Asymmetric CFTs and GSUGRA

Ralph Blumenhagen

Max-Planck-Institut für Physik, München

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In memoriam of Ioannis

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from conference photo at "Regional meeting 2015" at Nafplion

Introduction

Introduction

Guiding principle of string theory: 2D conformal field theories with $c = c_{\rm crit.}$ describe classical vacua of string theory (to all orders of α')

World-sheet point of view:

- There exist CFTs that describe special points in the moduli space of geometric string backgrounds: Toroidal orbifolds, Gepner models (for CYs), they often come with many moduli.
- There also exist asymmetric conformal field theories (ACFTs) that do not correspond to geometric backgrounds in an obvious manner: Asymmetric orbifolds, free fermion constructions, asymmetric partition functions for Gepner models, often the number of moduli is reduced

Introduction

Introduction

see e.g. (Narain, Sarmadi, Vafa),(Antoniadis, Bachas, Kounnas),(Ferrara, Kounnas),(Bianchi),(Brunner, Rajaraman, Rozali),(Dabholkar, Harvey)..

From the effective field theory point of view:

- There exist solutions with non-trivial NS-NS and R-R fluxes turned on. Via T-duality, one can generate also non-geometric fluxes: T-folds, R-flux.
- Such models are equivalent to gauged supergravities in the uncompactified dimensions: e.g. in 4D, $\mathcal{N} = 2$ GSUGRA, for such minima, the number of moduli is reduced

General expectation: At least some ACFTs do correspond to such non-geometric compactifications (to all orders of α')

Introduction

Introduction

This motivates a landscape study of a huge class of ACFTs in Type IIB, given by (asymmetric) simple current extensions of Gepner models. (Gepner),(Schellekens, Yankielowicz)

Questions:

- Can we classify all such models in 2D-dimensions with at least 8 supercharges?
- Are there hints that some of these classes can correspond to Minkowski minima of GSUGRA?
- Can 4D ACFTs with $\mathcal{N}=1$ susy correspond to minima of $\mathcal{N}=2$ GSUGRA?

Approaches via toroidal asymmetric orbifolds e.g. in (Dabholkar, Hull),(Hellerman, McGreevy, Williams),(Flournoy, Wecht, Williams),(Condeescu, Florakis, Kounnas,Lüst),...

Gepner models

Gepner models

Consider Gepner models with $c_{\text{int}} = 3, 6, 9$ corresponding to $D = 2, 4, 6$ internal spaces.

Gepner model: Simple current extension of the CFT

$$\underbrace{\text{free bosons}_{8-D}}_{c=8-D} \times \underbrace{\widehat{so}(8-D)}_{\text{fermions } c=4-\frac{D}{2}}, \times \underbrace{\bigotimes_{j=1}^{r} (k_j)}_{\text{internal}, \, c=\frac{3D}{2}}$$

with

- unitary models of $N = 2$ super Virasoro algebra $c = 3k/(k+2)$ with coset realization $SU(2)_k \times U(1)_2 / U(1)_{k+2}$
- each HWR is labeled as (l, m, s)
- $\widehat{so}(8-D)_1$ has four HWRs (o, v, s, c)

Simple currents

Simple currents

Idea of simple current extension: (Schellekens, Yankielowicz)

- A RCFT does have simple currents, i.e. primary fields J whose OPE (fusion rule) reads

$$J_a \times \phi_i = \phi_{J(i)}$$

- To each such simple current one can associate a new modular invariant partition function

$$Z_a(\tau,\bar\tau) = \vec\chi^T(\tau)\, M(J_a)\, \vec\chi(\overline{\tau}) = \sum_{k,l} \chi_k(\tau)\ (M_a)_{kl}\ \chi_l(\bar\tau)\,,$$

Important: Two matrices $M(J_a)$ and $M(J_b)$ do in general not commute $\rightarrow$ asymmetric CFTs

ACFTs

ACFTs

Gepner partition function:

$$Z_{\text{Gepner}}(\tau,\overline{\tau}) \sim \vec{\chi}^{\,T}(\tau)\, M(J_{\text{GSO}}) \prod_{r=1}^{N} M(J_i)\, \vec{\chi}(\overline{\tau})\Big|_{\phi_{\text{bsm}}^{-1}}$$

with

$$J_{\text{GSO}} = (0\;1\;1)\ldots(0\;1\;1)(s)\,,$$
$$J_i = (0\;0\;0)\ldots\underbrace{(0\;0\;2)}_{i^{\text{th}}}\ldots(0\;0\;0)(v)\,.$$

Asymmetric Gepner model:

$$Z_{\text{ACFT}} \sim \vec{\chi}^{\,T}(\tau)\, M(J_{\text{break}})\, M(J_{\text{enhance}})\, M(J_{\text{GSO}}) \prod_i M(J_i)\, \vec{\chi}(\overline{\tau})\Big|_{\phi_{\text{bsm}}^{-1}}$$

In general, part of the left-moving susy is broken.

