Title: Brane dynamics with broken supersymmetry

Speakers: Ivano Basile

Series: Quantum Fields and Strings

Date: November 23, 2021 - 2:00 PM

URL: https://pirsa.org/21110025

Abstract: We investigate interactions between branes of various dimensions, both charged and uncharged, in some non-supersymmetric string models. These include the USp(32) and U(32) orientifolds of the type IIB and type 0B strings, as well as the SO(16) x SO(16) projection of the exceptional heterotic string. The resulting ten-dimensional spectra are free of tachyons and the combinations of branes that they contain give rise to rich and varied dynamics. We focus on potentials that describe their mutual interactions, both in the probe regime and in the string-amplitude regime, finding qualitative agreement despite the absence of supersymmetry and confirming the Weak Gravity Conjecture for charged branes.

Brane dynamics with broken SUSY

Ivano Basile UMONS

Based on 2107.02814 **(review) + 2106.04574 + work in progress**

Lessons from SUSY breaking

naturalness + ~~SUSY~~ $\longrightarrow$ high scales

- **Support from swampland considerations**

(Cribiori, Lüst, Scalisi, 2021) (Castellano, Font, Herráez, Ibánez, 2021) (Dall'Agata, Emelin, Farakos, Morittu, 2021)

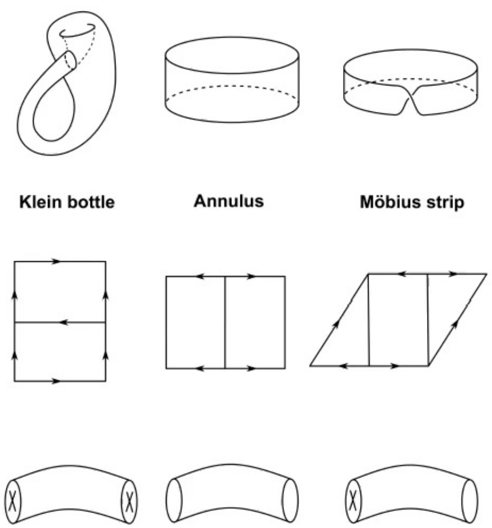
static + ~~SUSY~~ $\longrightarrow$ instabilities

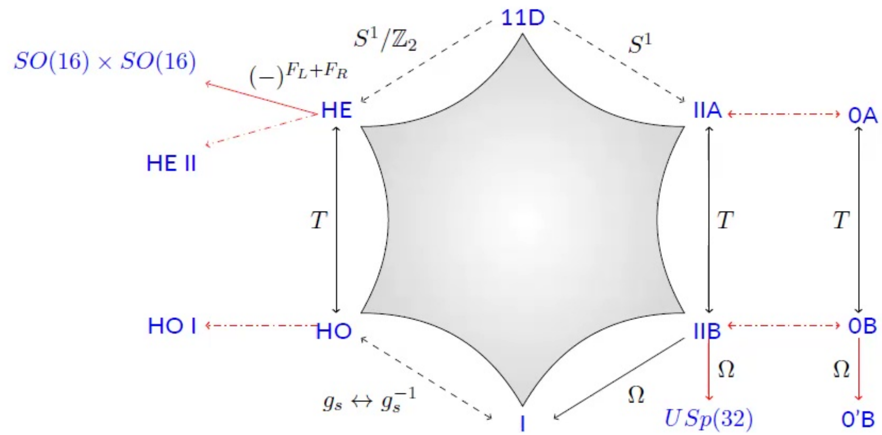
How I learned to stop worrying and love (string-scale) SUSY breaking

Orientifold models: IIB or 0B

O9 + 32 $\overline{\text{D9}}$

➔ $USp(32)$ (Sugimoto, 1999) or $U(32)$ (Sagnotti, 1995)





Heterotic model: $E_8 \times E_8$

projection + modular invariance

➔ $SO(16) \times SO(16)$

(Alvarez-Gaume, Ginsparg, Moore, Vafa, 1986) (Dixon, Harvey, 1986)

Game plan

1. Non-SUSY models

2. Macroscopic: backreaction & instabilities

3. Microscopic: brane dynamics $\longrightarrow$ hope for ~~SUSY~~ stringy regime?

Heterotic superstring: a quick primer

$$\mathcal{T}_{E_8\times E_8} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^6}\,\frac{1}{|\eta(\tau)|^{16}}\left[(V_8 - S_8)\,\overline{(O_{16}+S_{16})^2}\right]$$

- SUSY: $V_8 = S_8$
- Right-moving sector
  ➔ $E_8 \times E_8$ characters
- SYM multiplet

One-loop vacuum energy

$$\Lambda \propto \frac{1}{\alpha'}\,\mathcal{T}_{E_8\times E_8} \quad \rightarrow \quad \Lambda = 0$$

