INSTITUT POLYTECHNIQUE DE PARIS

GEOMETRY OF NON-SUSY STRINGS

with Z.K. Baykara and C. Vafa, [arXiv:2603.13468 [hep-th]]
+ M. Delgado, H. Parra de Freitas, [arXiv:2604.07433 [hep-th]]

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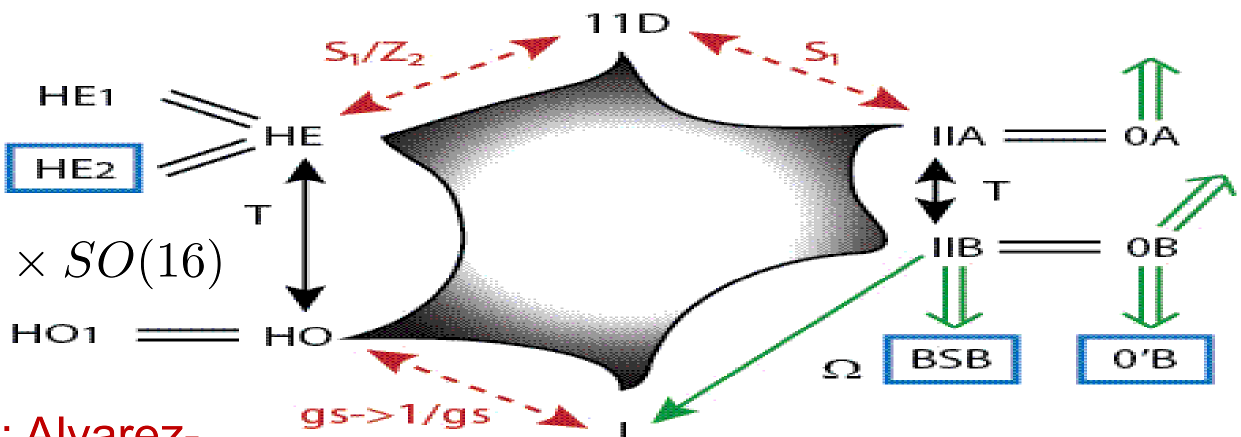
Quantum Gravity & Strings, Corfu

Outline

- Type 0 strings
- From type 0 to type II strings and M-theory
- M-theory on $S^1 \vee S^1$ as type 0A
- A duality web for non-SUSY strings
- Perspectives, Open questions

You all saw the duality diagram of 10d superstrings and M-theory.
Maybe not the SUSY+non-SUSY 10d strings duality diagram.



$SO(16) \times SO(16)$

(Dixon,Harvey; Alvarez-Gaume, Ginsparg,Moore,Vafa)

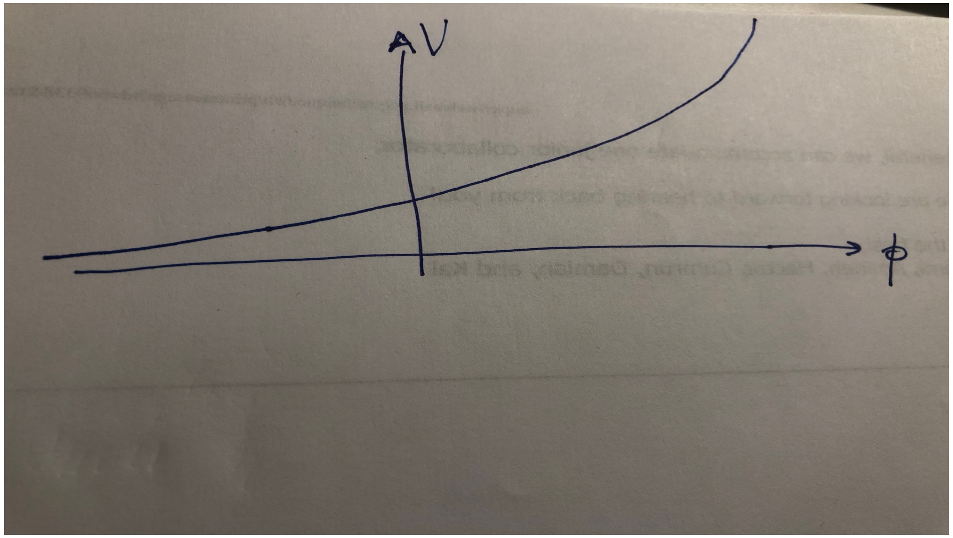
$USp(32)$ $U(32)$

Sugimoto Sagnotti

Why non-SUSY strings are hard

- SUSY breaking generate a (field-dependent) vacuum energy.

