Domain walls and anti-de Sitter vacua in four dimensions

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String phenomenology and dynamical vacuum selection
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based on works with C. Kounnas, D. Lüst & D. Tsimpis

Highlights

Why anti-de Sitter spaces?

Natural ingredients of string compactifications

- Preserve (all or part of) the supersymmetries
- Are supported by antisymmetric-tensor vev's
- Are accompanied by (partial) moduli stabilization
- Appear as NHGs of brane distributions

Provide a tool for probing various facets of string vacua and dynamics

- AdS/CFT ($AdS_5 \times S^5$ and D3-branes)
- Microscopic black-hole entropy and attractor mechanism, originally in $N = 2$ setups with $AdS_2 \times S^2$ NHGs
- ...

Here: AdS_4 backgrounds

We focus on type IIA/B theories and search for negative-energy 4-D vacua with unbroken supersymmetry and stabilized main moduli

- Provide AdS_4 vacua using 4-D supergravity tools
  - switch on the appropriate perturbative superpotential
  - translate the solution in the language of fluxes
- Identify the corresponding sources in the full 10-D space: D2/D4/D6/D8/NS5/KK or D3/D5/D7/NS5/KK
  - not localized (as for AdS_2) but *smeared* in transverse space
  - not point-like in 3-D space but *domain walls* interpolating between AdS_4 and flat spacetime

Make contact among the two items: *the NHG of the brane background is $AdS_4 \times T^6$ and all background fields faithfully reproduce the (super)potential and the moduli at its minimum*

Highlights

Scalar potential, superpotential and fluxes

Minima in $N = 1$ supergravities with $W(\phi)$ – no D-terms

- Scalar potential: $V = \mathrm{e}^{K}\left(|D_i W|^2 - 3|W|^2\right)$
- Auxiliary fields: $F_i = \mathrm{e}^{K/2} D_i W = \mathrm{e}^{K/2}\left(\partial_{\phi_i} W + W \partial_{\phi_i} K\right)$
- Supersymmetric extrema with $V(\phi_{\mathrm{min}}) < 0$
  - $F_i(\phi_{\mathrm{min}}) = 0 \ \forall i$
  - $W(\phi_{\mathrm{min}}) \neq 0$

Potential flat directions

Superpotential: main-moduli perturbative dependence and fluxes

- $F_{[n]}$, $H_{[3]}$ and $\omega_{[3]}$ vev's on internal cycles create fluxes and generate $W(S,T,U)$ [rich literature]
- Typical contributions – assuming toroidal prepotential:
  - $$W_{\rm IIA} = \overbrace{i\tilde{a}_0 S + i\tilde{c}_\ell U_\ell}^{H_{[3]}} \overbrace{- \tilde{a}_i S T_i - \tilde{d}_{i\ell} T_i U_\ell}^{\omega_{[3]}} \\ \underbrace{+ i\tilde{m}_0 T_1 T_2 T_3}_{F_{[0]}} \underbrace{- \tilde{m}_i T_j T_k}_{F_{[2]}} \underbrace{+ i\tilde{e}_\ell T_\ell}_{F_{[4]}} \underbrace{+ \tilde{e}_0}_{F_{[6]}}$$
  - $$W_{\rm IIB} = \overbrace{iS(a_0 + ia_\ell U_\ell + ib_0 U_1 U_2 U_3 + b_i U_j U_k)}^{H_{[3]}} \overbrace{- ic_\ell T_\ell}^{\omega_{[3]}} \\ \underbrace{+ e_0 + ie_\ell U_\ell + im_0 U_1 U_2 U_3 + m_i U_j U_k}_{F_{[3]}}$$

(not exhaustive)

Important remarks

- IIA/B mirror symmetry ($U \leftrightarrow T$) relates the various terms
- Stabilization of all moduli requires to go beyond CY
  - NS or R-flux back reaction in IIA
  - Kähler-moduli dependence in IIB requires *geometric fluxes* ($\omega_{[3]}$) whereas $W_{\text{IIB - CY}} = \int \Omega \wedge \left(F_{[3]} + SH_{[3]}\right) \Rightarrow$ no Ts
- The flux numbers are not arbitrary
  - they satisfy Jacobi identities (gauged-supergravity language) or Bianchi identities (internal-flux language)
  - they require branes (wrapping cycles) and orientifold planes (further breaking $N = 2 \to N = 1$) to cancel the RR tadpoles

Supersymmetric AdS_4 vacua in IIA

First examples [Behrndt, Cvetič, '04; Derendinger, Kounnas, Petropoulos, Zwirner, '04; Lüst, Tsimpis, '04]

