"30 years of supergravity"
Paris, October 19, 2006

superstring realisations of supergravity in ten dimensions

Carlo Angelantonj
(Turin University)

Nuclear Physics B122 (1977) 253–290

SUPERSYMMETRY, SUPERGRAVITY THEORIES AND THE DUAL SPINOR MODEL

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and
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Received 14 January 1977

We study the connection between the dual spinor model and supersymmetry. We show that in the low-energy region, the dual spinor model yields a supersymmetric Yang-Mills theory with O(4) internal symmetry and a supergravity theory with O(4) internal symmetry.

The correct model to be considered thus seems to be the $G = +1$ sector of the NS model together with the Weyl (left-handed) and Majorana (real) sector of the Ramond model. It seems indeed to be trouble-free (no tachyons, no ghosts).

In such a model fermion-fermion and boson-fermion scattering have exactly the same duality properties (see fig. 3).

GSO suggest to arrange the string states according to their two-dimensional statistics

Moreover, (in the light-cone) superstring states carry a representation of the SO(8) little group

It turns out that the GSO projection arranges states according to their SO(8) representations

The four SO(8) conjugacy classes are then in one-to-one correspondence with G-parity

Affine SO(8)$_{k=1}$ characters

$$O_8(q) = \mathrm{tr}_{\mathrm{NS}}\, \mathscr{P}^{(+)}_{\mathrm{GSO}}\, q^{L_0} = \frac{\theta_3^4(0|\tau) + \theta_4^4(0|\tau)}{2\eta^4(\tau)} \sim \mathbf{1}$$

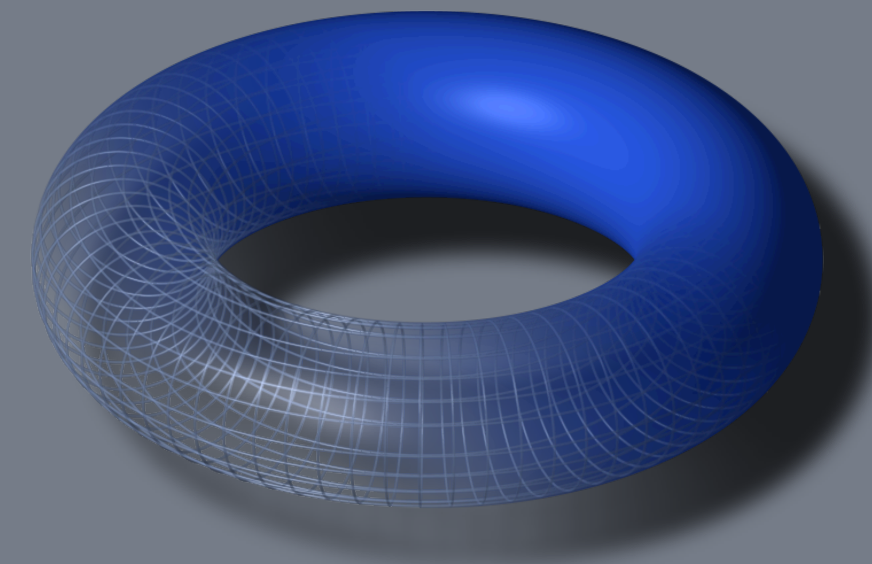
$$V_8(q) = \mathrm{tr}_{\mathrm{NS}}\, \mathscr{P}^{(-)}_{\mathrm{GSO}}\, q^{L_0} = \frac{\theta_3^4(0|\tau) - \theta_4^4(0|\tau)}{2\eta^4(\tau)} \sim \mathbf{8}_v$$

$$C_8(q) = \mathrm{tr}_{\mathrm{R}}\, \mathscr{P}^{(+)}_{\mathrm{GSO}}\, q^{L_0} = \frac{\theta_2^4(0|\tau) + \theta_1^4(0|\tau)}{2\eta^4(\tau)} \sim \mathbf{8}_c$$

$$S_8(q) = \mathrm{tr}_{\mathrm{R}}\, \mathscr{P}^{(-)}_{\mathrm{GSO}}\, q^{L_0} = \frac{\theta_2^4(0|\tau) - \theta_1^4(0|\tau)}{2\eta^4(\tau)} \sim \mathbf{8}_s$$

[Bianchi, Sagnotti 1992]

the torus partition function



$$\mathscr{T} = \int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^2}\,\mathrm{tr}\left(\mathscr{P}_{\mathrm{GSO}}\, q^{L_0}\, \bar{q}^{\tilde{L}_0}\right)$$

$$= \frac{1}{4}\int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^{2+4}}\, \frac{1}{|\eta|^{16}} \sum_{\substack{a,b=0,1\\ \tilde{a},\tilde{b}=0,1}} C\begin{bmatrix} a & b \\ \tilde{a} & \tilde{b}\end{bmatrix} \frac{\theta^4\begin{bmatrix} a \\ b\end{bmatrix}}{\eta^4}\, \frac{\bar{\theta}^4\begin{bmatrix} \tilde{a} \\ \tilde{b}\end{bmatrix}}{\bar{\eta}^4}$$

space-time momenta

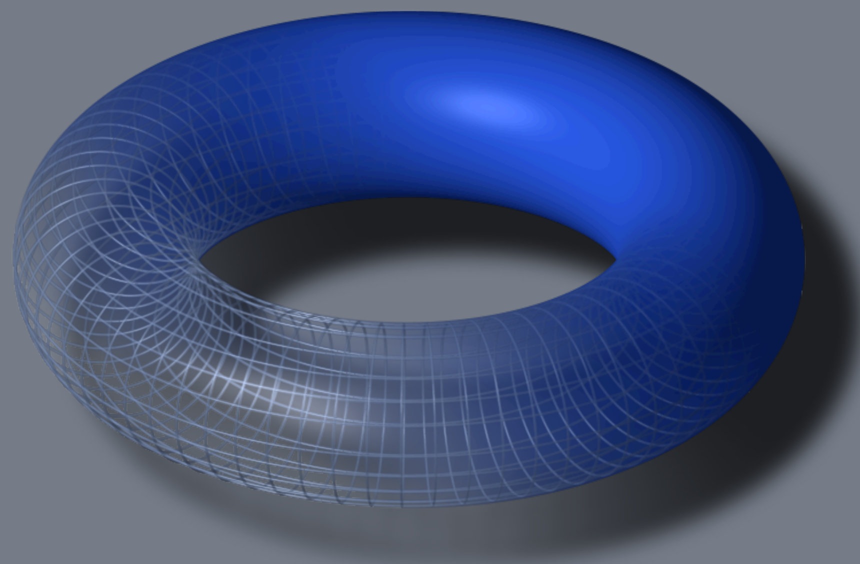
WS bosons

GSO phases

WS fermions

the phases determine the ten-dimensional spectrum, thus distinguish among the different superstrings

the torus partition function



$$\mathcal{T} = \sum_{i,j=1}^{4} \bar{\chi}_i X_{ij} \chi_j$$

$$\chi = (O_8\,,\, V_8\,,\, -S_8\,,\, -C_8)$$

X_{ij} is a matrix of non-negative integers such that

$$S^\dagger\, X\, S = X\,, \qquad T^\dagger\, X\, T = T$$

GSO phases $\Leftrightarrow$ modular invariance

Shapiro 1972

type IIA superstrings

$$\mathscr{T}_{\rm IIA} \sim (V_8 - S_8)(\bar{V}_8 - \bar{C}_8)$$

$g_{\mu\nu}\,,\ \phi\,,\ B_{\mu\nu}$ $\qquad$ $\psi^\mu_{\rm R}\,,\ \lambda_{\rm L}$ $\qquad$ $\psi^\mu_{\rm L}\,,\ \lambda_{\rm R}$ $\qquad$ $C_\mu\,,\ C_{\mu\nu\rho}$

