The effective field theory of axion monodromy

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arxiv:1101.0026 with Nemanja Kaloper (UC Davis) and Lorenzo Sorbo (U Mass Amherst)

arxiv:1105.3740 with Sergei Dubovsky (NYU) and Matthew Roberts (NYU)

arxiv:1203.6656

arxiv:1404.2912 with NK

Work in progress with NK and Alexander Westphal

I. Large field inflation

$$\frac{\Delta\phi}{m_{pl}} \sim \sqrt{\frac{r}{0.01}} \sim \frac{\sqrt{V}}{(1.06 \times 10^{16}\ GeV)^2}$$

Turner; Lyth

"High scale": $V^{1/4} \sim 10^{16}\ GeV\ \sim M_{GUT} \Rightarrow \Delta\phi > m_{pl} \sim 2 \times 10^{18} GeV$

Why is this confusing?

$$V \sim \sum_n c_n \frac{\phi^n}{M^{n-4}}$$

- UV scale $M \lesssim m_{pl}$
- Slow roll inflation (canonical kinetic terms)

$$M = m_{pl}:\ \ c_n \ll 1\ \forall n : c_2 \lesssim 10^{-10}; c_4 \lesssim 10^{-12}\ \ \ldots$$

Where is the danger?

(1) loops of inflaton, graviton give suppressed couplings

$$V_{loop} = V_{class} F\left(\frac{V}{m_{pl}^4}, \frac{V'}{m_{pl}^2}, \ldots\right)$$ Coleman and Weinberg; Smolin; Linde

perturbative corrections preserve symmetries

$$\phi \to \phi + a$$

(2) UV completion generically expected to break global symmetries

Hawking radiation, wormholes, couplings to other sectors...

(absent some mechanism!)

$$\delta\mathcal{L} \sim \sum_i g_i \frac{A_i^{s.b.}}{m_{pl}^{\Delta_i - 4}} \; ; g_i \sim \mathcal{O}(1)$$

Natural/pseudonatural inflation

Adams, Bond, Freese, Frieman, Olinto;
Arkani-Hamed, Cheng, Randall

$\phi \equiv \phi + 2\pi f_\phi$ forbids direct corrections $\delta V \sim \frac{\phi^n}{m_{pl}^{n-4}}$

$$V = \Lambda^4 \cos\left(\frac{\phi}{f_\phi}\right) + \cdots$$ ← Dynamical, nonperturbative breaking

Match to data: requires $f_\phi > m_{pl}$

Problem: $\delta V \sim \Lambda^4 \sum_{n>1} c_n \cos(n\phi/f_\phi)$

$$c_n \sim e^{-nS},\ S \lesssim \left(\frac{m_{pl}}{f_\phi}\right)^2$$

Banks, Dine, Fox, and Gorbatov;
Arkani-Hamed, Motl, Nicolis, and Vafa

II. Axion monodromy inflation in 4 dimensions

Kaloper and Sorbo; Kaloper, Lawrence, and Sorbo; Kaloper and Lawrence

Combines chaotic, natural inflation

$$S_{class} = \int d^4x\sqrt{g}\left(m_{pl}^2 R - \frac{1}{48}F^2 - \frac{1}{2}(\partial\varphi)^2 + \frac{\mu}{24}\varphi^* F\right)$$

$$F_{\mu\nu\lambda\rho} = \partial_{[\mu} A_{\nu\lambda\rho]}$$

$$\delta A_{\mu\nu\lambda} = \partial_{[\mu}\Lambda_{\nu\lambda]}$$

Compact U(1) gauge symmetry

$$\varphi \equiv \varphi + 2\pi f$$

F does not propagate.

Can jump across domain walls/membranes

Brown and Teitelboim

Effective field theory for original and recent string models, unwinding inflation

(Perhaps after some duality transformation)

