From Linear to Non-Linear SUSY and Back Again

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HEP 2017, Ioannina

→ Supersymmetry is spontaneously broken.

→ It is described by non-linear realizations.

→ This can be done with constrained superfields.

Applications

$\rightarrow$ Low energy theories. *Brignole, Feruglio, Zwirner '97, Antoniadis, Dudas, Ghilencea, Tziveloglou '10, Goodsell, Tziveloglou '14*

$\rightarrow$ Effective models for inflation. *Antoniadis, Dudas, Ferrara, Sagnotti '14, Ferrara, Kallosh, Linde '14, Dall'Agata, Zwirner '14, Dall'Agata, FF '15*

$\rightarrow$ Current dS phase of our universe. *Dudas, Ferrara, Kehagias, Sagnotti '15, Bergshoeff, Freedman, Kallosh, Van Proeyen '15, Hasegawa, Yamada '15, Cribiori, Dall'Agata, FF, Porrati '16*

$\rightarrow$ How to describe the SUSY breaking sector?

$\rightarrow$ How to describe matter?

$\rightarrow$ Is the description general?

SUSY breaking sector

F-term breaking

- Break SUSY with a chiral superfield ($\overline{D}_{\dot{\alpha}} X = 0$)

$$X = A + \sqrt{2}\,\theta^\alpha G_\alpha + \theta^\alpha \theta_\alpha F.$$

- When SUSY is broken:
  - $\langle F \rangle \neq 0$.
  - Goldstino: $\delta G_\alpha = -f\,\epsilon_\alpha + \cdots$
  - The scalar A is generically massive.

Nilpotent goldstino superfield

Rocek '78, Lindstrom, Rocek '79, Casalbuoni, De Curtis, Dominici, Feruglio, Gatto '89

- In the low energy the scalar can be removed from the spectrum by imposing

$$X^2 = 0 \quad \rightarrow \quad A^2 + 2\sqrt{2}\theta(AG) + 2\,\theta^2(2AF - G^2) = 0$$
$$\rightarrow \quad A = \frac{G^2}{2F}.$$

- This is equivalent to decoupling A.
- The superfield X now is

$$X = \frac{G^2}{2F} + \sqrt{2}\,\theta^\alpha G_\alpha + \theta^\alpha\theta_\alpha F.$$

Volkov–Akulov from X

- The simplest supersymmetric Lagrangian is

$$\mathcal{L} = \int d^4\theta X\overline{X} + \left\{ \int d^2\theta \, f \, X + c.c. \right\} .$$

- In component form (after eliminating F) we get

$$\mathcal{L} = -f^2 + i\partial_m \overline{G}\overline{\sigma}^m G + \frac{1}{4f^2}\overline{G}^2\partial^2 G^2 - \frac{1}{16f^6} G^2\overline{G}^2\partial^2 G^2 \partial^2 \overline{G}^2 .$$

Komargodski, Seiberg '09

- Fermion D.O.F. $\neq$ Boson D.O.F.
- $\delta G_\alpha = -f\epsilon_\alpha - (i/2f)\sigma^m_{\alpha\dot{\alpha}}\overline{\epsilon}^{\dot{\alpha}}\partial_m G^2 + \cdots$

Matter sector

→ Matter fields reside in superfields.

→ In the low energy some fields are heavy and decouple.

→ This is described by constraints on matter superfields.

Removing scalars

Brignole, Feruglio, Zwirner '97

- We have another chiral superfield ($\overline{D}_{\dot{\alpha}} Y = 0$)

$$Y = y + \sqrt{2}\theta\chi^y + \theta^2 F^y.$$

- We can have

$$X\,Y = 0.$$

- This gives

$$y = \frac{G\,\chi^y}{F} - \frac{G^2}{2F^2} F^y.$$

Keeping only scalars

Komargodski, Seiberg '09

- We have another chiral superfield ($\overline{D}_{\dot{\alpha}} H = 0$)

$$H = h + \sqrt{2}\theta\chi^H + \theta^2 F^H.$$

- We can have

$$\overline{X} D_\alpha H = 0.$$

- This gives

$$\psi^H = \sqrt{2} i\, \sigma^m \left(\frac{\overline{G}}{\overline{F}}\right) \partial_m h\,,$$

$$F^H = \left(\frac{\overline{G}^2}{2\overline{F}^2}\partial^2 h - \partial_n \left(\frac{\overline{G}}{\overline{F}}\right) \overline{\sigma}^m \sigma^n \frac{\overline{G}}{\overline{F}} \partial_m h\right).$$

Removing any selected component

Dall'Agata, Dudas, FF '16

- For a generic superfield

$$Q = q + \theta\chi^q + \cdots$$

- We propose the (irreducible) constraint

$$X\overline{X}\,Q = 0.$$

- This removes only the lowest component

$$q = \frac{G\,\chi^q}{\sqrt{2}F} + \cdots$$

From irreducible constraints

$\rightarrow$ All known constraints are explained.

