Inflation from axion monodromy

based on

McAllister, Silverstein & Westphal

and some or all of

Flauger, McAllister, EP, Silverstein, Westphal & Xu

Enrico Pajer

Cornell University, Ithaca

Perimeter
May 2009

Outline

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Cosmological data

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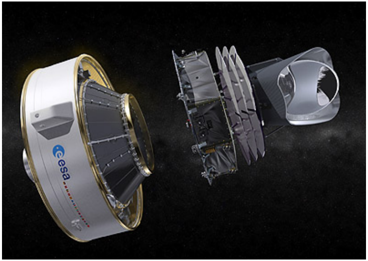
now Planck:"The satellite was successfully launched at 13:12:02 on 14 May 2009..."



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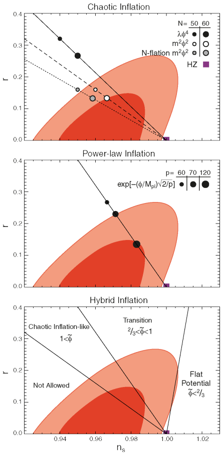
- Analogously, inflation is a UV-sensitive mechanism. E.g. Planck-suppressed dimension 6 operators (with natural coefficients) can and generically do spoil slow roll.
- If we invoke a symmetry, e.g. shift symmetry, we are sensitive to how and where it is broken.

Observations



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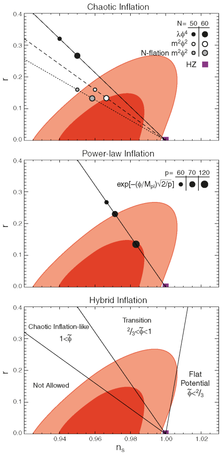

Numbers that we want to reproduce:

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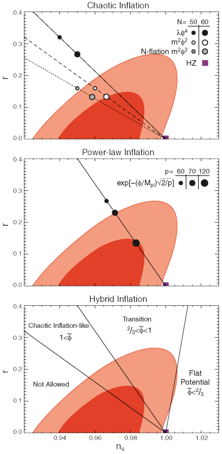

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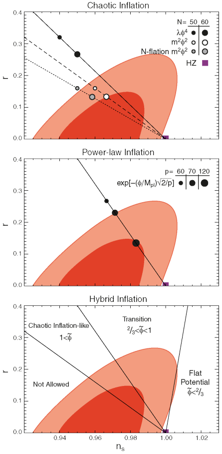

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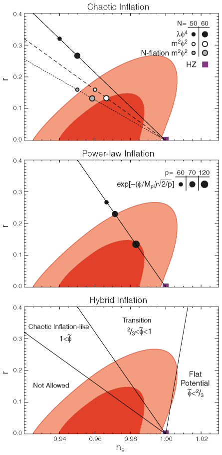

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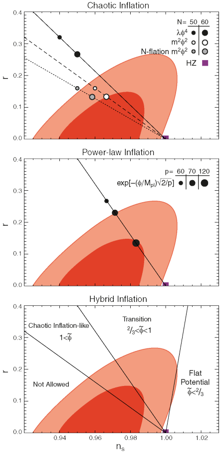

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- features in the scalar spectrum

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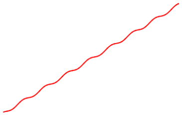
The effective potential

Inflation is driven by a real scalar field with potential

$$V(\phi) = \mu^3 \phi + b\mu^3 f \cos\left(\frac{\phi}{f}\right)$$



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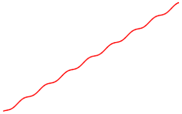

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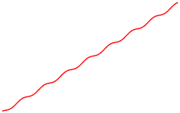

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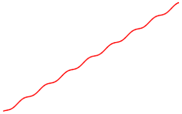

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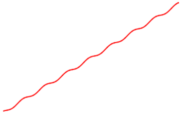

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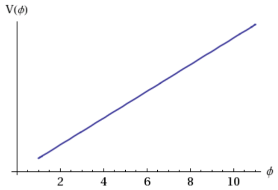
  [Banks et al. 03]
- Osciallations per e-folding $\sharp_{osci} \simeq 10^{-2}/f$