Heterotic model: SUSY breaking

$$\mathcal{T}_{SO(16)\times SO(16)} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^6} \frac{1}{|\eta(\tau)|^{16}} \Big[O_8 \, \overline{(V_{16}\, C_{16} + C_{16}\, V_{16})} + V_8 \, \overline{(O_{16}\, O_{16} + S_{16}\, S_{16})} - S_8 \, \overline{(O_{16}\, S_{16} + S_{16}\, O_{16})} - C_8 \, \overline{(V_{16}\, V_{16} + C_{16}\, C_{16})} \Big]$$

- No massless states (**level matching**)
- Gravitational sector + adjoint vector
- (**128**, **1**) $\oplus$ (**1**, **128**) spinor
- (**16**, **16**) spinor

One-loop vacuum energy

$$\Lambda \propto \frac{1}{\alpha'} \mathcal{T}_{SO(16)\times SO(16)} \quad \rightarrow \quad \Lambda = \frac{\mathcal{O}(1)}{\alpha'}$$

Orientifold amplitudes: IIB

$$\mathcal{K} = \frac{1}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{(V_8 - S_8)(2i\tau_2)}{\eta^8(2i\tau_2)}\,, \qquad \mathcal{A} = \frac{N^2}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{(V_8 - S_8)\left(\frac{i\tau_2}{2}\right)}{\eta^8\left(\frac{i\tau_2}{2}\right)}$$

Orientifold of IIB $\longrightarrow$ Klein bottle, annulus, **Möbius strip** $(N = 32)$

$$\mathcal{M}_{\mathsf{I}} = \frac{\varepsilon\, N}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{\left(\widehat{V}_8 - \widehat{S}_8\right)\left(\frac{i\tau_2}{2} + \frac{1}{2}\right)}{\widehat{\eta}^8\left(\frac{i\tau_2}{2} + \frac{1}{2}\right)}\,, \qquad \mathcal{M}_{\mathsf{BSB}} = \frac{\varepsilon\, N}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{\left(\widehat{V}_8 + \widehat{S}_8\right)\left(\frac{i\tau_2}{2} + \frac{1}{2}\right)}{\widehat{\eta}^8\left(\frac{i\tau_2}{2} + \frac{1}{2}\right)}$$

Orientifold amplitudes: 0B

$$\mathcal{K} \to \frac{1}{2}\left(-O_8 + V_8 + S_8 - C_8\right) , \qquad \mathcal{A} \to n\overline{n}\, V_8 - \frac{n^2 + \overline{n}^2}{2}\, C_8$$

Orientifold of (tachyonic) 0B $\longrightarrow$ (non-tachyonic) chiral 0'B ($n = \overline{n} = 32$)

O9-plane: zero tension (no NS-NS)

$$\mathcal{M}_{\text{0'B}} \to \frac{n + \overline{n}}{2}\, \widehat{C}_8$$

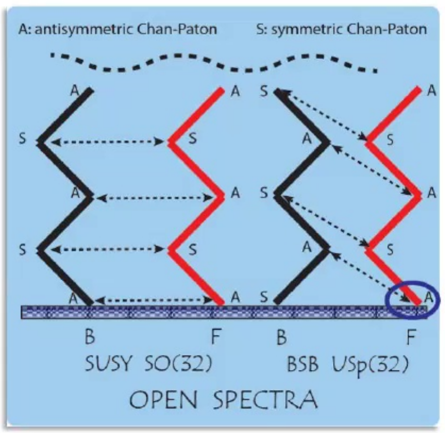
$$\widetilde{\mathcal{K}} = -\frac{2^6}{2} \int_0^\infty d\ell\, C_8$$

Brane SUSY breaking

SUSY ✓ in 10d bulk + SUSY ✗ on branes (Antoniadis, Dudas, Sagnotti, 1999)

Low-energy EFT: **goldstino + couplings** (Dudas, Mourad; Pradisi, Riccioni, 2000)

O9 + 32 $\overline{\text{D9}}$: **residual tension** $V(\phi) = T\, e^{\gamma\, \phi}$



No tachyons but back-reaction!

Tadpoles and back-reaction

String-scale back-reaction from tadpoles

Workarounds or alternatives?

- Non-tachyonic compactification of **tachyonic** models (Faraggi, Matyas, Percival, 2019-2021)
- Misaligned SUSY: help from modular invariance

  (Kutasov, Seiberg, 1991) (Dienes, 1994-2001) (Angelantonj, Cardella, Elitzur, Rabinovici, 2010) (Cribiori, Parameswaran, Tonioni, Wrase, 2020)
- Suppression of vacuum energy (Dienes, 1990) (Kachru, Kumar, Silverstein, 1999) (Angelantonj, Cardella, 2004)

  ➔ *Exponential for Scherk-Schwarz:* (Abel, Dienes, Mavroudi, Stewart, 2015-2017)

Can tame but never eliminate! $\longrightarrow$ New expansion parameters (fluxes)