Always a runaway in perturbation theory (talks A. Sagnotti, C. Angelantonj)



$$V = V_0 \, e^{\gamma \phi}$$

1) Type 0 strings

(Dixon,Harvey; Seiberg,Witten)

10d strings with no SUSY and a tachyon in their spectrum

They can be constructed as, either :

- Imposing (GSO) invariant states under $(-1)^{G_L+G_R}$

  (G= world-sheet fermion number)

- As the orbifold $0A = IIA/(-1)^F$

  ($F = F_L + F_R$ = spacetime fermion number)

Conversely, $IIA = 0A/(-1)^{G_L}$

called Q (quantum symmetry) later on

Sector	Type 0B	Type 0A
$(\mathrm{NS}^+, \mathrm{NS}^+)$	$g_{\mu\nu},\ B_{\mu\nu},\ \phi$	$g_{\mu\nu},\ B_{\mu\nu},\ \phi$
$(\mathrm{NS}^-, \mathrm{NS}^-)$	T	T
$(\mathrm{R}^+, \mathrm{R}^+)$	$\chi,\ C_{\mu\nu},\ D_{\mu\nu\rho\sigma}$	—
$(\mathrm{R}^-, \mathrm{R}^-)$	$\chi',\ C'_{\mu\nu},\ D'_{\mu\nu\rho\sigma}$	—
$(\mathrm{R}^+, \mathrm{R}^-)$	—	$A_\mu,\ C_{\mu\nu\rho}$
$(\mathrm{R}^-, \mathrm{R}^+)$	—	$A'_\mu,\ C'_{\mu\nu\rho}$

Table 1. Perturbative spectra of Type 0B and Type 0A string theories. The NSNS sector contains $g_{\mu\nu}, B_{\mu\nu}, \phi$, and a tachyon T. The RR sector is doubled relative to Type II, giving two RR gauge fields.

⟹ No spacetime fermions in 10d

There are two IIA theories: IIA and IIA'. They are mapped into each other by the worldsheet parity Ω

Useful to define $C_p^{\pm} \equiv \dfrac{C_p \pm C_p'}{2}$

Two important symmetries to consider:

$$Q: \quad T \to -T, \qquad A^+ \leftrightarrow A^-, \qquad C_3^+ \leftrightarrow C_3^- \qquad \text{(0A)}$$

$$Q: \quad T \to -T, \qquad \chi^+ \leftrightarrow \chi^-, \qquad C_2^+ \leftrightarrow C_2^-, \qquad D_4^+ \leftrightarrow D_4^- \qquad \text{(0B)}$$

$$\Omega: A^{\pm} \leftrightarrow \pm A^{\pm}, \qquad C_3^{\pm} \leftrightarrow \pm C_3^{\pm} \qquad \text{(0A)}$$

