New D-term uplift

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Supersymmetry

$\rightarrow$ Motivated from BSM physics.

$\rightarrow$ Motivated from UV complete theories.

BUT

$\rightarrow$ SUSY is (spontaneously) broken on de Sitter vacuum.

How is N=1 SUSY broken?

$\rightarrow$ F-term (chiral multiplet).

$\rightarrow$ D-term ($U(1)$ gauge multiplet).

$\rightarrow$ Other methods (complex linear, etc).

Fayet–Iliopoulos D-term

→ A gauge multiplet contains the component fields

$$V_{\rm WZ} = -\theta\sigma^m\overline{\theta}A_m - i\overline{\theta}^2\theta^\alpha\lambda_\alpha + i\theta^2\overline{\theta}_{\dot\alpha}\overline{\lambda}^{\dot\alpha} + \frac{1}{2}\theta^2\overline{\theta}^2 \mathrm{D}\,.$$

→ The simplest model with a Fayet–Iliopoulos term is

$$\mathcal{L} = \frac{1}{4}\left(\int d^2\theta\, W^2(V) + c.c.\right) - 2\xi\int d^4\theta\, V$$

$$= -\frac{1}{4}F^{mn}F_{mn} - i\lambda\sigma^m\partial_m\overline{\lambda} + \frac{1}{2}\mathrm{D}^2 - \xi\,\mathrm{D}\,.$$

Fayet, Iliopoulos ’74

Supersymmetry is broken spontaneously

$\rightarrow$ The auxiliary field gets a vev: $\langle \mathrm{D} \rangle = \xi$.

$\rightarrow$ The goldstino is: $\delta\lambda_\beta = -i\xi\,\epsilon_\beta + \cdots$

$\rightarrow$ The vacuum energy is: $\langle V \rangle = \frac{1}{2}\xi^2$.

How do we couple to supergravity?

Plan

$\rightarrow$ Freedman model and R-symmetry gauging.

$\rightarrow$ New model without R-symmetry gauging.

$\rightarrow$ Properties of the new D-term.

The Freedman model

The Noether method

- The gauge field of SUSY is the gravitino ψ_m^α, with supersymmetry transformation

$$\delta\psi_{m\alpha} = -2\,\partial_m \epsilon_\alpha + \cdots$$

- We start from $-e\,\xi\,\mathrm{D}$ and perform the Noether procedure

$$\partial_m\,\epsilon_\alpha(x) \to \psi_{m\alpha}\,.$$

- At some point we have to cancel

$$-ie\xi\,\epsilon^{klmn}\left(\overline{\psi}_k\overline{\sigma}_l\epsilon - \overline{\epsilon}\,\overline{\sigma}_l\psi_k\right)\partial_n A_m\,.$$

- Therefore we have to add

$$\mathcal{L}_{\psi\psi A} = \frac{i}{2} e\, \xi\, \epsilon^{klmn} \overline{\psi}_k \overline{\sigma}_l \psi_n A_m \,.$$

- This means that the gravitino is charged under the $U(1)$.

  → The FI term in supergravity requires R-symmetry gauging by A_m.

  → This has impact on model building. (Constraints on the gravitino mass.) *Barbieri, Ferrara, Nanopoulos, Stelle '82, Villadoro, Zwirner '05*

The complete model

Freedman '77

- Once we complete the procedure we have (on-shell)

$$e^{-1}\mathcal{L}\Big|_{\lambda=0} = -\frac{1}{2}R + \frac{1}{2}\epsilon^{klmn}\left(\overline{\psi}_k\overline{\sigma}_l\mathcal{D}_m\psi_n - \psi_k\sigma_l\mathcal{D}_m\overline{\psi}_n\right) - \frac{1}{4}F_{mn}F^{mn} + \frac{i}{2}e\xi\epsilon^{klmn}\overline{\psi}_k\overline{\sigma}_l\psi_n A_m - \frac{1}{2}\xi^2 \,.$$

- In superspace this would read

$$\mathcal{L} = -3\int d^4\theta\, E\, e^{\frac{2}{3}\xi V} + \frac{1}{4}\left(\int d^2\Theta\, 2\mathcal{E}\, W^2(V) + c.c.\right) \,.$$

A new supergravity embedding

Cribiori, Tournoy, FF, Van Proeyen '17

- We observe that $\lambda_\alpha/\mathrm{D}$ has a very nice property

$$\delta\left(i\frac{\lambda_\alpha}{\mathrm{D}}\right) = \epsilon_\alpha + \cdots$$

- To cancel the term

$$-ie\xi\,\epsilon^{klmn}\left(\overline{\psi}_k\overline{\sigma}_l\epsilon - \overline{\epsilon}\,\overline{\sigma}_l\psi_k\right)\partial_n A_m$$

during the Noether procedure, we introduce instead the term

$$-e\xi\,\epsilon^{klmn}\left(\overline{\psi}_k\overline{\sigma}_l\frac{\lambda}{\mathrm{D}} - \frac{\overline{\lambda}}{\mathrm{D}}\,\overline{\sigma}_l\psi_k\right)\partial_n A_m\,.$$

Supersymmetry has to be broken and by assumption: $\langle \mathrm{D}\rangle \neq 0$.

