New and Simpler Monodromy Inflation

Gary Shiu

Based on: Marchesano, GS, Uranga, arXiv:1404.3040 [hep-th],
to appear in JHEP

BICEP2 and Inflation

If the BICEP2 results are confirmed to be primordial, natural interpretations:

- Inflation took place
- The energy scale of inflation is the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

- The inflaton field excursion was super-Planckian

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96

- Great news for string theory due to strong UV sensitivity!

See Silverstein's talk

The Lyth Bound

assumes single field, slow-roll, vacuum fluctuations, …

Particle production during inflation can be a source of GWs

$$\left[\partial_\tau^2 + k^2 - \frac{a''}{a}\right](a\,\delta g_{ij}) = S_{ij}$$

Cook and Sorbo '11

Senatore, Silverstein, Zaldarriaga '11

Barnaby, Moxon, Namba, Peloso, GS, Zhou, '12

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vector particle production due to axionic a F∧ F coupling

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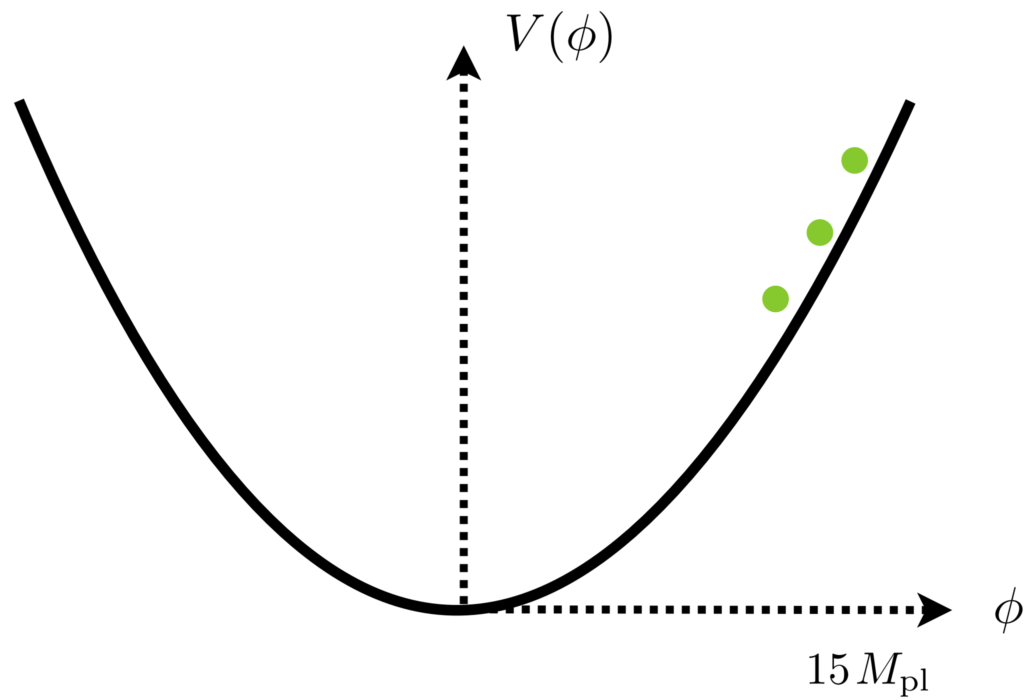
- Detectable tensors w/o too large non-Gaussianity
- Tensor spectrum is ***chiral*** *and* ***non-Gaussian.***
- ***Model building constraints:*** $f/M_P \geq 10^{-4}$ quite natural in string theory

Chaotic Inflation

Linde '86

- A poster child inflation model is $V = m^2\phi^2$:
  - Loop corrections involving inflaton and gravitons are small due to approximate shift symmetry

    $$\phi \mapsto \phi + \text{const.}$$



  - Coupling to UV degrees of freedom in quantum gravity a priori breaks this shift symmetry and lead to corrections that spoil inflation, because of the large field excursions

$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + \sum_{i=1}^{\infty} c_i\,\phi^{2i}\Lambda^{4-2i}$$

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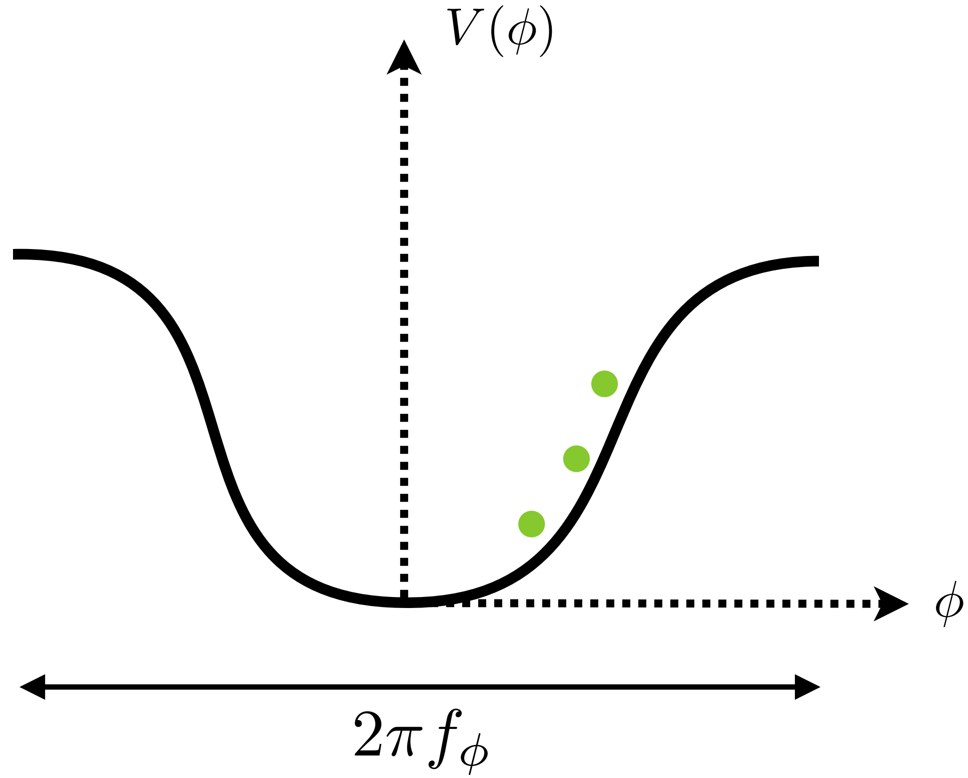
figure taken from Baumann & McAllister '14

