Title: Monodromy in the CMB: Gravity Waves and String Inflation

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Abstract: The sensitivity of inflationary models to Planck-suppressed operators motivates modeling inflation in string theory. The case of high-scale inflation is particularly interesting both theoretically and observationally. Observationally it yields a gravity wave (B mode polarization) signature, and theoretically it requires a large field excursion which is particularly sensitive to UV physics. I\'ll present a simple mechanism derived recently in collaboration with A. Westphal for obtaining large-field inflation, and hence a gravitational wave signature, from string theory. The simplest version of this mechanism, arising on twisted torus compactifications of string theory, yields an observationally distinctive version of chaotic inflation with a potential proportional to the 2/3 power of the inflaton, falsifiable on the basis of upcoming CMB measurements. This mechanism for extending the field range arises widely in string compactifications, though in all cases it requires sufficient symmetry to control the corrections to the slow-roll parameters. I will finish by describing further developments in this direction.

Monodromy in the CMB:

Gravity waves and String Inflation

with A. Westphal 0803.3085 [hep-th]

+ Works in progress with
  - Aharony; McAllister, AW
    (A. Westphal talk)
  - Green, Horn, Senatore

Inflation

Guth '81
Linde '82
AS '82

$$ds^2 = -dt^2 + a^2(t)\, d\vec{x}^{\,2} + \dots$$

$$H = \frac{\dot a}{a} = \text{const}$$

provides a solution to standard cosmological problems within effective field theory, diluting high-scale relics, but it is nonetheless UV-sensitive:

$$\varepsilon \equiv -\frac{\dot H}{H^2}\,, \quad \tilde\eta = \frac{\dot\varepsilon}{\varepsilon H}\,, \quad s = \frac{\dot c_s}{c_s H}$$

must be $\lesssim 10^{-2}$ to inflate, but get $\mathcal{O}(1)$ contributions from dimension 6 Planck-suppressed operators: In slow-roll inflation,

$$\eta = M_p^2 \frac{V''}{V} \sim 1 \quad \text{from} \quad V(\phi)\frac{(\phi-\phi_0)^2}{M_p^2}$$

$\Rightarrow$ Useful to formulate inflation in UV-complete theory of gravity

This UV-sensitivity is especially strong in any inflation model with observable tensor modes in the power spectrum:

Lyth: observable tensor modes $\Rightarrow \Delta\phi > M_p$ during inflation

Brief review of perturbations

$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

$$h_{ij} = a^2(t)\left[e^{2\zeta}\delta_{ij} + \gamma_{ij}\right]$$

$a^2(t) \sim e^{2Ht}$

scalar perturbation ($\delta\phi = 0$ gauge)

$\partial_i \gamma_{ij} = 0 = \gamma_{ii}$

tensor perturbations

Scalar perturbation :

e.g. Slow-roll inflation :

- Start in gauge $\delta\varphi \neq 0, \quad \zeta = 0$
- Action for $\delta\varphi$ is that of $\simeq$ massless field in dS
- solutions:

$$\left\{\begin{matrix} u(t) \\ u^*(t) \end{matrix}\right\} = \frac{H}{\sqrt{2k^3}}\left(1 \mp i\frac{k}{H}e^{-Ht}\right)e^{\pm i\frac{k}{H}e^{-Ht}}$$

$$\rightarrow \frac{H}{\sqrt{2k^3}} \quad \text{once} \quad \frac{k}{a} < H$$

$$\delta\varphi = a\,u(t) + a^{+}u^{*}(t)$$

- $\Rightarrow \quad \langle \delta\varphi_k \delta\varphi_{k'} \rangle \rightarrow (2\pi)^3 \delta^{(3)}(\vec{k}+\vec{k}')\dfrac{H^2}{2k^3}$
- similarly $\langle \gamma^{s}_{\vec{k}}\, \gamma^{s'}_{\vec{k}'} \rangle \rightarrow (2\pi)^3 \delta^{(3)}(\vec{k}+\vec{k}')\delta_{ss'}\dfrac{2H^2/M_p^2}{2k^3}$

...

- $\Rightarrow \quad \langle \delta\phi_k \delta\phi_{k'} \rangle \to (2\pi)^3 \delta^{(3)}(\vec{k}+\vec{k}') \dfrac{H^2}{2k^3}$

- similarly $\langle \gamma^s_{\vec{k}} \gamma^{s'}_{\vec{k}'} \rangle \to (2\pi)^3 \delta^{(3)}(\vec{k}+\vec{k}') \delta_{ss'} \dfrac{2H^2/M_p^2}{2k^3}$

In the case of the scalar, change to gauge
$\zeta \neq 0, \ \delta\phi = 0 \quad \left(h_{ij} = a^2(t)\left[e^{2\zeta} \delta_{ij} + \gamma_{ij} \right] \right)$

Bardeen et al, Mukhanov et al:
ζ constant outside horizon

$$\zeta = \frac{H}{\dot\phi}\delta\phi \Rightarrow \left\{ \begin{array}{l} P_\zeta = \dfrac{H^4}{12\pi^2 \dot\phi^2} \\ P_\gamma = \dfrac{2H^2}{\pi^2 M_p^2} \end{array} \right.$$

$$\boxed{r \equiv \frac{P_\gamma}{P_\zeta} = \frac{24\dot\phi^2}{H^2 M_p^2}}$$

★ Lyth '97: $r \leftrightarrow \frac{\Delta\phi}{M_{pl}}$:

$$N_e \simeq \int \frac{da}{a} = \int \frac{\dot{a}}{a}\,dt = \int H\,dt = \int \underbrace{\frac{H}{\dot{\phi}}}_{\text{vary slowly during inflation}} d\phi$$

$$\simeq \int \left(\frac{H M_p}{\sqrt{24}\,\dot{\phi}}\right)\left(\frac{d\phi}{M_p}\sqrt{24}\right)$$

$$\Rightarrow \quad N_e \simeq \sqrt{24}\,\frac{\Delta\phi}{M_p}\,\frac{1}{r^{\frac{1}{2}}}$$

$$\Rightarrow \quad \boxed{\frac{\Delta\phi}{M_p} \simeq r^{\frac{1}{2}}\,\frac{N_e}{\sqrt{24}}}$$

$\Rightarrow$ for observable $r \gtrsim 0.01$,

$\boxed{\Delta\phi \geq M_p}$ (also true in $c_s < 1$ case)

In slow-roll inflation, $V = 3M_p^2 H^2$

$$\ddot{\varphi}_0 + 3H\dot{\varphi}_0 + V'(\varphi_0) \equiv 0$$

$$\delta\ddot{\varphi}_k - \frac{\vec{k}^2}{a^2}\delta\varphi_k + 3H\delta\dot{\varphi}_k + \frac{1}{2}V''(\varphi_0)\delta\varphi \equiv 0$$

$$\varepsilon \equiv \frac{1}{2}M_p^2\left(\frac{V'}{V}\right)^2 \lesssim 10^{-2}, \quad \eta = M_p^2\frac{V''}{V} \lesssim 10^{-2}$$

$$\Rightarrow \boxed{r = \frac{24\dot{\varphi}^2}{H^2 M_p^2} = 24M_p^2\left(\frac{V'}{V}\right)^2 = 16\epsilon}$$

$\Rightarrow$ Must ensure $\epsilon \ll 1$, $\eta \ll 1$ over range $\Delta\varphi \gg M_p$ in any model with observable inflationary gravity waves.

