Non-supersymmetric D-branes

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Saclay

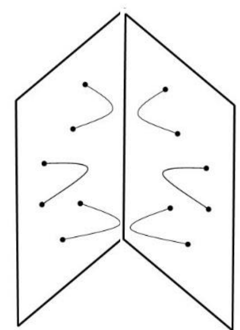
December 9th, 2019

FWF
Der Wissenschaftsfonds.

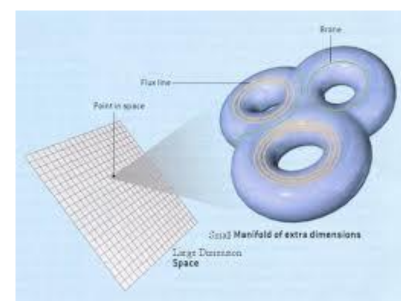
Outline

- Introduction and motivation

- D-branes and non-linear SUSY



- D-branes in flux compactifications



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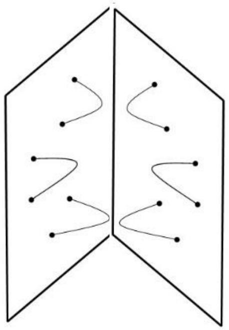

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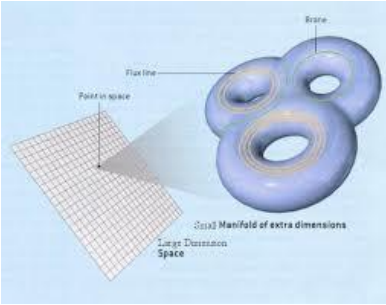

- Conclusion

dS vacua in String Theory/QG

- 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)

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  - We have no understanding of non-perturbative string theory (in dS)

$\Rightarrow$ We need to first take the supergravity limit

dS vacua in String Theory/QG

- What do we require from a trustworty dS solution?
  - What does $\frac{1}{\mathrm{g_s}}$, $\mathrm{vol}_6 \gg 1$ mean?
    Is $g_s \sim .5$ ok?

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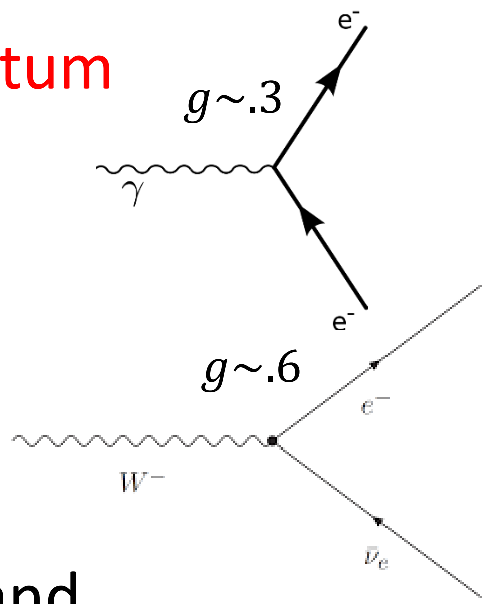

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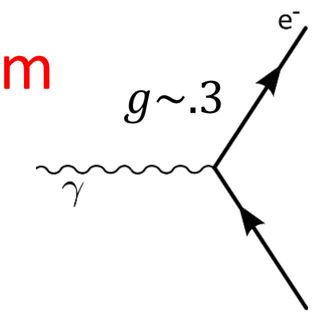

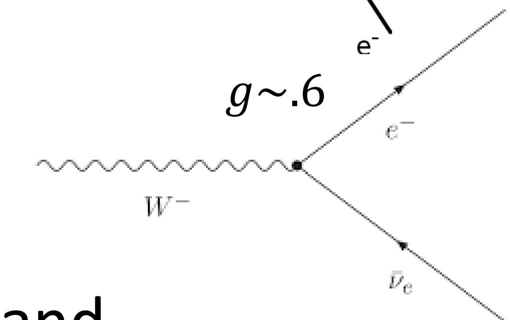

CC problem

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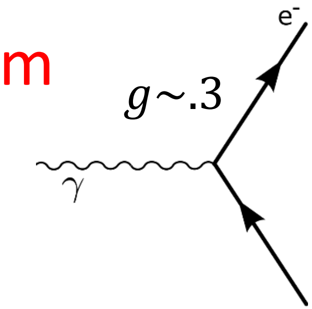