$\mathbb{Z}_2 \times \mathbb{Z}_2$ plane-symmetric T^6 reduction with a $\mathbb{Z}_2$ orientifold in truncated 4-D $N = 4$ gauged supergravity with

$$W_{\text{IIA}} \propto i\left[2S + 2(U_1 + U_2 + U_3) + 3T_1T_2T_3 - 3(T_1 + T_2 + T_3)\right]$$
$$+2S(T_1 + T_2 + T_3) + 6(T_1U_1 + T_2U_2 + T_3U_3)$$
$$-(T_1T_2 + T_2T_3 + T_3T_1) - 15$$

- Minimum at $S = T_i = U_i = \sqrt{5/3}$ with $V_{\text{min}} < 0$
- All fluxes present: $H_{[3]}, F_{[0]}, F_{[4]}$ and $\omega_{[3]}, F_{[2]}, F_{[6]}$ – necessary to satisfy Jacobi/Bianchi – plus O6/D6 identities

Further extensions [Villadoro, Zwirner, '05; Cámara, Font, Ibañez, '05]

Beyond $N = 1$ truncation of 4-D $N = 4$ gauged supergravity

- Identical stabilization with $W_{\text{IIA}} \propto$ first line above
- Only $H_{[3]}, F_{[0]}, F_{[4]}$ (massive IIA) – Bianchi/tadpole conditions satisfied with various localized/smeared sources $\supset$ O6/D6

Highlights

Motivations and summary

Emergence of AdS_4 vacua from flux compactifications

Sources and supersymmetric configurations

A concrete example

Outcome

The emergence of fluxes

Antisymmetric tensors are generated by extended sources

Our aim: characterize the source distributions that create the appropriate fluxes for 4-D vacua with $V_{\rm min} < 0$

Typical sources for $AdS_4 \times M_6$

The required branes (see next chapter) have 2 common spatial directions in the non-compact spacetime and wrap some internal cycles in M_6

- $F_{[n]}$ through $\Sigma_n \leftrightarrow$ D$(8-n)$-branes around $\tilde{\Sigma}_{6-n}$
- $H_{[3]}$ through $\Sigma_3 \leftrightarrow$ NS5-branes around $\tilde{\Sigma}_3$
- $\omega_{[3]} \leftrightarrow$ Kaluza–Klein monopoles

(last items are T-dual)

Supersymmetric backgrounds created by branes

- Setup: intersecting supersymmetric smeared branes
- Method: careful use of the "harmonic superposition rule" (due to the smearing the Hs are not necessarily harmonic)
- Solution: backgrounds satisfying Bianchi identities and form equations with calibrated (i.e. supersymmetric) sources also solve dilaton and Einstein equations [...; Koerber, Tsimpis, '07]
  - obtained by adding an appropriate S_{source} to S_{bulk}
  - e.g. $\mathrm{d}F + H \wedge F = -Q\, j$
- RR tadpole cancellation conditions (integrated Bianchi): extra spacetime filling branes
  - orientifold planes/D-branes
  - $j_{\text{O/D}} = H \wedge F$

Highlights

The setup

We want type IIA with $H_{[3]}$, $F_{[0]}$, $F_{[4]}$

$$W_{\rm IIA} = i\tilde{a}_0 S + i\tilde{c}_\ell U_\ell + i\tilde{m}_0 T_1 T_2 T_3 + i\tilde{e}_\ell T_\ell$$

We need NS5, D8, D4 (plus O6/D6: $2N_{O6} - N_{D6} = \tilde{a}_0\tilde{m}_0$)

	ξ^0	ξ^1	ξ^2	y	x^1	x^2	x^3	x^4	x^5	x^6
D4	$\otimes$	$\otimes$	$\otimes$		$\otimes$	$\otimes$				
D4$'$	$\otimes$	$\otimes$	$\otimes$				$\otimes$	$\otimes$		
D4$''$	$\otimes$	$\otimes$	$\otimes$						$\otimes$	$\otimes$
NS5	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$		$\otimes$	
NS5$'$	$\otimes$	$\otimes$	$\otimes$		$\otimes$			$\otimes$		$\otimes$
NS5$''$	$\otimes$	$\otimes$	$\otimes$			$\otimes$		$\otimes$	$\otimes$	
NS5$'''$	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$			$\otimes$
D8	$\otimes$	$\otimes$	$\otimes$		$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$

