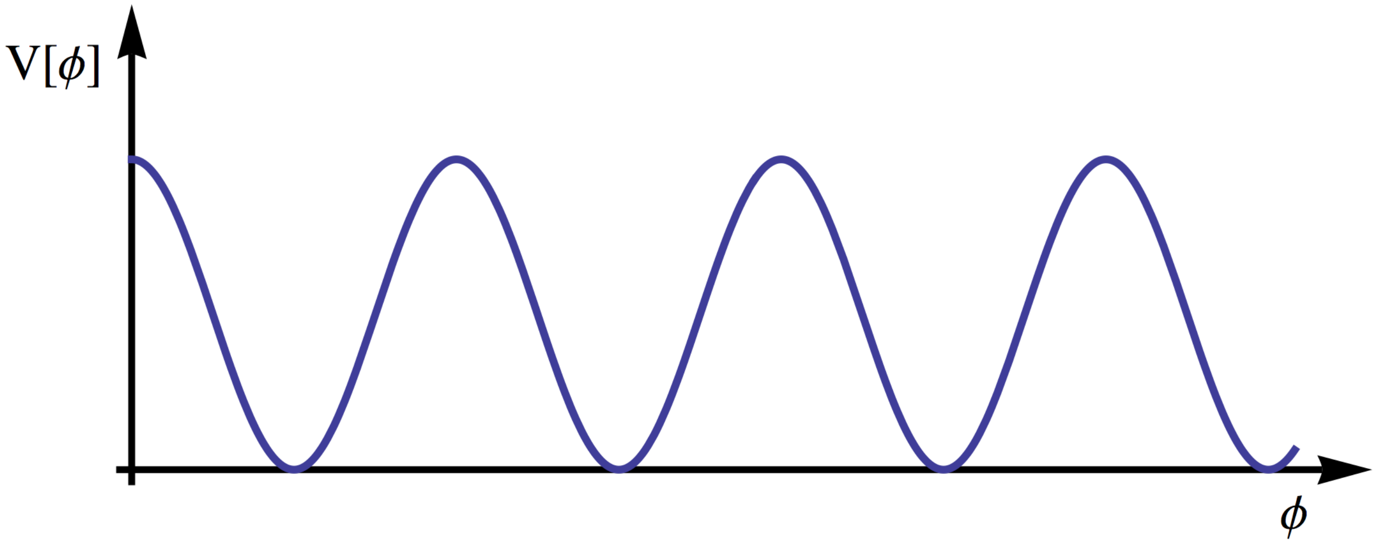
- the "problem" of trans-Planckian decay constants
- duality symmetries in string theory
- upper limits on Hubble scale during inflation

Based on work by (Kappl, Nilles, Winkler, 2015; Im, Nilles, Trautner, 2017)

Axionic Inflation

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

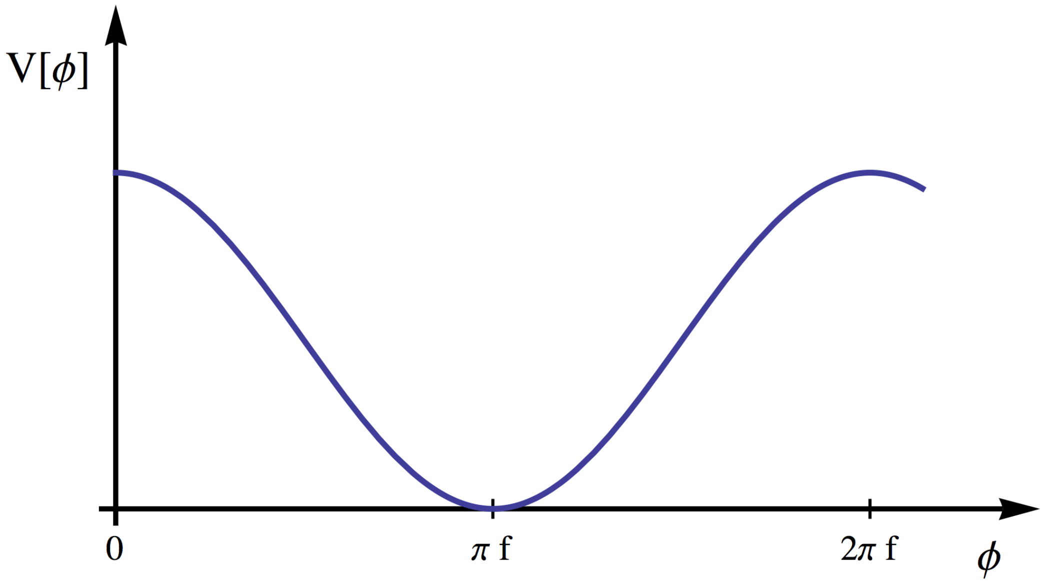
Nonperturbative effects break this symmetry to a remnant discrete shift symmetry



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

The Axion Potential

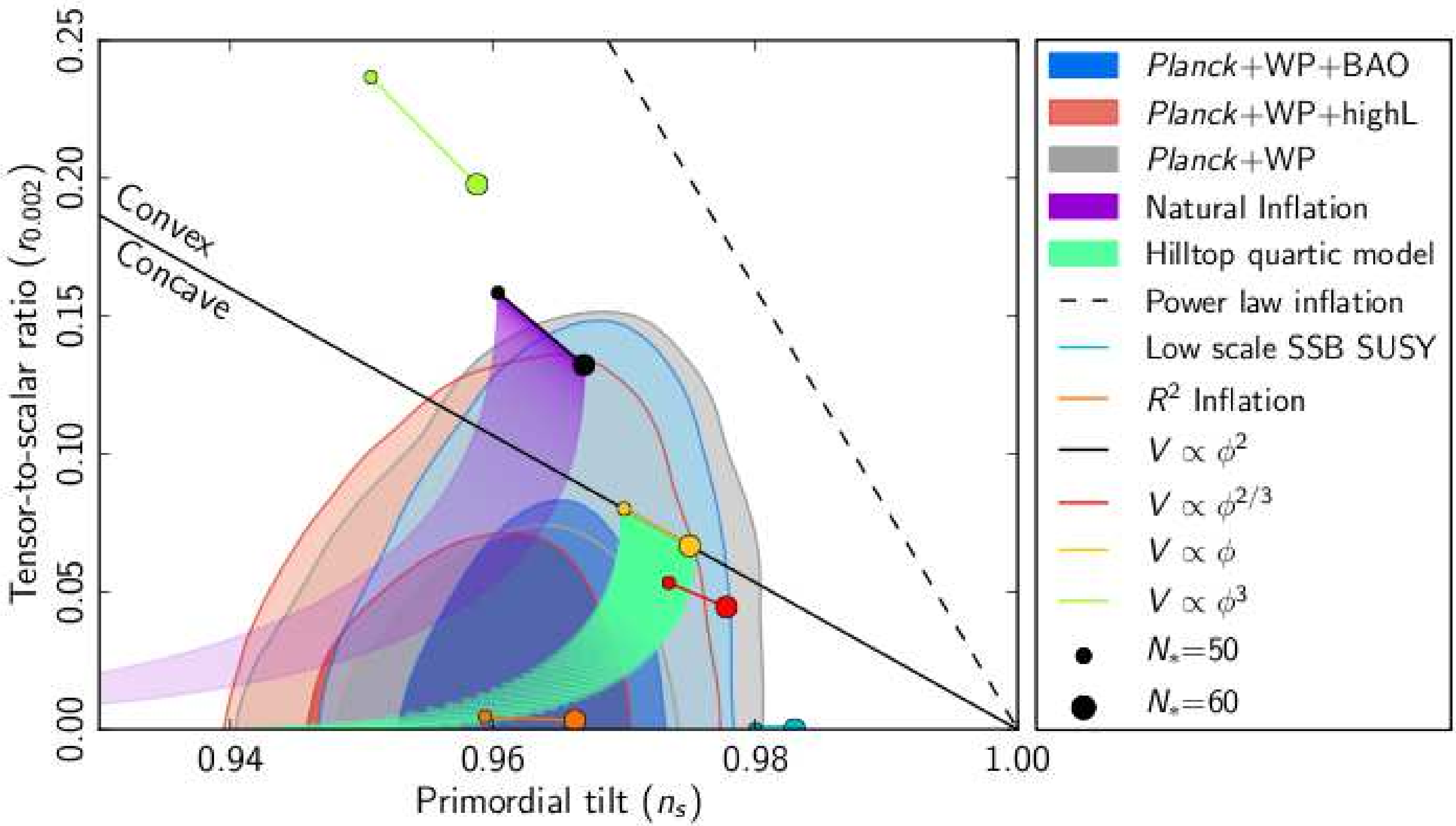
Discrete shift symmetry identifies $\phi = \phi + 2\pi n f$



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

ϕ confined to one fundamental domain

Planck results (Spring 2013)



The question of tensor modes

Sizeable tensor modes are of particular interest:

- they might lead us to scales of physics close to the Planck scale and the so-called "Lyth bound"
- potential $V(\phi)$ of order of GUT scale
- trans-Planckian excursions of the inflaton field
- For a quadratic potential $V(\phi) \sim m^2\phi^2$ it implies $\triangle\phi \sim 15 M_{\rm P}$ 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, in particular for a UV-completion in string theory (Banks, Dine, Fox, Gorbatov, 2003)

Aligned axions

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

(Kim, Nilles, Peloso, 2004)

- still we require $f \leq M_{\mathrm{P}}$ for the individual axions
- aligned axion has effective decay constant beyond the Planck scale
- string favours a multi-axion picture

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

This avoids the restrictions of the single axion model.