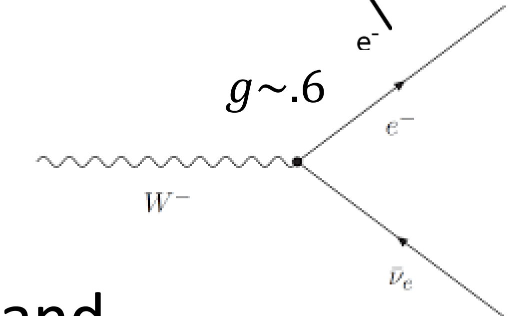

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No SUSY discovery

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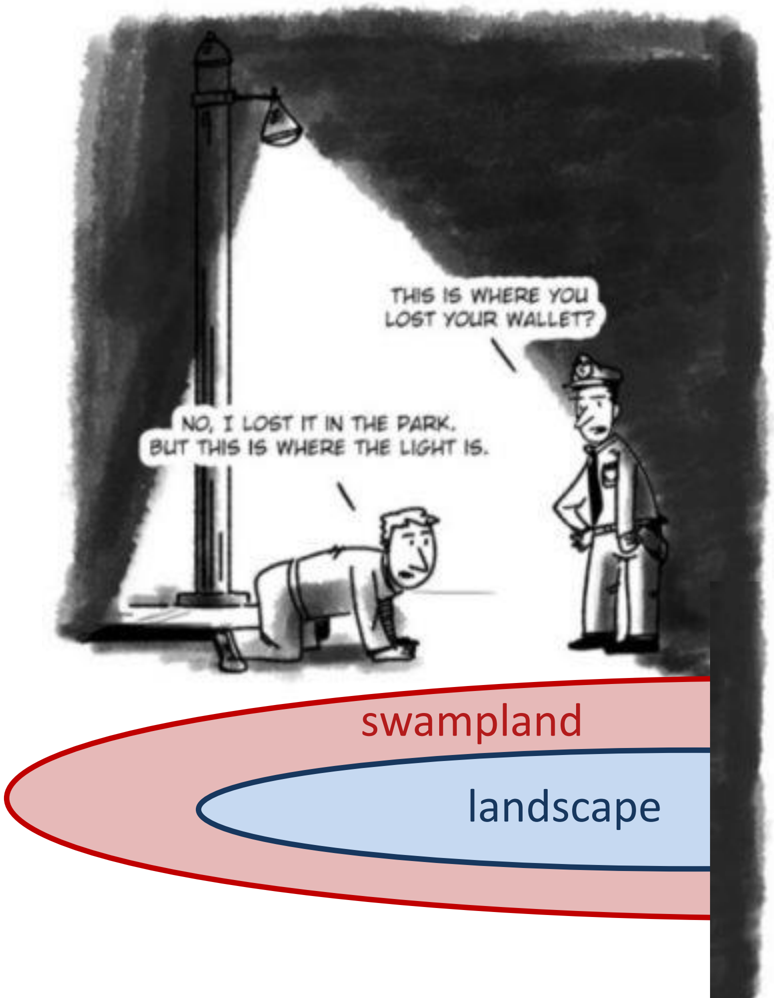
- Unfortunately no discovery of supersymmetry
- We are now faced with two problems:
  1. The cosmological constant problem
  2. The hierarchy problem

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

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   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

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2. <u>Non-supersymmetric branes break SUSY</u>

   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

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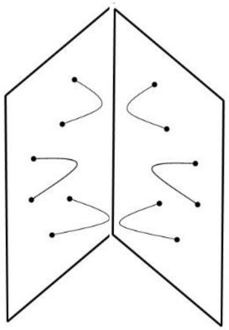

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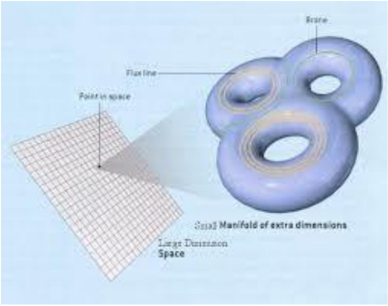


- Conclusion

D-brane SUSY breaking

- Consider a standard 4d $N = 1$ SUGRA theory:

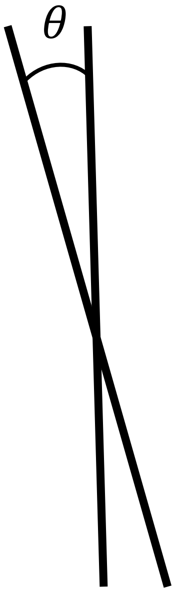
    1. All fields come in standard $N = 1$ multiplets, i.e. boson-fermion pairs

    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!

D-brane SUSY breaking

- 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



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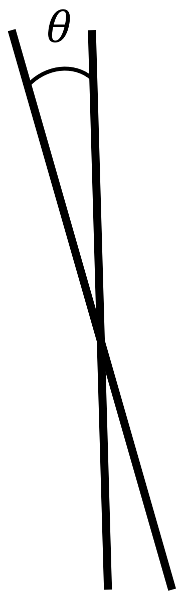
- We can write the action in terms of a standard F-term and a D-term, schematically

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

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



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

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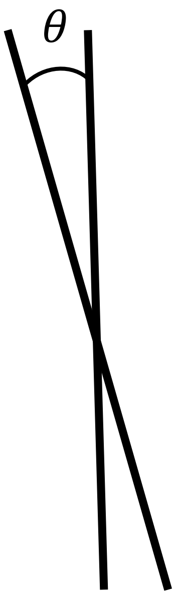

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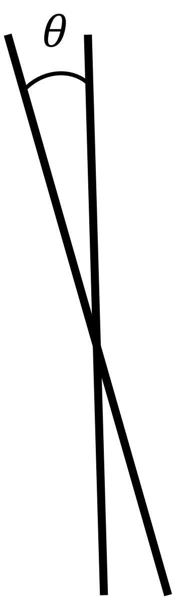

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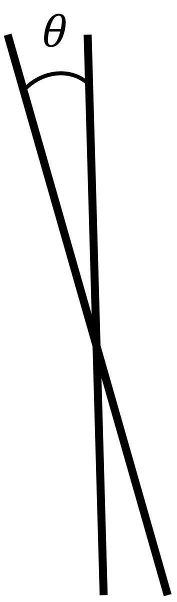
- For $\theta = 0$ this looks like standard SUGRA but otherwise it *does not*
- One can show that there is no field redefinition that leads to standard linear SUSY
- Trivial for $\theta = \pi$, i.e. brane-anti-brane or anti-brane on top of O-plane



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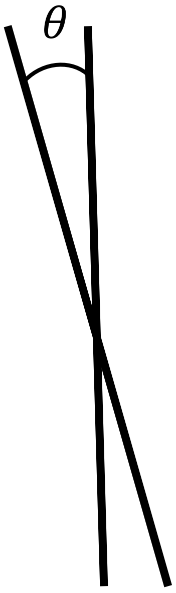
- This setup and all others can be written using standard SUSY with constrained multiplets
- Non-linear SUSY is constraining, and there exist non-renormalization theorems



