HERMANNfest 2022

Variations

on

heterotic strings and lattices

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based on: JHEP 10 (2020) 194, JHEP 08 (2021) 095, with B. Fraiman, M. Graña, C. Núñez, H. Parra De Freitas

2205.09764 [hep-th], with B. Acharya, G. Aldazabal, K. Narain, I. Zadeh

Hermann and the AEI

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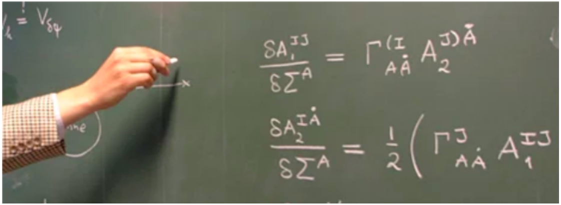

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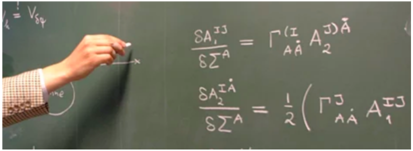

REPRESENTATIONS OF SUPERSYMMETRY IN ANTI-DE SITTER SPACE*)

H. Nicolai

CERN –– Geneva

1. Introduction

Anti-de Sitter space[1], or AdS for brevity, is the natural background for gauged extended supergravity theories[2] and Kaluza-Klein supergravity [for recent reviews, see Refs. 3) and 4) and the lectures by B. de Wit, M.J. Duff, P. Fré and P. van Nieuwenhuizen at this school]. It is most easily described as the connected hyperboloid in $\mathbb{R}^5$ which is defined as the set of points obeying

$$\eta^{AB} y_A y_B = y_0^2 - y_1^2 - y_2^2 - y_3^2 + y_4^2 = \frac{1}{a^2} \qquad (1.1)$$

The quantity a, which we set equal to one in what follows, is the inverse radius of AdS. It is not difficult to show[1] that (1.1) is an Einstein space with negative cosmological constant

$$R_{\mu\nu} = -\Lambda g_{\mu\nu} \, , \quad \Lambda = -3a^2 < 0 \qquad (1.2)$$

(our metric has signature +−−−), and that the curvature tensor is given by

$$R_{\mu\nu\rho\sigma} = a^2 (g_{\mu\rho} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\rho}) \qquad (1.3)$$

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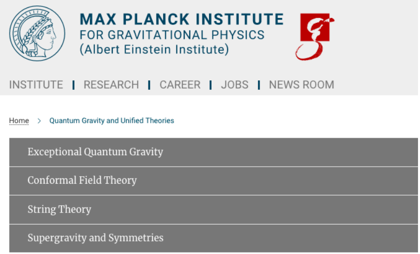
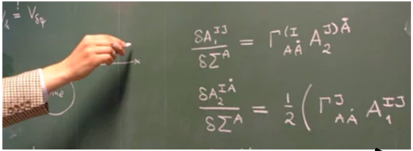
*) Lectures delivered at the Spring School on Supergravity and Supersymmetry, ICTP Trieste (Italy), April 1984.





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Nicolai Font

Hermann in Venezuela, 2005

Simón Bolívar University

Simón Bolívar birth house

Caracas

Salto Ángel

height 979 m, plunge 807 m

Variations on heterotic strings and lattices

Aims and motivation

- study gauge symmetry enhancement in heterotic toroidal compactifications

  which non-Abelian groups are allowed ?

- study non-supersymmetric heterotic compactifications

  e.g. heterotic on $\mathbb{T}^3/\mathbb{Z}_2$, where $\mathbb{Z}_2$ reflects 2 right-moving directions

  relation to M-theory on $\mathrm{K3}/\mathbb{Z}_2$?

