Title: Inflation from axion monodromy

Date: May 22, 2009 02:00 PM

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Abstract: TBA

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

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Outline

1. Motivations
2. Phenomenology of the effective model
3. A string theory model of axion monodromy
4. Constraints and phenomenology
5. Conclusions

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Cosmological data

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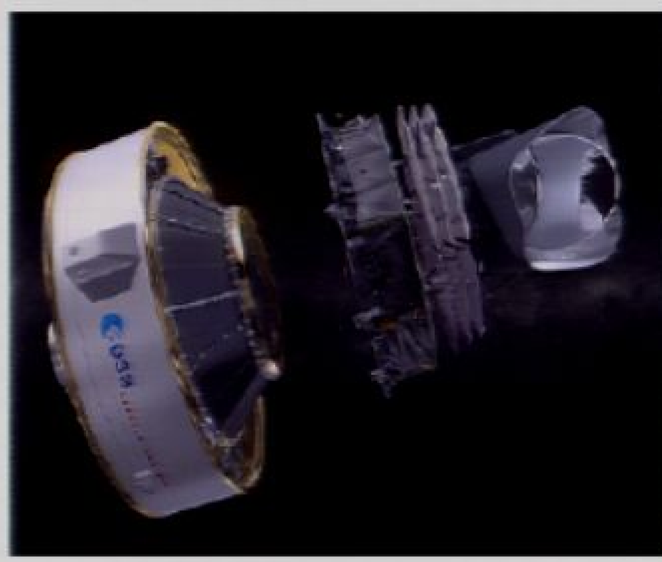
now Planck:“The satellite was successfully launched at 13:12:02 on 14 May 2009…”



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EFT approach: learn about higher scales studying UV-sensitive observables.

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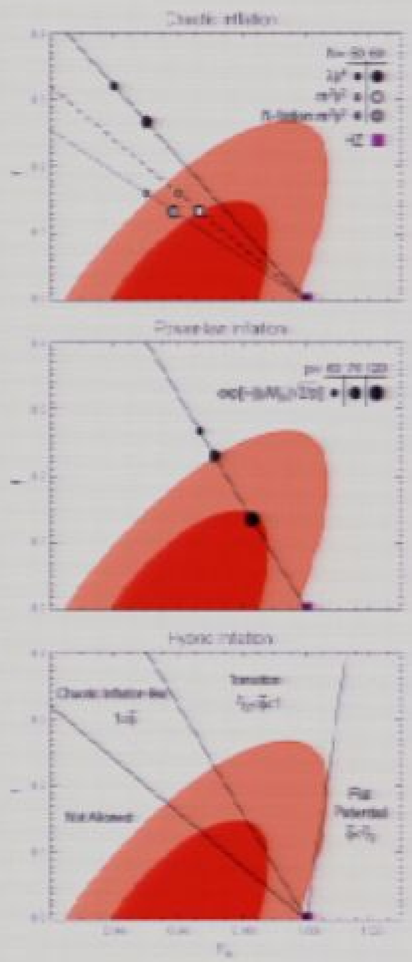
- Analogously, inflation is a UV-sensitive mechanism. E.g. Planck-suppressed dimension 6 operators (with natural coefficients) can and generically do spoil slow roll.
- If we invoke a symmetry, e.g. shift symmetry, we are sensitive to how and where it is broken.

Observations



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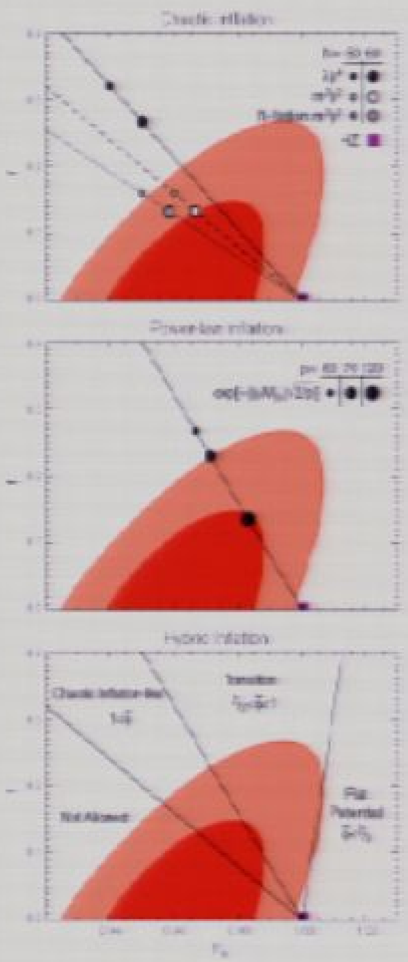

Numbers that we want to reproduce:

- COBE normalization $\Delta^2_{\mathcal{R}} = (2.445 \pm 0.096) \cdot 10^{-9}$ and spectral tilt $n_s = 0.960 \pm 0.013$ [WMAP5] .

