Axion monodromy

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and with Kaloper and AL
I. Introduction: “high scale inflation” in UV-complete theories

II. 4d models of axion monodromy

III. Quantum corrections

IV. Monodromy from strongly coupled QFT

V. Conclusions
I. Introduction

Scale of inflation

Observational upper bound on GW: \( V \lesssim 10^{16} \) GeV \( \sim M_{GUT} \)

Close to “unification scale”

\[
\alpha_i = \frac{e_i^2}{hc}
\]

See also:

- \( p \) decay
- \( \nu \) mass

If \( V \) near upper bound: detectable by PLANCK or ground-based CMB polarization experiments

Couplings unify (assuming MSSM above 1 TeV) at approximately \( 10^{16} \) GeV. Graph not to scale.
Detectable primordial GWs require large inflaton range

Single field slow-roll inflation with inflaton $\phi$

- $\left(\frac{\delta \rho}{\rho}\right) \sim \frac{H^2}{\dot{\phi}} \sim 10^{-5}$ from observations

- $N_e = \int dt H = \int \frac{d\phi}{\dot{\phi}} H = \int \frac{d\phi}{H} \frac{H^2}{\dot{\phi}} \gtrsim 60$

  upper bound on $V, H = \sqrt{V}/m_{pl}$

  $\Rightarrow$

  upper bound on $\frac{d\phi}{dN}, \Delta \phi$ during inflation to match observed flatness

$\Rightarrow \Delta \varphi \gg m_{pl}$
Effective field theory and large $\phi$

Effective field theory: expansion in $1/M$ for some UV scale $M$

$$V = \sum_n g_n \frac{\phi^n}{M^{n-4}}$$

generically

- $g_n \sim 1$ unless forbidden by symmetry
- $M \lesssim m_{pl}$

Expansion breaks down for $\phi > M$

- New degrees of freedom could become light
- Relevant d.o.f. very different
High scale inflation looks like a highly nongeneric theory

Consider $V \sim m^2 \phi^2$ or $V \sim \lambda \phi^4$

$\delta \rho / \rho \sim 10^{-5}$, $N_e \gtrsim 60 \implies$

- $\frac{m^2}{m_{pl}^2} \sim 10^{-12}$
- $\lambda \sim 10^{-14}$

Corrections $\delta V = \sum_n g_n \frac{\phi^n}{M^{n-4}}$

all $g_n$ must be small: infinite fine tuning!

else e.g. $\eta = m_{pl}^2 \frac{V''}{V} \geq 1$

Slow roll inflation requires approximate shift symmetry

$\phi \to \phi + a$
Perturbative quantum corrections

Small couplings $\frac{m^2}{m_{pl}^2}, \lambda$

$m_{pl}$ -suppressed couplings to gravity

$\Rightarrow$ loops of inflaton, graviton gives 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

Slow roll inflation safe against inflaton, graviton loops

perturbative corrections preserve symmetries
UV completions make slow roll difficult to maintain

Continuous global symmetries like \( \phi \rightarrow \phi + a \) are always (we think) broken

- Gravity breaks continuous global symmetries (Hawking radiation/virtual black holes, wormholes,...)

- String theory: continuous global symmetries tend to be gauged, anomalous

- Anomalous symmetries broken by nonperturbative effects (e.g. Peccei-Quinn symmetry of axion)

\[
\delta V \sim \Lambda^4 \sum_n c_n \cos\left(\frac{n\phi}{f_\phi}\right)
\]
One attempt: “pseudonatural inflation”

Use anomalous symmetry to generate potential

$$V = \Lambda^4 \cos \left( \frac{\phi}{f_\phi} \right) + \ldots$$

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

$$c_n \sim e^{-nS}, \left( \frac{f_\phi}{M} \right)^n$$

$\Lambda$ some dynamical scale; slow roll for $f_\phi \gg \Lambda$

large field if $f_\phi \gg m_{pl}$

Problem: $f_\phi > m_{pl}$ with $c_n$ small does not seem to be allowed

$$\frac{f_\phi}{M} \gg 1$$

Banks, Dine, Fox, and Gorbatov;
Arkani-Hamed, Motl, Nicolis, and Vafa
Consider compact scalar field \( \varphi \sim \varphi + f ; \ f \ll m_{pl} \)

