String Model Building for Particle Physics and Cosmology

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- **Fluxes and applications**

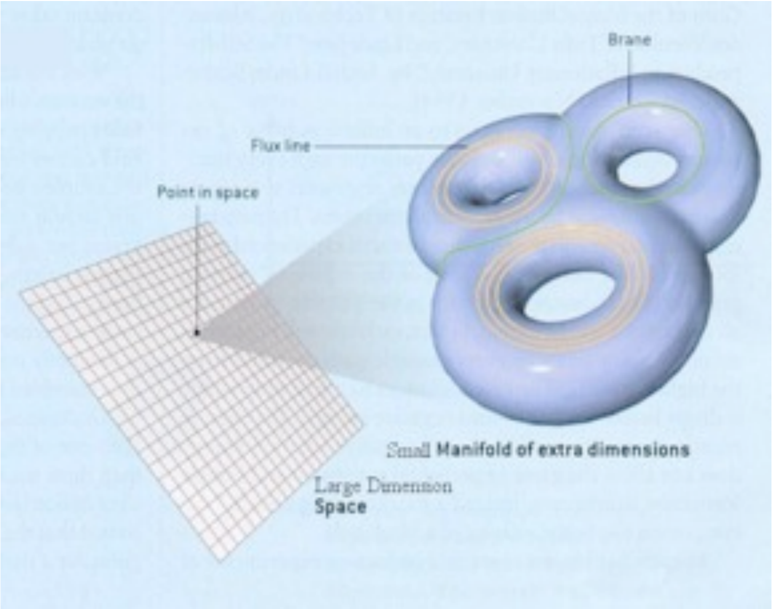
Plan

- Flux compactifications
- Moduli stabilization
- Supersymmetry breaking
- Inflation

Moduli stabilization

- Massless moduli mediate 5th forces. Unobserved
- Cosmological problems unless massive enough
- Need mechanisms for moduli stabilization

Focus on flux compactifications



Flux compactification

- In addition to metric background, introduce backgrounds for NSNS and RR p-form fields

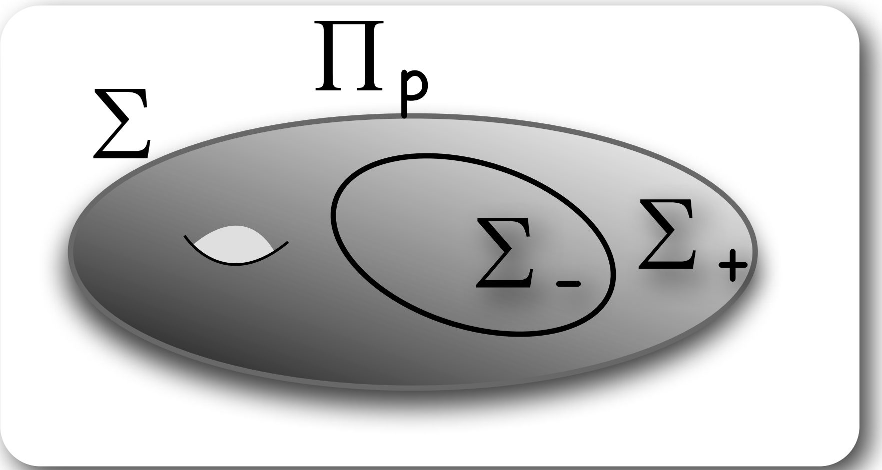
  Due to gauge invariance, backgrounds for field strength

- Topological sector defined by cohomology class

  In the absence of sources, $dF_{p+1}=0$

  Must specify fluxes over basis of cycles $\int_{\Lambda_k} F_{p+1} = N_k$

- Flux quantization



Flux compactification

- Fluxes introduce moduli dependence in potential energy

  Closed string moduli are stabilized

- Dating back to Freund-Rubin

  Ex: $AdS_5 \times S^5$

  S^5 volume not a modulus, but sits at a minimum of potential

  Vacua need not be Minkowski, but also AdS (or dS??)

  Focus on M_4, or in $(A)dS_4$ with hierarchycal length scales

Type IIB with 3-form fluxes

- Prototypical example: type IIB with NSNS and RR 3-form flux

  There are no 1- or 5-cycles on CY threefolds

- 10d action

$$S_{\rm IIB} = \frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{-g}\left(R - \frac{\partial_M\bar\tau\,\partial^M\tau}{2({\rm Im}\,\tau)^2} - \frac{1}{2}|F_1|^2 - \frac{|G_3|^2}{2\,{\rm Im}\,\tau} - \frac{1}{4}|\tilde F_5|^2\right)$$
$$+\frac{1}{2\kappa_{10}^2}\int C_4\wedge\frac{G_3\wedge\bar G_3}{4i\,{\rm Im}\,\tau} + S_{\rm local}\,.$$

Useful combination $\quad G_3 = F_3 - \tau H_3 \quad ; \quad \tau = C_0 + ie^{-\phi}$

Specify integrals, and local sources, satisfying RR tapole condition

$$Q_{\rm flux} + Q_{\rm D3} + Q_{\rm O3} = 0$$

Type IIB with 3-form fluxes

- Flux "tension" and charge

$$\mathcal{L}_G = -\frac{1}{24\kappa_{10}{}^2}\int_{\mathbf{X}_6} d^6y\, g^{\frac{1}{2}}\,\frac{(G_3)_{mnp}(\bar{G}_3)^{mnp}}{\mathrm{Im}\,\tau} = -\frac{1}{8\kappa_{10}{}^2}\int_{\mathbf{X}_6} d^6y\,\frac{G_3\wedge *_6\bar{G}_3}{\mathrm{Im}\,\tau}$$

$$\mathcal{L}_{C_4} = \frac{1}{2\kappa_{10}^2}\int C_4\wedge\frac{G_3\wedge\bar{G}_3}{4i\mathrm{Im}\,\tau}$$

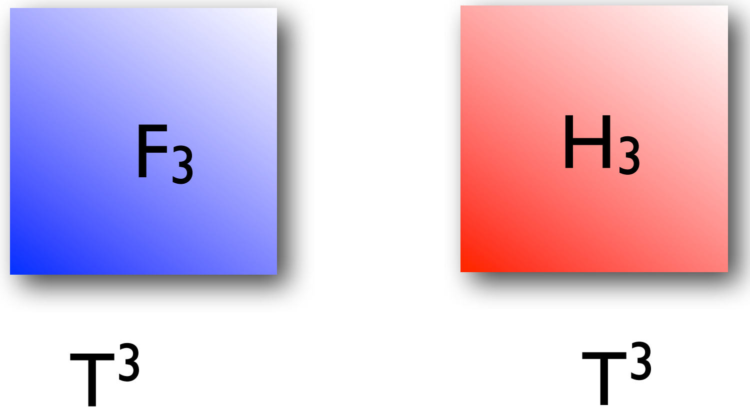
- "BPS-like" for ISD flux

$$*_{6d}G_3 = iG_3$$

- Allows solving for compactifications with 4d Minkowski
- Stabilizes complex structure moduli (and dilaton)