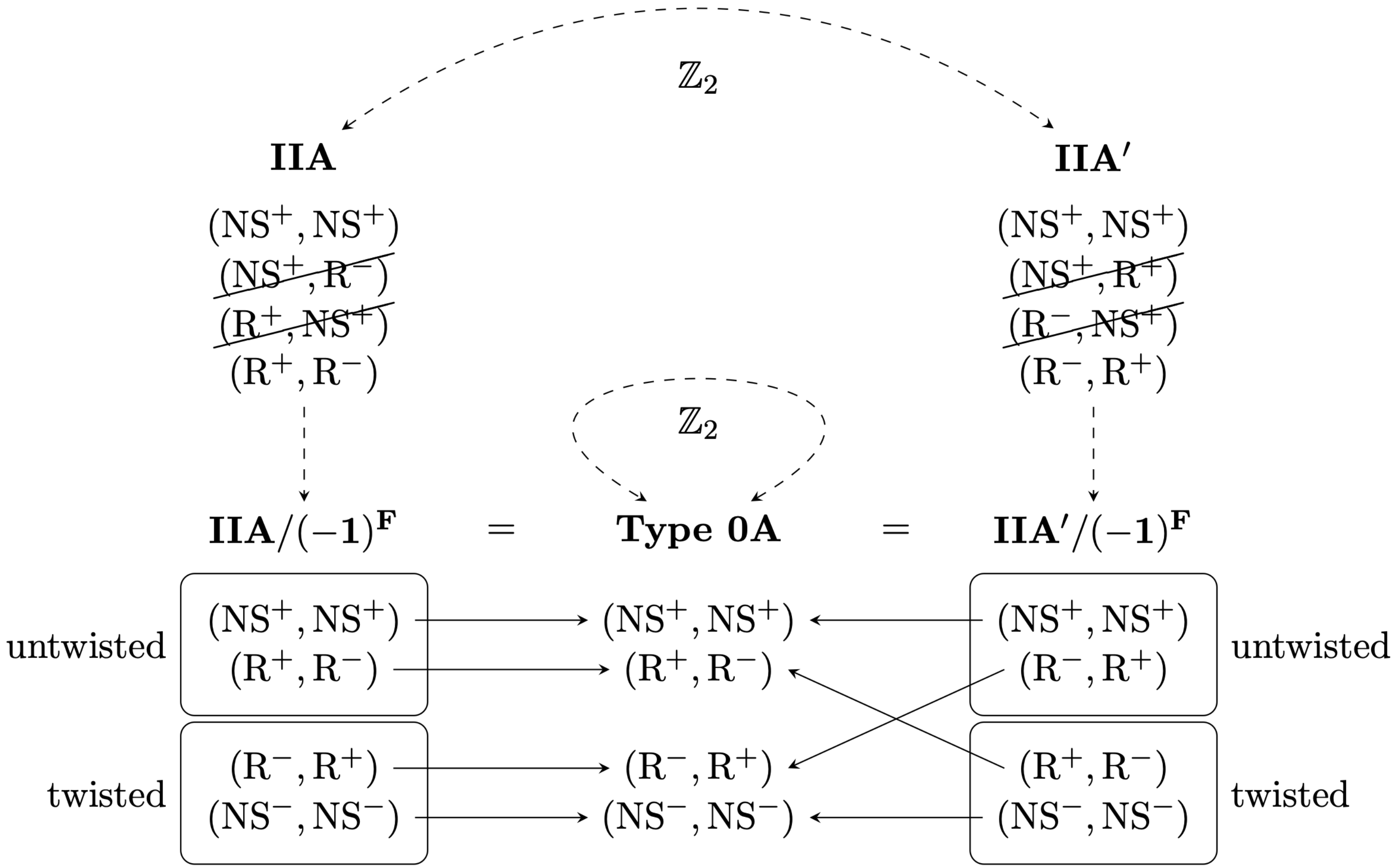


Figure 1. Type 0A obtained as the orbifold of Type IIA or Type IIA′ by $(-1)^F$. The theory IIA′ is related to IIA by the left–right mover exchange Ω. This becomes a $\mathbb{Z}_2$ symmetry of Type 0A. The $(-1)^F$ orbifolds differ by an exchange of twisted and untwisted RR sectors.

D-branes of type 0 strings

Type 0 strings have charged branes (Klebanov-Tseytlin)

Dp_+ : RR charges $\frac{1}{\sqrt{2}}(+,+)$

Positive coupling to the tachyon

Charges first set of RR fields

Charges second set of RR fields

Dp_- : RR charges $\frac{1}{\sqrt{2}}(+,-)$

Negative coupling to the tachyon

- normalized wrt to the tension of type II D-branes

- p=even (0A) and p=odd (0B)
- corresponding antibranes $\overline{Dp_\pm}$

D-brane spectrum:

Endpoints	Sector	Fields
$Dp^{\pm} - Dp^{\pm}$	NS^{+}	$A_{\mu},\ \phi^{i}$
$Dp^{\pm} - \overline{Dp^{\pm}}$	NS^{-}	T
$Dp^{+} - Dp^{-}$	R^{+}	ψ
$Dp^{+} - \overline{Dp^{-}}$	R^{-}	ψ^{c}

Obs: An equal number of $Dp_{+} - Dp-$ pairs have fermi-bose degeneracy.

2) From type 0 to type II strings and M-theory

Consider type II and type 0 strings on a circle (9d), with nontrivial boundary conds./holonomies. Then:

0A with Q holonomy, limit $R \to 0$ = type IIB in 10d

More generally,

$$IIA|^{S^1_R}_{(-1)^F \delta^2_P} = 0A|^{S^1_R}_{Q\delta_W} = 0B|^{S^1_{R^{-1}}}_{Q\delta_P}$$

$$X \to X + 2\pi R \qquad\qquad \tilde{X} \to \tilde{X} + \pi R^{-1}$$

(Scherk-Schwarz BC) LR asymmetric shift

mapping of D-branes

IIA on S^1_R $\Longleftrightarrow$ 0B on $S^1_{R^{-1}}$

$$D(2p) \qquad D^+(2p-1) - D^-(2p-1)$$

(SS boundary conds) (identified by $Q\delta_P$)

3) M-theory on $S^1 \vee S^1$ as type 0A

- In type IIA, the 10d gauge field $A_M \sim g_{M11}$ signals the existence of the M-theory circle.

- $D0$ branes in IIA are KK states in 11d.

- In type 0A there are two gauge fields A^+, A^- and two types of branes $D0^+, D0^-$ $\Rightarrow$ two circles ?