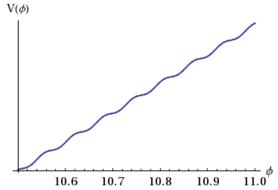
Background evolution

We solve the e.o.m. perturbatively in b:



zeroth order

$$\phi_0 = \left(\phi_{in}^{3/2} - \frac{\sqrt{3}}{2}\mu^{3/2}t\right)^{2/3}$$



first order

$$\phi_1 \simeq -3bf^2\phi_0 \sin\left(\frac{\phi_0}{f}\right)$$

Background oscillations

The (Hubble) slow-roll parameters oscillate

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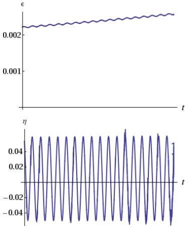

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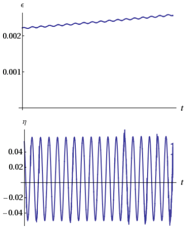

and can resonate with the perturbations ζ.
Notice that $\dot{\eta} \gg \epsilon$ so one can not use slow-roll formulae to compute the perturbations.

Spectrum of scalar perturbations

The oscialltions in the potential induce osciallations in the spectrum:

$$P_s(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \left[1 + \delta n_s \cos\left(\frac{\phi_k}{f}\right)\right]$$
$$= A_s \left(\frac{k}{k_*}\right)^{n_s-1+\frac{\delta n_s}{\ln(k/k_*)}\cos\left(\frac{\phi_k}{f}\right)}$$

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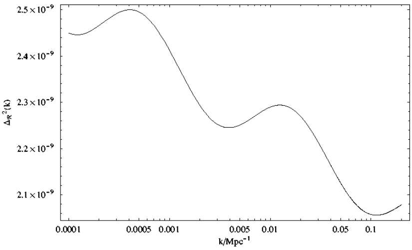

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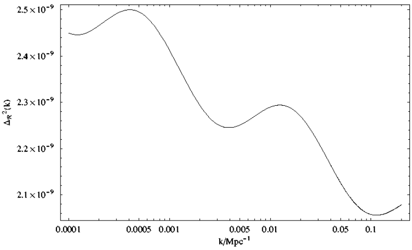


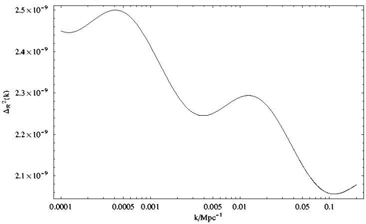
- The frequency is simply ϕ_k/f
- We have computed δn_s analytically at leading order in b

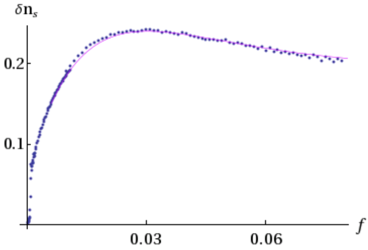
Solution of the Mukhanov-Sasaki equation

Slow roll is not enough! We solve Mukhanov-Sasaki equation perturbatively in b.
The amplitude of oscillations in the spectrum is

$$\delta n_s = -12b\sqrt{\frac{\frac{\pi}{8}\coth\left(\frac{\pi}{2f\phi_{in}}\right)f\phi_{in}}{(1+(3f\phi_{in})^2)}} \sim b\sqrt{f}$$

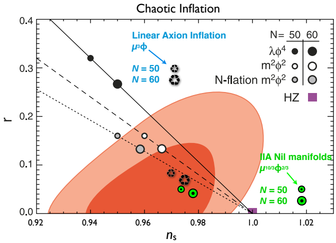
Valid for $\phi \gg M_{pl}$, $f \ll M_{pl}$ and $b \ll 1$. Excellent agreement with numerics.





Tensor modes

Large field model ⇒ detectable tensor modes



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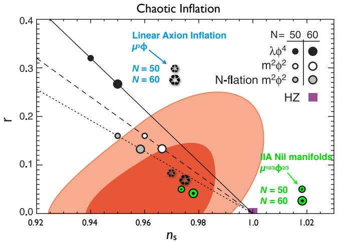

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Oscillations

Oscillations in the tensor spectrum are suppressed w.r.t. those in the scalar spectrum due to a hierachy in the slow-roll parameters

$$\begin{aligned} \epsilon &\sim \epsilon_0 + \epsilon_{osci}\cos(\phi/f) \\ \eta &\sim \eta_0 + \eta_{osci}\sin(\phi/f) \\ \eta_{osci} &\sim \epsilon_{osci}\,\phi/f \end{aligned}$$

Bispectrum of scalar perturbations

Canonical single-field slow-roll inflation gives $f_{NL} \ll 1$ [Maldacena 03] , undetectable. In fact

$$< \zeta_{k_1}(t)\zeta_{k_2}(t)\zeta_{k_3}(t) >= -i \int_{t_0}^{t} dt' < \left[\zeta_{k_1}(t)\zeta_{k_2}(t)\zeta_{k_3}(t), H_I(t')\right] >$$

where the intaracting Hamiltonian at order ζ^3 is

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Resonant enhancement of non-Gaussianity

Condition for the resonance

Schematically [Chen, Easther & Lim 08]

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Necessary condition

$$H < \omega < M_{pl} \,,$$

where ω is the (instant) frequency of oscillation of ϵ, η.