Marchesano, Shiu, and Uranga; Kaloper, Lawrence, and Westphal

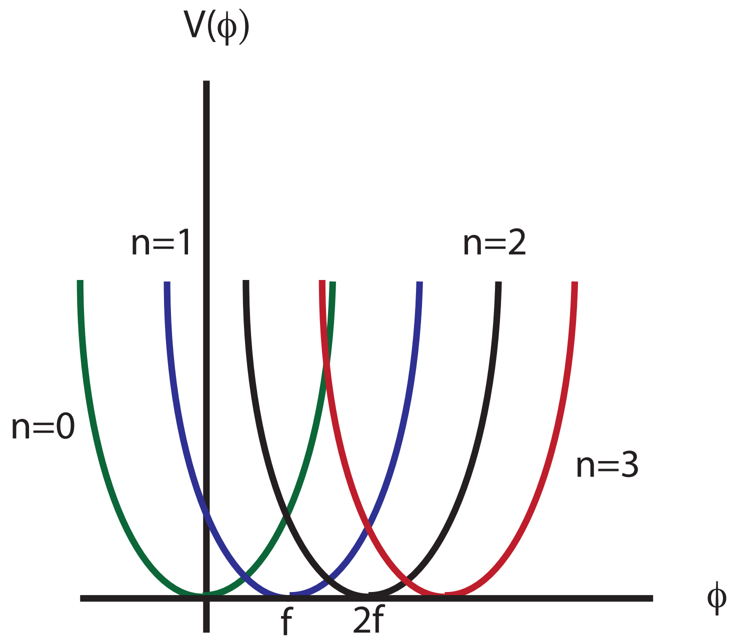
But note UV completions still very important!

Hamiltonian: $H_{tree} = \frac{1}{2}p_\phi^2 + \frac{1}{2}\left(p_A + \mu\phi\right)^2 + \; grav.$

Compactness of gauge group: $p_A = ne^2$ n jumps by membrane nucleation

Consistency condition: $\mu f_\varphi = e^2$

Monodromy: theory invariant under $\varphi \to \varphi + 2\pi f \;; n \to n-1$



Absent transitions: equivalent to

$$V = \frac{1}{2}\mu^2\varphi^2$$

Fits data OK if: $\mu \sim 10^{-5} m_{pl}$ can still have $f < m_{pl}$

$$e \sim M_{GUT} \Rightarrow f \sim .1 m_p$$

+ observable GW

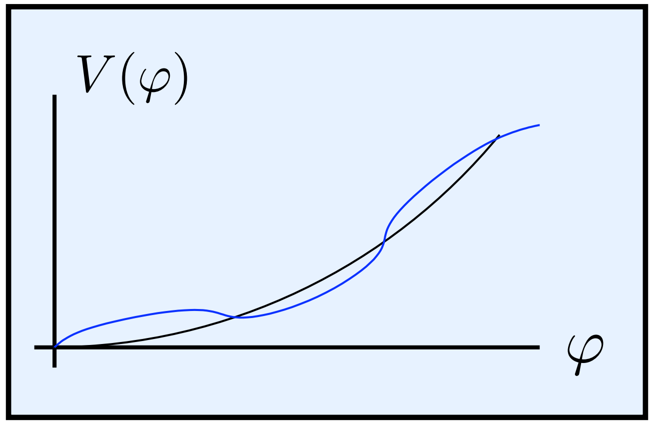
Will assume this can be achieved by some natural mechanism: worry about corrections

Why does this work?

Basic points:

- $\varphi \equiv \varphi + 2\pi f$ still protects theory from direct corrections $\delta V \sim \frac{\phi^n}{m_{pl}^{n-4}}$
- Coupling of φ to F: $\mu\varphi F$ governed by single small parameter

Corrections:



(1) Instanton effects

Couple φ to nonabelian gauge field G

$$\delta L = \frac{\varphi}{f} \text{ tr } G^* G$$

Instanton corrections: $\delta V \sim \Lambda^4 \cos \frac{2\pi\varphi}{f} + \ldots$

