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 $K = -\ln(S + \bar{S})$ 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
  ... + 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
(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:

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

- Hence (symbolically):

  \[ K \supset - \ln[(u - \bar{u})^4 + (u - \bar{u})^2(c - \bar{c})^2] \]
Superpotential and flux-tuning

- The F-theory superpotential takes the general form

  \[ W = N^A \prod_A(u^i, c^i) \]

- 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

\[ K = -2 \ln \tilde{V} - \ln \left( A + iB(c - \bar{c}) - \frac{D}{2}(c - \bar{c})^2 \right) \]

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; \( \tilde{V} \) is volume with \( \alpha' \)-correction

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

- 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 “$10 + \bar{5}$” 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

$$I: \ (3,2)_{1/6} + (\bar{3},1)_{-2/3} + (\bar{3},1)_{1/3} + (1,2)_{-1/2} + (1,1)_1$$

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

$$III: \ (3,2)_Y + (\bar{3},2)_{-Y-1/2} + (\bar{3},2)_{-Y+1/2} + (3,2)_{-Y} + (\bar{3},2)_{Y-1/2} + (\bar{3},2)_{Y+1/2}.$$
• ...thus, the SM spectrum (i.e. ‘choice I’) has a 30% chance without 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 $10 + \overline{5}$ 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

\[ \mathcal{L} \sim R_l^2 \left[ \frac{1}{g_l} \text{Tr}_f [F^4] + \left\{ \int_0^\infty dl \sum_w e^{-w^2 l/2 \pi} \right\} \left( \text{Tr}_f [F^4] + \frac{1}{8} \text{Tr}_f \left[ F^2 \right]^2 \right) \right] + \ldots , \]
F-theory corrections to unification (continued)

• Rewriting this in type IIB variables, we find

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

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

GUT implementation

• We start from

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

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

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

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

This allows for a full phenomenological analysis
The strategy of Ibanez/Marchesano/Regalado/Valenzuela

- Let $W_0$ and $g_s$ take its natural, $O(1)$ values
- Implement the above formulae (without loop-effect)
- One finds $M_{\text{GUT}} \simeq 3 \times 10^{14}$ GeV and $M_{\text{SUSY}} \simeq 5 \times 10^{10}$ 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 $M_{\text{GUT}}$ must be kept high which (based on the RG-analysis) forces $M_{\text{SUSY}}$ to remain low(ish)
Running/proton-decay constraints

\[ M_{\text{GUT}} \simeq 4.25 \times 10^{15} \text{ GeV} \left( \frac{10^5 \text{ GeV}}{M_{\text{SUSY}}} \right)^{2/9} \left( \frac{3.3}{\Lambda/M_{\text{KK}}} \right)^{1/3} \]
**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:

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

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 al. ’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 examples 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.