Theory invariant under shift \( \varphi \rightarrow \varphi + f \) physical state need not be

Let axion wind \( N \) times such that \( Nf_{\phi} \gg m_{pl} \)

Compactness of field space seems to control quantum corrections
Cartoon

Most models to date constructed within string theory

Illustrative example: type IIA with D4-brane wrapped on 2-torus

- $\tau$ has period = 1
- $\phi = m_{pl}\tau$
  - canonically normalized scalar

$$V(\phi) \sim \frac{m_s^4}{g_s} \sqrt{1 + (m_{pl}\phi)^2}$$

$n = \#$ of D4 windings

Shift $\tau \rightarrow \tau + 1$ is symmetry of torus, but stretches D-brane.

Shift $\tau$ $n$ times; D-brane becomes $n$ times as long.

Doesn’t quite work but illustrates point. Note potential flattens:

$$V \sim M^3\phi \quad \text{at large} \quad \phi$$

But see Berg, Pajer, and Sors; Kaloper and Sorbo

Saturday, April 2, 2011
• Known string realizations seem to give flat potentials, with relatively small powers
\[ V \sim M^{4-p} \varphi^{p<2} \]

Seems to the result of coupling to moduli, KK modes

Is a quadratic potential viable?

Dong, Horn, Silverstein, and Westphal

CMB data: \( p \leq 2 \) viable, smaller \( p \) more viable

• Quantum corrections studied model by model: these are complicated, and physical reason for flat potentials is not completely transparent.
Effective field theory approach

- Input basic fields, symmetries, topology of field space
- Expand action in powers of $1/M$ ($M = UV$ scale), include all terms consistent with symmetries
- Pinpoints physics behind suppressing corrections to slow roll
- Isolates fine tuning required.
- Provides a framework for building new string models

String theory has a complicated landscape
Realistic models very hard to construct
Quantum corrections difficult to compute

$\Rightarrow$ 4d effective field theory analysis is *always* important
II. 4d models of axion monodromy

Axion-four form model  Kaloper and Sorbo

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

$$F_{\mu\nu\lambda\rho} = \partial_{[\mu} A_{\nu\lambda\rho]} \quad \text{U}(1) \text{ gauge symmetry: } \delta A_{\mu\nu\lambda} = \partial_{[\mu} \Lambda_{\nu\lambda]}$$

$$\varphi \text{ periodic: } \varphi \rightarrow \varphi + f_\varphi$$

F does not propagate.

U(1) quantized

$$F_{\mu\nu\lambda\rho} = n e^2 \epsilon_{\mu\nu\lambda\rho} ; \quad n \in \mathbb{Z}$$

n can jump across domain walls/membranes
Dynamics

Single massive scalar degree of freedom

Hamiltonian: \[ H_{\text{tree}} = \frac{1}{2} p_\phi^2 + \frac{1}{2} (p_A + \mu \phi)^2 + \text{grav.} \]

Compact U(1): \[ p_A = ne^2 \]

\( p_A \) conserved by \( H_{\text{tree}} \)

Jumps by membrane nucleation

Consistency condition: \[ \mu f_{\phi} = e^2 \]

Realizes monodromy inflation: theory invariant if \[ \phi \rightarrow \phi + f_{\phi} ; n \rightarrow n - 1 \]

Good model for inflation: fits data well if \[ \mu \sim 10^{-6} m_{pl} \]

+ observable GW
Large-N gauge dynamics

\[ S_{class} = \int d^4 x \sqrt{g} \left( m_{pl}^2 R - \frac{1}{4 g_Y^2} \text{tr} G^2 - \frac{1}{2} (\partial \varphi)^2 + \frac{\varphi}{f_\varphi} \text{tr} G \wedge G \right) \]

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

Instanton expansion breaks down \textit{Witten; Giusti, Petrarca, and Taglienti}

\[ H_{tree} = H_{gauge} + \frac{1}{2} p_\varphi^2 + \frac{1}{2} (n \Lambda^2 + \mu \varphi)^2 \]

\[ \Lambda \quad \text{strong coupling scale of U(N) theory} \]

\[ \mu = \frac{\Lambda^2}{f_\varphi} \]

Can be related to 4-form version: \textit{Dvali}

\[ F_{\mu \nu \lambda \rho} \sim \text{tr} \ G_{[\mu \nu} G_{\lambda \rho]} \]
III. Quantum corrections

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

\[ \mu \sim 10^{-6} m_{pl} \quad \text{to match constraints on} \quad \delta \rho / \rho, \ N_e \]

What are the possible corrections?