Contents

Aria

Heterotic in 10 dim

Gross, Harvey, Martinec, Rohm '85

- R-movers (superstring) $+$ L-movers (bosonic)

  $\psi_R^M,\ X_R^M,\ \ M = 0, \ldots, 9$ $\qquad$ $X_L^M,\ Y_L^{\mathrm{I}},\ \ \mathrm{I} = 1, \ldots, 16$

- modular invariance $\Rightarrow$ Y_L^{I} must live on a 16-dim torus with even selfdual lattice

- only 2 such lattices

  $\Gamma_8 \oplus \Gamma_8\,,$ for the $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic

  $\Gamma_{16}\,,$ for the $\mathrm{Spin}(32)/\mathbb{Z}_2$ heterotic

Γ_8 : root lattice of E_8

$$\Gamma_{8q} = \left\{ (m_1, ..., m_{8q}), (m_1 + \tfrac{1}{2}, ..., m_{8q} + \tfrac{1}{2}) | m_k \in \mathbb{Z}, \sum_{k=1}^{8q} m_k = \text{even} \right\}$$

Narain lattice $\Gamma_{16+d,d}$

Narain '86

- new heterotic string theories in uncompactified dimensions < 10

R-movers (superstring)	+	L-movers (bosonic)
$\psi_R^\mu,\ X_R^\mu,\ \ \mu = 0,\ldots,9\text{-}d$		X_L^μ
$\psi_R^j,\ X_R^j,\ \ j = 1,\ldots,d$		$X_L^j,\ Y_L^{\mathrm{I}},\ \ \mathrm{I} = 1,\ldots,16$

- modular invariance $\Rightarrow$ $(Y_L^{\mathrm{I}}, X_L^j; X_R^j)$ must have momenta in an even selfdual lattice $\Gamma_{16+d,d}$, signature $(16+d,d)$

- infinite such lattices !

  obtained applying $\mathrm{SO}(16+d,d)$ transformations to reference lattice,

  e.g. $\Gamma_8 \oplus \Gamma_8 \oplus^d \mathrm{U}$ Ginsparg '87

  U: even, selfdual, signature (1,1)

Moduli

Narain, Sarmadi, Witten '86

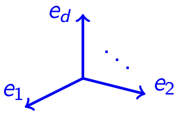
- new theories are really conventional compactifications on $\mathbb{T}^d$

- background parameters = moduli

  g_{ij} : metric of $\mathbb{T}^d$

  b_{ij} : vev of Kalb-Ramond B-field

  A_i^{I} : vev of gauge fields in Cartan sub-algebra
  Wilson lines



$g_{ij} = e_i \cdot e_j$

- $\Gamma_{16+d,d}$ lattice vectors = momenta of $(Y_L^{\mathrm{I}}, X_L^j; X_R^j)$

$$p^{\mathrm{I}} = \Pi^{\mathrm{I}} + A_i^{\mathrm{I}} w^i \,,$$

$$p_L = \frac{1}{\sqrt{2}} \left[n_i + (2g_{ij} - E_{ij})\, w^j - \Pi \cdot A_i \right] \hat{e}^{*i} \,,$$

$$p_R = \frac{1}{\sqrt{2}} \left[n_i - E_{ij} w^j - \Pi \cdot A_i \right] \hat{e}^{*i} \,.$$

$i, j = 1, \ldots, d$

$E_{ij} = g_{ij} + \frac{1}{2} A_i \cdot A_j + b_{ij}$

$\alpha' = 1$

$w^j \in \mathbb{Z}$: windings, $n_j \in \mathbb{Z}$: quantized momenta, $\Pi \in \Gamma_8 \oplus \Gamma_8$

Variatio 1

Symmetry enhancement in toroidal compactifications

Heterotic on $\mathbb{T}^d$

- generic moduli $\Rightarrow$ gravity multiplet + gauge multiplets of $\mathrm{U}(1)^{d+16}$

  of supersymmetry with 16 supercharges

- special moduli $\Rightarrow$ enhancing of $\mathrm{U}(1)^{d+16}$

  e.g. $A_i = 0, b_{ij} = 0, g_{ij} = E_{ij} = \delta_{ij} \Rightarrow \mathrm{E}_8 \times \mathrm{E}_8 \times \mathrm{SU}(2)^d$ rank $16 + d$