The KNP set-up

We consider two axions

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

with potential

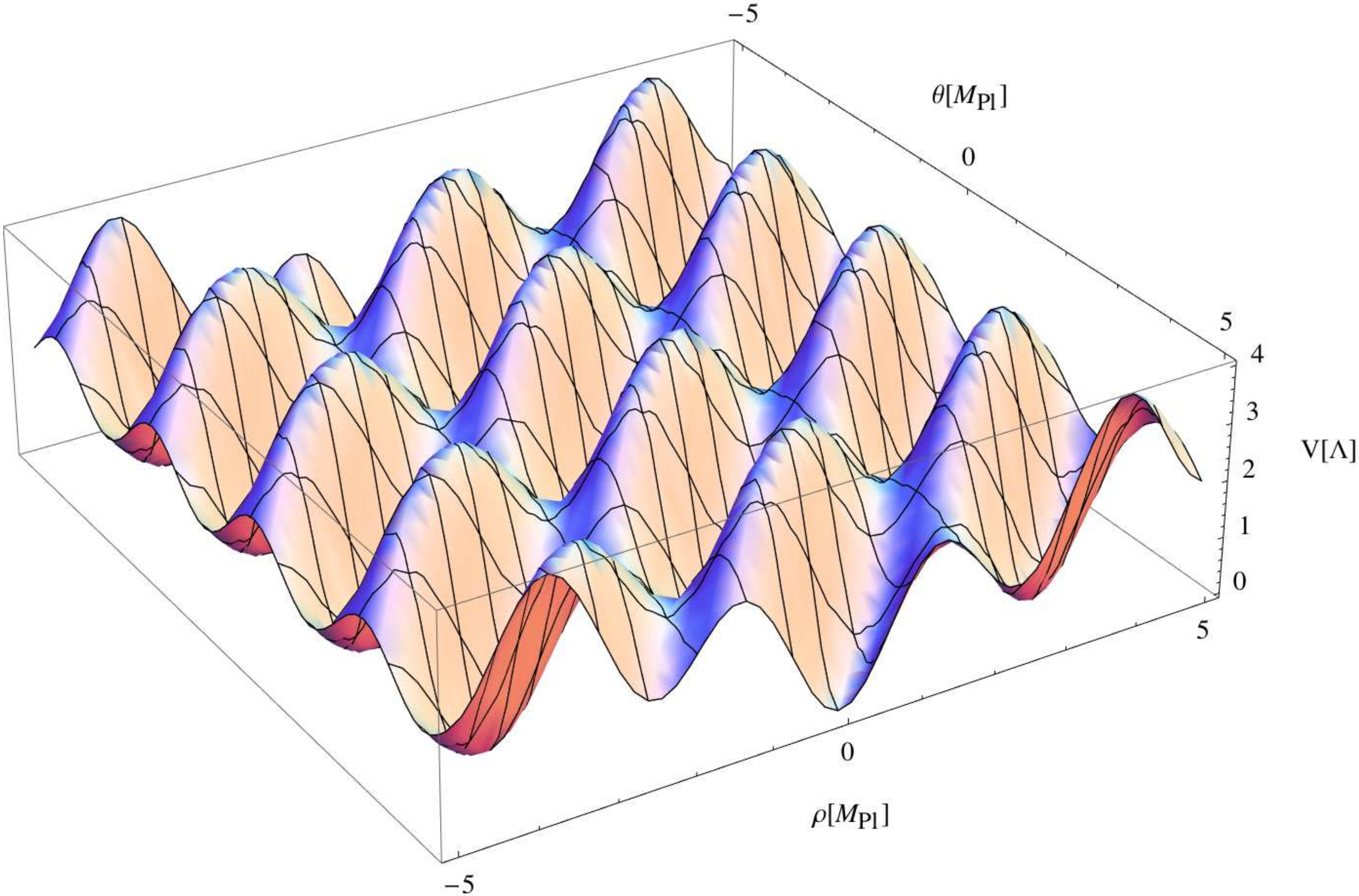
$$V(\theta,\rho) = \Lambda^4\left(2 - \cos\left(\frac{\theta}{f_1} + \frac{\rho}{g_1}\right) - \cos\left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right)$$

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

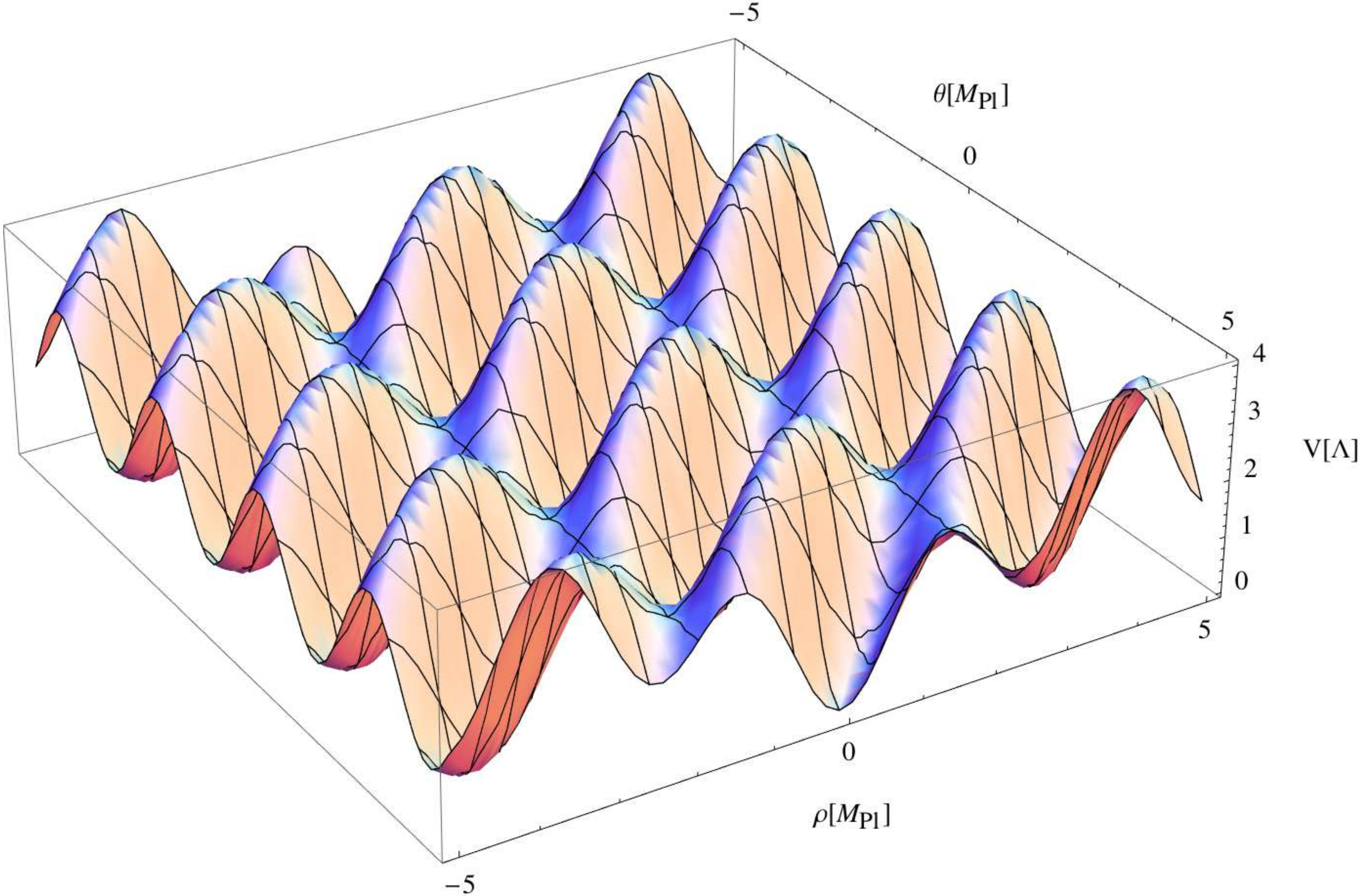
Alignment parameter defined through $\alpha = g_2 - \frac{f_2}{f_1} g_1$

