Natural inflation and moduli stabilization in heterotic orbifolds

Fabian Ruehle

Deutsches Elektronensynchrotron DESY
Hamburg

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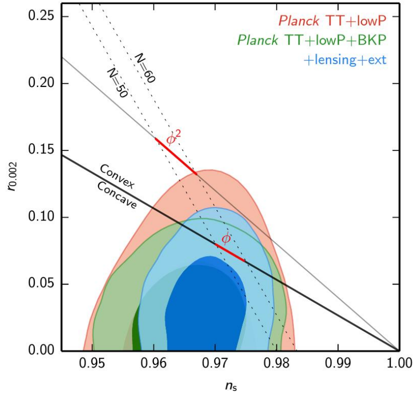
Based on [1503.07183] with Clemens Wieck

Motivation

Motivation - Large field models

Necessity of large field models

- Field range $\Delta\varphi \approx 20\sqrt{r} \quad \rightsquigarrow \quad r \gtrsim 0.002 \Rightarrow \Delta\varphi > M_{\rm Pl}$
- Joint Planck/BICEP analysis favors $r \approx 0.05$
  $\Rightarrow \Delta\varphi \approx 5 M_{\rm Pl}$ at 1.8σ, $H \sim M_{\rm GUT}^2 \sim 10^{-4} \ldots 10^{-5}$



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Challenges for trans-Planckian inflation

- Inflaton candidates (moduli) live in compact space
  $\Rightarrow$ field range bounded and sub-Planckian
- Need to worry about corrections to the inflaton potential
  $\Rightarrow$ Axionic shift symmetry can protect you (currently under discussion [Rudelius;Montero,Uranga,Valenzuela;Brown,Cottrell,Shiu,Soler] and [Bachlechner,Long,McAllister;Hebecker,Mangat,Rompineve,Witkowski])
- Need moduli stabilization at high scale ($\gtrsim H$)
  - to work in single field inflation
  - to avoid Polonyi problem/not spoil BBN

Outline

1. Introduction
   - Large field inflation and aligned inflation
   - Heterotic orbifolds
2. Inflation and moduli stabilization in heterotic orbifolds
   - Modular symmetries
   - Gaugino condensation and WS instantons
   - Moduli stabilization and alignment
3. Examples
   - Moduli stabilization and inflation with WS instantons only
   - Moduli stabilization and inflation with WS instantons and GC
4. Conclusion

Introduction

Large field inflation in string theory

Axion monodromy inflation

- Initially proposed by [Silverstein,Westphal,McAllister]
- Mechanism:
  - Start with **periodic inflaton**
  - Scalar potential **slightly breaks periodicity**
- Many string theoretic realizations [Palti,Weigand; Marchesano,Shiu, Uranga; Blumenhagen,Plauschinn; Hebecker,Kraus,Witkowski; . . .]

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Aligned axion inflation

- Initially proposed by [Kim,Nilles,Peloso]
- Mechanism:
  - Two **axions** with **almost aligned** axion decay constant
  - **Slight misalignment** gives almost-flat direction with effective trans-Planckian decay constant
- Many string theoretic realizations [Kappl,Krippendorf,Nilles;Long, McAllister,McGuirk;Ali,Haque,Jejjala;Tye,Wong;Ben-Dayan,Pedro,Westphal;. . .]

Recap: KNP mechanism

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Aligned axion inflation – Realization

- $W \supset Ae^{-(\beta_1 T_1 + \beta_2 T_2)} + Be^{-(n_1 T_1 + n_2 T_2)}$
  $V = \kappa_1 \left[1 - \cos(\beta_1 \tau_1 + \beta_2 \tau_2)\right] + \kappa_2 \left[1 - \cos(n_1 \tau_1 + n_2 \tau_2)\right]$

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- Perfect alignment (flat direction) if $\frac{\beta_1}{\beta_2} = \frac{n_1}{n_2}$