type IIB superstrings

$$\mathscr{T}_{\rm IIB} \sim (V_8 - S_8)(\bar{V}_8 - \bar{S}_8)$$

$g_{\mu\nu}\,,\ \phi\,,\ B_{\mu\nu}$ $\qquad$ $\psi^\mu_{\rm L}\,,\ \lambda_{\rm R}$ $\qquad$ $\psi^\mu_{\rm L}\,,\ \lambda_{\rm R}$ $\qquad$ $C_0\,,\ C_{\mu\nu}\,,\ C^{(+)}_{\mu\nu\rho\sigma}$

maximal supergravities in D=10

Nahm 1977

type IIA supergravity: $\mathcal{N} = (1,1)$

Cremmer, Julia, Scherk 1978
Giani, Pernici 1984
Campbell, West 1984

$$\{g_{\mu\nu}\,,\,\phi\,,\,B_{\mu\nu}\,,\,C_{\mu}\,,\,C_{\mu\nu\rho}\,;\,\psi^{\mu}_{\rm L}\,,\,\psi^{\mu}_{\rm R}\,,\,\lambda_{\rm L}\,,\,\lambda_{\rm R}\}$$

type IIB supergravity: $\mathcal{N} = (2,0)$

Schwarz 1983
Howe, West 1984

$$\{g_{\mu\nu}\,,\,\phi\,,\,B_{\mu\nu}\,,\,C_{0}\,,\,C_{\mu\nu}\,,\,C^{(+)}_{\mu\nu\rho\sigma}\,;\,2\psi^{\mu}_{\rm L}\,,\,2\lambda_{\rm R}\}$$

Although chiral type IIB is free of anomalies

Alvarez-Gaumé, Witten 1984

Dixon, Harvey 1986
Seiberg, Witten 1986

type 0A superstrings

$$\mathscr{T}_{0\mathrm{A}} = |O_8|^2 + |V_8|^2 + \bar{S}_8 C_8 + \bar{C}_8 S_8$$

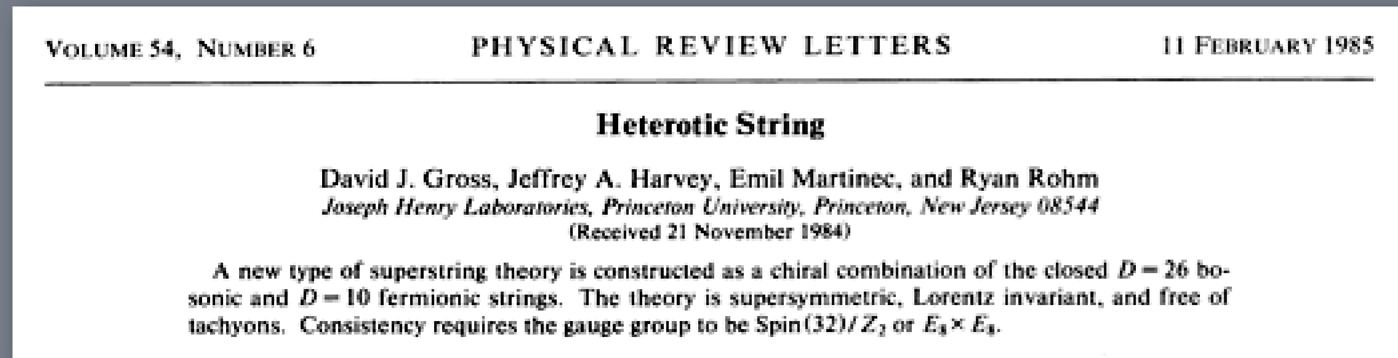
$T \qquad g_{\mu\nu}\,,\ \phi\,,\ B_{\mu\nu} \qquad C^1_\mu\,,\ C^1_{\mu\nu\rho} \qquad C^2_\mu\,,\ C^2_{\mu\nu\rho}$

type 0B superstrings

$$\mathscr{T}_{0\mathrm{B}} = |O_8|^2 + |V_8|^2 + |S_8|^2 + |C_8|^2$$

$T \qquad g_{\mu\nu}\,,\ \phi\,,\ B_{\mu\nu} \qquad C^1_0\,,\ C^1_{\mu\nu}\,,\ C^{(+)}_{\mu\nu\rho\sigma} \qquad C^2_0\,,\ C^2_{\mu\nu}\,,\ C^{(-)}_{\mu\nu\rho\sigma}$

purely bosonic and tachyonic!



Volume 54, Number 6 PHYSICAL REVIEW LETTERS 11 February 1985

Heterotic String

David J. Gross, Jeffrey A. Harvey, Emil Martinec, and Ryan Rohm
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 21 November 1984)

A new type of superstring theory is constructed as a chiral combination of the closed $D=26$ bosonic and $D=10$ fermionic strings. The theory is supersymmetric, Lorentz invariant, and free of tachyons. Consistency requires the gauge group to be $\mathrm{Spin}(32)/Z_2$ or $E_8\times E_8$.

$$\mathscr{T}_{\mathrm{SO}(32)} \sim (V_8 - S_8)(O_{32} + S_{32})$$

$$\mathscr{T}_{\mathrm{E}_8\times\mathrm{E}_8} \sim (V_8 - S_8)(\bar{O}_{16} + \bar{S}_{16})(\bar{O}_{16} + \bar{S}_{16})$$

to build string states we combine holomorphic states in the NS and R sector together with bosonic oscillators from the anti-holomorphic sector pointing along the space-time directions and along the internal directions

$$(V_8 - S_8)\times\alpha^{\mu}_{-1} \quad\rightarrow\quad g_{\mu\nu}\,,\ \phi\,,\ B_{\mu\nu}\,,\ \psi^{\mu}_{\mathrm{L}}\,,\ \lambda_{\mathrm{R}}$$

$$(V_8 - S_8)\times\alpha^{I}_{-1} \quad\rightarrow\quad A^{I}_{\mu}\,,\ \lambda^{I}_{\mathrm{L}}$$

$$\mathrm{Spin}(32)/\mathbb{Z}_2$$

$$\mathrm{E}_8\times\mathrm{E}_8$$

minimal supergravity in D=10

Nahm 1977

$$\{g_{\mu\nu}\,,\,\phi\,,\,B_{\mu\nu}\,;\,\psi^{\mu}_{\mathrm{L}}\,,\,\lambda_{\mathrm{R}}\}$$

Bergshoeff, de Roo, de Wit, van Nieuwenhuizen 1982

matter multiplet: super-Yang-Mills

Gliozzi, Scherk, Olive 1976
Brink, Scherk, Schwarz 1976
Chapline, Manton 1983

$$\{A_{\mu}\,;\,\lambda_{\mathrm{L}}\}$$

The only anomaly-free theories have gauge group

Green, Schwarz 1984

$\mathrm{E}_8 \times \mathrm{E}_8$ $\quad$ $\mathrm{SO}(32)$ $\quad$ $\mathrm{E}_8 \times \mathrm{U}(1)^{248}$ $\quad$ $\mathrm{U}(1)^{496}$

non-supersymmetric heterotic strings

$$\begin{aligned} \mathscr{T} \;&=\; V_8\left(\bar{O}_{16}\bar{O}_{16}+\bar{S}_{16}\bar{S}_{16}\right)-S_8\left(\bar{O}_{16}\bar{S}_{16}+\bar{S}_{16}\bar{O}_{16}\right)\\ &+\; O_8\left(\bar{V}_{16}\bar{C}_{16}+\bar{C}_{16}\bar{V}_{16}\right)-C_8\left(\bar{V}_{16}\bar{V}_{16}+\bar{C}_{16}\bar{C}_{16}\right) \end{aligned}$$

Alvarez-Gaumé, Ginsparg, Moore, Vafa 1986

massless excitations comprise $g_{\mu\nu}\,,\,\phi\,,\,B_{\mu\nu}$

gauge group $\mathrm{O}(16)\times\mathrm{O}(16)$

left-handed fermions in the reps $(\mathbf{128},\mathbf{1})+(\mathbf{1},\mathbf{128})$

right-handed fermions in the reps $(\mathbf{16},\mathbf{16})$

free-fermionic constructions

Antoniadis, Bachas, Kounnas, Windey 1986
Antoniadis, Bachas, Kounnas 1987
Kawai, Llewellen, Tye 1987
Lerche, Lüst, Schellekens 1987
Narain, Sarmadi, Vafa 1987