Type IIB with 3-form fluxes

$F_3 = H_3$



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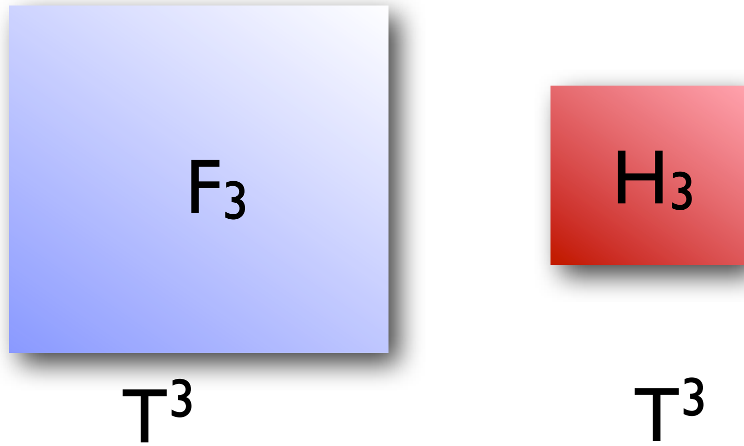
Type IIB with 3-form fluxes

$F_3 \neq H_3$



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Warped geometries

- Fluxes gravitate. Backreaction.

- For ISD flux the10d solution is warped M_4 x CY with warp and 5-form sourced by flux and local sources

$$ds^2 = Z(x^m)^{1/2}\, ds_{4d}^2 + Z(x^m)^{1/2}\, g_{mn}^{CY}\, dx^m\, dx^n$$

$$F_5 = (1+*_{10d})\, dZ^{-1}\, dx^0\, dx^1\, dx^2\, dx^3$$

$$\nabla^2\, Z(x\text{^}m) = g_s\, |G_3|\text{^}2 + g_s \sum \delta(D3/O3)$$

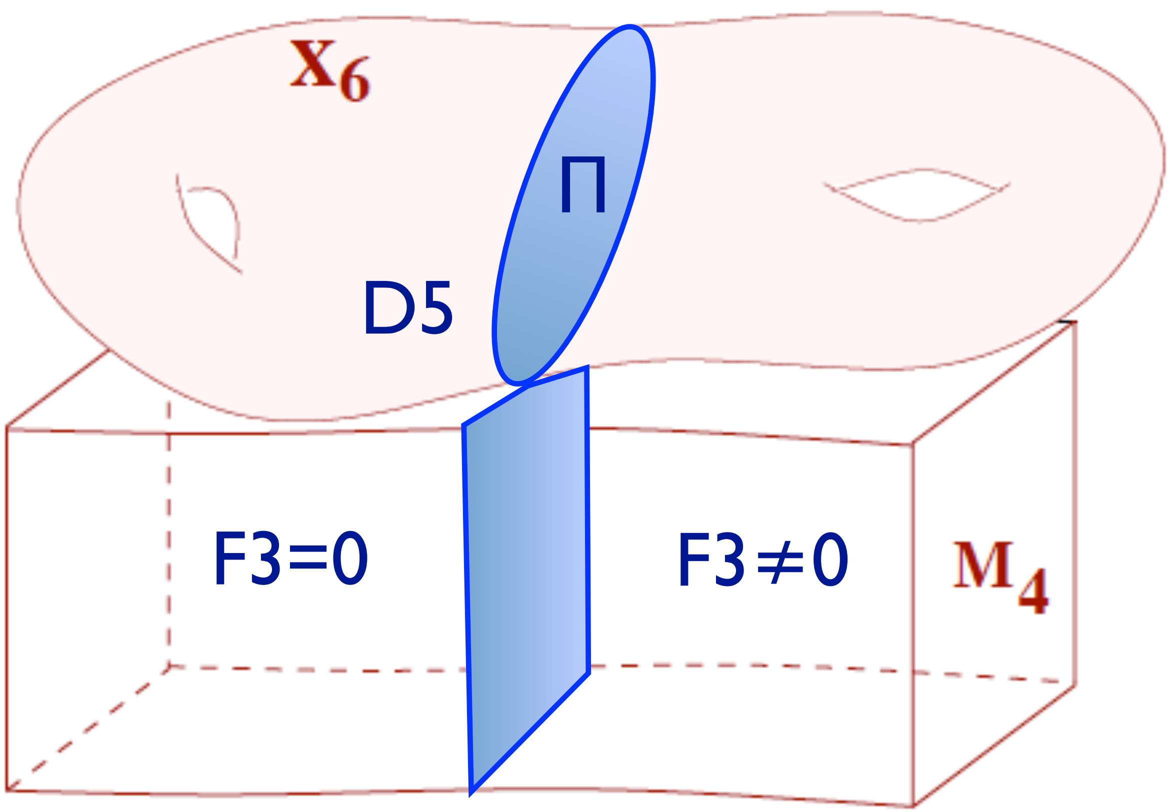
Analogous to 3-brane solution:
Intuition: ISD flux works like “effective” D3-brane

- Underlying CY makes life easy ⇒ Many explicit models

Flux superpotential

- Efect of flux on closed string moduli can be described in low energy effective field theory by W_{flux}