Effective field theory:

- Allow all terms consistent with symmetries, topology of field space
- Dimenson-d operators suppressed by \( M_{d-4} \)

Corrections controlled by:

- Compactness of scalar, U(1)
- Small coupling \( \mu / M_{uv} \ll 1 \)

Stability:

- Quantum jumps between branches mediated by membrane nucleation
Direct corrections to $V(\varphi)$

Periodicity of $\varphi \implies$ quantum corrections to $S$ must be

- Functions of $\partial^n \varphi$
- periodic functions of $\varphi$

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

$$f_{\varphi} \ll m_{pl}$$

Monodromy potential modulated by periodic effects

$$V_{corr} \ll \frac{1}{2} \mu^2 \varphi^2 \implies \Lambda^4 \ll M_{gut}^4$$

$$\eta = m_{pl}^2 \frac{V''}{V} \ll 1 \implies \frac{\Lambda^4}{f_{\varphi}^2} \ll \frac{V}{m_{pl}^2} = H^2$$

Example: feasible if $\Lambda \sim .1 \ M_{gut}$, $f > .01 \ m_{pl}$
• Gauge dynamics: $\Lambda = \Lambda_{QCD}$
from couplings $\frac{\varphi}{f_{\varphi}} \text{tr} \ G \wedge G$

instanton corrections take above form (if dilute gas approx good)
strong coupling effects (when dilute gas aprox fails)

$$\delta V \sim \Lambda^4 \min_k F\left(\frac{\varphi}{f_{\varphi}} + k\right)$$
multibranched function of $\varphi$

When using this effect to generate monodromy potential:
mixing between branches must be weak

When this generates corrections: mixing must be strong
(else trapped in a fixed branch)

• Gravitational dynamics: $\Lambda_4 \sim \frac{f_{n+4}}{m_{pl}^n}$

gravitational instantons, wormholes, etc.
Caveat: moduli stabilization

In any string theory: couplings in $V$ will depend on moduli $\psi$

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

Periodic corrections change sign many times since $f_\varphi \ll m_{pl}$

Moduli must be stabilized by different effects than instantons coupling to inflaton

$$M^2_\psi \equiv V_0''(\psi) \gg \frac{\Lambda^4}{m^2_{pl}}$$

Large $\varphi \gg m_{pl}$ sources potential for $\psi$

Stability requires $M^2_\psi \gg \mu^2 \varphi^2 / m^2_{pl} \sim \mu^2 / \epsilon \sim H^2$
Indirect corrections to $V(\varphi)$

Additional corrections must respect periodicity of $\varphi$

$\Rightarrow$ corrections to dynamics of four-form $F$

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

Consider $\delta \mathcal{L} = \sum_n d_n \frac{F^{2n}}{M^{4n-4}}$

Integrate out $F$: $F \sim \mu \varphi + \ldots$

$$\delta V_{\text{eff}} = V_{\text{class}} \times \left( \sum_{n=1}^{d_n+1} \frac{V_n}{M^{4n}} \right)$$

Safe if: $M^4 \gg V_{\text{class}} \sim M_{\text{gut}}^4$

Corrections of the form $\delta \mathcal{L} = \left( \sum_{n=1}^{d_n+1} \frac{F^{2n}}{M^{4n}} \right) (\partial \varphi)^2$

Gives same effect after redefining $\varphi$ to be canonically normalized
Small $M$ not always fatal