UV Sensitivity of Inflation

① Terms of order

$$V \cdot \frac{(\varphi - \varphi_0)^2}{M_p^2} \quad (\text{dimension } 6)$$

in the effective action can ruin inflation

② $\frac{\Delta\varphi}{M_p} \simeq r^{\frac{1}{2}} \frac{N_e}{\sqrt{24}}$ (Lyth)

GUT-scale inflation (with observable tensor modes) $\Leftrightarrow$ $\Delta\varphi > M_p$

③ General Single-field inflation involves higher derivative terms which affect solution + perturbations

cf Non-Gaussianity Creminelli; DBI, ...

From a different point of view, large-field "chaotic" inflation

A. Linde '83 seems very simple.

cf symmetries

- We find a mechanism for large-field inflation using monodromy, and realize it in a specific model →

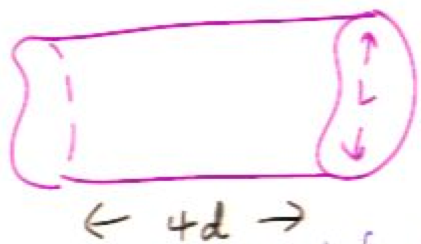
$$V(\phi)\Big|_{\phi \gg M_p} \simeq \mu^{\frac{10}{3}} \phi^{\frac{2}{3}}, \quad \Delta\phi \sim 9\,M_p, \quad n_s \simeq 0.98, \quad r \simeq 0.04$$

in a basic class of string compactifications

- Work in progress on other examples (e.g. Calabi-Yau models, with $V\big|_{\phi \gg M_p} \propto \phi$)

[other interesting recent approaches include N-flation Dimopoulos Kachru McGreevy Wacker, wrapped brane inflation Becker LeBlond Shandera ...]

Modeling inflation in string theory is a laborious process:



(D-4) dimensional compactification M_{D-4}

must first stabilize M_{D-4}:

many scalar field "moduli" with generically steep potential $U_{mod}(L, g, \dots)$ depending on discrete quantum #'s (BP, FMSW)

2001-2003 : moduli stabilized in corners

D>10 ES, MSS '01 '02 ; IIB GKP, '01 KKLT '03 DDF Conlon/Quevedo ... D3-D7

→ promising $\Delta\phi \ll M_p$ models KKLMMT, Racetrack, Roulette, Accidental

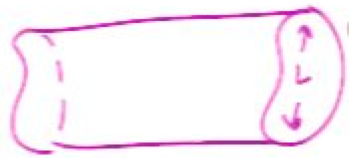
→ Novel mechanism(s) DBI ST, AST

→ observational opportunities cosmic strings CMP non-Gaussianity DBI

2005-2007 : · IIA on CY → AdS DGKT... KSS... HKTT...

· IIA on Nil manifold → dS ES '07

Bianchi II, ..., Scherk-Schwarz, Kaloper/Myers, ..

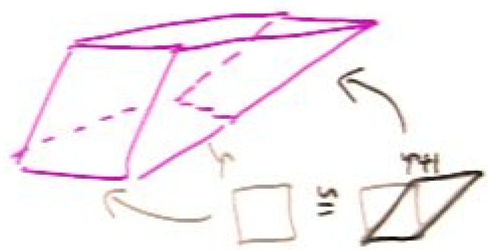


$(D-4)$ dimensional compactification X_{D-4}

The simplest compactification is a torus

(periodic boundary conditions)

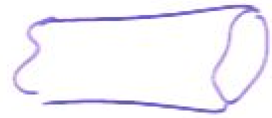
The next simplest* is a "twisted torus"



cf also

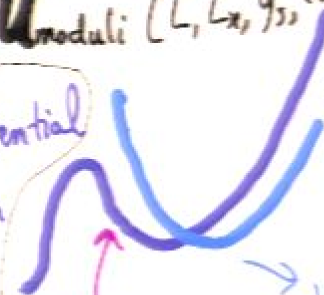
$K3 \times T^2/\mathbb{Z}_2$ Haack, Kallosh, Krause, Linde, Lust, Zagermann

Executive summary of IIA dS construction :



$$\left(ds^2 = L_u^2 \left(\frac{du_i^2}{\beta} + \beta\, du_i^2 \right) + L_x^2 \left(dx' + M\, u_1 du_2 \right)^2 \right)^2 \Big/ \sqrt{2}\, I_3$$

potential $\mathcal{U}_{moduli}(L, L_x, g_s, \ldots)$



positive potential barrier from negative scalar curvature + 5-branes & H-flux

positive contribution from fluxes e.g. $\int F_6 = K = \frac{(2\pi)^5}{\sqrt{2}} f_6$

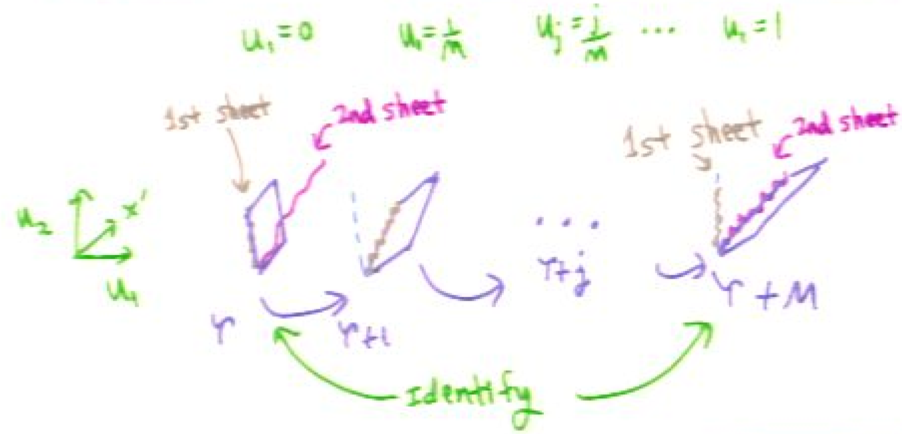
volumes (L, L_x), shape (β, angles)

negative middle term from O6 plane

- Simplest version : $\frac{M}{K} \sim 10^{-5}$, $f_6 \sim 100$, α' & loop corrections small (local 10d susy) subtlety : m_{KK}/m_{mod} not parametrically $\gg 1$
- Elaborate version : separate all scales parametrically with additional ingredients

Nil manifold (Twisted Torus):

$$ds^2 = L_u^2\left(\frac{du_1^2}{\beta} + \beta\, du_2^2\right) + L_x^2\left(dx' + M u_1 du_2\right)^2$$



D4 brane wrapped on u_2 direction:
scalar fields arise from transverse motion

- As move in u_1 direction away from $u_1=0$, the brane wraps a larger cycle $\Rightarrow$ heavier
- As move around u_1 circle, the D4 does not come back to itself : Monodromy

$\Rightarrow$ Scalar field range is unbounded geometrically (at fixed $M_p^2 \sim \mathrm{Vol}/g_s^2$)

Monodromy occurs frequently in string compactifications

e.g. • CYs Candelas et al, ...
(work in progress)

• fluxes, non-geometrical fluxes, monodrofolds

Schenk-Schwarz, Kaloper-Myers, Hellerman, McGreevy, Williams

Kachru et al, Hull et al, Lawrence-Schulz-Wecht, ...