(Schellekens, Yankielowicz),(Israel)

Classification of ACFTs

Classification of ACFTs

We distinguish

- Models with at least 8 supercharges arising from the right-moving sector $\rightarrow$ no independent superpotential, mass generation via Higgsing. Starting points: Gepner models for T^2, $K3$ and $K3 \times T^2$.
- 4D models with $\mathcal{N} = 1$ susy, 4 supercharges, Starting point: CY_3 Gepner Models (like $k = 3^5$ for quintic)

Introduce a rough classification scheme:

$$^{D}\mathfrak{N}_{[n_L, n_R]}$$

D: the number of umcompactified dimensions
$n_{L/R}$: number of left/right supersymmetries

Program

Program

Before presenting the results of our stochastic search, let me present some general structures that turn out to be important for bringing order into the landscape of ACFTs.

Super-Higgs mechanism

Super-Higgs mechanism

- Fluxes on T^4, $K3$ or $K3 \times T^2 \Rightarrow$ GSUGRA.
- Difficult: relate ACFT model to a concrete set of gaugings, fluxes
- Prerequisite: Super Higgs effect for an $\mathcal{N}'$-SUGRA to admit a Minkowski vacuum with $\mathcal{N}$-susy

(Deser,Zumino),(Cremmer, Julia, Scherk, van Nieuwenhuizen, Ferrara, Girardello),(Andrianopoli, D' Auria, Ferrara, Lledo)

Super-Higgs mechanism

Super-Higgs mechanism

4D Example: $\mathcal{N}' = 8$ GSUGRA $\rightarrow \mathcal{N} = 6$:

All massless states of Type IIB on T^6 fit into the supergravity multiplet

$$\begin{aligned} \mathcal{G}_{(8)} &= 1 \cdot [2] + 8 \cdot [\tfrac{3}{2}] + 28 \cdot [1] + 56 \cdot [\tfrac{1}{2}] + 70 \cdot [0] \\ &= (2) + (16) + (56) + (112) + (70) \end{aligned}$$

2 gravitinos become massive and must fit into massive $\mathcal{N} = 6$ Spin$=3/2$ supermultiplet

Super-Higgs mechanism

Super-Higgs mechanism

Massless $\mathcal{N} = 6$ supergravity multiplet

massless $$\mathcal{G}_{(6)} = 1 \cdot [2] + 6 \cdot [\tfrac{3}{2}] + 16 \cdot [1] + 26 \cdot [\tfrac{1}{2}] + 30 \cdot [0]$$
$$= (2) + (12) + (32) + (52) + (30)$$

massive Spin$=3/2$ supermultiplet (1/2 BPS)

massive $$\overline{\mathcal{S}}_{(6)} = 2 \times \big([\tfrac{3}{2}] + 6 \cdot [1] + 14 \cdot [\tfrac{1}{2}] + 14 \cdot [0]\big)$$
$$= (8) + (36) + (56) + (28)\,.$$

Perfect match of dof: $\mathcal{N}' = 8$ Sugra $\rightarrow \mathcal{N} = 6$ Sugra $+$ a pair of massive Spin$=3/2$ supermultiplets.

Such a gauging is kinematically allowed.

Asymmetric shift orbifolds

Asymmetric shift orbifolds

It turned out that a class of ACFTs can be understood as asymmetric $(-1)^{F_L}$ shift orbifolds. (Dixon, Kaplunovsky, Vafa),(Bluhm, Dolan, Goddard)

8D Example: Type IIB on a T^2 at self-dual radii $r_i = \sqrt{\alpha'}$. with the asymmetric orbifold action

$$\mathcal{A}_8 = \frac{T^2}{(-1)^{F_L}\, S\, W}$$

with

- F_L: left-moving space-time fermion number, that eliminates all states from the left R-sector.
- S, W: $\mathbb{Z}_2$ momentum/winding shifts