  extra massless states with winding and quantized momenta

- which $\mathrm{G}_{\mathsf{rk}} \times \mathrm{U}(1)^{d+16-\mathsf{rk}}$ occur ? Mohaupt '93, Cachazo, Vafa '00, Fraiman, Graña, Núñez '18

  will focus in maximal enhancing, i.e. $\mathsf{rk} = 16 + d$

- G is ADE, roots $\mathbf{p}_L^2 = 2$, $\mathbf{p}_L = \underbrace{(p^{\mathrm{I}}, p_L)}_{16+d}$, $\frac{1}{2} m_L^2 = \frac{1}{2} \mathbf{p}_L^2 + N_L - 1$

  $L \equiv$ root lattice of G

- which even L of signature $(16+d,0)$ can be embedded in $\Gamma_{16+d,d}$?

  answer can be found by applying Nikulin's formalism — Nikulin '80

  done in K3 context ($\Gamma_{18,2}$) — Shimada '00, Shimada, Zhang '01

  done in heterotic context — AF, Fraiman, Graña, Núñez, Parra De Freitas = FFGNP '20

- lattice data

  discriminant group: $A_L = L^*/L$

  discriminant form: $q_L = \left\{x^2 \bmod 2,\ x \in A_L\right\}$

- L of signature $(16+d,0)$ has embedding in $\Gamma_{16+d,d}$ if there exists

  an even lattice T of signature $(d,0)$ such that $(A_T, q_T) \simeq (A_L, q_L)$,

  or L has overlattice M with $(A_T, q_T) \simeq (A_M, q_M)$ and $L = M_{\text{root}}$

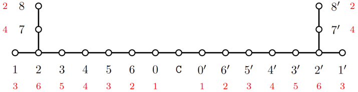
Finding all allowed L of rank $16 + d$

- start with all possible ADE ($d = 1$, 1137 rk 17; $d = 2$, 1599 rk 18) check existence of T

  $d = 2$, Shimada '00, Shimada, Zhang '01

- $d = 1$, simpler way based on extended Dynkin diagram (EDD) of $\Gamma_{17,1}$

  Vinberg '72, Goddard, Olive '85



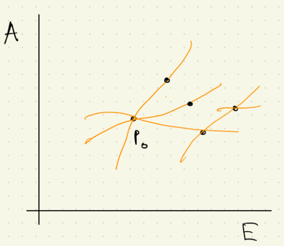
Cachazo, Vafa '00, Fraiman, Graña, Núñez '18

L's of maximal rank: delete 2 nodes such that remainders form ADE Dynkin

- $d = 2$, for $\Gamma_{18,2}$ no EDD

  instead use exploration algorithm

  FFGNP '20-21



All allowed groups of maximal rank for the heterotic on S^1

Fraiman, Graña, Núñez '18, FFGNP '20

* 44 groups, out of 1137 ADE of rank 17 e.g. ~~$D_{11} \oplus A_6$~~, ~~$2A_5 \oplus E_7$~~
* maximal enhancings at $E = R^2 + \frac{1}{2}A^2 = 1$, fixed point of T-duality $w \leftrightarrow n$, $E' = \frac{1}{E}, A' = \frac{A}{E}$
* global form known, e.g. $L = \mathrm{A}_{17},\ \mathrm{G} = \mathrm{SU}(18)/\mathbb{Z}_3$

All allowed groups of maximal rank for the heterotic on $\mathbb{T}^2$

FFGNP '20

* 325 groups, out of 1599 ADE of rank 18 e.g. ~~$D_{15} \oplus A_3$~~, ~~$2A_6 \oplus E_6$~~
* 359 distinct, for some 2 T's
* determined moduli, can always find points with $E_{ij} = \delta_{ij}$, i.e. with $b_{ij} = 0$
* global form known, e.g. $L = 3\mathrm{A}_6,\ \mathrm{G} = \mathrm{SU}(7)^3/\mathbb{Z}_7$