Connected theory of quantum gravity $\Rightarrow$

Two circles connected at a point: $S^1 \vee S^1$

Could only be a quantum geometry, joining point free to move.

$$S^1 \cup S^1 \Longleftarrow S^1 \vee S^1 \Longrightarrow S^1$$

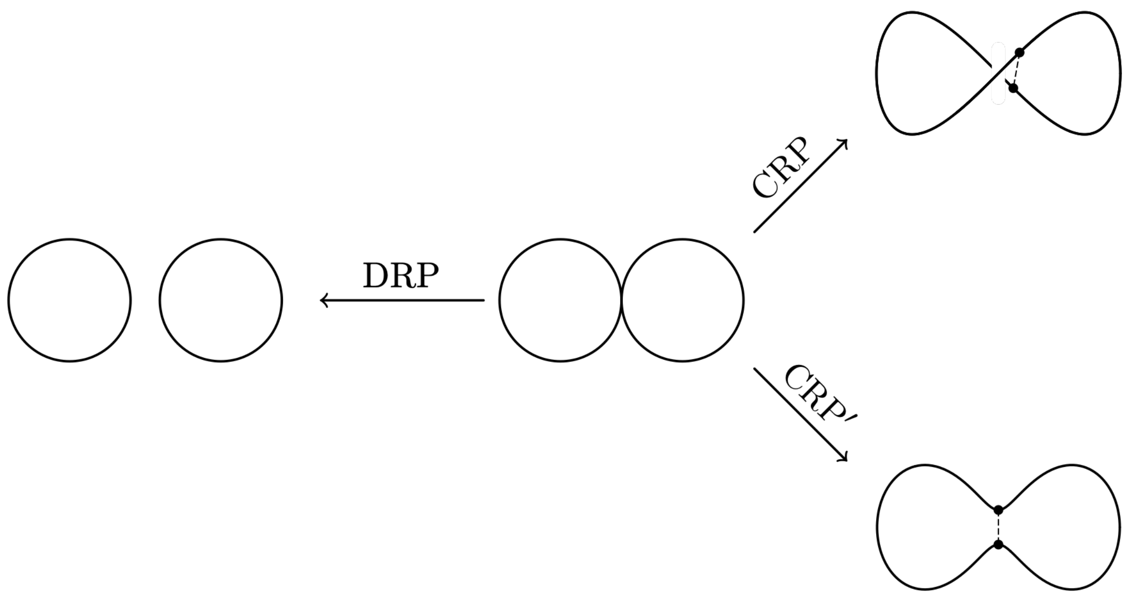


Figure 2. Disconnected resolution property (DRP) corresponds to resolving the singularity by disconnecting the two circles. Connected resolution property (CRP and CRP′) corresponds to resolving to the double cover. For CRP and CRP′ we further impose that the values of the fields on some pair of points corresponding to the resolved point agree. Fields that are smooth under all DRP and CRP and CRP′ will be said to have strong smoothness property SSP.

The metric on this space is

(SSP) (DRP) (DRP)

$$ds^2 = g_{\mu\nu}(x,\theta^{\pm})\; dx^\mu dx^\nu + A_{\mu +}(x,\theta^+)\; dx^\mu d\theta^+ + A_{\mu -}(x,\theta^-)\; dx^\mu d\theta^-$$
$$+ R_+^2(x,\theta^+) d\theta^{+2} + R_-^2(x,\theta^-) d\theta^{-2} .$$

(DRP) (DRP)

with $\phi \sim f(R_+ + R_-)$, $T \sim (R_+ - R_-) g(R_+, R_-)$

- The 3-form has opposite resolution property to the metric
- Neither resolution allowed classically. Only way singularity can be resolved is if one of the circles shrinks $\Longleftrightarrow$ tachyon condensation

