Constrained Multiplets from String Theory

Timm Wrase

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

INSTITUTE FOR THEORETICAL PHYSICS

Ioannina

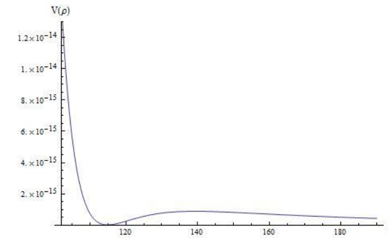
June 22th, 2016

Based on:

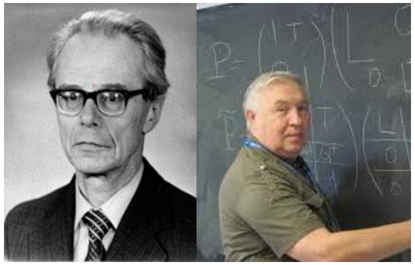
R. Kallosh, B. Vercnocke, TW 1606.XXXXX
B. Vercnocke, TW 1605.03961
E. Bergshoeff, K. Dasgupta, R. Kallosh, A. Van Proeyen, TW 1502.07627
R. Kallosh, TW 1411.1121

Outline

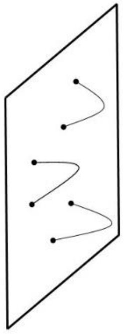
- KKLT dS vacua in string theory



- The nilpotent chiral superfield



- Constrained multiplets from D3-branes



- Conclusion

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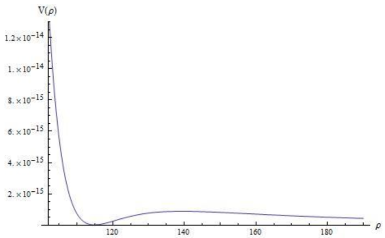

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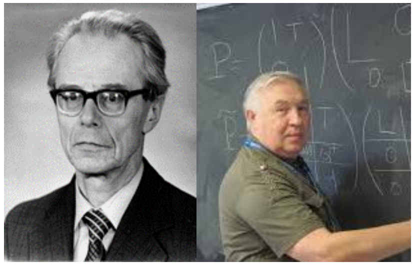

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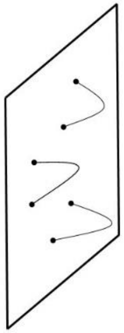


- Conclusion

dS vacua in string theory

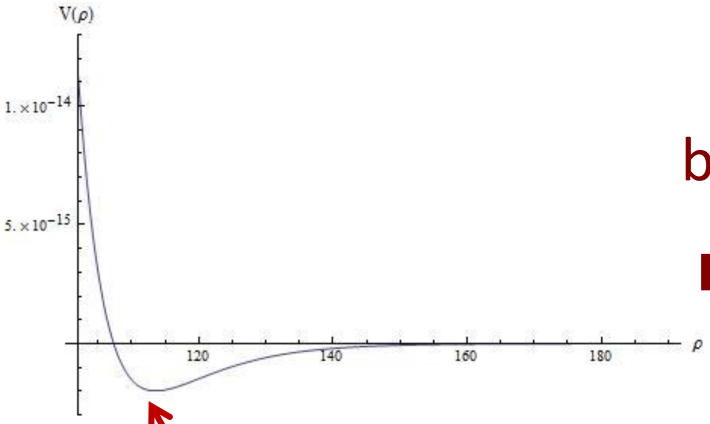
- The first dS vacua in string theory were constructed over a decade ago

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

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

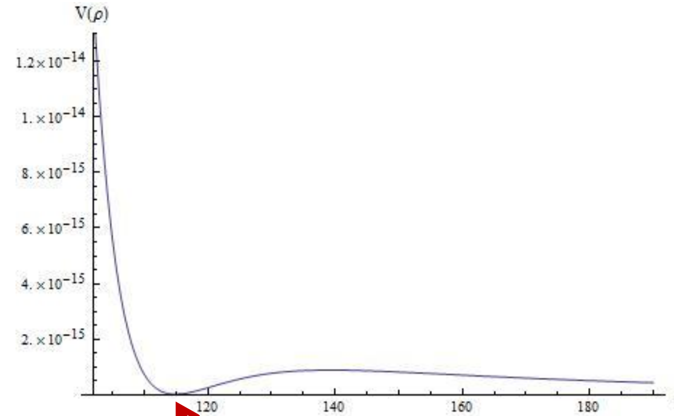
Conlon, Quevedo, Suruliz hep-th/0505076

- They were obtained via a two step procedure:



AdS vacuum

Adding an anti-D3-brane "uplift"



dS vacuum

dS vacua in string theory

- The uplifting term *seems to explicitly break supersymmetry*

$$V = e^K\left(K^{I\bar{J}} D_I W \overline{D_J W} - 3|W|^2\right) + \frac{\mu^4}{(T+\bar{T})^2}$$

$$K = -3\log(T+\bar{T})$$
$$W = W_0 - A\, e^{-aT}$$

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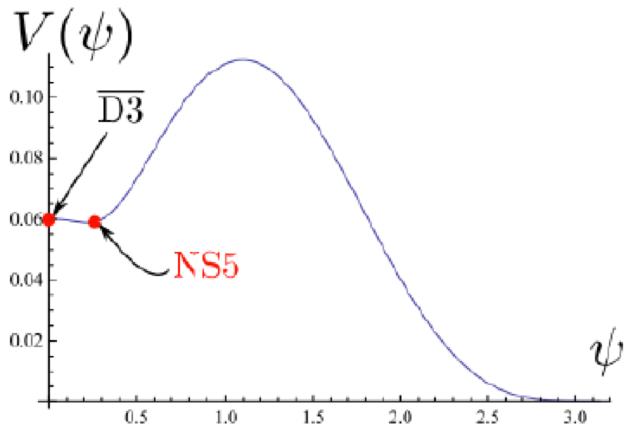
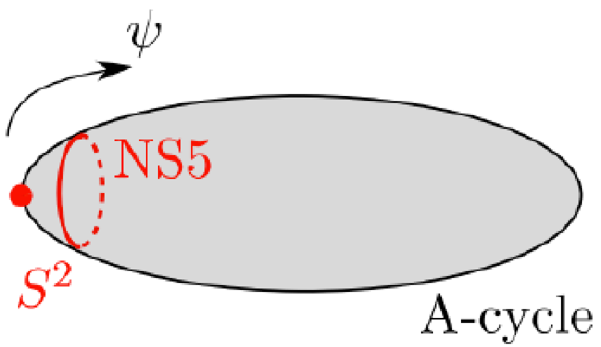
- Can we package the uplift term into K and W?

dS vacua in string theory

- The anti-D3-brane can decay to a SUSY vacuum, hence it is an excited state in a SUSY theory

Kachru, Pearson, Verlinde hep-th/0112197





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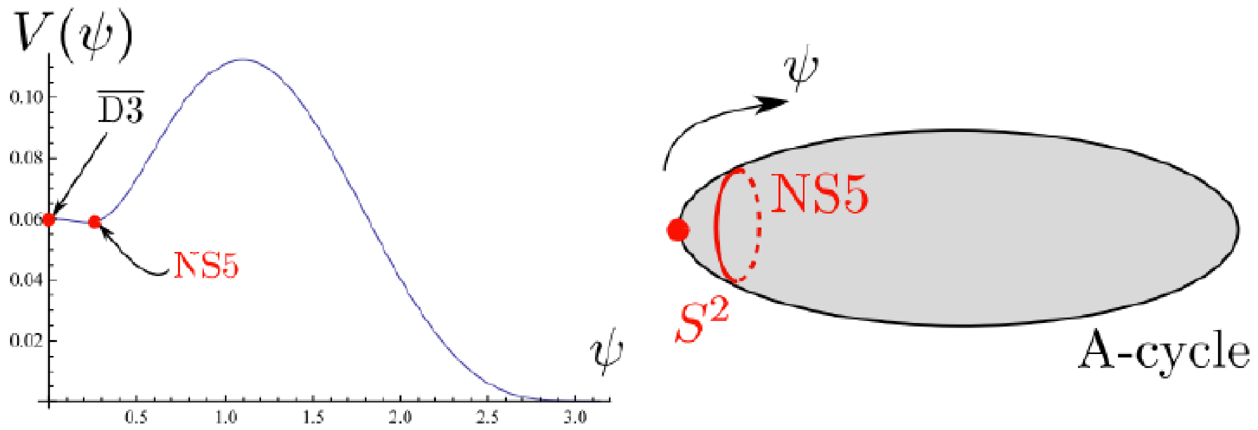
Kachru, Pearson, Verlinde hep-th/0112197



- How can we describe the uplift term in terms of W and K or as an D-term?