⇒ The mechanism we study here may arise far more generally

cf Westphal talk: monodromy in axion directions in closed string moduli space in the presence of wrapped branes

This geometrically unbounded field range contrasts with the (special) case of D3-branes:

$$M_p^2 \sim \frac{L^6}{(2\pi)^7 \alpha' g_s^2}$$

$\frac{\Delta\varphi}{M_p}$ also bounded by L

yields bound $\frac{\Delta\varphi}{M_p} \ll 1$

Baumann / McAllister

Becker LeBlond Shandera, Kobayashi et al, Lidsey, Huston, Ward ...

Wrapped branes, or large numbers of branes, yield larger field range geometrically, but in previously studied cases they led to potentially destabilizing back reaction. → Check dynamics and back reaction in our case:

The D4 effective action is

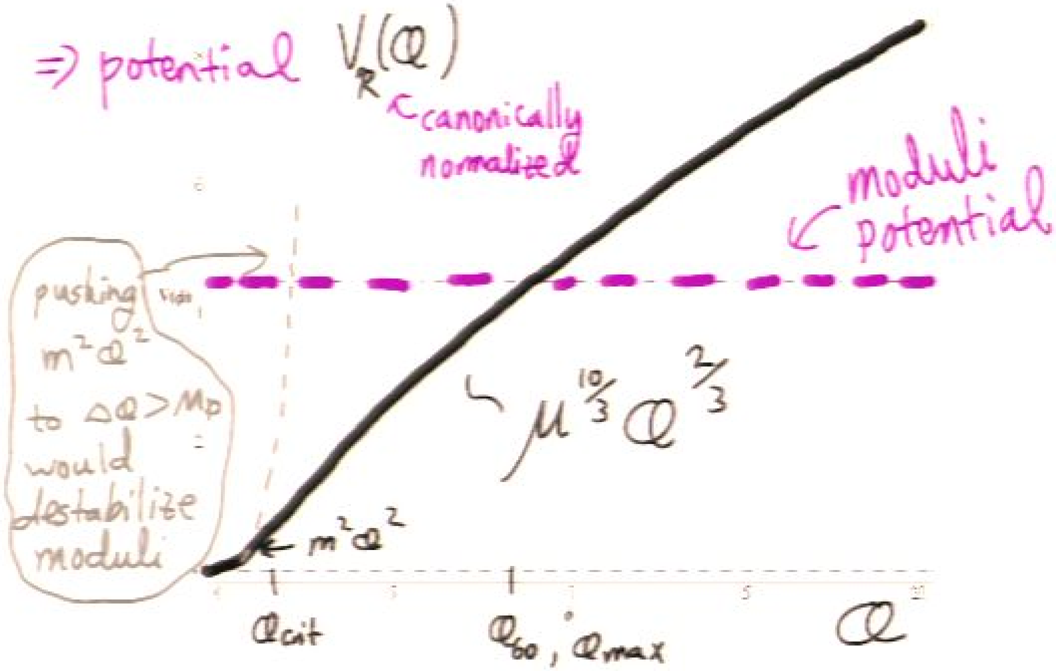
$$S_{D4} = -\frac{1}{(2\pi)^4 \alpha'^{5/2}} \int d^5\xi \, e^{-\Phi} \sqrt{\det \underbrace{G_{MN}^{(\varphi)}}_{} \partial_\alpha X^M \partial_\beta X^N} + S_{CS}$$

$$+ \alpha' \text{ h.d.} + \text{loops}$$

↖ compactification geometry + local sources

$$\underbrace{S_{D4,\varphi R}}_{\text{Nil geometry}} = \frac{1}{(2\pi)^4 \alpha'^2 g_s} \int d^4x \sqrt{-g} \left\{ \frac{L_u^2}{\beta} \left(\frac{\dot{u}_1^2}{2} \right) \sqrt{\beta L_u^2 + M^2 L_x^2 u_1^2} - \sqrt{\beta L_u^2 + M^2 L_x^2 u_1^2} + \dots \right\}$$

$\Rightarrow$ potential $V_R(\varphi)$ ← canonically normalized



Important crossover scales :

ϕ_* : eternal inflation

or

ϕ_{crit} $\quad$ $\phi_{60} = 9M_p$ $\quad$ ϕ_{max} $\quad$ ϕ

$m^2\phi^2$ $\quad$ $\mu^{\frac{10}{3}}\phi^{\frac{2}{3}}$

$V(\phi) > U_{mod}$ $\Rightarrow$ moduli destabilized for $\phi > \phi_{max}$

Computations $\rightarrow$

- For $\phi < \phi_{crit} \sim (2\pi)^{\frac{3}{2}} \frac{\beta^{\frac{1}{2}} \sqrt{g_s}\, L^{\frac{3}{4}}}{M L_2^{4/4}}$

$V_{\mathcal{R}}(\phi) \rightarrow \frac{1}{2}m^2\phi^2$ and $\boxed{\frac{1}{2}m^2\phi^2 \sim \left(\frac{\phi}{M_p}\right)^2 U_{mod,\mathcal{R}}}$

$\Rightarrow \frac{1}{2}m^2\phi^2$ <u>not</u> viable in this setup

(It would destabilize the moduli to push ϕ_{crit} to the $15M_p$ required for $m^2\phi^2$ chaotic inflation.) cf Kallosh Linde

The D4 effective action is

$$S_{D4} = -\frac{1}{(2\pi)^4 \alpha'^{5/2}} \int d^5\xi \, e^{-\Phi} \sqrt{\det \underbrace{G_{MN}(X)}_{} \partial_\alpha X^M \partial_\beta X^N} + S_{CS}$$

$$+ \alpha' \cdot \text{h.d.} + \text{loops}$$

← compactification geometry + local sources

$$\underbrace{S_{D4,\varphi_R}}_{\text{Nil geometry}} = \frac{1}{(2\pi)^4 \alpha'^2 g_s} \int d^4x \sqrt{-g} \left\{ \frac{L_u^2}{\beta} \left(\frac{\dot{u}_1^2}{2} \right) \sqrt{\beta L_u^2 + M^2 L_x^2 u_1^2} - \sqrt{\beta L_u^2 + M^2 L_x^2 u_1^2} + \dots \right\}$$