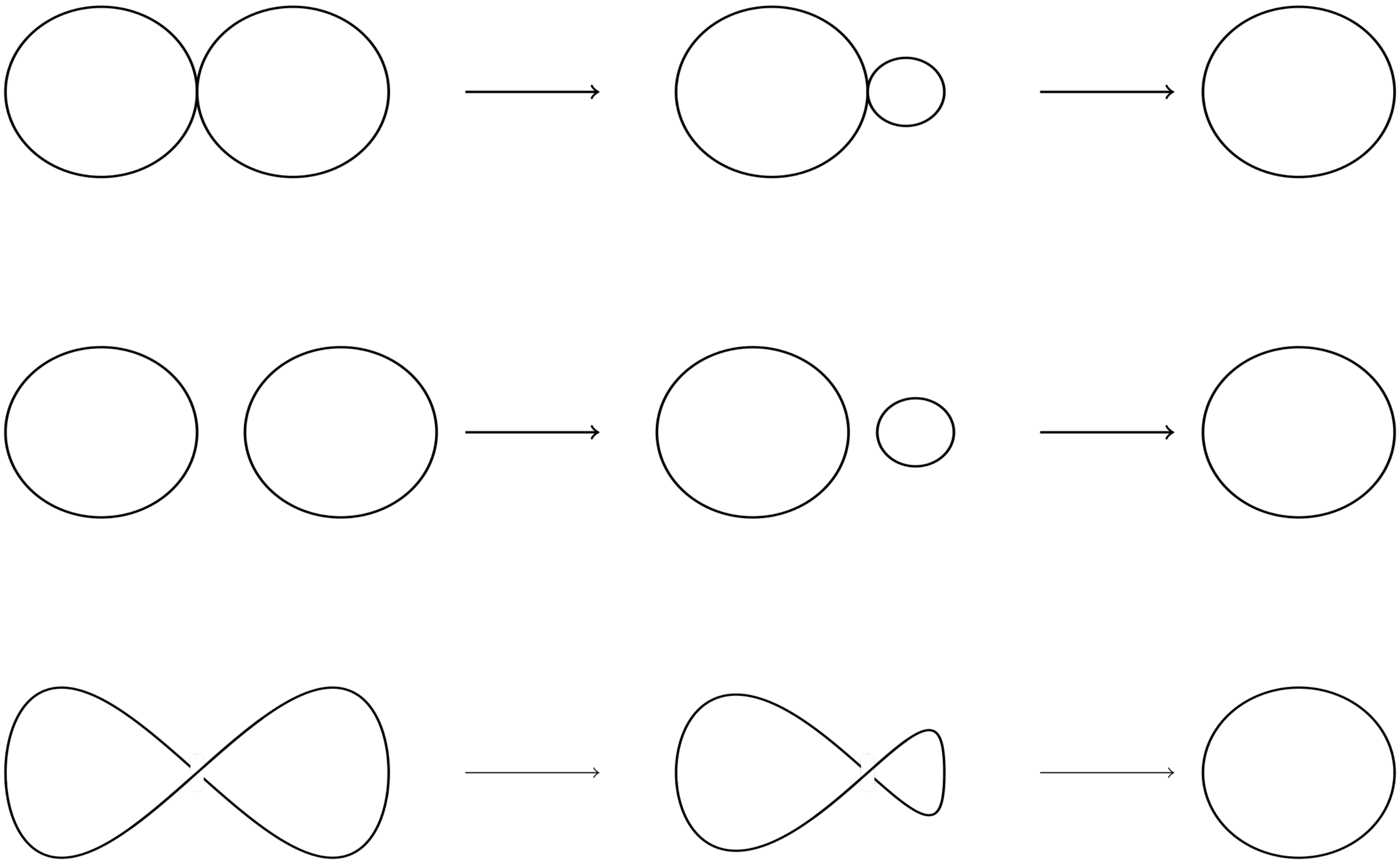


Figure 5. Tachyon condensation of 0A corresponds to shrinking of one of the circles, which leaves only one circle at the end, which is IIA, i.e., M-theory on S^1.

11d field	10d field	Resolution property
$g_{\mu\nu}$	$g_{\mu\nu}$	SSP
$g_{\mu\pm}$	$A_\mu^\pm$	DRP
$g_{\pm\pm}$	ϕ, T	DRP
$C_{\pm\mu\nu}$	$B_{\mu\nu}$	SSP
$C_{\mu\nu\rho}$	$C_{\mu\nu\rho}^\pm$	DRP
$\psi_{\mu\alpha}$	—	SSP*

Table 3. Relation between components of 11d M-theory fields on $S^1 \vee S^1$ and the resulting 10d massless fields of Type 0A, together with their assigned resolution properties. The resolution property of the gravitino SSP* corresponds to SSP with an odd identification $\psi \to -\psi$ at the contact point, removing the massless fermionic zero mode.

Symmetries:

- Quantum symmetry Q : exchange of the two circles $\theta^+ \leftrightarrow \theta^-$
- Worldsheet parity Ω : reflexion on the second circle $\theta^- \rightarrow -\theta^-$

Obs : CRP and CRP' are related by Ω

More evidence : D0 branes, IIB, tachyon condensation

$D0^{\pm}$ branes of 0A should correspond to the two momenta along the two circles.

