Axion monodromy

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I. Introduction: inflation vs UV completeness

II. Monodromy from strongly coupled QFT

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

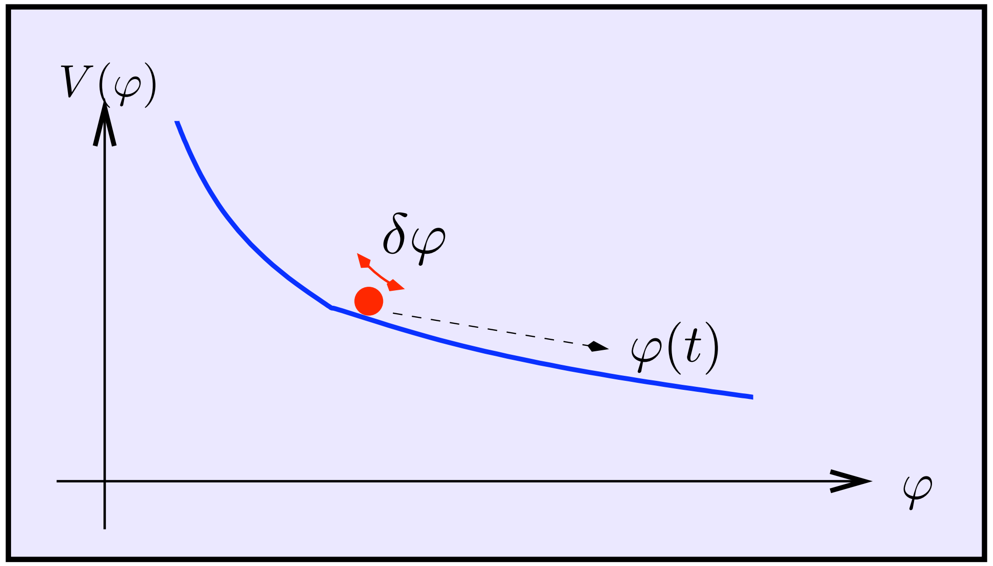
III. 4d model for large field inflation

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

IV. Conclusion

I. Introduction

"Slow roll" inflation matches CMB/LSS data well



Slow roll + vacuum dominance:

- $\epsilon = m_p^2 \left(\frac{V'}{V}\right)^2 \ll 1$
- $\eta = m_p^2 \frac{V''}{V} \ll 1$

Spacetime approximately de Sitter: $ds^2 = -dt^2 + e^{2\int dt H} d\vec{x}_3^2 \;, \quad H^2 = \frac{V}{m_p^2}$

Observed flatness of universe requires expansion factor $\sim e^{60}$

Need shallow potential

Quantum fluctuations generate structure: $\frac{\delta\rho}{\rho} \sim \frac{V^{3/2}}{m_p^3 V'} \sim \frac{\delta T_{CMB}}{T_{CMB}} \sim 5 \times 10^{-5}$

Quantum fluctuations of graviton generate gravitational waves:

$\mathcal{P}_g \sim \frac{V}{m_p^4}$ Detectable via CMB polarization experiments

Building sensible inflation models

The game is to get a potential which is shallow over a large range, consistent with naturalness

Impose softly broken shift symmetry? $\varphi \to \varphi + a$

- "Small field" models $\Delta\varphi < m_{pl}$

  Sub-Planckian physics sufficient: operators of form

$$\mathcal{O}_n = \frac{\varphi^n}{m_{pl}^{n-4}}$$

remain small

NB we are using the "reduced Planck mass"

$$m_{pl} = \frac{1}{\sqrt{8\pi G_N}}$$
$$\sim 2 \times 10^{18}\ GeV$$

- "Large field" models $\Delta\varphi > m_{pl}$

  We must control $\mathcal{O}_n$ for all n

  Requires UV complete theory at Planck scale

Large field models?

