EFTs and SUSY BREAKING in IIB WARPED COMPACTIFICATIONS

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MOTIVATION

- Developments in flux compactifications require systematic understanding of
  - space of flux vacua
  - properties of these vacua

- Warping one of many aspects that requires study
  - generic, large number of phenomenological applications
  - discuss steps taken in understanding mass scales, 4D EFT, SUSY Breaking ...

PLAN

- Review IIB flux compactifications and some essential background
- Warping and KK reduction, implications for 4D EFT
- SUSY Breaking
- Summary

IIB Flux Compactifications

- Explicit solutions

Data :

(1) Orientifold of CY_3, with moduli z_α, ρ_α (or F- theory base)

(2) Closed three form flux satisfying Dirac Quantization conditions

(3) Position of D-3 branes

(4) Gauss Law constraint

$$\frac{1}{2k_{10}^2 T_3} \int_{M_6} H_3 \wedge F_3 + Q_3 = 0$$

Solution

- Metric

$$ds^2 = e^{2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu + g_{mn}(y) dy^m dy^n$$

$$= e^{2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} \tilde{g}_{mn}(y) dy^m dy^n$$

- Warp factor

$$-\tilde{\nabla}^2 e^{-4A} = \frac{G_{mnp} \tilde{\bar{G}}^{mnp}}{12 \, \mathrm{Im}\,\tau} + 2\kappa_{10}^2 T_3 \tilde{\rho}_3^{loc}$$

- $\tilde{g}_{mn}$ & τ such that

  $G_3 = -i * G_3$

  condition fixes values of

  z_α, τ, reduces no. of 4-d

  massless degrees of freedom

(4) (4)

Hierarchy from Fluxes:

- Large (but finite) redshifts between points on internal manifold

-
  - conifold singularity on CY_3
  - much like KS solution

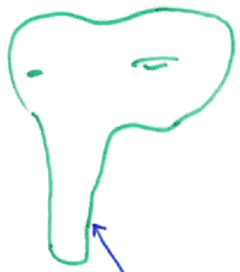
$$\frac{1}{2\pi\alpha'} \int_A F_3 = 2\pi M \qquad \frac{1}{2\pi\alpha'} \int_B H_{(3)} = -2\pi K$$

conifold deformed

$e^{A_m} \sim$ min. value of warp factor

Exponentially small in integer flux choices.

(5) (5)



← bulk $CY_3 \times M_4$

$$\frac{V_{bulk}}{(\alpha')^3} \gg 1$$

warp factor constant

throat $X_5 \times AdS_5$

$$\frac{V_{throat}}{V_{bulk}} \ll 1$$

- RS in string theory
- Such throats fairly generic in compactification

A. Hebecker, J. Russel
0607120

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Volume Modulus:

(S. Giddings
AM 0507158)

$$ds^2 = e^{2A} \eta_{\mu\nu} dx^\mu dx^\nu + e^{-2A} \tilde{g}_{mn} dy^m dy^n$$

$$-\tilde{\nabla}^2 e^{-4A} = \frac{G_{mnp} \tilde{\bar{G}}^{mnp}}{12 \, \mathrm{Im}\, \tau} + 2k_{10}^2 T_3 \tilde{\rho}_3^{loc}$$

- Kahler moduli unfixed
- But for universal kahler modulus

$$\tilde{g}_{mn} \to \lambda \tilde{g}_{mn}$$

$$e^{-2A} \to \frac{1}{\lambda} e^{-2A}$$

$e^{-2A} \tilde{g}_{mn}$ unchanged

- Modulus is associated with

$$e^{-4A} \to e^{-4A} + c$$

⑦

useful convention, fix particular part of e^{-4A},
e^{-4A_0} by

$$\int d^6y \sqrt{\tilde{g}}\, e^{-4A_0} = 0$$

then

- Einstein frame metric

$$ds^2 = \frac{1}{c}\left(e^{-4A_0}+c\right)^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + \left(e^{-4A_0}+c\right)^{1/2}\tilde{g}_{mn}dy^m dy^n$$

- $c \sim \nu^{2/3}$ $\qquad \nu$ volume in string units

- $e^{-4A_0} \to \mathcal{O}(1)$ in bulk

Note:
(1) Throats $e^{-4A_0} \gg c$

geometry independent of volume

(2) Hierarchy (Relative redshift)

$$e^{2H} = \frac{\left(c+e^{-4A_m}\right)^{+1/2}}{\left(c+e^{-4A_0}_{\text{bulk}}\right)^{+1/2}}$$

