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SPONTANEOUSLY BROKEN SUPERGRAVITY, CONSTRAINED SUPERFIELDS AND BRANES

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MOTIVATION

- Recent studies of inflation and susy breaking (ala Volkov-Akulov) within N=1, 4D sugra:

  Ketov & Starobinski '12; Ellis, Nanopoulos & Olive '13, Kehagias, Farakos & Riotto '13, …
  Ferrara, Kallosh, Linde, Porrati, Van Proeyen, Frè, Sorin '13, Antoniadis, Dudas, Ferrara, Sagnotti '14,….
  …Roest & Scalisi, Dall'Agata & Zwirner; Carrasco, Kallosh, Linde'15, ……. '17

  E.g. models with one or two chiral supermultiplets: inflaton T and goldstino S

- Another (related) aim of recent activity: to provide a 4D effective field theory ground for phenomenological models with spontaneously broken susy constructed in the framework of 10D string theory (e.g. KKLT-like models involving anti-D3-branes to generate de Sitter vacua)

- Most of the constructions of D=4 sugra with spontaneously broken susy use constrained (nilpotent) superfield description of the Volkov-Akulov goldstini (scalar partners are composed of goldstino bilinears) – this avoids the presence of extra scalar moduli and their stabilization

  Antoniadis, Dudas, Ferrara, Kehagias, Farakos, Kallosh, Linde, Porrati, Sagnotti, Scalisi, dall'Agata, Zwirner; Bergshoeff, Freedman, Kallosh, Van Proeyen; Hasegawa,Yamada; Kuzenko; Antoniadis, Markou; …, Aparicio, Quevedo, Valandro, …

- Original Volkov-Akulov construction '72 is directly related to worldvolume actions for superbranes *(Hughes & Polchinski '86, Kallosh '98, … Kallosh, Quevedo, Uranga '15…)*

  Its full coupling to N=1, D=4 sugra was given only recently: *Bandos, Martucci, D.S, Tonin '15*

- Earlier studies of local susy breaking & super-Brout-Englert-Higgs effect in sugra:

  Volkov & Soroka '73, Deser & Zumino '77, …, Lindstrom & Rocek '79, Samuel & Wess '83, Ivanov & Kapustnikov '84 -'90, …

ORIGINAL VOLKOV-AKULOV MODEL '72 AS A 3-BRANE

"Can neutrino be a Goldstone particle?"

- Goldstino as the manifestation of susy breaking

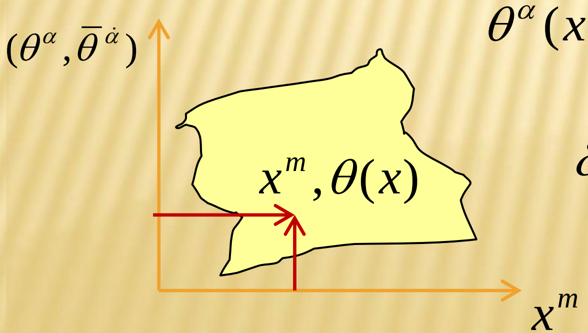
$$\chi^\alpha(x) \to \chi'^\alpha(x) = \chi^\alpha(x) + \varepsilon^\alpha + \text{nonlinear terms} \quad \Rightarrow \quad \{\mathrm{Q}, \overline{\mathrm{Q}}\}\chi = \sigma^m \partial_m \chi$$

- Volkov-Akulov superspace $z^M = (x^m, \theta^\alpha, \bar{\theta}^{\dot{\alpha}}) \quad m = 0,1,2,3 \quad \alpha, \dot{\alpha} = 1,2$

SUSY transform. $\delta\theta^\alpha = \varepsilon^\alpha, \quad \delta\bar{\theta}^{\dot{\alpha}} = \bar{\varepsilon}^{\dot{\alpha}}, \quad \delta x^m = i\theta\sigma^m\bar{\varepsilon} - i\varepsilon\sigma^m\bar{\theta}, \quad \sigma^m - \text{Pauli matrices}$

SUSY invariant VA (Cartan) 1-form: $E_0^m = dx^m + i\theta\sigma^m d\bar{\theta} - id\theta\sigma^m\bar{\theta}$

Consider a 4d worldvolume (of a 3-brane) placed in superspace $M_{(4,4)}$



$$\theta^\alpha(x) \equiv f^{-1}\chi^\alpha(x), \quad \bar{\theta}^{\dot{\alpha}}(x) \equiv f^{-1}\,\bar{\chi}^{\dot{\alpha}}(x)$$

spinor field appears on the brane worldvolume

$$\delta\chi^\alpha(x) = f\varepsilon^\alpha - \delta x^m \partial_m \chi^\alpha(x) = f\varepsilon^\alpha + if^{-1}(\varepsilon\sigma^m\bar{\chi} - \chi\sigma^m\bar{\varepsilon})\partial_m\chi^\alpha(x)$$

non-linear susy transform.