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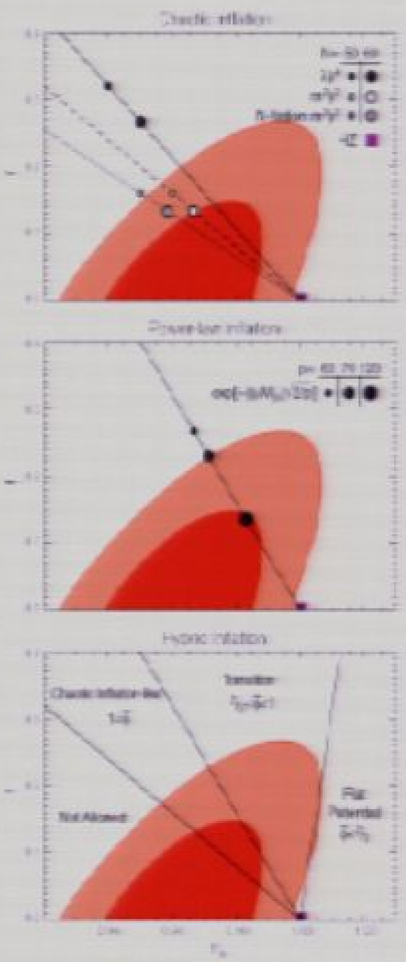

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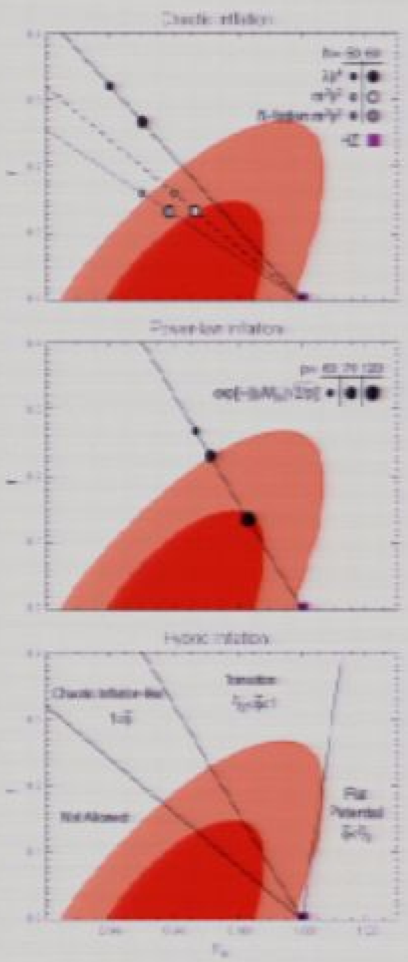

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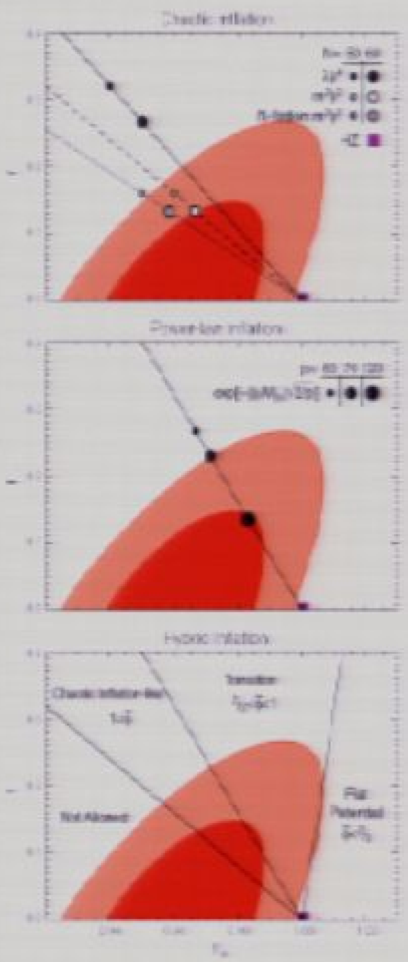

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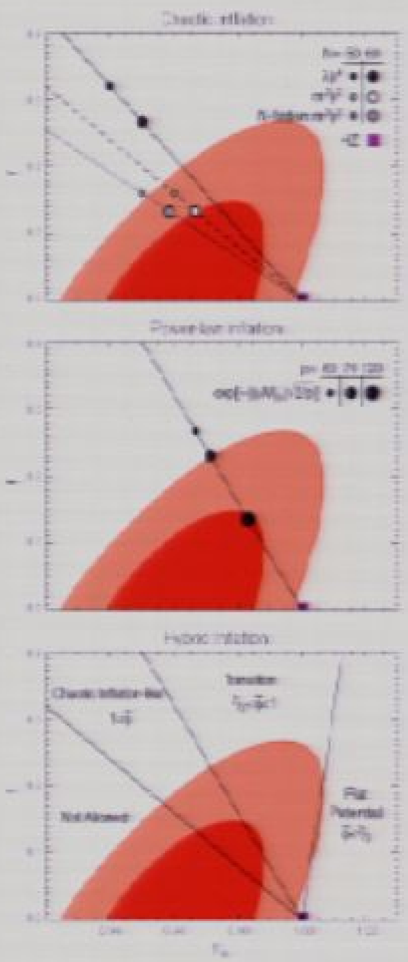