At special points of moduli space of toroidal (orbifold) compactifications zero-modes of world-sheet bosons can be fermionised

$$\mathscr{Z} = \int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^2} Z_{\rm B}^2 \sum_{\rm spin\ str} C \begin{bmatrix} \mathbf{a} \\ \mathbf{b} \end{bmatrix} Z_{{\rm long},3/2} \begin{bmatrix} a_\psi \\ b_\psi \end{bmatrix} \prod_{f=1}^{64} Z_{\rm F} \begin{bmatrix} a_f \\ b_f \end{bmatrix}$$

the phases are determined by demanding one loop modular invariance and two-loop factorisation *to summarise ...*

modular invariance for models of closed oriented strings is the rationale behind the Gliozzi-Scherk-Olive projection

it allows to extend string constructions
to lower dimensions and to non-geometrical spaces
(internal exact/abstract conformal field theories)

in turn, modular invariance automatically
yields an anomaly-free theory

What about open strings?

open strings alone do not yield a consistent theory
(they can join ends and form closed strings!)

oriented closed strings together with oriented open strings
do not yield consistent vacuum configurations

Orientifold constructions

ROM2F-87/25

OPEN STRINGS AND THEIR SYMMETRY GROUPS

Augusto Sagnotti

Dipartimento di Fisica

Università di Roma II, "Tor Vergata"

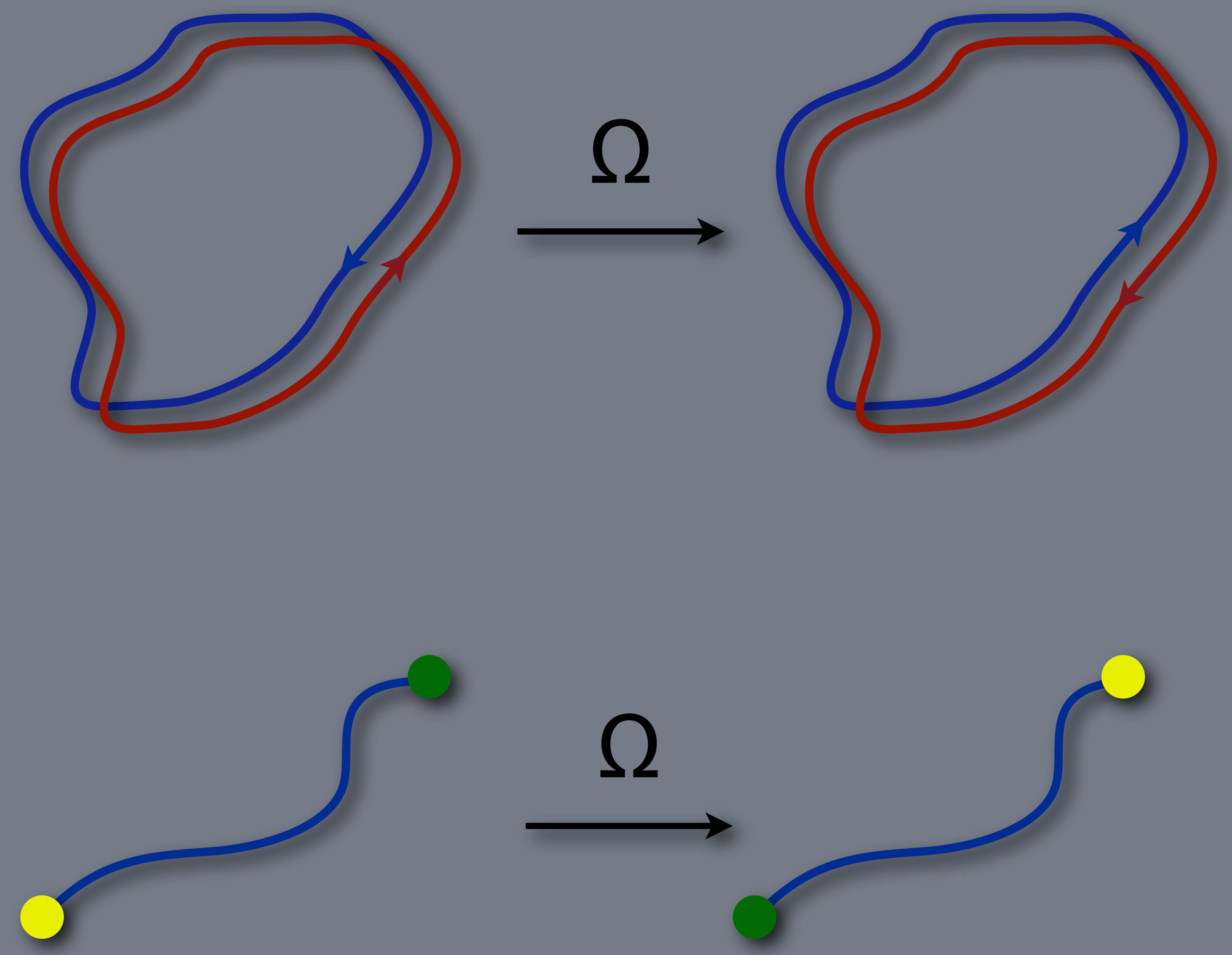
a consistent way of tying together closed and open superstrings

also: Govaerts 1989
Horava1989
Bern, Dunbar 1990
Green, 1994

Similarly to the GSO projection,
arrange closed and open string states
according to world-sheet parity Ω

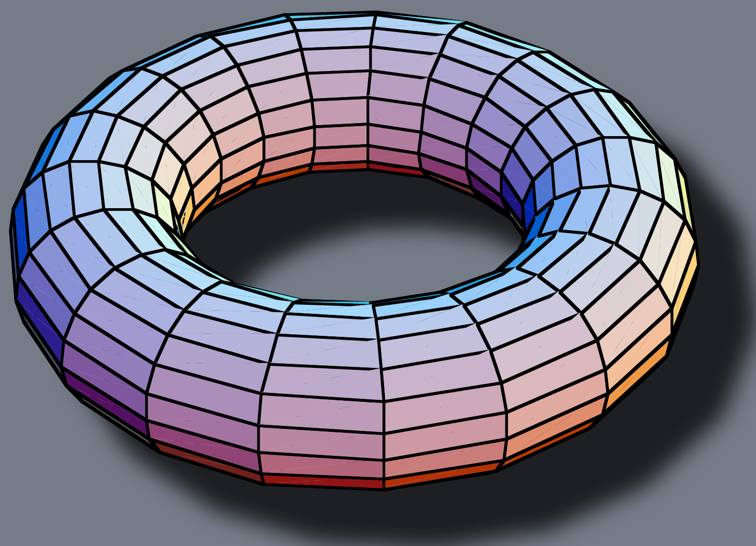
(this is allowed only if the parent theory is invariant under Ω)

retain only the part of the spectrum
with proper Ω parity



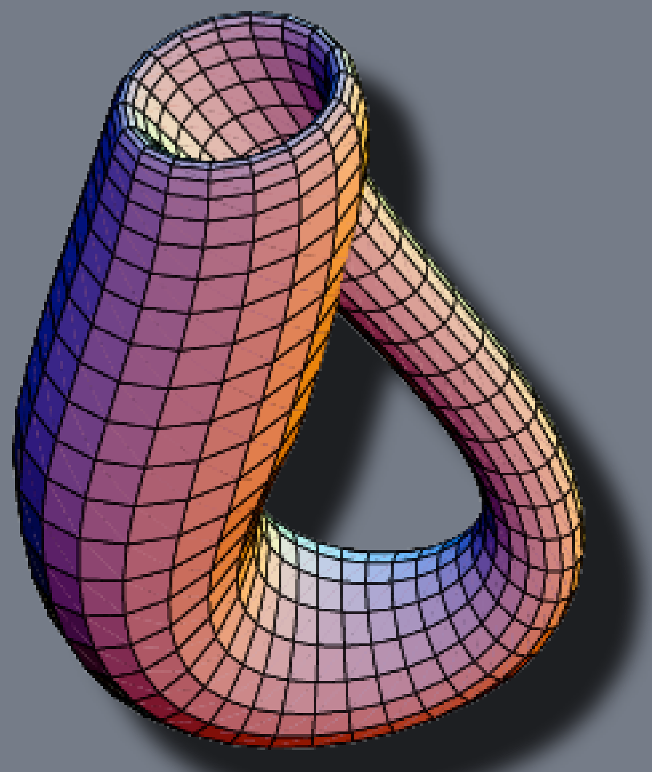
closed and open strings become unoriented!

