Non-supersymmetric D-branes

Timm Wrase



TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology



Saclay

December 9th, 2019



Outline

Introduction and motivation

• D-branes and non-linear SUSY

- D-branes in flux compactifications
- Conclusion









Outline

Introduction and motivation

D-branes and non-linear SUSY

- D-branes in flux compactifications
- Conclusion









- Incredibly hard questions:
 - Is string theory the only theory of Quantum Gravity?
 - We cannot quantize string theory in dS space
 - We have no understanding of non-perturbative string theory (in dS)

- Incredibly hard questions:
 - Is string theory the only theory of Quantum Gravity?
 - We cannot quantize string theory in dS space
 - We have no understanding of non-perturbative string theory (in dS)
 - ⇒ We need to first take the supergravity limit

• What do we require from a trustworty dS solution?

- What does
$$\frac{1}{g_s}$$
, $vol_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

• What do we require from a trustworty dS solution?

- What does
$$\frac{1}{g_s}$$
 , $vol_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

– Is it ok to use and balance quantum and classical corrections again each other?

• What do we require from a trustworty dS solution?

- What does
$$\frac{1}{g_s}$$
 , $vol_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

- Is it ok to use and balance quantum and classical corrections again each other?
- Can we maybe even study setups without (standard) supersymmetry?

• There exists only one single dS like quantum gravity solution we all agree on!

- What does
$$\frac{1}{g_s}$$
 , $vol_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

- Is it ok to use and balance quantum and classical corrections again each other?
- Can we maybe even study setups without (standard) supersymmetry?

There exists only one single dS like quantum gravity solution we all agree on!

– What does
$$\frac{1}{g_s}$$
 , $\mathrm{vol}_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

- Is it ok to use and balance quantum and classical corrections again each other?
- Can we maybe even study setups without (standard) supersymmetry?

There exists only one single dS like quantum gravity solution we all agree on!

- What does
$$\frac{1}{g_s}$$
 , $\operatorname{vol}_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

– Is it ok to use and balance quantum and classical corrections again each other?

CC problem

– Can we maybe even study setups without (standard) supersymmetry?

There exists only one single dS like quantum gravity solution we all agree on!

- What does
$$\frac{1}{g_s}$$
 , $\mathrm{vol}_6 \gg 1$ mean?
Is $g_s \sim .5$ ok?

- Is it ok to use and balance quantum and classical corrections again each other?
- Can we maybe even study setups without (standard) supersymmetry?



CC problem

No SUSY discovery

- The LHC has done a spectacular job at confirming the SM of particle physics
- Unfortunately no discovery of supersymmetry

No SUSY discovery

- The LHC has done a spectacular job at confirming the SM of particle physics
- Unfortunately no discovery of supersymmetry
- We are now faced with two problems:
 - 1. The cosmological constant problem
 - 2. The hierarchy problem

SUSY cannot really explain either

Non SUSY string theories

- Without SUSY things are substantially more complicated
- However, it appears that we need to understand the non-SUSY landscape vs. swampland in order to describe our universe



Non SUSY string theory solutions

1. Non-SUSY minima in standard linear SUGRA

We can consider string compactifications with ingredients that all preserve some supersymmetry, e.g. standard CY flux compactifications that give rise to 4d, N = 1 SUGRA theories

Non SUSY string theory solutions

1. Non-SUSY minima in standard linear SUGRA

We can consider string compactifications with ingredients that all preserve some supersymmetry, e.g. standard CY flux compactifications that give rise to 4d, N = 1 SUGRA theories

 Non-supersymmetric branes break SUSY We can use stringy ingredients that break supersymmetry, like anti-Dp-branes, e.g. the above plus anti-D3-brane uplift a la KKLT and LVS

Outline

Introduction and motivation

• D-branes and non-linear SUSY

- D-branes in flux compactifications
- Conclusion









- Consider a standard 4d N = 1 SUGRA theory:
 - 1. All fields come in standard N = 1 multiplets, i.e. boson-fermion pairs
 - 2. We can break SUSY via D-terms or F-terms but the theory still is invariant under linear SUSY

SUSY breaking via branes is different!