- $c \to \infty$, $c \gg e^{-4A_m}$ $\qquad e^{2H} \to 1$ (no throats)

$\boxed{\text{Throats, finite volume effects}}$

$$e^{2H} \sim \frac{e^{-2A_m}}{c^{1/2}}$$

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- $c \gg e^{-4A_m}$

EFT ~~[illegible]~~ derived

- moduli

$W = \int G \wedge \Omega \quad \to$ Gukov Vafa Witten

$K = -\ln[-i(\tau-\bar\tau)] - 3\ln[-i(\rho-\bar\rho)]$

$\quad - \ln[-\int \Omega\wedge\bar\Omega]$ (GKP)

- SUSY breaking soft terms

M. Grana, 0209200 $\quad$ Grana, Grimm, Jockers, Louis 0312232
Camara, Ibanez, Uranga 0311241, 0408036
Jockers, Louis 0409098
Colon, Quevedo, Suruliz 0505076

- Wavefunction of excitation same as zero flux case

- $m_{\text{modulus}} \sim \frac{1}{\nu}$ $\qquad m_{KK} \sim \frac{1}{\nu^{2/3}}$ $\qquad \frac{m_{\text{modulus}}}{m_{KK}} \sim \frac{1}{\nu^{1/3}}$

- $\boxed{\text{What happens at smaller volumes? particularly, when we have throats.}}$

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Warping and KK reduction

- Systematics discussed in

  S. Giddings, AM 0507158

  many subtleties,

Qualitative description (using dilaton)

- True eigenfunction no longer zero mode on $\tilde{g}_{mn}$

$$\delta\tau = \delta\tau_0 + \tilde{a}^i_{\tilde{K}\tilde{K}}\, \delta\tau_i^{\tilde{K}\tilde{K}}$$

- Mixing between δz^α and $\delta\tau$
- Mixing between fluxes and $\delta\tau$

→ "small" or "moderate" warping can organize these effects in $\frac{1}{c}$ expansion

→ "large" warping with throats
  - $\frac{e^{-4A_0}}{c} >> 1$ expansion unrelaible
  - strong mixing between zero modes and $\tilde{K}\tilde{K}$ modes, disturbing from 4D EFT

(10) → Need to solve EOM.

Throats and KK reduction:

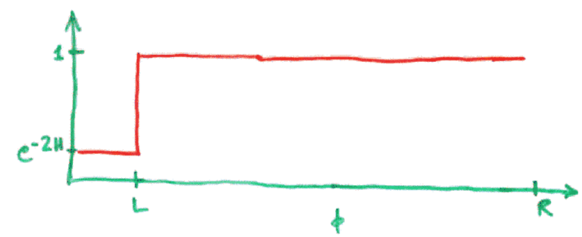
(Andrew Frey, AM 0603233)

- Toy example

$$ds^2 = e^{2A(\phi)} \eta_{\mu\nu} dx^\mu dx^\nu + (d\phi)^2 \qquad 0 < \phi < R$$

$$A(\phi) = 0 \qquad L < \phi < R \qquad \text{Region I}$$

$$A(\phi) = -H \qquad 0 < \phi < L \qquad \text{Region II}$$



- $\frac{L}{R} << 1$, $H >> 1$ is a throat
- scalar "τ"
  with 5d mass ${}^{(5)}M$
  and Neumann boundary conditions.

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- Dimensionally reduce

  $T_n(\phi)$ wavefunction

  ${}^{(4)}m_n$ 4-d mass

- Eigenvalue problem

$$-\frac{d^2}{d\phi^2} T_n = \left({}^{(4)}m_n^2 e^{2H} - M^2\right) T_n \quad \text{Region I}$$

$$-\frac{d^2}{d\phi^2} T_n = \left({}^{(4)}m_n^2 - M^2\right) T_n \quad \text{Region II}$$

- There can be bound states (much like QM)

$m_n^2 e^{2H} - M^2 > 0$

but, $m_n^2 - M^2 < 0$

oscillatory only in the throat region (localized modes)

~~apart from usual modes~~

Both quantities positive ~ bulk modes

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4D masses solutions to following equations (matching conditions at interface)

- $$\left.\begin{aligned} & e^{-4H}\sqrt{e^{2H}m_n^2 - M^2}\,\tan\left(\sqrt{e^{2H}m_n^2 - M^2}\,L\right) \\ & = \sqrt{M^2 - m_n^2}\,\tanh\left(\sqrt{M^2 - m_n^2}\,(R-L)\right) \end{aligned}\right\}\ \text{localized modes}$$

- $$\left.\begin{aligned} & e^{-4H}\sqrt{e^{2H}m_n^2 - M^2}\,\tan\left(\sqrt{e^{2H}m_n^2 - M^2}\,L\right) \\ & = \sqrt{m_n^2 - M^2}\,\tan\left(\sqrt{m_n^2 - M^2}\,(L-R)\right) \end{aligned}\right\}\ \text{bulk modes}$$

Spectrum best understood in terms of a plot ....