Exploring dynamics: low-energy description

$$\mathcal{S}_{\text{eff}} = \int d^{10}x \sqrt{-g} \left(\mathcal{R} - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{e^{\alpha\phi}}{12} H_3^2 + \dots \right)$$

Taming back-reaction

IR ingredients: electric and magnetic fluxes ($H_3 = dC_3$ or dB_3)

UV ingredients: p-branes

(Dudas, Mourad, Sagnotti, 2001)

Branes in the game

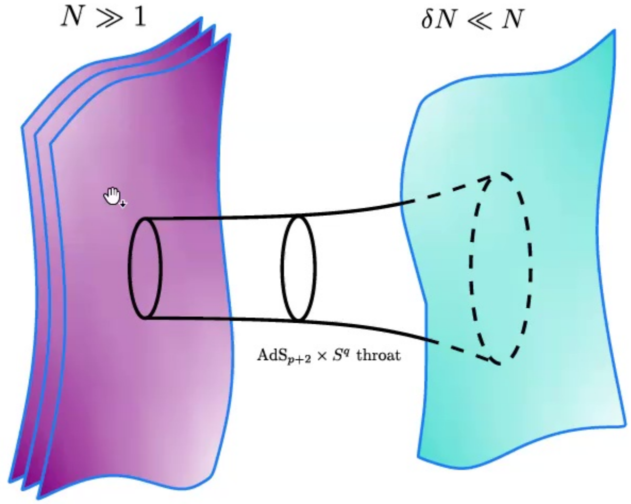
charged D1, D5 (+ D3, D7 in 0'B)

uncharged $p \neq 1\,,\, 5\,(+\,3\,,\,7)$

Alternative: stringy effective potential?

(Angelantonj, Florakis, 2013) (Abel, Dienes, 2021) (Abel, IB, Matyas, to appear)

A universe made of branes (Antonelli, IB, 2019)



$SO(1,p) \times SO(q)$ symmetry $\quad \rightarrow \quad \phi(r)\,,\, v(r)\,,\, b(r)$

$$ds^2 = e^{\frac{2}{p+1}v - \frac{2q}{p}b}\, dx^2_{1,p} + e^{2v - \frac{2q}{p}b}\, dr^2 + e^{2b}\, R_0^2\, d\Omega_q^2\,,$$

$$H_{p+2} = \frac{N}{e^{\alpha\phi}(R_0\, e^b)^q}\, e^{2v - \frac{q}{p}(p+2)b}\, d^{p+1}x \wedge dr$$

$$N = \int_{\mathbb{S}^q} \star\, e^{\alpha\phi}\, H_{p+2}$$

12

Geometry: near-horizon and attractor

Recover exact $\mathrm{AdS}_{p+2} \times \mathbb{S}^q$ with $[r < 0]$

$$e^{\phi} = e^{\phi_0}\,, \qquad e^{v} = \frac{L}{p+1}\left(\frac{R}{R_0}\right)^{-\frac{q}{p}}\frac{1}{-r}\,, \qquad e^{b} = \frac{R}{R_0}$$

$$\boxed{L_{\mathrm{AdS}}\,,\; R_{\mathbb{S}} \sim N^{\#} \gg 1\,, \quad g_s \sim N^{-\#} \ll 1}$$

Radial perturbations: $\delta\phi\,,\ \delta v\,,\ \delta b \propto (-r)^{\lambda}$

$$\lambda \in \left\{-1\,,\ \frac{1 \pm \sqrt{13}}{2}\,,\ \frac{1 \pm \sqrt{5}}{2}\right\} \quad \longrightarrow \quad \text{2 extremality-breaking deformations}$$

D3-branes: a curious exception

Type II D3-branes

Only case with $\mathrm{AdS}_5 \times \mathbb{S}^5$ near-horizon with $\phi = \text{const.}$

Type $0'$B D3-branes (Angelantonj, Armoni, 1999) (Dudas, Mourad, 2000)

Quasi-$\mathrm{AdS}_5 \times \mathbb{S}^5$ for $N \gg 1$. *Non-uniform* limit: $\frac{T}{N} \log u$

$$ds^2 = L^2(u)\,\frac{du^2}{u^2} + \frac{\alpha'^2\,u^2}{L^2(u)}\,dx_{1,3}^2 + R^2(u)\,d\Omega_5^2$$

$$L^2(u)\,,\; R^2(u)\,,\; g_s N \sim (\text{SUSY}) + \frac{T}{N}\,\log u$$

Geometry: "far-horizon" and broken spacetime

Away from branes: tadpole *dominates*

Solutions as $r \to \infty$: $\phi \,, v \,, b \propto y(r) + \textit{subleading}$

$$y'' \sim \hat{T}\, e^{\Omega\, y + L\, r}$$

$$\frac{1}{2}\,\Omega\, y'^2 + L\, y' \sim \hat{T}\, e^{\Omega\, y + L\, r} - \text{const.}$$

