D7-brane Chaotic Inflation
and
F-theory GUTs with High-Scale SUSY

in collab. with **S.C. Kraus / L. Witkowski** and **J. Unwin**

(U. of Heidelberg; U. of Notre Dame)

Part 1

- Brief review of 'D7-brane chaotic inflation' as a controlled SUGRA version of axion monodromy

Part 2

- F-theory unification in high-scale SUSY scenarios
- X, Y-induced proton decay constraints (without exponential suppression)
- Why the higher Landau levels make it difficult to suppress proton decay by localization

A New Class Axion Monodromy Models

- The ‘classical’ axion monodromy scenarios are difficult to describe within spontaneously broken supergravity

  Silverstein/Westphal, McAllister/Silverstein/Westphal,
  Kaloper/Sorbo ’08 (see however Weigand/Palti ’14)

- This situation may have fundamentally improved with a recent series of papers:

  Marchesano/Shiu/Uranga, 1404.3040
  Blumenhagen/Plauschinn 1404.3542
  AH/Kraus/Witkowski 1404.3711

  as well as:

  Ibanez/Valenzueala
  Arends,AH,. . . , Lüst, Mayrhofer, Weigand
  Franco/Galloni/Retolaza/Uranga

Also: Grimm; McAllister/Silverstein/Westphal/Wrase
Recent developments of ‘KNP’: Kappl/Krippendorf/Nilles; Ben-Dayan/Pedro/Westphal; Long/McAllister/McGuirk; Gao/Li/Shukla; Bachlechner et al.;
Non-geometric: Hassler/Lüst/Massai; etc.; etc.

Fundamental approach:

- Use fields with axionic shift symmetry (in Kähler potential)
- Break periodicity weakly by superpotential

Realizations:

(1) Marchesano/Shiu/Uranga:

- Several scenarios; one crucial aspect: 'Massive Wilson Lines'

(2) Blumenhagen/Plauschinn:

- Use C_0 of $S = 1/g_s + iC_0$.
- Since $K = -\ln(S + \overline{S})$ and $W = A(z) + SB(z)$, tuning for a small mass of S is easy
- Stabilizing $\text{Re}(S)$ remains a challenge

Realizations (continued):

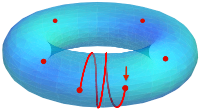
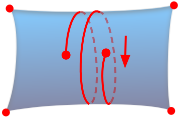
(3) 'Our' Chaotic-D7-brane scenario **(with Kraus/Witkowski)**

- Start with older 'D7-brane' proposal ('fluxbrane inflation')

  AH, Kraus, Lüst, Steinfurt, Weigand '11
  $\ldots +$ Küntzler '12

- Central point: In type IIB at at 'large complex structure', certain D7-brane position moduli have shift symmetry

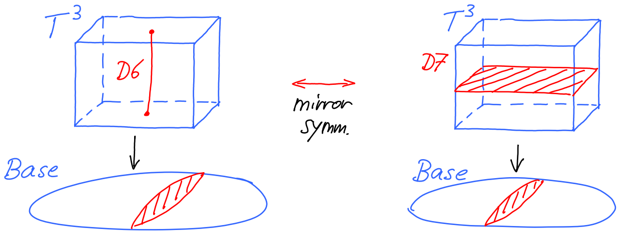
- In addition: They are part of the flux superpotential, which may induce a (small!) monodromy

Origin of Shift symmetry

(A) Via D6 branes in type IIA mirror dual

- D6-Wilson line ⇔ D7-position modulus
- Easy to visualize in SYZ picture...



Origin of Shift symmetry

(B) Via F-theory / Mirror symmetry of 4-folds

- D7 brane moduli and complex structure moduli are part of the complex structure of the F-theory 4-fold: $\{c, u\} \equiv \{z\} \equiv \{t\}$.

- For the mirror dual 4-fold, these are all (shift-symmetric) Kähler moduli:

$$K \supset -\ln[\kappa_{ijkl}(t-\bar{t})^i(t-\bar{t})^j(t-\bar{t})^k(t-\bar{t})^l]$$

- Hence (symbollically):

$$K \supset -\ln[(u-\bar{u})^4 + (u-\bar{u})^2(c-\bar{c})^2]$$

Superpotential and flux-tuning

- The F-theory superpotential takes the general form

$$W = N^A \, \Pi_A(u^i, c^i)$$

- By flux tuning, we assume

$$W = W_0 + \alpha c + \frac{\beta}{2} c^2$$

with

$$\alpha = \alpha(u^i, c^i) \ll 1$$
$$\beta = \beta(u^i, c^i) \ll 1$$

Complete Model with Moduli Stabilization

- Our 4d-supergravity analysis is based on

$$K = -2\ln\tilde{\mathcal{V}} - \ln\left(A + iB(c-\overline{c}) - \frac{D}{2}(c-\overline{c})^2\right)$$

and

$$W = W_0 + \alpha c + \frac{\beta}{2}c^2 + e^{-2\pi T_s}$$

- Here T_s is the 'blowup-cycle' of LVS;
  $\tilde{\mathcal{V}}$ is volume with α'-correction

- The full scalar potential follows from the standard supergravity formula and lead to a 'chaotic' potential for $\varphi \sim \mathrm{Re}(c)$

- For more details see **Lukas Witkowski's** parallel talk...