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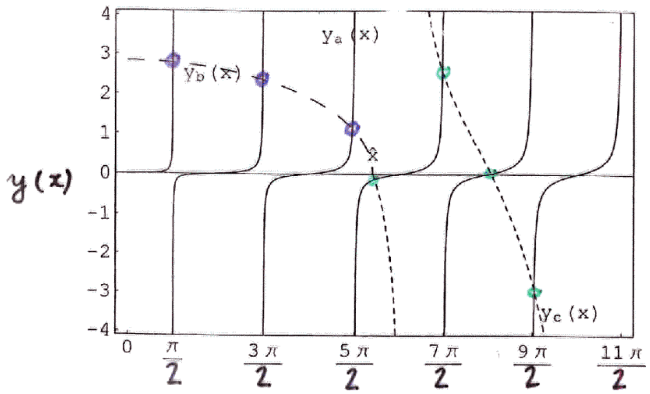

$$x = \sqrt{e^{2H} \, {}^{(4)}m^2 - M^2}$$

- Intersection between bold and dashed curves gives the spectrum

- : $\hat{x}$ cross over between localized and bulk modes

$$\hat{x} = \left(\sqrt{e^{2H} - 1}\right) LM$$

- As warping increased, $\hat{x}$ moves to the right

$\boxed{\text{bulk modes smoothly converted to localized modes}}$

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- Spectrum

$${}^{(4)}m_n^2 = e^{-2H} M^2 \left[1 + \frac{x_n^2}{M^2 L^2} \right]$$

Intersection at every interval of π

$ML \sim O(1)$

-
  - → $m_0 \sim e^{-H} M$
  - → $\frac{\Delta M}{M_0} = \frac{M_1 - M_0}{M_0} \sim 1$
  - → low lying spectrum highly localized
  - → $[e^H]$ localized modes

- Dilaton, dynamics in IIB flux vacua similar.

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Modeling the Dilaton :

- Assume
  (a) Dependence on single radial direction
  (b) Ignore mixing (for now)

- Equation for fluctuations of the dilaton

$$\left(\tilde{\nabla}^2 + e^{-4A} m_4^2 - g_s e^{4A} \frac{G_{mnp} \bar{\tilde{G}}^{mnp}}{12} \right) \delta\tau = 0$$

- After

$$dx = e^{-2A} dr \qquad \delta\tau = e^{-3A/2} \psi$$

Schrödinger form

$$\left(-\partial_x^2 + V(x) \right) \psi(x) = m^2 \psi(x)$$

with

$$V(x) = e^{-3A/2} \partial_x^2 e^{3A/2} + e^{2A} \frac{g_s}{12} G_{mnp} \bar{G}^{mnp}$$

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- Potential

$$V(x) = e^{-3A/2} \partial_x^2 e^{3A/2} + e^{8A} \frac{g_s}{12} G_{mnp} \bar{G}^{mnp}$$

Local function of the warp factor and fluxes. Semi-classical estimates

→ Throat
known throat geometries
Klebanov & Tseytlin
0002159
S. Franco et. al
0502113

$$\mathcal{E}_{thrt} \sim \frac{e^{2A_m}}{n'^2 \nu^{2/3}}$$

→ Bulk
scaling of potential $\mathcal{E}_{bulk} \sim \frac{1}{\nu^2}$

- Competition between volume and warping
  for $e^{-A_m} > \nu^{2/3}$
  wavefunctions localize

$$m_\tau \sim \frac{e^{A_m}}{n_f' \nu^{1/3}}$$

Goldberg & Wise
hep-ph/9907218
"Massive bulk scalar in RS"

Robust - models - numerical checks

Spectrum and Wavefunctions :

- $c \gg e^{-4A_m}$

wavefunction uniformly spread $\quad m_\tau \sim \frac{1}{\nu} \quad m_{KK} \sim \frac{1}{(\nu)^{2/3}}$

