Constrained Superfields in Supergravity and String Theory

Timm Wrase

Florence September 8th, 2016

Based on:

R. Kallosh, B. Vercnocke, TW 1606.09245
B. Vercnocke, TW 1605.03961
E. Bergshoeff, K. Dasgupta, R. Kallosh, A. Van Proeyen, TW 1502.07627
R. Kallosh, TW 1411.1121

PHYSICAL REVIEW D VOLUME 13, NUMBER 12 15 JUNE 1976

Progress toward a theory of supergravity*

Daniel Z. Freedman and P. van Nieuwenhuizen
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

S. Ferrara
Laboratoire de Physique Thêorique de l'Ecole Normale Supêrieure, 24 rue Lhomond, 75231 Paris Cedex 05, Franc

(Received 29 March 1976)

As a new approach to supergravity, an action containing only vierbein and Rarita-Schwinger fields ($V_{a\mu}$ and ψ_μ) is presented together with supersymmetry transformations for these fields. The action is explicitly shown to be invariant except for a ψ^5 term in its variation. This term may also vanish, depending on a complicated calculation. (Added note: This term has now been shown to vanish by a computer calculation, so that the action presented here does possess full local supersymmetry.)

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Focus week: “Supergravity, the next 10 years”

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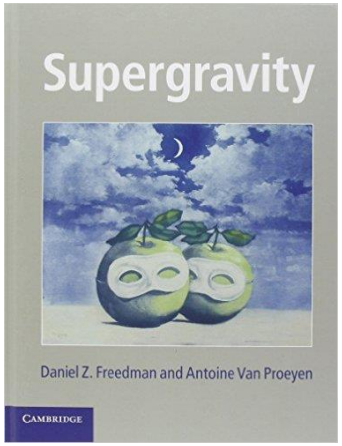
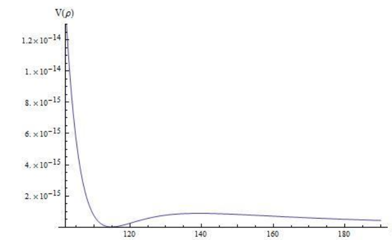
Focus week: "Supergravity, the next 10 years"

"Supergravity, together with string theory, is one of the most significant developments in theoretical physics."

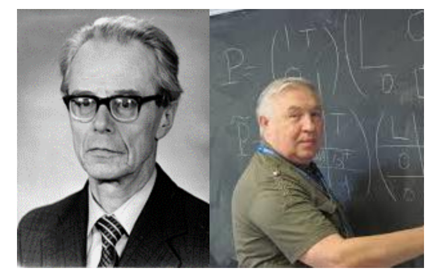


Outline

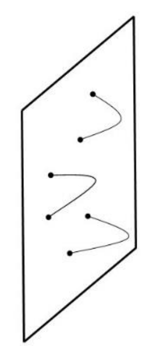
- KKLT dS vacua in string theory



- The nilpotent chiral superfield
  - The Volkov-Akulov theory
  - The nilpotent chiral superfield in supergravity
  - The nilpotent chiral superfield in string theory



- Constrained multiplets from D3-branes



- Conclusion

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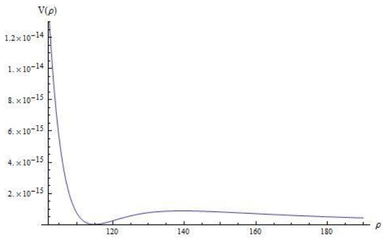

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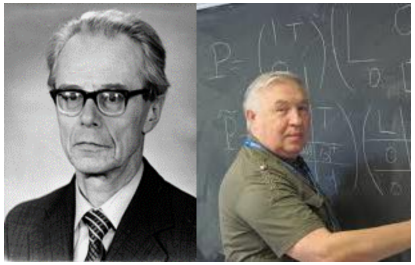

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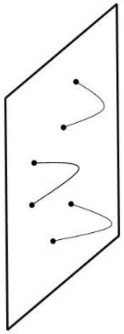
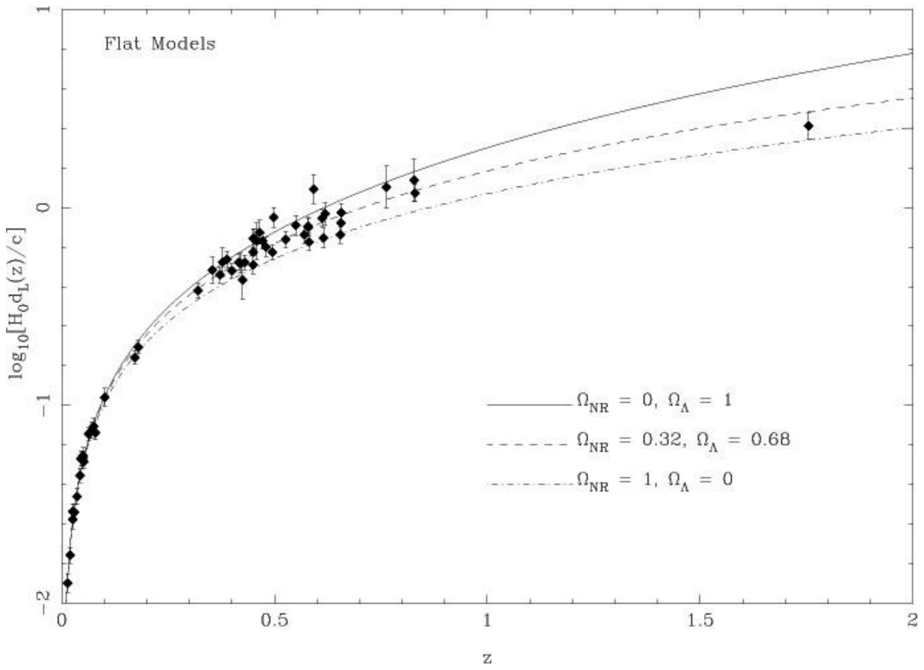