Heterotic on $\mathbb{T}^d/\mathbb{Z}_2$ (CHL strings)

- branch of superstring vacua with 16 supercharges in (10-d) dim, with gauge group of rank $(8+d)$
- first obtained in type I strings — Bianchi, Pradisi, Sagnotti '92
- later found in heterotic in fermionic formulation — Chaudhuri, Hockney, Lykken '95
- in bosonic formulation realized as $\mathrm{E}_8 \times \mathrm{E}_8'$ heterotic on $\mathbb{T}^d/\mathbb{Z}_2$

Chaudhuri, Polchinski '95

$\mathbb{Z}_2 :\quad X^9 \to X^9 + \frac{1}{2}(2\pi R),$ single out a S^1 in $\mathbb{T}^d$

$\mathrm{E}_8 \leftrightarrow \mathrm{E}_8',\qquad Y_\pm^{\mathrm{I}} \to \pm Y_\pm^{\mathrm{I}},\quad Y_\pm^{\mathrm{I}} = \frac{1}{\sqrt{2}}(Y^{\mathrm{I}} \pm Y^{\mathrm{I}+8}), \mathrm{I} = 1, ..., 8$

left-right asymmetric action $\longrightarrow$ asymmetric orbifold — Narain, Sarmadi, Vafa '87

- $\mathbb{Z}_2$ on momenta: $|p_+, p_-, p_L; p_R\rangle \to e^{i\pi n}|p_+, -p_-, p_L; p_R\rangle$ $\quad p_\pm^{\mathrm{I}} = \frac{1}{\sqrt{2}}(p^{\mathrm{I}} \pm p^{\mathrm{I}+8})$

$e^{i\pi n}$ from $X^9 \to X^9 + \pi R,\; P_9 = \dfrac{n}{R},\qquad e^{i\pi n} = e^{2i\pi P\cdot v},\;$ v : shift vector

CHL in 9 dimensions

- in $S^1/\mathbb{Z}_2$, Wilson line must be symmetric under $\mathrm{E}_8 \leftrightarrow \mathrm{E}_8'$

  $A = (\underset{\mathrm{E}_8}{a}, \underset{\mathrm{E}_8'}{a})$, $\quad a \in \mathbb{R}^8$, $\quad$ moduli: a, R of S^1

- $p_+ = \frac{1}{\sqrt{2}}(\rho + 2aw)$, $\quad p_- = \frac{1}{\sqrt{2}}(\pi - \pi')$

  $p_L = \frac{1}{\sqrt{2}R}\left(n + (R^2 - a^2)w - \rho \cdot a\right)$

  $p_R = \frac{1}{\sqrt{2}R}\left(n - (R^2 + a^2)w - \rho \cdot a\right)$

  $\Pi = (\pi, \pi'),\ \pi \in \mathrm{E}_8, \pi' \in \mathrm{E}_8'$

  $\rho = \pi + \pi',\ \rho \in \mathrm{E}_8$

- $\sqrt{2}(p_+, p_L; p_R) \ \leftrightarrow\ Z = |\ell, n, \rho\rangle$, $\quad \ell = 2w$, $\quad Z^2 = \rho^2 + 2\ell n \in 2\mathbb{Z}$

  Z spans Mikhailov lattice $\Gamma_{9,1} \simeq \Gamma_8 \oplus \mathrm{U}$

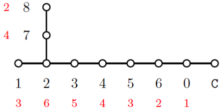
  states in orbifold spectrum correspond to $Z \in \Gamma_{9,1}$ Mikhailov '98, FFGNP '21

- generic moduli $\Rightarrow$ gravity multiplet + gauge multiplets of $\mathrm{U}(1)^9$