Their mass/ tension is $m_{D0^{\pm}} = \frac{M_s}{\sqrt{2}\lambda_s}\left(1 \mp \frac{T}{4} + \frac{3T^2}{32} + \ldots\right) \overset{?}{\Longrightarrow} m_{D0^{\pm}} = \frac{M_s}{\sqrt{2}\cdot\lambda_s\sqrt{1 \pm \frac{T}{2}}}.$

(Garousi, Klebanov-Tseytlin)

To first order, $\frac{\delta m}{m} \sim \frac{\delta R}{R} \sim T$

$D0^+ - D0^+ \, , \; D0^- - D0^-$ states are bosonic: KK states along the 1st and the 2nd circle (dilaton,tachyon= DRP)

$D0^+ - D0^-$ states are fermionic: KK states for gravitino (SSP)

IIB from 0A

$$
\begin{tikzcd}
0A|^{S^1_R}_{Q\delta_P} \arrow[r, "R \to 0"] \arrow[d] & IIB \\
M|^{(S^1 \vee S^1)\times S^1_R}_{Q\delta_P} \arrow[loop above, "Q"] \arrow[r, "R \to 0"] & M|^{T^2}_{Area=0} = IIB/F
\end{tikzcd}
$$

Tachyon condensation

$$m_{D0^\pm} = \frac{M_s}{\sqrt{2}\cdot\lambda_s\sqrt{1 \pm \frac{T}{2}}}.$$

For $\langle T \rangle = 2$, one gets $m_{D0^-} = \infty, \quad m_{D0^+} = \frac{M_s}{2\lambda_s}$

$\Uparrow$

Shrinking of the second circle

- Finite distance in tachyon field space
- No tower of light states

$\Longrightarrow$ agreement with the distance conjecture

Conjecture: shrinking of one circle $\Longrightarrow$ Type IIA

(tachyon condensation)

Worldsheet approach: Basile and Lust, [arXiv:2606.05287 [hep-th]].

Hand-waving energetics :

0A : Energy

tachyon cond. < 0

one-loop* > 0

IIA : Energy

0

*Kindly computed by L. Eberhardt (techniques in Baccianti,Chandra,Eberhardt, Hartman and Mizera)

$$V_{0\mathrm{A}} = V_{0\mathrm{B}} = -\frac{1}{2}\int_{\mathcal{F}} \frac{d^2\tau}{(\mathrm{Im}\tau)^6}\frac{1}{|\eta^{12}|^2}|\left(\vartheta_2^4|^2 + |\vartheta_3^4|^2 + |\vartheta_4^4|^2\right) \approx 11.36 \pm \frac{4\pi^6}{15}i.$$

5) Dualities for non-supersymmetric strings

(see also Altavista et al, [arXiv:2603.25786 [hep-th]] and [arXiv:2604.22915 [hep-th]])

There are various symmetries of M-theory on $S^1 \vee S^1$:

- Reflections:

$$P_- : (\theta^+, \theta_-) \to (\theta^+, -\theta_-)$$
$$P_+ : (\theta^+, \theta_-) \to (-\theta^+, \theta_-)$$
$$P = P_+ P_-$$

- Circle exchanges:

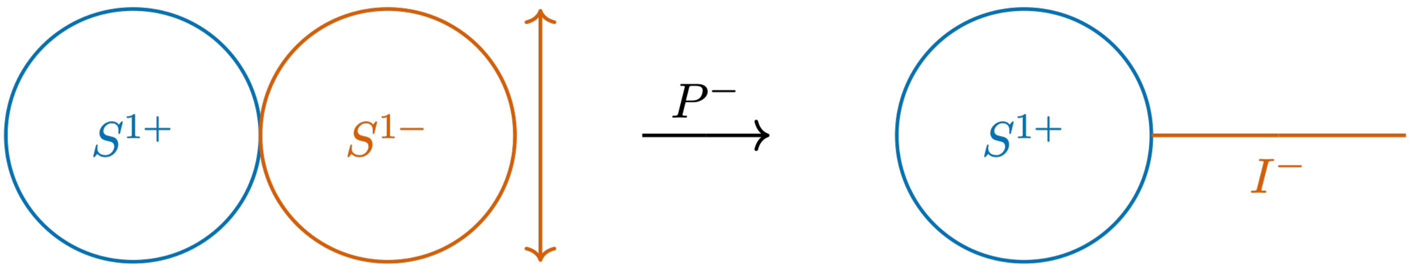
preserving the orientation: $S^1 \overset{\overset{Q}{\leftrightarrow}}{\vee} S^1$