A new FI D-term

- In superspace the full $U(1)$ sector is

$$\mathcal{L}_{NEW} = \frac{1}{4}\left(\int d^2\Theta\, 2\mathcal{E}\, W^2(V) + c.c.\right)$$
$$+8\,\xi \int d^4\theta\, E\, \frac{W^2\overline{W}^2}{\mathcal{D}^2 W^2 \overline{\mathcal{D}}^2 \overline{W}^2}\, \mathcal{D}^\alpha W_\alpha\,.$$

- And in components

$$e^{-1}\mathcal{L}_{NEW} = -\frac{1}{4}F_{mn}F^{mn} - i\overline{\lambda}\overline{\sigma}^m \mathcal{D}_m \lambda + \frac{1}{2}\mathrm{D}^2$$
$$-\xi \mathrm{D} + \xi\, \mathcal{O}(\lambda, \overline{\lambda})\,.$$

- The gravitino is not charged under the U(1).

The new term coupled to pure supergravity

- In superspace the coupling is

$$\mathcal{L} = -3\left(\int d^2\Theta\, 2\mathcal{E}\,\mathcal{R} + c.c.\right) + \left(\int d^2\Theta\, 2\mathcal{E}\, W_0 + c.c.\right)$$
$$+\mathcal{L}_{NEW}\,.$$

- And in components (on-shell)

$$\begin{aligned} e^{-1}\mathcal{L}\Big|_{\lambda=0} = & -\frac{1}{2}R + \frac{1}{2}\epsilon^{klmn}\left(\overline{\psi}_k\overline{\sigma}_l\mathcal{D}_m\psi_n - \psi_k\sigma_l\mathcal{D}_m\overline{\psi}_n\right) \\ & -\frac{1}{4}F_{mn}F^{mn} - \left(\frac{1}{2}\xi^2 - 3|W_0|^2\right) \\ & -\overline{W}_0\psi_a\sigma^{ab}\psi_b - W_0\overline{\psi}_a\overline{\sigma}^{ab}\overline{\psi}_b\,. \end{aligned}$$

New D-terms

- $\rightarrow$ No R-symmetry gauging.
- $\rightarrow$ Arbitrary gravitino mass.
- $\rightarrow$ No smooth supersymmetric limit.
- $\rightarrow$ Cosmological constant: $\frac{1}{2}\xi^2 - 3|m_{3/2}|^2$.
- $\rightarrow$ Electric-magnetic duality of the full theory:

$$F_{mn} \rightarrow \epsilon_{mnkl} F^{kl} \; .$$

Introducing matter

- Chiral superfields

$$\Phi^I = A^I + \sqrt{2}\Theta\chi^I + \Theta^2 F^I \,.$$

- The coupling to standard supergravity reads

$$\mathcal{L}_{K,W} = \int d^2\Theta\, 2\mathcal{E}\left[\frac{3}{8}(\overline{\mathcal{D}}^2 - 8\mathcal{R})e^{-\frac{1}{3}K(\Phi^i,\overline{\Phi}^i)} + W(\Phi^i)\right] + c.c.$$

- In component form (the bosonic sector) reads

$$\begin{aligned} e^{-1}\mathcal{L}_{K,W} =& -\frac{1}{2}R - K_{i\bar{j}}\,\partial A^i \partial \overline{A}^{\bar{j}} \\ & - e^K\left[(K^{-1})^{i\bar{j}}(W_i + K_i W)(\overline{W}_{\bar{j}} + K_{\bar{j}}\overline{W}) - 3W\overline{W}\right]. \end{aligned}$$

Adding the new D-term

- For

$$\mathcal{L} = \mathcal{L}_{K,W} + \mathcal{L}_{NEW}$$

- Then the scalar potential is

$$\mathcal{V} = \mathcal{V}_{\substack{\text{Standard}\\ \text{SUGRA}}} + \frac{\xi^2}{2} e^{2K/3} .$$

- There is generically a positive definite uplift.
- For constant ξ Kähler invariance is broken.
- SUSY is off-shell linearly realized.

Outlook

- $\rightarrow$ New embedding of the FI term in supergravity.
- $\rightarrow$ Is there more unknown new supergravity embeddings?
- $\rightarrow$ Applications to inflation/cosmology? *Aldabergenov, Ketov, '17, Antoniadis, Chatrabhuti, Isono, Knoops '18*
- $\rightarrow$ Relation to string theory / brane origin ?

A KKLT-type uplift!

→ For

$$K = -3\ln(T+\overline{T})\,,\ W = W(T)\,,$$

we find

$$\mathcal{V} = \mathcal{V}_{\substack{\text{Standard}\\\text{SUGRA}}} + \frac{\xi^2}{2}\frac{1}{(T+\overline{T})^2}\,.$$

→ This uplift usually constructed in SUGRA with non-linear local SUSY realization. *Ferrara, Kallosh, Linde '14, Kallosh, Wrase '14, Bandos, Heller, Kuzenko, Martucci, Sorokin '16*

→ Here this construction is straightforward and achieved without introducing non-linear realizations off-shell.

Thank you