...and now for something completely different:

(String-) GUTs with High-Scale SUSY

- If SUSY is broken far above 1 TeV, precision unification fails
- Naively, one might think that GUTs lose their motivation since the "$\mathbf{10}+\bar{\mathbf{5}}$" spectrum follows from anomaly cancellation
- This can be argued as follows:

Foot, Lew, Volkas, Joshi '89
Knochel, Wetterich '11

Starting from the **(3,2)** of the SM, anomaly cancellation allows only

$$\textbf{I}:\quad (3,2)_{1/6}+(\bar{3},1)_{-2/3}+(\bar{3},1)_{1/3}+(1,2)_{-1/2}+(1,1)_{1}$$

$$\textbf{II}:\quad (3,2)_{Y}+(\bar{3},1)_{-Y-1/2}+(\bar{3},1)_{-Y+1/2}+(1,2)_{-3Y}+(1,1)_{3Y-1/2}+(1,1)_{3Y+1/2}$$

$$\textbf{III}:\quad (3,2)_{Y}+(\bar{3},2)_{-Y-1/2}+(\bar{3},2)_{-Y+1/2}+(3,2)_{-Y}+(\bar{3},2)_{Y-1/2}+(\bar{3},2)_{Y+1/2}\,.$$

- ...thus, the SM spectrum (i.e. 'choice **I**') has a 30% chance whithout any deeper motivation

- However, the threefold replication of 'choice **I** requires explanation (statistically, one would expect some combination of the choices **I**, **II** and **III**)

By contrast:

- In an $SU(5)$ GUT (e.g. with hypercharge-flux-breaking), a simple choice of flux numbers explains the threefolds replication of the $\mathbf{10} + \overline{\mathbf{5}}$ spectrum

- We take this (plus, possibly, simplicity) as a motivation to consider GUTs even without low-scale SUSY

F-theory corrections to unification

Donagi/Wijnholt; Blumenhagen '08

- It is then natural to consider F-theory corrections to maintain precision unification in high-scale SUSY scenarios

Ibanez, Marchesano, Regalado, Valenzuela '12

- In contrast to previous discussions, we argue that both classical ('Blumenhagen type') and loop ('Donagi/Wijnholt-type') corrections have to be added

- Our argument is based on the type I / heterotic 1-loop formula

Bachas, Kiritsis '96

$$\mathcal{L} \sim R_I^2 \Big[\frac{1}{g_I} \text{Tr}_f[F^4] + \Big\{ \int_0^\infty dl \sum_w e^{-w^2 l/2\pi} \Big\} \Big(\text{Tr}_f[F^4] + \frac{1}{8} \text{Tr}_f[F^2]^2 \Big) \Big] + \cdots \,,$$

F-theory corrections to unification (continued)

- Rewriting this in type IIB variables, we find

$$\mathcal{L} \sim \frac{1}{g_s} \mathrm{Tr}_f \left[F^4 \right] + \mathrm{Tr}_{\mathrm{Adj}} \left[F^4 \right] \mathrm{Log}(1/\epsilon)$$

- Here we clearly see both the classical ('Blumenhagen') and loop (Donagi/Wijnholt) terms

GUT implementation

Dolan/Marsano/Schäfer-Nameki '11

- We start from

$$\alpha_i^{-1}(m_Z) = \alpha_{\mathrm{GUT}}^{-1} + \frac{1}{2\pi} b_i^{\mathrm{MSSM}} \log\left(\frac{M_{\mathrm{KK}}}{m_Z}\right) + \delta_i^{\mathrm{MSSM}} + \delta_i^{\mathrm{tree}} + \delta_i^{\mathrm{loop}} \,,$$

GUT implementation (continued)

- More specifically

$$\delta_i^{\mathrm{MSSM}} = \frac{1}{2\pi}\left(b_i^{\mathrm{SM}} - b_i^{\mathrm{MSSM}}\right)\log\left(\frac{M_{\mathrm{SUSY}}}{m_Z}\right)$$

$$\delta_i^{\mathrm{loop}} = \frac{1}{2\pi} b_i^{5/6} \log\left(\frac{\Lambda}{M_{\mathrm{KK}}}\right)$$

Conlon; Conlon/Palti '09

$$\delta_i^{\mathrm{tree}} = \frac{b_i^H}{g_s}\int_S \left[f_Y \wedge i^* B_- - \frac{1}{10} f_Y \wedge f_Y - f_Y \wedge f_S\right]$$

Mayrhofer/Palti/Weigand '13

- This allows for a full phenomenological analysis

The strategy of Ibanez/Marchesano/Regalado/Valenzuela

- Let W_0 and g_s take its natural, $\mathcal{O}(1)$ values
- Implement the above formulae (without loop-effect)
- One finds $M_{\rm GUT} \simeq 3 \times 10^{14}$ GeV and $M_{\rm SUSY} \simeq 5 \times 10^{10}$ GeV
- The unavoidable dimension-6 proton decay must be suppressed by localization of X, Y gauge bosons away from the matter curves