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- features in the scalar spectrum

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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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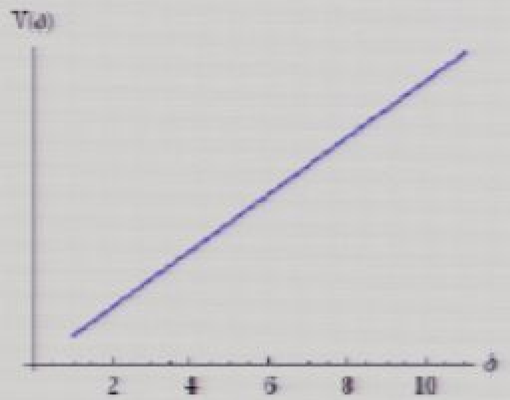
- Osciallations per e-folding $\sharp_{osci} \simeq 10^{-2}/f$

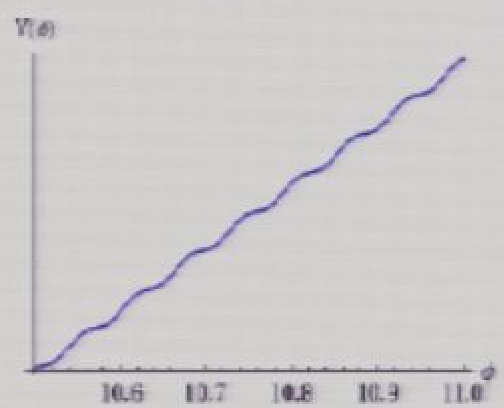
Background evolution

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

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

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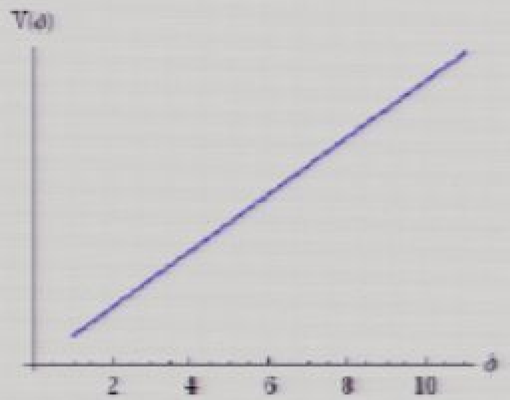

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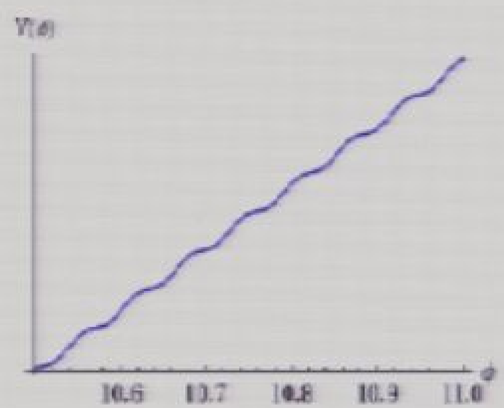

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The (Hubble) slow-roll parameters oscillate

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \epsilon_0 + \epsilon_{osci}\cos\left(\frac{\phi_0}{f}\right)$$

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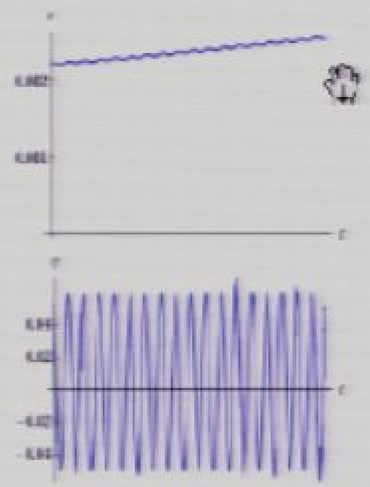

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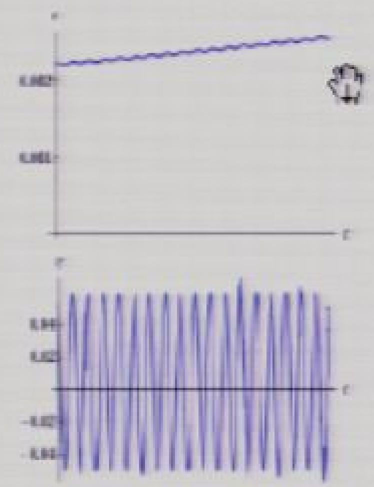

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Notice that $\dot{\eta} \gg \epsilon$ so one can not use slow-roll formulae to compute the perturbations.