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

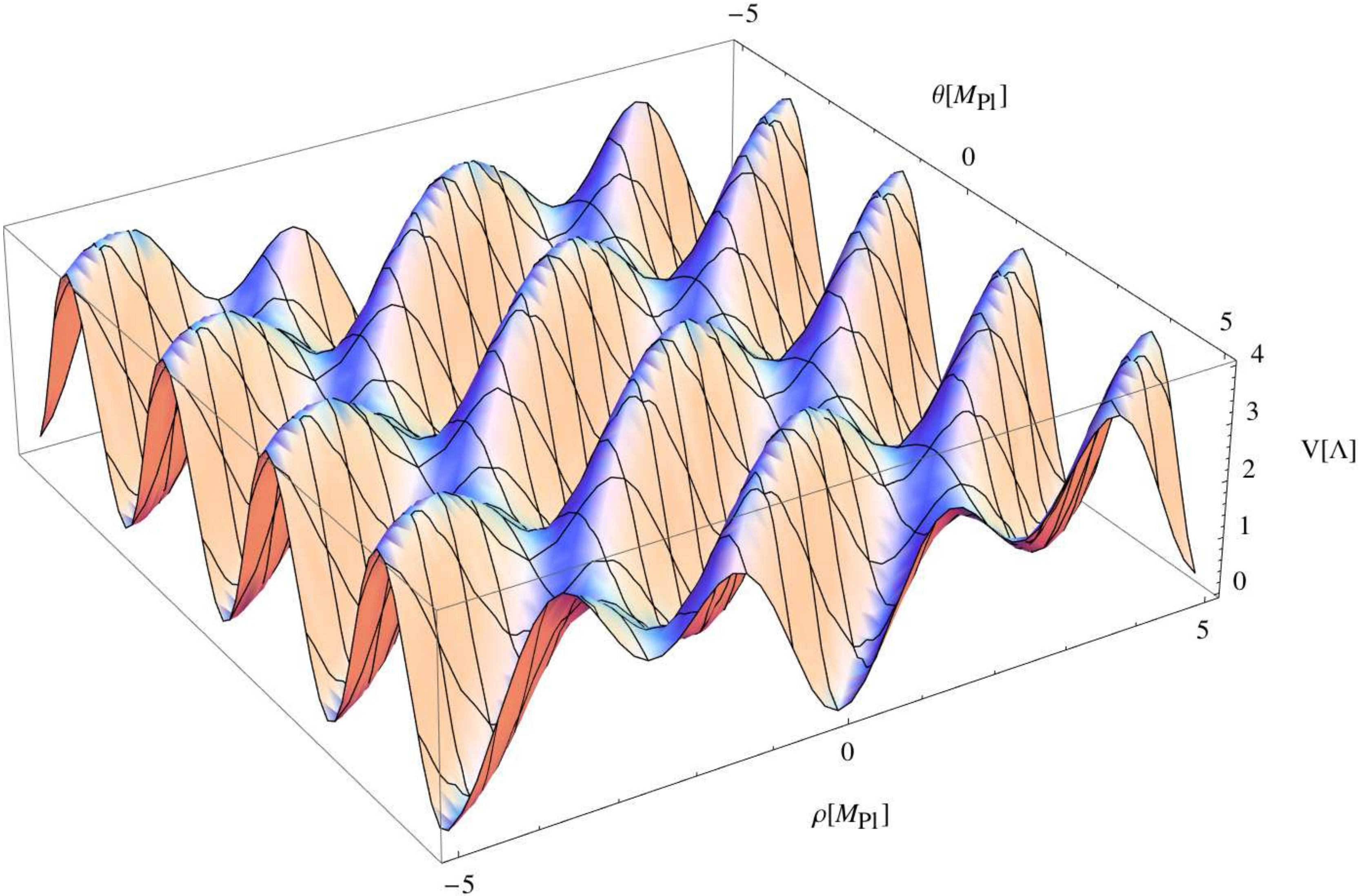
Potential for $\alpha = 1.0$



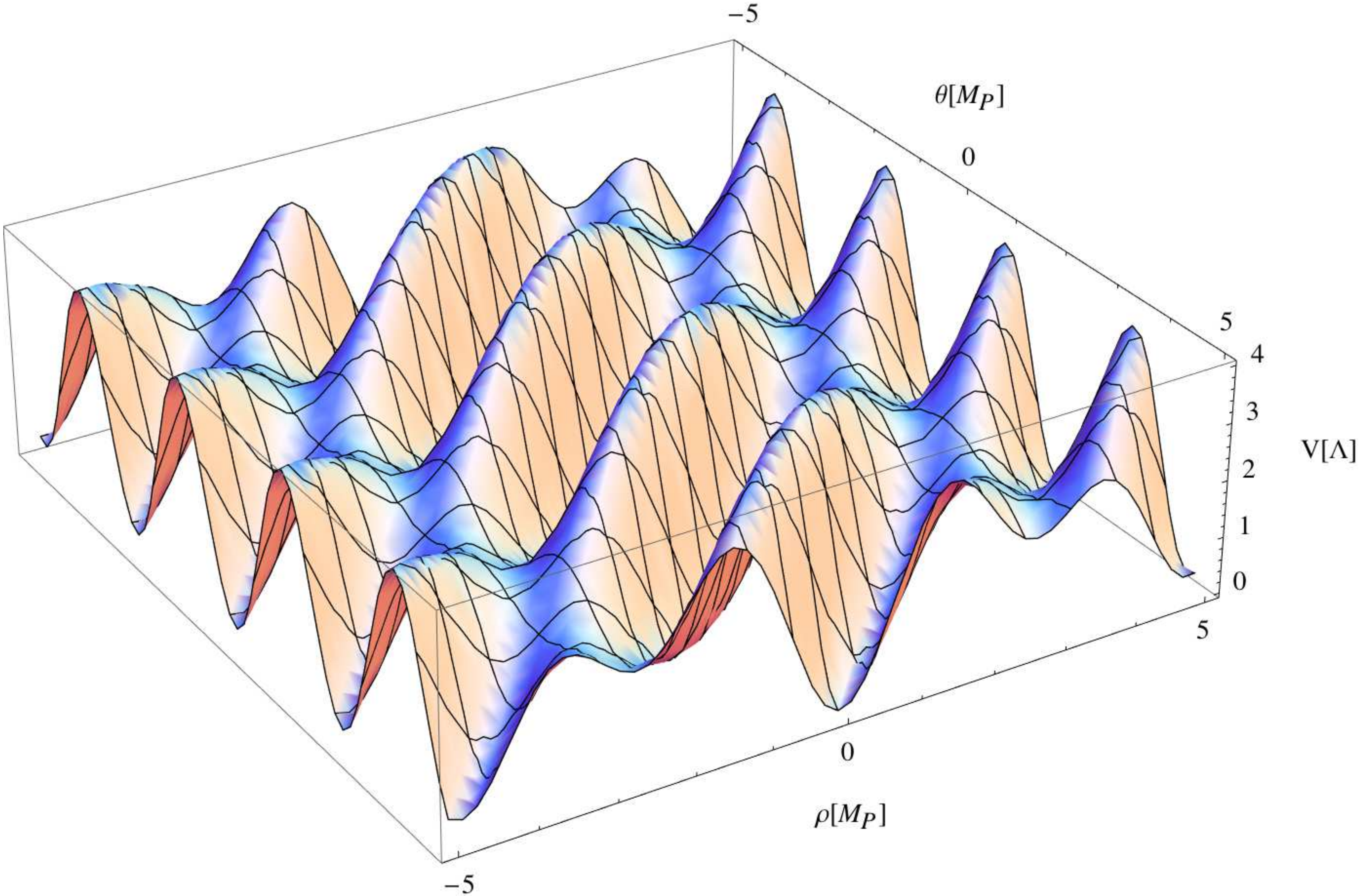
Potential for $\alpha = 0.8$



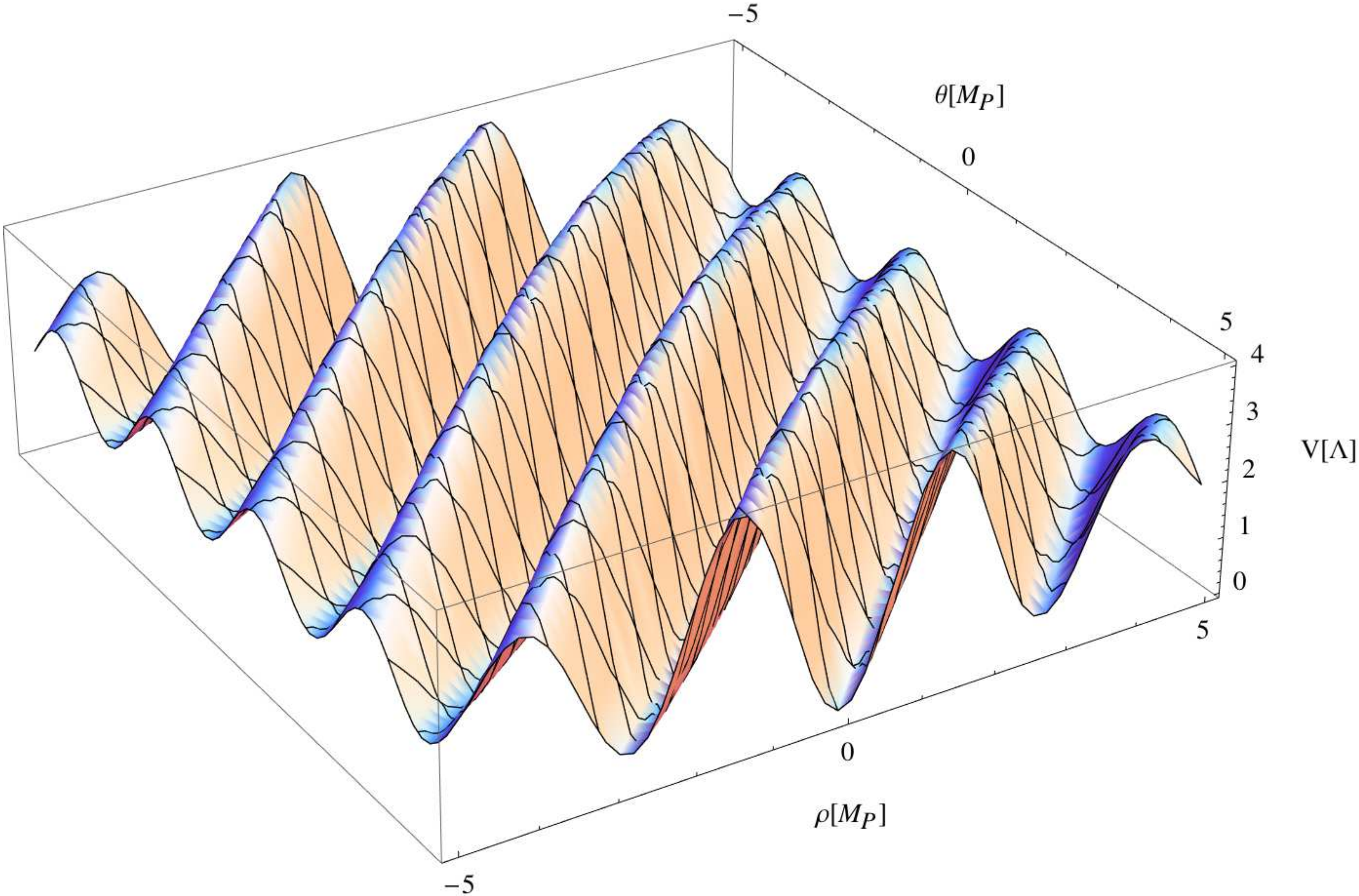
Potential for $\alpha = 0.5$



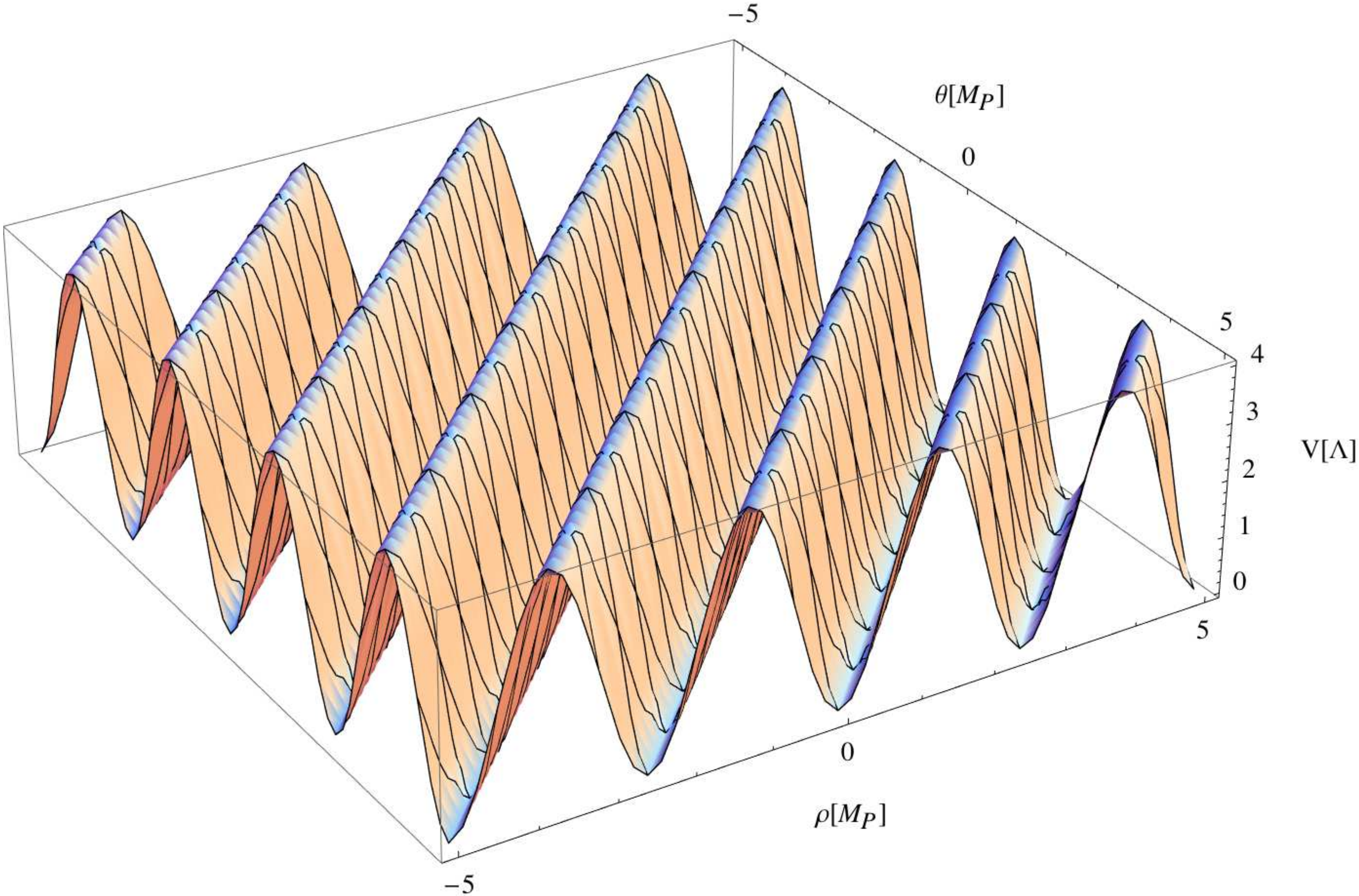
Potential for $\alpha = 0.3$



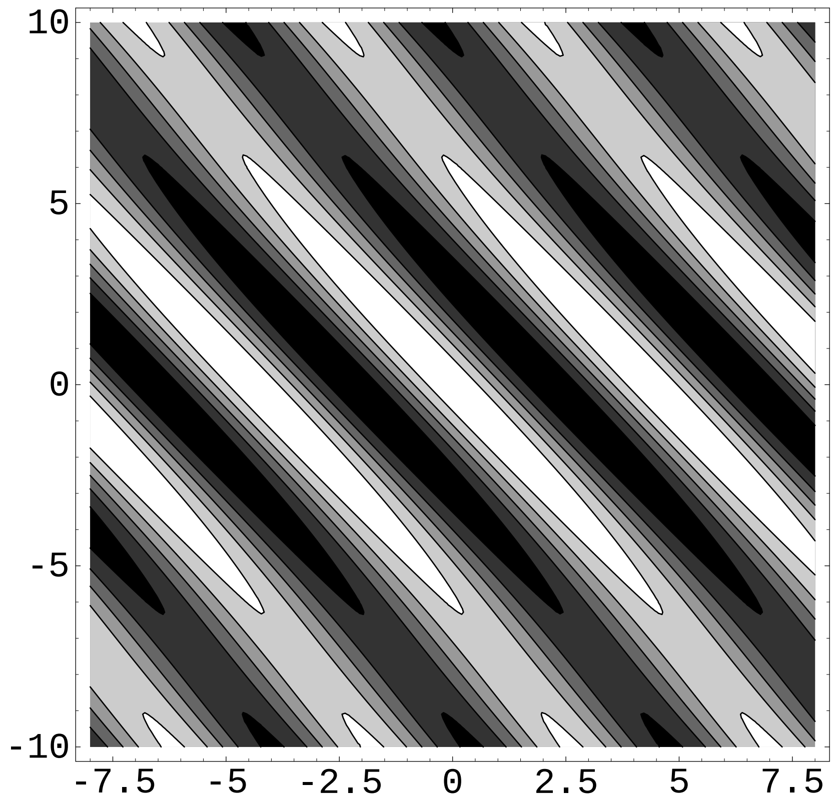
Potential for $\alpha = 0.1$



Potential for $\alpha = 0$



The aligned Axion Landscape



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.

UV-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 $f_{\rm eff}$?

Remember that in case of a single axion we had the limit

- $f \leq M_{\rm string}$ (Banks, Dine, Fox, Gorbatov, 2003)
- derived from dualities in string theory (e.g. T-duality)

In the multi-axion case these arguments are not directly applicable, but we still have to worry about these questions, also in view of the "weak gravity conjecture".

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

$T-$Duality

String dualities give important constraints on the axion decay constants, especially $T-$duality $SL(2,Z)$:

$$T \to \frac{aT - ib}{icT + d}$$

generated by an inversion and a shift

$$T \to 1/T, \qquad T \to T + i.$$

$$G = K + \log |W|^2$$

must be invariant under T-duality.