Many string theory scenarios:

$$V(\varphi) = M_1^4 \sqrt{1 + \frac{\varphi^2}{M_2^2}} \quad M_2 \ll m_{pl}$$

- For small $\varphi$ \quad $V \sim \frac{1}{2} \mu^2 \varphi^2$ ; $\mu = \frac{M_1^4}{M_2^2}$
- For $\varphi \gg m_{pl}$ \quad $V \sim m^3 \varphi$; $m^3 = \frac{M_1^4}{M_2^2}$

Out of range of 4d effective field theory; requires understanding of UV completion (eg 10d SUGRA) to compute
Example: backreaction on compactification

Consider string modulus $\psi$
determines KK scale: $L_0 e^{-\psi/m_{pl}}; \mathcal{V}_D \sim L^D; \ m_{pl}^2 = m_*^{D+2} \mathcal{V}_D$

$$\mathcal{L}_\psi = \frac{1}{2} (\partial \psi)^2 - \frac{1}{2} M_\psi^2 \psi^2 + c \frac{\psi}{m_{pl}} F^2 + \ldots$$

Integrate out $\psi$:

$$\frac{\psi}{m_{pl}} = c \frac{F^2}{M_\psi^2 m_{pl}^2} \sim c \frac{V}{m_{pl}^2 M_\psi^2} = c \frac{H^2}{M_\psi^2}$$

$$\frac{\delta m_{pl}^2}{m_{pl}^2} \sim \frac{H^2}{M_\psi^2}$$

Since $\eta = m_{pl}^2 \frac{V'''}{V} ; \epsilon = m_{pl}^2 \frac{(V')^2}{V^2}$

We must have $\frac{\delta m_{pl}^2}{m_{pl}^2} \sim \frac{H^2}{M_\psi^2} \ll 1$ Moduli coupling to inflaton must be fairly heavy

If coupling to $F$ is:

$$\sim \frac{(\psi - \psi_0)^2}{m_{pl}^2} F^2 \quad \text{corrections proportional to} \quad \frac{\psi_0}{m_{pl}}$$

$$\frac{\psi_0}{m_{pl}} \sim 1 \quad \text{also edge of validity of effective field theory}$$

Dong, Horn, Silverstein, and Westphal
Example: Coleman-Weinberg corrections

Consider scalar fields $\psi_n$ (e.g. moduli, KK states, etc.)

$$\delta \mathcal{L} \sim \frac{1}{2} (\partial \psi_n)^2 - \frac{1}{2} M_n^2 \psi_n^2 - \sum_k d_{n,k} \frac{F_n^{2n}}{M^{4n-2}} \psi_n^2$$

Integrate out $F^2 \sim V_{\text{class}} = \frac{1}{2} \mu^2 \varphi^2$

Effective mass for $\psi : M_{\text{eff}}^2 = M_{\psi}^2 + M^2 \sum_k d_{n,k}' \frac{V^2}{M^{4n}}$

Integrate out $\psi_n : \delta V_{\text{CW}}(\varphi) \sim M_{\text{eff}}(\phi)^4 \ln \frac{M_{\text{eff}}}{M}$

Must include all such states with $M_n^2 < M^2$

Corrections safe if $n_{\text{eff}} M_{\psi}^2 \ll M^2 ; V \ll M^4$
Kaluza-Klein corrections

Roughly \( n_{\text{eff}} = \frac{m_{\text{pl}}^2}{m_*^2} \); \( m_* = (m_s, m_{\text{pl}}, 10) \gtrsim M_{\text{gut}} \)

\[
V_{CW} = \sum_{KK} \int d^4q \ln \left( q^2 + M_{n,\text{eff}}^2 \right)
\]

\[
\sim V_D \int d^{D+4}q \ln \left( q^2 + \sum_k d_k \frac{V_{\text{tree}}^k}{M^{4k-4}m_{\text{pl}}^2} \right)
\]

\[
\sim m_*^{D+4} V_D(\psi) + m_*^2 V_D \sum_k d_k \frac{V_{\text{tree}}^k}{M^{4k-4}m_{\text{pl}}^2}
\]

\[
\sim \delta V(\psi) + V_{\text{tree}} F \left( \frac{V_{\text{tree}}}{M^4} \right)
\]

Corrections safe if \( V_{\text{class}} \ll M^4 \)