Spectrum of scalar perturbations

The osciallations in the potential induce osciallations in the spectrum:

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

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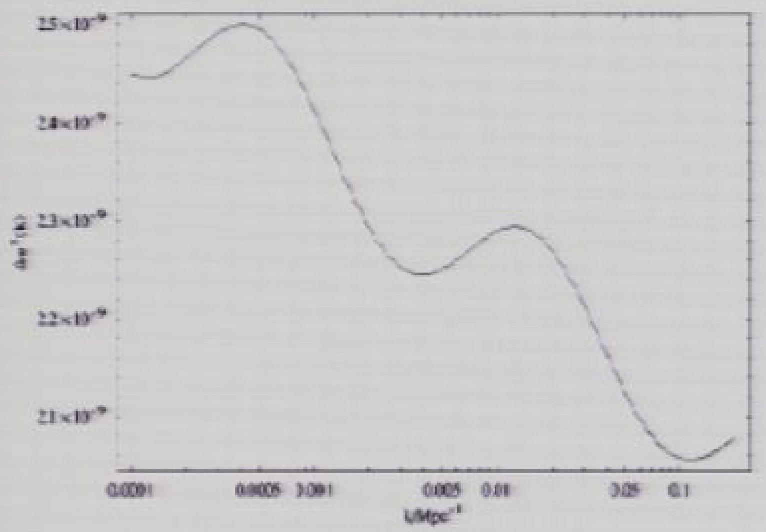

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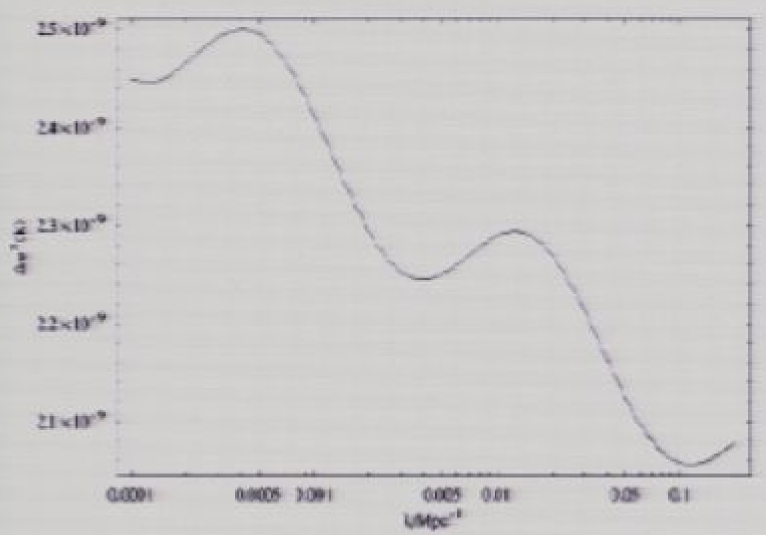

- The frequency is simply ϕ_k/f
- We have computed δn_s analytically at leading order in b

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

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

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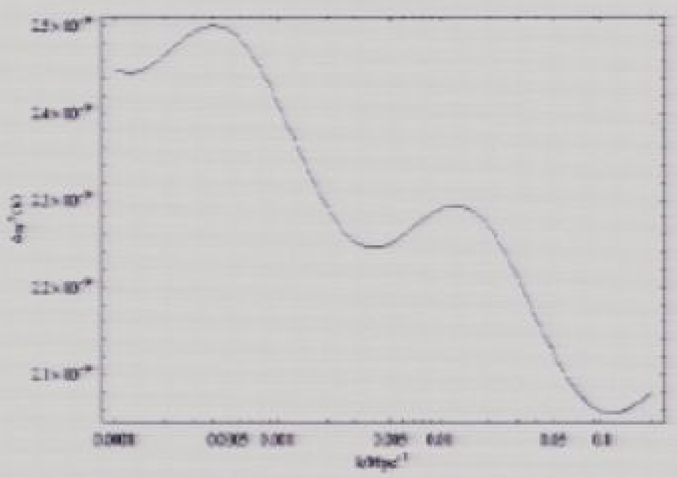