$T-$Duality

K and W might transform nontrivially. Consider e.g.

$$K = -3\log{(T+\bar{T})}.$$

This Kähler potential transforms under $SL(2,Z)$ as

$$K \rightarrow K + \log{|icT+d|^6}$$

and has to be compensated by a superpotential transforming as a modular form (of weight -3):

$$W \rightarrow (icT+d)^{-3} W\ .$$

Not just a Cosine

In string theory we do not just get cosine potentials, but obtain modular functions (e.g. Dedekind-functions) from

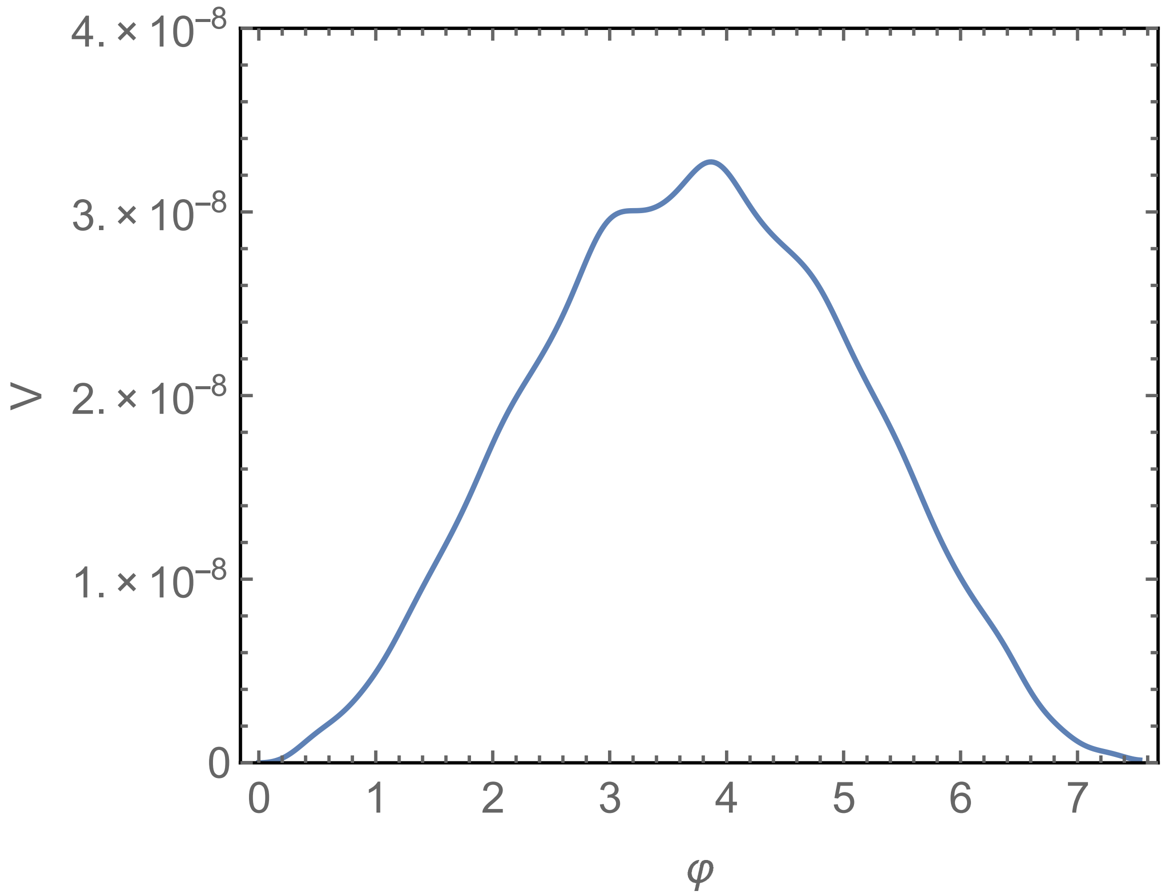
- world sheet instanton effects,
- gauge kinetic functions and gaugino condensates.

So we might consider instead a modular function

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

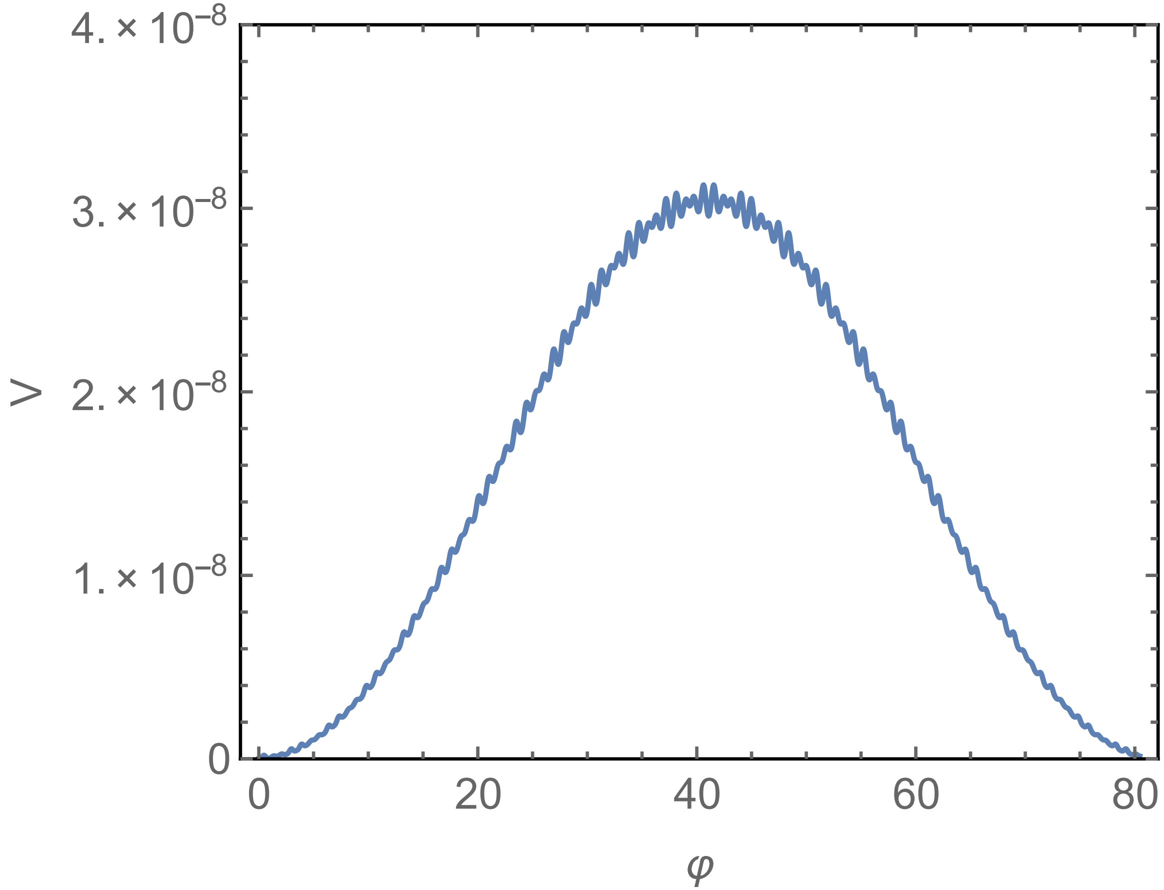
The higher harmonics give wiggles in the potential that perturb the flat direction and might stop inflation. In the case of a single axion this prevents a trans-Planckian f.

Wiggles in the aligned potential



The wiggles in the case of weak alignment (small f)

Wiggles in the aligned potential



Strong alignment (leading to superPlanckian f)

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 $f_{\rm eff}$.