NB if KK mode couples to F as \( \frac{(\psi_n - \psi_{0,n})^2}{m_{\text{pl}}^2} F^2 \) tree level corrections subleading if

\( H^2 < M_{KK}^2 \); \( \psi_{n,0} < m_{\text{pl}},10 \)
Additional “stringy” light states

Consider square torus with sides of length $L$; D4 wrapped $n$ times

$$m_W^2 = \frac{m_s^4 L^2}{1+n^2}; \quad m_p^2 = \frac{1}{L(1+n^2)} \quad ; \quad n = \frac{\varphi}{f_\varphi} = \frac{F}{\mu f_\varphi}$$

$n \gg 1$: strings have spectrum of asymmetric torus with sides of length

$$L_W = \frac{n}{m_s^2 L} \quad ; \quad L_p \sim \frac{n}{L}$$

and volume

$$V_{\text{eff}} \sim \frac{n^2}{m_s^2} \sim \frac{F^2}{m_s^2 e^4}$$

where $e^2 = \mu f_\varphi$ is the unit of quantization of F flux.
Leading quantum correction

\[ V_{CW} = \sum_{k,l} \int d^4q \ln \left( q^2 + m^2_{W,k} + m^2_{p,k} \right) + \ldots \]

\[ \sim \frac{F^2}{m^2_s e^4} \int d^6q \ln q^2 + \ldots \]

\[ \sim \frac{m^4_s}{e^4} F^2 + \ldots \]

Effect is to renormalize \( e^2 \rightarrow m^2_s \sim M^2_{gut} \sim 10^{-4} m^2_{pl} \)

Dangerous: \( \mu = 10^{-6} m_{pl} \) to match observation

\[ \Rightarrow \ f_\phi \sim 10^2 \ m_{pl} \]

Must ensure renormalization of \( e \) is suppressed:

\[ f_\phi \sim .1 \ m_{pl} \Rightarrow \ e^2 \sim (.1 M_{gut})^2 \]
• NB model above is crude (and known not to work for other reasons) so this is a caveat and not a fatal flaw

• Even if $\mu^2$ pushed above $10^{-6}m_{pl}$

we may still get successful large field inflation of the form, e.g.

$$V(\varphi) = M_1^4 \sqrt{1 + \frac{\varphi^2}{M_2^2}}$$

but this requires more than our 4d EFT can do at present
Success of monodromy inflation requires that transition between branches is slow compared to time scale of inflation (must complete 60 e-folds before such transitions)
Bounds on membrane tension

Transitions occur by bubble nucleation. Let:

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

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

Phenomenological bound on $T$

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

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

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

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

$$T \gg (0.2 V^3)^{1/4} \sim (0.9 M_{gut})^3$$

Borderline; should check against explicit models

N.B. $E$ larger for large $V$; transitions more likely early in inflation
IV. Monodromy from strongly coupled QFT

We wish to study monodromy in a setting where we have control over nonperturbative physics

- Understand flattening of potential.

- Understand stability of metastable branches.

Look for strongly coupled gauge theory with gravitational dual
A nonsupersymmetric QFT

N type IIA D4-branes wrapped on $S^1$ with radius $\beta$

Antiperiodic boundary conditions for fermions break SUSY

Bosons get mass from loops

Massless sector: U(N) gauge theory

$\theta$ angle from D-brane coupling to RR 1-form potential

$$S_{WZ} = \int_{S^1 \times R^4} C^{(1)} \wedge \text{Tr} F \wedge F$$

For constant RR field polarized along $S^1$ (Wilson line)

$$\theta = \frac{2\pi C^\beta \beta}{\sqrt{\alpha'}}$$

$\cdot g_{5,YM}^2 = 4\pi^2 \sqrt{\alpha'} g_s$

$\cdot g_{4,YM}^2 = g_5^2 / 2\pi \beta$
Decoupling limit and gravitational dual

\[ \sqrt{\alpha'} \to 0, \ g_s \to \infty \quad \text{such that} \quad g_{5,YM}^2, g_{4,YM}^2 \quad \text{held fixed} \]

\[ N \to \infty, \ \lambda = g_{4,YM}^2 N \quad \text{fixed} \]

massless open strings decouple from closed strings, oscillator modes at low energies

throat is locally

\[ \sim R^4 \times S^1 \times R_u \times S^4 \]

Dual gravity solution for small \[ \theta \ll \frac{N}{\lambda} = g_{4,YM}^{-2} \]

found by Witten (1998)
Phases of theory

(1) “Throat” is infinite -- no mass gap. “Deconfined” phase.

