30 Nov. 2017 @ IBS, CPTU

Visible and hidden sectors in magnetized D-brane systems

Keigo SUMITA (角田慶吾)

Waseda University (早稲田大学)

Based on

- Phys. Rev. D96 (2017) no.2, 026019
- Recent development (work in progress)

In collaboration with

- Hiroyuki Abe (Waseda University)
- Tatsuo Kobayashi (Hokkaido University)
- Shohei Uemura (Kyoto Sangyo University)

Outline

1. Introduction
2. Review : magnetized toroidal orbifold
3. SYM system and Superfield description
4. Model : MSSM sector
5. Model : MSSM+SUSY breaking
6. Model : MSSM+SUSY breaking + Moduli stabilization
7. Summary

Introduction : Superstring theory

- Incorporate the gravity into the elementary particles
- Quantum gravity without inconsistency
- Gauge theories (the SM?)

The most promising candidate for “the final theory”

- String phenomenology
- 4D effective theory consistent with the SM
- Hidden sector

Introduction : Extra dimensional space

- Superstrings predict 6D extra space
- 4D chiral spectrum vs Higher dimensional SUSY
- Origin of the flavor structure

Toroidal compactification with Magnetic fluxes and orbifolding

- Generations of chiral fermions
- Calculable spectrum : Hierarchical Yukawa couplings

Bachas '95
Cremades, Ibanez, Marchesano '04
Abe, Kobayashi, Ohki '04
Abe, Choi, Kobayashi, Ohki '09

Introduction : D-brane system

- D-branes in type IIB superstrings
- Effective Super-Yang-Mills (SYM) theories

  - U(N) gauge group
  - 4D,6D,8D,10D and their mixtures

Higher-dimensional U(N) SYM theories
compactified on Magnetized Toroidal Orbifolds

- MSSM
- SUSY breaking
- Moduli stabilization

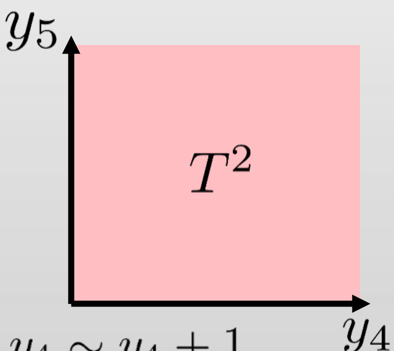
Review : 6D U(2) SYM on magnetized T^2

$$\mathcal{L} = \frac{1}{4g^2}\mathrm{Tr}\left(F^{MN}F_{MN}\right) + \frac{i}{2g^2}\mathrm{Tr}\left(\bar{\lambda}\Gamma^M D_M \lambda\right)$$

$$F_{MN} = \partial_M A_N - \partial_N A_M - i\,[A_M, A_N]$$
$$D_M \lambda = \partial_M \lambda - i\,[A_M, \lambda]$$

- Torus periodicity and KK mode expansion

$$X_M = (x_\mu, y_m), \qquad \mu : 0,1,2,3, \quad m = 4,5$$



$$y_4 \sim y_4 + 1$$
$$y_5 \sim y_5 + 1$$

$$A_M(x^\mu, y^m) = \sum_n \varphi_{n,M}(x^\mu) \times \phi_{n,M}(y^m)$$

$$\lambda(x^\mu, y^m) = \sum_n \chi_n(x^\mu) \times \psi_n(y^m)$$

Cremades, Ibanez, Marchesano '04

Review : 6D U(2) SYM on magnetized T^2

- Constant Abelian Flux on T^2

$$F_{45} = 2\pi M$$ Gauge potential $A_4 = 0, \quad A_5 = 2\pi M y_4$

- Gauge symmetry breaking : U(2) → U(1) × U(1)

$$M = \begin{pmatrix} M_a & 0 \\ 0 & M_b \end{pmatrix} \qquad (M_a, M_a \in Z)$$

- Zero mode equation

$$\psi_0 = \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

$$i\Gamma_m D^m \psi_0(y) = 0$$

$$\downarrow$$

$$\psi_+ = \begin{pmatrix} \psi_+^{aa} & \psi_+^{ab} \\ \psi_+^{ba} & \psi_+^{bb} \end{pmatrix}$$

$$[\partial_4 \pm i\partial_5 \pm 2\pi (M_a - M_b) y_4] \psi_\pm^{ab} = 0$$

$$[\partial_4 \pm i\partial_5] \psi_\pm^{aa} = 0$$ (Trivial)