Garcia del Moral, Parameswaran, Quiroz, Zavala 1707.07059

Misaligned SUSY for branes

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

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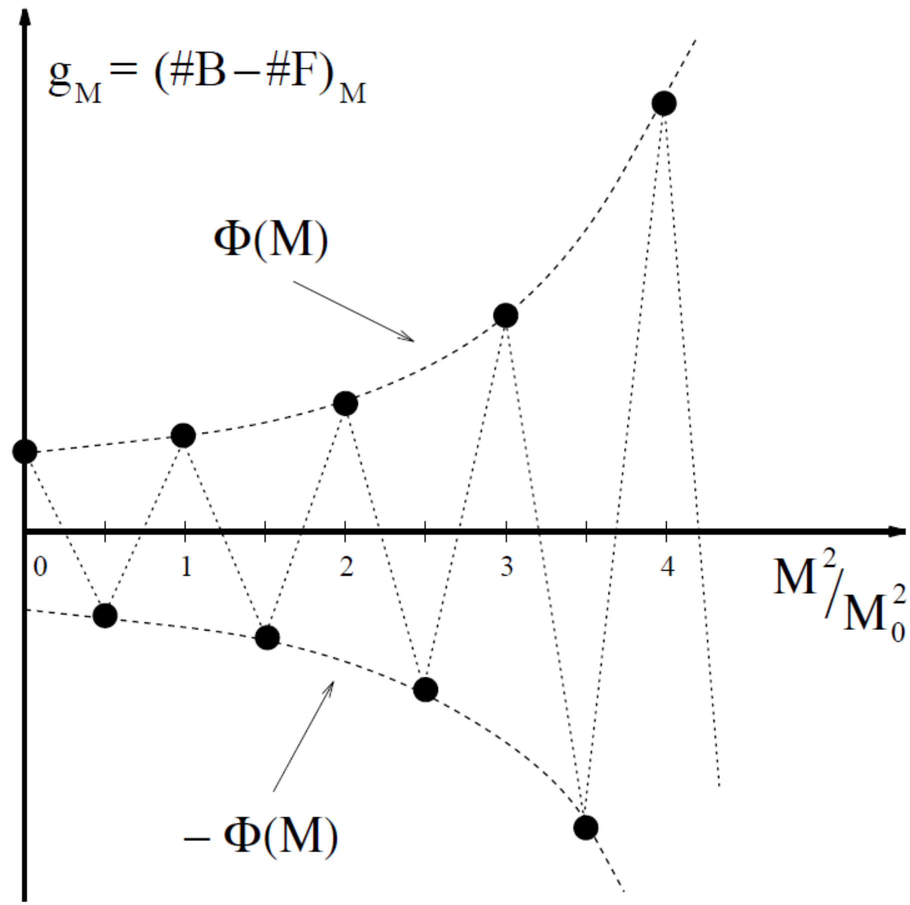
$\Rightarrow$ Misaligned SUSY

Misaligned SUSY for branes

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

M^2/M_0^2	# Bosons	# Fermions
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

Abel, Dudas, Lewis, Partouche 1812.09714

Dienes hep-th/9503055

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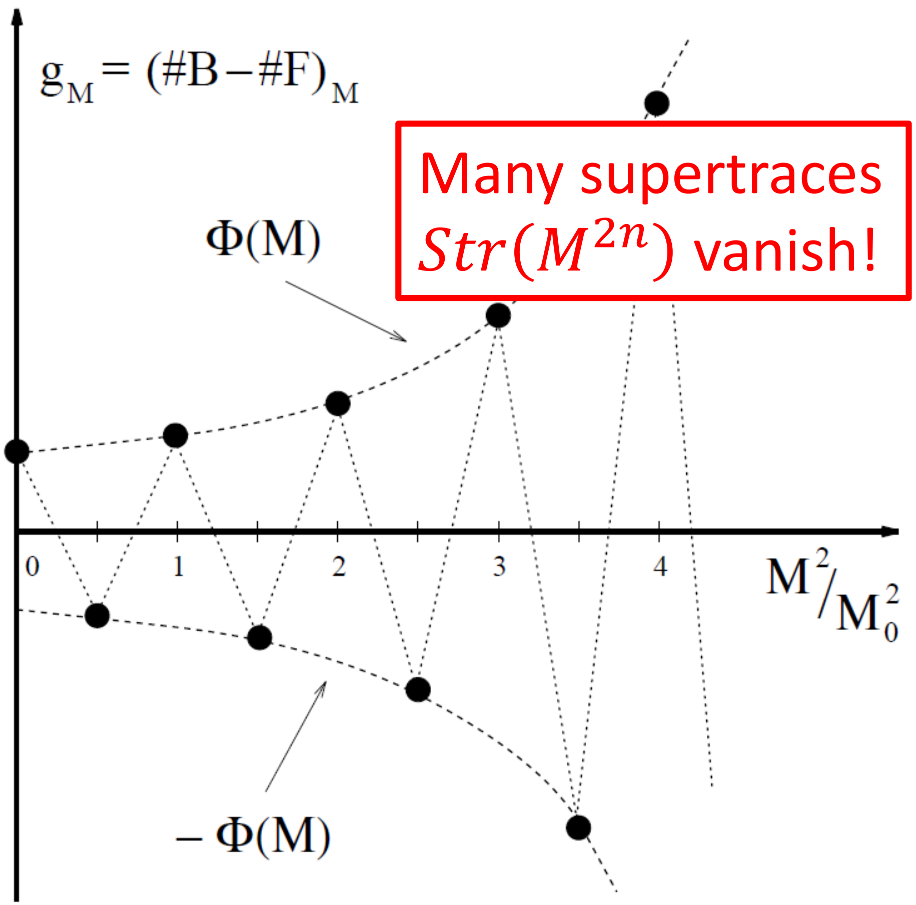

Many supertraces $Str(M^{2n})$ vanish!