The closed-string sector



$$\mathscr{T} = \frac{1}{2}\int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^6}\frac{1}{|\eta|^{16}}(V_8 - S_8)(\bar{V}_8 - \bar{S}_8)$$

$$\mathscr{K} = \frac{1}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\frac{1}{\eta^8}(V_8 - S_8)(2i\tau_2)$$

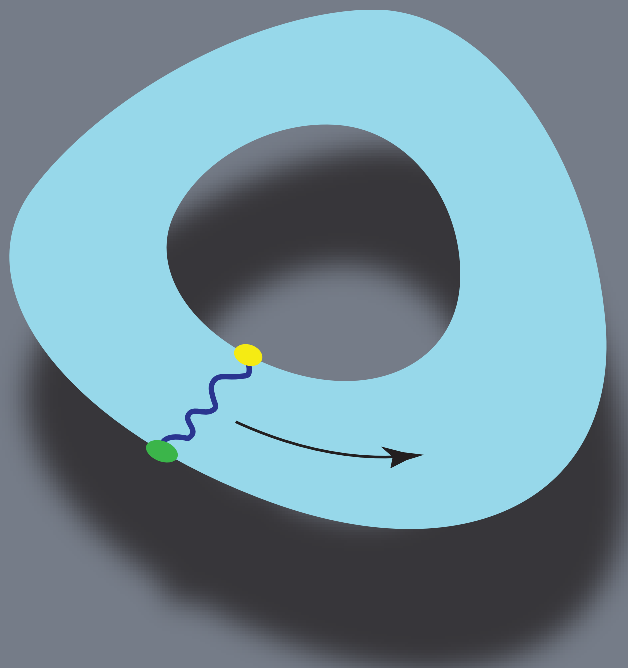


the massless closed-string excitations

$$\mathscr{T} + \mathscr{K} = g_{\mu\nu}\ ,\ \phi\ ,\ C_{\mu\nu}\ ,\ \psi^{\mu}_{\rm L}\ ,\ \lambda_{\rm R}$$

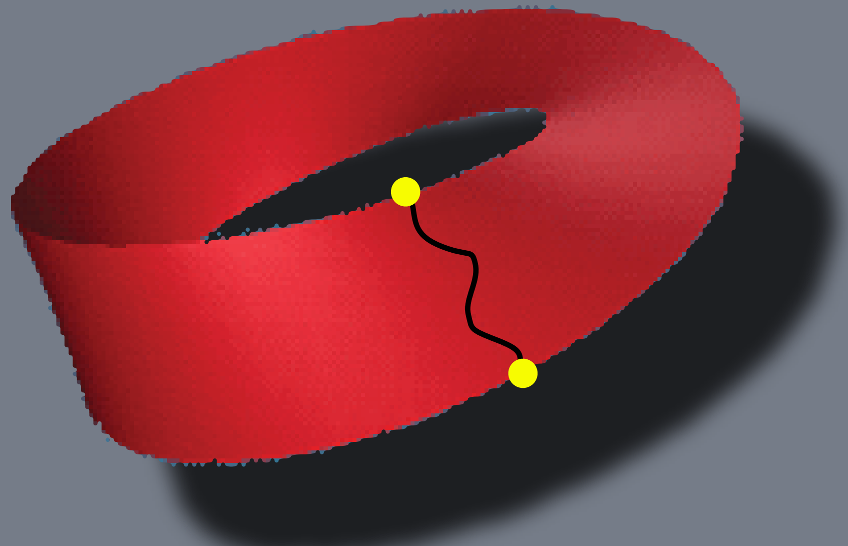
minimal D=10 N=(1,0) supergravity

The open-string sector



$$\mathscr{A} = \frac{1}{2} N^2 \int_0^\infty \frac{dt}{t^6} \frac{1}{\eta^8} (V_8 - S_8)(\tfrac{it}{2})$$

$$\mathscr{M} = \pm \frac{1}{2} N \int_0^\infty \frac{dt}{t^6} \frac{1}{\eta^8} (V_8 - S_8)(\tfrac{1+it}{2})$$

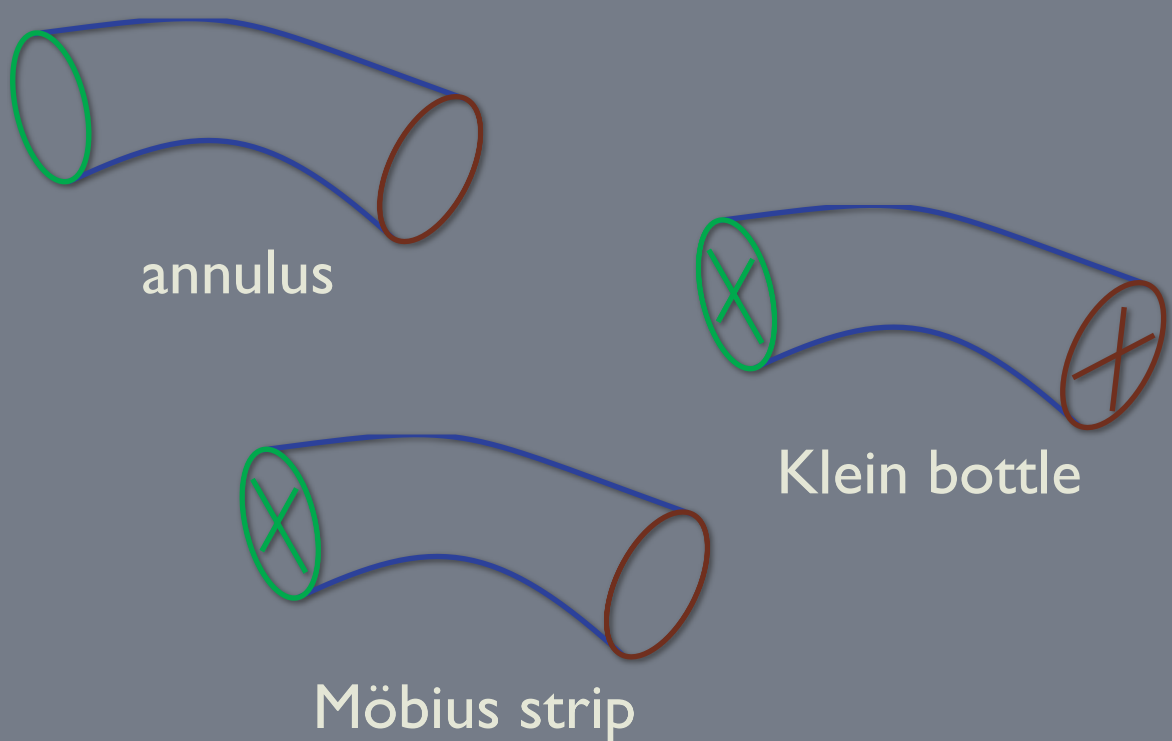


the massless open-string excitations

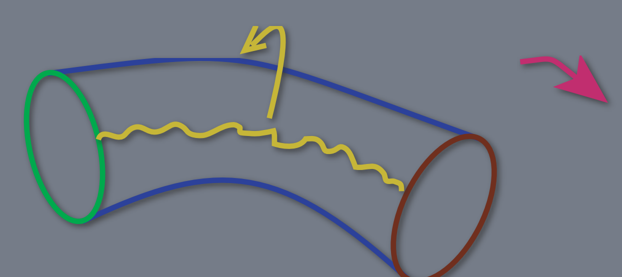
$$\mathscr{A} + \mathscr{M} = \frac{N^2 \pm N}{2} \, (A\mu \, , \, \lambda_{\rm L})$$

minimal D=10 N=(1,0) super-Yang-Mills
with gauge group SO(N) or USp(N)

the new amplitudes are NOT modular invariant
have a dual interpretation according to our choice of proper time