- Conclusion

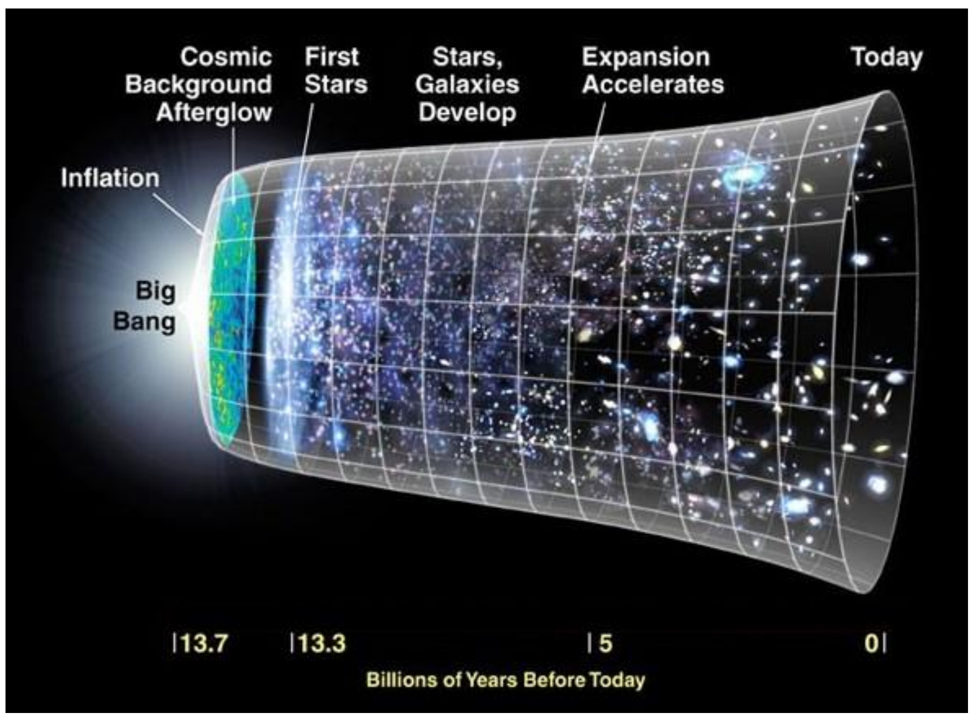
Accelerated expansion of our universe

In 1998 the Supernova Cosmology Project and the High-Z Supernova Search Team observed type Ia supernovae and found evidence for an accelerated expansion of our universe



Accelerated expansion of our universe

This discovery lead to the 2011 Nobel Prize for
Saul Perlmutter, Adam Riess and Brian Schmidt
and the following picture of our universe