Abel, Dudas, Lewis, Partouche 1812.09714

Dienes hep-th/9503055

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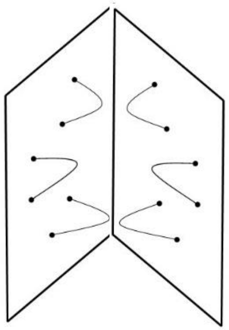

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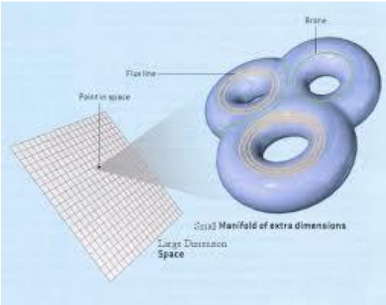


- Conclusion

dS vacua in string theory

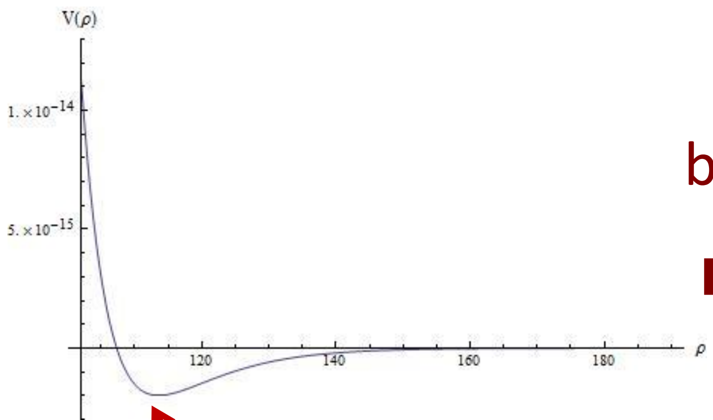
- The first dS vacua in string theory were constructed over a decade ago

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

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

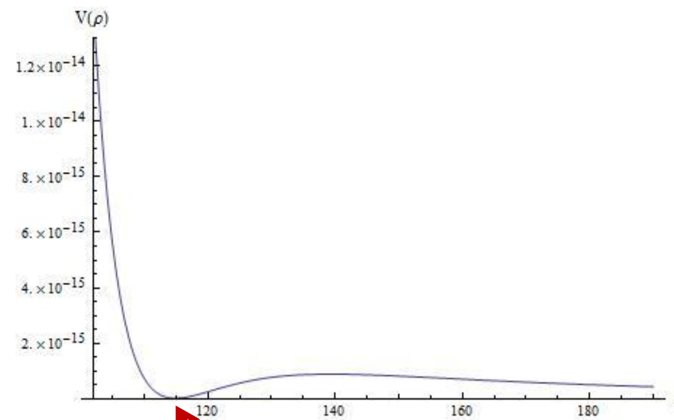
Conlon, Quevedo, Suruliz hep-th/0505076

- They were obtained via a two step procedure:



AdS vacuum

Adding an anti-D3-brane “uplift”



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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 ?

Classical dS vacua in type IIA

- 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

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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 F_1 flux and metric flux to avoid no-go theorems

	y_1	y_2	y_3	y_4	y_5	y_6
O5	x	x	-	-	-	-
O5	-	-	x	x	-	-
D5	-	-	-	-	x	x

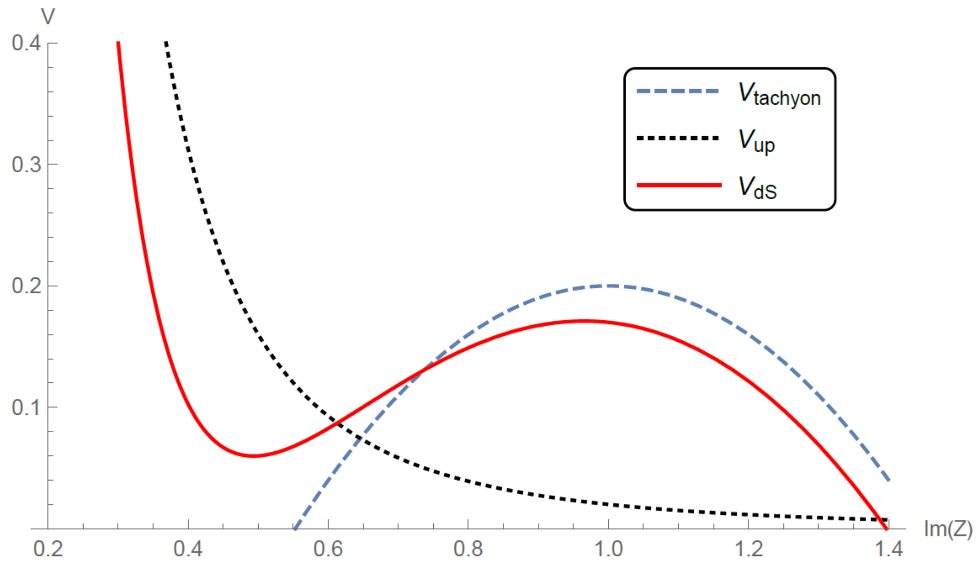
- On-going work with Paul Marconnet and David Andriot