Outline

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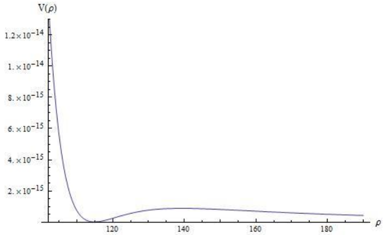
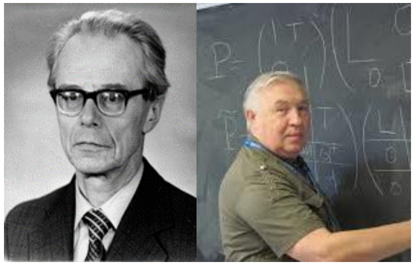


- The nilpotent chiral superfield



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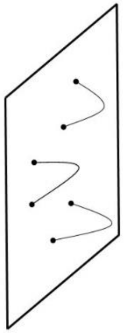

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- If we break supersymmetry we expect a massless goldstone fermion, the goldstino
- Is the neutrino a goldstone particle?

Volkov, Akulov 1972, 1973

The nilpotent chiral superfield

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Not necessarily!

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- Is the neutrino a goldstone particle?

Volkov, Akulov 1972, 1973

$$S_{VA} = \int E^0 \wedge E^1 \wedge E^2 \wedge E^3, \qquad E^\mu = dx^\mu + \bar{\chi}\gamma^\mu d\chi$$

- Invariant under: $\delta_\epsilon \chi = \epsilon + (\bar{\chi}\gamma^\mu \epsilon)\partial_\mu \chi$

The nilpotent chiral superfield

- SUSY 101: supersymmetry relates bosons and fermions

Not necessarily!

- If we break supersymmetry we expect a massless goldstone fermion, the goldstino
- Is the neutrino a goldstone particle? No, but interesting!

Volkov, Akulov 1972, 1973

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The nilpotent chiral superfield

$$S_{VA} = \int E^0 \wedge E^1 \wedge E^2 \wedge E^3 = \int d^4x \, \det(E),$$

$$E^\mu = dx^\mu + \bar{\chi}\gamma^\mu d\chi = dx^\nu\left(\delta^\mu_\nu + \bar{\chi}\gamma^\mu \partial_\nu \chi\right)$$

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- Invariant under: $\delta_\epsilon \chi = \epsilon + (\bar{\chi}\gamma^\mu \epsilon)\partial_\mu \chi$
- There is only one fermion!
- Supersymmetry is non-linearly realized
- Supersymmetry is spontaneously broken

The nilpotent chiral superfield

- In $N = 1$ supersymmetry in 4d we can have a so called nilpotent chiral superfield

Volkov, Akulov 1972, 1973
Rocek; Ivanov, Kapustnikov 1978
Lindstrom, Rocek 1979
Casalbuoni, De Curtis, Dominici, Feruglio, Gatto 1989
Komargodski, Seiberg 0907.2441

- This can be thought of as a chiral superfield that squares to zero

$$S = s + \sqrt{2}\theta\chi + \theta^2 F, \qquad S^2 = 0$$

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$$s = \frac{\chi\chi}{2F} = \frac{\chi_1\chi_2}{F} \quad \Rightarrow \quad s\chi = 0 \ \text{ and } \ s^2 = 0$$

The nilpotent chiral superfield

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- These nilpotent chiral superfields consists only of fermions!
- Supersymmetry is non-linearly realized and spontaneously broken ($F \neq 0$)
- There are a variety of different actions but all are related to S_{VA} via non-linear field redefinitions

Kuzenko, Tyler 1009.3298, 1102.3043

The nilpotent chiral superfield

- The bosonic supergravity action for a single nilpotent field $s^2 = 0$ is very simple Antoniadis, Dudas, Ferrara, Sagnotti 1403.3269

$$K = s\bar{s} = -\ln(1 - s\bar{s})$$
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- χ is the Goldstino and gets eaten by the gravitino

The nilpotent chiral superfield

- Very interesting possibilities for cosmological model building in supergravity, i.e. inflation and dS vacua

See talks by Alex Kehagias, Renata Kallosh and Emilian Dudas

Antoniadis, Dudas, Ferrara, Sagnotti	1403.3269
Ferrara, Kallosh, Linde	1408.4096
Kallosh, Linde	1408.5950
Dall'Agata, Zwirner	1411.2605
Kallosh, Linde, Scalisi	1411.5671
Carrasco, Kallosh, Linde Roest	1504.05557
Scalisi	1506.01368
Carrasco, Kallosh, Linde Roest	1506.01708
Hasegawa, Yamada	1509.04987
Ferrara, Kallosh, Thaler	1512.00545
Carrasco, Kallosh, Linde	1512.00546
Dudas, Heurtier, Wieck, Winkler	1601.03397
Kallosh, Linde, TW	1602.07818
Farakos, Kehagias, Racco, Riotto	1605.07631