- Gravity waves and "Lyth bound"

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

  Close to "unification scale". If GW observable, V must be close to this scale

  Observable GW $\Rightarrow\ \Delta\varphi \gg m_{pl}$ Lyth, hep-ph/9606387

- PNGB-driven inflation

  Scalar field $\varphi \equiv \varphi + 2\pi f$ Corrections of form $\delta V(\varphi) \sim \varphi^n$ forbidden

  "Natural inflation": inflaton potential takes form   Freese, Frieman and Olinto

  $$V(\varphi) = \Lambda^4 \left(1 - \cos\left(\frac{\varphi}{f}\right)\right)$$ eg via instanton effects

  Shallow if $\Lambda \ll f$ can easily be done naturally

  Fits CMB data if $f \sim \text{few} \times m_{pl}$

Large field models and UV completions

- Quantum gravity breaks global symmetries

Holman et al; Kamionkowski and March-Russell; Barr and Seckel; Lusignoli and Roncadelli; Kallosh, Linde, and Susskind

- Instanton actions get small when $f > m_{pl}$

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

$\Rightarrow$ Symmetries cannot control operators like $\frac{\varphi^n}{m_{pl}^{n-4}}$, $\cos \frac{n\varphi}{f}$ for $n \gg 1$

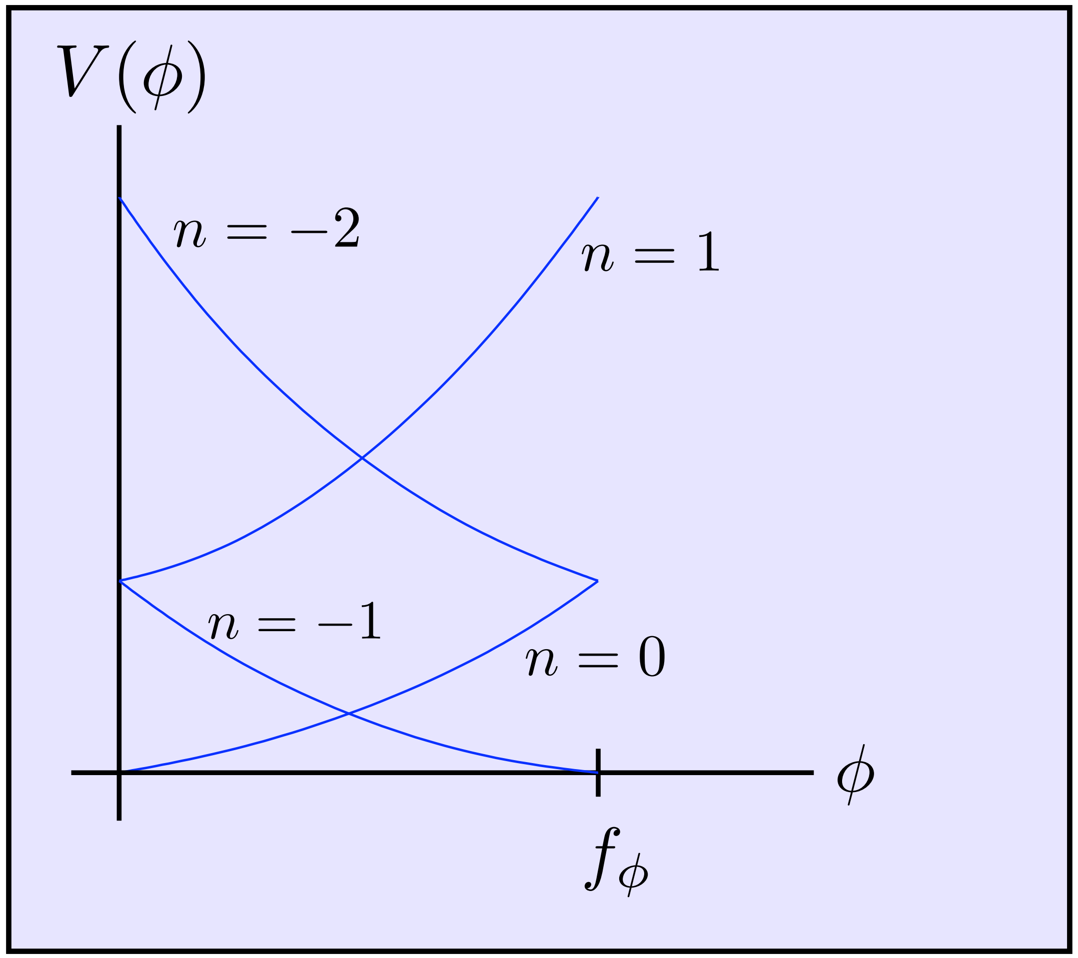
Spoils slow roll inflation

Candidate solution: monodromy in field space

Silverstein and Westphal; McAllister, Silverstein, and Westphal

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 $N f_\phi \gg m_{pl}$