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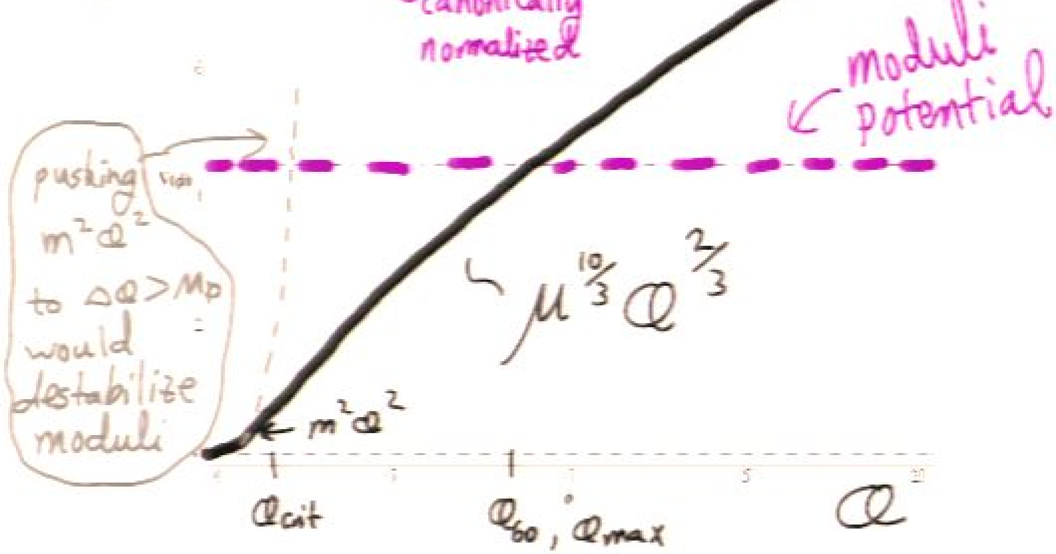
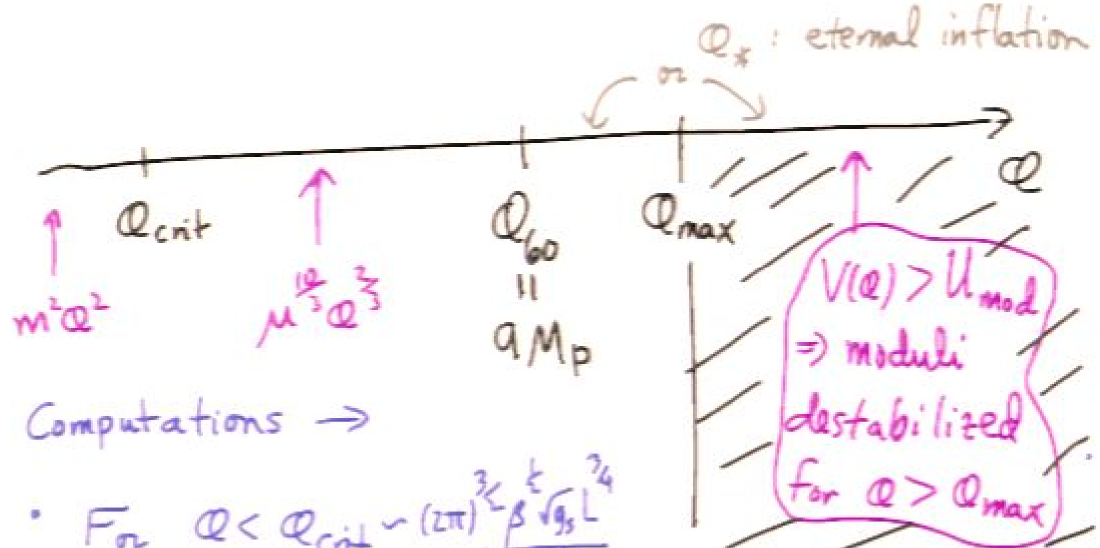


Important crossover scales :



Computations $\rightarrow$

- For $\phi < \phi_{crit} \sim (2\pi)^{\frac{3}{2}} \frac{\beta^{\frac{1}{2}} \sqrt{g_s}\, L^{\frac{7}{4}}}{M L_2^{9/4}}$

$V_{\mathcal{R}}(\phi) \rightarrow \frac{1}{2}m^2\phi^2$ and $\boxed{\frac{1}{2}m^2\phi^2 \sim \left(\frac{\phi}{M_p}\right)^2 U_{mod,\mathcal{R}}}$

$\Rightarrow \frac{1}{2}m^2\phi^2$ <u>not</u> viable in this setup

(It would destabilize the moduli to push ϕ_{crit} to the $15 M_p$ required for $m^2\phi^2$ chaotic inflation.) cf Kallosh Linde

... Computations →

- $$\boxed{V(\varphi) = \mu^{10/3}\,\varphi^{2/3}}$$ pertains

  for $\varphi_{crit} << \varphi << \varphi_{max}$

  $(2\pi)^{3/4}\,\tilde{\gamma}^{5/4-1/2}$ $\quad\quad \frac{\tilde{\gamma}^{5}}{(2\pi)^3}\cdot(\text{consts})$

  where $\tilde{\gamma} = \frac{1}{\beta^{1/2}}\left(\frac{K}{M}\right)^{1/4} >> 1$ in dS construction

- $N_e = 60 \Rightarrow \Delta\varphi = 9\,M_p \leq \varphi_{max}$

  $\Rightarrow \tilde{\gamma} \gtrsim 190$

- $\left(\frac{\delta\rho}{\rho}\right)^2 \sim P_s \sim 10^{-10} \sim (2\pi)^{3/2} N_e^{2/3}\ \frac{1}{\tilde{\gamma}^{1/3}}\ \frac{1}{K^{3/2}}\cdot\text{const}$

  $\Rightarrow K \lesssim 10^6 \leftrightarrow f_6 \leq 310 \Rightarrow \beta M^{1/2} \leq 0.04$

$\Rightarrow$ Altogether modest parameters
e.g. $\beta \sim 0.04$ $M \sim 1$, $f_6 \sim 300$, $\Delta u_1 \sim 20$
fits in simplest version of IIA dS

$\Rightarrow$ So far, good candidate for model realizing our monodromy mechanism

⇒ So far, good candidate for model realizing our monodromy mechanism

Now must check self-consistency

- back reaction

- effects of moduli-stabilizing ingredients on ε & η

cf KKLMMT

$\Delta\eta$ of order 1 or 0.1 would ruin inflation
$\Delta\eta$ of order 0.01 affects n_s prediction
$\widetilde{n_s}$ tilt

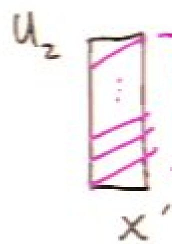
- generic α' & loop corrections

Back reaction:

$$ds^2 = L_u^2 \left(\frac{du_1^2}{\beta} + \beta\, du_2^2 \right) + L_x^2 \left(dx' + M u_1 du_2 \right)^2$$

$\Delta\phi = 9 M_p$ means $\Delta u_1 \sim 20\, M^{\frac{1}{2}}$

in our model $\Rightarrow$



D4-brane

~20 wrappings at $\phi \sim 9 M_p$

cf Becker et al ...