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- Slight misalignment $k := \frac{1}{n_2} - \frac{\beta_1}{\beta_2}\frac{1}{n_1}$ (need $k \approx 0.1 .. 0.2$)
- Effective one-axion model with decay constant

$$f_{\text{eff}} \approx \frac{\beta_1^2 \sqrt{(\beta_1^{-2} + \beta_2^{-2})(\beta_1^{-2} + n_1^{-2})}}{k n_1 \beta_2}$$

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   $\Rightarrow$ Both **effects related**:
   - Both governed by **modular forms** (Dedekind eta function)
   - Near alignment from **fixed modular weights** of Kähler and superpotential

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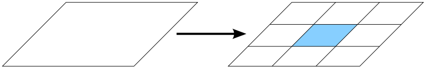

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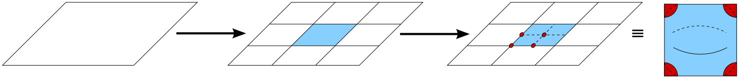

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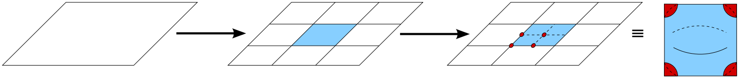

[Dixon,Harvey,Vafa,Witten]

Orbifold data

- $\theta : (z_1, z_2, z_3) \mapsto (e^{2\pi i v_1} z_1, e^{2\pi i v_2} z_2, e^{2\pi i v_3} z_3)$

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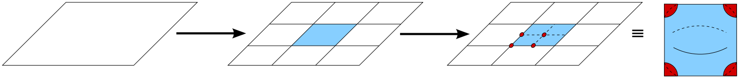

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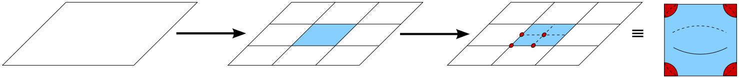

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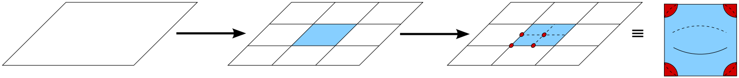

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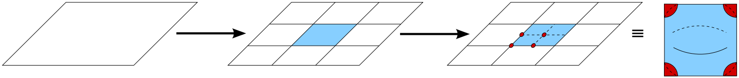

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Advantages of orbifolds

- **Exact CFT** description $\Rightarrow$ **Calculability**
- Known to yield **good** particle **pheno**
  [Blaszczyk,Buchmüller,Hamaguchi,Kim,Kyae,Lebedev,Nilles,Raby,
  Ramos-Sanchez,Ratz,FR,Trapletti,Vaudrevange,...]

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Modular symmetry

Modular transformation

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Dedekind η-function

- $\eta(T) = e^{-\frac{\pi T}{12}} \prod_{r=1}^{\infty} \left(1 - e^{-2\pi r T}\right) \approx e^{-\frac{\pi T}{12}}$ for big T
- $\eta(T) \to (icT + d)^{\frac{1}{2}}\ \eta(T)$ (up to phase)

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CFT selection rules

- Strings have to close on WS:
  $(\theta^{k_1}; a^1_i e_i; V_{k_1}, v_{k_1}) \times \dots \times (\theta^{k_L}; a^L_i e_i; V_{k_L}, v_{k_L}) \equiv (\mathbb{1}; 0; 0, 0)$

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  - Only $\mathcal{N} = 2$ subsectors contribute
  - Only T_i that belong to torus without fixed points; just fixed planes enter
  - For these, $c_i = N_i/N$ where N is orbifold order and N_i is the twist order that leaves i^{th} torus invariant
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Superpotential from gaugino condensation

- $W \supset B\ e^{\frac{-24\pi^2}{\beta} f(S,T)}$

$$= B(\Phi_\alpha)\ \exp\left(\frac{-24\pi^2}{\beta} S\right)\ \exp\left(-\frac{\pi}{12}\sum_i \tilde{c}_i b_i^{\mathcal{N}=2}\right)$$

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Target space gauge anomaly

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Anomalous U(1), GS mechanism and FI term