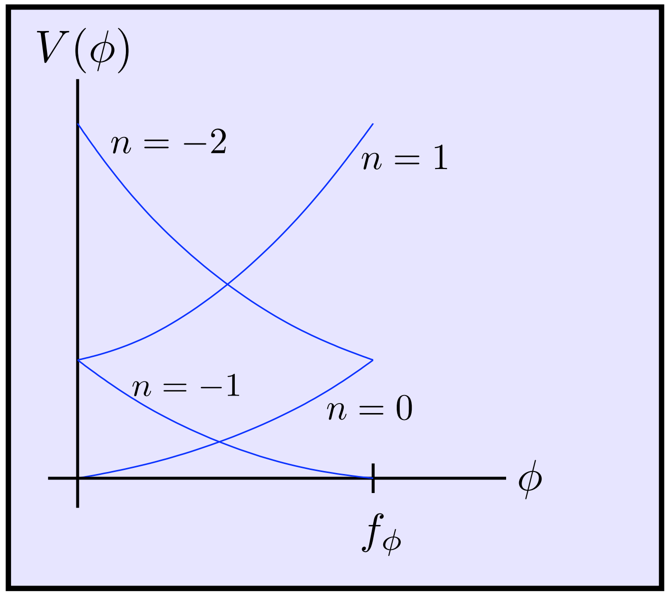
Compactness of field space seems to control quantum corrections

- Known string realizations seem to give flat potentials, with relatively small powers

$$V \sim M^{4-p} \varphi^{p<2}$$

Dong, Horn, Silverstein, and Westphal

- Scenario seems to be viable in string theory but: quantum corrections studied model by model: these are complicated, and physical reason for flat potentials is not completely transparent.



Strategies: study calculable 4d models (part II)

effective field theory analysis (part III)

Some lessons:

- Must take care that metastable states stay metastable, do not decay too quickly

- Quadratic inflation viable only if moduli coupling to inflaton are heavy

II. Monodromy from strongly coupled QFT

Goal: study axion monodromy in a calculable context, via gauge/gravity duality

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

Antiperiodic boundary conditions for fermions break SUSY

Bosons get mass from loops

Massless sector: U(N) gauge theory

- $g^2_{5,YM} = 4\pi^2\sqrt{\alpha'}g_s$
- $g^2_{4,YM} = g^2_5/2\pi\beta$

θ angle from D-brane coupling to RR 1-form potential

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

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

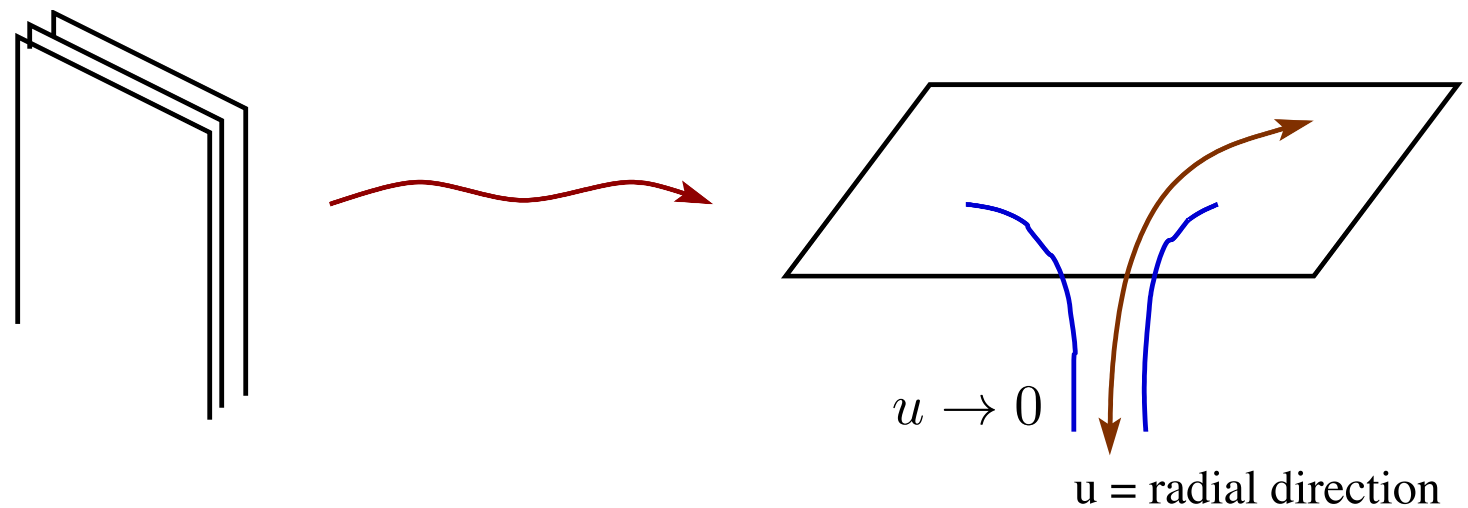
$$\theta = \frac{2\pi C_\beta \beta}{\sqrt{\alpha'}}$$