The background fields

$H_{[3]}$, $F_{[0]}$, $F_{[4]}$ – *living inside* M_6 – *and* ϕ: *y-dependent*

$$e^{2\phi} = \left(\prod_{\alpha=1}^{4} H_\alpha^{\mathrm{NS5}}\right)\left(\prod_{\ell=1}^{3} H_\ell^{\mathrm{D4}}\right)^{-\frac{1}{2}} \left(H^{\mathrm{D8}}\right)^{-\frac{5}{2}}$$

$$H_{x^2x^4x^6} = -\partial_y H_1^{\mathrm{NS5}}\left(H^{\mathrm{D8}}\right)^{-1} \quad H_{x^2x^3x^5} = -\partial_y H_2^{\mathrm{NS5}}\left(H^{\mathrm{D8}}\right)^{-1}$$

$$H_{x^1x^3x^6} = -\partial_y H_3^{\mathrm{NS5}}\left(H^{\mathrm{D8}}\right)^{-1} \quad H_{x^1x^4x^5} = -\partial_y H_4^{\mathrm{NS5}}\left(H^{\mathrm{D8}}\right)^{-1}$$

$$F_{x^3x^4x^5x^6} = \partial_y H_1^{\mathrm{D4}} \quad F_{x^1x^2x^5x^6} = \partial_y H_2^{\mathrm{D4}}$$

$$F_{x^1x^2x^3x^4} = \partial_y H_3^{\mathrm{D4}} \quad F = -\partial_y H^{\mathrm{D8}}\left(\prod_{\alpha=1}^{4} H_\alpha^{\mathrm{NS5}}\right)^{-1}$$

$ds^2_{10}(y)$

$$
\begin{aligned}
\mathrm{d}s^2_{10} = &\left\{ H^{\mathrm{D8}} \left(\prod_{\ell=1}^{3} H_\ell^{\mathrm{D4}} \right) \right\}^{-\frac{1}{2}} \eta_{\mu\nu} \mathrm{d}\xi^\mu \mathrm{d}\xi^\nu \\
&+ \left(\prod_{\alpha=1}^{4} H_\alpha^{\mathrm{NS5}} \right) \left\{ H^{\mathrm{D8}} \left(\prod_{\ell=1}^{3} H_\ell^{\mathrm{D4}} \right) \right\}^{\frac{1}{2}} \mathrm{d}y^2 \\
&+ \sqrt{\frac{H_2^{\mathrm{D4}} H_3^{\mathrm{D4}}}{H_1^{\mathrm{D4}} H^{\mathrm{D8}}}} \left\{ H_3^{\mathrm{NS5}} H_4^{\mathrm{NS5}} \, (\mathrm{d}x^1)^2 + H_1^{\mathrm{NS5}} H_2^{\mathrm{NS5}} \, (\mathrm{d}x^2)^2 \right\} \\
&+ \sqrt{\frac{H_1^{\mathrm{D4}} H_3^{\mathrm{D4}}}{H_2^{\mathrm{D4}} H^{\mathrm{D8}}}} \left\{ H_2^{\mathrm{NS5}} H_3^{\mathrm{NS5}} \, (\mathrm{d}x^3)^2 + H_1^{\mathrm{NS5}} H_4^{\mathrm{NS5}} \, (\mathrm{d}x^4)^2 \right\} \\
&+ \sqrt{\frac{H_1^{\mathrm{D4}} H_2^{\mathrm{D4}}}{H_3^{\mathrm{D4}} H^{\mathrm{D8}}}} \left\{ H_2^{\mathrm{NS5}} H_4^{\mathrm{NS5}} \, (\mathrm{d}x^5)^2 + H_1^{\mathrm{NS5}} H_3^{\mathrm{NS5}} \, (\mathrm{d}x^6)^2 \right\}
\end{aligned}
$$

Equations, conditions and remarks

- Two supercharges survive the calibration constraints
- $H^{\sharp}_{\sharp}(y)$ are *not* harmonic functions: the branes are *smeared in y*

$$\text{Eqs. for } H^{\alpha}_{[3]}, F_{[0]}, F^{\ell}_{[4]} \begin{cases} \partial_y F = j(y) \\ Q = \int \mathrm{d}y\, j \end{cases}$$

- Freedom: family of solutions $[j(y)]$
- Requirements for $\mathrm{AdS}_4 \times T^6 \leftrightarrow \mathbb{R}^{1,3} \times T^6$
  - dilaton $\underset{y \to 0}{\longrightarrow}$ constant (avoid runaway, set leading order)
  - finiteness of total charges $Q^{\alpha}_{\mathrm{NS5}}$, Q_{D8}, Q^{ℓ}_{D4}
  - $H^{\sharp}_{\sharp}(y)$ constant at large y (asymptotic flatness)