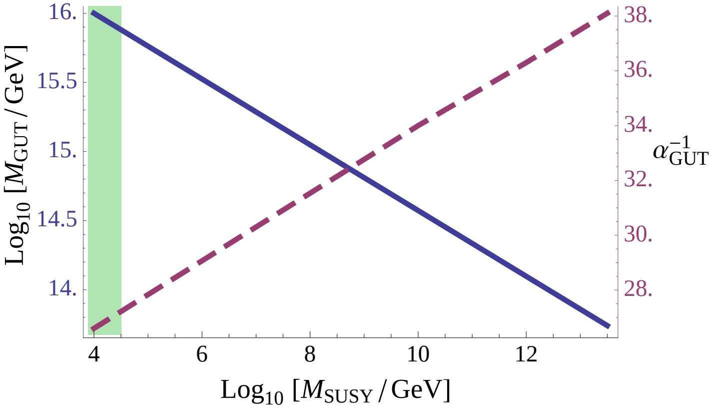
see also Hamada/Kobayashi '12; Kakizaki '13

Our strategy

- We believe (see below) that it is very hard to suppress X, Y-induced proton decay
- Then $M_{\rm GUT}$ must be kept high which (based on the RG-analysis) forces $M_{\rm SUSY}$ to remain low(ish)

Running/proton-decay constraints

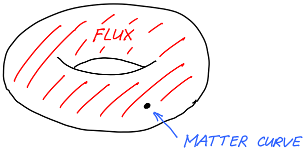
$$M_{\rm GUT} \simeq 4.25 \times 10^{15}\ {\rm GeV} \left(\frac{10^5\ {\rm GeV}}{M_{\rm SUSY}}\right)^{2/9} \left(\frac{3.3}{\Lambda/M_{\rm KK}}\right)^{1/3}$$



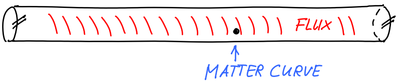
The crucial X, Y-localization issue

see also Klebanov/Witten '03; Beasley/Heckman/Vafa
Cecotti/Cheng; Conlon/Palti/Dudas/Camara;
Font/Ibanez/Aparicio/Marchesano;...

- Let $S = T^4 = T^2 \times T^2$, with the matter curve on the small T^2



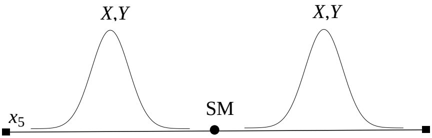
- The best localization arises for $T^2 = S^1 \times S^1$



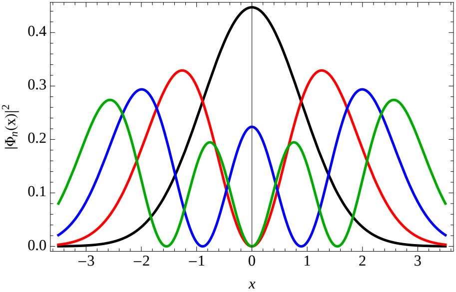
- The X, Y wavefunctions now correspond to those of a scalar field on a line with linearly varying mass term

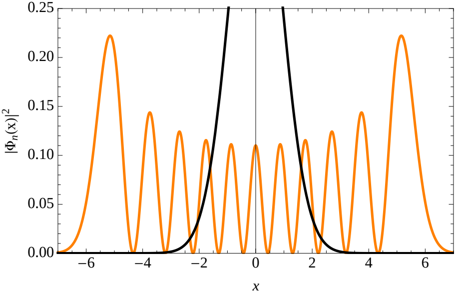
- The relevant equation of motion is precisely the Schrödinger equation of a harmonic oscillator

Hayashi/Kawano/Tsuchiya/Watari '09



- Including higher modes (Landau levels):





- One can place the matter curve away from the zero-mode
- But higher modes 'spread out', reaching the matter curve
- We provide a detailed analytical treatment, including summation over higher Landau level modes
- The resulting decay rate is astonishingly simple:

$$\frac{\Gamma}{\Gamma_{\rm 4D}} \sim \left(\sum_{n=0}^{\infty} \frac{L_5}{2n^{1/3} x_{\rm max}(n)} \right)^2 \sim N^2 \geq 1$$

- The only way out appears to be localizing fermions in the same GUT multiplet away from each other
- We believe that this is very difficult
- One can 'split' the multiplets, but this destroys our motivation

See e.g. Font/Ibanez '08; Dudas/Palti '10; Callaghan et a. '11; Krippendorf et al '14

Summary/Conclusions

Part 1

- Considerable progress towards moduli stabilization in monodromy models has recently been made

- In particular, the dynamics of D7-branes in flux compactifications provides a ground where explicit exampes appear within reach ('Chaotic D7-brane inflation')

Part 2

- F-theory GUTs remain an interesting new-physics options even without TeV-scale SUSY

- There are strong arguments (GUT paradigm + proton decay) to expect SUSY at $\lesssim$ 100 TeV

- Raising the SUSY scale further remains a worthwhile challenge