Easy to make subleading: interesting signatures cf Eva's talk

(2) Corrections to 4-form energetics: $\delta L = \frac{1}{M^{4n-4}} F^{2n}$

Effective potential: $\delta V = \frac{(\mu^2 \varphi^2)^n}{M^{4n-4}}$

Corrections small if $M^4 \gg V_{inf} \sim\sim (10^{16}\ GeV)^4$

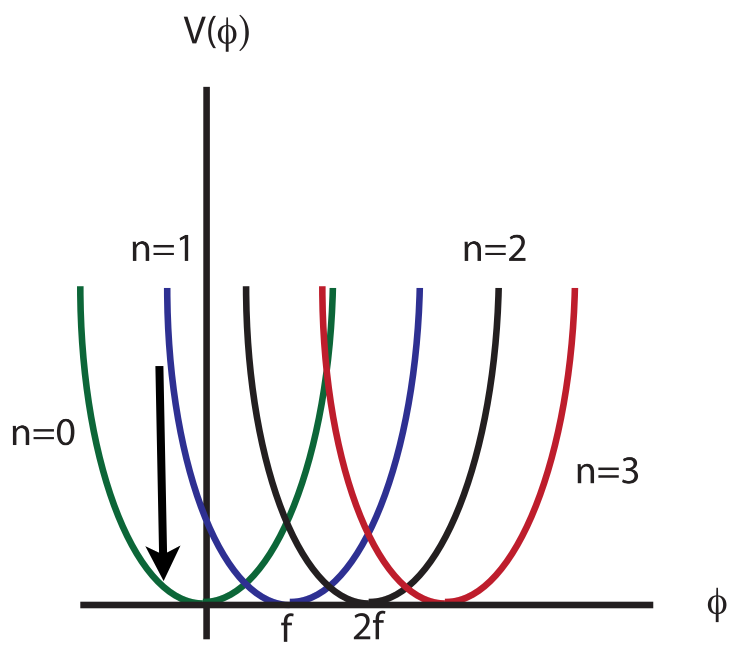
(3) Coupling to moduli: $V = V_0(\psi) + \frac{1}{2}\mu^2 \left(\frac{\psi}{m_{pl}}\right) \varphi^2 + \Lambda^4 \sum_n c_n \left(\frac{\psi}{m_{pl}}\right) \cos\left(\frac{n\varphi}{f_\varphi}\right)$

ψ stable if $M_\psi > \frac{\sqrt{V_{inf}}}{m_p} \sim 10^{14}\ GeV$

and minimum of μ wrt ψ within a Planck distance from minimum of V_0

but see Dong, Horn, Silverstein, Westphal;
McAllister, Silverstein, Westphal, and Wrase

Quantum stability



(1) Jumps between branches

$$n \to n - 1$$

For "unwrapped" φ

$$\Delta\varphi = f$$

For $f > H \sim 10^{14}\ GeV$
ruled out by observation

transition rate must be slow
compared to time scale of inflation

Constraints:

Transitions occur by bubble nucleation. Let:

- T = tension of bubble wall
- E = energy difference between branches

Extremely sensitive to energy scale

Decay probability: $\Gamma \sim \exp\left(-\frac{27\pi^2}{2}\frac{T^4}{(\Delta E)^3}\right)$ (thin wall) Coleman

Phenomenological bound on T: branch-changing bubbles

$$\varphi = N f_\varphi \; ; \Delta\varphi = f_\varphi$$

$$\Delta E^4 \sim V'(\varphi) f_\varphi \sim \frac{V}{N}$$

N.B.: E larger for large V; transitions more likely early in inflation

$$\Gamma \ll 1 \Rightarrow T^{1/3} \gg \left(\tfrac{2}{27\pi^2 N^3}\right)^{1/4} V^{1/4}$$

Let: $f_\phi \sim .1\, m_{pl}; \;\; N \sim 100; V \sim M_{gut}^4$

$$T \gg (.2V^3)^{1/4} \sim (.9M_{gut})^3$$

- Borderline; should check against explicit models
- UV complete 2d models: T ~ M AL

(2) Jumps of parameters

$$L_{\varphi - F} = \mu \left(\frac{\psi}{m_p} \right) \varphi F$$

$V(\psi)$ can have multiple local minima; transitions cause μ to jump

Not restricted to monodromy inflation!

Can occur during, after inflation

$$\Delta\mu \sim 0.1\mu \Rightarrow P_{jump} < 1 \text{ if } T^{1/3} > .5 M_{GUT}$$

$\Delta E \sim \left(\frac{\Delta\mu}{\mu} V \right)^{1/4} \Rightarrow$ Jumps more likely at earlier times

Interesting signatures?

Monodromy from strongly coupled gauge theory

Large-N gauge dynamics

$$S_{class} = \int d^4x\sqrt{g}\left(m_{pl}^2 R - \frac{1}{4g_{YM}^2}\mathrm{tr}G^2 - \frac{1}{2}(\partial\varphi)^2 + \frac{\varphi}{f_\varphi}\mathrm{tr}G\wedge G\right)$$

G: field strength for U(N) gauge theory with N large; strong coupling in IR

Instanton expansion breaks down Witten; Giusti, Petrarca, and Taglienti

$$H \sim H_{gauge} + \frac{1}{2}p_\varphi^2 + \frac{1}{2}\left(n\Lambda^2 + \mu\varphi\right)^2 + \ldots$$ for $\varphi/f \ll 1$