The nilpotent chiral superfield

- This nilpotent superfield also arises in string theory for example from anti-D3-branes in KKLT

McGuirk, Shiu, Ye 1206.0754

Ferrara, Kallosh, Linde 1408.4096

Kallosh, TW 1411.1121

Bergshoeff, Dasgupta, Kallosh, Van Proeyen, TW 1502.07627

Kallosh, Quevedo, Uranga 1507.07556

Bandos, Martucci, Sorokin, Tonin 1511.03024

Aparicio, Quevedo, Valandro 1511.08105

García-Etxebarria, Quevedo, Valandro 1512.06926

Dasgupta, Emelin, McDonough 1601.03409

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See talk by Fernando Quevedo

dS vacua in string theory

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

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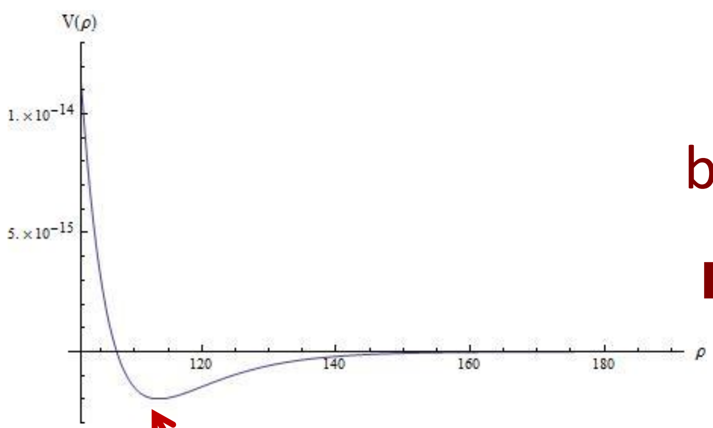
Conlon, Quevedo, Suruliz   hep-th/0505076

dS vacua construction are often a two step procedure:



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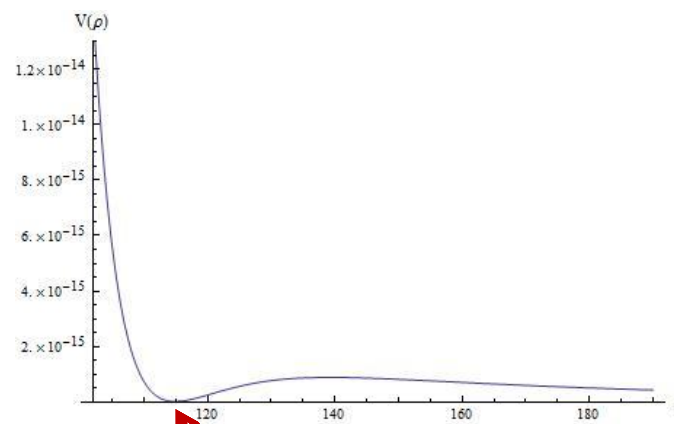

dS vacuum

The nilpotent chiral superfield

- A very interesting observation

Ferrara, Kallosh, Linde 1408.4096

$$K = -3\ln(T + \bar{T}) + s\bar{s}$$
$$W = W_0 + Ae^{-aT} + \mu^2 s$$

- The scalar potential for $s^2 = 0$ is

$$V = V_{KKLT} + \frac{\mu^4}{(T + \bar{T})^3}$$

The nilpotent chiral superfield

- Similarly for warping

Ferrara, Kallosh, Linde 1408.4096

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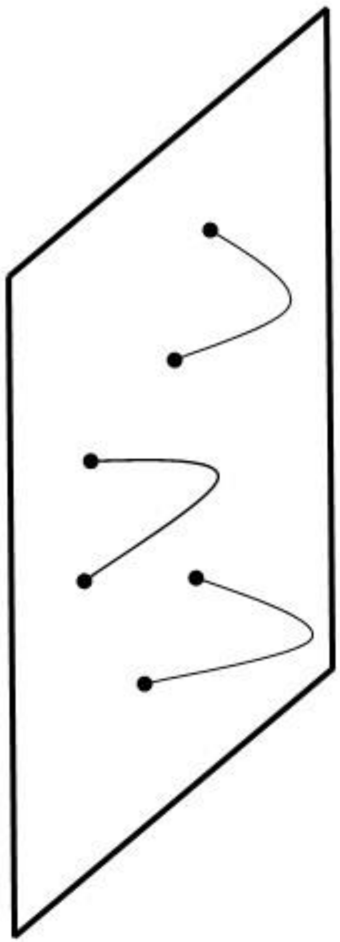
- The second term is exactly what is expected for an anti-D3-brane uplift!