Decoupling limit and gravitational dual

$\sqrt{\alpha'} \to 0, g_s \to \infty$ such that $g^2_{5,YM}, g^2_{4,YM}$ held fixed

$N \to \infty, \lambda = g^2_{4,YM} N$ 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 to QFT energy scale

Dual gravity solution for small $\theta \ll N/\lambda = g^{-2}_{4,YM}$

found by Witten (1998)

Phases of theory

(I) "Throat" is infinite -- no mass gap. "Deconfined" phase.

Vacuum energy independent of θ

(II) "Throat" ends at $u = u_0$

Mass gap at $\Lambda_{QCD} \sim u_0/\lambda$ $(u_0 \sim \lambda/\beta$ for small $\theta)$

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

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

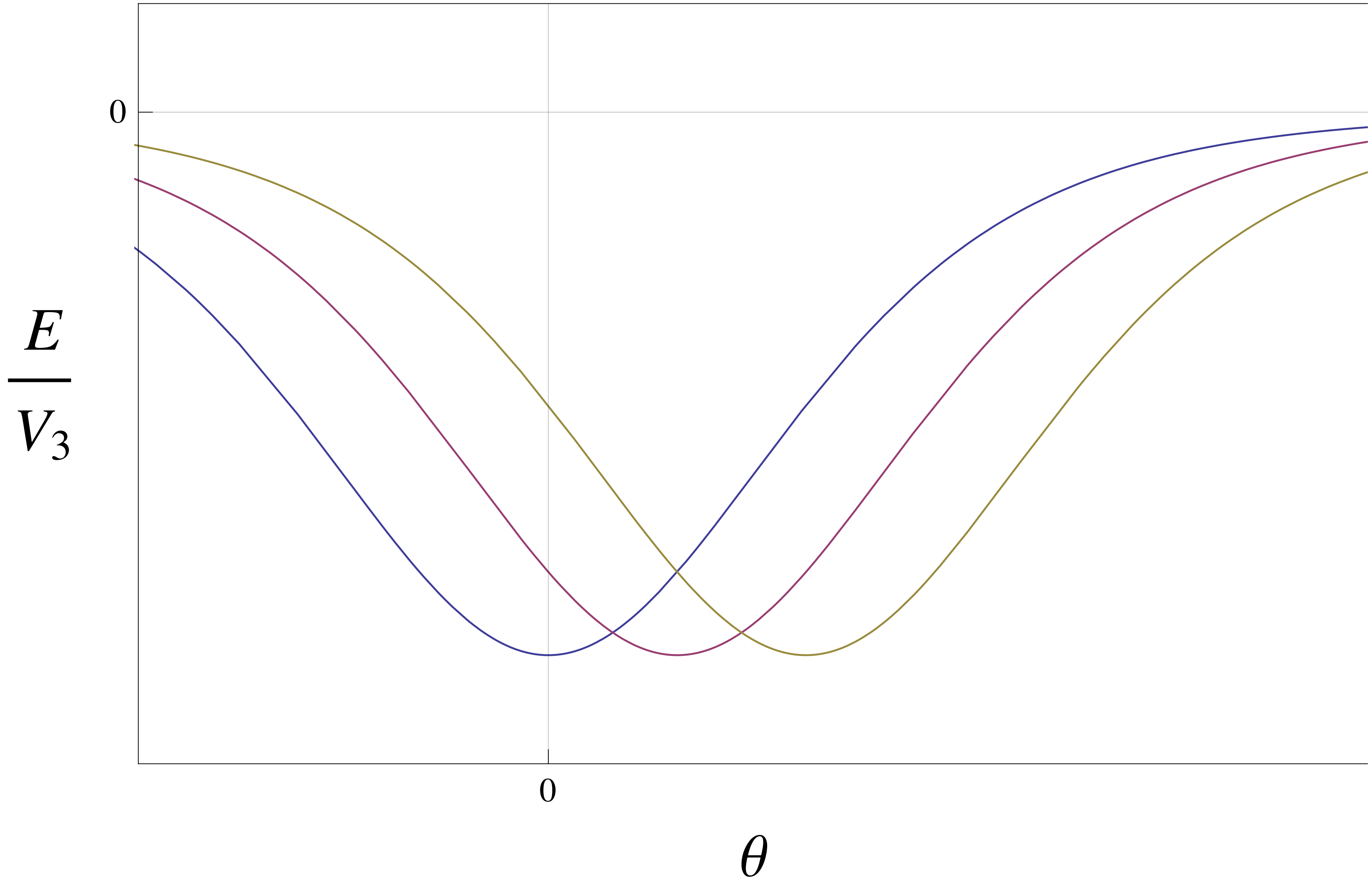
Witten; DLR

This always has lower energy