Λ strong coupling scale of U(N) theory

$$\mu = \Lambda^2/f$$

$E(\varphi) \sim N^2\mathcal{E}\left(\frac{\varphi}{Nf}\right) \Rightarrow$ monodromy potential

$\mathrm{tr}G\wedge G = F^{(4)}$ Dvali

Example

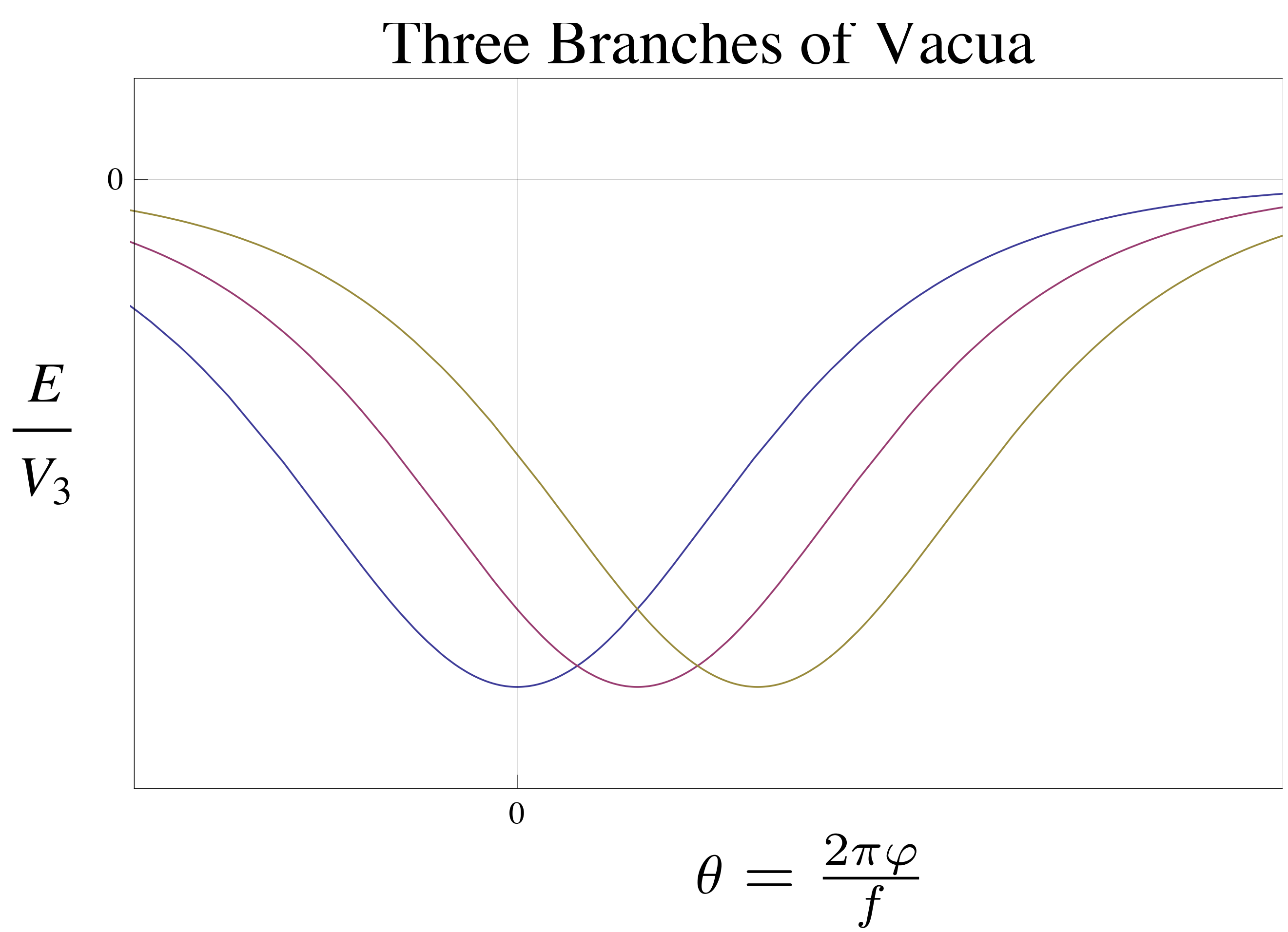
Witten; Dubovsky, Lawrence, and Roberts

N type IIA D4-branes wrapped on S^1 with radius β

Antiperiodic boundary conditions for fermions break SUSY

Massless sector: U(N) gauge theory

$N \to \infty, \lambda = g^2_{4,YM} N$ fixed: theory has gravitational dual w/ monodromy Witten