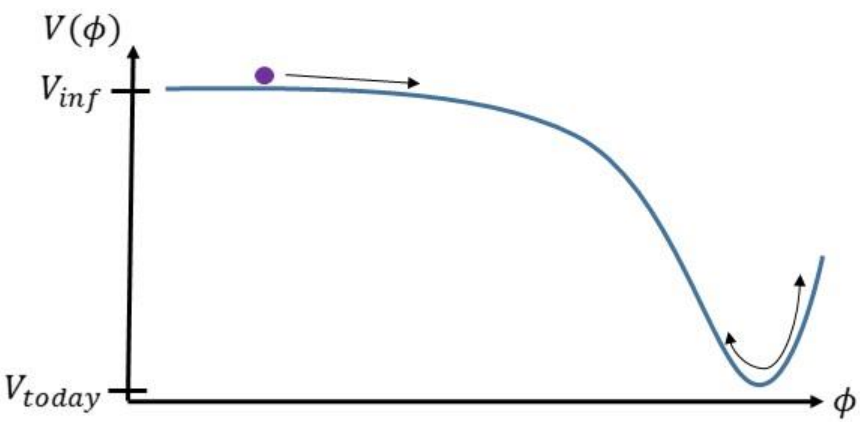
Accelerated expansion of our universe

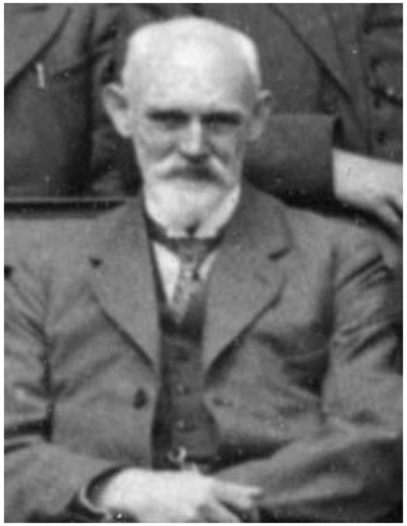
The tremendous amount observational progress in the last decade has led to very stringent bounds. Combining results from the Planck Satellite with other astrophysical data leads to

Planck Collaboration 1502.01589

$$w = -1.006 \pm .045$$

dS vacua /Λ: $w = -1$





dS vacua in string theory

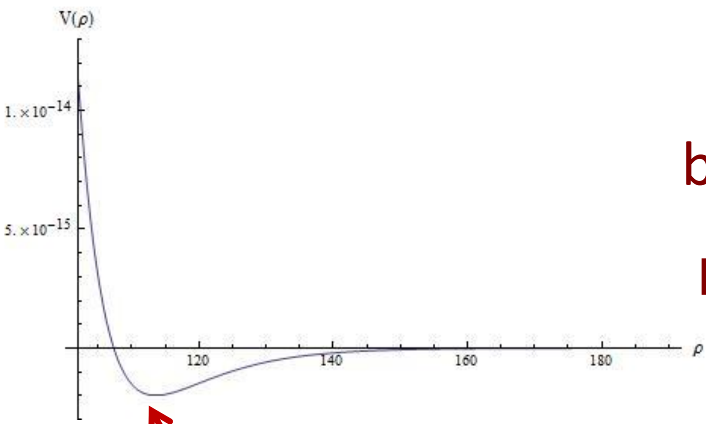
- The first dS vacua in string theory were constructed over a decade ago

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

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

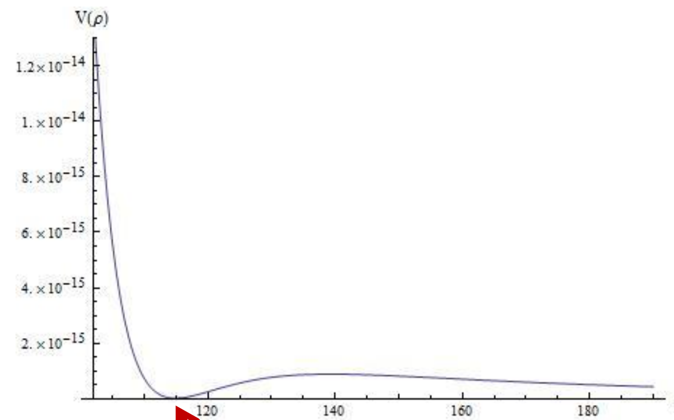
Conlon, Quevedo, Suruliz   hep-th/0505076

- 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 the 4D $N = 1$ SUSY:

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

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

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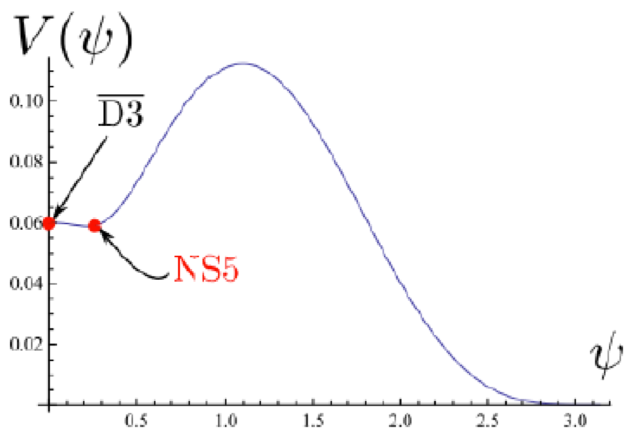
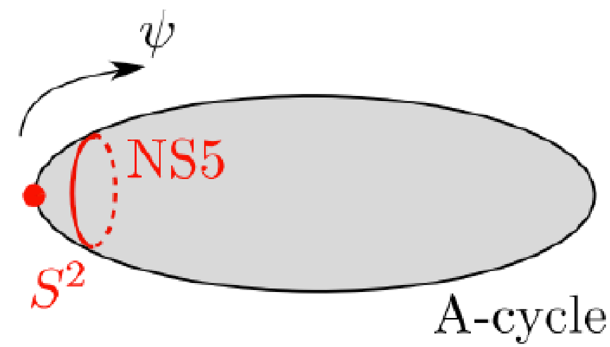
- Can we package the uplift term into K and W or a D-term?

