Discrete Gauge Symmetries, Chern Simons terms and Axion Monodromy

Angel M. Uranga
IFT-UAM/CSIC, Madrid


c.f. Shiu’s talk
Retolaza’s parallel session talk

String Pheno 2014, Trieste
Plan

Discrete gauge symmetries, $Z_n$ particles and strings

String theory realizations
  - Torsion homology
  - Flux compactifications

Gauge symmetries from 3- and 2-forms
  - Axion monodromy

String theory realizations
  - Torsion homology
  - Flux compactifications

Conclusions
\( Z_n \) discrete gauge symmetries

Can realize \( Z_n \) as \( U(1) \) Higgsed by field of charge \( n \)

4d Lagrangian for gauge field and phase \( \phi \) of scalar field

\[
\left| F_2 \right|^2 + \left| d\phi - nA_1 \right|^2
\]

Gauge transformation

\[ A_1 \rightarrow A_1 + d\lambda \quad ; \quad \phi \rightarrow \phi + n\lambda \]

Can be dualized to 4d BF theory

\[
\left| H_3 \right|^2 + nB_2 \wedge F_2 + \left| F_2 \right|^2
\]

\( Z_n \) symmetry read from coefficient of BF coupling

Dualizing also gauge field to dual gauge potential, we get

\[
\left| H_3 \right|^2 + \left| dV_1 - nB_2 \right|^2
\]

Gauge transformation

\[ B_2 \rightarrow B_2 + d\Lambda_1 \quad ; \quad V_1 \rightarrow V_1 + n\Lambda_1 \]

Banks, Seiberg
Charged objects

Relevant 4d fields: $\phi, A_1, B_2, V_1$

Particles and strings (Zn annihilation on instantons and junctions)

- Strings defined by holonomy given by scalar field shift (and coupling to dual 2-form $B_2$)
- Particles defined by integral of $*F_2$ on surrounding $S^2$ (and coupling to $A_1$)

Can generalize to arbitrary p-forms in arbitrary dimensions

Berasaluce-González, Ramírez, AU; also Quevedo, Trugenberger
Many (interrelated) stringy realizations

- **Torsion homology**
  - Cámara, Ibáñez, Marchesano; Berasaluce-González, Cámara, Marchesano, Regalado, A.U.

- **BF couplings on D-branes**
  - Rparity, Btriality in MSSM models
  - Berasaluce-González, Ibáñez, Soler, A.U.

- **Discrete isometries & magnetized D-branes**
  - Non-abelian selection rules on Yukawas
  - Berasaluce-González, Cámara, Marchesano, Regalado, A.U.

- **Flux compactifications**
  - Berasaluce-González, Cámara, Marchesano, A.U.

- **Supercritical strings**
  - Berasaluce-González, Montero, Retolaza, A.U.

C.f. Montero’s parallel session talk
Many (interrelated) stringy realizations

**Focus on...**

- Torsion homology
- BF couplings on D-branes
  - MSSM models
- Discrete isometries & magnetized D-branes
- Non-abelian selection rules on Yukawas
- Flux compactifications
- Supercritical strings

**Authors:**
- Cámara, Ibáñez, Marchesano;
- Berasaluce-González, Cámara, Marchesano, Regalado, A.U.
- Berasaluce-González, Ibáñez, Soler, A.U.
- Berasaluce-González, Cámara, Marchesano, Regalado, A.U.
- Berasaluce-González, Cámara, Marchesano, A.U.
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**C.f.** Montero’s parallel session talk
Zn symmetries from torsion p-forms

Compactifications of p-forms on spaces with torsion homology

Ex: M-theory on 7d space (e.g. G2) X with \( H_2(X,\mathbb{Z}) = H_4(X,\mathbb{Z}) = \mathbb{Z}_n \)

- M2's on 2-cycles are \( \mathbb{Z}_k \) particles
- Instantons are M2 on 3-chains, emit torsion M2's
- M5's on 4-cycles are \( \mathbb{Z}_k \) strings
- Junctions are M5 on 5-chains, emit torsion M5's

Gauging manifest using non-harmonic forms (massive U(1))

Ex: \( d\eta_2 = n \omega_3 \)

\[ C_3 = A_1(x^\mu) \wedge \eta_2(y^m) + \phi(x^\mu) \omega_3(y^m) \]

\[ G_4 = (d\phi - n A_1) \wedge \eta_2 + \ldots \]