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Size of the effect

A good fit to the numerical computations is [Chen, Easther & Lim 08]

$$< \zeta_{k_1}\zeta_{k_2}\zeta_{k_3} > \quad = (2\pi)^7 \delta^3(K) \frac{P^2}{(k_1 k_2 k_3)^2} f_{res} \sin\left(\frac{2\log(K)}{\phi f}\right)$$

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- Inversely proportional to $f^{3/2}$
- Oscillations appear at all scales, both in spectrum and in the bispectrum
- Such non-scale-invariant signal has not yet been compared with the data.

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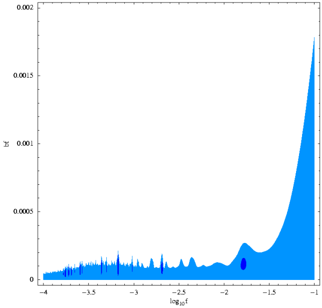
- non-G can be large for small f. No one has put bounds from the data.



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  - How generically are the wripples? Which scale sets the frequency and amplitude?

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- If this model is correct, what do we learn about the high energy physics?
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  - At which scale and how is this symmetry broken?
  - How generically are the wripples? Which scale sets the frequency and amplitude?

We are going to present a possible embedding of this effective model in string theory and address the above questions.

Axions in field theory

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- Continuous shift symmetry is broken to a discrete shift symmetry by non-perturbative effects
- The axion decay constant f determines the periodicity of the canonically normalized axion

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 + \Lambda^4 \cos\left(\frac{\phi}{f}\right) \Rightarrow \phi(x) \to \phi(x) + 2\pi f$$

Outline

Axion in string theory

String theory seen from a low energy 4D observer has in general many axions:

- Model independent axions such as dualizing $B_{\mu\nu}$ or $C_{\mu\nu}$

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- The axion decay constant f is determined by geometrical data of the compactification

Shift symmetry

Consider the 4D axion $b(x)$ from $B_{ij} = b(x)\omega_{ij}$ for some internal two-form ω. In (bosonic) closed string theory, the vertex operator for b particles at zero momentum integrated over the world-sheet is

$$V(k=0) = \int_{ws} d^2\sigma \epsilon^{\alpha\beta} \partial_\alpha X^i \partial_\beta X^j \omega_{ij} b = \int_{ts} B$$

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Breaking of the shift symmetry

Two ingredients can invalidate the above argument:

- Non-perturbative effects
- World sheet with boundaries, i.e. D-branes

A cartoon of the model

We consider Type IIB (orientifolds) because moduli stabilization is more developed.

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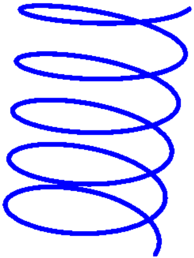
- The moduli stabilization á la KKLT does not spoil the shift symmetry.
- Non-perturbative corrections (e.g. to the Kähler potential) induce small wripples

Linear potential for the inflaton

The shift symmetry can be broken in the presence of boundaries.

Consider a D5-brane wrapped on a two-cycle Σ.
The DBI action



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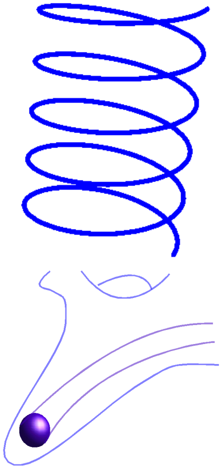

The shift $b(x) \to b(x) + \text{const}$ of $b(x) = \int_\Sigma B_2$ stores some potential energy.

$$V(b) = T_5 \sqrt{L^4 + b^2} \sim T_5 b \quad \text{for large } b$$

This generates the linear inflaton potential (and break SUSY). COBE normalization and control require to red-shift T_5