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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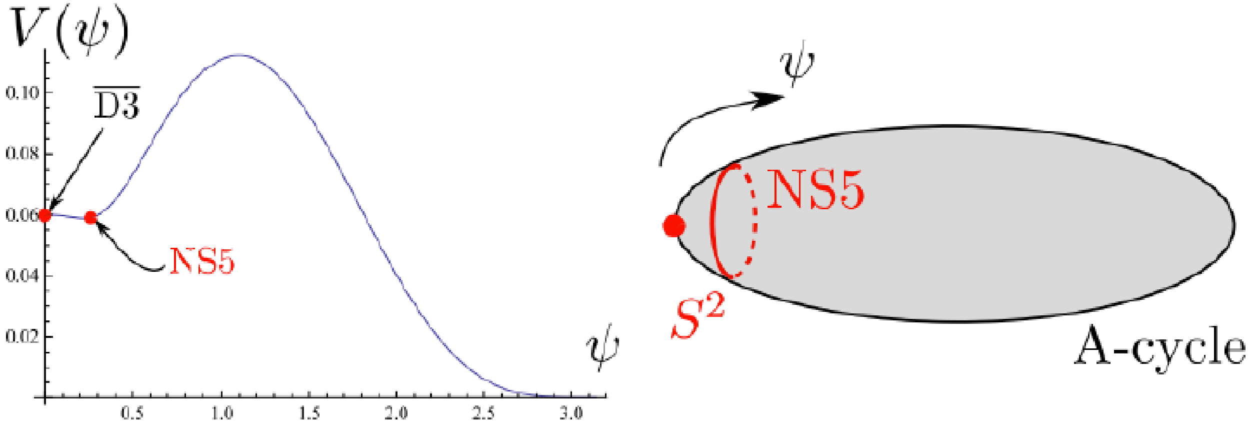

- How can we describe the uplift term in terms of W and K or as an D-term?

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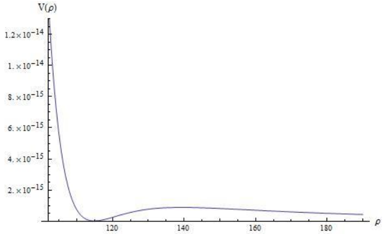

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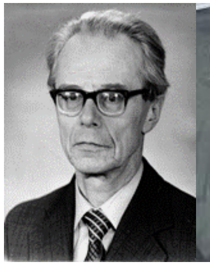

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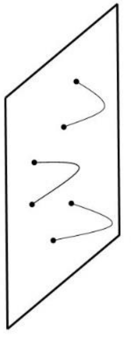

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The nilpotent chiral superfield

- <u>SUSY 101:</u> supersymmetry relates bosons and fermions

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Not necessarily!

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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

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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!

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- Is the neutrino a goldstone particle? No, but interesting!

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

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

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

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- 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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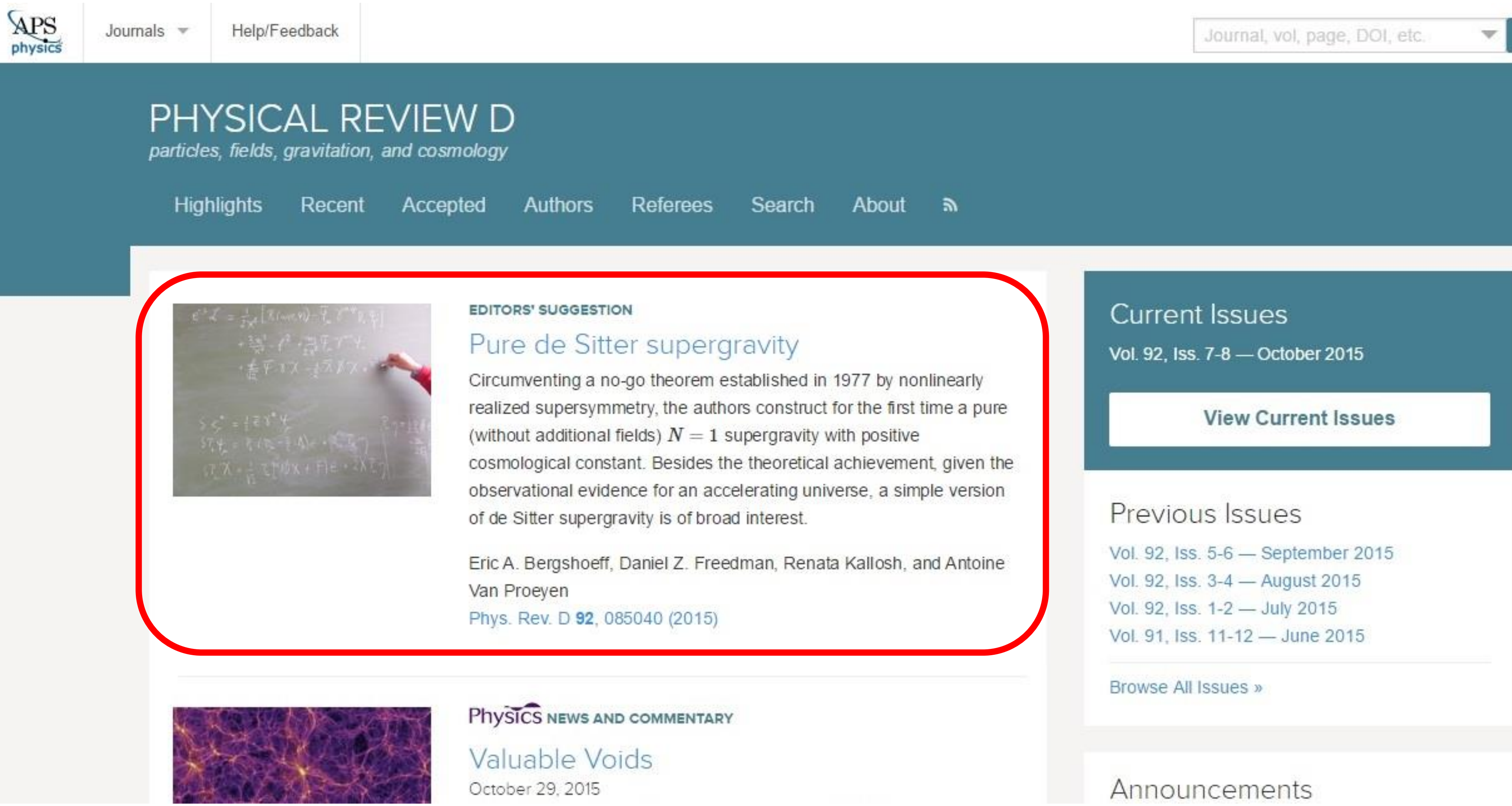
- χ is the Goldstino and gets eaten by the gravitino