Cremades, Ibanez, Marchesano ’04

Review : 6D U(2) SYM on magnetized T^2

$$[\partial_4 + i\partial_5 + 2\pi\,(M_a - M_b)\,y_4]\,\psi_+^{ab} = 0$$

$$[\partial 4 - i\partial_5 - 2\pi\,(M_a - M_b)\,y_4]\,\psi_-^{ab} = 0$$

For $M_{ab} \equiv M_a - M_b > 0$

$$\begin{cases} \psi_+^{ab} \text{ has } M_{ab} \text{ degenerate zero-modes} \\ \psi_-^{ab} \text{ has no zero-modes} \end{cases}$$

- Chirality projection
- Degenerate zero-modes :

generations of quarks and leptons

Cremades, Ibanez, Marchesano '04

Review : 6D U(2) SYM on magnetized T^2

- Zero-mode wavefunction (Cremades, Ibanez, Marchesano '04)

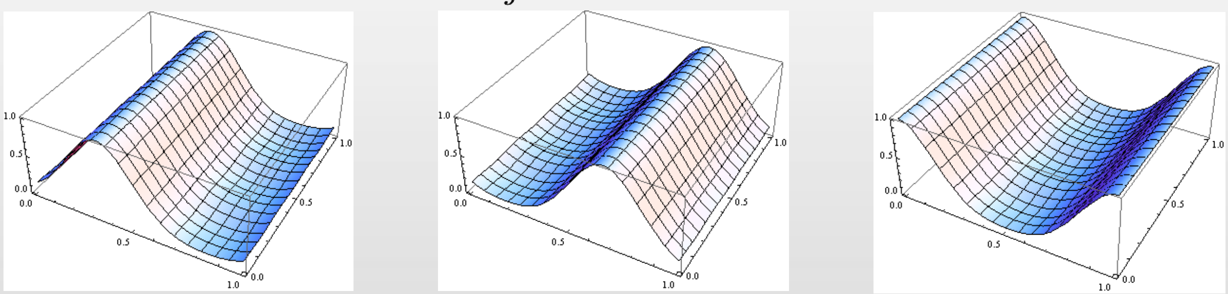
$$\Theta^{j,M_{ab}}(y_4,y_5) = \mathcal{N}_j e^{-M_{ab}\pi y_4^2}\cdot \vartheta \begin{bmatrix} j/M_{ab} \\ 0 \end{bmatrix} (-M_{ab} i\,(y_4+iy_5)\,, M_{ab} i)$$

$$j = 1, \ldots, M_{ab}$$

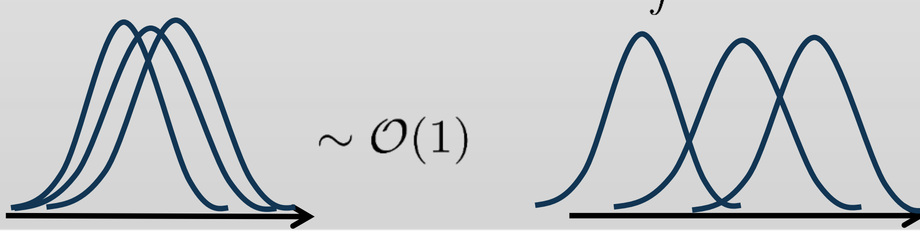
Jacobi theta function

$$\vartheta \begin{bmatrix} a \\ b \end{bmatrix} (\nu,\tau) = \sum_{l\in\mathbb{Z}} e^{\pi i (a+l)^2\tau} e^{2\pi i (a+l)(\nu+b)}.$$

- Quasi-localization : $|\Theta_j^M|^2$ for $M=3$



- Hierarchical Yukawa couplings : $y_{IJK} = \int dy^2\ \Theta^{I,M_{ab}}(y)\Theta^{J,M_{bc}}(y)\Theta^{I,M_{ca}}(y)$