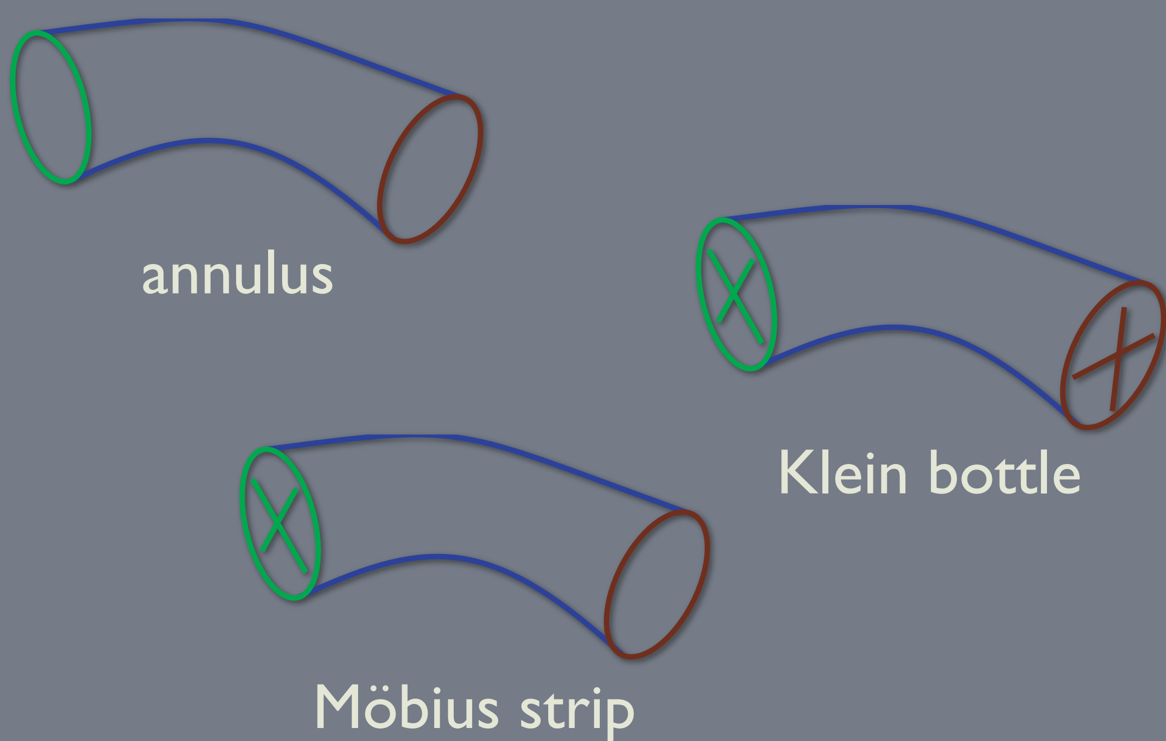


for “vertical time”

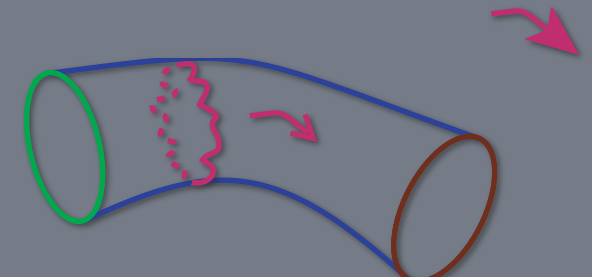


one loop for open strings

the new amplitudes are NOT modular invariant
have a dual interpretation according to our choice of proper time

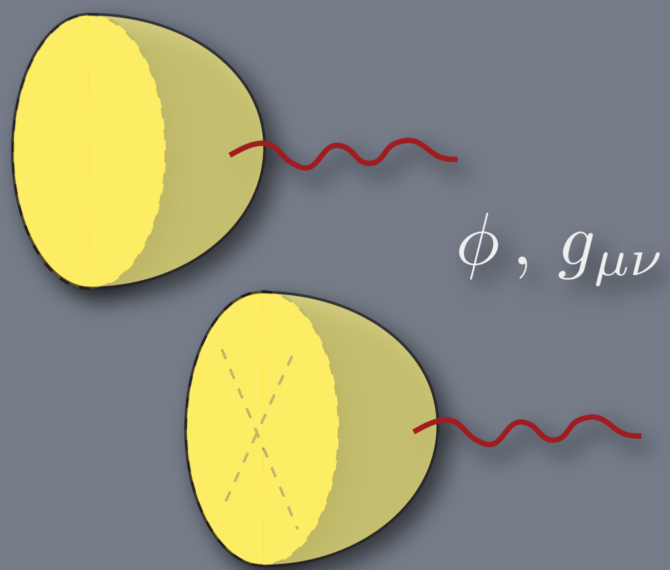


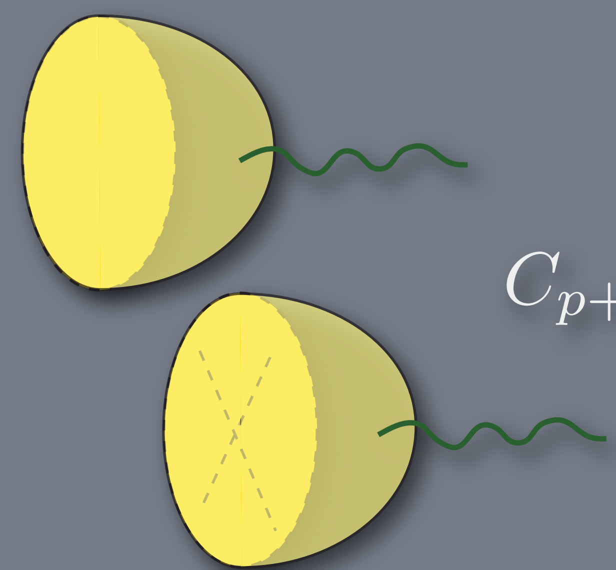
for “horizontal time”



tree level
free propagation
for closed strings

divergencies are due to the exchange of closed-string massless states





Green, Schwarz 1985
Douglas, Grinstein 1987
Marcus, Sagnotti 1987
Weinberg 1987
Bianchi, Sagnotti 1988

picture $\left(-\frac{1}{2}\,,\,-\frac{3}{2}\right)$

Bianchi, Pradisi, Sagnotti 1992

cancellation of tadpoles $\quad N \pm 32 = 0$

uniquely selects the gauge group $\quad \mathrm{SO}(32)$

in this framework the cancellation of RR tadpoles automatically gives anomaly-free theories

from the point of view of low-energy supergravity
the non-vanishing tadpoles introduce new couplings

$$(\tau_D + \tau_{\mathscr{O}}) \int_{\mathscr{M}_{p+1}} d^{p+1}x \, \sqrt{-g} \, e^{-\phi} \; + \; (q_D + q_{\mathscr{O}}) \int_{\mathscr{M}_{p+1}} C_{p+1}$$