The nilpotent chiral superfield

- The fermionic part of the action is pretty complicated
- Constrained multiplets in local supersymmetry are different from global supersymmetry ⇒ lots of checks needed

Bergshoeff, Freedman, Kallosh, Van Proeyen 1507.08264
Hasegawa, Yamada 1507.08619
Dudas, Ferrara, Kehagias, Sagnotti 1507.07842
Ferrara, Porrati, Sagnotti 1508.02939
Antoniadis, Markou 1508.06767
Kuzenko 1508.03190
Kallosh 1509.02136
Kallosh, TW 1509.02137
Dall'Agata, Ferrara, Zwirner 1509.06345
Schillo, Van der Woerd, TW 1511.01542
Bandos, Martucci, Sorokin, Tonin 1511.03024
Kallosh, Karlsson, Murli 1511.07547
Ferrara, Kallosh, Thaler 1512.00545
Dall'Agata, Farakos 1512.02158
Ferrara, Kallosh, Van Proeyen, TW 1603.02653
Dall'Agata, Dudas, Farakos 1603.03416
Cribiori, Dall'Agata, Farakos 1607.01277
Bandos, Heller, Kuzenko, Martucci, Sorokin 1608.05908

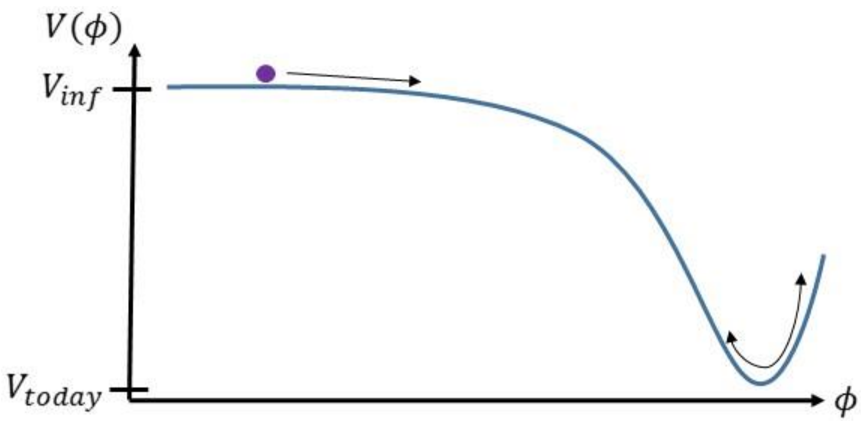
The nilpotent chiral superfield



The nilpotent chiral superfield

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

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
Scalisi	1607.01030
McDonough, Scalisi	1609.00364



The nilpotent chiral superfield

- Couple the nilpotent chiral superfield to a regular chiral multiplet Φ

$$K = -\frac{1}{2}(\Phi - \bar{\Phi})^2 + s\,\bar{s}$$
$$W = s\,f(\Phi)$$

- The bosonic action is obtained as usual with the additional simplification that $s = \bar{s} = 0$

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- Inflation ends in a SUSY Minkowski vacuum

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$$W = \left(1 + \left(\sqrt{3} + \lambda\right) s\right) f(\Phi)$$

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$$V = e^K\left(K^{s\bar{s}} D_s W \overline{D_s W} + K^{\Phi\bar{\Phi}} D_\Phi W \overline{D_\Phi W} - 3|W|^2\right)$$