$\sim \mathcal{O}(1)$ $\qquad$ $\sim \mathcal{O}(10^{-5})$

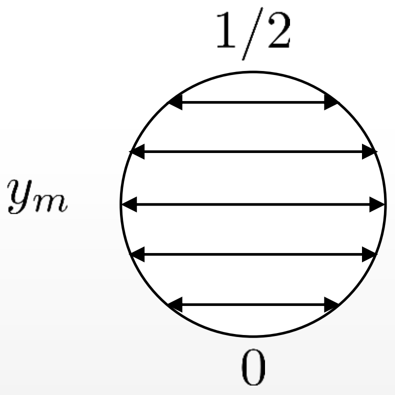
Arkani-Hamed, Schmaltz '00

Review : Magnetized T^2 with Z_2 orbifolding

- Z_2 orbifold : $(y_4, y_5) \sim (-y_4, -y_5)$

$$\psi_\pm(x_\mu, -y_m) = \pm P\psi_\pm(x_\mu, y_m)P^{-1}$$

Projection operator : $P^2 = 1$



- Z_2 even and odd zero-modes

$$j = 1, 2, \ldots, M$$

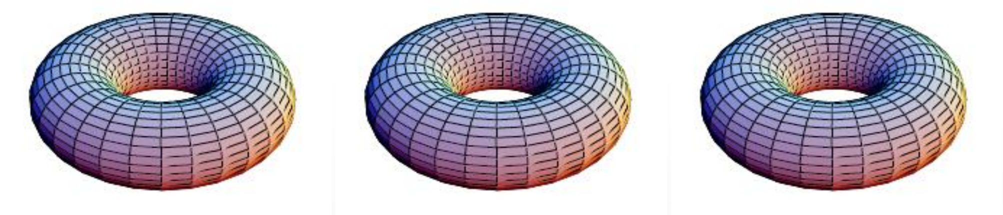
$$\psi^j(y) \rightarrow \begin{cases} \psi^j_{\text{even}}(y) = \frac{1}{\sqrt{2}}\left(\psi^j(y) + \psi^{M-j}(y)\right) \\ \psi^j_{\text{odd}}(y) = \frac{1}{\sqrt{2}}\left(\psi^j(y) - \psi^{M-j}(y)\right) \end{cases}$$

M	0	1	2	3	4	5	2n	2n+1
Pure T^2	1	1	2	3	4	5	2n	2n+1
Even	1	1	2	2	3	3	n+1	n+1
Odd	0	0	0	1	1	2	n-1	n

Abe, Kobayashi, Ohki '08

SYM systems
and
Superfield description

Toroidal compactification



- Torus parameter : $(R_i, \tau_i) \quad i \ : \ 1,2,3$
- Complex coordinate : $z^i \equiv \frac{1}{2}\left(y^{2+2i} + \tau_i y^{3+2i}\right) \qquad \bar{z}^{\bar{i}} \equiv \left(z^i\right)^*$
- Periodicity : $z_i \sim z_i + 1 \qquad z_i \sim z_i + \tau_i$

$$ds^2 = G_{MN} dX^M dX^N = \eta_{\mu\nu} dx^\mu dx^\nu + 2h_{i\bar{j}} dz^i d\bar{z}^{\bar{j}}$$

$$h_{i\bar{j}} = 2(2\pi R_i)^2 \delta_{i\bar{j}}$$

Superfield description of D-brane systems

- Higher-dimensional SYM theory : D = 4, 6, 8, 10
- 10D SYM compactified on $T^2 \times T^2 \times T^2$
- 4D N=1 decomposition of 10D fields

$$A_M = (A_\mu,\ A_i) \qquad\qquad i\ :\ 1,2,3$$

$$\lambda = (\lambda_0,\ \lambda_i) \qquad\qquad A_i \equiv -\frac{1}{\mathrm{Im}\tau_i}\left(\bar{\tau}_i A_{2+2i} - A_{3+2i}\right)$$

4D N=1 vector superfield $\quad V \equiv -\theta\sigma^\mu\bar{\theta}A_\mu + i\bar{\theta}\bar{\theta}\theta\lambda_0 - i\theta\theta\bar{\theta}\bar{\lambda}_0 + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D$