Target space gauge anomaly

- $E_8 \times E_8$ broken to non-Abelian GGs & multiple U(1)'s
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- Typically Φ_α charged under several $\mathrm{U}(1)_i$ factors
  $\Rightarrow$ D-flatness requires more VEVs: $V_{D,\,i} \propto \sum_\alpha q_\alpha^i |\Phi_\alpha|^2 = 0$

Superpotential

Schematic form of final superpotential

$$W \supset A(\Phi)\ e^{-(n_1 T_1 + n_2 T_2)} + B(\Phi)\ e^{\frac{-24\pi^2}{\beta} S}\ e^{-(\beta_1 T_1 + \beta_2 T_2)}$$

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Typical values of β_i

- Depend on particle content, typically $\sim -\frac{2\pi}{12}$
- Calculated using `orbifolder` [Nilles,Ramos-Sanchez,Vaudrevange,Wingerter]

General remarks on moduli stabilization and inflation

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  3. Use F-term stabilizer fields and FI-terms to stabilize S and T_i [Wieck,Winkler;Kappl,Nilles,Winkler]

Examples

Example 1: Using two instantons

Fields

Untwisted fields χ, twisted fields $\varphi^{(k)}$

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Kähler potential

$$K = -\ln(S+\overline{S}) - \ln(T_1+\overline{T}_1-|\chi_A|^2) - \ln(T_2+\overline{T}_2-|\chi_B|^2) + f(T,U)|\Phi_\alpha|^2$$

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$$\begin{aligned} W \supset\ & \chi_A\left[\chi_1\chi_2 e^{-q/\delta_{\mathrm{GS}} S} - \chi_3\chi_4\right] \\ & + \chi_B\left[\chi_5\varphi^{(1)}\varphi^{(1)}\varphi^{(4)} e^{-\pi/12(2T_1+2T_2)} - \chi_6\chi_7\right] \\ & + \chi_C\left[\varphi^{(1)}\varphi^{(3)}\varphi^{(4)}\varphi^{(4)} e^{-\pi/12(6T_1+4T_2)} - \chi_8\chi_9\right] \end{aligned}$$

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$\chi_{A,B,C}$	S	T_1	T_2	A_1	A_2	A_3	B_1	B_2	B_3
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- Rotate to aligned basis $(T_1, T_2) \to (\widetilde{T}_1, \widetilde{T}_2)$
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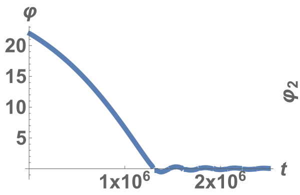

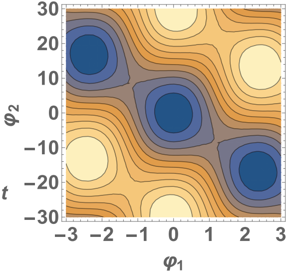

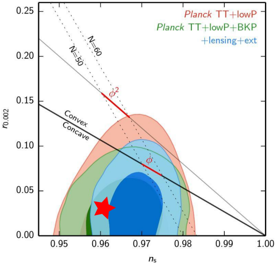

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- Thus [de Carlos,Casas,Munoz] and [Dundee,Raby,Westphal] problematic
- $W \supset \chi_1[C\; e^{-\frac{24\pi^2}{\beta}S}\; e^{-(\beta_1 T_1+\beta_2 T_2)} - B_1]$

  $+\, \chi_2[A_2 e^{-\frac{q}{\delta_{\text{GS}}}S} - B_2]$
  - Need $\langle\chi_1\rangle \neq 0$ since it corresponds to mesonic mass term
  - has to be around Hubble scale to avoid BBN problems
  - Get high-scale SUSY breaking $\sim \langle\chi_1\rangle B_1$

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A_1	A_2	A_3	B_1	B_2	B_3
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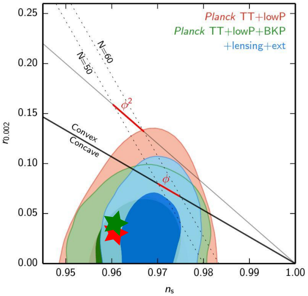

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- Stabilization
  - for **GC+WS instantons tension**
  - for **2 WS instantons easier**

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Thank you for your attention!