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- $f(0)$ controls SUSY breaking, λ controls the cc

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- Most generic $W = g(\Phi) + s\, f(\Phi)$

The nilpotent chiral superfield

- Let us couple such a model to matter fields U^i

Kallosh, Linde, TW 1602.07818

$$K = k(\Phi, \overline{\Phi}) + s\,\bar{s} + \sum U^i \overline{U}^{\bar{\imath}}$$
$$W = g(\Phi) + s\,f(\Phi) + A_{ij} U^i U^j + B_{ijk}(s, \Phi) U^i U^j U^k + \cdots$$

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- At this point the matter sector does not affect the inflationary sector at all

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Kallosh, Linde, TW 1602.07818

$$K = k(\Phi, \bar{\Phi}) + s\,\bar{s} + \sum U^i \bar{U}^{\bar{\imath}}$$
$$W = g(\Phi) + s\,f(\Phi) + A_{ij} U^i U^j + B_{ijk}(s, \Phi) U^i U^j U^k + \cdots$$

- There is a critical point at $U^i = 0$

- At this point the matter sector does not affect the inflationary sector at all

- All matter fields have a positive mass, if $\partial_\Phi k = 0$ during inflation: $\mu_i^2 = V + \frac{3}{4}|g(\Phi)|^2 + \left|\lambda_i \pm \frac{1}{2} g(\Phi)\right|^2 > 0$

Eigenvalues of A_{ij}

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

Retolaza, Uranga 1605.01732

Vercnocke, TW 1605.03961

Kallosh, Vercnocke, TW 1606.09245

Bandos, Heller, Kuzenko, Martucci, Sorokin 1608.05908

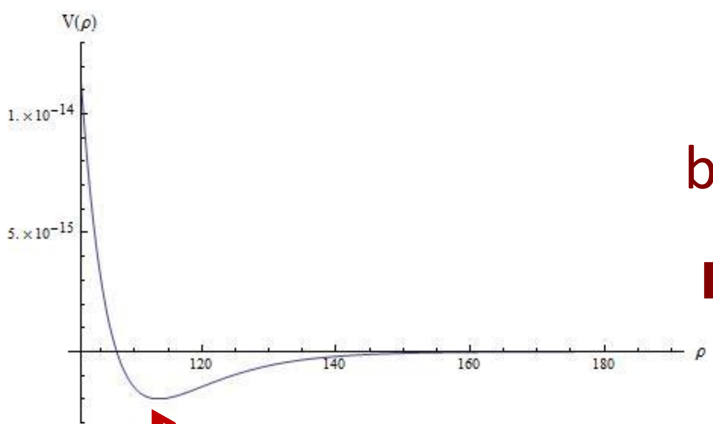
dS vacua in string theory

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

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

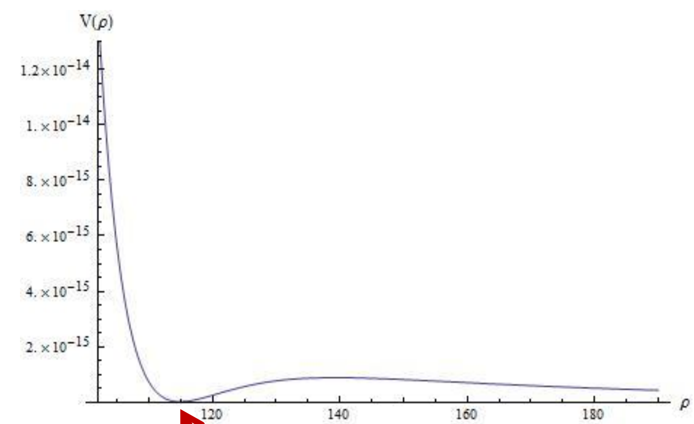
Conlon, Quevedo, Suruliz hep-th/0505076

dS vacua construction are often 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 the 4D $N = 1$ SUSY:

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

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

- How do we package the uplift term into K and W or a D-term?

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

$$K = -3\ln(T + \bar{T} - s\bar{s})$$
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$$V = V_{KKLT} + \frac{\mu^4}{3(T + \bar{T})^2}$$

- The second term is exactly what is expected for an anti-D3-brane uplift!
- Seems to hint at a connection to D-branes