- Compute W_{flux} from tension of domain wall introducing flux

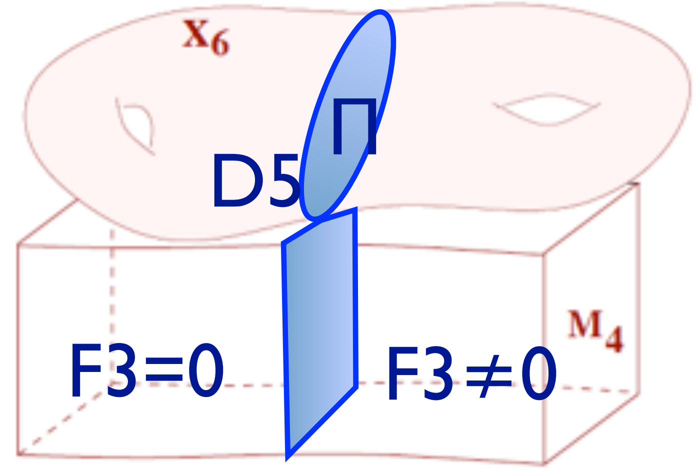


Flux superpotential

- Compute W_{flux} from tension of domain wall introducing flux

D5 is magnetic source for C2

$$dF_3 = \delta_3(\Pi) \wedge \delta_0(x^3)\, dx^3$$



Integrate over dual 3-cycle Π' x interval in x3

$$\Delta \int_{\Pi'} F_3 = 1$$

From DW tension

$$W_{F_3} = \int_{\Pi} \Omega_3 = \int_{\mathbf{X}_6} F_3 \wedge \Omega_3$$

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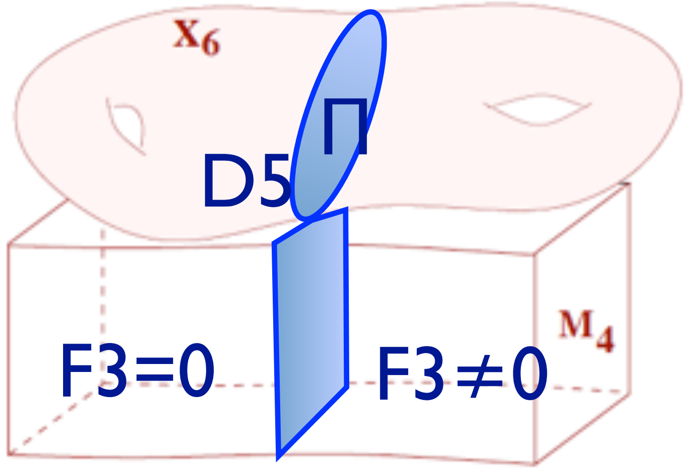

Integrate over dual 3-cycle Π' x interval in x3

$$\Delta \int_{\Pi'} F_3 = 1$$

From DW tension

$$W_{\rm GVW} = \int_{\mathbf{X}_6} G_3 \wedge \Omega_3$$

For general F3, H3 fluxes

Supersymmetry

- Can be studied from warped supergravity background
- Also from 4d effective theory

$$K = -\log(\int_X \Omega \wedge \overline{\Omega}) - \log(\tau - \overline{\tau}) - 3\log(\rho + \overline{\rho})$$

$$W_{\text{flux}} = \int_X G_3 \wedge \Omega$$

Scalar potential $V = e^K \left(g^{a\bar{b}} D_a W \, D_{\bar{b}} \overline{W} - 3|W|^2 \right)$

For complx. structure + dilaton $V = e^K \left(g^{i\bar{j}} D_i W \, D_{\bar{j}} \overline{W} \right)$

Vacuum: $D_i W_{\text{flux}} = 0$ $\quad D_\tau W \sim \int_X \overline{G}_3 \wedge \Omega$ $\quad G_3|_{(3,0)} = 0$

G3 is ISD $\quad D_{z_i} W \sim \int_X G_3 \wedge \chi_{(2,1),i}$ $\quad G_3|_{(1,2)} = 0$

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“No-scale structure”

Vacuum: $D_i W_{\text{flux}} = 0$ $\quad D_\tau W \sim \int_X \overline{G}_3 \wedge \Omega \quad G_3|_{(3,0)} = 0$

G3 is ISD $\quad D_{z_i} W \sim \int_X G_3 \wedge \chi_{(2,1),i} \quad G_3|_{(1,2)} = 0$

SUSY: G3 is (2,1) $\quad D_\rho W \sim \int_X G_3 \wedge \Omega \quad G_3|_{(0,3)} = 0$

F-theory description

- M-theory on elliptic CY4 in limit of vanishing fiber size
- Both NSNS and RR 3-form flux become M-theory 4-form flux

$$G_{(4)} = -\frac{G_{(3)} d\bar{w}}{\tau - \bar{\tau}} + \mathrm{h.c.}$$

Stabilizes 4-fold complex str. moduli: some are 7-brane moduli!

Flux superpotential: $W = \int_{\mathbf{X}_8} G_4 \wedge \Omega_4$

Vacuum: G4 is SD

Susy: G4 is (2,2)

Towards the SM

- MSSM from magnetized D7s

N_α	(n^1_α, m^1_α)	(n^2_α, m^2_α)	(n^3_α, m^3_α)	
$N_a = 3$	(0,1)	(3,1)	(-3,1)	$D7_1$
$N_b = 1$	(1,0)	(0,1)	(-1,0)	$D7_2$
$N_c = 1$	(1,0)	(-1,0)	(0,1)	$D7_3$
$N_d = 1$	(0,1)	(3,1)	(-3,1)	$D7_1$

(need few extra branes, adding few extra matter)

Flash back

- Can add Susy or Susy breaking 3-form flux to stabilize moduli

Susy
$$G_3 = \frac{8}{\sqrt{3}} e^{-\frac{\pi i}{6}} (d\bar{z}_1 dz_2 dz_3 + dz_1 d\bar{z}_2 dz_3 + dz_1 dz_2 d\bar{z}_3)$$

Stabilizes at $\tau_1 = \tau_2 = \tau_3 = \tau = e^{2\pi i/3}$

Non-susy
$$G_3 = 2\,(d\bar{z}_1 dz_2 dz_3 + dz_1 d\bar{z}_2 dz_3 + dz_1 dz_2 d\bar{z}_3 + d\bar{z}_1 d\bar{z}_2 d\bar{z}_3)$$

Stabilizes e.g. at $\tau_1 = \tau_2 = \tau_3 = \tau = i$

Full moduli stabilization & deSitter

Corrections

- Earlier no-scale structure disappears upon including corrections
- Perturbative and non-perturbative, in α' and g_s
- Corrections may be small in large volume, small g_s regime, but not compared to zero!

Generalized fluxes

- Above set of fluxes is not really the most general
- Geometric, non-geometric, U-dual fluxes
- Superpotentials depending on all moduli

Full moduli stabilization & deSitter

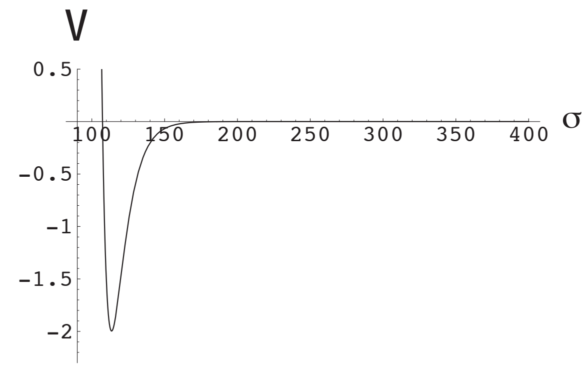
- Use non-perturbative effects from D3-brane instantons

[Kachru, Kallosh, Linde, Trivedi]

One-modulus toy model

$$W = W_{0,\text{flux}} + A(z_0)e^{-T}$$

Susy AdS vacua with stabilized moduli



- Must tune W_0 t<< 1 to achieve controlable regime

Can be relaxed in other scenarios (Large Volume Stabilization)

- Generalization: D3-instantons for each independent Kahler modulus?

