New horizons with Non-linear supersymmetry

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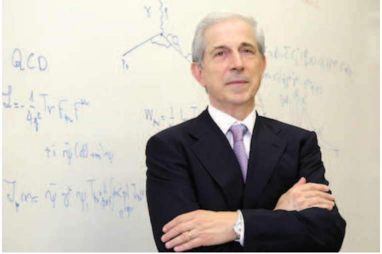

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2. **The Low-energy Effective Field Theory From Four-dimensional Superstrings**
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Outline

- Motivations
- Non-linear SUSY and the goldstino
- Non-linear SUSY and the MSSM
- Non-linear SUSY and Starobinsky inflation
- Extended supersymmetry and brane dynamics

Non-linear supersymmetry $\Rightarrow$ goldstino mode χ

Volkov-Akulov '73

Why study goldstino interactions:

- Effective field theory of SUSY breaking at low energies $m_\chi << m_{susy}$

  e.g. gauge mediation dominant vs gravity mediation

  χ: longitudinal gravitino with $m_\chi \simeq \dfrac{m_{susy}^2}{M_{Planck}} \lesssim m_{soft} << m_{susy}$

  $M_{Planck} \to \infty$: SUGRA decoupled

  massless χ coupled to matter $\sim 1/m_{susy}$

- Brane dynamics: half SUSY of the bulk broken but NL realized

  $\Rightarrow$ strongly constrain coupling of brane to bulk fields

Non-linear SUSY transformations:

$$\delta\chi_\alpha = \frac{\xi_\alpha}{\kappa} + \kappa\,\Lambda^\mu_\xi\,\partial_\mu\chi_\alpha \qquad \Lambda^\mu_\xi = -i\left(\chi\sigma^\mu\bar{\xi} - \xi\sigma^\mu\bar{\chi}\right)$$

κ: goldstino decay constant (SUSY breaking scale) $\qquad \kappa = (\sqrt{2}m_{susy})^{-2}$

Volkov-Akulov action:

Define the 'vierbein': $\quad E^a_\mu = \delta^a_\mu + \kappa^2\, t^a_\mu \qquad t^a_\mu = i\chi\overleftrightarrow{\partial}_\mu\sigma^a\bar{\chi}$

$\delta(\det E) = \kappa\,\partial_\mu\left(\Lambda^\mu_\xi \det E\right) \Rightarrow$ invariant action:

$$S_{VA} = -\tfrac{1}{2\kappa^2}\int d^4x\,\det E = -\tfrac{1}{2\kappa^2} - \tfrac{i}{2}\chi\sigma^\mu\overleftrightarrow{\partial}_\mu\bar{\chi} + \dots$$

D-brane examples

Type II (closed) strings on 4d Minkowski $M_4 \times X_6$ internal 6d manifold

X_6 flat $\Rightarrow$ $N = 8$ SUSY ; X_6 Calabi-Yau $\Rightarrow$ $N = 2$ SUSY

Single stack of N Dp-branes $\Rightarrow$ half SUSY is spontaneously broken $p \geq 3$

$(p - 3)$ dims wrapped around cycles in X_6 $\Rightarrow$ 4d effective field theory

- Gauge group: $G = U(N)$ (generically)
- SUSY: half remains unbroken Q_e ; other half NL realized Q_o

  broken SUSY commutes with G $\Rightarrow$ goldstino $= U(1)$ gaugino of Q_e

Intersecting branes: useful framework for model building

Standard Model embedding

Two D-brane stacks: N_1 Dp_1 and N_2 Dp_2

$\Rightarrow$ bifundamental matter on their intersections: chiral fermions

L-SUSY: generally broken but preserved for special intersection angles

e.g. for $X_6 = T^2 \times T^2 \times T^2$ when $\theta_1 + \theta_2 + \theta_3 = 0$

NL-SUSY: generally all (both $U(1)_1 \times U(1)_2$ gauginos = goldstinos)

special angles $\Rightarrow$ only a linear combination

Remark: string consistency (e.g. tadpole cancellation) $\Rightarrow$ need orientifolds

non-dynamical planes $\Rightarrow$ break half-SUSY explicitly

$\Rightarrow$ goldstino gets a volume suppressed mass

NL-SUSY only locally $\rightarrow$ restored in the large volume limit

Constrained superfields

Rocek-Tseytlin '78, Lindstrom-Rocek '79, Komargodski-Seiberg '09

spontaneous global $S\!\!\!/USY$: no supercharge but still conserved supercurrent

$\Rightarrow$ superpartners exist in operator space (not as 1-particle states)