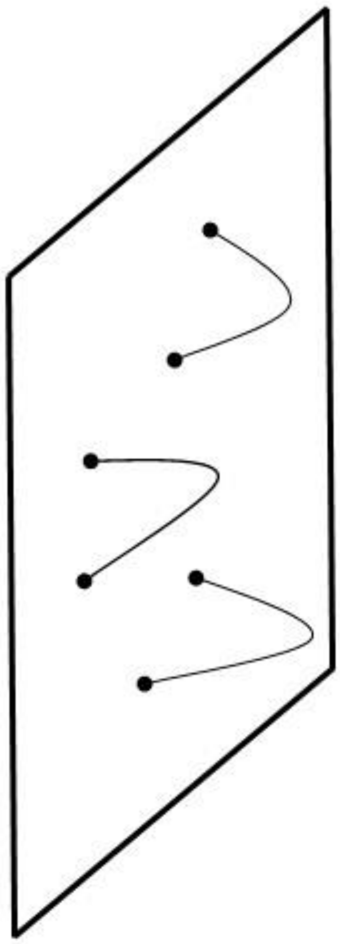
The nilpotent chiral superfield

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

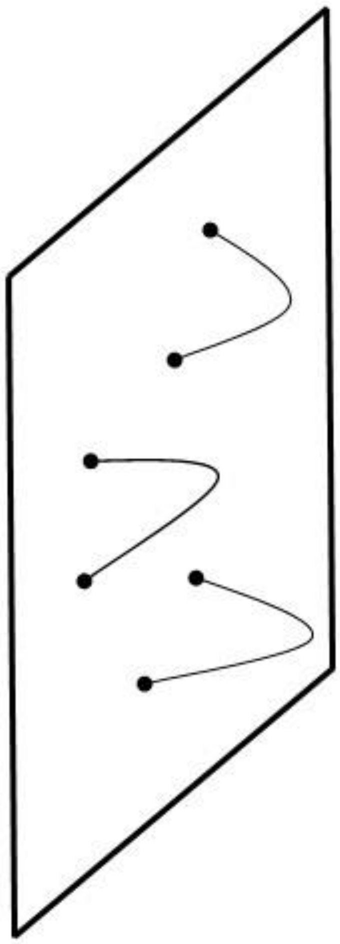
- There is a κ-symmetry that allows us to gauge away half of the fermionic degrees of freedoms



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



The nilpotent chiral superfield

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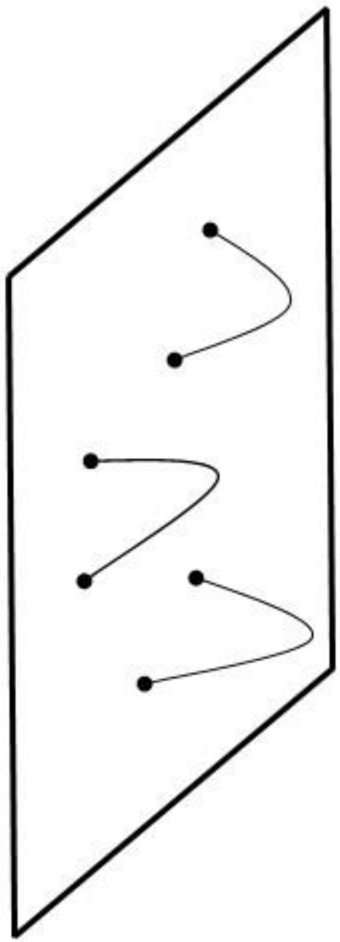
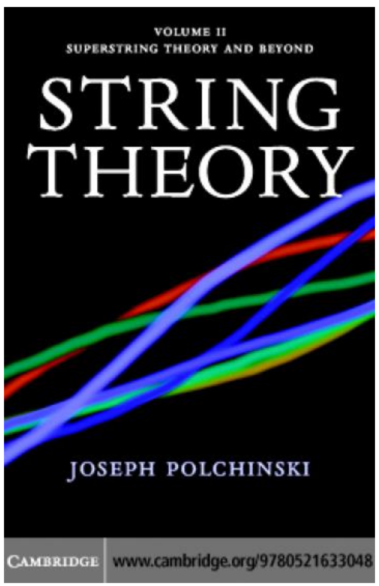
- The complete action for single Dp-brane in flat space is known
- The complete action for a stack of Dp-branes is not known
- The action of a single Dp-brane in a flux background is only known to leading (quadratic) order in fermions



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-

The nilpotent chiral superfield

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Polchinski Volume 2

this supersymmetry is
non-linearly realized

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

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

The nilpotent chiral superfield

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  Uranga hep-th/9912145
- 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

- It was known that the DBI action for D-branes in a flat background and neglecting bosons is of the VA-type

Kallosh 1997

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

where $E^a = \left(\delta_\mu^a + \bar{\theta}^1 \Gamma^a \partial_\mu \theta^1\right) dx^\mu$ and $\theta^2 = 0$

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- In the same gauge one finds

Aganagic, Popescu, Schwarz hep-th/9610249

$$S_{CS} = 0$$

- Connection to the nilpotent field but no difference between D3 and anti-D3 ↔ contrary to KKLT construction

The nilpotent chiral superfield

- The gauge choice $\theta^2 = 0$ is not compatible with an orientifold projection: $\theta^1 = \Gamma_{0123}\theta^2$

The nilpotent chiral superfield

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- In a gauge fixing that is compatible with the O3 orientifold projection one finds

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

The nilpotent chiral superfield

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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

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

The nilpotent chiral superfield

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

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

- This action breaks 16 supercharges spontaneously
- These are non-linear realized $\delta_\epsilon\lambda = \epsilon + \bar{\lambda}\gamma^\mu\epsilon\partial_\mu\lambda$