- Consider a standard 4d N = 1 SUGRA theory
- Add a SUSY breaking brane that is not exactly but almost calibrated
- For small angles θ SUSY breaking is small

- Consider a standard 4d N = 1 SUGRA theory
- Add a SUSY breaking brane that is not exactly but almost calibrated
- For small angles θ SUSY breaking is small
- We can write the action in terms of a standard F-term and a D-term, schematically

 $V = V_F + V_D \cdot (1 + \sin \theta)$

• For $\theta \ll 1$ this looks like standard SUGRA

• Consider a standard 4d N = 1 SUGRA theory

 $V = V_F + V_D \cdot (1 + \sin \theta)$

Cribiori, Roupec, Tourney, Van Proeyen, Wrase 20xx.xxxx

• For $\theta \ll 1$ this looks like standard SUGRA



• Consider a standard 4d N = 1 SUGRA theory

$$V = V_F + V_D \cdot (1 + \sin \theta)$$

Cribiori, Roupec, Tourney, Van Proeyen, Wrase 20xx.xxxx

• For $\theta = 0$ this looks like standard SUGRA but otherwise it *does not*

• Consider a standard 4d N = 1 SUGRA theory

 $V = V_F + V_D \cdot (1 + \sin \theta)$

Cribiori, Roupec, Tourney, Van Proeyen, Wrase 20xx.xxxx

- For $\theta = 0$ this looks like standard SUGRA but otherwise it *does not*
- One can show that there is no field redefinition that leads to standard linear SUSY
- Trivial for $\theta = \pi$, i.e. brane-anti-brane or anti-brane on top of O-plane

• Consider a standard 4d N = 1 SUGRA theory

 $V = V_F + V_D \cdot (1 + \sin \theta)$

Cribiori, Roupec, Tourney, Van Proeyen, Wrase 20xx.xxxx

- For $\theta = 0$ this looks like standard SUGRA but otherwise it *does not*
- This setup and all others can be written using standard SUSY with constrained multiplets
- Non-linear SUSY is constraining, and there exist non-renormalization theorems

Garcia del Moral, Parameswaran, Quiroz, Zavala 1707.07059

 (broken) supersymmetry: Loop contribution from a fermion are (almost) cancelled by a boson

- (broken) supersymmetry: Loop contribution from a fermion are (almost) cancelled by a boson
- String theory has infinite towers of states with ever growing number of states

- (broken) supersymmetry: Loop contribution from a fermion are (almost) cancelled by a boson
- String theory has infinite towers of states with ever growing number of states
- Imagine a non-supersymmetric string theory where we can calculate the 1-loop partition function
- How do the infinite number of non-SUSY states cancel among each other (finiteness of string theory)

- (broken) supersymmetry: Loop contribution from a fermion are (almost) cancelled by a boson
- String theory has infinite towers of states with ever growing number of states
- Imagine a non-supersymmetric string theory where we can calculate the 1-loop partition function
- How do the infinite number of non-SUSY states cancel among each other (finiteness of string theory)

 \Rightarrow Misaligned SUSY

Spectrum for an anti-D3-brane on top of an O3-plane

M^2/M_0^2	# Bosons		
0	0	8	
1	128	0	
2	0	1,152	
3	7,680	0	
4	0	42,112	
	•••		

Work in progress with Niccolo Cribiori, Susha Parameswaran, Flavio Tonioni



Dienes hep-th/9503055

Abel, Dudas, Lewis, Partouche 1812.09714

Spectrum for an anti-D3-brane on top of an O3-plane

M^2/M_0^2	# Bosons # Fermion		
0	0	8	
1	128	0	
2	0	1,152	
3	7,680	0	
4	0	42,112	

Work in progress with Niccolo Cribiori, Susha Parameswaran, Flavio Tonioni



Dienes hep-th/9503055

Abel, Dudas, Lewis, Partouche 1812.09714

Outline

Introduction and motivation

• D-branes and non-linear SUSY

- D-branes in flux compactifications
- Conclusion









dS vacua in string theory

• The first dS vacua in string theory were constructed over a decade ago

Kachru, Kallosh, Linde, Trivedi hep-th/0301240

Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058

Conlon, Quevedo, Suruliz hep-th/0505076

• They were obtained via a two step procedure:



dS vacua in string theory

• The first dS vacua in string theory were constructed over a decade ago

Kachru, Kallosh, Linde, Trivedi hep-th/0301240

Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058

Conlon, Quevedo, Suruliz hep-th/0505076

• It seems that the two step procedure and the anti-D3-brane are not necessarily needed: SUSY breaking in CS sector

Saltman, Silverstein hep-th/0402135

Marsh, Vercnocke, Wrase 1411.6625

Gallego, Marsh, Vercnocke, Wrase 1707.01095

 \Rightarrow Anti-branes seem to be useful but not necessary ?

• Stable dS vacua have been searched for but only critical points have been found (until recently)

> Flauger, Robbins, Paban, TW 0812.3886 Caviezel, Koerber, Körs, Lüst, TW, Zagermann 0812.3551 Danielsson, Haque, Shiu, Van Riet 0907.2041 Caviezel, TW, Zagermann 0912.3287 Danielsson, Koerber, Van Riet 1003.3590

 Stable dS vacua have been searched for but only critical points have been found (until recently)

> Flauger, Robbins, Paban, TW 0812.3886 Caviezel, Koerber, Körs, Lüst, TW, Zagermann 0812.3551 Danielsson, Haque, Shiu, Van Riet 0907.2041 Caviezel, TW, Zagermann 0912.3287 Danielsson, Koerber, Van Riet 1003.3590

• The above is a standard 4d N = 1 SUGRA where it is notoriously difficult to stabilize the sGoldstino

Covi, Gomez-Reino, Gross, Louis, Palma, Scrucca 0804.1073 Jungshans 1603.08939 Junghans, Zagermann 1612.06847

Aside: Classical dS vacua in type IIB

- There seem to be classical dS solution in type IIB string theory with O5-planes and D5-branes
- One needs F₁ flux and metric flux to avoid no-go theorems

	<i>y</i> ₁	<i>y</i> ₂	<i>y</i> ₃	y_4	${\mathcal Y}_5$	<i>y</i> ₆
05	Х	Х	-	-	-	-
05	-	-	X	X	-	-
D5	-	-	-	-	Х	X

• On-going work with Paul Marconnet and David Andriot

- Tachyon always along 3-cycle moduli
- These 3-cycles can be wrapped by anti-D6-branes

Kallosh, Wrase 1808.09427

$$V_{dS} = -m^2 (Im(Z) - 1)^2 + \frac{N_{\overline{D6}}}{Im(Z)^3}$$





- Checked explicitly in the simplest example $S^3 \times S^3/Z_2 \times Z_2$
- The one tachyonic direction is now stable



- Checked explicitly in the simplest example $S^3 \times S^3/Z_2 \times Z_2$
- The one tachyonic direction is now stable
- dS solutions at slightly shifted values, *do not seem to be trustworthy* in this example (small volume, large coupling) Kallosh, Wrase 1808.09427

KK monopoles in massive IIA



- Similarly, stable dS vacua were found by including KK monopoles Blåbäck, Danielsson, Dibitetto 1810.11365
- Obstinate tachyon is now gone but one flat direction seems to remain

KK monopoles in massive IIA



- Similarly, stable dS vacua were found by including KK monopoles Blåbäck, Danielsson, Dibitetto 1810.11365
- Obstinate tachyon is now gone but one flat direction seems to remain

 \Rightarrow Anti-branes seem to be useful but not necessary ?