$\Rightarrow$ constrained superfields: 'eliminate' superpartners

Goldstino: chiral superfield X_{NL} satisfying $X_{NL}^2 = 0 \Rightarrow$ [27]

$$X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F \qquad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

$$= F\Theta^2 \qquad \Theta = \theta + \frac{\chi}{\sqrt{2}F}$$

$$\mathcal{L}_{NL} = \int d^4\theta X_{NL}\bar{X}_{NL} - \frac{1}{\sqrt{2}\kappa}\left\{\int d^2\theta X_{NL} + h.c.\right\} = \mathcal{L}_{Volkov-Akulov}$$

$$F = \frac{1}{\sqrt{2}\kappa} + \dots$$

Reduce the ‘little’ fine-tuning in MSSM

MSSM upper bound on the lightest scalar mass:

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right] \lesssim (130\,GeV)^2$$

$m_h \simeq 126$ GeV $\Rightarrow m_{\tilde{t}} \simeq 3$ TeV or $A_t \simeq 3m_{\tilde{t}} \simeq 1.5$ TeV

$\Rightarrow$ **compatible with SUSY** but % to a few ‰ fine-tuning

minimum of the potential: $m_Z^2 = 2\frac{m_1^1 - m_2^2 \tan_\beta^2}{\tan^2\beta - 1} \sim -2m_2^2 + \cdots$

RG evolution: $m_2^2 = \; m_2^2(M_{\rm GUT}) - \frac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\frac{M_{\rm GUT}}{m_{\tilde{t}}} + \cdots$

$$\sim m_2^2(M_{\rm GUT}) - \mathcal{O}(1) m_{\tilde{t}}^2 + \cdots$$

Goldstino couplings to matter supermultiplets

replace spurion superfield $S = m_{soft}\theta^2$ by goldstino constrained superfield

$$S \to \sqrt{2}\kappa m_{soft} X_{NL} = \frac{m_{soft}}{m_{susy}} X_{NL}$$

$\Rightarrow$ Non-linear MSSM

F-auxiliary in X_{NL}: dynamical field with no derivatives to be solved

$$-\bar{F} = m_{susy}^2 + \frac{B\mu}{m_{susy}^2} h_1 h_2 + \frac{A_u}{m_{susy}^2} \tilde{u}_R \tilde{q} h_2 + \cdots$$

$\Rightarrow$ compact form for all goldstino couplings at linear and non-linear level with

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{X_{NL}} + \mathcal{L}_H + \mathcal{L}_m + \mathcal{L}_{AB} + \mathcal{L}_g$$

$$\mathcal{L}_H = \sum_{i=1,2} \frac{m_i^2}{m_{susy}^4} \int d^4\theta\, X_{NL}^\dagger X_{NL}\, H_i^\dagger e^{V_i} H_i$$

$$\mathcal{L}_m = \sum_{\Phi} \frac{m_\Phi^2}{m_{susy}^4} \int d^4\theta\, X_{NL}^\dagger X_{NL}\, \Phi^\dagger e^V \Phi \quad ; \quad \Phi = Q, U^c, D^c, L, E^c$$

$$\mathcal{L}_{AB} = \frac{1}{m_{susy}^2} \int d^2\theta\, X_{nl} \left(A_u H_2 Q U^c + A_d Q D^c H_1 + A_e L E^c H_1\right) + \frac{B\mu}{m_{susy}^2} \int d^2\theta\, X_{NL} H_1 H_2 + h.c.$$

$$\mathcal{L}_g = \sum_{i=1}^{3} \frac{1}{8g_i^2} \frac{m_{\lambda_i}}{m_{susy}^2} \int d^2\theta\, X_{NL}\, \mathrm{Tr}\,[W^\alpha W_\alpha]_i + h.c.$$

Phenomenological analysis I.A.-Dudas-Ghilencea-Tziveloglou '10

Higgs potential is modified:

$$V = V_{MSSM} + 2\kappa^2 \left| m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B\mu h_1 h_2 \right|^2 + \mathcal{O}(\kappa^4) \quad \Rightarrow$$