$\rightarrow$ Negligible back reaction, and negligible correction to G_N from multiple species cf N-flation

Moduli shifts and $V_R(\varphi)$:

Inflaton potential $V_R\left(\varphi\,;\, L e^{\frac{\sigma}{M_p}}, \ldots\right)$ ← canonically normalized

depends on moduli $\frac{\sigma}{M_p}$ as well as φ

$\Rightarrow$ φ-dependent shifts of

moduli : $\frac{\sigma}{M_p} \sim \frac{\partial_\sigma V_R}{\partial_\sigma^2 (U_{mod} + V_R)} \sim \frac{V_R}{U_{mod}}$

$\Rightarrow$ correction to φ-dependence of full scalar potential $U + V$

$$U_{tot} \sim U_{mod}(L) + V_R(\varphi, L) + c_{2a} \frac{V_R(\varphi, L)^2}{U_{mod}(L)}$$

$$\Rightarrow \boxed{\Delta\eta \sim \eta \frac{V_R}{U_{mod}} \le \mathcal{O}(\eta) \quad \checkmark}$$

Must control total $\varepsilon = \frac{1}{2} M_p^2 \left(\frac{V'}{V}\right)^2$ and

$\eta = M_p^2 \frac{V''}{V}$ over full range $\Delta\varphi = 9 M_p$

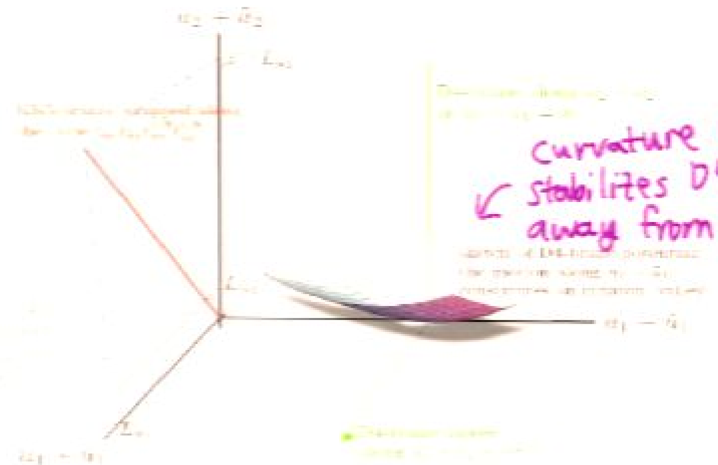
cf KKLMMT... Kachru McAllister Sundrum

$\Delta\eta \sim 1$ generic

This is somewhat easier than it sounds here, because of the monodromy ...

Since the D4-brane executes ≥ 20 circuits of the compactification during inflation, the methods for controlling ε & η may be similar in each sub-Planckian interval $\Delta u_1 = 1$

... and because of the symmetries and the extended nature of moduli-stabilizing ingredients in IIA dS construction:



curvature meta-stabilizes D4 away from O6

The KK5-branes and O6-plane involved in moduli stabilization are <u>extensive</u> along φ $\Rightarrow$

As in QFT formulation of chaotic inflation, symmetry prevents large corrections to $V(\varphi)$.

- $\alpha' \mathcal{R}$ & loop corrections
  $\rightarrow$ small corrections to ε & η

- Parametric limit (arbitrarily small corrections) would entail additional ingredients (e.g. NS5 branes) as in IIA dS construction.

- Standard Model & Reheating not yet explicitly included
  (Work in progress)

e.g. potential curvature corrections are small and of a simple form:

$$S_{D4} \to \frac{1}{(2\pi)^4 g_s'} \int d^5\xi \, e^{-\Phi} \sqrt{\det(G_{MN} + \alpha' c R_{MN}) \partial_\alpha X^M \partial_\beta X^N} \cdot \left(1 + \tilde{c}\alpha' R + \cdots\right)$$

(Putting all covariant possibilities in)

Now $R_{u_1u_1} = -\frac{L_x^2 M^2}{2L_u^2}$ $\quad R_{u_2u_2} = -\frac{L_x^2 M^2}{2L_u^4}\left(L_u^2 - L_x^2 M^2 u_1^2\right)$

and $R = \frac{L_x^2 M^2}{L_u^4} \longrightarrow \ll 1$

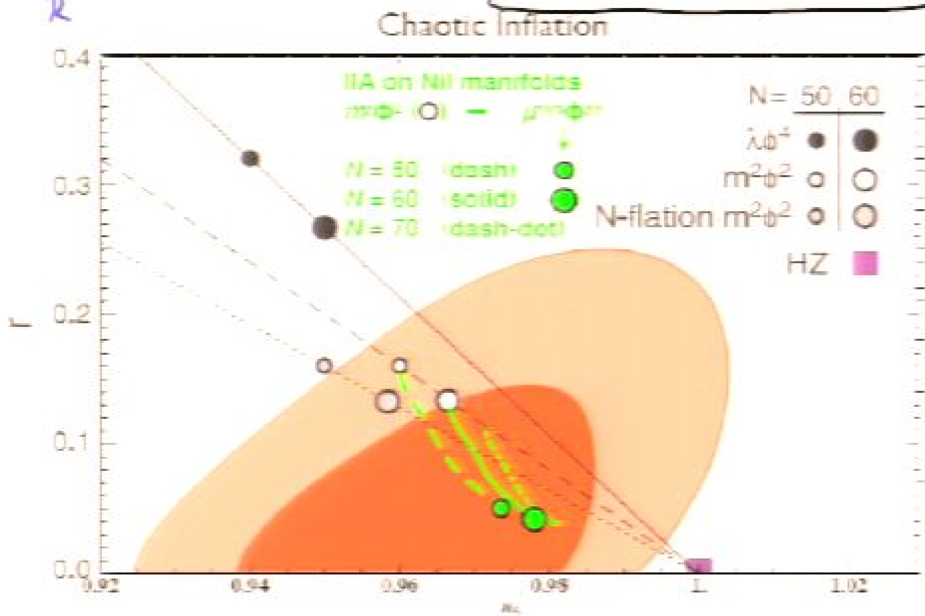
while $G_{u_1u_1} = L_u^2$, $G_{u_2u_2} = L_u^2 + L_x^2 M^2 u_1^2$

$\Rightarrow$ same shape $\mu^{10/3}\phi^{2/3}$, with small $\Delta\mu$ from these corrections...

→ This appears to provide a viable model realizing monodromy mechanism

⇒ Observational predictions

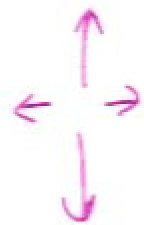
$V_R(\mathcal{C}) = \mu^{\frac{10}{3}} \mathcal{C}^{\frac{2}{3}} \Rightarrow \boxed{r \simeq 0.04,\ n_s \simeq 0.98}$



- For single-field version, $f_{NL}^{\text{squeezed}} \sim 0.01$, $f_{NL}^{\text{equilateral}} \simeq 0 \Rightarrow$ distinct from $c_s \ll 1$ case

<u>multifield</u> extension required for f_{NL}^{squeezed}

The tensor signal is detectable via CMB experiments sensitive to polarization:



gravity wave ⇒ locally anisotropic propagation of CMB photons. Scattering of CMB off e^-'s present during re-ionization & recombination

→ polarization

The observational situation is very healthy. ("instant" gratification...)