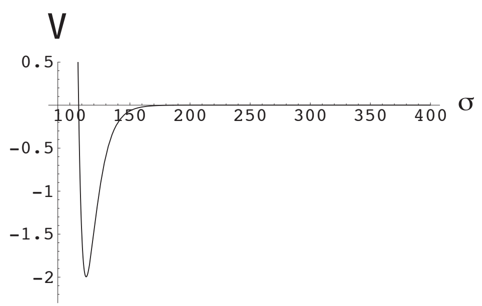
- Clash with SM arising from D7's

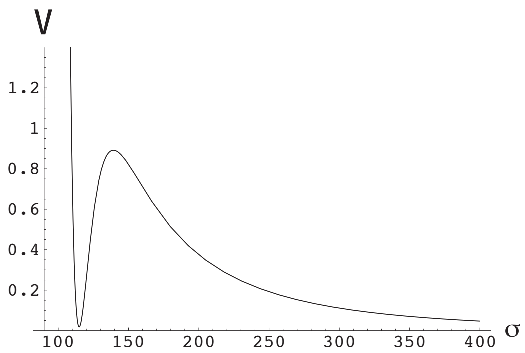
Intersections of instanton with D7's lead to supos involving SM fields

$$W = e^{-T} \to W = e^{-T}\Phi_1 \ldots \Phi_n$$

Full moduli stabilization & deSitter

- Proposal to add sources of extra tension for uplifting to deSitter

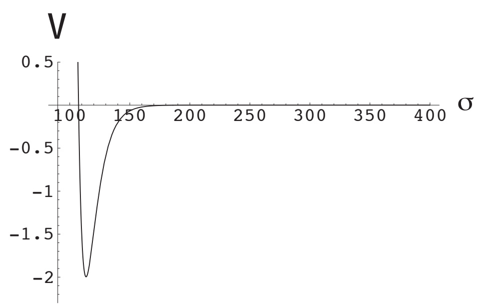


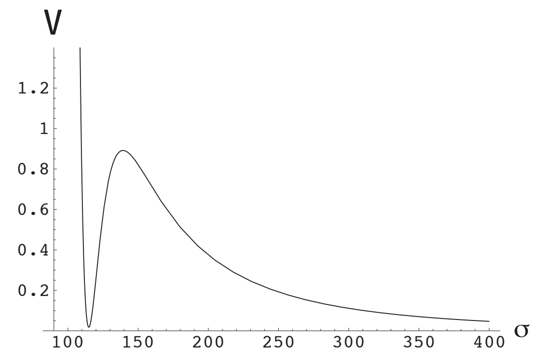


- Anti D3-branes

Full moduli stabilization & deSitter

- Proposal to add sources of extra tension for uplifting to deSitter





- Anti D3-branes

- D-terms: anti-instantons on D7s

- F-terms fon flux supo itself

- DSB sectors

- D-terms: anti-instantons on D7s

- Hard to make anything explicit enough (new: nilpotent goldstino)

Generalized fluxes

- Flux compactifications in type IIA involve even and odd forms

⇒ Talk both to Kahler and complex structure moduli!

What about mirror symmetry?

- Using T-duality in local T^3 fibration, H_3 turns e.g. into geometric twist

⇒ Geometric fluxes

- Compactification on non-CY geometries, possibly 4d N=1

SU(3) holonomy → SU(3) structure

⇒ Generalized complex geometry, mirror symmetry, ...

- Painful lack of explicit compact examples

Generalized fluxes

- Generalized geometric and non-geometric fluxes from T-duality

Regard T^3 as T^2 (trivially) fibered over S^1

H_3 is monodromy $b \to b+1$ for $b=\int_{T2} B$

Particular SL(2,Z) monodromy on $T=A_{T2}+ib$

One T-duality along T2 gives $\tau \to \tau+1$ in SL(2,Z) of τ

⇒ Geometric twisting, geometric flux

One S1 non-trivially fibered over two directions $\omega^a{}_{bc}$

Two T-dualities give non-geometric SL(2,Z) monodromy on T

⇒ Non-geometric twisting, non-geometric flux $Q^{ab}{}_c$

Full T-duality covariance suggests

⇒ locally non-geometric R^{abc}

- Generalized geometry. Double (&exceptional) field theory, ...

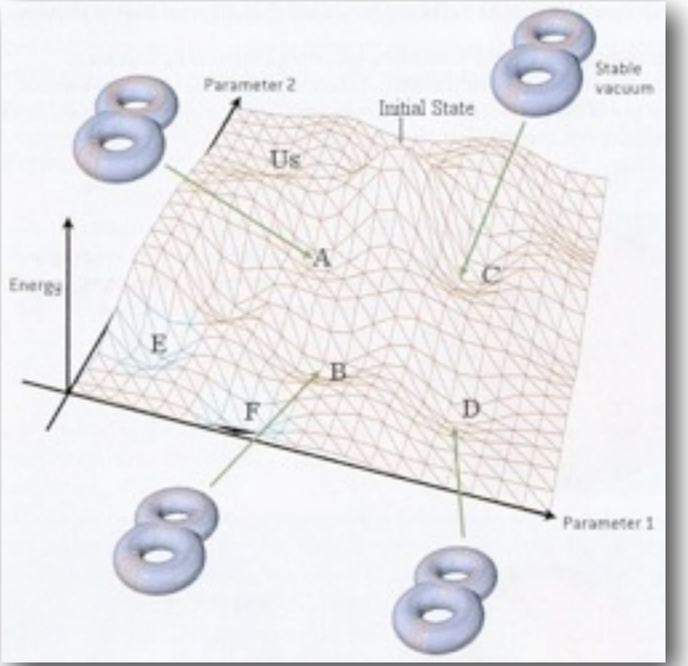
Flux landscape

- The general picture is compelling enough

Internal data determine 4d physics

symmetries, spectrum, couplings

Many choices: **"Landscape"**



Flux landscape, part of full string landscape

Various estimates by flux counting

Revision of "naturalness": cosmological constant, hierarchy,...

Yeah, but...

What about some real Physics?