$m_{1,2}, B\mu$: soft mass parameters, μ: higgsino mass

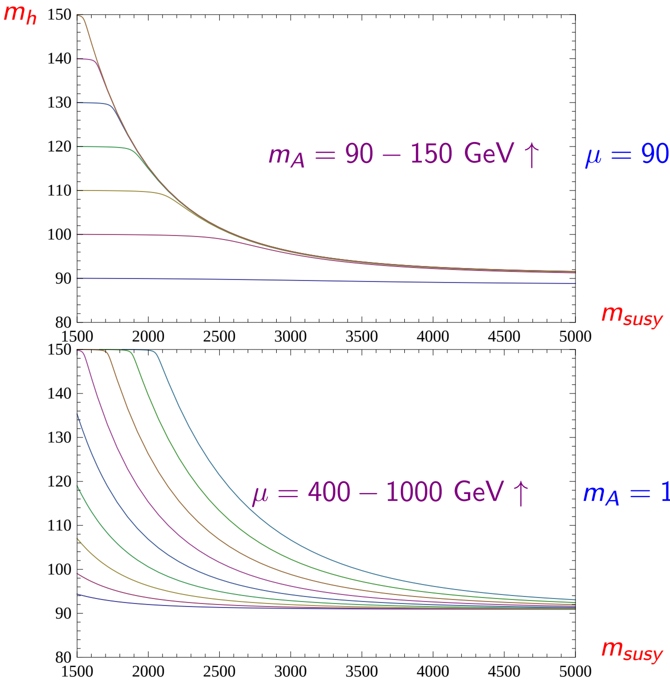
Classical value of light higgs mass can be increased significantly

for $m_{susy} \sim$ a few TeV

large $\tan\beta$ limit: $m_h^2 = m_Z^2 + \frac{v^2}{2m_{susy}^2}(2\mu^2 + m_Z^2)^2 + \cdots$

Quartic higgs coupling increases for large soft masses $\Rightarrow$

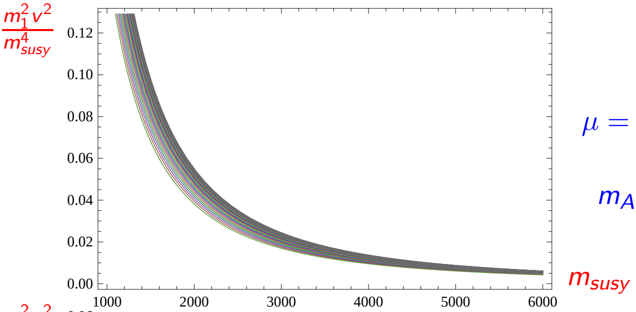
MSSM 'little' fine tuning of the EW scale is alleviated



$\mu = 900$ GeV; $\tan\beta = 50$

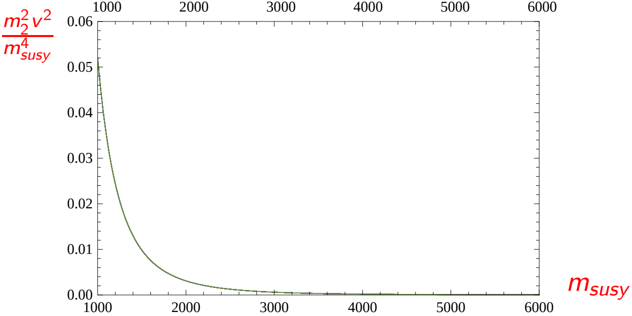
$m_A = 150$ GeV; $\tan\beta = 50$

Validity of perturbative expansion: $m_i^2 v^2 / m_{susy}^4 << 1$



$\mu = 900$ GeV; $\tan\beta = 50$

$m_A = 90 - 650$ GeV $\uparrow$



Fine-tuning analysis

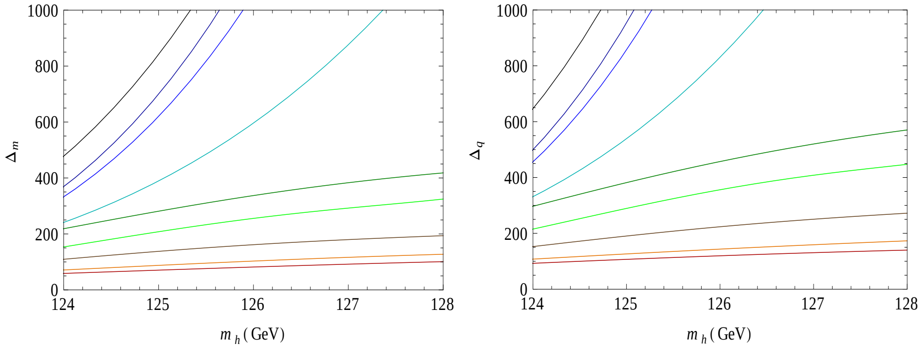
I.A.-Babalic-Ghilencea '14

Fine-tuning measures:

Ellis-Enqvist-Nanopoulos-Zwirner '86
Barbieri-Giudice '88, Anderson-Castano '94

$$\Delta_m = \max\left|\Delta_{\gamma^2}\right|, \quad \Delta_q = \Big\{\sum_\gamma \Delta^2_{\gamma^2}\Big\}^{1/2}, \quad \text{with} \;\; \Delta_{\gamma^2} \equiv \frac{\partial \ln v^2}{\partial \ln \gamma^2}$$

$$\gamma = \{m_0, m_{12}, A_t, B_0, \mu_0\}, \quad v = \text{EW scale}$$



Minimal values of Δ_m (left) and Δ_q (right) for $\tan\beta = 10$ and m_{susy} from the lowest to the top curve: 2.8 TeV (red), 3.2 TeV (orange), 3.9 TeV (brown), 5 TeV (green), 5.5 TeV (dark green), 6.3 TeV (cyan), 7.4 TeV (blue), 8 TeV (dark blue), 8.7 TeV (black).