Bock et al ("Weiss report")

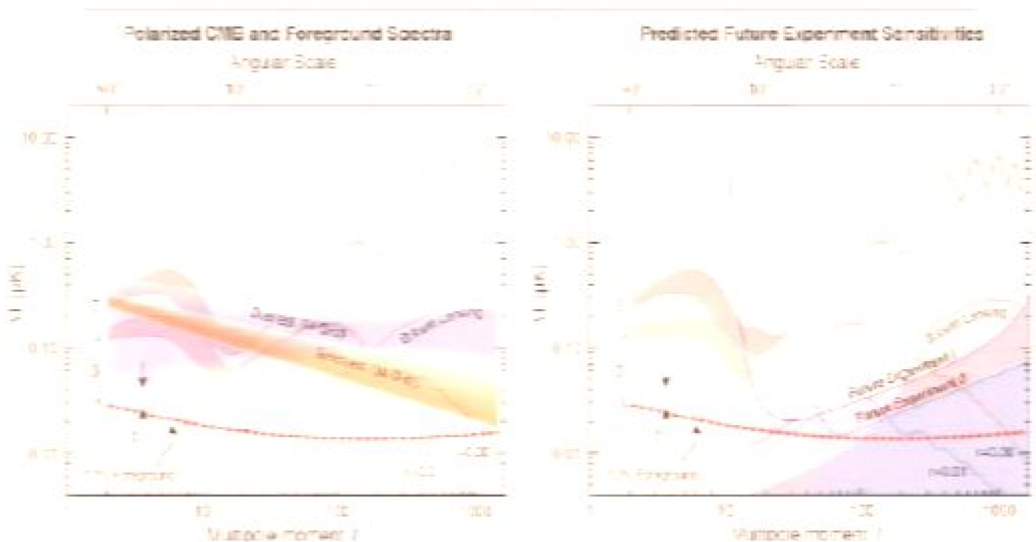


Figure 2.2: CMB Polarization Power Spectra, Backgrounds and Estimated Sensitivity of Future Experiments. Thin, wiggly curves in the two panels show the predictions for the angular power spectrum of the CMB polarization signal (E modes and B modes) in the standard cosmological model (as of 2005). The E signal is reasonably well predicted, but the B signal depends linearly on the gravitational wave amplitude, as measured by the tensor-to-scalar ratio, r. The B curves shown are for r=0.3 (red) and r=0.01 (blue). For l < 20, the thickness of the theory curves reflects the current degree of uncertainty about the epoch of reionization. The predicted B-mode signal due to the distortion of E modes by weak gravitational lensing is shown in green (see §3).

Left: Current estimates of the polarized Galactic foreground signals and their uncertainty due to synchrotron emission from cosmic ray electrons and thermal emission from interstellar dust grains, as described in §4. The red dashed curve is an estimate for the residual foreground contamination after modeling using multi frequency observations described in §4.

Right: Estimated instrumental sensitivities for a space mission of the type called for in our roadmap (grey shading) and two sample ground-based experiments (solid lines), based on the assumptions listed in §10.

- CLOVER, QUIET, BICEP/SPUD, SPIDER (ground)
  Polarbear, EBEX, BRAIN, ... → $\Delta r \sim 0.01$!
- CMBPOL? (satellite)

Observational Status:

Planck: $\Delta n_s \sim 0.01$

$\Delta f_{NL} \sim 5\text{-}10$

$\Delta r \sim 0.1$

Ground-based Polarization expts:

$\Delta r \sim 0.01$

$\Rightarrow$ Will distinguish wildly different mechanisms for inflation

- small field — cf KKLMMT, talks here
- large field — monodromy (N-flation)
- $c_s \ll 1$ — (DBI)
- multiple fld

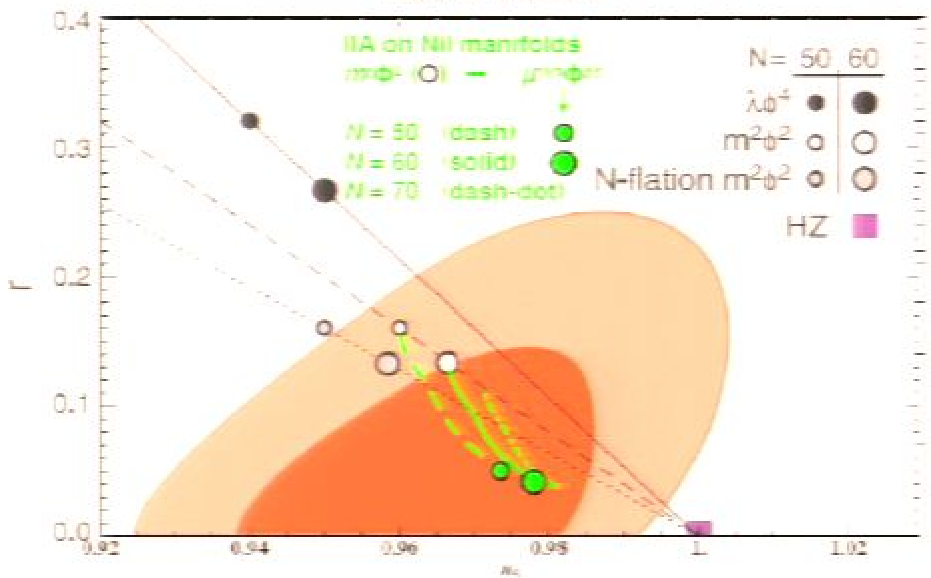
$$\boxed{\text{The combination of UV sensitivity \& observational accessibility strongly motivates research in this direction.}}$$

→ This appears to provide a viable model realizing monodromy mechanism

⇒ Observational predictions

$V_R(\varphi) = \mu^{\frac{10}{3}} \varphi^{\frac{2}{3}} \Rightarrow \boxed{r \simeq 0.04,\ n_s \simeq 0.98}$

Chaotic Inflation



• For single-field version, $f_{NL}^{\text{squeezed}} \sim 0.01$,

$f_{NL}^{\text{equilateral}} \simeq 0 \Rightarrow$ distinct from $c_s \ll 1$ case

<u>multifield</u> extension required for f_{NL}^{squeezed}

Bock et al ("Weiss report")