• AdS vacua can be *parametrically controlled*. Can keep N_{O6} fixed and send $F_4 \rightarrow \infty$ (no tadpole constraint)

DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

• AdS vacua can be *parametrically controlled*. Can keep N_{O6} fixed and send $F_4 \rightarrow \infty$ (no tadpole constraint)

DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

• dS vacua scaling: $vol_6 \propto N_{O6}^3$, $e^{-\phi} \propto \sqrt{N_{O6}}$ Junghans 1811.06990 Banlaki, Chowdhury, Roupec, Wrase 1811.07880





• AdS vacua can be *parametrically controlled*. Can keep N_{O6} fixed and send $F_4 \rightarrow \infty$ (no tadpole constraint)

DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

• dS vacua scaling: $vol_6 \propto N_{O6}^3$, $e^{-\phi} \propto \sqrt{N_{O6}}$

Junghans 1811.06990

Banlaki, Chowdhury, Roupec, Wrase 1811.07880



• AdS vacua can be *parametrically controlled*. Can keep N_{O6} fixed and send $F_4 \rightarrow \infty$ (no tadpole constraint)

DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

• dS vacua scaling: $vol_6 \propto N_{O6}^3$, $e^{-\phi} \propto \sqrt{N_{O6}}$

Junghans 1811.06990

Banlaki, Chowdhury, Roupec, Wrase 1811.07880

N₀₆ is bounded in any compactification so we cannot have parametric control over dS vacua Ooguri, Palti, Shiu, Vafa 1810.05506



Anti-branes naughty or nice?

- Brane with anti-branes can lead to instabilities
- Anti-D3-brane at the bottom of KS throat can annihilate against fluxes, but that seems to be no problem

Michel, Mintun, Polchinski, Puhm, Saad 1412.5702 C.-Maldonado, Diaz, VR, Vercnocke 1507.01022 C.-Maldonado, Diaz, Gautason 1603.05678

Anti-branes naughty or nice?

- Brane with anti-branes can lead to instabilities
- Anti-D3-brane at the bottom of KS throat can annihilate against fluxes, but that seems to be no problem

Michel, Mintun, Polchinski, Puhm, Saad 1412.5702 C.-Maldonado, Diaz, VR, Vercnocke 1507.01022 C.-Maldonado, Diaz, Gautason 1603.05678

• Anti-D6-brane in type IIA not necessarily problematic

Danielsson, Gautason, Van Riet 1609.06529 Blåbäck, Gautason, Ruipérez, Van Riet 1907.05295



Anti-branes naughty or nice?

- Brane with anti-branes can lead to instabilities
- Anti-D3-brane at the bottom of KS throat can annihilate against fluxes, but that seems to be no problem

Michel, Mintun, Polchinski, Puhm, Saad 1412.5702 C.-Maldonado, Diaz, VR, Vercnocke 1507.01022 C.-Maldonado, Diaz, Gautason 1603.05678

• Anti-D6-brane in type IIA not necessarily problematic

Danielsson, Gautason, Van Riet 1609.06529 Blåbäck, Gautason, Ruipérez, Van Riet 1907.05295

• Bifid throats for axion monodromy inflation

Retolaza, Uranga, Westphal 1504.02103



• We break supersymmetry at the string scale:

 $m_{4d} \ll m_{KK} \ll m_{string} = m_{SUSY} \ll m_{Pl}$

• In KKLT or LVS we reduce these scales via warping $m_{4d} \ll m_{KK}^{warped} \ll m_{string}^{warped} = m_{\rm SUSY} \ll m_{Pl}$

• We break supersymmetry at the string scale:

 $m_{4d} \ll m_{KK} \ll m_{string} = m_{SUSY} \ll m_{Pl}$

• In KKLT or LVS we reduce these scales via warping

$$m_{4d} \ll m_{KK}^{warped} \ll m_{string}^{warped} = m_{SUSY} \ll m_{Pl}$$

Does it make sense to use or do we even have 4d N = 1 supergravity theory?