Natural Inflation

Freese, Frieman, Olinto '90

- String models where the inflaton is an axion in principle can avoid this problem



  - Shift symmetry broken by non-perturbative effects+UV completion, but periodicity is exact
  - In string theory axions generically come from p-forms, so above the KK scale the shift symmetry becomes a gauge symmetry

$$\phi = \int_{\pi_p} C_p$$

$$F_{p+1} = dC_p$$
$$C_p \to C_p + d\Lambda_{p-1}$$

Dimopoulos et al.' 05

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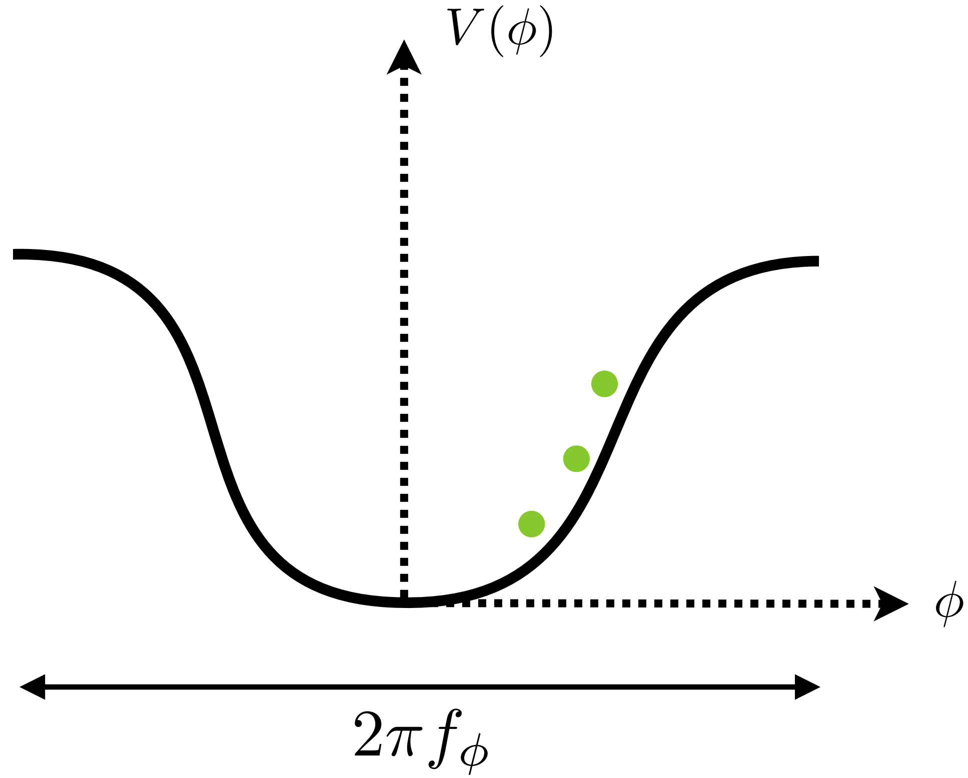
  - Shift symmetry broken by non-perturbative effects+UV completion, but periodicity is exact
  - In string theory axions generically come from p-forms, so above the KK scale the shift symmetry becomes a gauge symmetry
  - However, these axions have sub-Planckian decay constants



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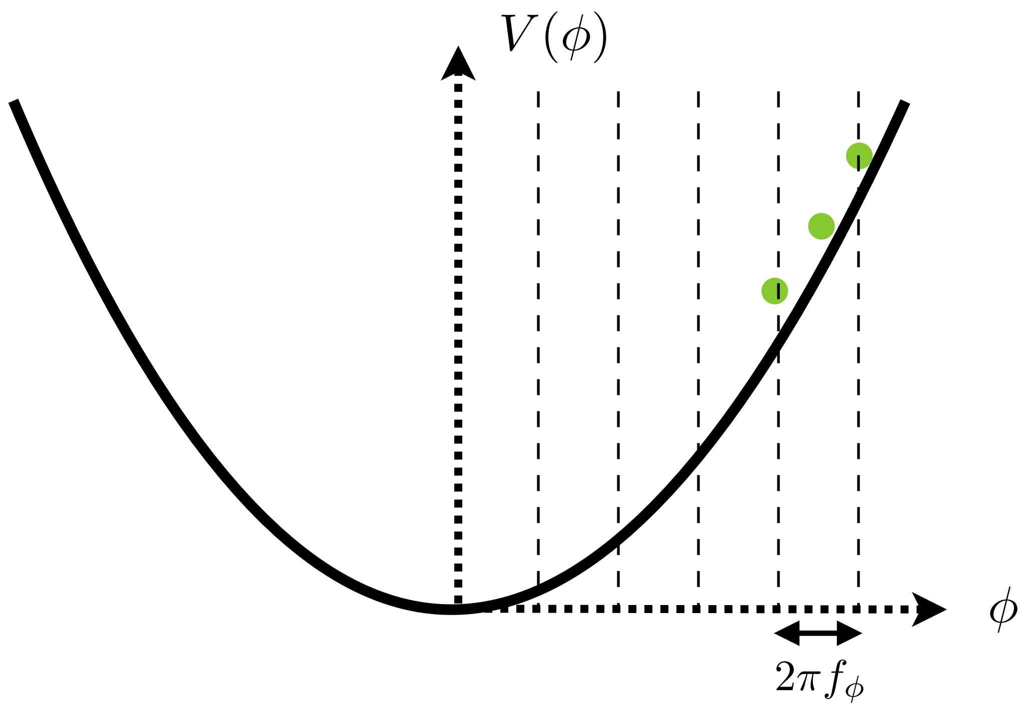
Banks et al. '03 *Svrcek & Witten '06*