4D N=1 chiral superfield $\quad \phi_i \equiv \frac{1}{\sqrt{2}}\varphi_i + \sqrt{2}\theta\lambda_i + \theta\theta F_i$

$$\mathcal{K} = \frac{2}{g^2}h^{i\bar{j}}\mathrm{Tr}\left[\left(\sqrt{2}\bar{\partial}_{\bar{i}} + \bar{\phi}_{\bar{i}}\right)e^{-V}\left(-\sqrt{2}\partial_j + \phi_j\right)e^V + \bar{\partial}_{\bar{i}}e^{-V}\partial_j e^V\right]$$

$$\mathcal{W} = \frac{1}{g^2}\epsilon^{\mathrm{ijk}}e_{\mathrm{i}}{}^{i}e_{\mathrm{j}}{}^{j}e_{\mathrm{k}}{}^{k}\mathrm{tr}\left[\sqrt{2}\phi_i\left(\partial_j\phi_k - \frac{1}{3\sqrt{2}}[\phi_j,\phi_k]\right)\right]$$

Marcus, Sagnotti, Siegel ’83
Arkani-Hamed, Gregoire, Wacker ’02

Superfield description of D-brane systems

- D=4,6,8 are obtained by dimensional reduction of D=10
- Some of ϕ_i becomes the position modulus
- Overlap of different SYMs requires additional multiplets
- Magnetized toroidal orbifold compactification and

  4D effective actions in the superfield desctirption

Abe, Kobayashi, Ohki, K.S. '12
Abe, Horie, K.S. '15

Model : MSSM sector

MSSM sector : two typical models

- Two typical models : D9 model vs D7 model
- Massless open string moduli

  - D9 contans some harmful massless modes
- Association with hidden sectors

  - D9 inevitably overlaps hidden D-branes

D7 model

8D $\mathrm{U}(4)_{\mathrm{A}}$ SYM on $T^2 \times T^2 \times T^2$
and
8D $\mathrm{U}(4)_{B}$ SYM on $T^2 \times T^2 \times T^2$

- Field contents

Position modulus

A sector : $\mathrm{U}(4)_{\mathrm{A}}$ adjoint $\phi_1^A,\ \tilde{\phi}_2^A,\ \phi_3^A$

B sector : $\mathrm{U}(4)_{\mathrm{B}}$ adjoint $\phi_1^B,\ \phi_2^B,\ \tilde{\phi}_3^B$

A-B sector : Bi-fundamental $\phi_2^{AB},\ \phi_3^{BA}$

$(\mathbf{4},\overline{\mathbf{4}})$ of $\mathrm{U}(4)_{\mathrm{A}} \times \mathrm{U}(4)_{\mathrm{B}}$

D7 model

- Magnetized background

$$M_A^{(1)} = \begin{pmatrix} -5\times \mathbf{1}_3 & 0 \\ 0 & -4 \end{pmatrix}, \qquad M_A^{(3)} = -M_A^{(1)}$$

$$M_B^{(1)} = \begin{pmatrix} 0\times \mathbf{1}_2 & 0 \\ 0 & -12\times \mathbf{1}_2 \end{pmatrix}, \qquad M_B^{(2)} = \begin{pmatrix} 0\times \mathbf{1}_2 & 0 \\ 0 & 1\times \mathbf{1}_2 \end{pmatrix}$$

- Gauge symmetry breaking

$$U(4)_A \to U(3)_C \times U(1)_\ell$$
$$U(4)_B \to U(2)_L \times U(2)_R$$

- 4D N=1 Supersymmetry

$$F_i = D_L = 0 \qquad D_C = D_\ell = \frac{-5}{\mathcal{A}_1} + \frac{5}{\mathcal{A}_3} \qquad D_R = \frac{-12}{\mathcal{A}_1} + \frac{1}{\mathcal{A}_2}$$

$$\Leftrightarrow \quad \mathcal{A}_1/\mathcal{A}_2 = 12, \qquad \mathcal{A}_1/\mathcal{A}_3 = 1$$