susy breaking parameter
3-brane tesnion

VOLKOV-AKULOV ACTION

- volume of 4d surface in superspace (*space-filling non-BPS 3-brane*)

$g_{ij}(x) = E^m_{0i} E^m_{0j} \eta_{mn}$ - induced metric in the brane 4d worldvolume

$$E_0^m = dx^i E^m_{0i}(\chi(x)) = dx^m + if^{-2}(\chi\sigma^m d\bar{\chi} - d\chi\sigma^m\bar{\chi}) = dx^i[\delta_i^m + if^{-2}(\chi\sigma^m\partial_i\bar{\chi} - \partial_i\chi\sigma^m\bar{\chi})]$$

$$S_{VA} = -f^2 \int_{M_4} d^4x \sqrt{-\det g_{ij}(x)} = -f^2 \int_{M_4} d^4x \det E^m_{0i}(\chi(x))$$

$$= -\int_{M_4} d^4x \left(f^2 + \underbrace{i(\chi\sigma^m\partial_m\bar{\chi} - c.c.)}_{\text{Dirac Lagrangian}} + f^{-2}(\chi\partial\chi)^2 + f^{-4}(\chi\partial\chi)^3 + \cancel{f^{-6}(\chi\partial\chi)^4} \right)$$

positive cosm. constant

- no bosonic superpartners
- no kappa-symmetry

$\rightarrow$ N=1, D=4 susy is completely broken in the vacuum

Unique (modulo field redefinitions) **susy invariant** effective **low-energy** goldstino **action**

CONSTRAINED SUPERFIELD REALIZATION OF THE VA GOLDSTINO

(Ivanov, Kapustnikov '77; Rocek 78', …,Samuel, Wess '83; Casalbuoni et al. 89', …, Komargodski, Seiberg 09',..)

Most popular example:

$$S(x_L,\theta)=s(x_L)+\theta\chi(x_L)+\theta^2F(x_L)$$ chiral superfield constrained by: $S^2=0 \;\Rightarrow\; s=\frac{\chi\chi}{4F}$

$$x_L^m=x^m+i\theta\sigma^m\bar\theta,\qquad z_L^{\mathrm{M}}=(x_L^m,\theta^\alpha);\qquad z^M=(x^m,\theta^\alpha,\bar\theta^{\dot\alpha})$$

$$S_{NS}=\int d^8z\,S\bar S+f\left(\int d^4z_L S+c.c.\right)=\int d^4x\left(-i\chi\sigma^m\partial_m\bar\chi-\partial\frac{\chi\chi}{4F}\partial\frac{\bar\chi\bar\chi}{4\bar F}+f(F+\bar F)+F\bar F\right)$$

Upon integrating F:

$$S_{NS}=-\int d^4x\left(f^2+i\chi\sigma^m\partial_m\bar\chi+f^{-2}\chi\chi\partial^2(\bar\chi\bar\chi)+f^{-6}\chi^2\bar\chi^2\partial^2\chi^2\partial^2\bar\chi^2\right)$$

$$S_{VA}=-\int_{M_4}d^4x\left(f^2+i\chi\sigma^m\partial_m\bar\chi+f^{-2}(\chi\partial\chi)^2+f^{-4}(\chi\partial\chi)^3+\cancel{f^{-6}(\chi\partial\chi)^4}\right)$$

From general theory of non-linear realizations it follows that the VA model is universal: all models of spontaneous susy breaking involving goldstino should be related to the VA model by a non-linear transformation of $\chi^\alpha(x)$ whose general form was obtained only quite ricently *Kuzenko & Tyler* 10'-11'

$$\chi^\alpha_{VA}=\chi^\alpha(1+f^{-4}(\chi\partial\chi)^2+f^{-6}(\chi\partial\chi)^3)+f^{-2}(\sigma^m\bar\chi)^\alpha\partial_m\chi^2$$

RELATION BETWEEN VA AND CONSTRAINED SUPERFIELDS

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$$S_{VA} = -f^2 \int_{M_4} d^4x \det E_{0i}^m(\chi(x))$$

Promote VA action to an integral in the whole superspace using Grassmann-odd δ-functions

$$\delta(\theta^2) = \theta^\alpha \theta_\alpha$$

$$S_{VA} = -f^2 \int_{M_4} d^4x\, d^2\theta\, d^2\bar{\theta}\, \underbrace{(\theta - f^{-1}\chi(x))^2 (\bar{\theta} - f^{-1}\bar{\chi}(x))^2 \det E_{0i}^m(\chi(x))}$$

$$= -f^2 \int_{M_4} d^4x\, d^2\theta\, d^2\bar{\theta}\, V(x,\theta,\bar{\theta})$$