Cámara, Ibáñez, Marchesano

cf. Ftheory talks
**Zn symmetries from torsion p-forms**

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**Ex: M-theory on 7d space (e.g. G2) X with H_2(X,Z)=H_4(X,Z)=Z_n**

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**Incidentally, three comments:**

- M-theory lift of Z_n symmetries from D6-brane U(1)’s
- Can get non-abelian symmetries
- For later, useful to think about torsion as a ‘geometric flux’ (as in twisted tori)
Discrete symmetries from ‘flux cathalysis’

D-branes \(\mathbb{Z}\)-valued in homology but \(\mathbb{Z}_n\)-valued in K-theory

D-branes can decay in the presence of
NSNS 3-form flux (""""Freed-Witten anomaly"""")

Maldacena, Moore, Seiberg

General branes and fluxes (beyond K-theory)

Berasaluce-González, Cámara, Marchesano, AU

Discrete gauge symmetries from flux cathalysis

4d BF coupling from 10d Chern-Simons term
Discrete symmetries from ‘flux cathalysis’

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Discrete gauge symmetries from flux cathalysis

4d BF coupling from 10d Chern-Simons term

**Ex: IIA Freund-Rubin**

\[
\int_{4d \times X_6} \overline{F}_6 \wedge B_2 \wedge F_2 \rightarrow \int_{4d} n B_2 \wedge F_2
\]

\( \mathbb{Z}_n \) particles are D0s, annihilate on NS5 on X6

\( \mathbb{Z}_n \) strings are F1s, annihilate on D6 on X6
Discrete symmetries from ‘flux cathalysis’

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Berasaluce-González, Cámara, Marchesano, AU

Discrete gauge symmetries from flux cathalsis

4d BF coupling from 10d Chern-Simons term

Ex: IIB with NSNS flux on A-cycle

\[ \int_{4d \times X_6} H_3 \wedge C_2 \wedge F_5 \rightarrow \int_{4d} n C_2 \wedge F_2 \]

Zn particles are D3s on B-cycle, annihilate on D5 on X6

Zn strings are D1s, annihilate on D3 on A-cycle
Zn domain walls and gauge symmetries

Berasaluce-González, Cámara, Marchesano, AU
Shiu, Marchesano, AU

Can consider other Zn charged objects in 4d

Lagrangian for 3-form eating up a 2-form

\[ |F_4|^2 + |dC_2 - nC_3|^2 \]

Gauge transformation

\[ C_3 \rightarrow C_3 + d\Lambda_2 \quad ; \quad C_2 \rightarrow C_2 + n\Lambda_2 \]

Can be dualized to $\Phi F_4$ theory

\[ |F_4|^2 + n\phi F_4 + |d\phi|^2 \]

Kaloper, Sorbo, Lawrence

Dualizing also 3-form (to “(-1)form”), we get

\[ |d\phi|^2 + \phi^2 \]

Chaotic inflation model

No gauge invariance manifest in axion language

Corrections constrained to powers of $F_4$ due to dual gauge inv.
Zn domain walls and gauge symmetries

Berasaluce-González, Cámara, Marchesano, AU
Shiu, Marchesano, AU

Axion, because of discrete periodicity of full theory

 Implemented by the presence of Zn domain walls

Charged under C3, across a wall,

\[ \phi \rightarrow \phi + 1/n \quad ; \quad F_4 \rightarrow F_4 + 1 \]

n walls annihilate on string, charged under C2

Periodicity under \( \phi \rightarrow \phi + 1 \) (and \( F_4 \rightarrow F_4 + n \))

Axion monodromy:
Potential is periodic but multivalued

cf Westphal, Shiu, Hebecker’s talks

Easy to give string embedding
Many (interrelated) stringy realizations

Focus on...

- Torsion homology
  Berasaluce-González, Cámara, Marchesano, AU
  Shiu, Marchesano, AU

- Flux compactifications

related: Hebecker, Kraus, Witkowski;
Blumenhagen, Plauschinn;
McAllister, Silverstein, Westphal;
...