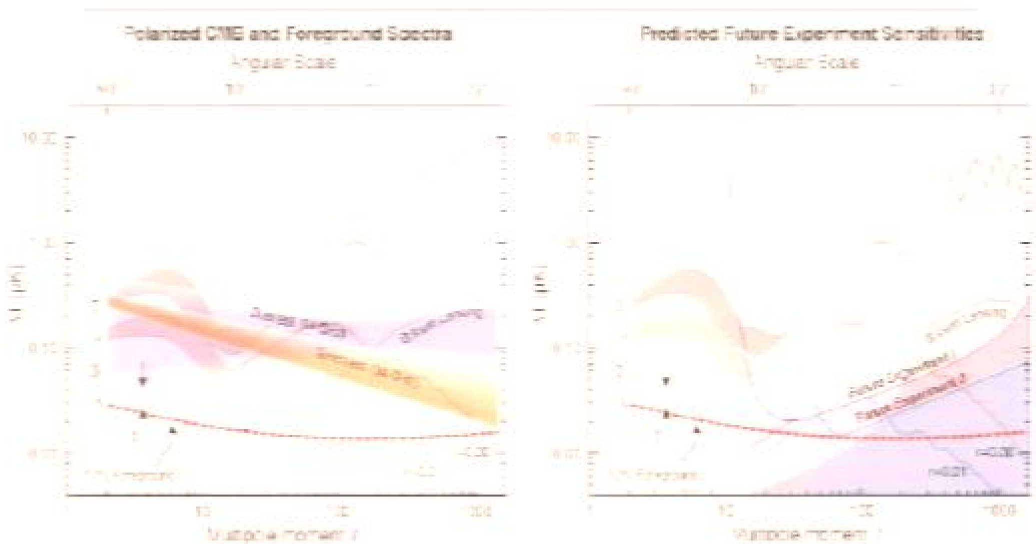


Figure 2.2: CMB Polarization Power Spectra, Backgrounds and Estimated Sensitivity of Future Experiments. Thin, wiggly curves in the two panels show the predictions for the angular power spectrum of the CMB polarization signal (E modes and B modes) in the standard cosmological model (as of 2005). The E signal is reasonably well predicted, but the B signal depends linearly on the gravitational wave amplitude, as measured by the tensor-to-scalar ratio, r. The B curves shown are for r=0.3 (red) and r=0.01 (blue). For l < 20, the thickness of the theory curves reflects the current degree of uncertainty about the epoch of reionization. The predicted B-mode signal due to the distortion of E modes by weak gravitational lensing is shown in green (see §3).

Left: Current estimates of the polarized Galactic foreground signals and their uncertainty, due to synchrotron emission from cosmic ray electrons and thermal emission from interstellar dust grains, as described in §4. The red dashed curve is an estimate for the residual foreground contamination after modeling using multi frequency observations described in §4.

Right: Estimated instrumental sensitivities for a space mission of the type called for in our roadmap (grey shading) and two sample ground-based experiments (solid lines), based on the assumptions listed in §10.

- CLOVER, QUIET, BICEP/SPUD, SPIDER (ground) Polarbear, EBEX, BRAIN, ... $\Delta r \sim 0.01$!
- CMBPOL? (satellite)

Observational Status:

Planck: $\Delta n_s \sim 0.01$

$\Delta f_{NL} \sim 5\text{-}10$

$\Delta r \sim 0.1$

Ground-based Polarization expts:

$\Delta r \sim 0.01$

$\Rightarrow$ Will distinguish wildly different mechanisms for inflation

- small field
- large field
- $c_s \ll 1$
- multiple fld

cf KKLMMT, talks here
monodromy
(N-flation)
(DBI)

The combination of UV sensitivity & observational accessibility strongly motivates research in this direction.

Monodromy in closed string moduli spaces

McAllister, ES, AW

- Monodromies were central in formal work on SUSY gauge theories and string compactification (e.g. Calabi-Yau's)

Consider e.g.

CY, ...

2-cycle Σ (size $L_2\sqrt{\alpha'}$) e.g. locally preserve $N=4$ SUSY

Axions from $B_2^{(NS)}$ & $C_2^{(RR)}$ on Σ_2:

wrapped D5: potential

$$V \sim \frac{1}{g_s}\sqrt{L_2^4+b^2}\left(\frac{1}{\alpha'^2}\right)$$

$\Rightarrow V \propto b$ large b

monodromy

Wrapped NS5: potential

$V \propto c$ large c

monodromy

Again we must require <u>dynamical</u> consistency with moduli stabilization

(here {Kallosh-Linde or GKP + KKLT or Saltman, ES $\otimes^3$} + 03/07 version of Grimm/Louis)

In the 2 cases: warp down Σ_2 & brane

wrapped D5: potential

$$V \sim \frac{1}{g_s}\sqrt{L_2^4 + b^2}\left(\frac{1}{\alpha'^2}\right)$$

$$\Rightarrow V \propto b \quad \text{large } b$$

monodromy

⊖ Generic η problem if fix moduli with KKLT non-perturbative effects:

$$e^{-T} \qquad T = \frac{L^4}{g_s} + b^2$$

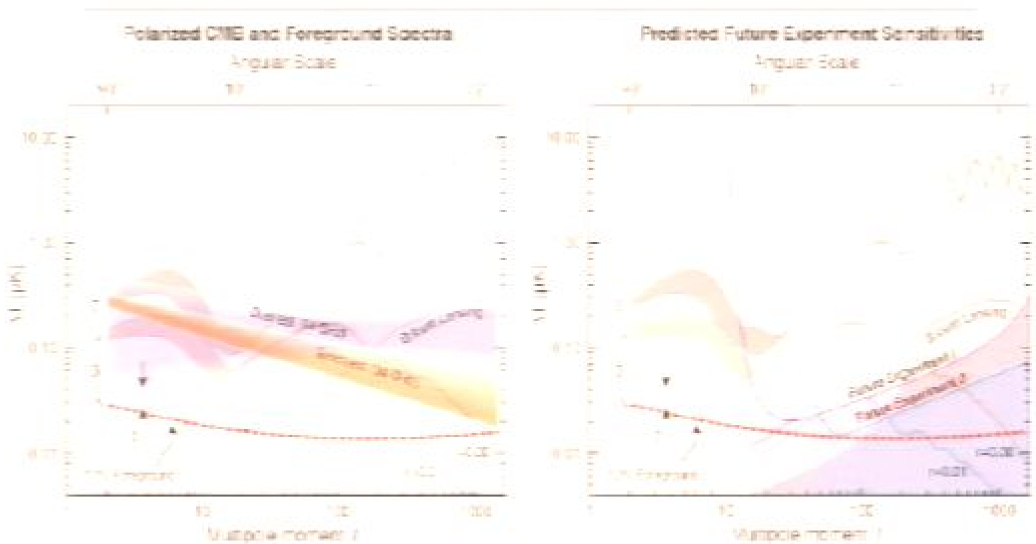
Wrapped NS5: potential

$$V \propto c \quad \text{large } c$$

monodromy

✓ Moduli-stabilizing effects, & D-instantons, give <u>suppressed</u> c_2 dependence cf Grimm

Bock et al ("Weiss report")



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  Polarbear, EBEX, BRAIN, ... } $\Delta r \sim 0.01$!
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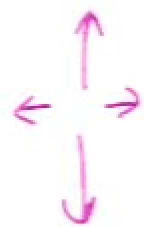
The tensor signal is detectable via CMB experiments sensitive to polarization:



gravity wave ⇒ locally anisotropic propagation of CMB photons. Scattering of CMB off e^-'s present during re-ionization & recombination