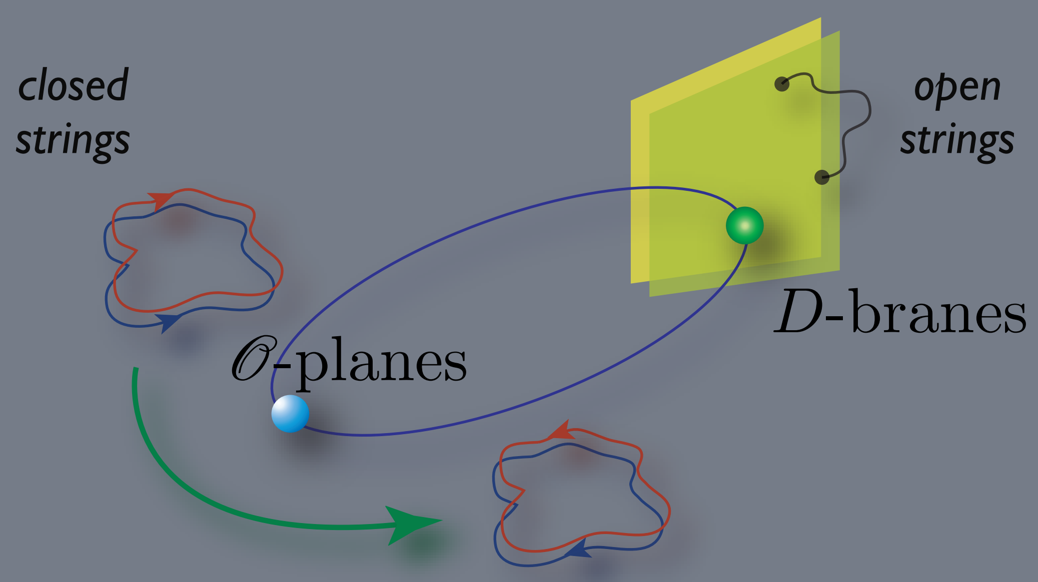
these correspond to tension and RR charge
of extended objects

VOLUME 75, NUMBER 26 PHYSICAL REVIEW LETTERS 25 DECEMBER 1995

Dirichlet Branes and Ramond-Ramond Charges

Joseph Polchinski*
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106-4030
(Received 10 October 1995)

We show that D-branes, extended objects defined by mixed Dirichlet-Neumann boundary conditions, break half the supersymmetries of the type II superstring and carry a complete set of electric and magnetic Ramond-Ramond charges. The product of the electric and magnetic charges is a single Dirac unit, and the quantum of charge is that required by string duality. This is strong evidence that D-branes are intrinsic to type II string theory and are the Ramond-Ramond sources needed for string duality. Also, we find in the IIa string a 9-form potential, which gives an effective cosmological constant.



	τ	q
$\mathscr{O}^+$	$-$	$-$
$\mathscr{O}^-$	$+$	$+$
D	$+$	$+$

Tadpole conditions:

$$\sum q_{\mathscr{O}} + q_D = 0 \qquad \text{(neutrality)}$$

$$\sum \tau_{\mathscr{O}} + \tau_D = 0 \qquad \text{(massless)}$$

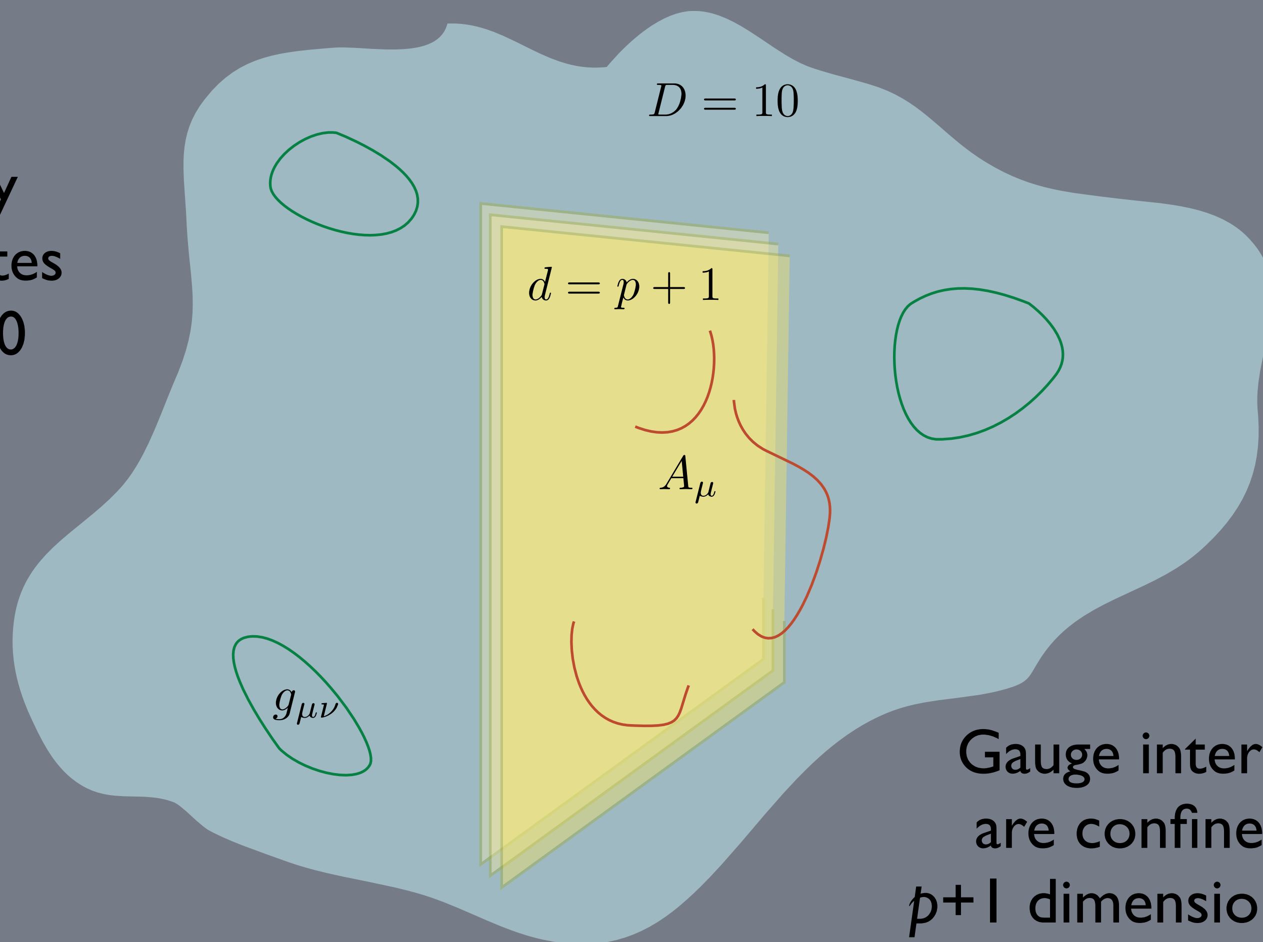
open-string invariant *d.o.f.*

$$\text{NS} : \text{sign}(\tau_{\mathscr{O}}\tau_D) \text{ sym.}$$

$$\text{R} : \text{sign}(q_{\mathscr{O}}q_D) \text{ sym.}$$

Gravitational vs gauge interactions

Gravity propagates in *D*=10



Gauge interactions are confined on a *p*+1 dimensional space

$$g_{\mu\nu} = g_{\mu\nu}(x^\mu, y^a) \qquad A_\mu = A_\mu(x^\mu)$$

new scenarios for string phenomenology

(large extra dimensions, intersecting brane worlds, ...)

an instance of string-string duality

minimal 10D supergravity is unique
modulo the choice of the gauge group

heterotic SO(32) *type I superstring*

have different microscopic d.o.f.

are the two theories related in some way?

low-dimensional supergravity in the string frame

$$\int d^{10}x\sqrt{-g_{\mathrm{H}}}e^{-2\phi_{\mathrm{H}}}\left[R+(\partial\phi_{\mathrm{H}})^2+(dB)^2+F^2\right]$$

$$\int d^{10}x\sqrt{-g_{\mathrm{I}}}\left[e^{-2\phi_{\mathrm{I}}}\left(R+(\partial\phi_{\mathrm{I}})^2\right)+(dC)^2+e^{-\phi_{\mathrm{I}}}F^2\right]$$

field redefinition $\quad \phi_{\mathrm{H}}=-\phi_{\mathrm{I}} \quad \Rightarrow \quad g_{s,\mathrm{H}}=\frac{1}{g_{s,\mathrm{I}}}$

strong-weak coupling duality

Polchinski, Witten 1995
see Hull's talk

lower-dimensional compactifications

Bianchi, Sagnotti 1992
Gimon, Polchinski 1996

for instance $T^4/\mathbb{Z}_2$

closed strings — *D=6 N=(1,0) supergravity coupled to 1 tensor multiplet and 20 hypers*

open strings — *gauge group U(16)xU(16)*
hypers in 2(120,1)+2(1,120)+(16,16)