D7 model

$$Z_2 \;:\; (z_1, z_2, z_3) \;\to\; (-z_1, -z_2, z_3)$$
$$Z_2' \;:\; (z_1, z_2, z_3) \;\to\; (z_1, -z_2, -z_3)$$

- Orbifold transformation : $P_A,\, P_A',\, P_B,\, P_B',$

$$\begin{aligned} Z_2 \;:\; & \phi^A_{1,2} \to -P_A \phi^A_{1,2} P_A^{-1}, && \phi^A_3 \to +P_A \phi^A_3 P_A^{-1} \\ & \phi^B_{1,2} \to -P_B \phi^B_{1,2} P_B^{-1}, && \phi^B_3 \to +P_B \phi^B_3 P_B^{-1} \\ & \phi^{AB}_2 \to -P_A \phi^{AB}_2 P_B^{-1}, && \phi^{BA}_3 \to +P_B \phi^{BA}_3 P_A^{-1} \end{aligned}$$

$$\begin{aligned} Z_2' \;:\; & \phi^A_{2,3} \to -P_A' \phi^A_{2,3} {P'}_A^{-1}, && \phi^A_1 \to +{P'}_A \phi^A_1 {P'}_A^{-1} \\ & \phi^B_{2,3} \to -P_B' \phi^B_{2,3} {P'}_B^{-1}, && \phi^B_1 \to +{P'}_B \phi^B_1 {P'}_B^{-1} \\ & \phi^{AB}_2 \to -P_A' \phi^{AB}_2 {P'}_B^{-1}, && \phi^{BA}_3 \to -{P'}_B \phi^{BA}_3 {P'}_A^{-1} \end{aligned}$$

$$P_A = P_A' = P_B = -P_B' = \mathbf{1}_4$$

D7 model : zero-mode contents

$$\phi_1^B = \begin{pmatrix} 0 & H \\ 0 & 0 \end{pmatrix}, \qquad \phi_2^{AB} = \begin{pmatrix} Q_L & 0 \\ L_L & 0 \end{pmatrix}, \qquad \phi_3^{BA} = \begin{pmatrix} 0 & 0 \\ Q_R & L_R \end{pmatrix}$$

$$\phi_1^A,\ \tilde{\phi}_2^A,\ \phi_3^A,\ \phi_2^B,\ \tilde{\phi}_3^B = 0$$

- Three generations of $Q_L,\ L_L,\ Q_R,\ L_R$
- Five generations of $H = (H_u,\ H_d)$
- Hopeful spectrum : $\mathrm{Im}\,\tau_1 = 1.5$ $\quad \frac{\langle H_{u4}\rangle}{\langle H_{u5}\rangle} = 0.29 \quad \frac{\langle H_{d4}\rangle}{\langle H_{d5}\rangle} = 0.38 \quad \frac{\langle H_{d3}\rangle}{\langle H_{d5}\rangle} = 0.10$

	Sample values	Observed
$(m_u, m_c, m_t)/m_t$	$(1.7\times10^{-5}, 5.7\times10^{-3}, 1)$	$(1.5\times10^{-5}, 7.5\times10^{-3}, 1)$
$(m_d, m_s, m_b)/m_b$	$(2.0\times10^{-3}, 6.8\times10^{-2}, 1)$	$(1.2\times10^{-3}, 2.3\times10^{-2}, 1)$
$(m_e, m_\mu, m_\tau)/m_\tau$	$(2.7\times10^{-4}, 5.9\times10^{-2}, 1)$	$(2.9\times10^{-4}, 6.0\times10^{-2}, 1)$
$\lvert V_{\mathrm{CKM}}\rvert$	$\begin{pmatrix} 0.96 & 0.29 & 0.01 \\ 0.29 & 0.96 & 0.07 \\ 0.01 & 0.07 & 1.0 \end{pmatrix}$	$\begin{pmatrix} 0.97 & 0.23 & 0.0035 \\ 0.23 & 0.97 & 0.041 \\ 0.0087 & 0.040 & 1.0 \end{pmatrix}$

Abe, Kobayashi, Tatsuta, K.S. '14

MSSM+SUSY breaking

Dynamical Supersymmetry Breaking (DSB)