- Decrease "c" adiabatically

wavefunctions and mass change continously

$\rightarrow \quad c < e^{-4A_m}$ throat develops

$\rightarrow \quad c < e^{-A_m}$ wave functions localized

$m_\tau \sim \frac{e^{A_m}}{n' \nu^{1/3}} \sim m_{KK}$

warped string scale

$m_s^w \sim g_s^{1/4} \frac{e^{A_m}}{\nu^{1/3}}$

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Comments

- 4D EFT in ~~long~~ ~~throat~~ strong warping regime

Gukov Vafa Witten (GVW) Superpotential :

" dynamics of moduli with other modes integrated out "

$\rightarrow$ localization upon adiabatic change in volume suggest

GVW valid for light modes localized in long throats

But $\frac{\Delta m}{m} \sim 1$, would need to integrate out along with KK modes. Leaving clasically massless Kahler Moduli.

- Mixing of $\tilde{K}\tilde{K}$ modes energetically favourable, fourier decomposition of localized wavefunction will have $\tilde{K}\tilde{K}$ mode

$e^{-A_m} > c$

competition between localization & $\tilde{K}\tilde{K}$ energy.

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Susy Breaking :

(C. Burgess, P. Camara
S de Alwis, S. Giddings
AM, F. Quevedo
K. Suruliz 0610255)

- Susy broken by (0,3) flux, gravitino acquires a mass by super-higgs effect.

- IIB gravitino equations of motion

$$\Gamma^{MNP} \hat{D}_N \Psi_P = -\frac{i}{2} \Gamma^P \Gamma^M \hat{\lambda}^* P_P - \frac{i}{48} \Gamma^{NPQ} \Gamma^M \hat{\lambda} G^*_{NPQ}$$

$$\hat{D}_N \Psi_P = D_N \Psi_P - R_P \Psi_N - S_P \Psi_N^*$$

$$R_M = \frac{i}{480} \left(\Gamma^{M_1 \dots M_5} F_{M_1 \dots M_5} \right) \Gamma_M$$

$$S_M = \frac{1}{96} \left(\Gamma_M{}^{NPQ} G_{NPQ} - 9 \Gamma^{NP} G_{MNP} \right)$$

$$P_M = \frac{1}{1 - BB^*} \partial_M B \qquad B = \frac{1 + i\tau}{1 - i\tau}$$

- After estimating size of various terms, mixing of 10d modes. Relevant dynamical equation

$$(\nu)^{2/3} \gamma^{\mu\nu\rho} \partial_\nu \psi_\rho \otimes \eta(y) + \frac{1}{24} \gamma^{\mu\nu} \psi_\nu^* \otimes e^{4A} G_{mnp} \gamma^{\widetilde{mnp}} \eta^* + \dots = 0$$

$$\Psi^{\mu}_{10}(x, y) = \psi^\mu(x) \otimes \eta(y)$$

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- Comparing the size of kinetic and mass terms,

$$e^{-A_m} > \nu^{2/3}$$

$$m_{\frac{3}{2}} \sim \frac{e^{A_m}}{\nu^{1/3}}$$

- $m_{\frac{3}{2}}$ same as the kk scale?
Can we use a N=1 D=4 Sugra formalism ?

- Exploit the existence of a SUSY limit ($N_0 \to 0$)
For the lightest gravitino $m \to 0$, while others remain at the kk scale

- Recall that in KKLT
$N_0 \to 0$
to control the α' corrections to the kahler potential.

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- $m_{\frac{3}{2}} = e^{K/2}|W|$

$(\mathcal{V})^{2/3} > e^{-4A_m}$ $\qquad m_{\frac{3}{2}} \sim \frac{|W|}{\mathcal{V}}$

$$K \sim -2\log\mathcal{V} = -3\log(\rho+\bar{\rho})$$

$e^{-A_m} > (\mathcal{V})^{2/3}$ $\qquad m_{\frac{3}{2}} \sim \frac{e^{A_m}}{\mathcal{V}^{1/3}}|W|$

$$K \sim 2A_m - \frac{2}{3}\log\mathcal{V}$$

- In general expect an interpolating formula with expansion parameter of size $\frac{e^{-A_m}}{\mathcal{V}^{2/3}}$ can write many interpolations

- Kahler potential for $e^{-A_m} > (\mathcal{V})^{2/3}$ does not seem to respect no-scale structure, but we expect important corrections in the def^n of holomorphic coordinates.