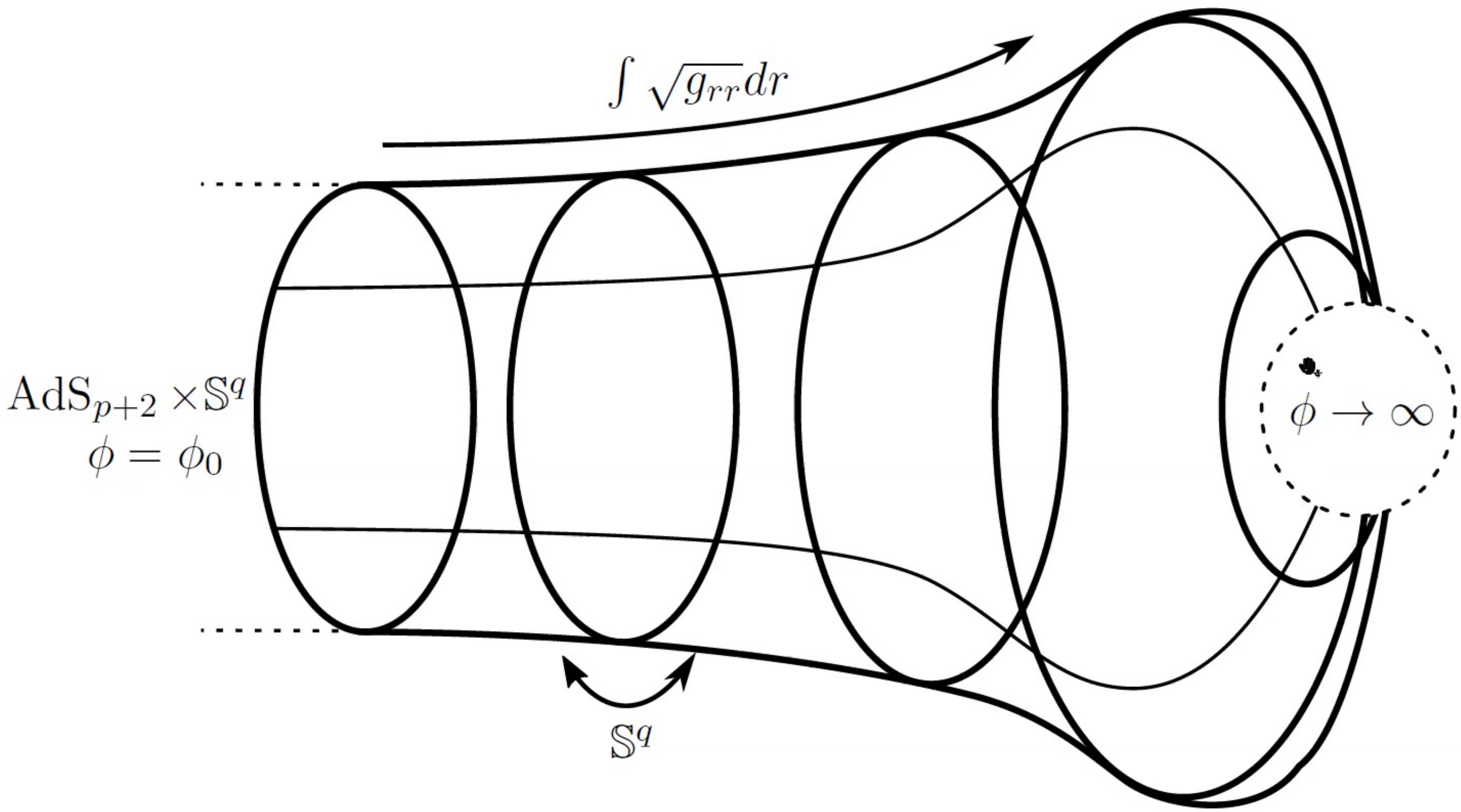
where $\Omega = \frac{D-2}{8}\,\gamma^2 - \frac{2(D-1)}{D-2} = \frac{D-2}{8}\left(\gamma^2 - \gamma^2_{\text{crit}}\right)$ (IB, Mourad, Sagnotti, 2018)

➔ $\phi \,, v \,, b \propto r^2$ (due to $\Omega = 0$)

➔ **finite-distance singularity! Spacetime breaks.**

...connection to swampland? (Buratti, Calderón-Infante, Delgado, Uranga, 2021)

$$\int^{\infty} \sqrt{g_{rr}}\, dr < \infty$$



$\int \sqrt{g_{rr}} dr$
$\mathrm{AdS}_{p+2} \times \mathbb{S}^q$
$\phi = \phi_0$
$\phi \to \infty$
$\mathbb{S}^q$

An integrable case: uncharged D8-branes (Dudas, Mourad, 2000)