- Yes, the SUSY action correctly describes the physics for $E \ll m_{KK}$
- SUSY makes life simple and constrains the action

- Yes, the SUSY action correctly describes the physics for $E \ll m_{KK}$
- SUSY makes life simple and constrains the action
- We want almost vanishing cosmological constant

$$V_F = m_{SUSY}^4 - 3m_{\frac{3}{2}}^2 m_{Pl}^2 \approx 0$$

$$m_{\frac{3}{2}} \sim \frac{m_{string}^2}{m_{Pl}} \ll m_{string}$$

• So we can have a 4d SUSY theory with gravitino

Conclusion

- Non-supersymmetric branes lead to conceptually different low energy SUGRA theories
- Non-linear SUSY plus stringy insights lead still to fairly constrained and controlled actions

Conclusion

- Non-supersymmetric branes lead to conceptually different low energy SUGRA theories
- Non-linear SUSY plus stringy insights lead still to fairly constrained and controlled actions
- These models might give insights into non-SUSY landscape vs. swampland, in particular dS vacua but hopefully much more

Conclusion

- Non-supersymmetric branes lead to conceptually different low energy SUGRA theories
- Non-linear SUSY plus stringy insights lead still to fairly constrained and controlled actions
- These models might give insights into non-SUSY landscape vs. swampland, in particular dS vacua but hopefully much more



• Consider a theory with a single massless fermion λ

$$S_{VA} = -\int d^4x (1 + \bar{\lambda}\gamma^{\mu}\partial_{\mu}\lambda + \cdots)$$

• For appropriately higher order terms, the above action is invariant under a fermionic symmetry:

$$\delta_{\epsilon} \lambda = \epsilon + \left(\overline{\lambda} \gamma^{\mu} \epsilon \right) \partial_{\mu} \lambda$$

• Consider a theory with a single massless fermion λ

$$S_{VA} = -\int d^4x (1 + \bar{\lambda}\gamma^{\mu}\partial_{\mu}\lambda + \cdots)$$

• For appropriately higher order terms, the above action is invariant under a fermionic symmetry:

$$\delta_{\epsilon} \lambda = \epsilon + \left(\overline{\lambda} \gamma^{\mu} \epsilon \right) \partial_{\mu} \lambda$$

• The above symmetry is supersymmetry!

$$\{\delta_{\epsilon_1}, \delta_{\epsilon_2}\}\lambda = (\bar{\epsilon_1}\gamma^{\mu}\epsilon_2 + \bar{\epsilon_2}\gamma^{\mu}\epsilon_1)\partial_{\mu}\lambda$$

• Consider a theory with a single massless fermion λ

$$S_{VA} = -\int d^4x (1 + \bar{\lambda}\gamma^{\mu}\partial_{\mu}\lambda + \cdots)$$

• For appropriately higher order terms, the above action is invariant under a fermionic symmetry:

$$\delta_{\epsilon} \lambda = \epsilon + \left(\overline{\lambda} \gamma^{\mu} \epsilon \right) \partial_{\mu} \lambda$$

• We have a supersymmetric theory with a single fermion!

• Consider a theory with a single massless fermion λ

$$S_{VA} = -\int d^4x (1 + \bar{\lambda}\gamma^{\mu}\partial_{\mu}\lambda + \cdots)$$

• For appropriately higher order terms, the above action is invariant under a fermionic symmetry:

$$\delta_{\epsilon} \lambda = \epsilon + \left(\overline{\lambda} \gamma^{\mu} \epsilon \right) \partial_{\mu} \lambda$$

 In any standard theory with spontaneously broken SUSY we have a Goldstino and all other fields are generically massive, so at low energies we have the above

• Consider a theory with a single massless fermion λ

$$S_{VA} = -\int d^4x (1 + \bar{\lambda}\gamma^{\mu}\partial_{\mu}\lambda + \cdots)$$

• For appropriately higher order terms, the above action is invariant under a fermionic symmetry:

$$\delta_{\epsilon}\lambda = \epsilon + (\bar{\lambda}\gamma^{\mu}\epsilon)\partial_{\mu}\lambda$$