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Susy Breaking in microscopic theory:

D3, D-7 branes in warped environment

- Single D3

$$\to S_3 = -|\mu_3|\int d^4x\, e^{-\phi}\sqrt{-\det(P(E))} + \mu_3\int P[C_4]$$

$$E_{MN} = g_{MN} + B_{MN}$$

$$\to S_3 = -\int d^4x \left\{ |\mu_3|\frac{1}{2(\mathcal{V})^{2/3}}\tilde{g}_{mn}\partial_\mu Y^m \partial^\nu Y^n + |\mu_3|\frac{1}{(\mathcal{V})^{4/3}}e^{4A} - \mu_3 C_{0123} \right\}$$

$$\to V = \frac{1}{(\mathcal{V})^{2/3}}e^{4A} - (\mathcal{V})^{2/3}C_{0123}$$

- Trace of mass matrix

$$\tilde{g}_{mn}^{mn}\partial_m\partial_n V = \frac{1}{(\mathcal{V})^{2/3}}\tilde{\nabla}^2\left(e^{4A} - (\mathcal{V})^{4/3}C_{0123}\right)$$

$$= \frac{1}{(\mathcal{V})^{2/3}}\cdot\frac{1}{24\,\mathrm{Im}\,\tau}\cdot e^{8A}G_{AISD}\,\tilde{\cdot}\,\bar{G}_{AISD}$$

(non ISD fluxes)

$$m \sim \frac{1}{(\mathcal{V})^{1/3}}e^{A_m}$$

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- D-7 branes, similar calculation following

P. Camara, L. Ibanez, A. Uranga 0408036

mass generated by flux contribution

$$m \sim \frac{e^{A_m}}{\gamma^{1/3}} \qquad \text{susy or non-susy}$$

4D Effective description:

- Primarily focus on warping dependence

- Soft Susy breaking terms:

$$K = \hat{K}(h,h^*) + \tilde{K}_{a\bar{b}}(h,h^*)\, \ell^a \ell^{\bar{b}} + \frac{1}{2} Z_{ab}(h,h^*)\, \ell^a \ell^b$$

superpotential $\sim W$ gauge kinetic functions $\sim F_{AB}$

- Hidden sector auxiliary vevs. (Brignole, Ibanez & Munoz, Kaplunovsky & Louis)

$$F^m = e^{G/2} K^{m\bar{n}} \partial_{\bar{n}} G, \quad G = e^{\frac{K}{2}} |W|$$

scalar $$m^2_{a\bar{b}} = \left(m^2_{3/2} + V_0\right) \tilde{K}_{ab} - F^m F^n \left(\partial_m \partial_{\bar{n}} \tilde{K}_{a\bar{b}} - \tilde{K}^{c\bar{d}} \partial_m \tilde{K}_{a\bar{d}} \partial_n \tilde{K}_{c\bar{b}}\right)$$

gaugino $$M_{AB} = \frac{1}{2} \left[(\mathrm{Re}\, F)^{-1} \right]_{AC} F^m \partial_m F_{CB}$$

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- D3, D7 Kahler potential

$$\mathcal{K} = 2A_m + K(\phi,\phi^*) + K_Y(\phi,\phi^*)\, Y^* Y + K_{\tilde{Y}^a}(\phi,\phi^*)\, \tilde{Y}^{a*} \tilde{Y}^a$$

Y - D7 complex scalar

$\tilde{Y}^a$ - D3 complex scalar $a = 1..3$

- SUSY case

superpotential acquires D-7 brane modulus dependence

$$W = W_{GVW} + \frac{\omega(\phi)}{2} Y^2$$

$$V = e^K \frac{|\omega Y|^2}{K^Y}$$

- Broken SUSY

soft mass

$$m_Y^2 = m^2_{\frac{3}{2}} - F^m F^{\bar{n}} \partial_m \partial_{\bar{n}} \ln K_Y$$

- Both cases the powers of the warp factor in the RHS agree with the microscopic computation.

Summary :

- Warping generic feature in IIB flux compactification with many phenomenological applications.

- Has important effects on 4D EFT when

$$\nu^{2/3} < e^{-A_m}$$

redshifting of masses, localization of wavefunctions

- Gravitino also exhibits similar behavior, for $W_0 \sim 1$, SUSY breaking 10 D. For $W_0 << 1$, can study soft terms by adding a term linear in A_m to the Kahler potential

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