Classical dS vacua in type IIA

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

Kallosh, Wrase 1808.09427

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



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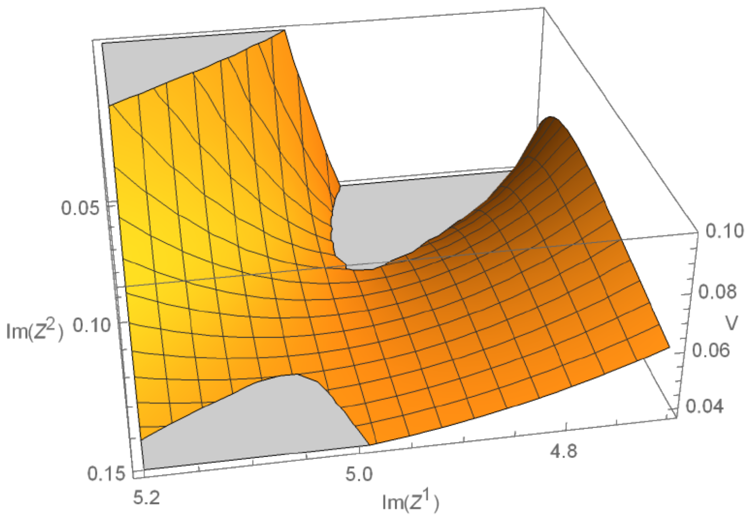

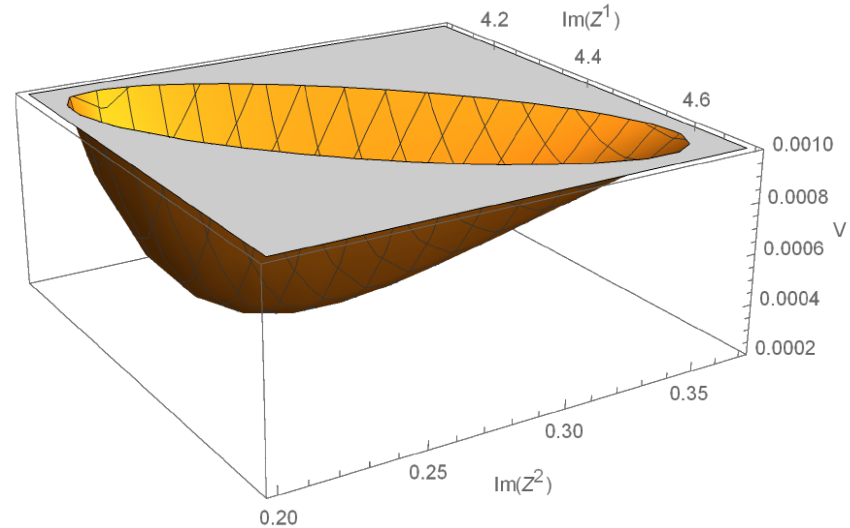

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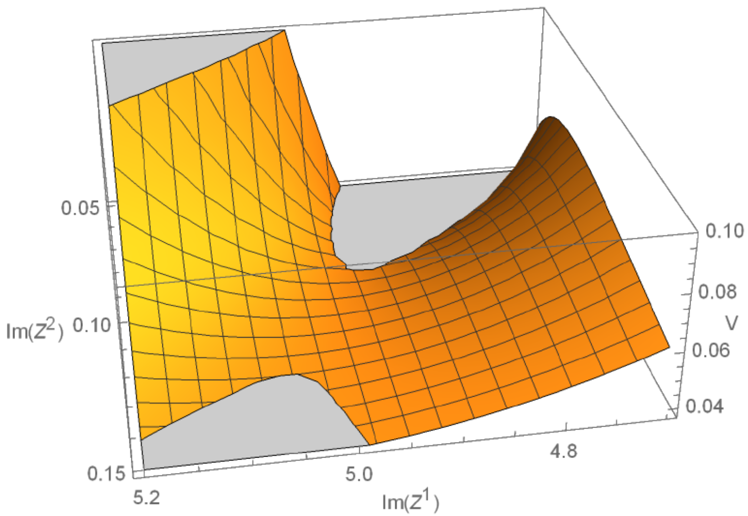