- Seems to hint at a connection to D-branes

The nilpotent chiral superfield

Let us recall some facts about Dp-branes:

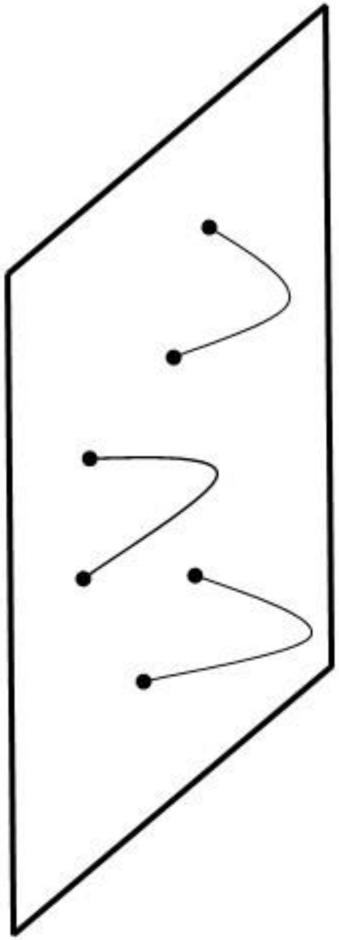


- The bosonic worldvolume fields are a vector A_μ and transverse scalars ϕ^i
- The fermionic degrees of freedoms are packaged into two 10d Majorana-Weyl spinors θ^1, θ^2
- There is a κ-symmetry that allows us to gauge away half of the fermionic degrees of freedoms

The nilpotent chiral superfield

Let us recall some facts about Dp-branes:

- The complete action for single Dp-brane in flat space is known
- The complete action for a stack of Dp-branes is not known



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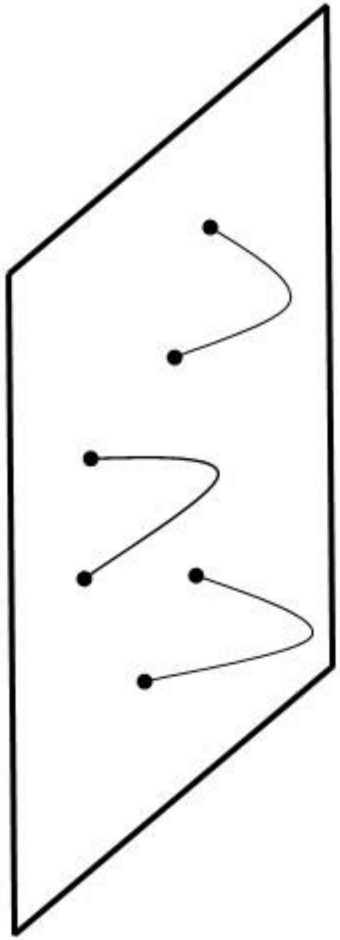
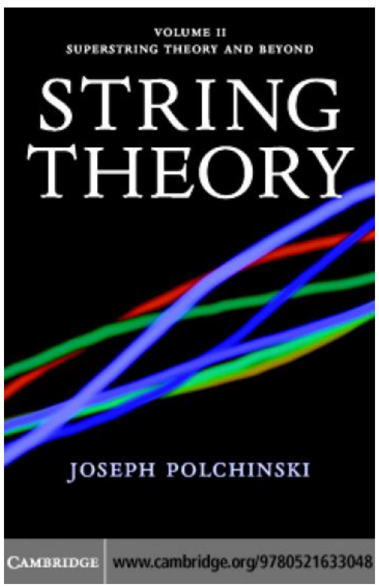
- The complete action for a stack of Dp-branes is not known
- The action of a single Dp-brane in a flux background is only known to leading (quadratic) order in fermions