Axion Monodromy Inflation

Siverstein & Westphal '08

Idea: Combine chaotic inflation and natural inflation



The axion periodicity is lifted, allowing for super-Planckian displacements. The UV corrections to the potential should still be constrained by the underlying symmetry.

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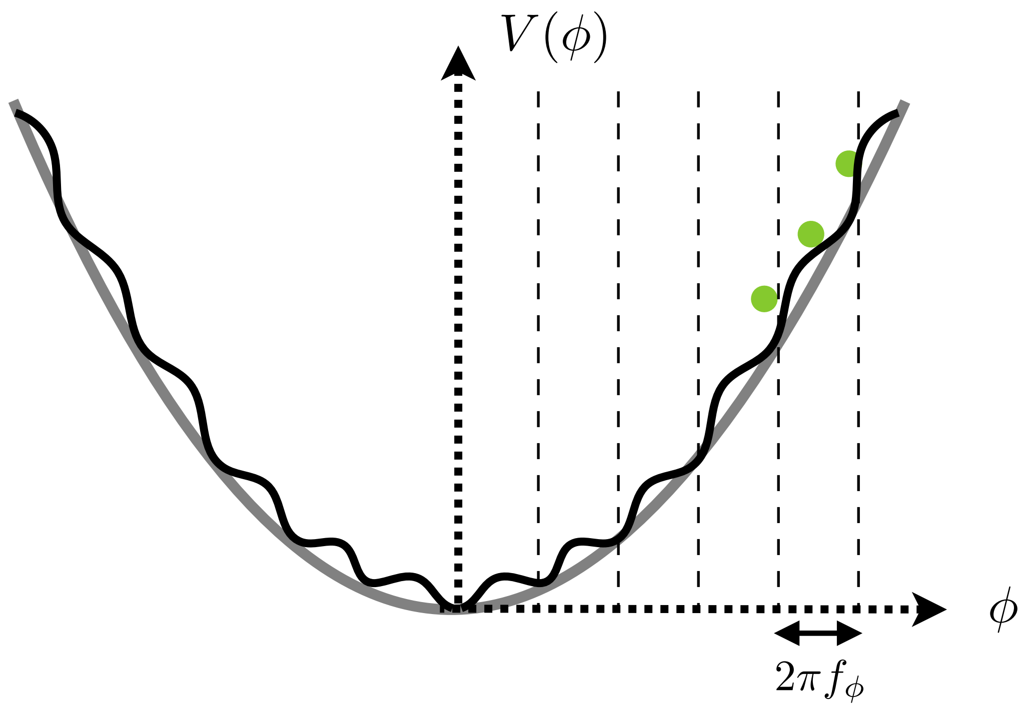

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Axion Monodromy Inflation

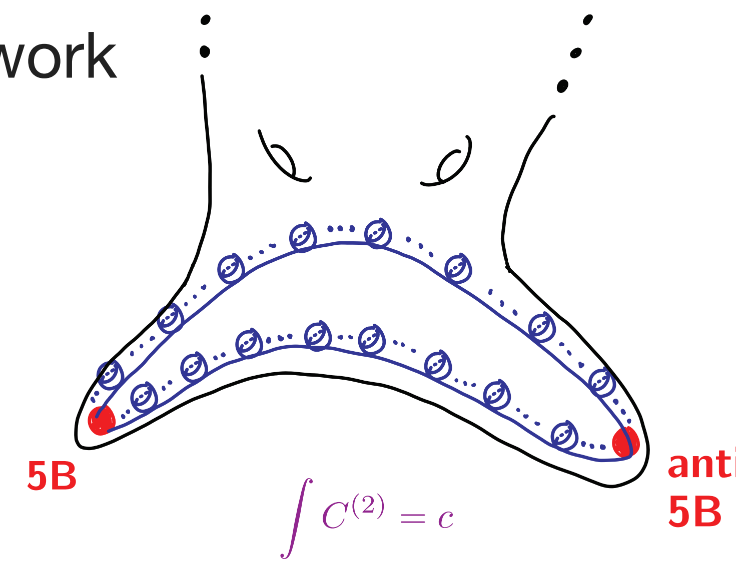
Siverstein & Westphal '08

Idea: **Combine chaotic inflation and natural inflation**

Early developments:

- ✦ McAllister, Silverstein, Westphal → String scenarios
- ✦ Kaloper, Lawrence, Sorbo → 4d framework

see Siverstein's talk



taken from McAllister, Silverstein, Westphal '08

F-term Axion Monodromy Inflation

Obs: Axion Monodromy ~ Giving a mass to an axion

- Done in string theory within the moduli stabilization program: adding ingredients like background fluxes generate superpotentials in the effective 4d theory

Idea: Use same techniques to generate an inflation potential

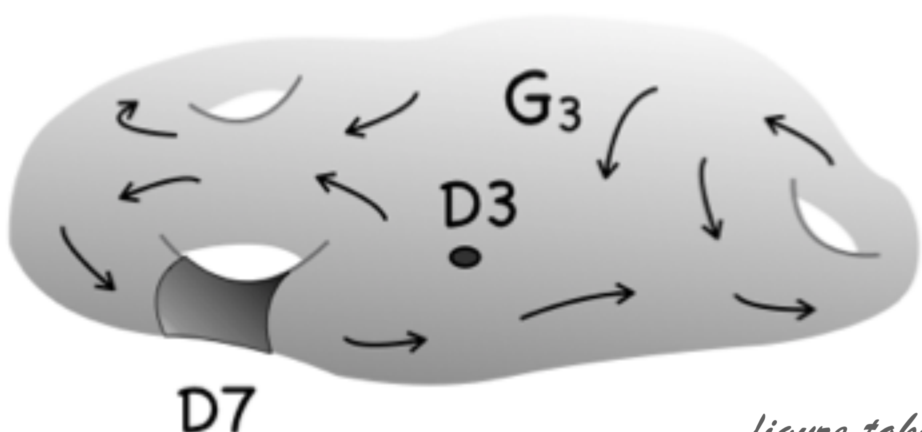


figure taken from Ibañez & Uranga '12

F-term Axion Monodromy Inflation

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✦ Done in string theory within the moduli stabilization program: adding ingredients like background fluxes generate superpotentials in the effective 4d theory

Idea: Use same techniques to generate an inflation potential

- Simpler models, all sectors understood at weak coupling
- Spontaneous SUSY breaking, no need for brane-anti-brane
- Clear endpoint of inflation, allows to address reheating

Toy Example: Massive Wilson line

- Simple example of axion: (4+d)-dimensional gauge field integrated over a circle in a compact space Π_d

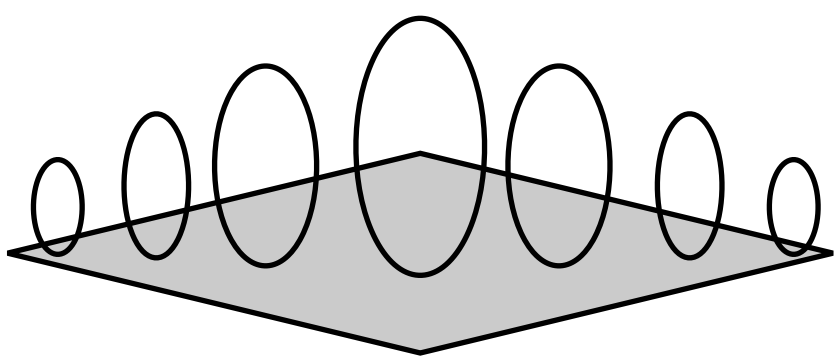
$$\phi = \int_{S^1} A_1 \qquad \text{or} \qquad A_1 = \phi(x)\,\eta_1(y)$$

  - ϕ massless if $\Delta\eta_1 = 0 \Rightarrow S^1$ is a non-trivial circle in Π_d

    exact periodicity and (pert.) shift symmetry

  - ϕ massive if $\Delta\eta_1 = -\mu^2\,\eta_1 \Rightarrow kS^1$ homologically trivial in Π_d

    (non-trivial fibration)



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$$F_2 = dA_1 = \phi\, d\eta_1 \sim \mu\phi\,\omega_2 \quad \Rightarrow$$ shifts in ϕ increase energy via the induced flux F_2

$\Rightarrow$ periodicity is broken and shift symmetry approximate

MWL and twisted tori

- Simple way to construct massive Wilson lines: consider compact extra dimensions Π_d with circles fibered over a base, like the twisted tori that appear in flux compactifications

- There are circles that are not contractible but do not correspond to any harmonic 1-form. Instead, they correspond to torsional elements in homology and cohomology groups

$$\mathrm{Tor}\, H_1(\Pi_d, \mathbb{Z}) = \mathrm{Tor}\, H^2(\Pi_d, \mathbb{Z}) = \mathbb{Z}_k$$

- Simplest example: twisted 3-torus $\tilde{\mathbb{T}}^3$

$$H_1(\tilde{\mathbb{T}}^3, \mathbb{Z}) = \mathbb{Z} \times \mathbb{Z} \times \mathbb{Z}_k$$