Tadpole cancellation: 4 stacks of spacetime filling O6/D6s

Density: $j^{\alpha}_{\mathrm{O6/D6}} = H^{\alpha}_{[3]} F_{[0]}$

A continuous solution for $H^{\sharp}_{\sharp}$ with a harmonic piece (linear in y) and with continuous $\partial_y H^{\sharp}_{\sharp}$ vanishing at $y \geq y_0$

$$H^{\mathrm{NS}}_{\alpha} = \begin{cases} c^{\mathrm{NS}}_{\alpha} y \left\{ 1 + \frac{3}{2} \left(\frac{y}{y_0} \right)^{-\frac{5}{3}} \right\} & y < y_0 \\ \frac{5}{2} c^{\mathrm{NS}}_{\alpha} y_0, & y \geq y_0 \end{cases}$$

$$H^{\mathrm{D8}} = \begin{cases} c^{\mathrm{D8}} y \left\{ 1 + \frac{3}{5} \left(\frac{y}{y_0} \right)^{-\frac{8}{3}} \right\} & y < y_0 \\ \frac{8}{5} c^{\mathrm{D8}} y_0 & y \geq y_0 \end{cases}$$

$$H^{\mathrm{D4}}_{\ell} = \begin{cases} c^{\mathrm{D4}}_{\ell} y \left\{ 1 - \frac{1}{2} \left(\frac{y}{y_0} \right) \right\} & y < y_0 \\ \frac{1}{2} c^{\mathrm{D4}}_{\ell} y_0 & y \geq y_0 \end{cases}$$

Near-horizon properties

- NHG ($y \to 0$): $\mathrm{AdS}_4 \times T^6$
  - constant dilaton
  - constant $H_{[3]}^{\alpha}$, $F_{[0]}$, $F_{[4]}^{\ell}$ equal to the charges $Q_{\mathrm{NS5}}^{\alpha}$, Q_{D8}, Q_{D4}^{ℓ}
  - constant $Q_{\mathrm{O6/D6}}^{\alpha} = V_{\Sigma_3^{\alpha}} Q_{\mathrm{NS5}}^{\alpha} Q_{\mathrm{D8}}$ (tadpole condition)
  - supersymmetry is enhanced to 4 real supercharges ($N = 1$)
- In the NHG: the constant metric of the T^6 plus the dilaton allow to compute the moduli T_i, U_i of the torus and S

Back to the superpotential

The NH fields $H_{[3]}^{\alpha}$, $F_{[0]}$, $F_{[4]}^{\ell}$ can be identified with the flux (or gauging) parameters of the superpotential $\tilde{a}_0$, c_ℓ, $\tilde{m}_0$, $\tilde{e}_\ell$

- the above S, T_i, U_i ensure $DW_{\mathrm{IIA}} = 0$
- the tadpole cancellation translates into $2N_{\mathrm{O6}} - N_{\mathrm{D6}} = \tilde{a}_0 \tilde{m}_0$

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The outcome   *Last slide*

Summary: AdS_4 supergravity vacua with "all" stabilized moduli

- Exhibited using pure 4-D gauged-supergravity techniques
- Reproduced as the NH data of 10-D brane distributions

The branes are visible in spacetime as membranes creating a thick wall – due to the smearing in a non-compact direction

- These features are common to numerous examples in IIA or IIB
- Introduction of KK monopoles is often necessary
- Appearance of nilM_6 for IIB

Further investigation: dynamics of the branes / of the wall

- Microscopic entropy of the AdS_4 vacua
- Generalized attractor mechanism
- Contact with AdS_4 bubble nucleation and transitions

Appendix

The orientifold planes in the NS5/D8/D4 system

	ξ^0	ξ^1	ξ^2	y	x^1	x^2	x^3	x^4	x^5	x^6
O6	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$	
O6′	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$			$\otimes$		$\otimes$
O6″	$\otimes$	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$	$\otimes$	
O6‴	$\otimes$	$\otimes$	$\otimes$	$\otimes$		$\otimes$	$\otimes$			$\otimes$

Tadpole density

$$j^{\alpha}_{\mathrm{O6/D6}} = H^{\alpha}_{[3]} F_{[0]} = \frac{\partial_y H^{\mathrm{D8}} \partial_y H^{\mathrm{NS5}}_{\alpha}}{H^{\mathrm{D8}} \prod_{\beta=1}^{4} H^{\mathrm{NS5}}_{\beta}}$$