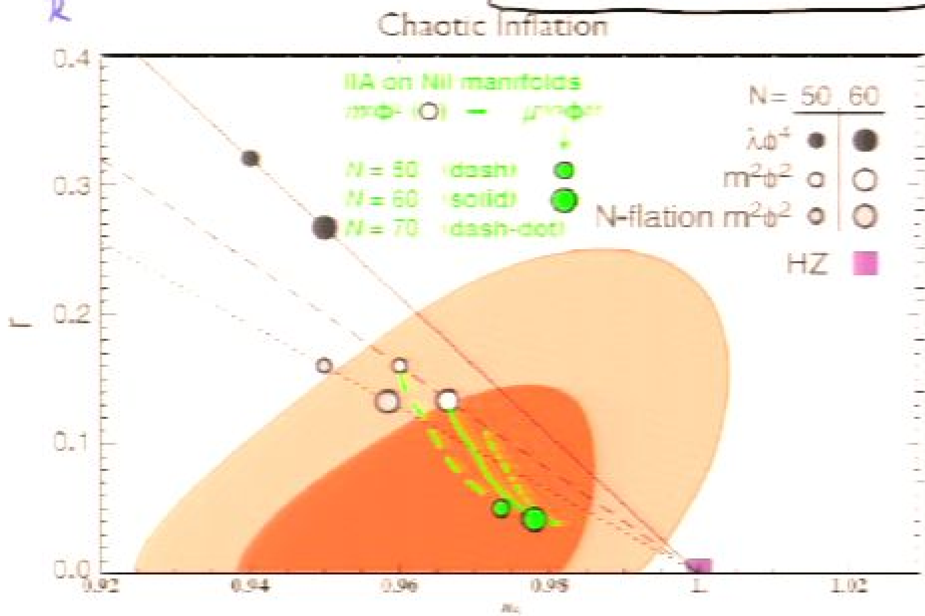
→ polarization

The observational situation is very healthy. ("instant" gratification...)

→ This appears to provide a viable model realizing monodromy mechanism

⇒ Observational predictions

$V_R(\varphi) = \mu^{\frac{10}{3}} \varphi^{\frac{2}{3}} \Rightarrow \boxed{r \simeq 0.04,\ n_s \simeq 0.98}$



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$$V \sim \frac{1}{g_s}\sqrt{L_2^4 + b^2}\left(\frac{1}{\alpha'^2}\right)$$

$\Rightarrow$ $V \propto b$ large b

monodromy

... problem

Wrapped NS5: potential

$V \propto c$ large c

monodromy

✓ Moduli-stabilizing

Reheating

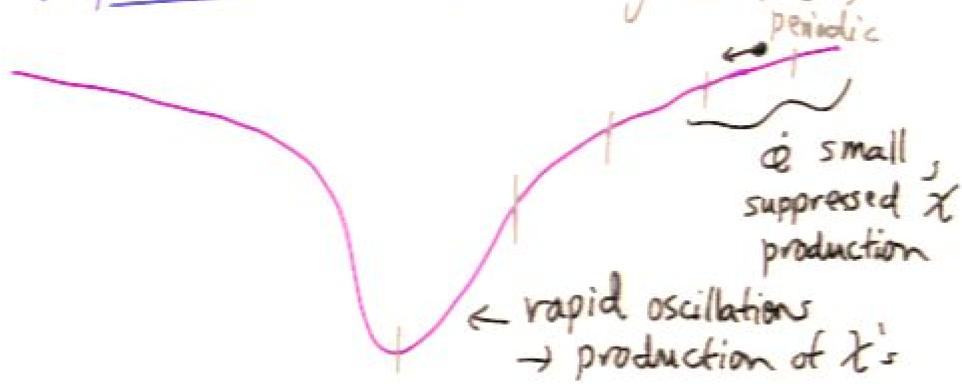
In ordinary chaotic inflation, the inflaton must couple to other degrees of freedom in order to reheat

Small couplings $g \leq 10^{-3}$ prevent destabilization of $V(\phi)$

$$g^2 \chi^2 \phi^2 \rightarrow \text{production of } \chi\text{'s}$$

KLS, ..

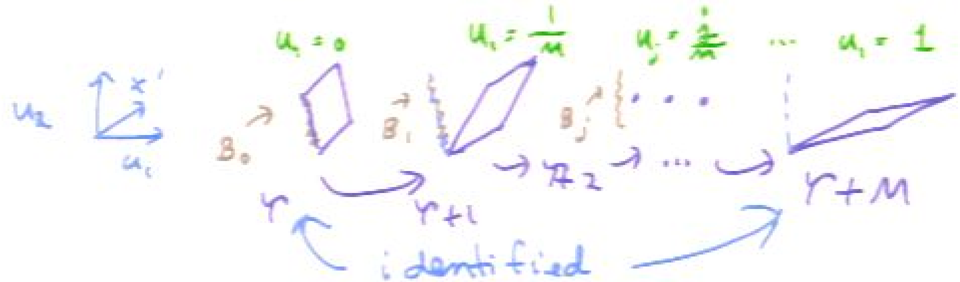
$\hookrightarrow$ periodic in our case: $g^2 \chi^2 f(\phi)$



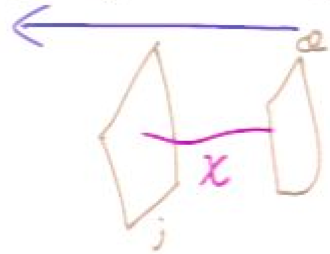
Trapped Inflation

cf Kofman Linde Starobinski; Tong ES
Kofman Linde Liu McAllister
Maloney E.S.

B. Horn, O. Green, T. Rube, L. Senatore, ES
(in progress)



There are stable positions for other D4-branes along the trajectory



$\Rightarrow g^2(\phi-\phi_j)^2\chi_j^2$ → produce χ's, slowing $\phi(t)$...

$\phi(t)$ = t-dependent χ mass

So far...

- Relatively simple class of compactification geometries $\rightarrow \begin{cases} \text{monodromy} \Rightarrow \text{large } \Delta\varphi \\ \text{homogeneity} \Rightarrow \text{easier to control } \Delta V \end{cases}$

Candidate e.g.'s $V(\varphi) \propto \varphi^{2/3} \rightarrow r = 0.04$
$n_s = 0.98$

in progress $\begin{cases} V(\varphi) \propto \varphi & \text{B, C monodromies} \\ V(\varphi) \propto \varphi^{\frac{2k}{k+2}} & \text{higher-dimensional } SO(d,d,\mathbb{Z}) \text{ monodromies} \end{cases}$

(Aharony)

→ distinctive signatures; falsifiable on the basis of the tensor signal

- Reasonably explicit small-field models also arise in string theory

cf other talks here

⇒ No general prediction about detectable r from string theory at the level of model building.

Initial conditions?

- small-field inflation requires landing on a tiny $\Delta\phi$, with somewhat smooth initial patch of size H^{-1}

Genericity?

- Both types of models use common ingredients
- More symmetry required for chaotic inflation?
  - But monodromy reduces this to a small-field problem
  - Tuneability of ε, η not automatic in small-field models (cf IIA CY no-go)