The nilpotent chiral superfield

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

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



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

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

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

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Polchinski Volume 2

↕ this supersymmetry is non-linearly realized

The nilpotent chiral superfield

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Polchinski Volume 2

- The full action is essential the bosonic action except that all fields are promoted to superfields

$$S^{D3/\overline{D3}} = -\int d^4\sigma\, e^{-\phi}\sqrt{\det(-g_{\mu\nu} + \alpha' F_{\mu\nu})} \pm \int e^F C$$

$$g_{\mu\nu} = \eta_{ab}\Pi^a_\mu \Pi^b_\nu + \delta_{ij}\Pi^i_\mu \Pi^j_\nu,$$

$$\Pi^a_\mu = \delta^a_\mu - \bar{\theta}\Gamma^a \partial_\mu \theta$$

$$\Pi^i_\mu = \partial_\mu \phi^i - \bar{\theta}\Gamma^i \partial_\mu \theta$$

The nilpotent chiral superfield

- To simplify our life and make the connection to the nilpotent field fully explicit we restrict to an anti-D3-brane on top of an O3-plane in flat space
- This setup is stable at weak string coupling and the O3-plane projects out the bosonic degrees of freedoms but leaves all the fermionic degrees of freedom

Uranga hep-th/9912145

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- The O3-plane breaks explicitly 16 supercharges. These are the supercharges that are linearly realized on the anti-D3-brane so we are left with 16 non-linearly realized supercharges

The nilpotent chiral superfield

- After κ-fixing we are left with one 10d MW spinor λ
- The DBI and WZ term are in this case

$$S_{DBI} = -\int \sqrt{-g} = -\int E^0 \wedge E^1 \wedge E^2 \wedge E^3 = |S_{CS}|$$

$$\text{with } E^a = \left(\delta_\mu^a + \bar{\lambda}\Gamma^a \partial_\mu \lambda\right) dx^\mu$$

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$$\text{with } E^a = \left(\delta_\mu^a + \bar{\lambda}\Gamma^a \partial_\mu \lambda\right) dx^\mu$$

- This leads to

$$S^{D3} = 0, \qquad S^{\overline{D3}} = -2\int E^0 \wedge E^1 \wedge E^2 \wedge E^3$$

Makes sense since for a D3-brane all world volume degrees of freedom are projected out

The nilpotent chiral superfield

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- This action breaks 16 supercharges spontaneously
- These are non-linear realized $\delta_\epsilon\lambda = \epsilon + \bar{\lambda}\gamma^\mu\epsilon\partial_\mu\lambda$
- Can decompose the 16 component 10d spinor λ into four 4d spinors $\lambda^0, \lambda^i, i = 1,2,3$, where λ^0 is a singlet under transverse $SU(3)$ holonomy group and λ^i a triplet
- How do we remove the λ^i?

The nilpotent chiral superfield

- We can study the anti-D3-brane on top of an O3-plane in a GKP background with (2,1) ISD flux

Bergshoeff, Dasgupta, Kallosh, Van Proeyen, TW 1502.07627

- Such a background preserves $N = 1$ SUSY in 4d

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Bergshoeff, Dasgupta, Kallosh, Van Proeyen, TW 1502.07627

- Such a background preserves $N = 1$ SUSY in 4d
- The fermionic action is only known to quadratic order
- One finds again $S^{D3} = 0, \;\; S^{\overline{D3}} \neq 0$ and

The nilpotent chiral superfield

- We can study the anti-D3-brane on top of an O3-plane in a GKP background with (2,1) ISD flux

Bergshoeff, Dasgupta, Kallosh, Van Proeyen, TW 1502.07627

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$$S^{\overline{D3}} = T_3 e^{4A_0 - \phi_0} \Big(\bar{\lambda}_-^{\bar{0}} \gamma^\mu \nabla_\mu \lambda_+^0 + \bar{\lambda}_-^{\bar{\imath}} \gamma^\mu \nabla_\mu \lambda_+^j \delta_{i\bar{\jmath}} - \frac{i}{2\sqrt{2}} e^{\phi_0} G_{uv\bar{p}} \bar{\Omega}_{\bar{u}\bar{v}\bar{w}} \, g^{u\bar{u}} g^{v\bar{v}} \, e_{\bar{\imath}}^{\bar{p}} \, e_{\bar{\jmath}}^{\bar{w}} \, \bar{\lambda}_-^{\bar{\imath}} \lambda_-^{\bar{\jmath}} + h.c \Big)$$