For $p = 8, N = 0$ (uncharged), EOMs simplify dramatically

$$ds^2 = \left|y^2\right|^{\frac{1}{18}} e^{-\frac{y^2}{8}} dx_{1,8}^2 + e^{-\frac{3}{2}\Phi_0} \left|y^2\right|^{-\frac{1}{2}} e^{-\frac{9y^2}{8}} dy^2$$
$$\phi = \frac{3}{4} y^2 + \frac{1}{3} \log\left|y^2\right| + \Phi_0$$

- Most symmetric background available with (string-scale) ~~**SUSY**~~
- Perturbatively stable (IB, Mourad, Sagnotti, 2018)...
- ...but large corrections at *edges of interval* $\int \sqrt{g_{yy}}\, dy < \infty$

Brane nucleation (Antonelli, IB, 2019)

AdS vacua $\rightarrow$ *flux tunneling* (Brown, Teitelboim, 1987-1988), (Blanco-Pillado, Schwartz-Perlov, Vilenkin, 2009)

$$\mathcal{E}_{\text{vac}} \propto -N^{-3} \quad \text{or} \quad -N^{-2} \qquad N \longrightarrow N - \delta N \quad : \quad \text{out of EFT}$$

Instantons $\longleftrightarrow$ branes (D1 or NS5)? right charge & dim.

AdS $\longrightarrow$ **near-horizon** of brane stack...

$\longrightarrow$ brane-antibrane nucleation

$$S^E_{\text{brane}} = \left[\tau_p \,\text{Area} - \frac{N\mu_p}{e^{\alpha\phi} R^q}\,\text{Vol}\right]_{\text{extremum}} = B_{\text{CdL}}$$

Brane nucleation: string theory "knows"

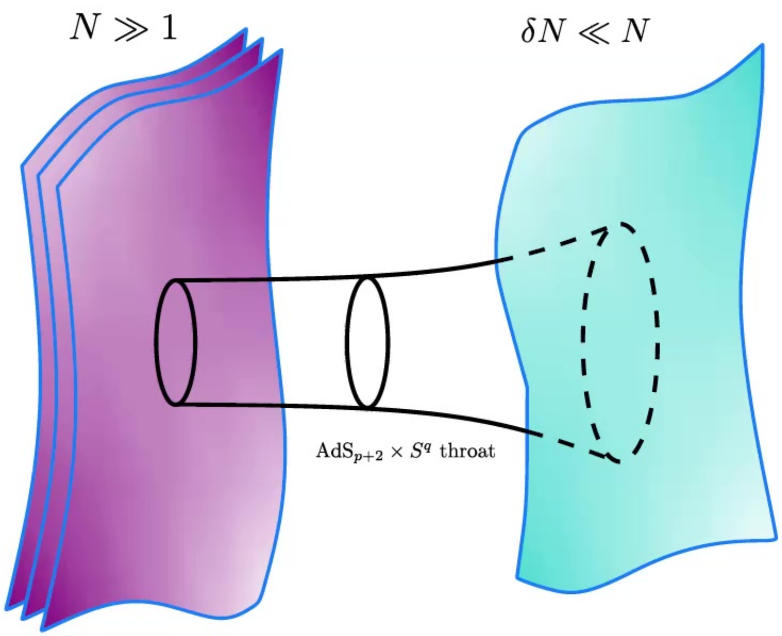
$$S^E_{\text{brane}}(\beta) = \tau_p \, \Omega_{p+1} \, L^{p+1} \left[\frac{1}{(\beta^2-1)^{\frac{p+1}{2}}} - \frac{p+1}{2} \beta \int_0^{\frac{1}{\beta^2-1}} \frac{x^{\frac{p}{2}}}{\sqrt{1+x}} \, dx \right]$$

Consistency:

- *existence:* nucl. parameter $\beta \equiv v_0 \left(\frac{\mu_p}{\tau_p} \right) g_s^{-\frac{\alpha}{2}} > 1$
- *semi-classical:* $\beta = \mathcal{O}(N^0) \longrightarrow \tau_p = T_p \, g_s^{-\frac{\alpha}{2}}$

$$\tau_p^{\text{string}} = \frac{T_p}{g_s^{\sigma}} \qquad \boxed{\sigma = 1 + \frac{1}{2} \alpha^{\text{string}}_{\text{electric}}}$$

Interactions in probe regime: charged branes (IB, 2021)



D1 probing D1

$$V_{1 \ll 1} = T_1 \left(\frac{L_{\mathrm{AdS}}}{Z} \right)^2 \left(1 \pm v_0 \, \frac{\mu_p}{T_p} \right)$$

D3 probing D3

$$V_{3 \ll 3} = U^4 \left(5 - 4 \, \log U \right)$$

- **Weak gravity bound** ($v_0 > 1$)