- SYM system : restricted field contents and their couplings
- Supersymmetric $SU(N_C)$ gauge theory with N_F fundamental flavors $(Q, \tilde{Q})$
- For $N_C > N_F$, the Affleck-Dine-Seiberg potential is obtained

$$W_{\rm ADS} = c \times \left(\frac{\Lambda^{3N_C - N_F}}{\det Q\tilde{Q}} \right)^{1/(N_C - N_F)}$$

- The simplest DSB model with a singlet X [I. Affleck, M. Dine & N. Seiberg '85]

$$W = gXQ\tilde{Q} + c \times \left(\frac{\Lambda^{3N_C - N_F}}{\det Q\tilde{Q}} \right)^{1/(N_C - N_F)}$$

$$\langle Q\tilde{Q} \rangle = \Lambda^2 \qquad W_{\rm effective} = gX\Lambda^2$$

DSB models in Magnetized D-brane systems

- Gauge Symmetry Breaking : $\mathrm{G} \rightarrow U(N_C) \times U(1) \times U(1)$
- Field contents ; $Q(\boldsymbol{N}_C, -1, 0), \quad \tilde{Q}(\bar{\boldsymbol{N}}_C, 0, +1), \quad X(0, +1, -1)$
- Degeneracy $(Q,\ \tilde{Q},\ X) = (N_F,\ N_F,\ 1)$
- Global symmetries allowing the coupling of $XQ\tilde{Q}$
- $N_C > N_F$ in order to get W_{ADS}

Many successful models (without the visible sector) !

Abe, Kobayashi, K.S. '16

DSB with the MSSM sector

- Consistency with the visible D7-branes

$$Z_2 \ : \ (z_1, z_2, z_3) \ \rightarrow \ (-z_1, -z_2, z_3)$$

$$Z_2' \ : \ (z_1, z_2, z_3) \ \rightarrow \ (z_1, -z_2, -z_3)$$

$$\mathcal{A}_1/\mathcal{A}_2 = 12, \qquad \mathcal{A}_1/\mathcal{A}_3 = 1$$

- Harmful zero-modes connecting the two sectors

Additional D7 models

8D $\mathrm{U}(1)_C$ SUSY gauge thoery on $T^2 \times T^2 \times T^2$
and
8D $\mathrm{U}(N_C+1)_D$ SYM on $T^2 \times T^2 \times T^2$

- Additional field contents

C sector : Singlet $\phi_1^C,\ \tilde{\phi}_2^C,\ \phi_3^C$

D sector : $\mathrm{U}(\mathrm{N}_\mathrm{C}+1)_D$ adjoint $\phi_1^D,\ \phi_2^D,\ \tilde{\phi}_3^D$

C-D sector : Fundamental charged under $\mathrm{U}(1)_\mathrm{C}$ $\phi_2^{CD},\ \phi_3^{CD}$

A-C,A-D,B-C,B-D sector : Bi-fundamentals and others

Configuration of a Magnetized orbifold

- Magnetized background

$$M_C^{(1)} = M_C^{(3)} = 0$$

$$M_D^{(1)} = \begin{pmatrix} 12 \times \mathbf{1}_{N_C} & 0 \\ 0 & 0 \end{pmatrix}, \qquad M_D^{(2)} = \begin{pmatrix} -1 \times \mathbf{1}_{N_C} & 0 \\ 0 & 0 \end{pmatrix}$$

- SUSY is preserved by $\mathcal{A}_1/\mathcal{A}_2 = 12, \qquad \mathcal{A}_1/\mathcal{A}_3 = 1$
- Gauge symmetry breaking

$$U(1)_C \times U(N_C+1)_D \to U(N_C) \times U(1)_C \times U(1)_D$$

- Orbifold parity : $P_C = -P_C' = 1 \quad P_D = P_D' = \mathbf{1}_{N_C+1}$

Configuration of a Magnetized orbifold

- The essential structure of DSB is realized
- One singlet X and five generations of $(Q, \tilde{Q})$; $N_F = 5$
- Extra zero-modes are completely eliminated
  - MSSM and DSB are decoupled to each other
- For $N_C > N_F = 5$, we get

$$W_{\text{effective}} = g\Lambda^2 X$$

Dynamical scale of the SUSY $SU(N_C)$

MSSM + SUSY breaking
+ Moduli stabilization

Moduli stabilization in IIB superstrings

Dilaton	S
Complex structure	U_1, U_2, U_3
Kähler moduli	T_1, T_2, T_3

- 3-form fluxes to stabilize S and U
- D-term potential for T_i
- Ratios of T_i are stabilized at a SUSY vacuum
- One flat direction of Kähler moduli