two normal 1-cycles

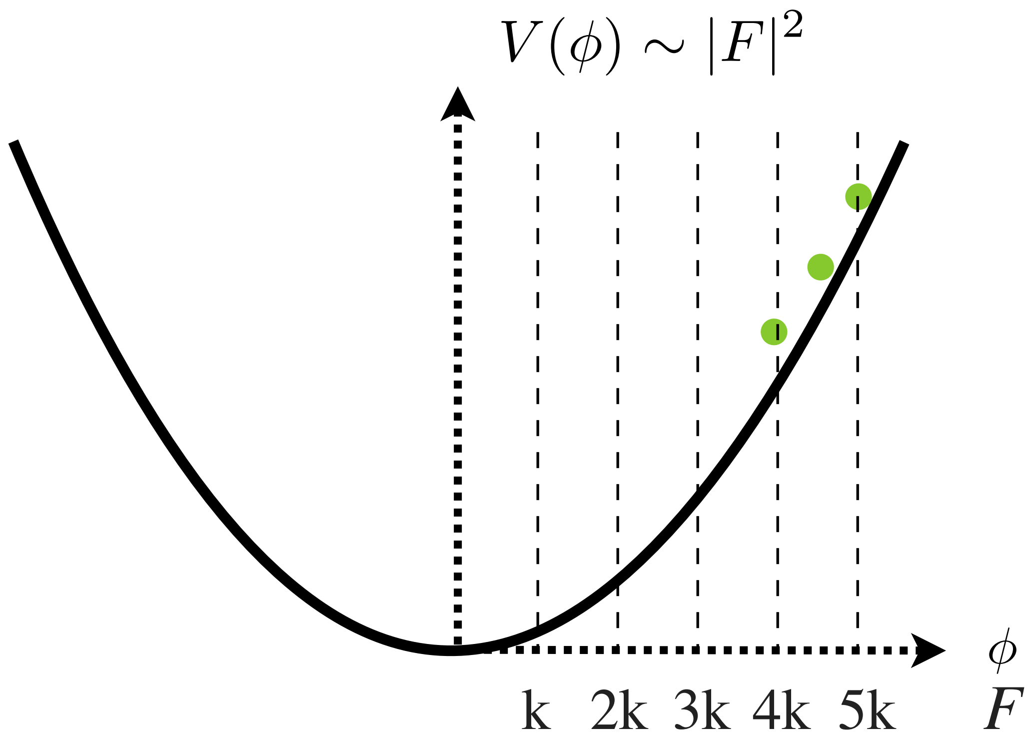
one torsional 1-cycle

$$d\eta_1 = k dx^2 \wedge dx^3 \longrightarrow F = \phi\, k\, dx^2 \wedge dx^3$$

$$\mu = \frac{kR_1}{R_2 R_3}$$

under a shift $\phi \to \phi + 1$
F_2 increases by k units

MWL and monodromy



Question: How does monodromy and approximate shift symmetry help prevent wild UV corrections?

Torsion and gauge invariance

- Twisted tori torsional invariants are not just a fancy way of detecting non-harmonic forms, but are related to a hidden gauge invariance of these axion-monodromy models

- Let us again consider a 7d gauge theory on $M^{1,3}$ x $\tilde{\mathbb{T}}^3$

  - Instead of A_1 we consider its magnetic dual V_4

$$V_4 = C_3 \wedge \eta_1 + b_2 \wedge \sigma_2 \xrightarrow{d\eta_1 = k\,\sigma_2} dV_4 = dC_3 \wedge \eta_1 + (db_2 - kC_3) \wedge \sigma_2$$

  - From dimensional reduction of the kinetic term:

$$\int d^7x \, |dV_4|^2 \longrightarrow \boxed{\int d^4x \, |dC_3|^2 + \frac{\mu^2}{k^2} |db_2 - kC_3|^2}$$

    - Gauge invariance $\quad C_3 \to C_3 + d\Lambda_2 \qquad b_2 \to b_2 + k\Lambda_2$
    - Generalization of the Stückelberg Lagrangian

Quevedo & Trugenberger '96

Effective 4d theory

- The effective 4d Lagrangian

$$\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

describes a massive axion, has been applied to QCD axion ⇒ generalized to arbitrary V(ϕ)

Kallosh et al. '95
Dvali, Jackiw, Pi '05
Dvali, Folkerts, Franca '13

- Reproduces the axion-four-form Lagrangian proposed by Kaloper and Sorbo as 4d model of axion-monodromy inflation with mild UV corrections

$$\int d^4x\, |F_4|^2 + |d\phi|^2 + \phi F_4 \qquad \begin{aligned} F_4 &= dC_3 \\ d\phi &= *_4 db_2 \end{aligned}$$

Kaloper & Sorbo '08

- It is related to an F-term generated mass term

Groh, Louis, Sommerfeld '12

Effective 4d theory

- Effective 4d Lagrangian

$$\boxed{\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2}$$

$$F_4 = dC_3$$
$$d\phi = *_4 db_2$$

- Gauge symmetry ⇒ UV corrections only depend on F_4

$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}\mu^2\phi^2 + \Lambda^4 \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}}$$

- Shift sym in ϕ
- Gauge sym in F_4

$$\mu^2\phi^2 \sum_n c_n \left(\frac{\mu^2\phi^2}{\Lambda^4}\right)^n$$

⇒ suppressed corrections up to the scale where $V(\phi) \sim \Lambda^4$

⇒ effective scale for corrections $\Lambda \to \Lambda_{\text{eff}} = \Lambda^2/\mu$

⇒ flattening effects are of this form; spectrum of r constrained.