 Note, however, that SUSY is non-linear realized and mismatch between bosons and fermions



momentum is measured by the integral of the corresponding current over the world-sheet boundary,

$$\frac{1}{2\pi\alpha'}\int_{\partial M} ds\,\partial_n X'^9 , \qquad (13.2.3)$$

which up to normalization is just the (0 picture) vertex operator for the collective coordinate, with zero momentum in the Neumann directions. We conclude by analogy that the D-brane also spontaneously breaks 16 of the 32 spacetime supersymmetries, the ones that are explicitly broken by the open string boundary conditions. The integrals

$$\int_{\partial M} ds \, \mathscr{V}'_{\alpha} = - \int_{\partial M} ds \, (\beta^9 \, \widetilde{\mathscr{V}}')_{\alpha} \,, \qquad (13.2.4)$$

which measure the breaking of supersymmetry, are just the vertex op-

Let us recall some facts about D-branes *in flat space*:

• The D-brane breaks half of the supersymmetry *spontaneously* and the other half is linearly realized





Let us recall some facts about D-branes *in flat space*:

- The D-brane breaks half of the supersymmetry *spontaneously* and the other half is linearly realized
- <u>Example</u>: a D3-brane (or an anti-D3-brane)
- It preserve 16 linearly realized supercharges, i.e. N = 4 in 4d
- The worldvolume fields $A_{\mu}, \lambda^{0}, \phi^{i}, \lambda^{i}, i = 1, 2, 3$ can be package into an N = 4 multiplet



Let us recall some facts about D-branes *in flat space*:

- The D-brane breaks half of the supersymmetry spontaneously and the other half is linearly realized
- <u>Example</u>: a D3-brane (or an anti-D3-brane)
- 16 supercharges are spontaneously broken at the string scale $\mathcal{O}(\alpha')$
- The Goldstone fermions aka Goldstinos are λ^0 and λ^i , i = 1, 2, 3



Let us recall some facts about D-branes *in flat space*:

- The D-brane breaks half of the supersymmetry *spontaneously* and the other half is linearly realized
- Example: An anti-D3-brane on top of an O3

Kallosh, Wrase 1411.1121

$$A_{\mu}, \lambda^{0}, \phi^{i}, \lambda^{i} \xrightarrow{O3 \text{ projection}} \lambda^{0}, \lambda^{i}$$

Let us recall some facts about D-branes *in flat space*:

- The D-brane breaks half of the supersymmetry *spontaneously* and the other half is linearly realized
- Example: An anti-D3-brane on top of an O3

Kallosh, Wrase 1411.1121

$$A_{\mu}, \lambda^{0}, \phi^{i}, \lambda^{i} \xrightarrow{O3 \text{ projection}} \lambda^{0}, \lambda^{i}$$

$$S = -d^{4}x \int \left(1 + \overline{\lambda}^{A} \gamma^{\mu} \partial_{\mu} \lambda^{A} + \cdots\right), \qquad A, B = 0, 1, 2, 3$$

$$\delta_{\epsilon^{A}} \lambda^{B} = \epsilon^{A} \delta_{A}^{B} + \left(\overline{\lambda}^{A} \gamma^{\mu} \epsilon^{A}\right) \partial_{\mu} \lambda^{B}$$

Let us recall some facts about D-branes *in flat space*:

- The D-brane breaks half of the supersymmetry *spontaneously* and the other half is linearly realized
- Example: An anti-D3-brane on top of an O3

Kallosh, Wrase 1411.1121

$$A_{\mu}, \lambda^{0}, \phi^{i}, \lambda^{i} \xrightarrow{O3 \text{ projection}} \lambda^{0}, \lambda^{i}$$

$$S = -d^{4}x \int \left(1 + \bar{\lambda}^{A}\gamma^{\mu}\partial_{\mu}\lambda^{A} + \cdots\right), \qquad A, B = 0, 1, 2, 3$$

$$\delta_{\epsilon^{A}}\lambda^{B} = \epsilon^{A}\delta_{A}^{B} + \left(\bar{\lambda}^{A}\gamma^{\mu}\epsilon^{A}\right)\partial_{\mu}\lambda^{B}$$
Exactly as Volkov-Akulov above!