changing the orientation: $S^1 \overset{\overset{E}{\leftrightarrow}}{\vee} S^1$

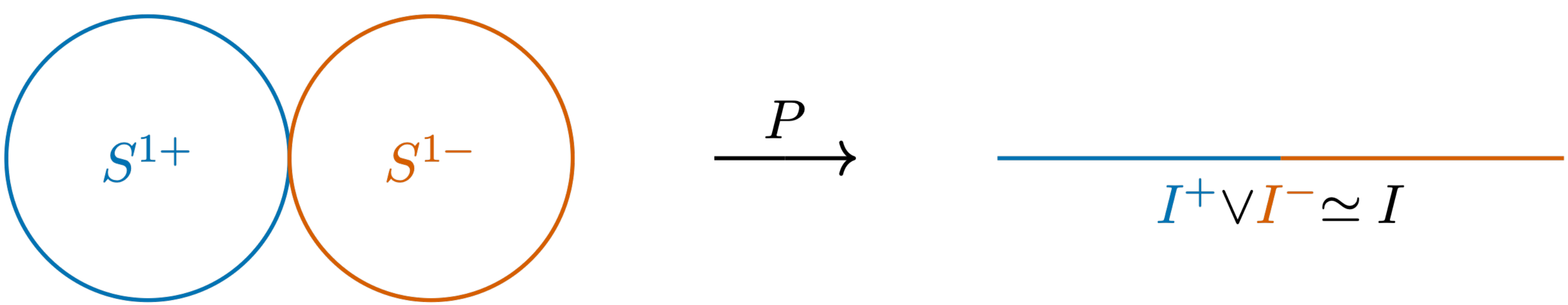
Quotienting by all possible combinations seem to fit most 10d non-SUSY strings.

Some examples:

- $0A/\Omega$ orientifold : $S^{1+} \vee (S^{1-} \updownarrow)$
  (Bianchi-Sagnotti)



- Horava-Witten M-theory : $(S^1 \vee S^1) \updownarrow$



- E-type heterotic strings: $S^1 \overset{E}{\leftrightarrow} \vee\ S^1$

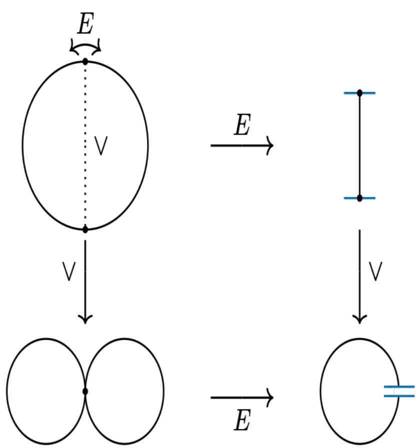
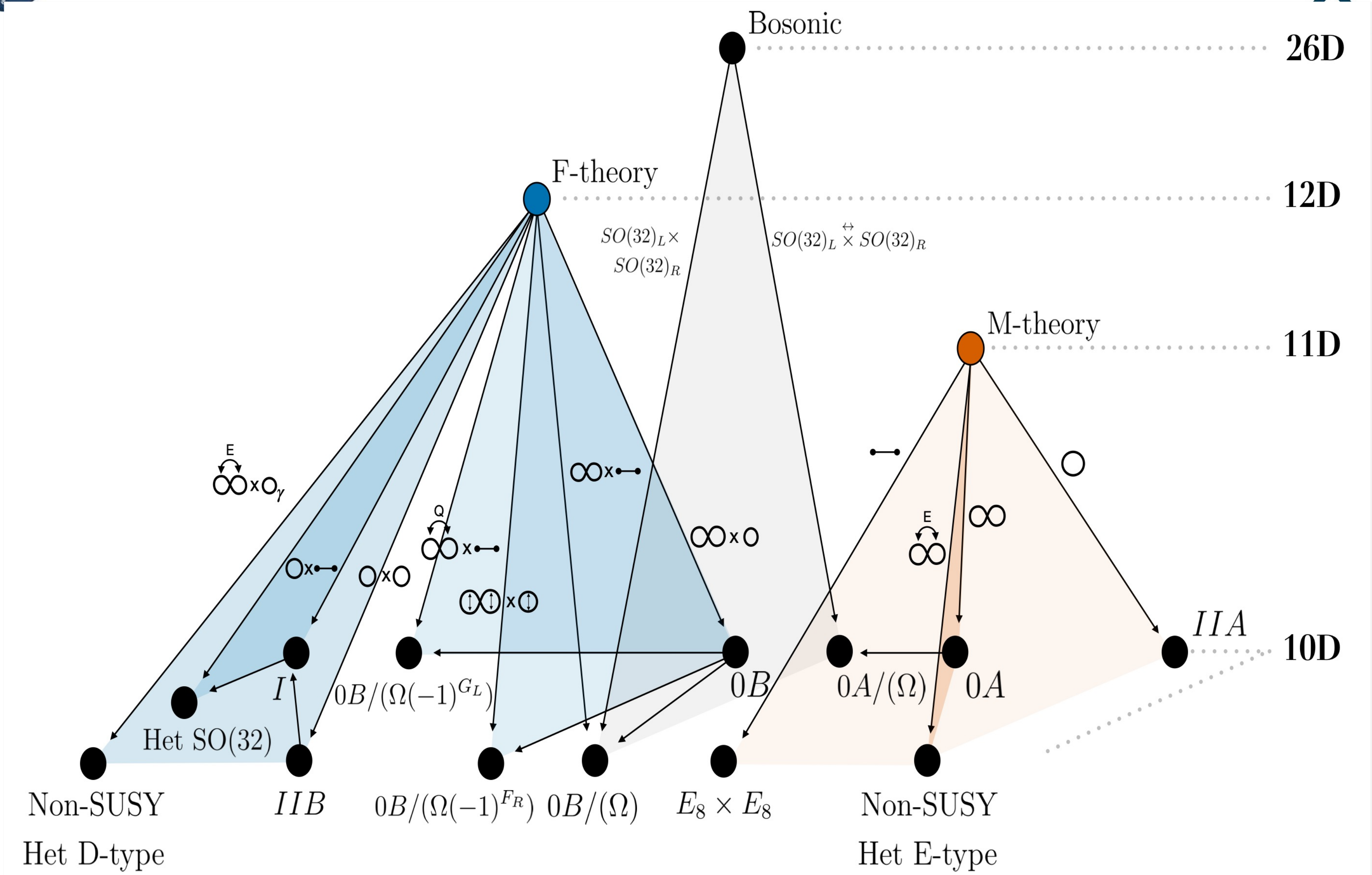