Constrained scalar superfield
of Lindstrom & Rocek '79

$$V^2 = 0, \quad V D^2 \bar{D}^2 V = 16 V$$

RELATION BETWEEN VA AND CONSTRAINED SUPERFIELDS

Irreducible constrained chiral superfield *(Ivanov & Kapustnikov, Rocek '78)*

$$X = -\tfrac{1}{4} f\, \overline{D}^2 V, \quad \overline{D}_\alpha X = 0, \quad X^2 = 0, \quad -\tfrac{1}{4} X \overline{D}^2 \overline{X} = f\, X$$

$$F_X = f + O(\chi^2)$$

Relation between *X* and *S*

Note that S^2=0 is scale-invariant *S* -> *YS*, where *Y* is arbitrary chiral sf.

$$S = X\, Y$$

$$S_{NS} = \int d^8 z\, S\overline{S} + f\left(\int d^4 z_L S + c.c.\right) = \int d^8 z\, X\overline{X}Y\overline{Y} + f\left(\int d^4 z_L XY + c.c.\right) = f\left(\int d^4 z_L X + c.c.\right)$$

On the mass shell*: Y=1+Z*, where *ZX=0.*

COUPLING VA GOLDSTINO TO N=1, D=4 SUGRA, SUPER-BEHIGGS EFFECT AND DE SITTER VACUA

- *Volkov -Soroka model '73*
- *Deser, Zumino '77,…, Lindstrom, Rocek '79; Ferrara et al; Samuel, Wess '83; Ivanov, Kapustnikov '84 -'90,…*

2013-16 *Antoniadis, Dudas, Ferrara, Kehagias, Farakos, Kallosh, Linde, Porrati, Sagnotti, dall'Agata, Zwirner, Farakos; Bergshoeff, Freedman, Kallosh, Van Proeyen; Hasegawa,Yamada; Kuzenko; Antoniadis, Markou;…, Schillo, van der Woerd, Wrase, …*

Sugra coupled to scalar Φ(z), vector V(z), W_α(z), and goldstino S(z) superfields

$$S_{NS} = \frac{3}{4\kappa^2}\int d^8 z\,\mathrm{Ber}\,E_M^A\, e^{-\frac{\kappa^2}{3}K(\bar\Phi, e^V\Phi, S, \bar S)} + \frac{m}{2\kappa^2}\int d^6 z_L \mathcal{E}\Big(W(\Phi,S) + \mathbf{tr}\,\mathrm{g}(\Phi,S)\mathbf{W}_\alpha \mathbf{W}^\alpha\Big)$$

Kahler potential　　chiral measure　　superpotential　　SYM kin.term

$z^M = (x^m, \theta^\alpha, \bar\theta^{\dot\alpha}),\qquad E^A = dz^M E_M^{\ A}(z)$ - supervielbeins encode fields of sugra multiplet

COUPLING VA GOLDSTINO TO N=1, D=4 SUGRA, SUPER-BEHIGGS EFFECT AND DE SITTER VACUA

- We can always use local supersymmetry and impose unitary gauge

$$\delta\chi = \varepsilon(x) + \ldots \quad \to \quad \chi = 0$$

Upon the integration over the Grassmann coordinates θ and of the auxiliary field F_S of the goldstino multiplet, the effect of the goldstino boils down to a single term:

$$S_{Susy\, breaking} = -f^2 \int d^4x \det e \; \frac{W_S(\varphi, F_{mn})\overline{W}_{\bar S}(\bar\varphi, \bar F_{mn})}{K_{S\bar S}(\varphi, \bar\varphi, A_m)}$$

Positive (de-Sitter) contribution to the cosmological constant $\lambda = f^2$

The same effect one gets by coupling to the sugra-matter system of the VA brane:

$$S_{VA} = -f^2 \int d^4\xi \left(\det \mathrm{E}_i^a(x^m(\xi), \chi(\xi), \bar\chi(\xi))\right) \mathcal{F}(\Phi, V, \varphi(\xi))$$

in the static gauge $x=\xi$, and in the unitary gauge $\chi(x)=0$

CONCLUSION

- Spontaneous susy breaking and appearance of VA goldstini
  - can be triggered by the presence in the theory of brane-like objects (non-linear realizations)
  - or described in the IR effective field theory limit by constrained (nilpotent) superfields
- The two descriptions are equivalent for a general class of models and produce the same physical effects
- SUSY breaking generates a positive contribution to the vacuum energy thus allowing for the appearance of de Sitter vacua in supergravity and string theory.
- This makes these supergravity models attractive for inflationary model building
- **The effective field theories** with susy breaking constructed by coupling the goldstino to supergravity and matter are **too general**. One should look for additional physical inputs to single out from this wide class of models a physically relevant ones.
- Realization of the local susy breaking with the use of the space-filling VA 3-brane coupled to gravity and matter multiplets may by useful for finding a more direct connection of these 4d effective field theories to string theory constructions involving anti-D-branes, like the KKLT model and its refinings