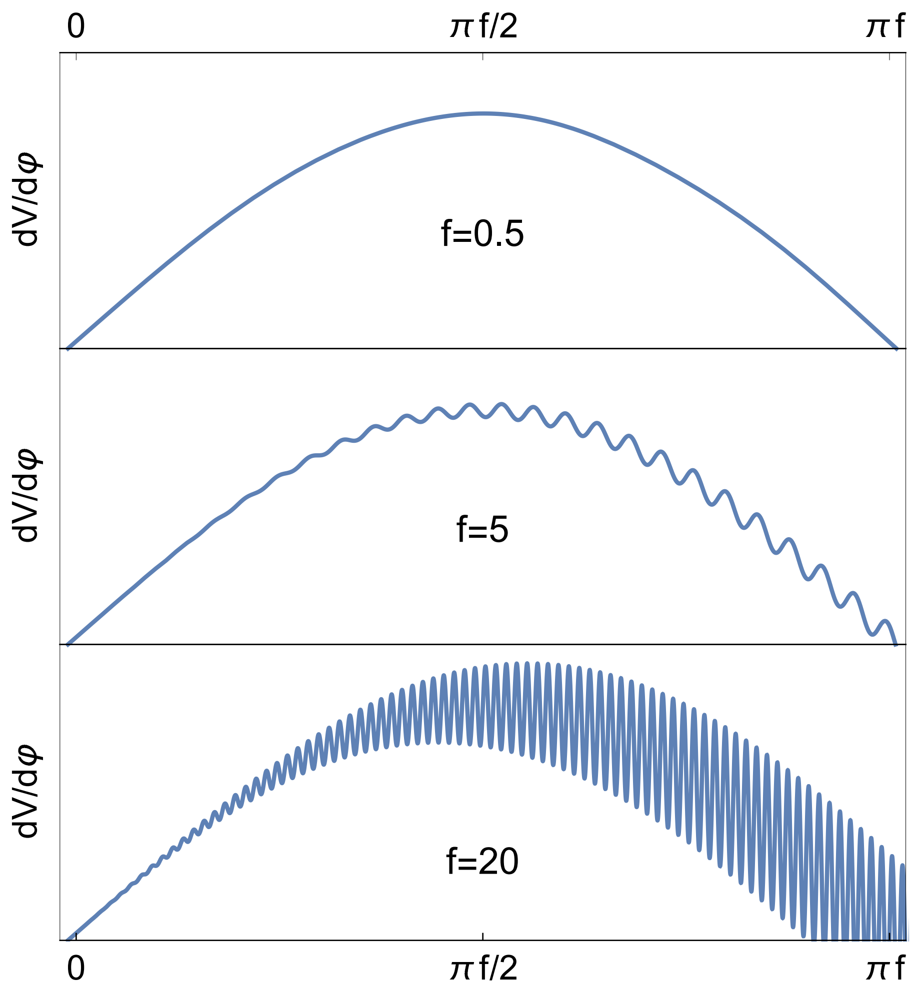
Explicit calculation are necessary to clarify the situation,

- but 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.

(Kappl, Nilles, Winkler, 2015; Choi, Kim, 2015; Kobayashi, Nitta, Urakawa, 2016)

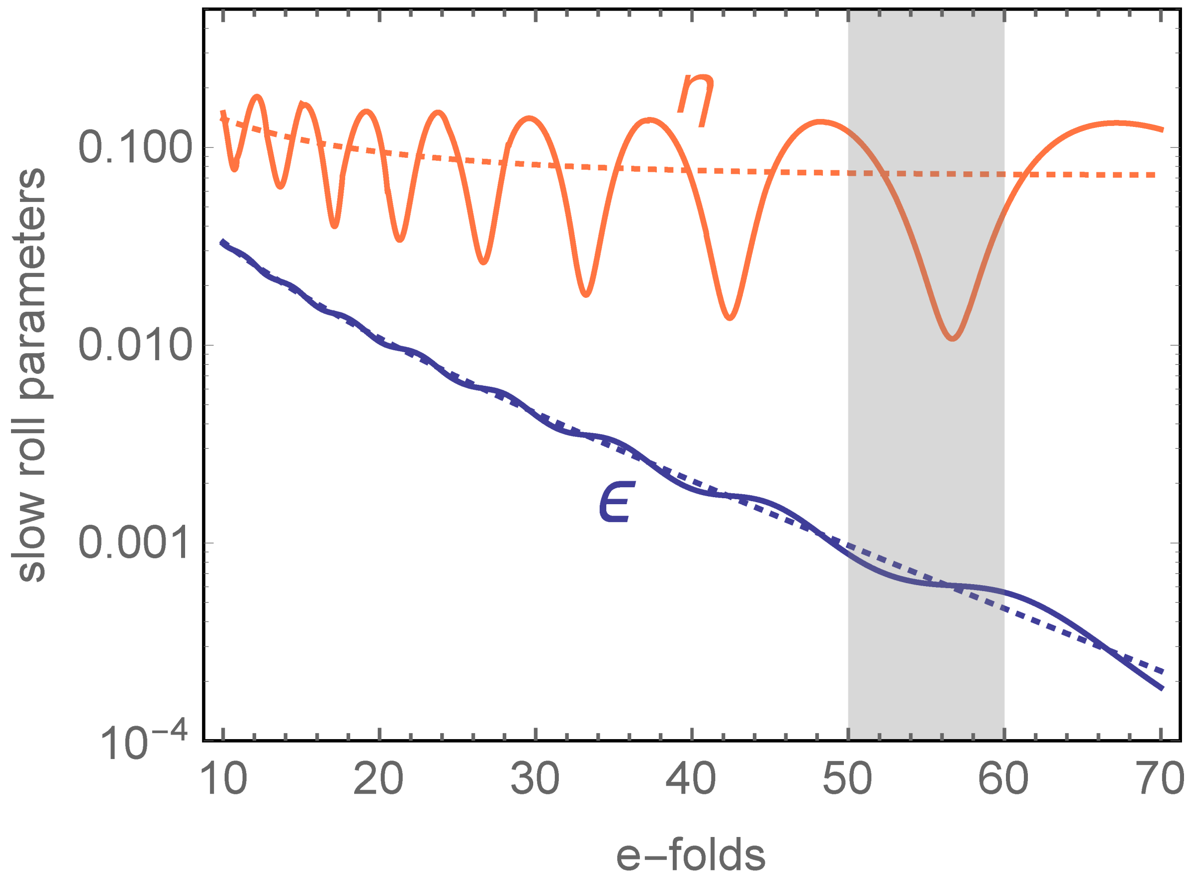
Slope of Potential



Wiggly structure becomes important

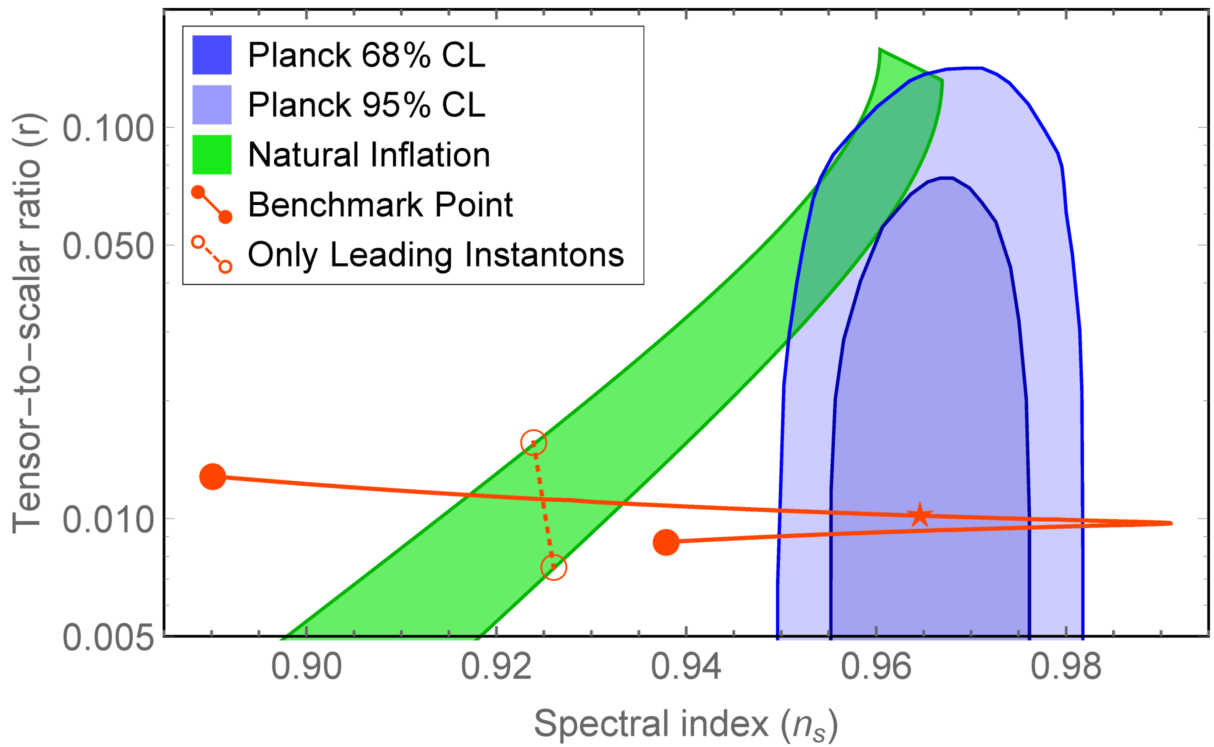
(Abe, Kobayashi, Otsuka, 2015; Kappl, Nilles, Winkler, 2015)