RR tadpole conditions ensure cancellation of irreducible anomalies

$$273 - 29n_{\mathrm{T}} + n_{\mathrm{V}} - n_{\mathrm{H}} = 0$$

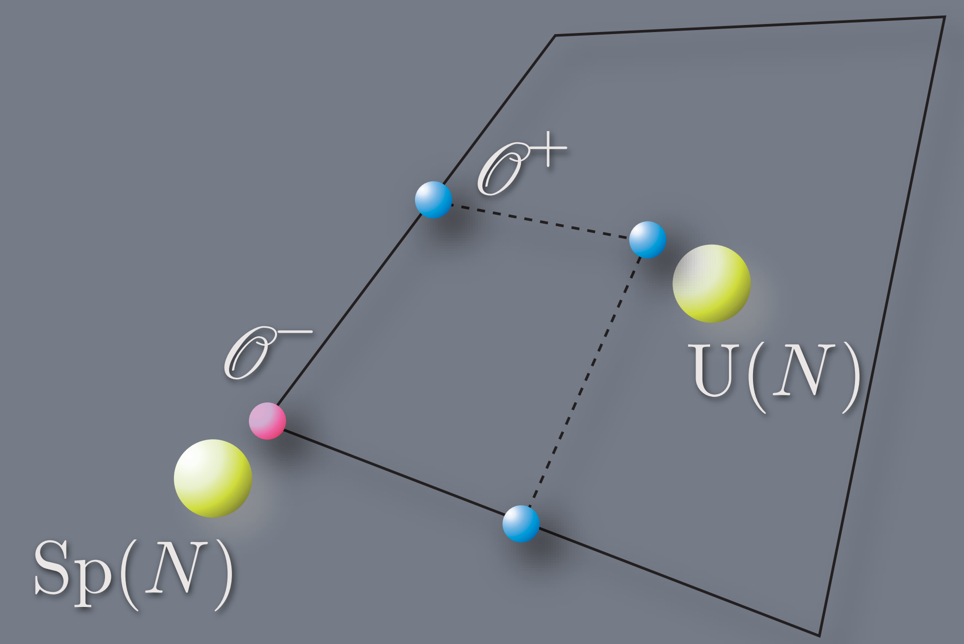
reducible anomalies factorise

$$\mathscr{I}_8 \sim \left(\mathrm{tr}R^2 - \mathrm{tr}F_1^2 - \mathrm{tr}F_2^2\right)\left(\mathrm{tr}F_1^2 + \mathrm{tr}F_2^2\right)$$

can be disposed of by the Green-Schwarz mechanism

$T^4/\mathbb{Z}_2$ *with a non-vanishing B_{ab} background*

Bianchi, Pradisi, Sagnotti 1992
C.A. 1999



new features:

- *rank reduction of gauge group*
- *unitary and symplectic groups*
- *varying number of tensor multiplets*

as usual, irreducible anomalies cancel
if RR tadpoles conditions a imposed

reducible anomaly does not factorise any more

$$
\begin{aligned}
\mathscr{I}_8^{(r)} &= -\frac{2^{r/2}}{64}\left(2^{(2-r)/2}\,\mathrm{tr}R^2 - \mathrm{tr}F_1^2 - \mathrm{tr}F_2^2 - \mathrm{tr}F_3^2 - \mathrm{tr}F_4^2\right)^2 + \\
&+ \frac{2^{r/2}}{64}\left(\mathrm{tr}F_1^2 + \mathrm{tr}F_2^2 - \mathrm{tr}F_3^2 - \mathrm{tr}F_4^2\right)^2 + \\
&+ \frac{2^{r/2}}{64}(2 - 2^{(r-2)/2})\left(\mathrm{tr}F_1^2 - \mathrm{tr}F_2^2 + \mathrm{tr}F_3^2 - \mathrm{tr}F_4^2\right)^2 + \\
&+ \frac{2^{r/2}}{64}(4 - 2^{(r-2)/2})\left(\mathrm{tr}F_1^2 - \mathrm{tr}F_2^2 - \mathrm{tr}F_3^2 + \mathrm{tr}F_4^2\right)^2
\end{aligned}
$$

a generalised Green-Schwarz mechanism now takes place

In general, for n_T tensor multiplets the residual anomaly polynomial takes the form

Sagnotti 1992
Ferrara, Minasian, Sagnotti 1996
Ferrara, Riccioni, Sagnotti, 1998

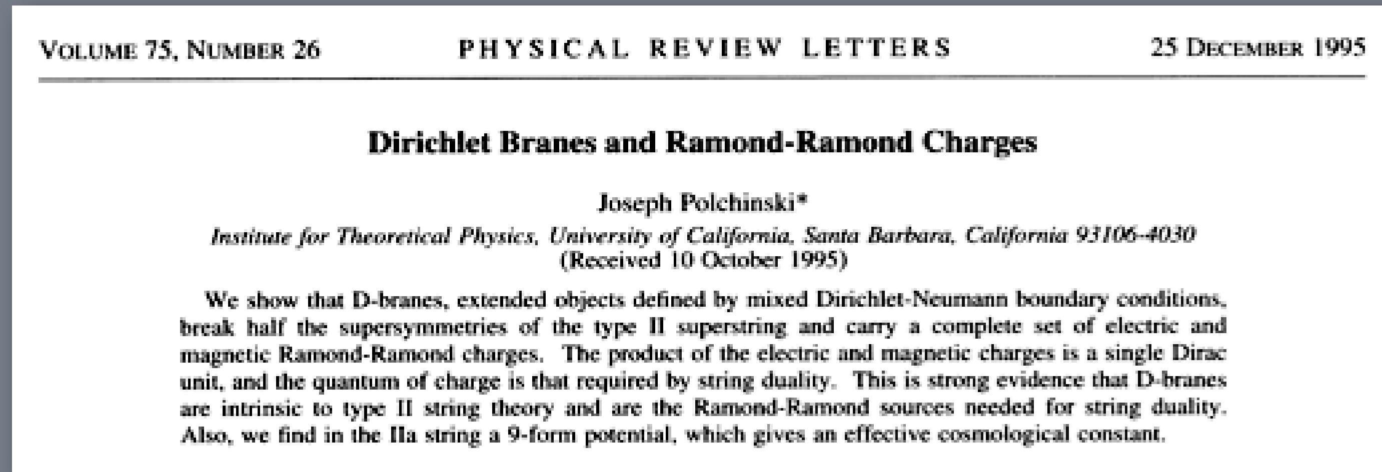
$$\mathcal{I}_8 = -\sum_{x,y} c_x^r c_y^s \eta_{rs} \mathrm{tr}_x F^2 \mathrm{tr}_y F^2$$