Figure 4. The two routes to obtaining E-type heterotic strings. The bottom route corresponds to first identifying $\frac{\pi}{2} \sim -\frac{\pi}{2}$ on the covering $\hat{S}^1$ and obtaining $S^1 \vee S^1$, then exchanging the two circles by E and obtaining S^1 with the quantum boundary. The top route corresponds to quotienting by E first to get the Hořava-Witten interval, then identifying the boundaries.

Gauge group	Tachyons	Fermions
E-type		
E_8	$(\mathbf{1})$	$(\mathbf{248})_+$ $(\mathbf{248})_-$
$SO(16) \times SO(16)$	—	$(\mathbf{128},\mathbf{1})_+$ $(\mathbf{1},\mathbf{128})_+$ $(\mathbf{16},\mathbf{16})_-$
$E_7 \times SU(2) \times E_7 \times SU(2)$	$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{2})$	$(\mathbf{56},\mathbf{2},\mathbf{1},\mathbf{1})_+$ $(\mathbf{1},\mathbf{1},\mathbf{56},\mathbf{2})_+$ $(\mathbf{56},\mathbf{1},\mathbf{1},\mathbf{2})_-$ $(\mathbf{1},\mathbf{2},\mathbf{56},\mathbf{1})_-$
$E_8 \times SO(16)$	$(\mathbf{1},\mathbf{16})$	$(\mathbf{1},\mathbf{128})_+$ $(\mathbf{1},\mathbf{128}')_-$
D-type		
$SO(32)$	$(\mathbf{32})$	—
$SO(24) \times SO(8)$	$(\mathbf{1},\mathbf{8})$	$(\mathbf{24},\mathbf{8_v})_+$ $(\mathbf{24},\mathbf{8_c})_-$
$SU(16) \times U(1)$	$(\mathbf{1},\pm 1)$	$(\mathbf{120},+2)_+$ $(\overline{\mathbf{120}},-2)_+$ $(\mathbf{120},-2)_-$ $(\overline{\mathbf{120}},+2)_-$



Bosonic
26D
F-theory
12D
$SO(32)_L\times SO(32)_R$
$SO(32)_L \overset{\leftrightarrow}{\times} SO(32)_R$
M-theory
11D
E
Q
E
IIA
10D
I
$0B/(\Omega(-1)^{G_L})$
$0B$
$0A/(\Omega)$
$0A$
Het SO(32)
Non-SUSY
Het D-type
IIB
$0B/(\Omega(-1)^{F_R})$
$0B/(\Omega)$
$E_8\times E_8$
Non-SUSY
Het E-type

Perspectives, Open Questions

- The web of dualities of non-SUSY strings essentially unknown territory.

- We proposed a formulation of 0A as a compactification of M-theory on a quantum $S^1 \vee S^1$ space. Most non-SUSY 10d strings obtained by involutions (BDMPV, Altavista et al) .

- Tachyon condensation corresponds to shrinking one of the circle, leading to IIA

- F-theory description of the axio-dilaton and the tachyon.

Many open questions :

- The conditions we imposed on various fields (DRP,SSP) are exotic, motivated by the structure of D-branes. Further evidence needed.
- Sugimoto/BSB model (Sugimoto; Antoniadis,E.D.,Sagnotti,99; talk Augusto) not yet incorporated