Interactions in various regimes: charged and uncharged

Dp probing D8

$$V_{p\ll 8} = y^{\frac{2}{9}(p-2)}\, e^{\frac{p-5}{8}\, y^2}$$

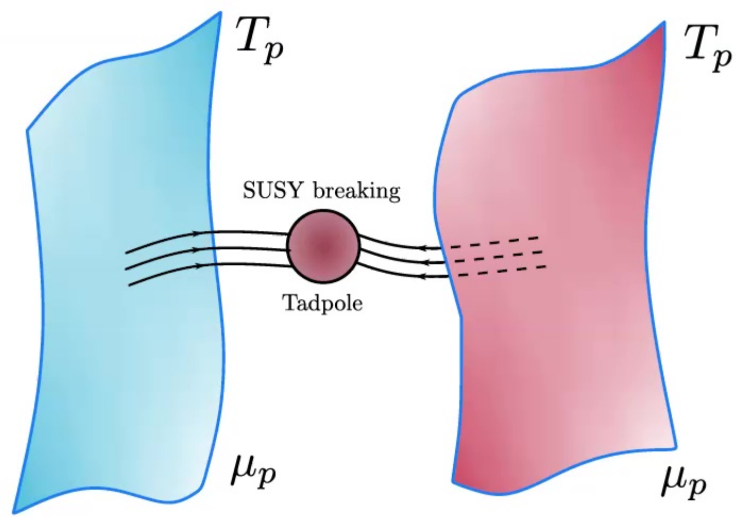
D8 probing D1, D3

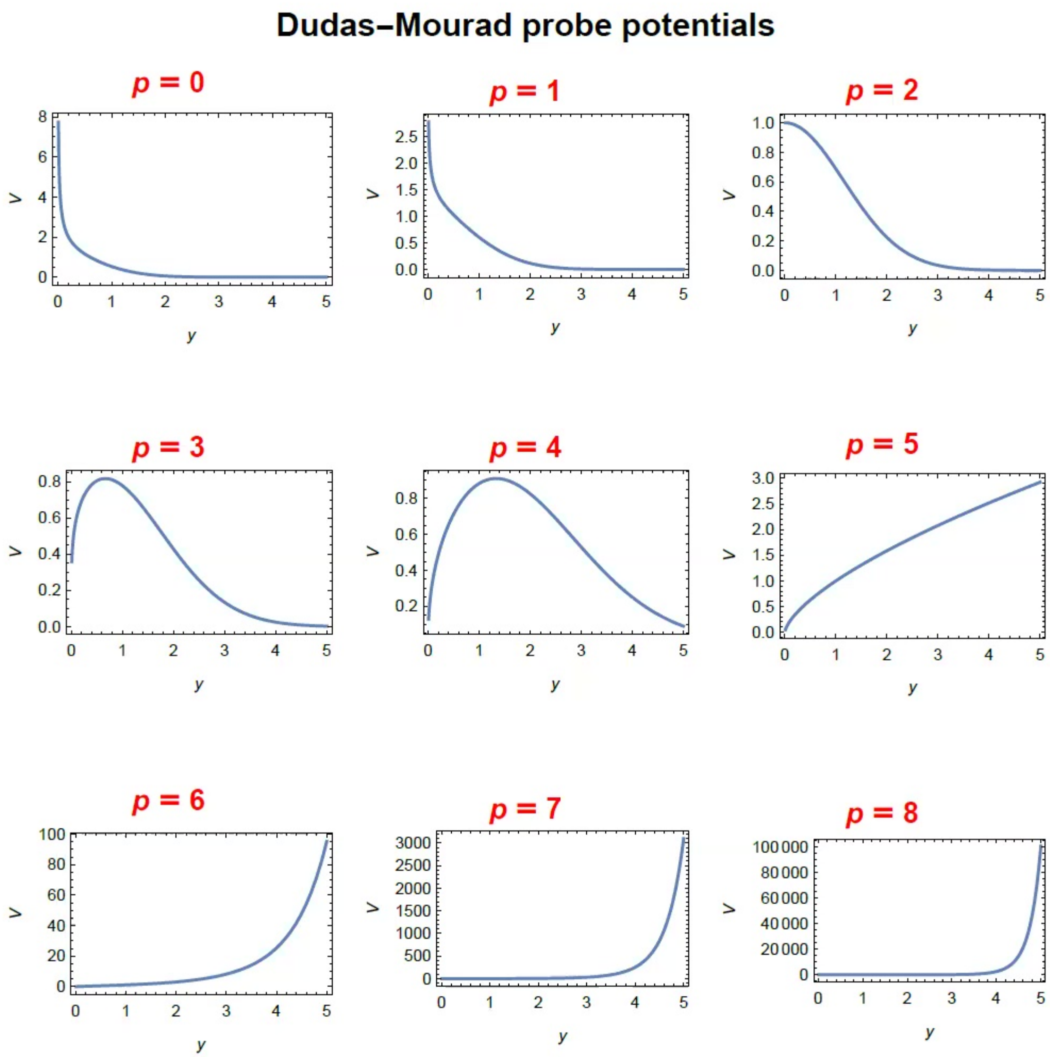
$$V_{8\ll 1} = N_8 T_8 R_{\mathbb{S}}^7 \left(\frac{L_{\text{AdS}}}{Z}\right)^2$$