Backreaction, transitions by DW nucleation, computable

OBS: 4d instanton leads to cosine modulation, not to jump across branches
“Massive Wilson lines” (torsion p-forms)

Compactifications of 1-forms on cycles with torsion 1-homology

Ex: D6 on 3cycle space $\Pi$ with $H_1(\Pi,\mathbb{Z})=\mathbb{Z}n$

- axion $\Phi$ is gauge field on torsion 1-cycle (massive)
- 4d domain wall is monopole (D4 ending on D6) wrapped on 1-cycle
- 4d string is monopole (D4 ending on D6) wrapped on 2-chain
- 4d instanton (cosine modulation) is F1 worldsheet on 2-chain

3- and 2-form from dual gauge potential and non-harmonic forms

Ex: $d\eta_1 = n \omega_2$

KK reduction

$A_4 = C_3(x^\mu) \wedge \eta_1(y^m) + C_2(x^\mu) \wedge \omega_2(y^m)$

$F_5 = (dC_2 - nC_3) \wedge \omega_2 + \ldots$

In axion language

WL $\Phi$ not a modulus:

$A_1 = \phi \eta_1 \quad F_2 = \phi n \omega_2$

F2 kinetic terms implies quadratic growth of energy with $\Phi$
“Massive Wilson lines” (torsion p-forms)

Compactifications of 1-forms on cycles with torsion 1-homology

- Ex: D6 on 3cycle space $\Pi$ with $H_1(\Pi,\mathbb{Z})=\mathbb{Z}_n$

- In geometric terms
  WL $\phi$ not a modulus, turns on F2 flux on 2-chain of torsion 1-cycle
  F2 kinetic terms implies quadratic growth of energy with $\phi$

- UV completion allows discussing backreaction
  For large F2, change Maxwell to DBI: potential becomes linear

$$V(\phi)$$
Fluxed axion monodromy

Use 10d Chern-Simons terms to get 4d $\Phi F_4$ term, equiv use flux catalysis to get $Z_n$ domain walls

Ex: IIB with NSNS flux on A-cycle

$$F_4 = \int_B F_7 ; \quad \int_A H_3 = n$$

$$\int_{4d \times X_6} \overline{H}_3 C_0 F_7 \to \int_{4d} n C_0 F_4$$

10d IIB axion has a monodromy. Origin of energetic cost?
GVW supo

$$W = \int_{X_6} (F_3 - \tau \overline{H}_3) \wedge \Omega$$

Period of C0 changes $n$ units of F3 flux on A
4d Domain Wall is D5 on B (also from origin of F4)
4d instanton is D(-1) (cosine modulation)

UV completion, backreaction:

10 periods require $O(10)$ units of flux. Expect GVW remain good approx.
Conclusions

Discrete gauge symmetries everywhere

Zn charged particles and strings

Pretty well explored, motivate study of topological couplings in setups like torsion, fluxes, ...

Zn charged domain walls

‘Exotic’ gauge symmetries (3- and 2-forms)

Monodromic axions, with controlled potential

String constructions UV complete 4d Kaloper-Sorbo

Applications to inflation

Topological structure of monodromy in axion field space

Natural interplay with flux moduli stabilization

Need mechanisms for scales e.g. warping. A. Retolaza’s talk
Fine-tuning, Anthropic and the String Landscape

Instituto de Física Teórica UAM-CSIC
Madrid, 8-10 October 2014
http://workshops.ift.uam-CSIC.es/ws/anthropic

SPEAKERS:
T. Banks (Santa Cruz & Rutgers U.)
I. Bena (CEA Saclay)
J.J. Blanco-Pillado (UPV)
R. Bousso (Berkeley U.)
A.R. Brown (Stanford U.)
U. Danielsson (Uppsala U.)
F. Denef (Columbia U.)
J.F. Donoghue (Massachusetts U.)
B. Freivogel (Amsterdam U.)
B. Greene* (Columbia U.)
A.H. Guth (MIT)
L.J. Hall (Berkeley U.)
C.J. Hogan (Chicago U. & Fermilab)
M. Kleban (New York U.)
U. Meissner (Bonn U.)
L. McAllister (Cornell U.)
F. Quevedo (ICTP)
L. Randall (Harvard U.)
S. Sethi (Chicago U.)
A. Vilenkin (Tufts U.)
A. Westphal (DESY)
To be confirmed

ORGANIZERS:
J. Garriga
L.E. Ibañez
F. Marchesano
A.N. Schellekens
A.M. Uranga
anthropic@uam.es
Thank you!