Transitions between branches strongly suppressed

Improved version of natural inflation

$$x = \frac{\lambda\varphi}{2\pi N f}$$

$$\frac{E}{V_3}(x) = \frac{2\lambda N^2}{3^7\pi^2\beta^4}\left(1 - \frac{1}{(1+x^2)^3}\right)$$

Match to CMBR

$$V \sim A - \frac{B}{\varphi^6} \Rightarrow n_s \sim 0.965 \;;\; r \sim 8 \times 10^{-4}$$

$$\Delta\varphi \sim 2m_{pl} \;;\; x > 1$$

see also Dine, Draper, and Monteux

III. Corrections

Kaloper and Lawrence

"High scale" stringy models consistent with unification at M_{GUT}

Heterotic models, M on G2, type II with branes,...

$$M_{uv} = (m_s, m_{10,pl}, m_{11,pl}, m_{KK}) = \left(\frac{1}{\text{few}} - \text{ few}\right) \times M_{GUT}$$

$$M_{moduli} \lesssim H = \frac{M_{GUT}^2}{m_{pl}}$$ without extra work

- $V \sim M_{GUT}^4$ motivates deeper study of "stringy" compactifications
- Corrections due to UV physics at edge of being observable

"Edge of respectability"

(1) Corrections to potential

$$V = \frac{1}{2}\mu^2\varphi^2 + c\frac{\left(\frac{1}{2}\mu^2\varphi^2\right)^2}{M_{uv}^4} + \dots$$
$$= \frac{1}{2}\mu^2\varphi^2 \pm \lambda\varphi^4 + \dots$$

Example $c \sim 1, M_{uv} = 2.3\ M_{GUT} \Rightarrow \begin{cases} r \sim .2 \\ \frac{\Delta P_S}{P_S} \sim \pm .18 \end{cases}$

(2) Nonperturbative jumps in n, μ

Fluctuations in bubble walls

$$S = T\int d^3x(\partial X)^2 \Rightarrow \delta(\sqrt{T}X) = \sqrt{H}$$

$T^{1/3} \sim M_{GUT} \Rightarrow$ Fluctuations in bubble walls compete w/ inflaton fluctuations

Fluctuations in bubble walls compete w/ inflaton fluctuations

D'Amico, Gobetti, Kleban, and Schillo

Transition just before visible epoch $\Longrightarrow$ hemispherical asymmetry

IV. London equation for monodromy

Kaloper, Lawrence, and Westphal

Dual of axion-4 form

$$\mathcal{L} = -\frac{1}{48}(F^{(4)})^2 - \frac{1}{2}\mu^2\left(A^{(3)} - \frac{1}{\mu}H^{(3)}\right)^2 + \varphi^* dH$$

- Integrate out H

$$\mathcal{L} = -\frac{1}{48}(F^{(4)})^2 - \frac{1}{2}(\partial\varphi)^2 - \mu\varphi^* F$$

- Integrate out φ : $H = dB^{(2)}$

$$A \to A + d\Lambda$$

$$B \to B + \Lambda$$ B can be gauge fixed to zero

$$\mathcal{L} = -\frac{1}{48}(F^{(4)})^2 - \frac{1}{2}\mu^2 A^2$$

φ dual to longitudinal mode of A

Should be renormalizable (cf massive QED)

Julia-Toulouse mechanism

Julia and Toulouse; Quevedo and Trugenberger

Membranes electrically charged under A

$$\mathcal{L} = -\frac{1}{48}(F^{(4)})^2 - \frac{1}{2}\mu^2 A^2$$

$$\downarrow$$

4-form coupled to membrane condensate?

- UV complete model (eg via string theory)?

  D-brane condensates often dual to fundamental fields

  Strominger; Witten; ...

- Mechanism for small μ ?

2d analog: Schwinger model

Lawrence; Seiberg

Charged fermions = 2d domain walls

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\gamma^{\mu}\left(\partial_{\mu} - iA_{\mu}\right)\psi$$

$\updownarrow$ Bosonization:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(\partial\varphi)^2 - \varphi\epsilon^{\mu\nu}F_{\mu\nu}$$

$\updownarrow$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}A^2$$