Keep rocking

After all, we are dealing with a theory
which is much more clever than any of us

Fluxes and D-branes

- Must consider the interplay of different ingredients

- Focus on inter-relations between (field strength) fluxes and D-branes

- Efects at several levels

  - Topological: Freed-Witten consistency conditions

  - (Susy) Open string moduli stabilization

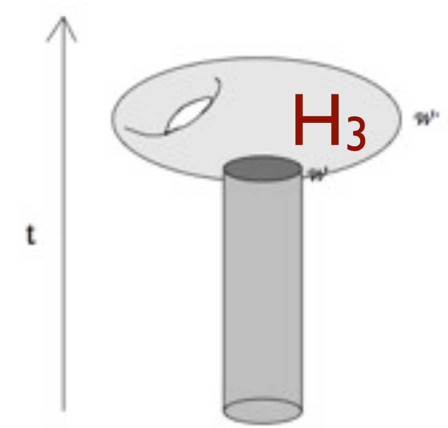
  - Susy breaking

Freed-Witten consistency conditions

- Certain D-branes are inconsistent in presence of NSNS 3-form flux
- Certain D-branes can decay in the presence of NSNS 3-form flux

Take D6-brane on 3-cycle with non-trivial H_3

$$\int_{\mathrm{D6}} H_3 \wedge \tilde{A}_4$$



Flux is magnetic source for D6 U(1)

Must be cancelled by boundaries of outgoint D4's

- Invariance of flux superpotential under D-brane gauge
- Ensures D-brane instantons respect gaugings in fluxes
- Analogous statements for RR fluxes

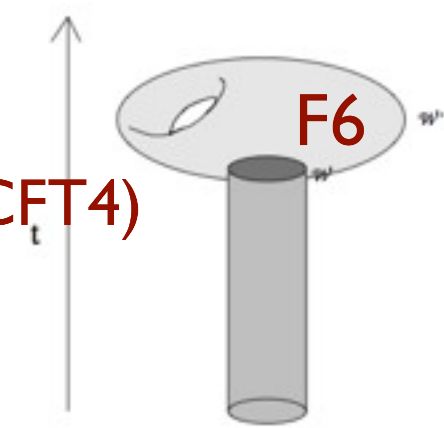
Freed-Witten and discrete symmetries

- D-branes Z-valued in homology but Zn-valued in “K-theory”

- Torsion classes signal discrete gauge symmetries

  Discrete gauge symmetries from flux cathalysis

  Ex: Freund-Rubin (analogous to Zk center in AdS5/CFT4)



$$\int_{4d\times X_6} \overline{F}_6 \wedge B_2 \wedge F2 \rightarrow k \int_{4d} B_2 \wedge F_2$$

Instanton: NS5 on X6. Emits k D0-branes (Zk particles)

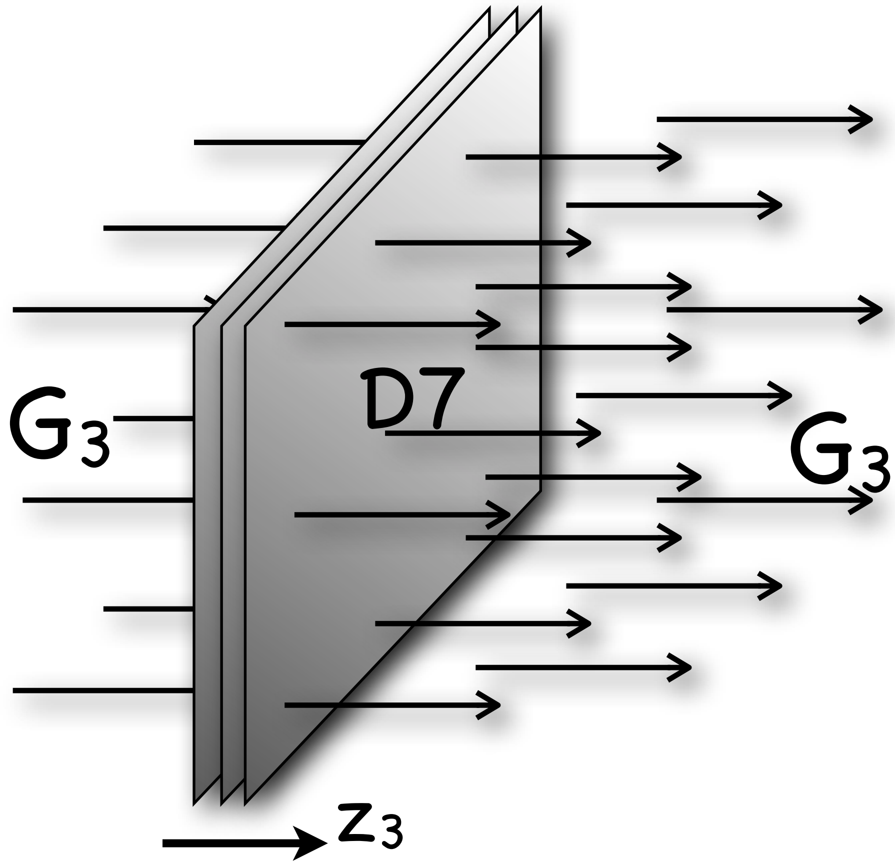
Junction: D6 on X6. Emits k F1’s (Zk strings)

- Can also do Zk domain walls. See later

Fluxes, susy breaking and soft terms

- An appealing scenario: Susy MSSM D-brane sector and non-susy flux
- Soft terms arise from effect of non-susy flux on susy D-branes

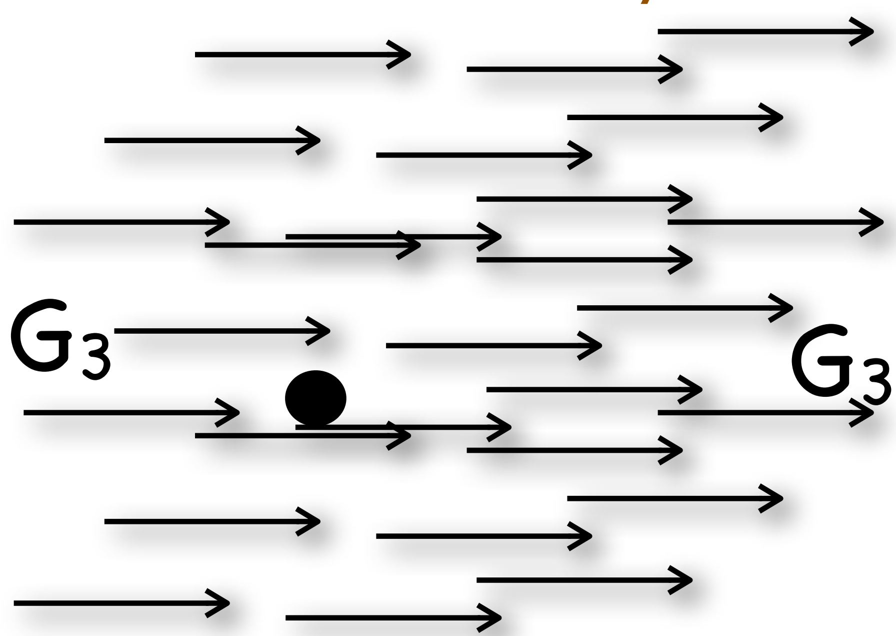
Explicitly computable using D-brane world-volume action in general supergravity background, or using 4d effective theory approach