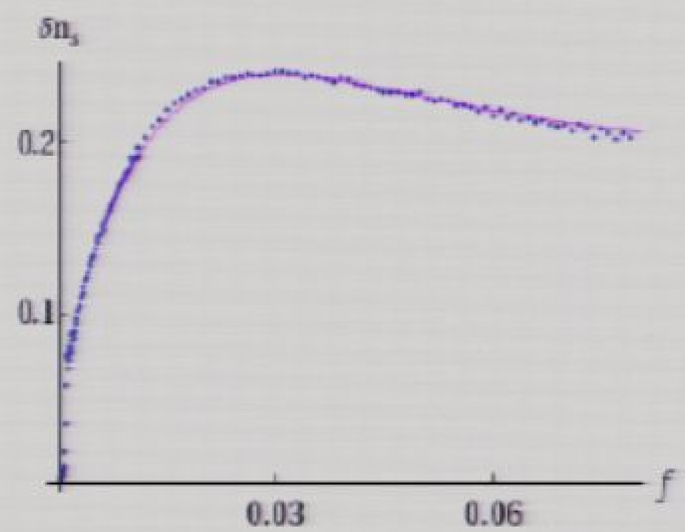

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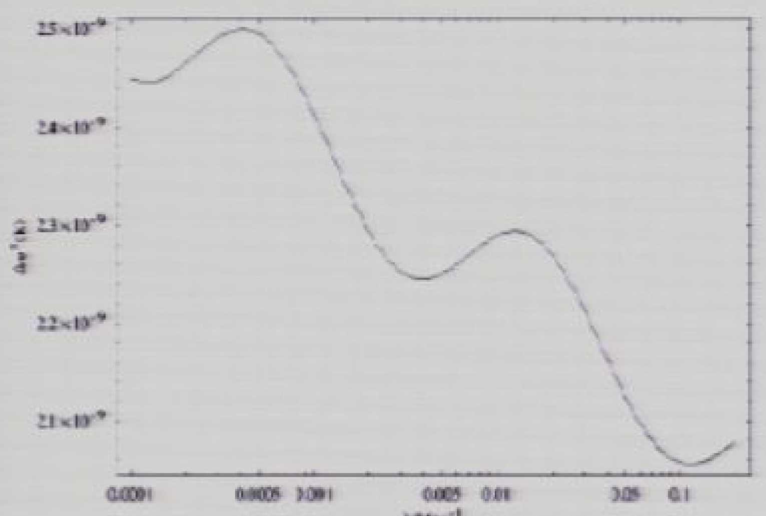

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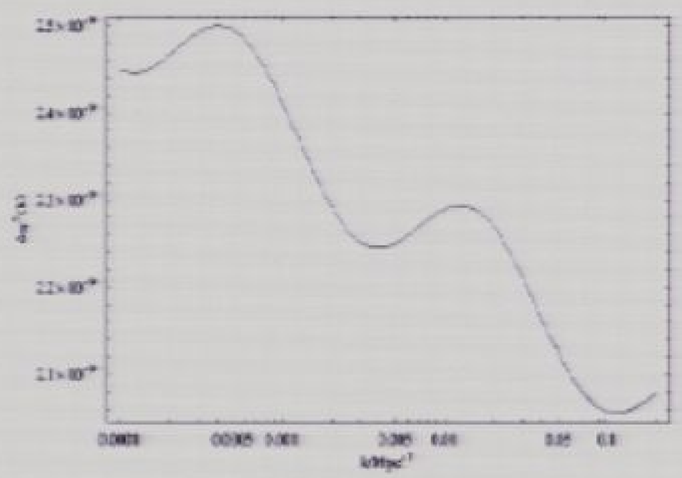
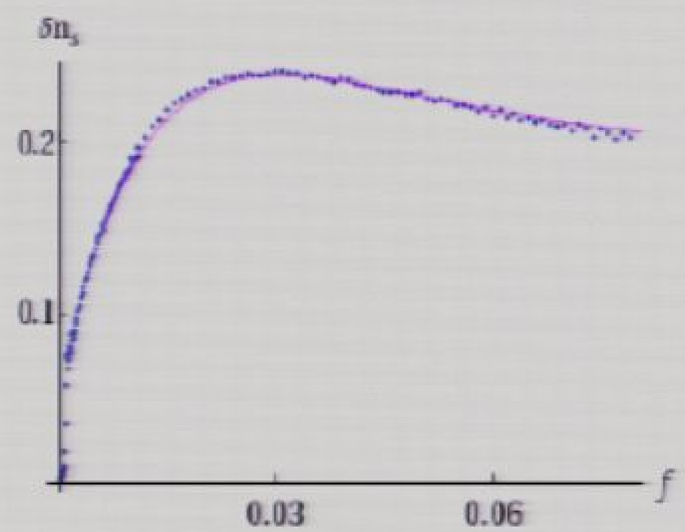
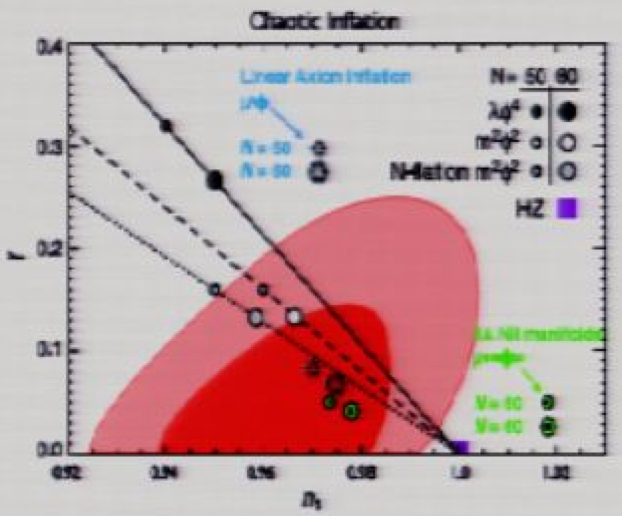




Tensor modes

Large field model $\Rightarrow$ detectable tensor modes



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$$r \simeq 0.07$$

This is within Planck sensitivity!