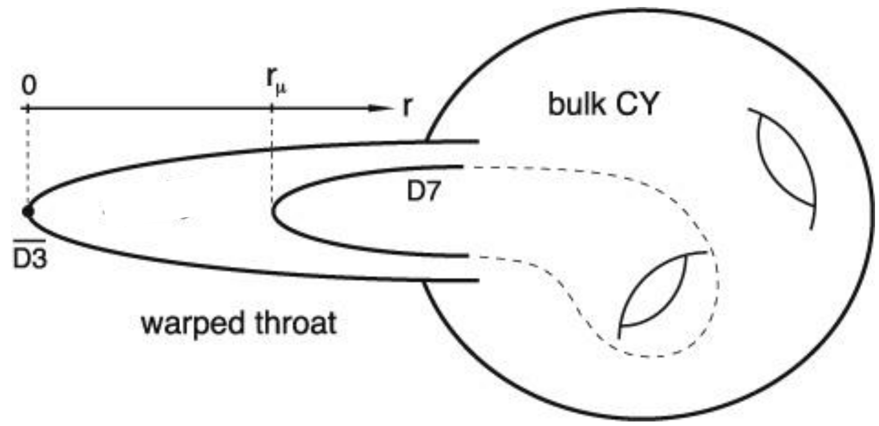
- The (2,1) flux gives a mass to the triplet λ^i

The nilpotent chiral superfield

- What about warping?

Kallosh, Quevedo, Uranga 1507.07556
García-Etxebarria, Quevedo, Valandro 1512.06926
Retolaza, Uranga 1605.01732

- In KKLT the anti-D3-brane needs to be placed at the bottom of a throat



The nilpotent chiral superfield

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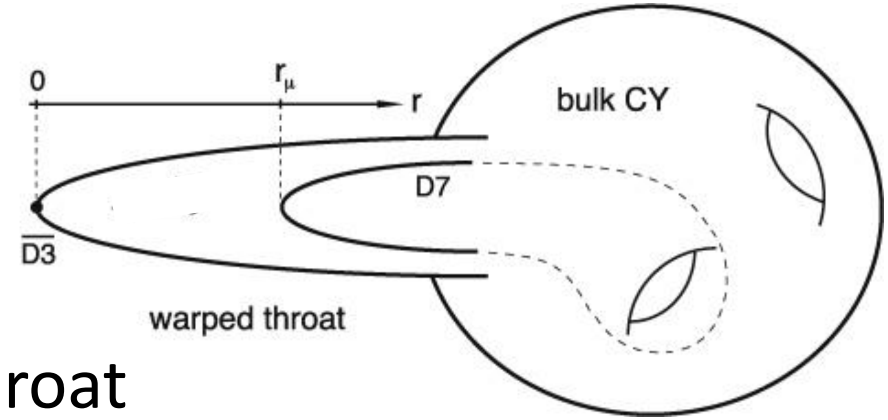

- We can have O3 planes at the bottom of the KS throat
- There are also other throats that allow for an anti-D3-brane on top of an O3-plane at the bottom of a throat

The nilpotent chiral superfield

Summary:

- We know that the action for an anti-D3-brane on top of an O3-plane in flat space is of VA type (just have extra triplet)
- This triplet gets a mass in a GKP background with (2,1) flux

The nilpotent chiral superfield

Summary:

- We know that the action for an anti-D3-brane on top of an O3-plane in flat space is of VA type (just have extra triplet)
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- The singlet is invariant under non-linear SUSY transformations $\Rightarrow$ the action is the VA action
- The setup of an $O3^-$ plane on top of an anti-D3-brane can arise at the bottom of a warped throat (including KS)

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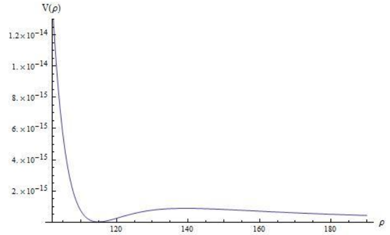
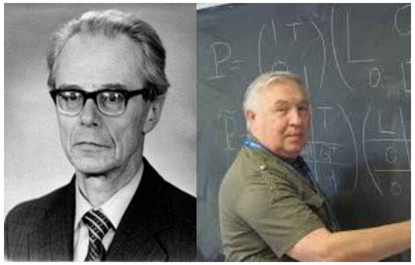
$\Rightarrow$ anti-D3-brane goldstino $\lambda^0 \Leftrightarrow S^2 = 0$ provides the uplift

Outline

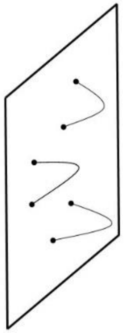
- KKLT dS vacua in string theory



- The nilpotent chiral superfield



- Constrained multiplets from D3-branes



- Conclusion

More Constrained Multiplets

- Since the anti-D3-brane breaks supersymmetry spontaneously, we should be able to package all worldvolume fields into $N = 1$ multiplets