Fluxes, susy breaking and soft terms

- D3s in ISD 3-form flux background

  ISD flux background: same tension and 4-form charge as a D3-brane
  Gravitational attraction cancels against Coulomb repulsion:
  No terms induced, even for non-susy flux



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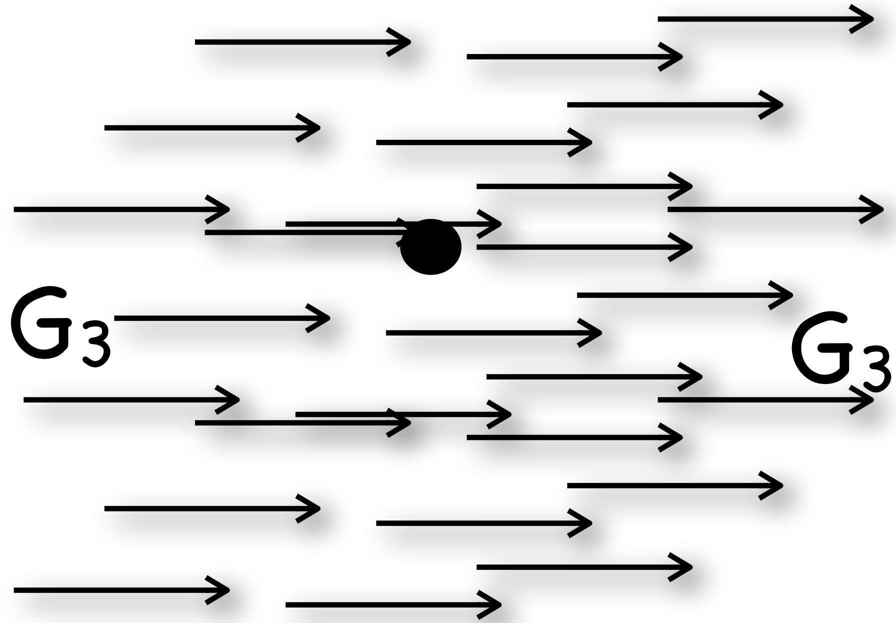

- Anti-D3s in ISD 3-form flux background

  Effects add up instead of cancelling

  Scalars stabilize at max of flux density

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$$m^2 \sim |G_{(0,3)}|^2$$

$$M \sim G_{(0,3)}$$

$$A \sim G_{(0,3)}$$

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Effects add up instead of cancelling

Scalars stabilize at max of flux density

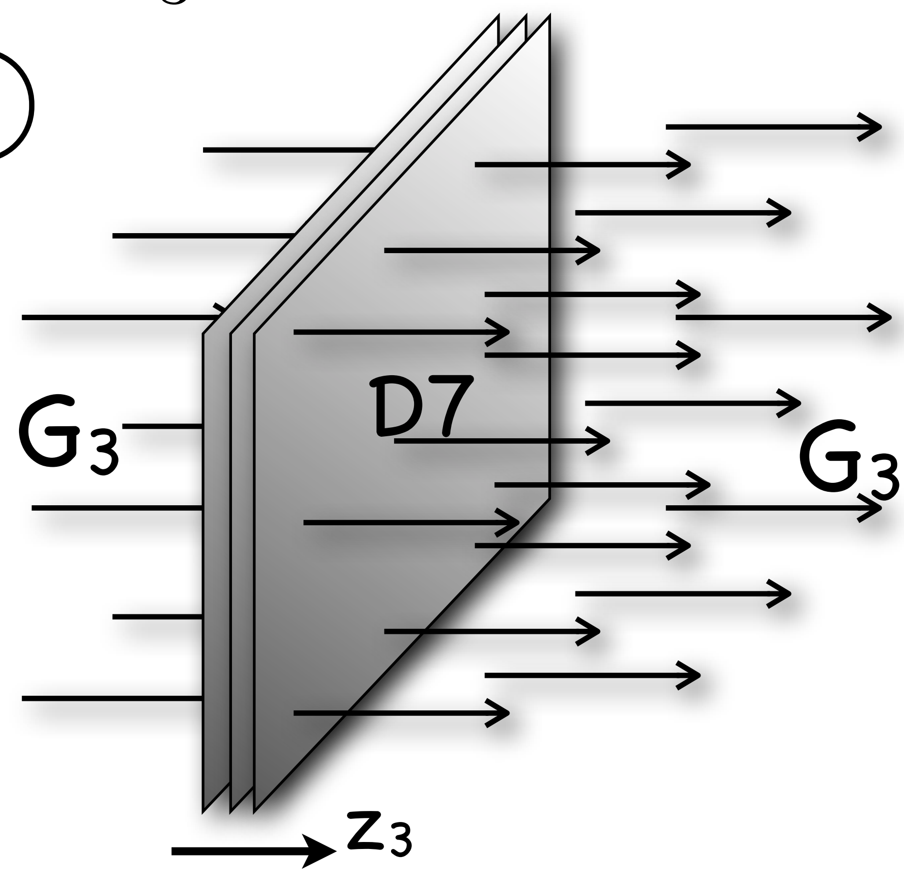
Fluxes, susy breaking and soft terms

- D7s in ISD 3-form flux background

  Same tension and 4-form charge as a D3-brane: naively cancellation
  But flux itself, induces D3 or antiD3 on D7 volume

$$G_3 = \omega_2 \wedge dz_3 + \omega_2' \wedge d\bar{z}_3$$

ISD ASD SD



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ISD ASD SD

- Non-trivial terms, even for ISD flux

  Supersymmetric masses (mu-term): 3-form flux fix D7 moduli

  Soft terms: Similar to those of antiD3s

- Can recover both D3 and D7 results from effective theory

  Flux components are vevs for moduli auxiliary fields: spurions

$$D_\tau W \sim \int_X \overline{G}_3 \wedge \Omega \quad D_{z_i} W \sim \int_X G_3 \wedge \chi_{(2,1),i} \quad D_\rho W \sim \int_X G_3 \wedge \Omega$$