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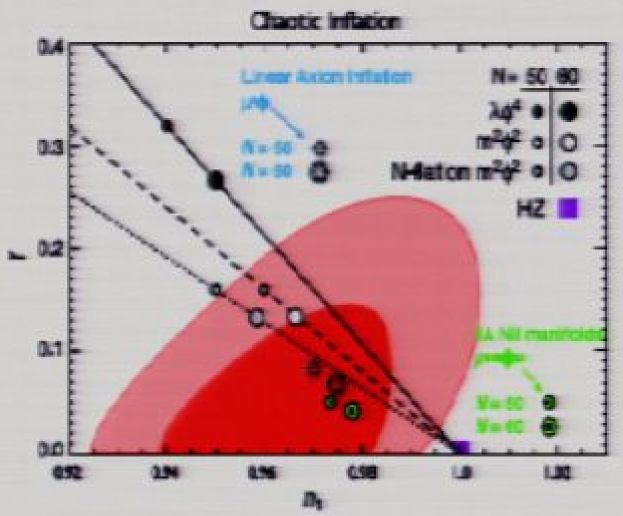

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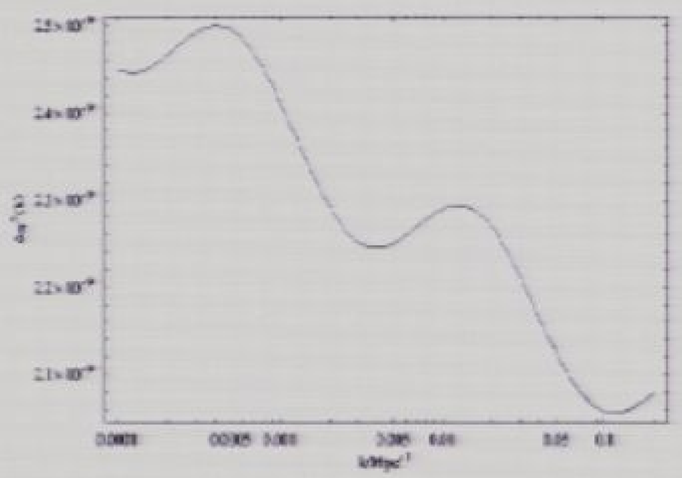

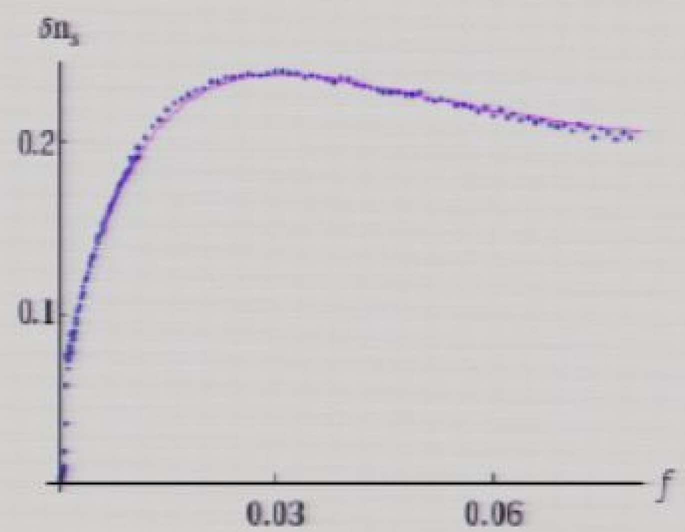

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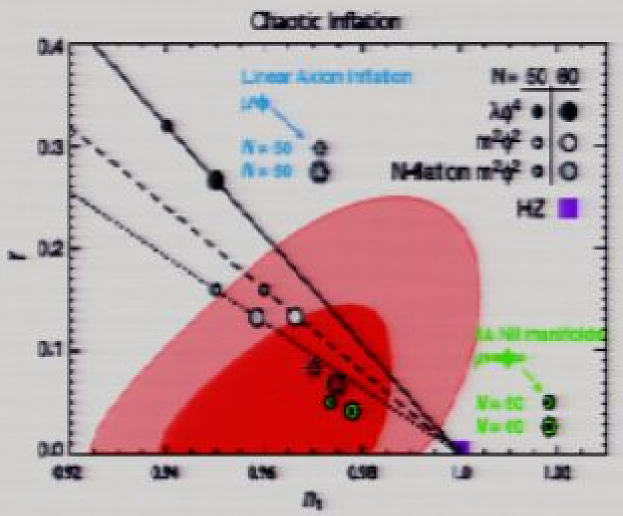