Asymmetric shift orbifolds

Asymmetric shift orbifolds

Partition function: notation of (Angelantonj, Sagnotti)

$$Z_{\rm ACFT} = \frac{1}{2}\Big[(V_8 - S_8)(\overline{V}_8 - \overline{S}_8)\Lambda^{(2)}_{\vec{m},\vec{n}}$$
$$+(V_8 + S_8)(\overline{V}_8 - \overline{S}_8)(-1)^{\vec{m}+\vec{n}}\,\Lambda^{(2)}_{\vec{m},\vec{n}}$$
$$+(O_8 - C_8)(\overline{V}_8 - \overline{S}_8)\Lambda^{(2)}_{\vec{m}+\frac{\vec{1}}{2},\vec{n}+\frac{\vec{1}}{2}}$$
$$+(O_8 + C_8)(\overline{V}_8 - \overline{S}_8)(-1)^{\vec{m}+\vec{n}}\,\Lambda^{(2)}_{\vec{m}+\frac{\vec{1}}{2},\vec{n}+\frac{\vec{1}}{2}}\Big]$$

Untwisted sector massless spectrum:

- 64 bosonic/fermionic modes that fit into the 8D $\mathcal{N}=1$ supergravity multiplet plus 2 vectormultiplets

Asymmetric shift orbifolds

Asymmetric shift orbifolds

Twisted sector partition function:

$$Z_{\rm ACFT} = \frac{1}{2}\Big[(O_8 - C_8)(\overline{V}_8 - \overline{S}_8)\Lambda^{(2)}_{\vec{m}+\frac{\vec{1}}{2},\vec{n}+\frac{\vec{1}}{2}} + (O_8 + C_8)(\overline{V}_8 - \overline{S}_8)(-1)^{\vec{m}+\vec{n}}\,\Lambda^{(2)}_{\vec{m}+\frac{\vec{1}}{2},\vec{n}+\frac{\vec{1}}{2}}\Big]$$

Twisted sector massless spectrum:

- $O_8\overline{V}_8$ can combine with states from

$$\Lambda^{(2)}_{\vec{m}+\frac{\vec{1}}{2},\vec{m}+\frac{\vec{1}}{2}} = q^0 \sum_{\vec{m}} \overline{q}^{\frac{1}{4}\sum_i (2m_i+1)^2}$$

to form a level matched massless state. The four states $m_1, m_2 \in \{0, -1\}$ give rise to four $\mathcal{N} = 1$ vectormultip..

Asymmetric shift orbifolds

Asymmetric shift orbifolds

- These four states provide the W-bosons of an $SU(2) \times SU(2)$ non-abelian gauge group.
- Coulomb-branch corresponds to changing the two radii of the T^2.

This is just a simple 8D example of a more general class of asymmetric shift orbifolds with non-abelian gauge groups

- 6D: D_4-lattice, $[0, 2]$ susy with maximal $SU(2)^4$, called $\mathcal{A}_6$
- 6D: D_6-lattice, $[0, 4]$ susy with maximal $SU(2)^6$, called $\mathcal{A}_4$ (Dixon, Kaplunovsky, Vafa, 1987)

Note: Due to the $(-1)^{F_L}$ factor, one does not expect that these models are related to NS-NS fluxes/gaugings!

ACFTs in 8D

ACFTs in 8D

Extensive search of asymmetric simple current extensions for $\mathbf{k} \in \{(1,1,1),(2,2),(1,4)\}$ Gepner models with $c = 3$.

Only 2 different models (massless spectra) were found (second for $\mathbf{k} = (2,2)$)

class	spectrum	realization
${}^{8}\mathfrak{N}_{[1,1]}$	$\mathcal{G}_2$	T^2
${}^{8}\mathfrak{N}_{[0,1]}$	$\mathcal{G}_1 + 6 \times \mathcal{V}_1^{SU(2)^2}$	$\mathcal{A}_8$

The ACFT ${}^{8}\mathfrak{N}_{[0,1]}$ has no massless state from the left R-sector and features a non-abelian $SU(2)^2$ gauge symmetry.