Energy dependence implies monodromy potential for θ

Think of θ as nondynamical axion $\theta = \phi/f_\phi$

Three Branches of Vacua



Large-x behavior

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

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

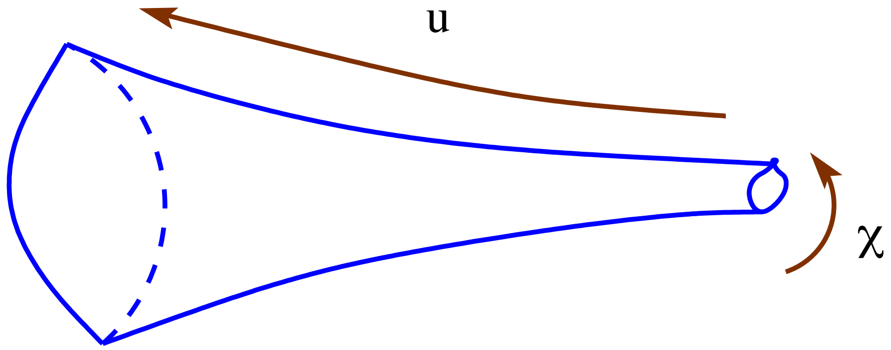
- $\frac{E}{V_3}\left(x = \frac{\lambda\theta}{4\pi^2 N}\right) = \frac{2\lambda N^2}{3^7\pi^2\beta^4}\left(1 - \frac{1}{(1+x^2)^3}\right) \rightarrow_{x\rightarrow\infty} \frac{2\lambda N^2}{3^7\pi^2\beta^4}\left(1 - \frac{1}{x^6}\right)$

  Potential flattens (response of E to θ depends on Λ_{QCD})

Viable model of inflation

Stability at large x

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



- Winding modes about χ 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.