E-brane (D-brane instanton)

- Localized at a point in the 4D spacetime
- Finite volume in the extra dimensional space

Sequestered : $A_i e^{-a_i T_i}$ $\longrightarrow$ Moduli stabilization

Not sequestered : $A_i e^{-a_i T_i} \Psi_1 \Psi_2 \ldots$

Blumenhage, Cvetic, Weigand '07
Ibanez, Uranga '07

E-branes in D7 brane systems

- E3-brane (wrapping a 4-cycle)

  - If there is no charged zero-mode, we get

$$\begin{aligned} W &= W_0 + A_i e^{-4\pi T_i} \\ K &= -\log(T_i + \bar{T}_i) \end{aligned}$$

  the modulus is stabilized at a SUSY vacuum

- Origin of the constant term, W_0

  - E(-1)-brane (completely localized at a point)

    $W = A_S e^{-4\pi S} \to A_S e^{-4\pi \langle S \rangle}$ (stabilized by 3-form fluxes)

  - The stringy fluxes can directly produce W_0

Specific model in the D7-brane system

- E3-brane sequestered from $\mathrm{D7_A}$, $\mathrm{D7_B}$, $\mathrm{D7_C}$, $\mathrm{D7_D}$
- A successful configuration ;

  One E3-brane on $T^2 \times T^2 \times T^2$ with $P_E = P'_E = 1$

$$W_{\mathrm{Non-perturbative}} = Ae^{-a_1 T_1}$$

- Interplay of the DSB and the moduli stabilization dynamics

$$W_{\mathrm{total}} = W_0 + Ae^{-aT_1} + B\Lambda^2 X$$

F-term uplifting

- Solving the RGE for the hidden gauge coupling, we get

$$\Lambda \sim M_{\rm compact} e^{\frac{2\pi}{N_F - 3N_C} 4T_3 + 24S}$$

- Massless direction of the D-terms :

$$\begin{aligned} T_1 &= \frac{12}{17}\mathcal{T} + \cdots \\ T_3 &= \frac{12}{17}\mathcal{T} + \cdots \end{aligned}$$

$$\begin{aligned} W_{\rm total} &= W_0 - Ae^{-a\mathcal{T}} + Be^{-b\mathcal{T} - c\langle S\rangle} X \\ K &= -3\log(\mathcal{T} + \bar{\mathcal{T}}) \end{aligned}$$

resembles a model shown in [Abe, Higaki, Kobayashi ’07]

$$a = 4\pi\frac{12}{17}$$

$$b = 4\pi\frac{12}{17}\frac{2}{3N_C - N_F}$$

$$c = 4\pi\frac{24}{3N_C - N_F}$$

- W_0 tunned to realize the Polonyi vacuum

$$W_0 = Ae^{-a\mathcal{T}_0} + B(1 - X_0)e^{-b\mathcal{T}_0 - c\langle S\rangle}$$

Polonyi-KKLT vacuum

- Consistent DSB and KKLT dynamics
- At the vacuum, we find

$$m_{3/2} \sim B \exp[-4\pi \frac{24}{3N_C - N_F}\langle S\rangle] \sim \mathcal{O}(10^{-15}) M_{\text{Planck}}$$

$$m_{\text{soft}} \sim \frac{m_{3/2}}{4\pi} \sim \mathcal{O}(\text{TeV})$$

Summary

- Magnetized toroidal orbifold compactification
- Superfield description of effective D-brane systems
- The MSSM-like model without massless open strings
- Dynamical SUSY breaking
- Kähler moduli stabilization due to E-branes
- Interplay of DSB and moduli stabilization

Future prospects

- Phenomenology in detail : SUSY spectrum …
- String theoretical consistency
- Cosmology

Thank you very much !!