Effective 4d theory

- Effective 4d Lagrangian

$$\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

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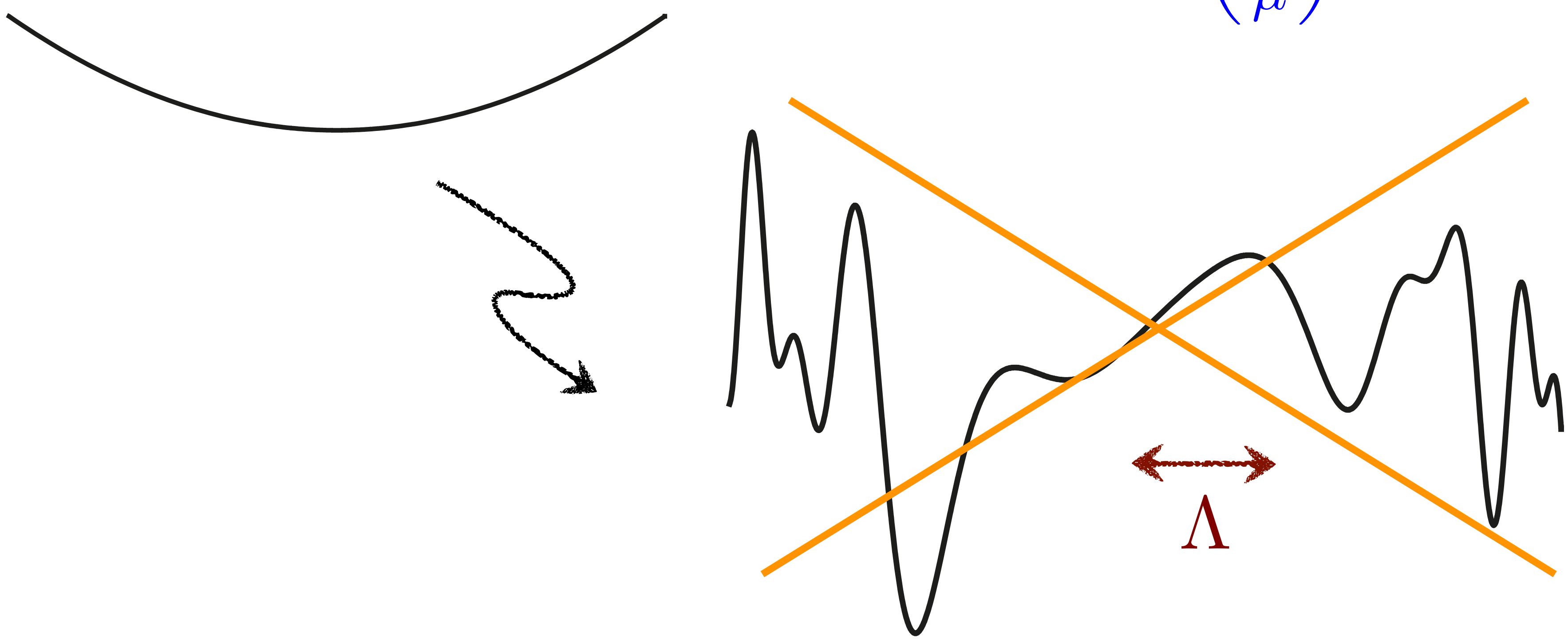
$$\Lambda \to \Lambda_{\text{eff}} = \Lambda\left(\frac{\Lambda}{\mu}\right)$$



Discrete symmetries and domain walls

- The integer k in the Lagrangian

$$\int d^4x\, |F_4|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

corresponds to a discrete symmetry of the theory broken spontaneously once a choice of four-form flux is made. This amounts to choose a branch of the scalar potential

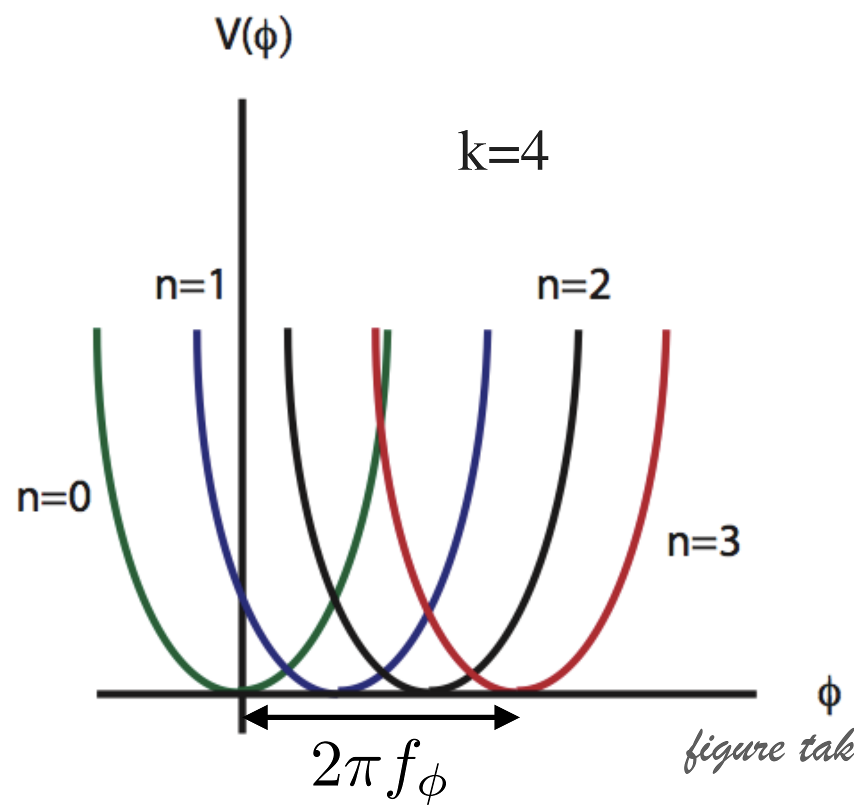


figure taken from Kaloper & Lawrence '14

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- Branch jumps are made via nucleation of domain walls that couple to C_3, and this puts a maximum to the inflaton range