- special moduli $\Rightarrow$ enhancing of $\mathrm{U}(1)^9$

All allowed groups of maximal rank for the $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic on $S^1/\mathbb{Z}_2$ FFGNP '21

i	L	E	a
1	A_9	2	$\frac{1}{3} w_1$
2	$\mathrm{A}_1 + \mathrm{A}_2 + \mathrm{A}_6$	2	$\frac{1}{6} w_2$
3	$\mathrm{A}_4 + \mathrm{A}_5$	2	$\frac{1}{5} w_3$
4	$\mathrm{D}_5 + \mathrm{A}_4$	2	$\frac{1}{4} w_4$
5	$\mathrm{E}_6 + \mathrm{A}_3$	2	$\frac{1}{3} w_3$
6	$\mathrm{E}_7 + \mathrm{A}_2$	2	$\frac{1}{2} w_6$
7	$\mathrm{A}_1 + \mathrm{A}_8$	2	$\frac{1}{4} w_7$
8	D_9	2	$\frac{1}{2} w_8$
0	$\mathrm{E}_8 + \mathrm{A}_1$	2	0



$\Gamma_{9,1}$ a.k.a. E_{10}

* can be obtained deleting one node in EDD of $\Gamma_{9,1}$

* all groups at Kac-Moody level 2

* all G simply connected

* $E = R^2 + a^2 = 2$, fixed point of T-duality

$\ell \leftrightarrow n, \quad E' = \frac{4}{E}, \; a' = \frac{2a}{E}$

Weyl reflection about node C

All allowed groups of maximal rank for the $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic on $\mathbb{T}^2/\mathbb{Z}_2$ FFGNP '21

* 61 groups, found using exploration algorithm

* Mikhailov lattice: $\Gamma_{9,1} \oplus \mathrm{U}(2)$ not self-dual

* C algebras appear

* ADE at Kac-Moody level 2, C at level 1

* global form known

e.g. $L = 2\mathrm{A}_1 \oplus 2\mathrm{A}_3 \oplus \mathrm{C}_2$, $\mathrm{G} = \left(\mathrm{SU}(2)^2 \times \mathrm{SU}(4)^2 \times \mathrm{Sp}(4)\right)/\mathbb{Z}_2 \times \mathbb{Z}_2$ Cvetič, Dierigl, Lin, Zhang '21

* match results from F-theory on K3 Hamada,Vafa '21, Fraiman, Parra De Freitas '21

Variatio 2

Non-supersymmetric heterotic on $\mathbb{T}^3/\mathbb{Z}_2$

Setup 1. Heterotic on $\mathbb{T}^3$

- internal momenta live on Narain lattice $\Gamma_{19,3}$

- 7-dimensional theory with 16 supercharges

  masless gravity multiplet (with 3 graviphotons)

  masless gauge multiplets of $\mathrm{U}(1)^{19}$ at generic moduli

  charges of massive states span $\Gamma_{19,3}$

- strong coupling dual: M-theory on K3 Witten '95

  2nd cohomology group with K3 intersection form $\sim \; \Gamma_{19,3}$

  C_{MNP} in 11-dim $\longrightarrow \; C_{\mu mn}$ in 7-dim, 19+3 $\mathrm{U}(1)$ vectors

  membranes wrapped on 2-cycles of K3 $\longrightarrow$ charged states

Setup 2. Heterotic on non-supersymmetric $\mathbb{T}^3/\mathbb{Z}_2$

- $\mathbb{Z}_2$: reflection of s from 19 L-movers and 2 from 3 R-movers (superstring sector)
  supersymmetry breaking, left-right asymmetric action

- expected duality to M-theory on K3 quotiented by analogous $\mathbb{Z}_2$
  $\mathbb{Z}_2$ reflects holomorphic 2-form, leaves volume form invariant

- there exist 75 such *non-symplectic* involutions Nikulin '83
  classified in terms of lattice $\mathrm{I} \subset \Gamma_{19,3}$ left invariant by involution