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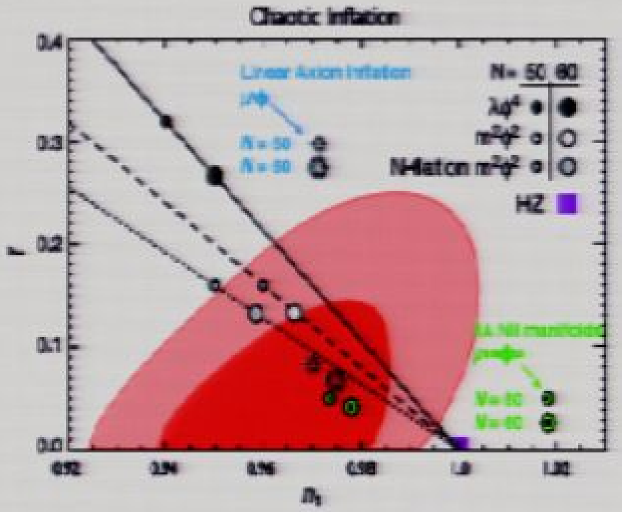

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Bispectrum of scalar perturbations

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

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

where the intaracting Hamiltonian at order ζ^3 is

$$\begin{aligned} H_I &= \int a\epsilon^2\zeta\zeta'^2 + a\epsilon^2\zeta(\partial\zeta)^2 - 2\epsilon\zeta'(\partial\zeta)(\partial\chi) \\ &\quad + \frac{a}{2}\epsilon\dot{\eta}\zeta^2\zeta' + \frac{\epsilon}{2a}(\partial\zeta)(\partial\chi)(\partial^2\chi) + \frac{\epsilon}{4a}(\partial^2\zeta)(\partial\chi)^2, \\ \chi &\equiv a^2\epsilon\partial^{-2}\dot{\zeta} \end{aligned}$$

Resonant enhancement of non-Gaussianity

Condition for the resonance

Schematically [Chen, Easther & Lim 08]

$$\zeta_k = u_k a^\dagger_k + u^*_k a_{-k}$$

$$< \zeta^3 > \sim u^3 \int \epsilon^2 u^3 + \epsilon \dot{\eta} u^3 + \dots$$

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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]

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

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The size of the resonant non-G is

$$f_{res} \simeq \frac{9}{4}\frac{b}{(f\phi)^{3/2}}$$

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Large non-G?

- Liner in b as for the spectrum
- Inversely proportional to $f^{3/2}$

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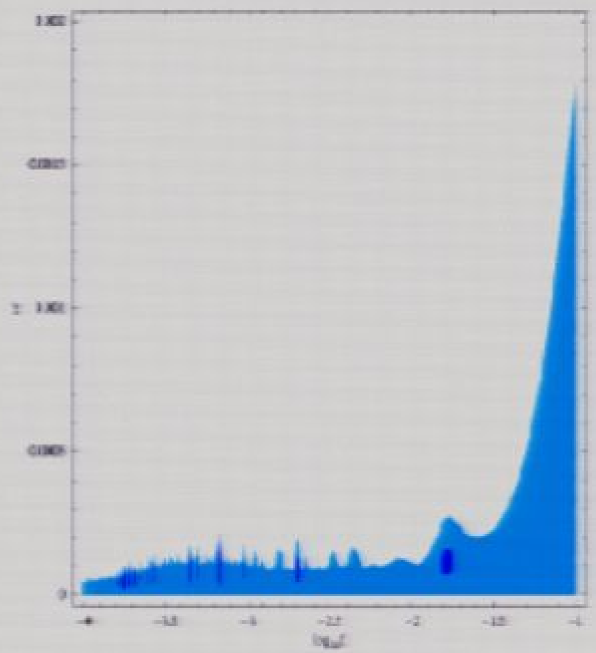

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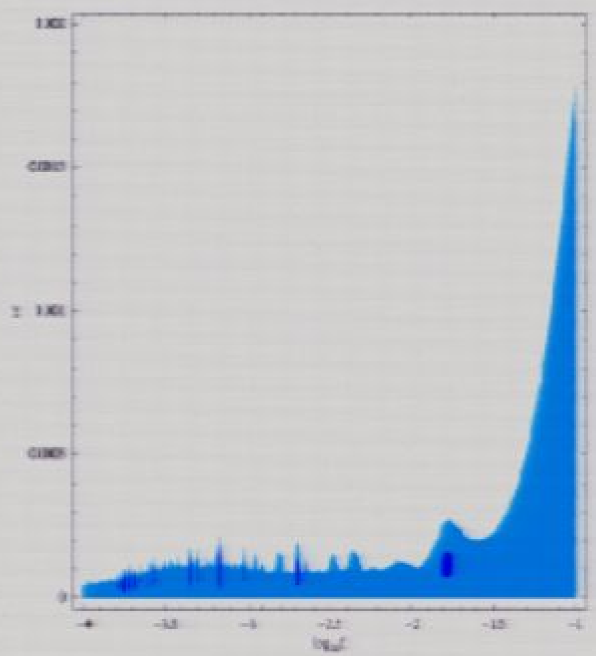

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We are going to present a possible embedding of this effective model in string theory and address the above questions.