- Domain walls analysed in string constructions:

Berasaluce-Gonzalez, Camara, Marchesano, Uranga '12

  - They correspond to discrete symmetries of the superpotential/ landscape of vacua, and appear whenever axions are stabilized
  - k domain walls decay in a cosmic string implementing $\phi \to \phi+1$

Other string examples

- We can integrate a bulk p-form potential C_p over a p-cycle to get an axion

$$F_{p+1} = dC_p, \quad C_p \to C_p + d\Lambda_{p-1} \qquad\qquad c = \int_{\pi_p} C_p$$

- If the p-cycle is torsional we will get the same effective action

$$\int d^{10}x |F_{9-p}|^2 \quad \longrightarrow \quad \int d^4x \, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

- The topological groups that detect this possibility are

$$\mathrm{Tor}\, H_p(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H^{p+1}(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H^{6-p}(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H_{5-p}(\mathbf{X}_6, \mathbb{Z})$$

one should make sure that the corresponding axion mass is well below the compactification scale (e.g., using warping)

Franco, Galloni, Retolaza, Uranga '14

Other string examples

- Axions also obtain a mass with background fluxes
- Simplest example: $\phi = C_0$ in the presence of NSNS flux H_3

$$W = \int_{\mathbf{X}_6} (F_3 - \tau H_3) \wedge \Omega \qquad \tau = C_0 + i/g_s$$

- We also recover the axion-four-form potential

$$\int_{M^{1,3} \times \mathbf{X}_6} C_0 H_3 \wedge F_7 = \int_{M^{1,3}} C_0 F_4 \qquad F_4 = \int_{\mathrm{PD}[H_3]} F_7$$

- M-theory version: *Beasley, Witten '02*
- A rich set of superpotentials obtained with type IIA fluxes

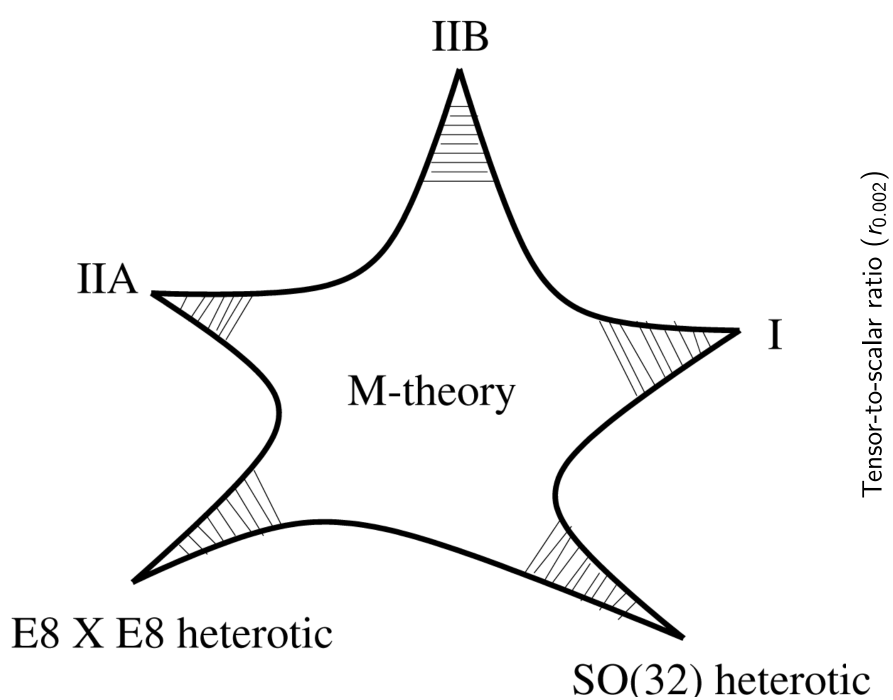
$$\int_{\mathbf{X}_6} e^{J_c} \wedge (F_0 + F_2 + F_4) \qquad J_c = J + iB$$