Vacuum energy independent of $\theta$

(II) “Throat” ends at $u = u_0$

Mass gap at $\Lambda_{QCD} \sim u_0/\lambda$  

$\left( u_0 \sim \lambda/\beta \text{ for small } \theta \right)$  

Less useful for studying 4d confinement (at small $x$)

$E(\theta) \sim \lambda N^2 V \left( x = \frac{\lambda \theta}{4\pi^2 N} \right)$  

Witten; DLR

This always has lower energy

Energy dependence implies monodromy potential for $\theta$

Think of $\theta$ as nondynamical axion  

$\theta = \phi/f_\phi$
Three Branches of Vacua
Large-x behavior

\[ \int_{S^1_{u=\infty}} d\chi C^{(1)}_\chi = \int dud\chi F_{u\chi} = \theta + 2\pi n \]

For \( x \sim \frac{\lambda n}{2\pi N} \gg 1 \) must take backreaction of 2-form flux into account

- \( \Lambda_{QCD} \sim \frac{u_0}{\lambda} \sim \frac{1}{\beta(1+x^2)} \)

Throat recedes into IR, glueballs become 4d objects

- \( \frac{E}{V_3} \left( x = \frac{\lambda \theta}{4\pi^2 N} \right) = \frac{2\lambda N^2}{3^7 \pi^2 \beta^4} \left( 1 - \frac{1}{(1+x^2)^3} \right) \rightarrow x \rightarrow \infty \frac{2\lambda N^2}{3^7 \pi^2 \beta^4} \left( 1 - \frac{1}{x^6} \right) \)

Potential flattens (response of E to \( \theta \) depends on \( \Lambda_{QCD} \))
Stability at large $x$

$R_u \times S^1$ becomes long, thin cylinder

- Winding modes about $\chi$ when $x = \frac{\lambda \theta}{4 \pi^2 N} \gg \lambda^{1/3}$

- Casimir forces dominate over RR 2-form flux when $x^7 \gg N \lambda^{1/2}$

Result in both cases is to “pinch off” cylinder for $u > u_0(x)$

But we already know a solution; branch with lower energy.
Conjecture: a given branch with $x = 0$ at minimum ceases to exist at large $x$
Nonperturbative instabilities

D6-brane is a source for RR 2-form charge.

Two candidate domain wall solutions

- D6-brane wrapping $S^4$ sitting at $u = u_0$  

- D6-brane wrapping $S^3(\varphi) \subset S^4$ filling $\mathbb{R}^4$

\[ \varphi \text{ appears as QFT mode} \]

\[ \theta = 2\pi(n - 1) + \delta \]

\[ \theta = 2\pi n + \delta \]

 analogous to Kachru, Pearson, Verlinde

Domain wall when $\varphi$ varies in space

Nucleation of second domain wall has lower action at large $x$
• Height of barrier \( \Delta E \sim \frac{\lambda^2 N}{\beta^4 x^{11}} \) at large \( x \)

• Scaling applied to DBI action of D6 \( S \sim \frac{\lambda^2 N}{x^{11}} \)

metastable branch beginning at \( x = 0 \) should end when \( x^{11} \gg \lambda^2 N \)
V. Conclusions

• Check stability in explicit string models

• Interesting observational signals if a single branch-changing or mass-changing bubble nucleates early within our horizon?

• General issue: monodromy inflation does not seem \textit{parametrically} safe. Should we worry?

Perhaps this is interesting:

• Implies number of e-foldings could be close to lower bound
• Implications for measurements of curvature, pre-inflation transients

• Other interesting applications of axion monodromy

  Kerr black holes; axion condensation via Penrose process. Instability/disappearance of branch can lead to observable axion decays

Kaloper and AL, in progress

Dubovsky and Gorbenko