Accordingly, the field strengths of the 2-forms include combinations of Chern-Simons forms, and the kinetic term for the gauge vectors involves couplings to the scalars v_r in the tensor multiplets

$$e^{-1}\,\mathscr{L} \sim -\tfrac{1}{2} v_r c^{rz} \mathrm{tr}_z F_{\mu\nu} F^{\mu\nu}$$

singularities $\Rightarrow$ *transitions to tensionless strings*

Seiberg, Witten 1996
Duff, Lu, Pope 1996



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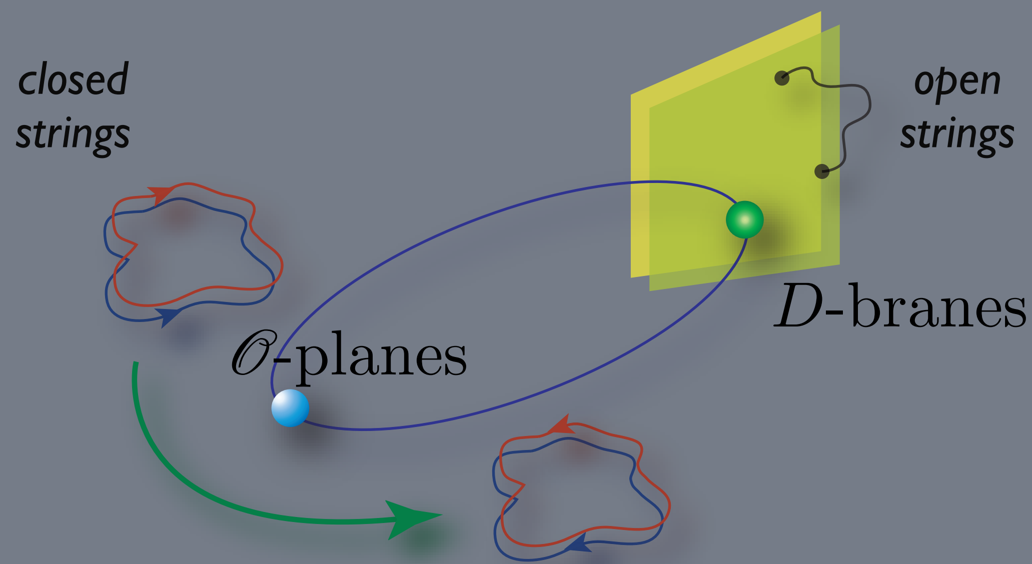

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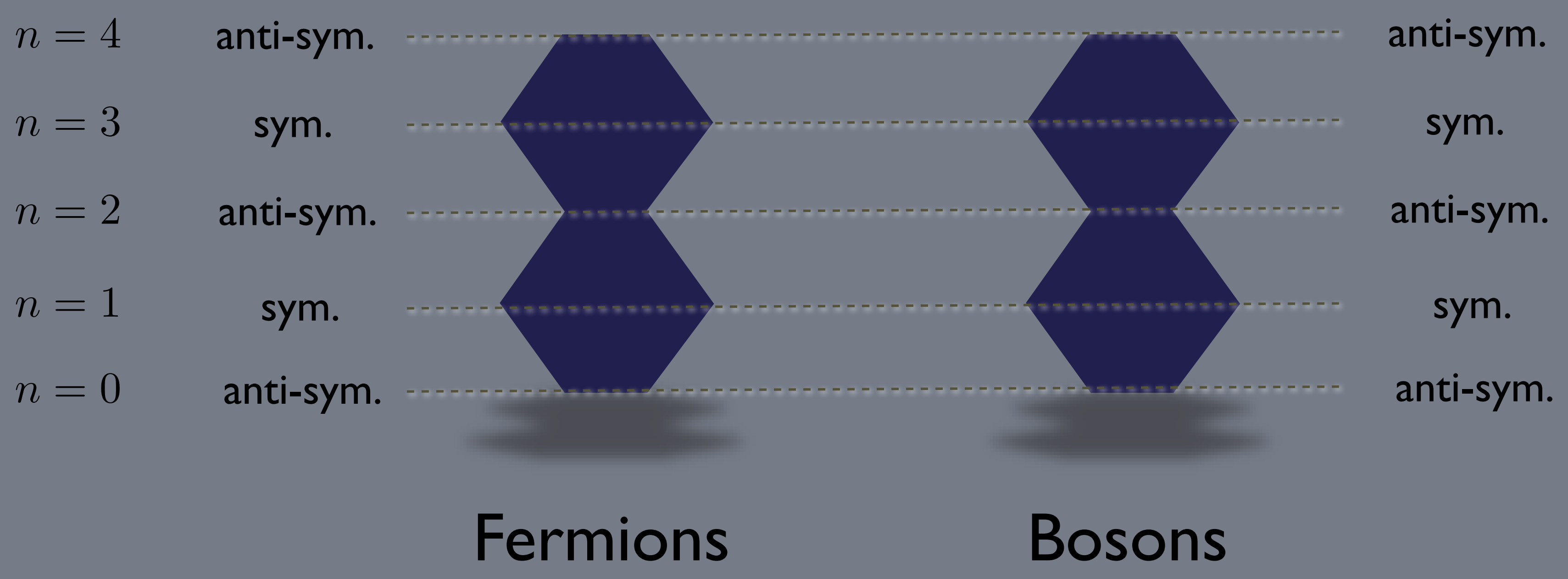
Brane Supersymmetry

Open-String spectrum

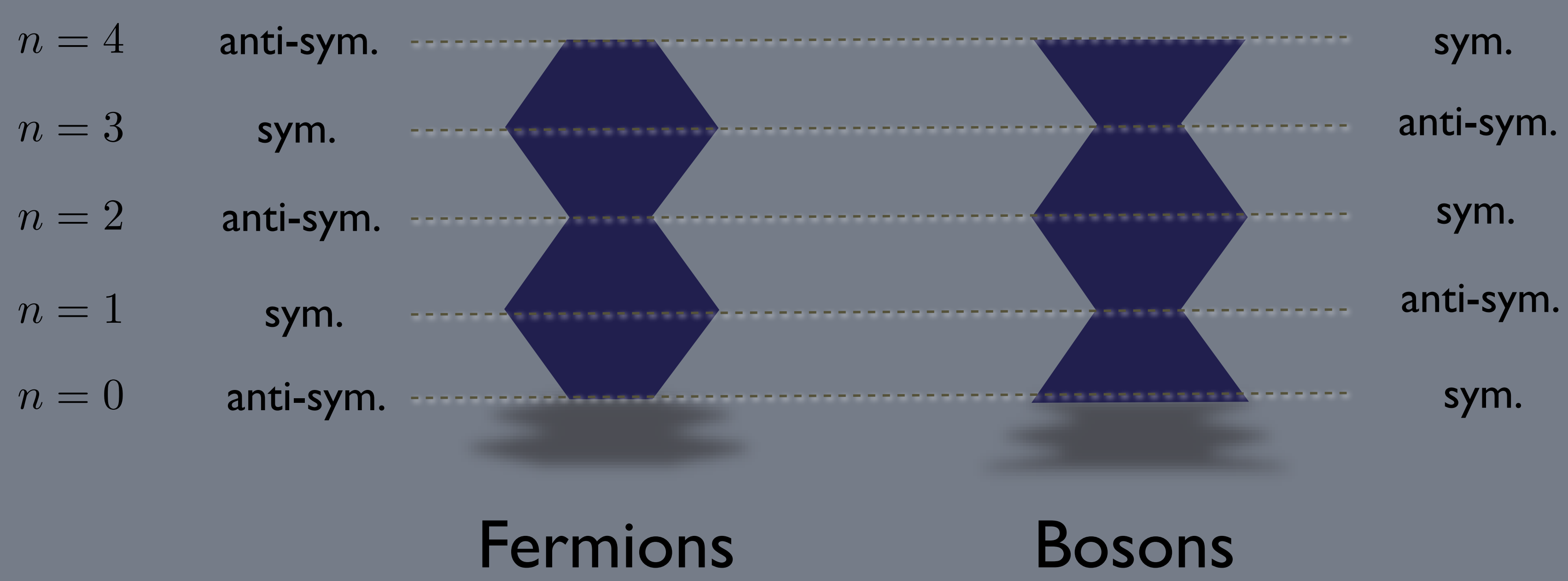


SO(32) and fermions in the adjoint

Brane Supersymmetry Breaking

Sugimoto 1999
Antoniadis, Dudas, Sagnotti 1999
C.A. 1999
Aldazabal, Uranga 1999

Open-String spectrum



USp(32) and fermions in the 496

$$\mathscr{O}^{+} \oplus 16 \text{ D-branes} \quad \Rightarrow \quad \mathscr{O}^{-} \oplus 16 \text{ anti-D-branes}$$

$\Delta M \sim 1/\sqrt{\alpha'}$ but Λ at tree-level *how to shift the vacuum in string theory?*

how to implement the Fischler-Susskind mechanisms?

urgent problem for the younger generation!!