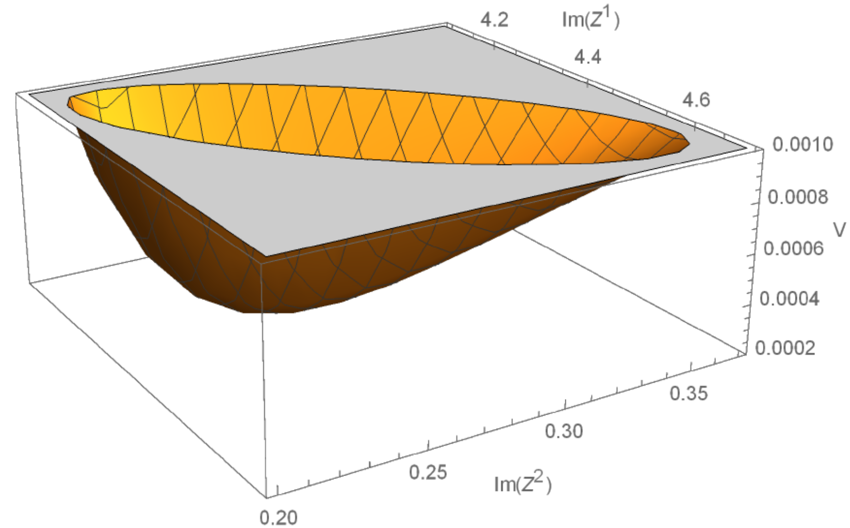

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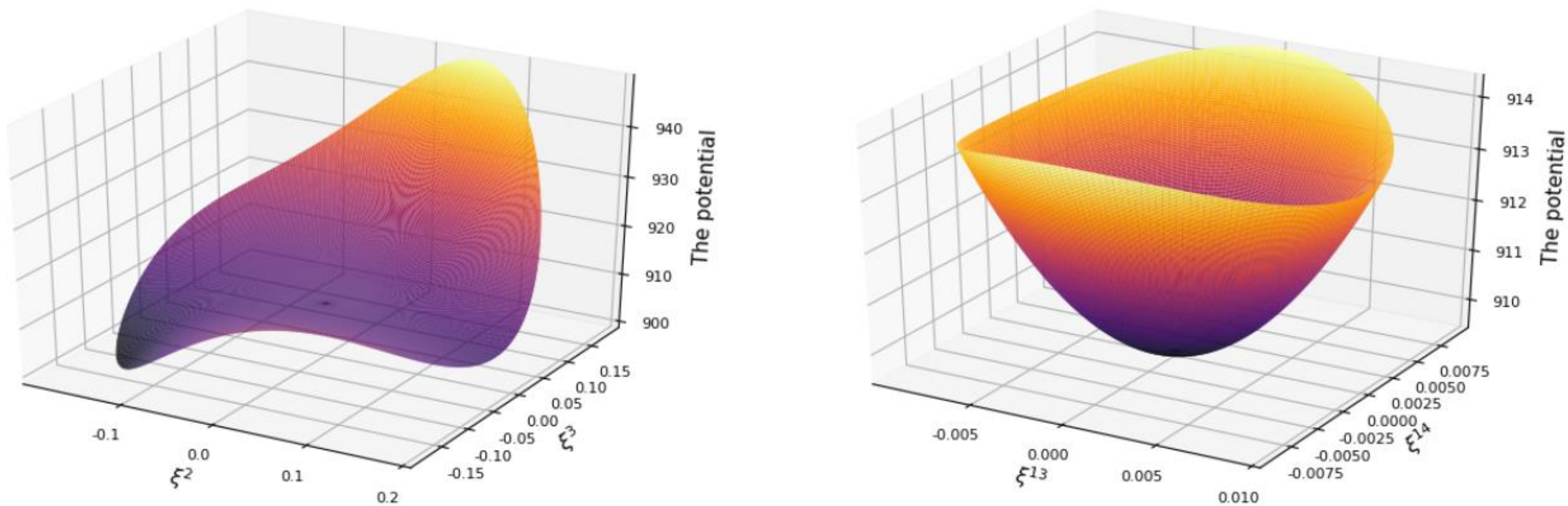
- The one tachyonic direction is now stable
- dS solutions at slightly shifted values, *do not seem to be trustworthy* in this example (small volume, large coupling)

Kallosh, Wrase 1808.09427

KK monopoles in massive IIA



- Similarly, stable dS vacua were found by including KK monopoles

Blåbäck, Danielsson, Dibitetto 1810.11365

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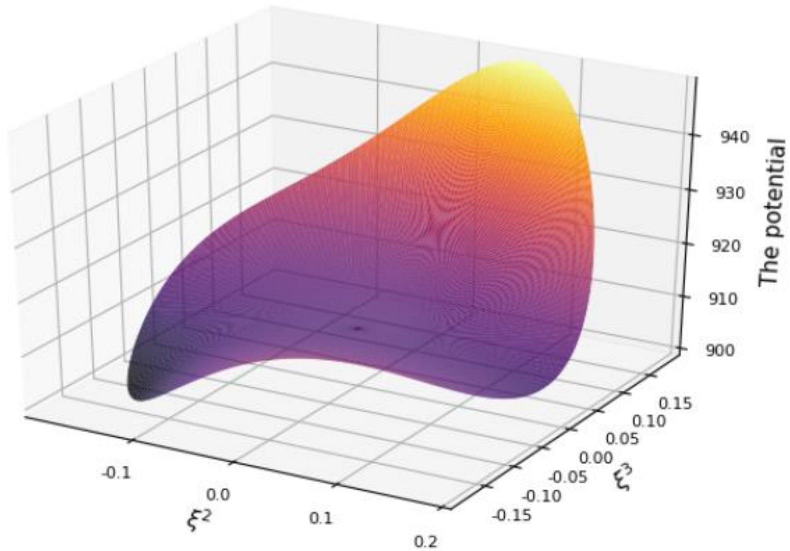

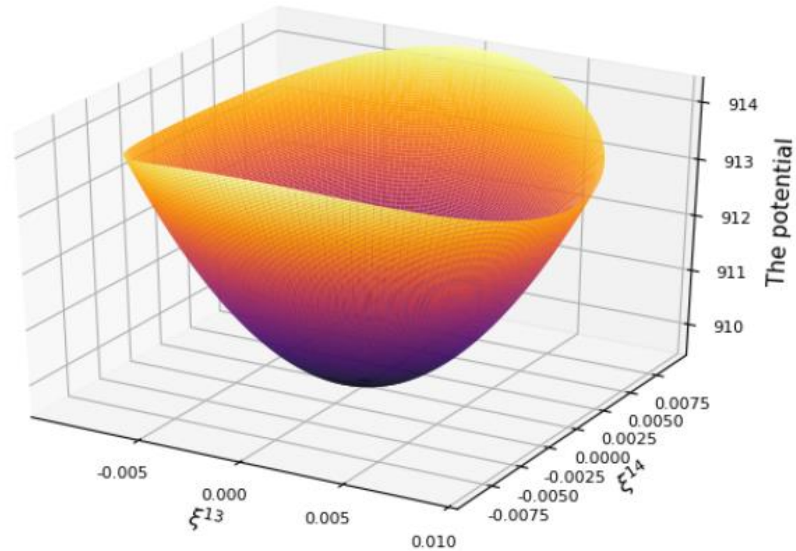

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- AdS vacua can be *parametrically controlled*. Can keep N_{O6} fixed and send $F_4 \to \infty$ (no tadpole constraint)