raw data at http://wwwth.mpp.mpg.de/members/blumenha/Examples.zip

ACFTs in 6D

ACFTs in 6D

Generating O(10^8) of Type IIB models, we only found:

class	spectrum beyond SUGRA	realization
${}^6\mathfrak{N}_{[2,2]}$	–	Type IIB on T^4
${}^6\mathfrak{N}_{[1,1]}(\mathrm{B})$	$21 \times \mathcal{T}_{(0,2)}$	IIB on $K3$
${}^6\mathfrak{N}_{[1,1]}(\mathrm{A})$	$20 \times \mathcal{V}_{(1,1)}$	IIB on $K3/(-1)^{F_L}$
${}^6\mathfrak{N}_{[0,2]}$	$4, 8, 12 \times \mathcal{V}_{(1,1)}$	Coulomb-branch: $\mathcal{A}_6$
${}^6\mathfrak{N}_{[0,1]}$	$9 \times \mathcal{T}_{(0,1)} + (8+n) \times \mathcal{V}_{(0,1)}$ $+(20+n) \times \mathcal{H}_{(0,1)}$	gauge enhancement: $T^4/\{\Theta, \Theta S(-1)^{F_L}\}$

with $0 \leq n \leq 4$.

Comments on $\mathfrak{D}_6\mathfrak{N}_{[0,1]}$

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Constraints from anomaly cancellation.

Assume: Type IIB model with spectrum $(n_T^B + 1, n_V^B, n_H^B)$.

- the n_T^B extra tensors can only arise from the R-R sector.
- first, assume that also all the vectors arise from the R-R sector

Changing the GSO projection in left-sector, the corresponding Type IIA model will have the spectrum

$$(n_T^A + 1, n_V^A, n_H^A) = (n_V^B + 1, n_T^B, n_H^B) \,,$$

i.e. the R-R tensors and vectors are exchanged.

Comments on $\mathfrak{D}_6\mathfrak{N}_{[0,1]}$

Comments on $\mathfrak{D}_6\mathfrak{N}_{[0,1]}$

Under R-R vectors there are no charged states $\Rightarrow$ only gravitational anomaly

$$\mathcal{A}_G = \alpha \mathrm{Tr}(R^4) + \beta\big(\mathrm{Tr}(R^2)\big)^2$$

where

$$\alpha \sim 244 - 29\, n_T^{B/A} - n_H^{B/A} + n_V^{B/A}\,, \qquad \beta \sim n_T^{B/A} - 8\,.$$

- Both Type IIB/A models cancel irreducible anomaly $\Rightarrow$ $n_T = n_V$.
- Type II superstring has no CS-term $\Rightarrow$ cancel reducible anomaly $\Rightarrow$ $n_T = 8$.

This is the ${}^6\mathfrak{N}_{[0,1]}$ model we found enhanced by NS-NS vectors-hypers.

6D Gaugings

6D Gaugings

Susy breaking by fluxes

- Fluxes on T^4: gauged $\mathcal{N} = [2,2] \to \mathcal{N} = [0,2]$ minima, super Higgs not possible
- Fluxes on $K3$: gauged $\mathcal{N} = [1,1] \to \mathcal{N} = [0,1]$ minima, super Higgs not possible

ACFT is expected to only describe NS-NS fluxes, which carry 3 indices like H_{ijk}.

K3 only contains 2-cycles $\Rightarrow$ (non-)geometric fluxes cannot be supported.

Asymmetric orbifold realization

Asymmetric orbifold realization

Our ${}^{6}\mathfrak{N}_{[0,1]}$ model was discussed before (Hellerman, McGreevy, Williams)

An asymmetric toroidal orbifold realization was provided

$$\text{Model 6D} = \frac{T^4}{\mathbb{Z}_2 \times \mathbb{Z}_2'}\,.$$

with

$$\mathbb{Z}_2 = \Theta\,, \qquad \mathbb{Z}_2' = \Theta\, S\,(-1)^{F_L}$$

(reflection $\Theta : z_i \to -z_i$).

Note: the orbifold involves $(-1)^{F_L}$.

Outlook: ACFTs in 4D

Outlook: ACFTs in 4D

The ACFT landscape becomes much richer:

- We found models with $\mathcal{N} = 8, 6, 5, 4, 3, 2, 1$ supersymmetry
- There are fluxes/gaugings on T^6, $K3 \times T^2$ and CY_3: found a couple of series precisely compatible with super Higgs effect.
- For ${}^4\mathfrak{N}_{[0,1]}$ one has to deal with superpotential. Proposed $\mathcal{N} = 1$ minima of $\mathcal{N} = 2$ GSUGRA

(please see upcoming talk by Michael Fuchs)

Pre-conclusions

Pre-conclusions

- Gained a compelling understanding of the ACFT landscape with extended susy
- Not all consistent models will allow a realization in terms of asymmetric Gepner models (string islands)
- As will be discussed, in 4D the super Higgs mechanism plays an important role

Thank You!