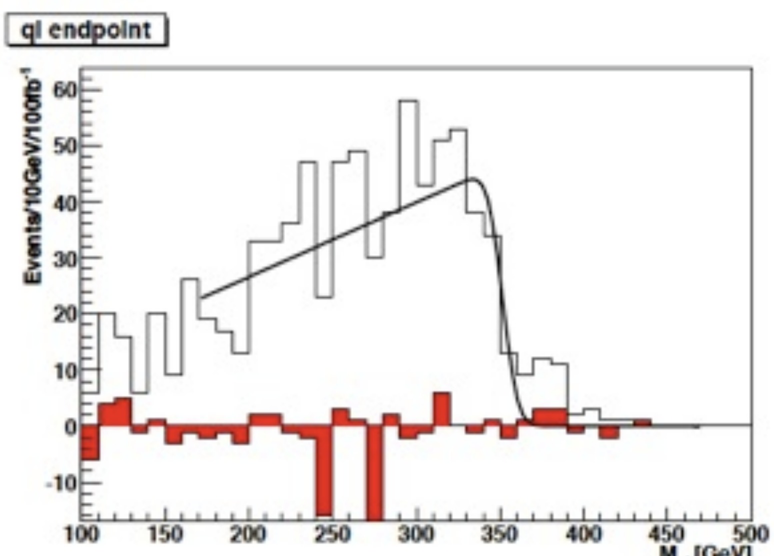
Fluxes, susy breaking and soft terms

- Gravity mediation (in general, not universal, no mSUGRA)
- Scales $$M_{SUSY} \sim f\frac{\alpha'}{R^3} \sim f\frac{M_c^2}{M_p}$$ f: possible local suppression

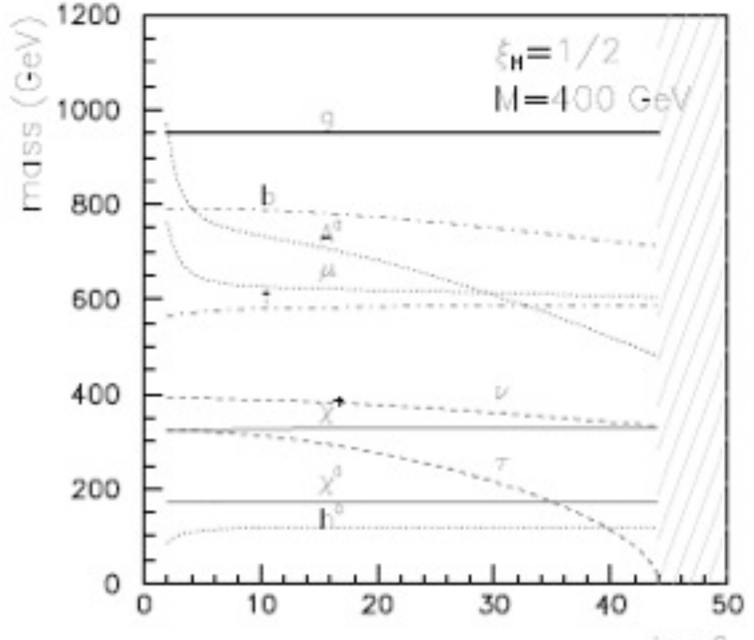
LowE Susy: TeV soft terms from $M_c \sim 10^{11}\text{GeV}$

~~LowE Susy:~~ Choose $M_c \sim 10^{14}\text{GeV}$ then $M_{SUSY} \sim 10^{10}\text{GeV}$

- Can get to make plots



Ex: spectrum reconstruction from edges
Conlon, Kom, Suruliz, Allanach, Quevedo '07

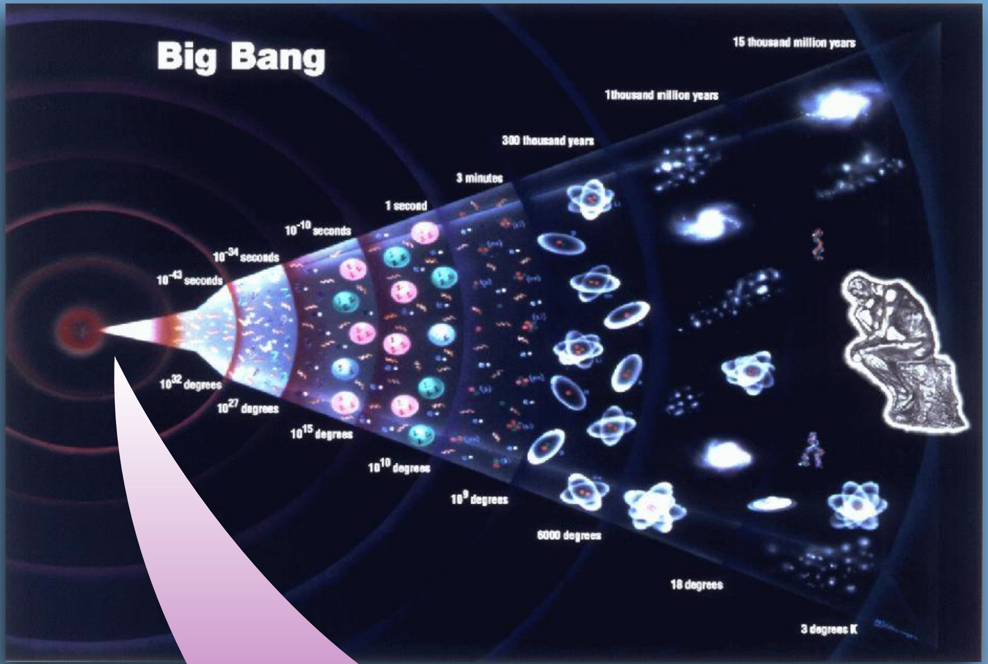


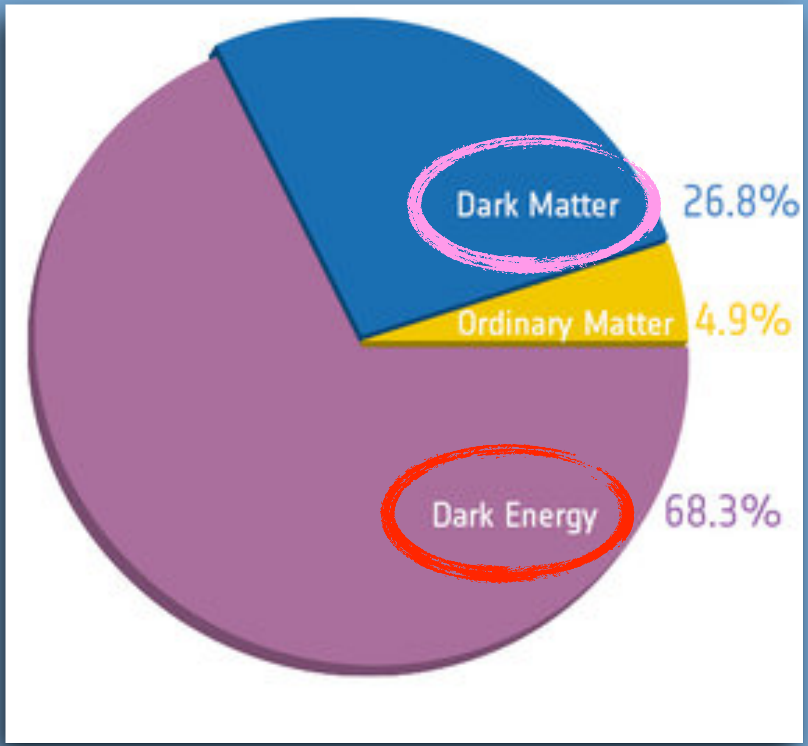
Ex: MSSM parameters Aparicio, Cerdeno, Ibañez '08