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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

1. Motivations
2. Phenomenology of the effective model
3. A string theory model of axion monodromy
4. Constraints and phenomenology
5. Conclusions

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

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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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- World sheet with boundaries, i.e. D-branes

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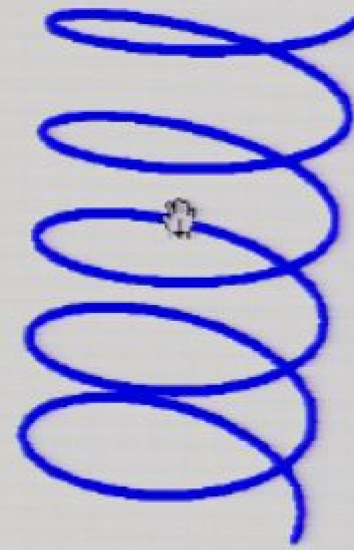
Linear potential for the inflaton

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

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

$$-T_5 \int d^5x e^{-\Phi} \sqrt{\det\left(G^{ind} + B^{ind}\right)}$$



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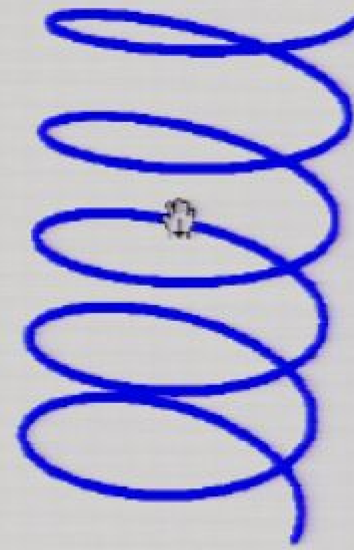

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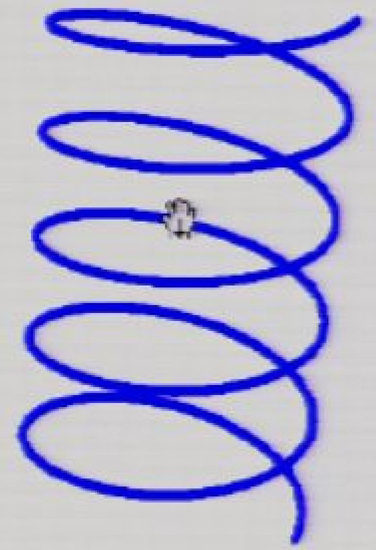
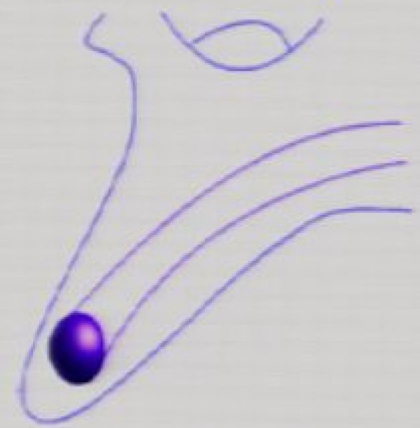


The shift $b(x) \to b(x) + \text{const}$ of $b(x) = \int_\Sigma B_2$ stores some potential energy.

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



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	$g_{\mu\nu}$
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chiral multiplets	$h_-^{(2,1)}$	z^k
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The tree-level Kähler potential and superpotential

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c^a and b^a enjoy a shift symmetry (world-sheet argument). No-scale structure of $K \Rightarrow T_\alpha$ are not stabilized.

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c^a and b^a enjoy a shift symmetry (world-sheet argument). No-scale structure of $K \Rightarrow T_\alpha$ are not stabilized. Non-perturbative corrections, from ED3 or gaugino condensation on D7's, lead to

$$W = W_0 + \sum_{\alpha=1}^{h_+^{1,1}} A_\alpha e^{-a_\alpha T_\alpha},$$

which stabilize T_α [Kachru et al. 03] .

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c^a and b^a enjoy a shift symmetry (world-sheet argument). No-scale structure of $K \Rightarrow T_\alpha$ are not stabilized. Non-perturbative corrections, from ED3 or gaugino condensation on D7's, lead to

$$
W = W_0 + \sum_{\alpha=1}^{h_+^{1,1}} A_\alpha e^{-a_\alpha T_\alpha} ,
$$

which stabilize T_α [Kachru et al. 03] .

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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\begin{aligned}
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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- c^a still enjoy a shift symmetry

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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4. **Constraints and phenomenology**
5. Conclusions

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A series of constraints follow from consistency and computability

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

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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

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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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