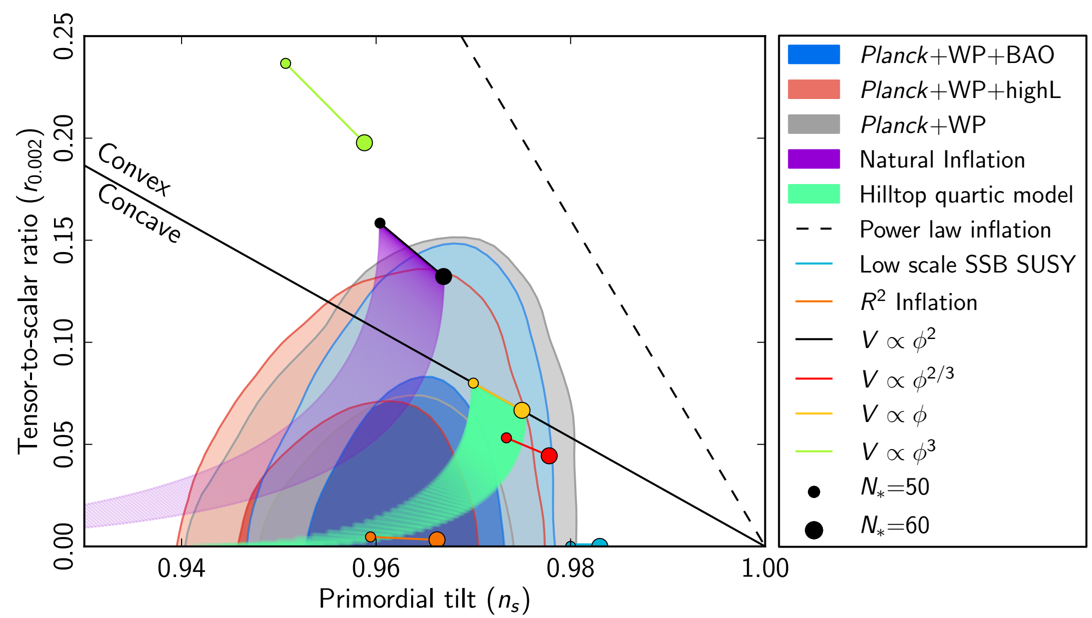
potentials higher than quadratic

- Massive axions detected by torsion groups in K-theory

Conclusions

- F-term axion monodromy inflation provides a ***new, concrete*** way of implementing monodromy into inflation, in a way compatible with spontaneous supersymmetry breaking.
- Hidden gauge invariance tames dangerous UV corrections. Discrete symmetries classified by K-theory torsion groups.
- A broad class of large field inflationary scenarios that can be implemented in any limit of string theory w/ rich pheno:





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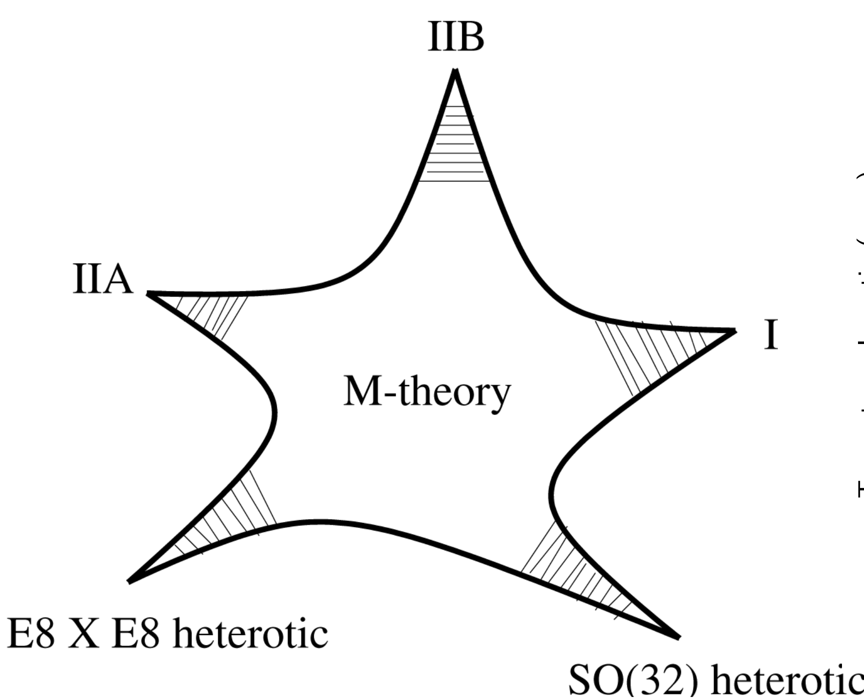

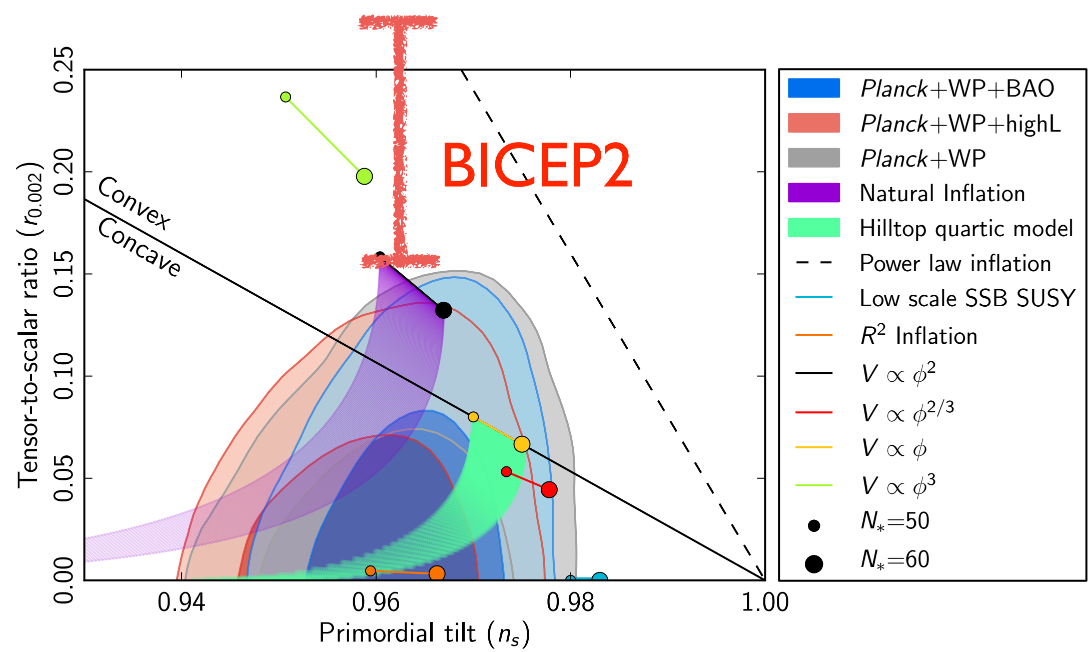

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