$\rightarrow$ We can build new constrained superfields.

$\rightarrow$ This corresponds to formal decoupling of eliminated fields.

Is this description general?

Formal sgoldstino decoupling

Casalbuoni, De Curtis, Dominici, Feruglio, Gatto '89, FF, Kehagias '13

- The mass of the scalar is generated from the Kähler potential term

$$\delta K = -\lambda X^2 \overline{X}^2.$$

- In the formal limit

$$\lambda \to \infty$$

the sgoldstino gets an infinite mass and decouples.

- The superspace equations of motion have a λ part which should vanish identically

$$\bar{D}^2 (X \overline{X}^2) = 0 \ \to \ X^2 = 0.$$

Often questioned if there always exists in the IR $X^2 = 0$. *Dudas, Gersdorff, Ghilencea, Lavignac, Parmentier '11*

The goldstino and the Ferrara–Zumino supercurrent

- For every chiral model we have *(Ferrara, Zumino '74)*

$$\overline{D}^{\dot{\alpha}} \mathcal{J}_{\alpha\dot{\alpha}} = D_\alpha \mathcal{Z} \, ,$$

where

$$\mathcal{Z} = 4W - \frac{1}{3}\overline{D}^2 K \, .$$

- It has been proposed that in the IR when SUSY is broken, on-shell one finds

$$\mathcal{Z} \sim X \ \rightarrow \ \mathcal{Z}^2 = 0 \, . \qquad \textit{Komargodski, Seiberg '09}$$

Counterexample: The X–Y system in the IR

- We can study for example the system

$$X^2 = 0\,, \quad X\,Y = 0\,.$$

- For

$$\mathcal{L} = \int d^4\theta \left(X\overline{X} + Y\overline{Y}\right) + \left\{ \int d^2\theta \,(f\,X + g\,Y) + c.c. \right\},$$

we find

$$\mathcal{Z}^2 = \frac{64}{9} g^2\,Y^2 \neq 0\,.$$

But is there always the $X^2 = 0$ constrained superfield?

F-term breaking

Cribiori, Dall'Agata, FF '17

- Break SUSY with a chiral superfield Φ and parametrize it (independent of UV details) as

$$\Phi = X + S\,,$$

  using the constrained superfields
  - Goldstino: $X^2 = 0$.
  - Sgoldstino: $\overline{X}\, D_\alpha S = 0$.

- Equivalently in components

$$\begin{aligned} A^\Phi &= s + \frac{G^2}{2F}\,, \\ \chi^\Phi &= G + \mathcal{O}(\overline{G})\,, \\ F^\Phi &= F + \mathcal{O}(\overline{G})\,. \end{aligned}$$

Example: Decoupling the Sgoldstino

- Consider

$$\begin{aligned}\mathcal{L} &= \int d^4\theta \left(\Phi\overline{\Phi} - \mu\,\Phi^2\overline{\Phi}^2\right) + \left\{\int d^2\theta\, f\,\Phi + c.c.\right\} \\ &= \int d^4\theta \left(|X|^2 + |S|^2 - \mu\left[4|X|^2|S|^2 + |S|^4\right]\right) \qquad (1) \\ &\quad + f\left(\int d^2\theta (X+S) + c.c.\right) .\end{aligned}$$

- In the IR the scalar decouples and we find

$$S = 0\,,$$

and (1) becomes the V–A.

- For more complicated models, the decoupling of S might be more complicated, but this cannot change the $X^2 = 0$.

Conclusions

$\rightarrow$ Always $X^2 = 0$ in the IR for F-term and D-term breaking.
Cribiori, Dall'Agata, FF '17

$\rightarrow$ X not essentially aligned with $\mathcal{Z}$.

$\rightarrow$ Use the constraint $X\overline{X}Q = 0$ for matter.
Dall'Agata, Dudas, FF '16

$\rightarrow$ Supergravity?

Thank you!