Slow roll parameters



ϵ (η) depend on first (second) derivative

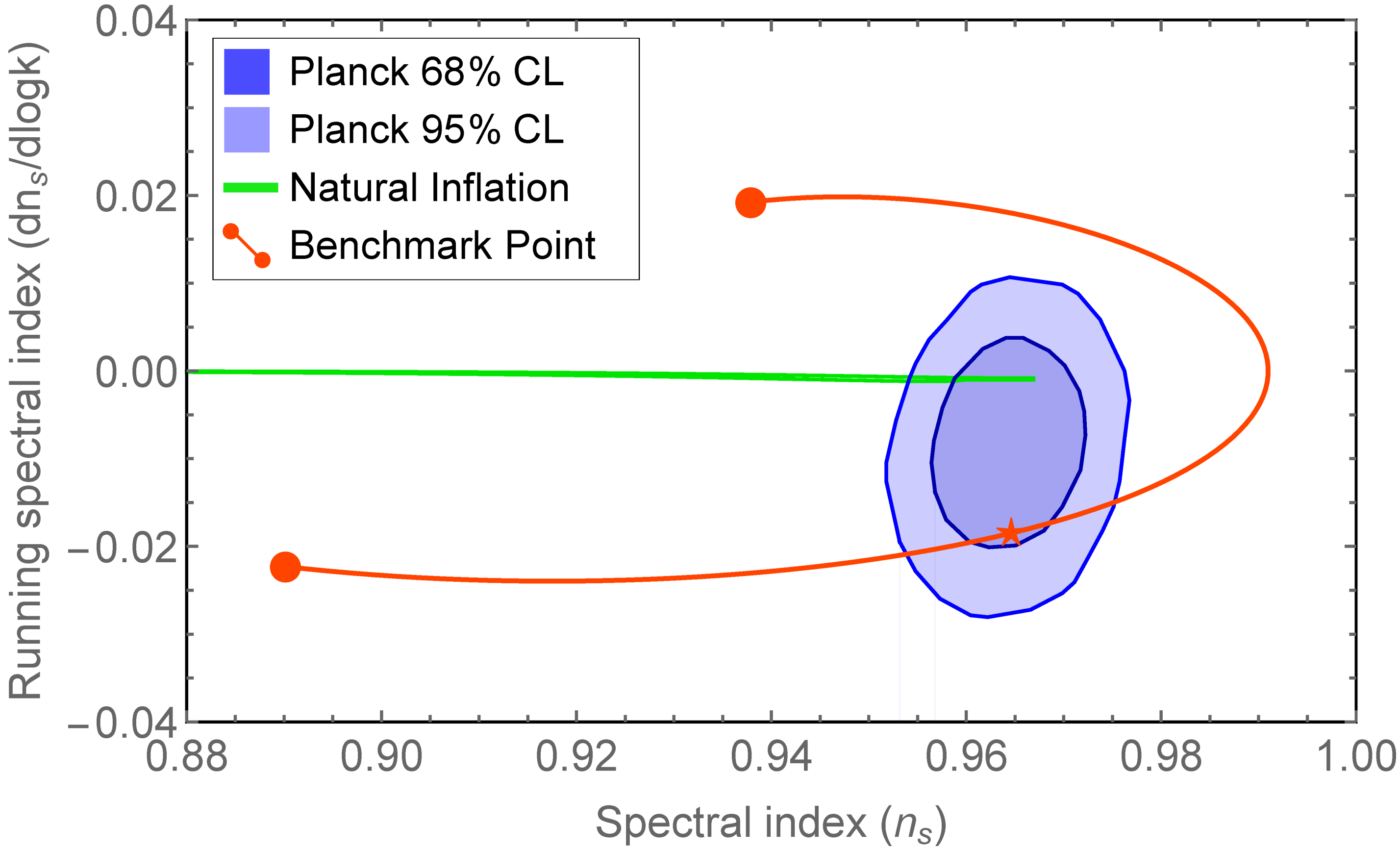
$n_s - r$ plane



Strong variations of n_s on the number of e-folds.

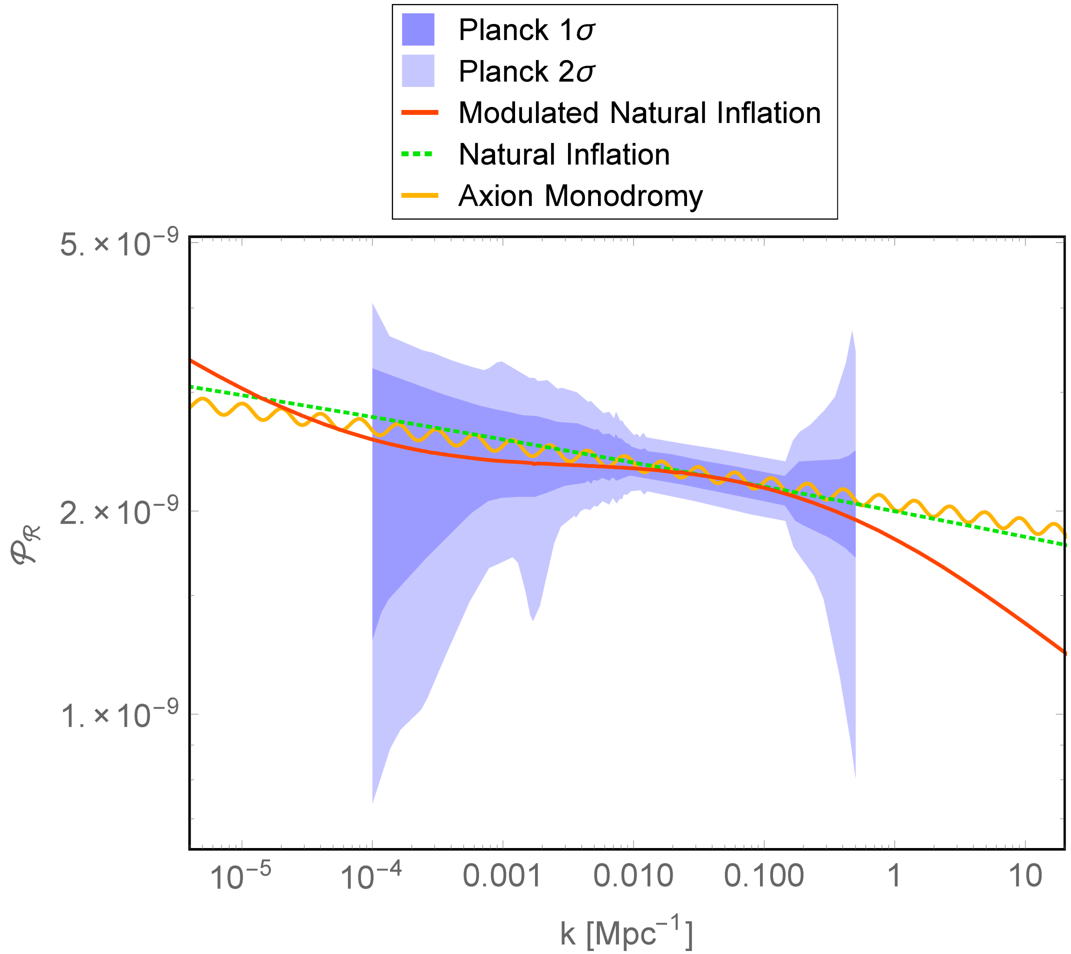
(Kappl, Nilles, Winkler, 2015)

Running of spectral index



Comparison of spectral index with Planck data

Scalar power spectrum

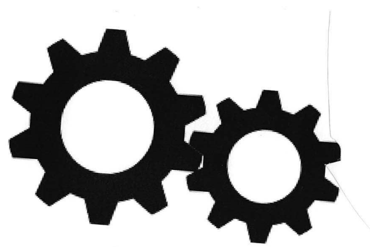


Comparison to Planck reconstructed power spectrum

More than two axions

The alignment mechanism can be extended to more than two axions and find an interpretation as a "clockwork"

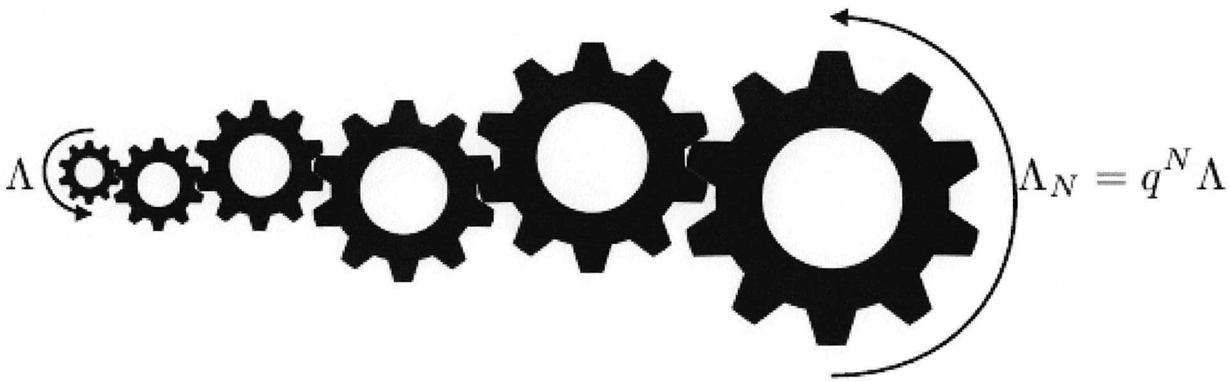
(Choi, Kim, Yun, 2014; Choi, Im, 2015; Kaplan, Rattazzi, 2015; Guidice, McCullough, 2016)



The two-axion alignment as a clockwork with two gears, e.g. "minutes" and "hours"

The Multi-Axion Clockwork

Alignment with N axions (Picture from Giudice and McCullough, 2016)