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

The nilpotent chiral superfield

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- The fermionic action is only known to quadratic order
- One finds again $S^{D3} = 0$, $S^{\overline{D3}} \neq 0$ and

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

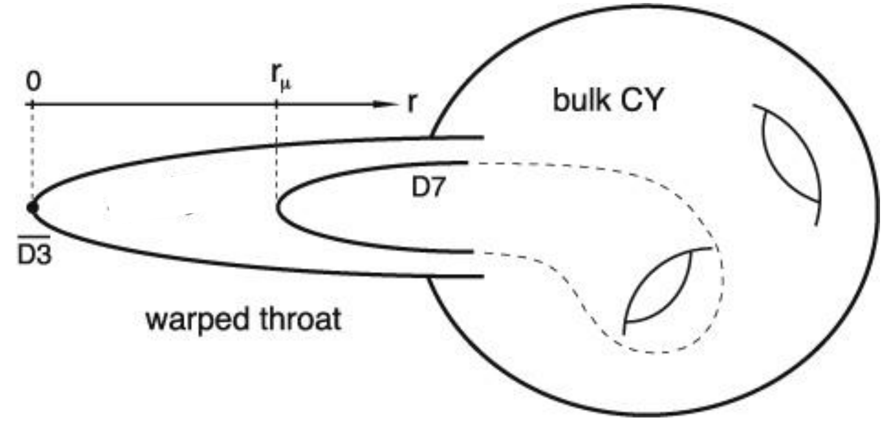
- The (2,1) flux gives a mass to the triplet λ^i

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



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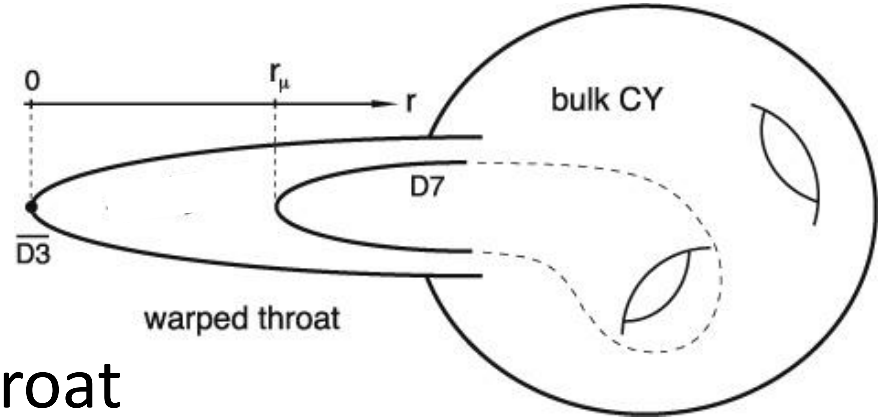

- We can have O3 planes at the bottom of the KS throat

- 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)
- This triplet gets a mass in a GKP background with (2,1) flux
- 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)

The nilpotent chiral superfield

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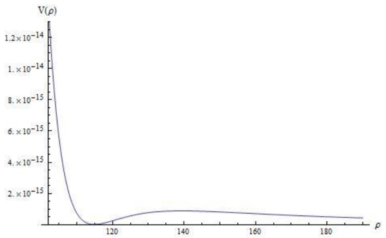
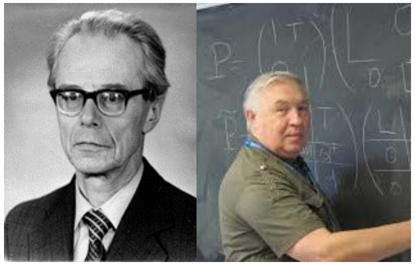
$\Rightarrow$ anti-D3-brane goldstino $\lambda^0 \Leftrightarrow S^2 = 0$ provides the uplift

Outline

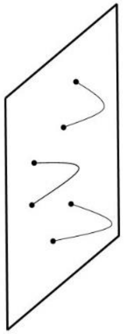
- KKLT dS vacua in string theory



- The nilpotent chiral superfield
  - The Volkov-Akulov theory
  - The nilpotent chiral superfield in supergravity
  - The nilpotent chiral superfield in string theory



- 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 anti-D3-brane 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
Kallosh, Karlsson, Mosk, Murli 1603.02661
Dall'Agata, Dudas, Farakos 1603.03416

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

- 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

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

$$S^2 = S\, Y^i = 0$$

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 1606.09245

- 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 under non-linear supersymmetry

More Constrained Multiplets

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Kallosh, Vercnocke, TW 1606.09245

- Vector field A_μ and scalars ϕ^i can be package into

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

More Constrained Multiplets

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

Kallosh, Vercnocke, TW   1606.09245

- Vector field A_μ and scalars ϕ^i can be package into

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

Conclusion

- A nilpotent chiral multiplet has started to play an interesting role in cosmological model building
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- There are actually many more constraint multiplets that arise from D-branes that spontaneously break SUSY:

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- 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

<u>Side note:</u>

- 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

Side note 2:

- 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