4D $\mathcal{N} = 1$ data

gravity multiplet	1	$g_{\mu\nu}$
vector multiplets	$h_{+}^{(2,1)}$	V^{κ}
chiral multiplets	$h_{-}^{(2,1)}$	z^{k}
	1	(ϕ, l)
	$h_{-}^{(1,1)}$	(b^{a}, c^{a})
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Supermultiplets

$$G^a \equiv 2\pi \left(c^a - i\frac{b^a}{g_s} \right) ,$$

$$T_\alpha \equiv i\rho_\alpha + \frac{1}{2} c_{\alpha\beta\gamma} v^\beta v^\gamma + \frac{g_s}{4} c_{\alpha bc} G^b (G - \bar{G})^c ,$$

intersection numbers $c_{IJK} = \int \omega_I \wedge \omega_J \wedge \omega_K$

4D $\mathcal{N} = 1$ data

The tree-level Kähler potential and superpotential

$$\begin{aligned} K &= -2\log \mathcal{V}_E = -2\log\left[\frac{1}{6}c_{\alpha\beta\gamma}v^{\alpha}(T,G)v^{\beta}(T,G)v^{\gamma}(T,G)\right] \\ W &= W_0 \end{aligned}$$

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Non-perturbative breaking of shift symmetry

Non-perturbative effects could spoil the shift symmetry. In fact they induce an η-problem for b^a, analogous to D3-brane inflation.

Moduli stabilization

The supersymmetric conditions ensuring a minimum are

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0 &= D_\alpha W = -A_\alpha a_\alpha e^{-a_\alpha T_\alpha} - W\frac{v^\alpha}{2\mathcal{V}_E}\,, \\
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Non-perturbative breaking of shift symmetry

It is crucial to know what, how and when breaks the shift symmetry. Moduli stabilization á la KKLT is incompatible with b^a shift symmetry.

The axion decay constant

Which values can f take? Direct KK reduction from $C_2 = c(x)\omega/2\pi$ gives

$$\frac{f^2}{M_{pl}^2} = \frac{g_s \pi^2}{3\mathcal{V}_E}\left(\frac{\int \omega \wedge *\omega}{(2\pi)^{10}(\alpha')^3}\right) \propto \frac{L_c^2}{\mathcal{V}_E}\,.$$

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Axion decay constant in string theory

The axion decay constant is given in terms the intersection numbers, geometrical data of the compact manifold.

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A series of constraints follow from consistency and computability

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High scale inflation and KKLT stabilization lead an upper bound on the volume (lower bound on m_s/M_{pl})

$$\begin{aligned} \tau_\alpha &\ll 73 - 8\log\left(\frac{v^\alpha\pi\sqrt{g_s}}{2g_s}\right), \\ \mathcal{V}_E &< h_+^{(1,1)}\sqrt{g_s}\,1.8\cdot 10^4, \end{aligned}$$

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Lower bound from absence of backreaction

A lower bound from the above constaint is $\frac{f}{M_{pl}} > \frac{0.1}{\mathcal{V}_E^{2/3}}$

The amplitude of modulations

In general there are non-perturbative corrections that break the continuous shift symmetry of $c(x)$ to a discrete shift symmetry. They superimpose wripples on the linear potential

$$V(\phi) = \mu^3\phi + b\mu^3 f \cos\left(\frac{\phi}{f}\right)$$

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- F-term corrections (K) are generically present. They need instantons with four fermionic zero modes, e.g. non-BPS instantons. Few is known due to the lack of holomorphicity. We make the educated guess

$$K = -2\log\left[\mathcal{V}_E + e^{-S_{ED1}}\cos(c)\right] = -2\log\left[\mathcal{V}_E + e^{-\frac{2\pi v^+}{\sqrt{g_s}}}\cos(c)\right].$$

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- D-term corrections (W) should be holomorphic. They can arise from instantons with two fermionic zero modes It is still controversial if such instantons exist.

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The result of the moduli stabilization is

$$V_{SUGRA} = \mathcal{U}_{mod}\left(1 + e^{-S_{ED1}}\frac{4}{v_\alpha}\frac{2\pi}{\sqrt{g_s}}\partial_{\tau_\alpha} v_+ \cos c\right)$$

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- Enhanced by high moduli stabilization barrier.

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Evaluating these on the oscillating solution one finds that they are suppressed by powers of

$$\frac{\omega}{M_*} \sim \frac{\omega}{M_\Box} \lesssim 10^{-3}$$

Outline

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