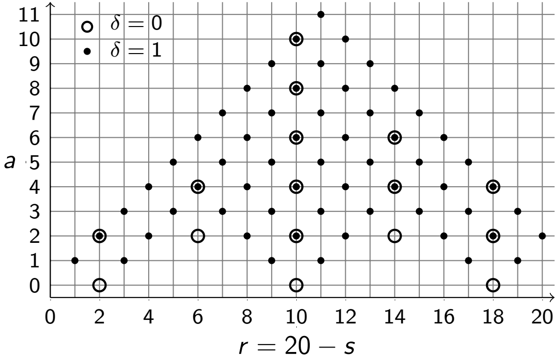
- invariant lattice I, even, signature $(r-1,1)$, $1 \leq r \leq 20$, $\mathrm{I}^*/\mathrm{I} = \mathbb{Z}_2^a$

- normal lattice $\mathrm{N} = \mathrm{I}^\perp$, even, signature $(s,2)$, $s = 20 - r$, $\mathrm{N}^*/\mathrm{N} = \mathbb{Z}_2^a$

- $P \in \Gamma_{19,3}$ has decomposition $P = (P_\mathrm{N}, P_\mathrm{I}), P_\mathrm{N} \in \mathrm{N}^*, P_\mathrm{I} \in \mathrm{I}^*$

Classification of Nikulin non-symplectic involutions of $\Gamma_{19,3}$

- characterized by (r, a, δ), $r = \mathrm{rk}(\mathrm{I})$, $\mathrm{I}^*/\mathrm{I} = \mathbb{Z}_2^a$, $\delta = \begin{cases} 0 & \text{if } P_\mathrm{I}^2 \in \mathbb{Z} \quad \forall P_\mathrm{I} \in \mathrm{I}^* \\ 1 & \text{otherwise} \end{cases}$



- $(r, a, \delta) \Rightarrow$ unique I up to $\mathrm{SO}(r-1, 1)$, N up to $\mathrm{SO}(s, 2)$

  e.g. $(r, a, \delta) = (3, 1, 1) \Rightarrow \mathrm{I} \sim \mathrm{A}_1 \oplus \mathrm{U}$, $\mathrm{N} \sim \mathrm{E}_7 \oplus \mathrm{E}_8 \oplus 2\mathrm{U}$

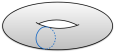
Construction of asymmetric $\mathbb{T}^3/\mathbb{Z}_2$ orbifold

reminder of closed strings on orbifolds

Dixon, Harvey, Vafa, Witten'85,86

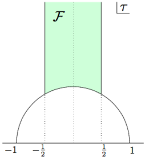
* $\exists$ twisted sectors: strings close up to action of orbifold generator g
* orbifold projection: physical states must be invariant under action of g

both required by modular invariance of 1-loop partition function



1-loop vacuum amplitude

$$Z_{\text{1-loop}} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\, \mathcal{Z}(\tau, \bar{\tau})$$



* in $\mathcal{Z}(\tau, \bar{\tau})$ there is a sum over twisted sectors and a projection

Construction of asymmetric $\mathbb{T}^3/\mathbb{Z}_2$ orbifold

- on R-movers orbifold generator g acts as rotation by π in a 2-plane

  $\Rightarrow g^2$ acts as $-\mathbb{1}$ on space-time fermions g is actually order 4

- on $\Gamma_{19,3}$, $\quad g|P_{\rm N}, P_{\rm I}\rangle = f(P_{\rm N}) e^{2i\pi P_{\rm I}\cdot v} | -P_{\rm N}, P_{\rm I}\rangle$

- v : shift vector, $\quad 4v \in {\rm I}$

  invariant lattice ${\rm I}$ characterized by (r, a, δ)

- $\mathbb{Z}_4$ phase $f(P_{\rm N})$: $f(0) = 1, \quad f(P_{\rm N}) f(-P_{\rm N}) = e^{2i\pi P_{\rm N}^2} = e^{2i\pi P_{\rm I}^2} = e^{2i\pi P_{\rm I}\cdot w}$

  $w \in {\rm I}^*,\ w^2 + \frac{1}{2}(s-2) \in 2\mathbb{Z}$, always exists

- $g^2 |P_{\rm N}, P_{\rm I}\rangle = e^{2i\pi P_{\rm I}\cdot(2v+w)} |P_{\rm N}, P_{\rm I}\rangle$