$$V_{8\ll 3} = N_8\, T_8\, U^4 \left(1 + \frac{3}{8}\, g_s\, T\, \log U\right)$$

String amplitudes

$$V_{p\sim q} = (q-p-4)\, \frac{N_p N_q}{r^{7-q}}$$





Dp-D8 qualitative features

- $p < 4$: repulsive
- $p > 4$: attractive

Matches w/o SUSY!

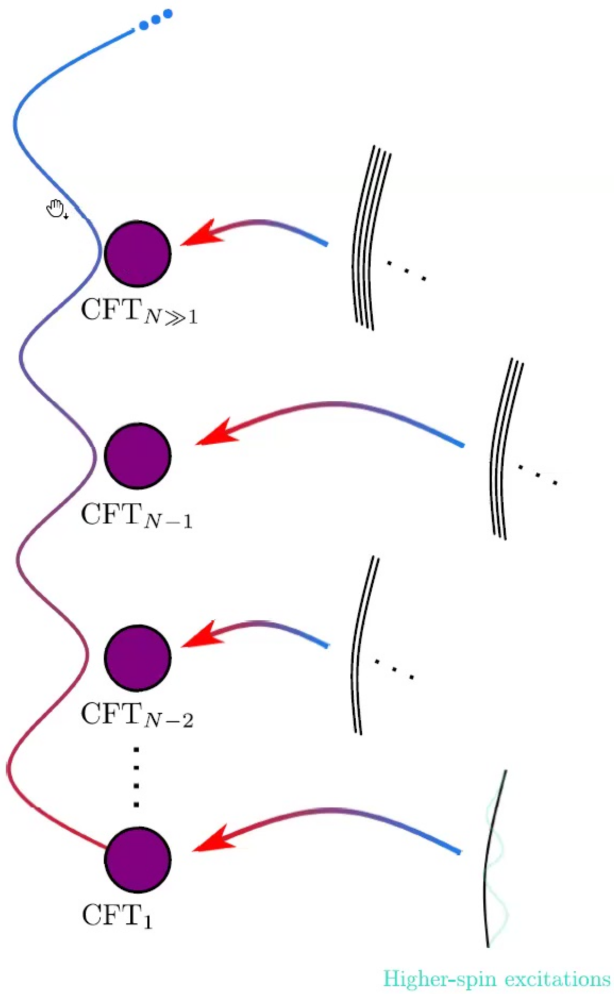
Holographic D1-branes

World-volume gauge theory (Sugimoto, 1999) (Dudas, Mourad, 2000)

$$S^E_{\text{D1}} = \frac{1}{g^2_{\text{YM}}} \text{Tr} \int d^2\zeta \bigg((\partial_+ A_-)^2 + \partial_+ X_i \, [\mathcal{D}_- \, , X_i] - \frac{1}{4} [X_i \, , X_j] \, [X_i \, , X_j]$$
$$+ \psi_+ \, [\mathcal{D}_- \, , \psi_+] + \psi_- \, \partial_+ \psi_- + \psi_- \, \Gamma_i \, [X_i \, , \psi_+] + \lambda^A_- \, \partial_+ \, \lambda^A_- \bigg)$$

- $USp(32)$ orientifold $\rightarrow$ **repulsive** potential (*tunneling*): $V^{\text{1-loop}}_{1\sim 1} = - r^2 \log r^2$
- Weak gravity bound: **matches w/ probe!**

Dual RG flows



Dual RG flow(s)

Integrate out brane separation

(Gubser, Hashimoto, Klebanov, Krasnitz, 1998) (Gubser, Hashimoto, 1999)

(Intriligator, 2000) (Costa, 2000) (Caetano, Peealers, Rastelli, 2020)

→ *holographic flows*

(Antonelli, IB, Bombini, 2018) (Ghosh, Kiritsis, Nitti, Witkowski, 2021)

Two limiting cases:

- $N \gg 1 \quad \longrightarrow$ KK tower
- $N = 1 \quad \longrightarrow$ HS tower (dual frame?)

Hopeless?

General $N = \mathcal{O}(1)$: gauge theory **strongly coupled** in the IR.

Workarounds?