Cosmological Standard Model

(ΛCDM, "concordance model")

Flash back





inflation

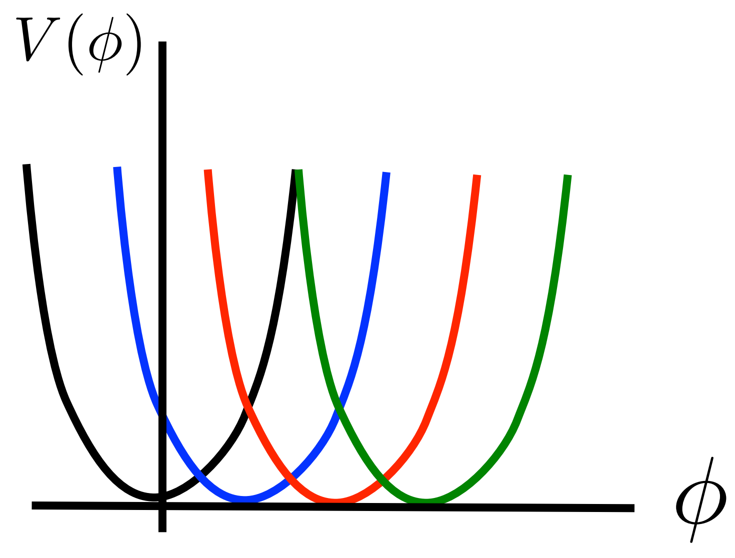
Fluxes, 3-forms and axion monodromy

- Recent interest in large field inflation
- Scalars with shift symmetry (axions) are well protected

  continuous symmetry broken by non-pert effects to a discrete periodicity

- String theory axions have sub-Planckian decay constant

Axion monodromy:
Potential is periodic but multivalued



Field theory analogue:
theta dependent vacuum energy
in large N pure gluodynamics Witten

Discrete Zn gauge symmetries

Flash back

- Discrete gauge symmetries

  Zn particles, Zn strings, ...

- There are Zn gauge symmetries associated to 4d domain walls

  Zn symmetry of a 3-form that eats up a 2-form

$$\frac{1}{2}|F_4|^2 + |db_2 - n\, c_3|^2$$

Gauge invariance

$$c_3 \to c_3 + d\Lambda_2 \quad ; \quad b_2 \to b_2 + n\Lambda_2$$

Discrete Zn gauge symmetries

Flash back

- Discrete gauge symmetries

  Zn particles, Zn strings, ...

- There are Zn gauge symmetries associated to 4d domain walls

  Zn symmetry of a 3-form that eats up a 2-form

$$\frac{1}{2}|F_4|^2 + |db_2 - n\, c_3|^2$$

Gauge invariance

$$c_3 \to c_3 + d\Lambda_2 \quad ; \quad b_2 \to b_2 + n\Lambda_2$$

- Dualizing b2 to an axion, get Kaloper-Sorbo description of axion monodromy models.

Discrete Zn gauge symmetries

Flash back

- 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 $C_3 \to C_3 + d\Lambda_2 \quad ; \quad C_2 \to C_2 + n\Lambda_2$

- Can be dualized to Φ F4 theory

$$|F_4|^2 + n\,\phi F_4 + |d\phi|^2$$

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

$$|d\phi|^2 + \phi^2$$ Massive axion

Can arise in D-brane & flux models

Fluxes, 3-forms and axion monodromy

- Structure is automatic in flux compactifications

After all, fluxes produce the stabilization of axions in moduli!!

10d Chern-Simons ⇒ modified field strengths

$$\int_{10d} B_2 \wedge F_p \wedge F_{p+2} \quad \Rightarrow \quad \tilde{F}_{p+2} = dC_{p+1} + B_2 \wedge F_p$$

Integrating over fluxed CY with $\phi = \int_{\Sigma_2} B_2$, $M = \int_{\Pi_p} F_p$

Change in axion induces extra flux

$$\Delta\phi \to \Delta \int_{\Sigma_2 \times \Pi_p} \tilde{F}_{p+2} = \phi M$$

Fluxes, 3-forms and axion monodromy

- A nice class: axions in flux compactifications

  Change in axion induces extra flux

$$\Delta\phi \to \Delta \int_{\Sigma_2\times\Pi_p} \tilde{F}_{p+2} = \phi M$$

  Kinetic term for (p+2)-form leads to axion potential

  In 4d terms, Kaloper-Sorbo lagrangian

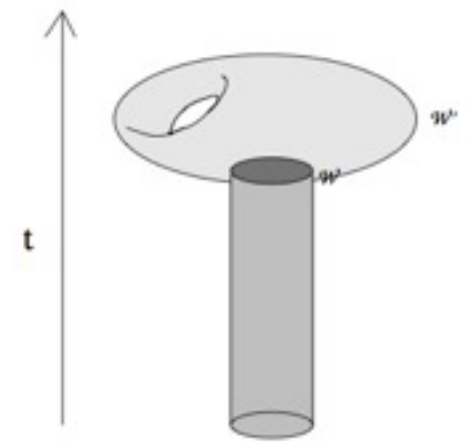
$$\int_{10d} B_2 F_p F_{p+2} \to \int_{4d} M\,\phi\, F_4$$

- Monodromy

  Multiple branches connected by domain walls changing (p+2)-form flux. They are D(6-p) on (4-p)-cycle

Fluxes, 3-forms and axion monodromy

- Many other realizations



Ex: IIB with NSNS flux on A-cycle

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

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

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

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

Period of C0 changes n units of F3 flux on A

4d Domain Wall is D5 on B

4d instanton is D(-1) (cosine modulation)

Conclusions

- It is amazing that something close to the SM can be realized in string theory

- Branes provide a tractable setup for SM model building in string theory

  Not more fundamental, but more manifest geometric intuition

- Program is not closed: Continuous progress

  - Moduli stabilization
  - Neutrino masses, non-perturbative operators
  - Discrete symmetries. Fluxed inflation models.

- Expect continuous progress and new results
  and useful input from LHC & cosmo