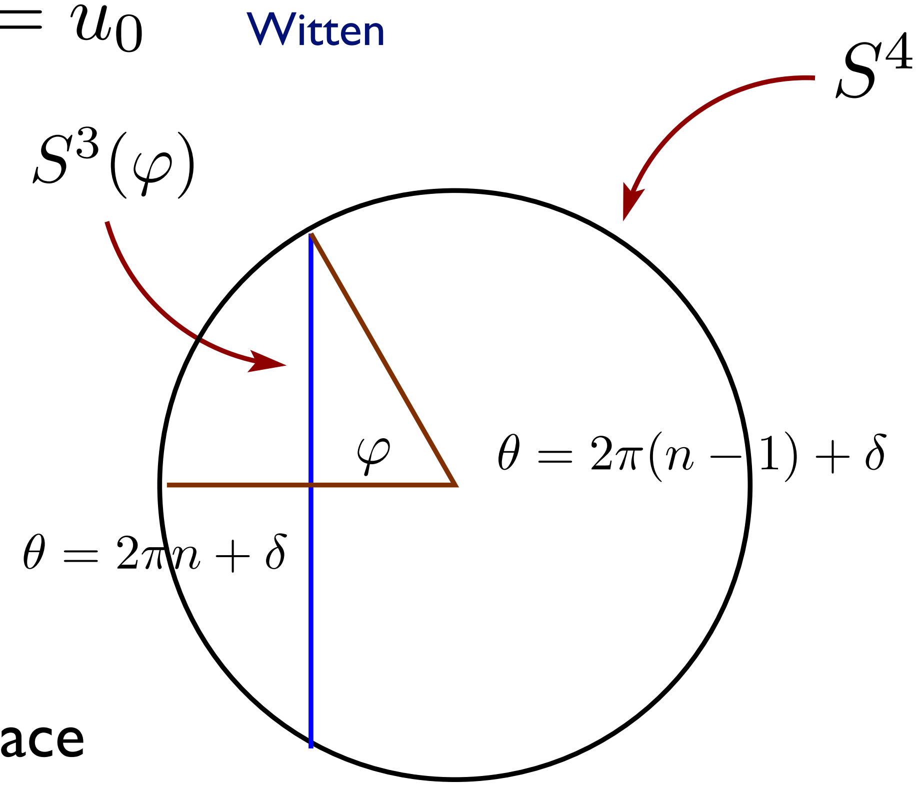
Two candidate domain wall solutions

- D6-brane wrapping S^4 sitting at $u = u_0$ Witten
- D6-brane wrapping $S^3(\varphi) \subset S^4$ filling R^4

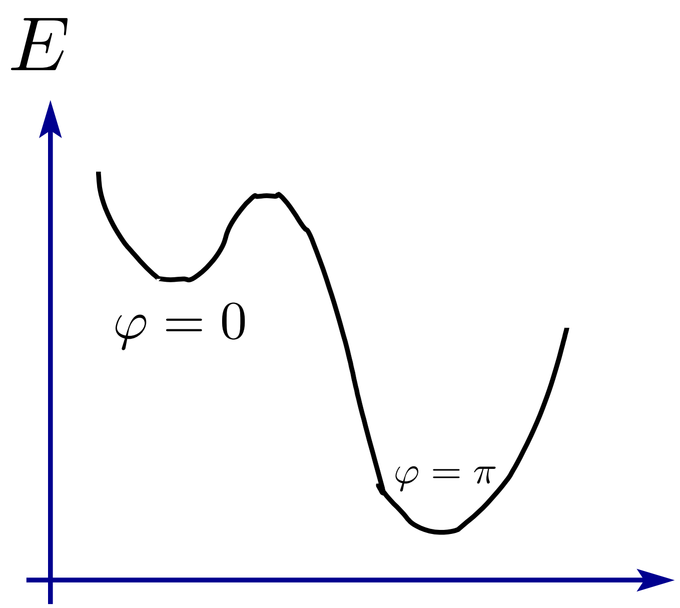
φ appears as QFT mode

analogous to Kachru, Pearson, Verlinde

Domain wall when φ 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 $x^{11} \gg \lambda^2 N$

III. 4d models of axion monodromy

Axion-four form model

Kaloper and Sorbo

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

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

φ periodic: $\varphi \longrightarrow \varphi + f_\varphi$

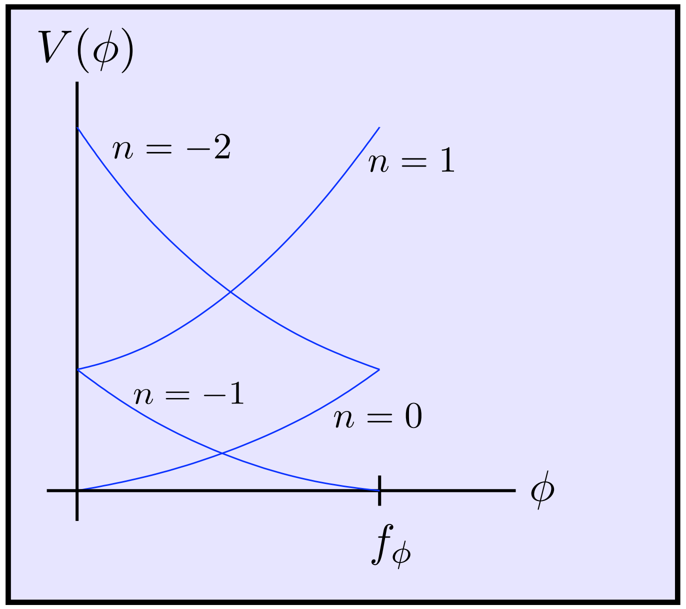
F does not propagate.
U(1) quantized

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

n can jump across domain walls/membranes

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

$$p_A = ne^2$$



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

+ observable GW

Does this survive quantum corrections?