- $N \gg 1$: still strongly coupled

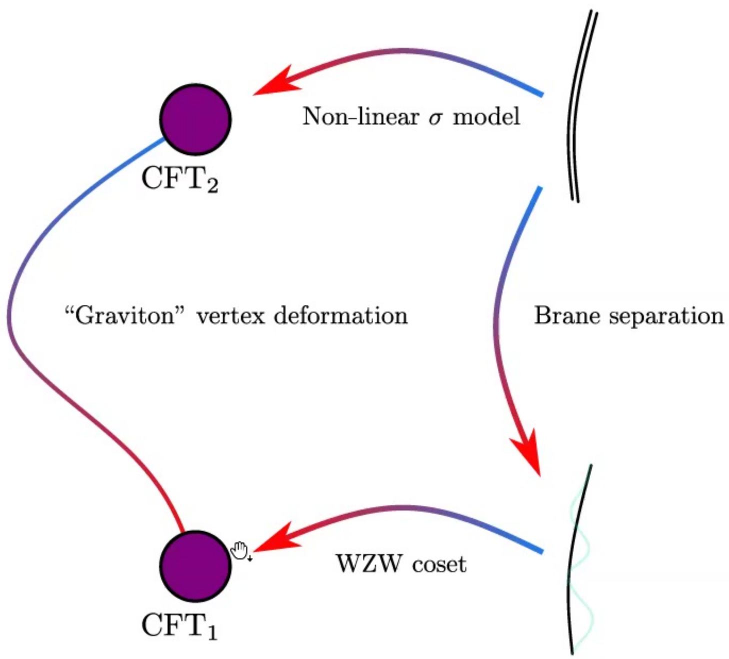
$$g^2_{\text{bulk}} N \propto N^{-\frac{1}{4}} N \gg 1$$

➔ **Large-charge** approach for $SO(8)$ symmetry?

(Alvarez-Gaume, Hellerman, Loukas, Orlando, Reffert, Schmidt, Watanabe, ..., 2015-2021)

- $N = 1$: **last step** treatable! scalars decouple
  Methods similar to (Delmastro, Gomis, Yu, 2021) (Dempsey, Klebanov, Pufu, 2021) (Dalley, Klebanov, 1993)

The last step



Dual CFT_{IR}: $N = 2 \to 1$ with RG flow

- Low-energy NLσM at minima

$$ds^2_{U(N)} = \sum_k d\mathbf{x}_k^2 + 2\sum_{p<q} \|\mathbf{x}_p - \mathbf{x}_q\|^2 \,\mathrm{Tr}\,\theta\theta^\dagger$$

➔ *integrate around large VEV* $\mathbf{r} = \mathbf{x}_1 - \mathbf{x}_2$

$$ds^2_{\text{IR}} = \left(\delta_{ij} + \frac{r_i\, r_j}{\pi\, r^4}\,\log\frac{\Lambda_{\text{UV}}}{\Lambda_{\text{IR}}}\right) dr^i dr^j$$

➔ **Ricci flow:** NLσM *decouples* in CFT_{IR}

...same for BSB model

A lonely D-string: BSB case

- Scalars X^i and fermions ψ^i decouple: free $\mathcal{N} = (0,1)$ SCFT!

➔ due to $SO(8)$ triality: $8_V \simeq 8_S \simeq 8_C$

...compatibly with AdS stability (Ooguri, Vafa, 2016)

- Gauge sector $\xrightarrow{\text{(non-)Abelian bosonization}}$ WZW coset model (Chung, Tye, 1993)

$$\frac{SO(8\times 3)_1}{SU(2)_{8\times 2}} \times \frac{SO(16\times 2)_1}{SU(2)_{16\times 1}} \xrightarrow{\text{central charges}} \left(c_L^{IR},\, c_R^{IR}\right) = \left(12 - \frac{8}{3},\, 16 - \frac{8}{3}\right)$$

An amusing hint of (S-)duality?

- **Disconnected** sectors: free heterotic-like string + non-geometric (WZW)
- From EFT: $\phi \to -\phi$ and $G \to e^{-\phi} G$ gives $V_{\text{dual}} \propto e^{-4\phi}$. **Disconnected spheres?**

$$e^{-4\phi} = e^{-2\phi} \times e^{-2\phi}$$

...reminiscent of D-instanton contributions (Polchinski, 1994) (Green, 1995)

Heterotic case: interpolating models (Blum, Dienes, 1997)

Take-home message(s)

- ~~SUSY~~ backreaction $\longrightarrow$ "Broken" spacetime **at finite distance**
- ~~SUSY~~ brane interactions $\longrightarrow$ consistency across **various regimes** ✓

➔ *probe, amplitudes, holographic*

Consistent broken SUSY?

- For $USp(32)$ **(BSB)**: free $\mathcal{N} = (0, 1)$ SCFT! *(+ WZW coset)*

➔ Amusing hints of duality?

$$10_{\text{dimensions}} = 8_{\text{triality}} + 2_{\text{strings}}$$

~~SUSY~~ recovered in final state **due to $SO(8)$ triality**

Punchline

(Natural) SUSY breaking $\xrightarrow{\text{Dynamics}}$ Phenomenology & Duality ???