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

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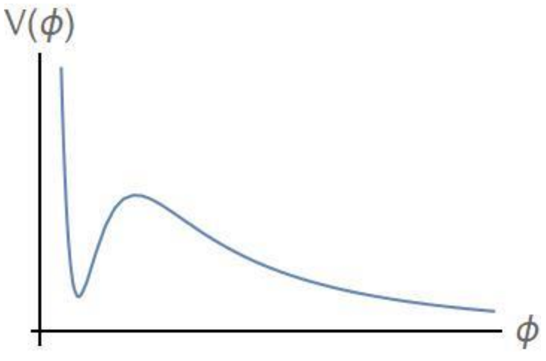
Junghans 1811.06990

Banlaki, Chowdhury, Roupec, Wrase 1811.07880

$$V(\phi) \propto \frac{a}{\phi^2} - \frac{b}{\phi^3} + \frac{c}{\phi^4}$$



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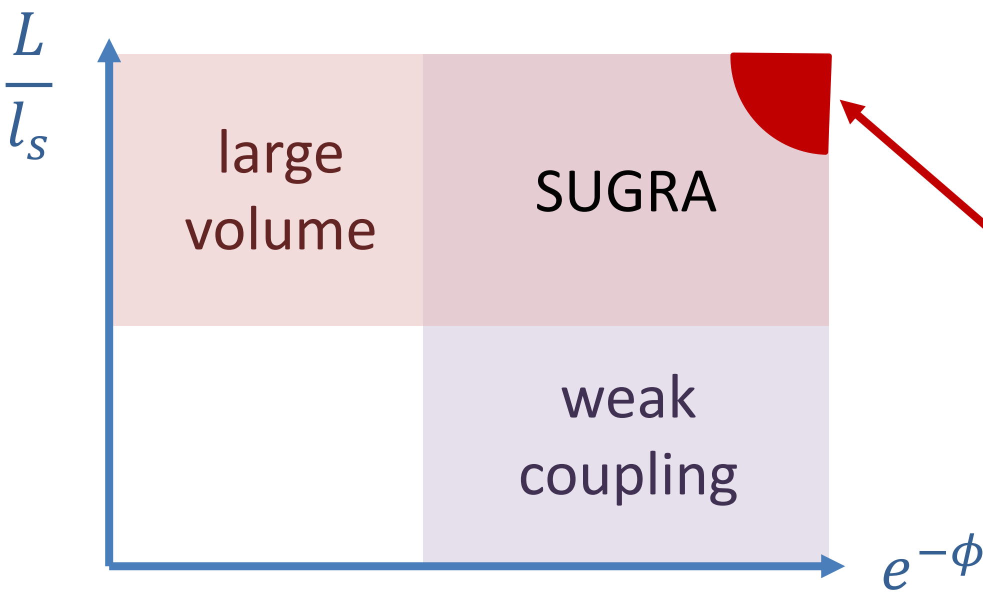

N_{O6} is bounded in any compactification so we cannot have parametric control over dS vacua

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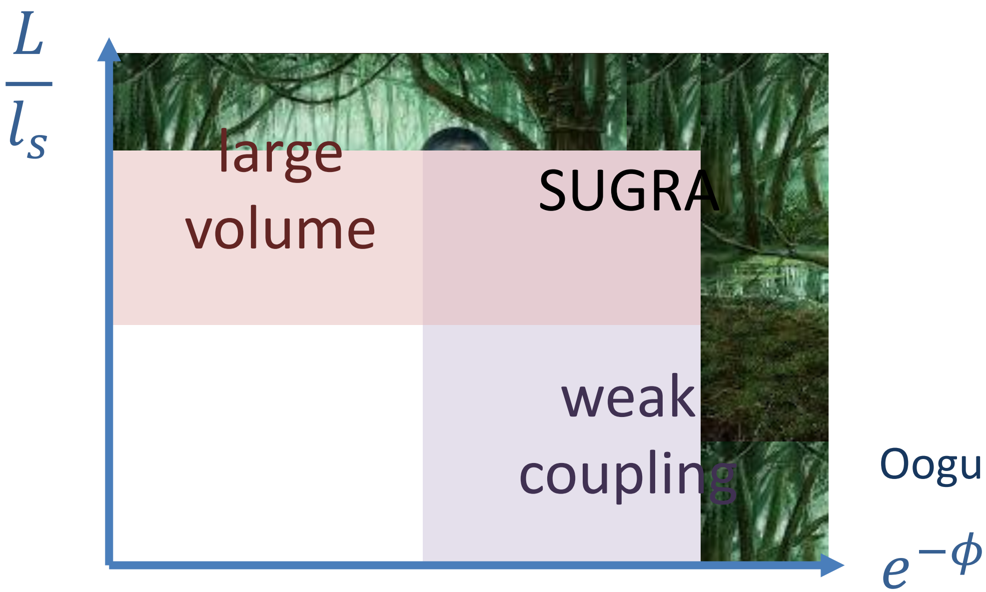
Junghans 1811.06990