- The worldvolume fields are

$$\lambda^0, \qquad \lambda^i, \qquad A_\mu, \qquad \phi^i, \qquad i = 1,2,3$$

$$S^2 = 0 \qquad ? \qquad ? \qquad ?$$

More Constrained Multiplets

- There are many more constrained multiplets:

Komargodski, Seiberg 0907.2441
Dall'Agata, Ferrara, Zwirner 1509.06345
Ferrara, Kallosh, Thaler 1512.00545
Dall'Agata, Farakos 1512.02158
Ferrara, Kallosh, Van Proeyen, TW 1603.02653
Dall'Agata, Dudas, Farakos 1603.03416

$$S\,Y^i = 0, \qquad S\,W_\alpha = 0, \qquad S(\Phi - \bar{\Phi}) = 0, \qquad \ldots$$

- Which ones arise from the worldvolume fields?

More Constrained Multiplets

- For an anti-D3-brane on top of an O3-plane we have four 4d fermions λ^0 and λ^i

Vercnocke, TW 1605.03961

- The anti-D3-brane action in a fixed background is

$$K = S\bar{S} + \delta_{i\bar{\imath}} Y^i \bar{Y}^{\bar{\imath}}$$
$$W = \mu^2 S + m_{ij} Y^i Y^j$$

$$\boxed{S^2 = S\, Y^i = 0}$$

with $\bar{m}_{\bar{\imath}\bar{\jmath}} \propto e^{\phi_0} G_{uv\bar{p}} \bar{\Omega}_{\bar{u}\bar{v}\bar{w}}\, g^{u\bar{u}} g^{v\bar{v}}\, e^{\bar{p}}_{\bar{\imath}}\, e^{\bar{w}}_{\bar{\jmath}}$

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More Constrained Multiplets

- Include all worldvolume fields of the anti-D3-brane

Kallosh, Vercnocke, TW 1606.xxxxx

- Worldvolume fields (after field redefinitions) transform as

$$
\begin{aligned}
\delta_\epsilon \lambda^0 &= \epsilon + \left(\bar{\lambda}^0 \gamma^\mu \epsilon\right)\partial_\mu \lambda^0 \\
\delta_\epsilon A_\mu &= \left(\bar{\lambda}^0 \gamma^\nu \epsilon\right) F_{\mu\nu} \\
\delta_\epsilon \lambda^i &= \left(\bar{\lambda}^0 \gamma^\mu \epsilon\right)\partial_\mu \lambda^i \\
\delta_\epsilon \phi^i &= \left(\bar{\lambda}^0 \gamma^\mu \epsilon\right)\partial_\mu \phi^i
\end{aligned}
$$

- These are the expected transformation

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Kallosh, Vercnocke, TW 1606.xxxxx

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$$S\, W_\alpha = S\, \overline{D}_{\dot{\alpha}} \overline{H}^{\bar{\imath}} = 0$$

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Kallosh, Vercnocke, TW 1606.xxxxx

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- Consistent with certain `truncated' D3-brane actions previously discussed in the literature

Cecotti, Ferrara Phys. Lett. B 1987

Bagger, Galperin hep-th/9608177

Bagger, Galperin hep-th/9707061

Gonzalez-Rey, Park, Rocek hep-th/9811130

Rocek, Tseytlin hep-th/9811232

Ferrara, Porrati, Sagnotti 1411.4954

Ferrara, Sagnotti 1506.05730

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Real orthogonal multiplet $S(\Phi - \bar{\Phi}) = 0$

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- A nilpotent chiral multiplet has started to play an interesting role in cosmological model building
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Conclusion

- A nilpotent chiral multiplet has started to play an interesting role in cosmological model building
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THANK YOU!

dS vacua in string theory

Side note:

- This anti-D3-brane uplift has been heavily debated in the last several years
- In the supergravity limit, where one uses many anti-D3-branes ($g_s\, p \gg 1$) there seem to be issues
- The case of a single anti-D3-brane works equally well as uplift and seems to be fine

$\Rightarrow$ Polchinski 1509.05710 and references therein

dS vacua in string theory

<u>Side note 2:</u>

- We do not need an anti-D3-brane uplift in order to get KKLT and LVS dS vacua

- One simple uplift alternative is a non-zero F^i in the complex structure direction

Silverstein, Saltmann hep-th/0402135

Kallosh, Linde, Vercnocke, TW 1406.4866

Marsh, Vercnocke, TW 1411.6625

Gallego, Marsh, Vercnocke, TW to appear