Can we get quadratic inflation or does the potential flatten?

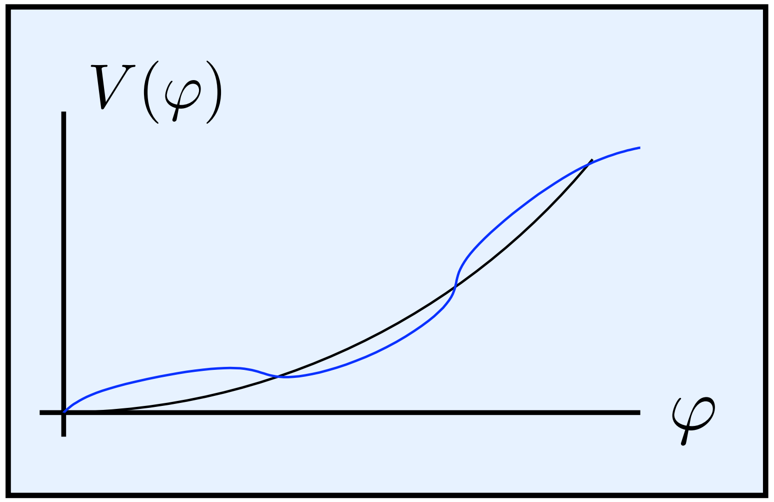
(1) Direct corrections to $V(\varphi)$

Periodicity of φ $\Rightarrow$ quantum corrections to S must be

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

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

Monodromy potential modulated by periodic effects



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

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

Example: feasible if $\Lambda \sim .1\ M_{gut},\ f > .01\ m_{pl}$

Caveat: moduli stabilization

In any string theory: couplings in V will depend on moduli ψ

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

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

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

$$M_\psi^2 \equiv V_0''(\psi) \gg \frac{\Lambda^4}{m_{pl}^2}$$

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

Stability requires $M_\psi^2 \gg \mu^2\varphi^2/m_{pl}^2 \sim \mu^2/\epsilon \sim H^2$

(2) Indirect corrections to $V(\varphi)$

Additional corrections must respect periodicity of φ

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

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

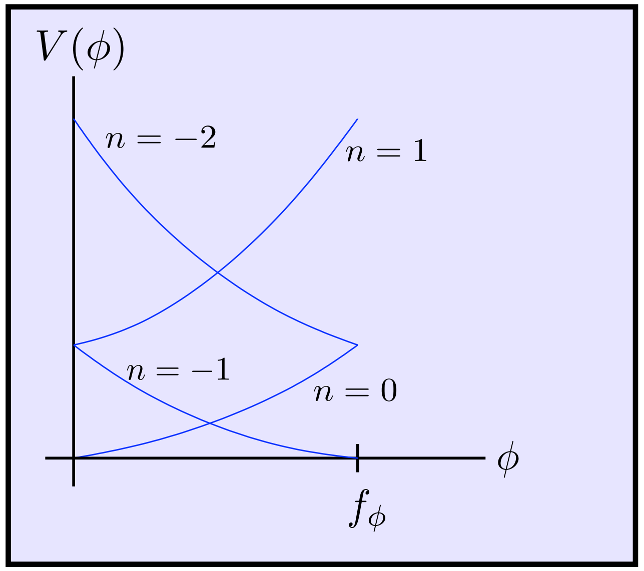
Consider $\delta\mathcal{L} = \sum_n d_n \frac{F^{2n}}{M^{4n-4}}$

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

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

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

Bounds on membrane tension from quantum stability



Transitions occur by bubble nucleation. Let:

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

Coleman

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

Rate should be slow compared to time scale of inflation

$\Longrightarrow$ Phenomenological bound on T

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

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

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

V. Conclusions

- PNGB-driven inflation in UV-complete theory must use monodromy mechanism

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

  Kaloper and AL, in progress

- General issue: monodromy inflation does not seem *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

  Dubovsky and Gorbenko