Banlaki, Chowdhury, Roupec, Wrase 1811.07880



N_{O6} 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

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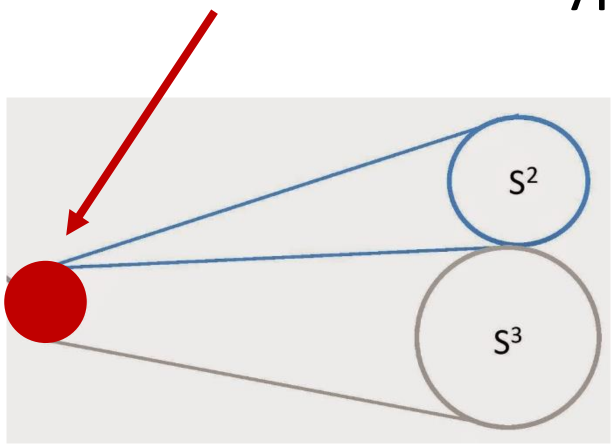
- Anti-D6-brane in type IIA not necessarily problematic

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



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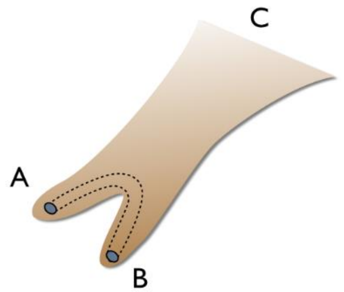
- Bifid throats for axion monodromy inflation

Retolaza, Uranga, Westphal 1504.02103



SUSY breaking

- We break supersymmetry at the string scale:

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

- In KKLT or LVS we reduce these scales via warping

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Does it make sense to use or do we even have

4d $N = 1$ supergravity theory?

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

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- SUSY makes life simple and constrains the action
- We want almost vanishing cosmological constant

$$V_F = m^4_{\cancel{SUSY}} - 3m^2_{\frac{3}{2}}\, m^2_{Pl} \;\approx\; 0$$

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

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

Conclusion

- Non-supersymmetric branes lead to conceptually different low energy SUGRA theories
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THANK YOU!

The Volkov-Akulov model

- 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:

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

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- The above symmetry is supersymmetry!

$$\{\delta_{\epsilon_1}, \delta_{\epsilon_2}\}\lambda = (\bar{\epsilon}_1\gamma^\mu\epsilon_2 + \bar{\epsilon}_2\gamma^\mu\epsilon_1)\partial_\mu\,\lambda$$

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- We have a supersymmetric theory with a single fermion!

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- 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

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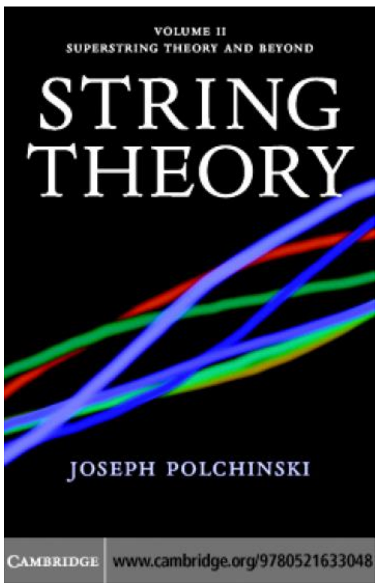
- Note, however, that SUSY is *non-linear realized* and mismatch between bosons and fermions

D-branes in string theory



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

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

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

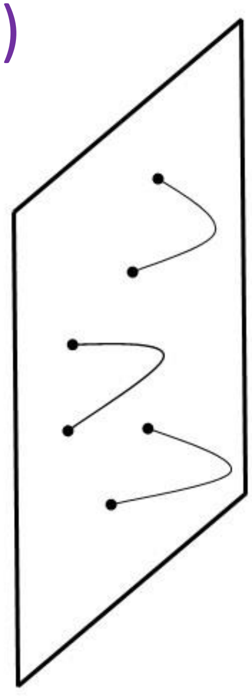
$$\int_{\partial M} ds\,\mathscr{V}'_{\alpha} = -\int_{\partial M} ds\,(\beta^9\tilde{\mathscr{V}}')_{\alpha} \,, \tag{13.2.4}$$

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

D-branes in string theory

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: a D3-brane (or an anti-D3-brane)



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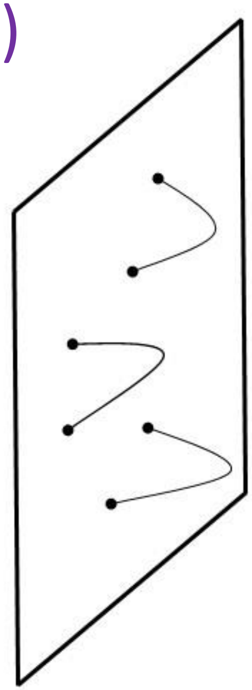
- It preserve 16 linearly realized supercharges, i.e. $N = 4$ in 4d
- The worldvolume fields $A_\mu, \lambda^0, \phi^i, \lambda^i, i = 1, 2, 3$ can be package into an $N = 4$ multiplet



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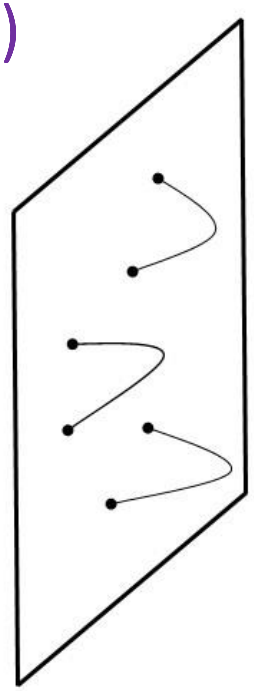
- <u>Example:</u> a D3-brane (or an anti-D3-brane)
- 16 supercharges are spontaneously broken at the string scale $\mathcal{O}(\alpha')$
- The Goldstone fermions aka Goldstinos are λ^0 and $\lambda^i, i = 1, 2, 3$



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Kallosh, Wrase 1411.1121

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Exactly as Volkov-Akulov above!