Intermediate Summary

Sizeable tensor modes are possible,

- but there is most probably an upper limit on f_{eff} and r,
- we might have "wiggles" and running indices

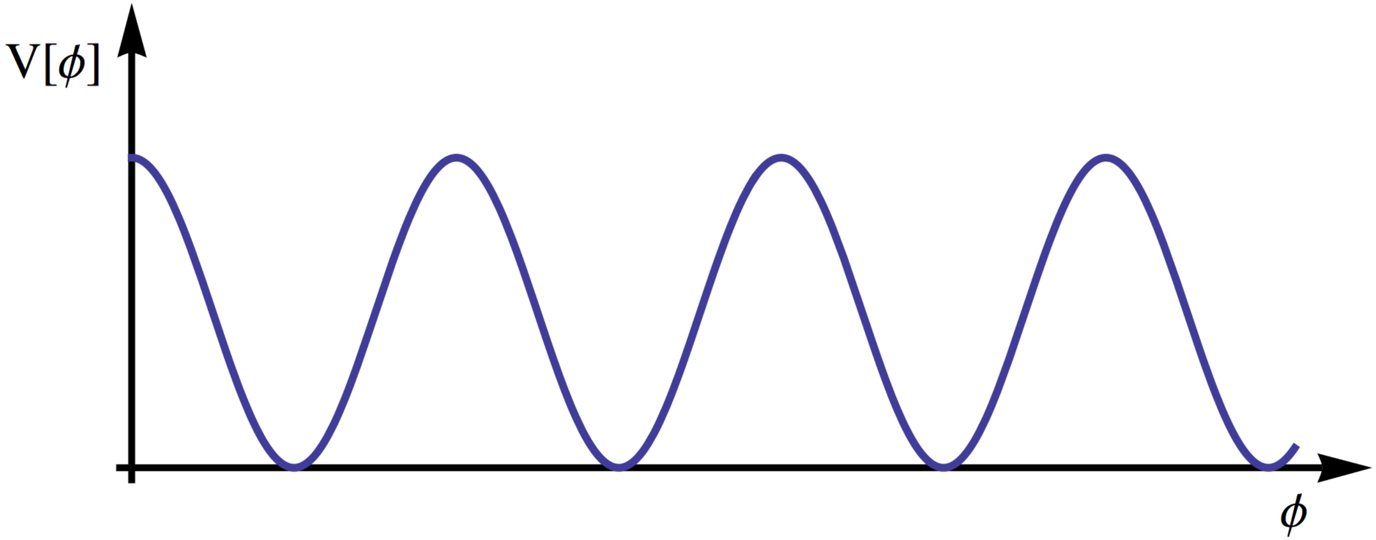
We are in a region where we lose computational control.

- the UV-completion requires higher harmonics
- the "cosine" is no longer just a "cosine"
- multi-axion "clockwork systems" might extend the axionic field range (Choi, Kim, Yun, 2014)

We need experimental observations to clarify the situation and teach us new lessons about gravity.

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.

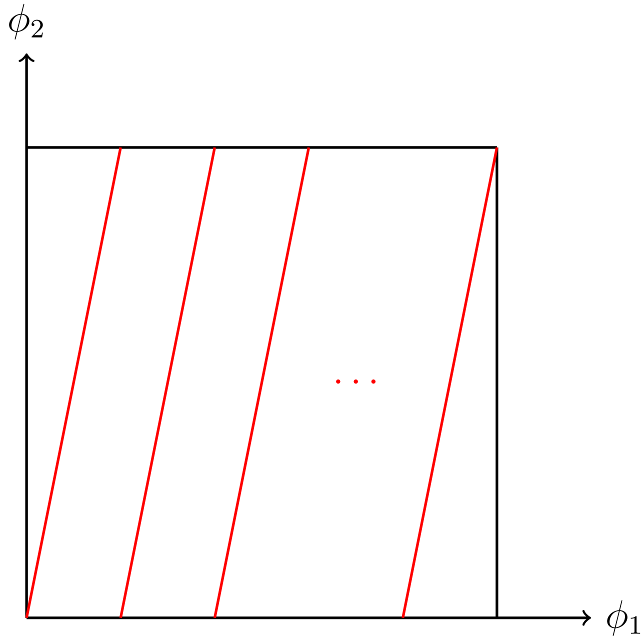
Multi-Axion-models

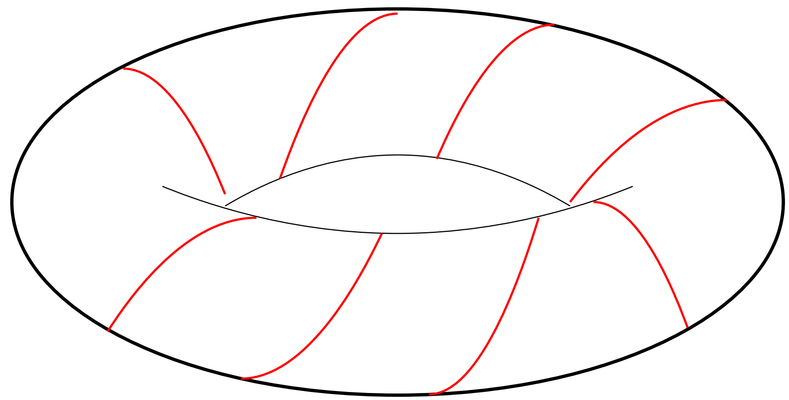
Consider a system with two (or more) axions

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

- 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 $N_{\rm DW} = 1$ (Choi, Kim, 1985)
- aligned axion "clockwork" can enlarge the axion scale from TeV to 10^{11} GeV (Higaki, Jeong, Kitjima, Takahashi, 2015)
- enhancing axion-photon-photon coupling via clockwork (Farina, Pappadopulo, Rompineve, Tesi, 2016)

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)

The relaxion mechanism

Axions could be at the origin of mass hierarchies. This requires (Graham, Kaplan, Rajendran, 2015)

- a slowly rolling (relaxion) field,
- stopped by nonperturbative effects.
- Large mass hierarchies need a long time evolution of the relaxion field
- and an unconventional cosmological evolution.

Again we need a huge relaxion decay constant for a consistent description of the present stage of the universe:

- the problem can be solved via aligned axions à la KNP (sometimes called clock-work axion).

(Choi, Im, 2015; Kaplan, Rattazzi, 2015)

Tensor Modes from Extra Dimensions

Extra space dimensions might provide new ingredients:

- strength of gravity could vary in bulk
- weak scale hierarchy problem might be solved via large or warped extra dimensions

This could influence the size of tensor modes. We consider

- large extra dimensions (LED) (Arkani-H., Dimopoulos, Dvali, 1998)
- warped extra dimensions (RS) (Randall, Sundrum, 1999)
- linear dilaton model (LD) (Antoniadis, Dimopoulos, Giveon, 2001)

Matter fields live on visible brane, gravity on hidden brane. The inflaton can reside on either of them. (Im, Nilles, Trautner, 2017)

The mechanism

We start with a warm-up example

- one large extra dimension (LED)
- inflaton field on visible (IR) brane
- we assume that the mechanism of radius stabilisation does not influence the tensor modes

This simplification is called IRB assumption

- scalar modes are essentially d=4 dimensional

(Giudice, Kolb, Lesgourgues, Riotto, 2002)

- tensor modes are influenced by bulk effects
- relevance of effective Planck mass during inflation

Effective Planck Mass

Effective Planck mass during inflation

$$M^2_{\mathrm{Pl,eff}} \;=\; M^3\, 2\,\pi\, R\, \left(1 - \tfrac{2}{3}\,\pi^2\, R^2\, H^2\right)$$

has to be compared to

$$M^2_{\mathrm{Pl,eff}}\Big|_{H=0}^{\mathrm{LED}} = \; M^3\, 2\,\pi\, R\;.$$

This leads to enhanced tensor modes and

$$\tfrac{2}{3}\,\pi^2\, R^2\, H^2 \;<\; 1$$

implies an upper limit on Hubble scale during inflation.

(Im, Nilles, Trautner, 2017)

Results

Results are model dependent (Im, Nilles, Trautner, 2017)

- we obtain enhanced tensor modes in LED and RS within IRB-scenario
- surprisingly the IRB assumption is not applicable to the Linear Dilaton (LD) case
- a satisfactory picture requires contributions from the hidden brane ("remote inflation")
- "remote inflation" is an option in the RS scenario as well

  (Nihei, 1999; Kaloper, 1999; Kim, Kim, 1999)
- LD case with dilaton as stabilizer field is consistent with IRB assumption and leads to reduced tensor modes

  (Kehagias, Riotto, 2016)

Summary

Sizeable tensor modes are a challenge for model building

- especially for a consistent UV-completion
- restrictions from string theory via dualities
- effective theories (like aligned axions) as one way out
  - extend upper limit on $f_{\rm eff}$ via "clockwork"
  - specific signatures of "modulated natural inflation"
- extra dimensions as another way out
  - enhanced tensor modes imply upper limit on H
  - remote inflation as a new option
  - implication of reduced tensor modes?

Sizeable tensor modes: a window of opportunity