Construction of asymmetric $\mathbb{T}^3/\mathbb{Z}_2$ orbifold

- 1-loop modular invariance (level-matching) $\Rightarrow\ 2v^2 + \frac{s}{4} \in \mathbb{Z}$

- level-matching not possible for $(r, a, \delta) = (1, 1, 1), (2, 2, 1)$ $\quad$ I too small

- for most other (r, a, δ), v unique up to T-dualities of invariant lattice I

  moduli of I, sign$(r-1, 1)$: radius R, $(r-2)$-dim Wilson line A

  T-dualities: $R \to 1/R$, discrete translations of A

  T-dualities: Weyl reflections about a set of roots of I

  e.g. $(r, a, \delta) = (10, 0, 0)$, $\mathrm{I} \sim \mathrm{U} \oplus \mathrm{E}_8$ a.k.a. E_{10}

  $(r, a, \delta) = (5, 3, 1)$, $\mathrm{I} \sim \mathrm{U} \oplus 3\mathrm{A}_1$

Results

- full partition function $\mathcal{Z}(\tau, \bar{\tau})$

- $\mathcal{Z}(\tau, \bar{\tau}) \Rightarrow$ spectrum $\quad \mathcal{Z}(\tau, \bar{\tau}) \sim \sum_{\text{states}} \left[\#\text{bosons} - \#\text{fermions}\right] e^{i\pi\tau m_L^2} \, e^{-i\pi\bar{\tau} m_R^2}$

- from gravity multiplet survive graviton, dilaton, Kalb-Ramond, 1 graviphoton

- from generic $\mathrm{U}(1)^{19}$ gauge multiplets survive scalars, vectors of $\mathrm{U}(1)^{r-1}$

enhancing at special moduli of lattices I (Coulomb branch) and N (Higgs branch)

- massless fermions only for special moduli, fermions always charged under $\Gamma_{19,3}$

  membrane states in M-theory

  most of K3 quotients by Nikulin involutions are not spin

  $\Rightarrow$ only bosons from KK modes of 11-dim supergravity

Results

- tachyons appear in twisted sectors

  become massive in regions of moduli space, but quantum effective potential likely to drive to negative mass

  might signal different stable background ?! Basile, Mourad, Sagnotti '18

- points with different (r, a, δ) are connected by transitions $r \to (r+1)$

  e.g. $(2,0,0) \longrightarrow (3,1,1)$

$$\mathrm{I} = \mathrm{U},\ \mathrm{N} = \mathrm{E}_8 \oplus \mathrm{E}_8 \oplus 2\mathrm{U} \longrightarrow \mathrm{I} = \mathrm{A}_1 \oplus \mathrm{U},\ \mathrm{N} = \mathrm{E}_7 \oplus \mathrm{E}_8 \oplus 2\mathrm{U}$$

$$\mathrm{E}_8 \supset \mathrm{E}_7 \oplus \mathrm{A}_1$$

  interpreted as motion along Higgs and Coulomb branches

Aria da Capo

Final remarks 1

- Studied heterotic strings compactified on $\mathbb{T}^d$ and $\mathbb{T}^d/\mathbb{Z}_2$ (CHL)
- Found all groups of maximal enhancing in 9dim, 8dim, using methods based on underlying momentum lattices (Narain or Mikhailov)
- Methods can be extended to lower dim, done in 7dim Fraiman, Parra De Freitas '21
- Results give support to String Universality:
  group algebras and global structure satisfy criteria to be in landscape
  Cvetič, Dierigl, Lin, Zhang '20, 21, Montero, Vafa '21, Hamada, Vafa '21

Final remarks 2

- Studied heterotic strings compactified on non-supersymmetric $\mathbb{T}^3/\mathbb{Z}_2$
- Elaborated world-sheet description as asymmetric orbifolds
  - * determined massless and tachyonic spectrum
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- To do: relate to M-theory on $\mathrm{K3}/\mathbb{Z}_2$ in more detail

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¡ Felices 70 Hermann !

¡ Y que cumplas muchos años más !