$$m_{susy} \simeq 3 \text{ TeV} \Rightarrow \Delta^{NL} \sim \Delta/10$$ [20]

Invisible decays of Higgs and Z boson

Other relevant couplings at order $\mathcal{O}(\kappa)$: $\frac{1}{m_{susy}^2}\times$

$$\left(m_1^2\,\chi\,\psi_{h_1^0}\,h_1^{0\,*}+m_2^2\,\chi\,\psi_{h_2^0}\,h_2^{0\,*}\right)+B\mu\,\left(\chi\,\psi_{h_2^0}\,h_1^0+\chi\,\psi_{h_1^0}\,h_2^0\right)+$$

$$\sum_{i=1,2}\frac{m_{\lambda_i}}{\sqrt{2}}\,\tilde{D}_i^a\,\chi\lambda_i^a+\sum_{i=1}^{2}\frac{m_{\lambda_i}}{\sqrt{2}}\,\chi\,\sigma^{\mu\nu}\,\lambda_i^a\,F_{\mu\nu,\,i}^a+h.c.$$

$\Rightarrow$ invisible higgs decay $h\to\chi+$ NLSP if NLSP is light enough

otherwise inverse decay studied in the past

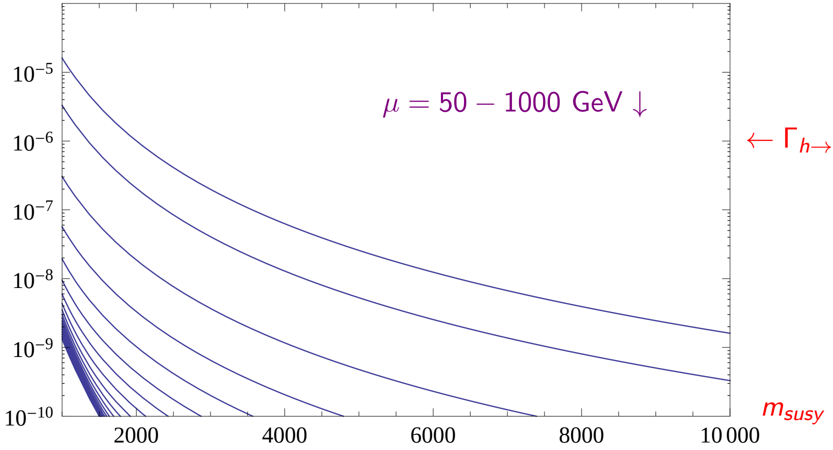
taking also into account the goldstino components of higgsinos/gauginos

from SUSY terms: $\sim h_i^0\lambda\tilde{h}_i^0$

Similarly $Z\to\chi+$ NLSP $\Rightarrow m_{susy}\gtrsim$ 400-700 GeV from Z-width

$\Delta\Gamma_Z\lesssim 2.3$ MeV

$\Gamma_{h\to\chi+\mathrm{NLSP}}$ $m_A = 150$ GeV; $\tan\beta = 50$; $(m_{\lambda_1}, m_{\lambda_2}) = (70, 150)$ GeV



Non-linear SUSY in supergravity

I.A.-Dudas-Ferrara-Sagnotti '14

$$K = -3\log(1 - X\bar{X}) \equiv 3X\bar{X} \quad ; \quad W = f\,X + W_0 \qquad\qquad X \equiv X_{NL}$$

$$\Rightarrow \quad V = \frac{1}{3}|f|^2 - 3|W_0|^2 \quad ; \quad m_{3/2}^2 = |W_0|^2$$

- V can have any sign   contrary to global NL SUSY
- NL SUSY in flat space $\Rightarrow f = 3\,m_{3/2}M_p$
- Dual gravitational formulation: $\mathcal{R}^2 = 0 \leftarrow$ chiral curvature superfield
- Minimal SUSY extension of R^2 gravity

Starobinsky model of inflation

$$\mathcal{L} = \frac{1}{2}R + \alpha R^2$$

Lagrange multiplier ϕ $\Rightarrow \mathcal{L} = \frac{1}{2}(1+2\phi)R - \frac{1}{4\alpha}\phi^2$

Weyl rescaling $\Rightarrow$ equivalent to a scalar field with exponential potential:

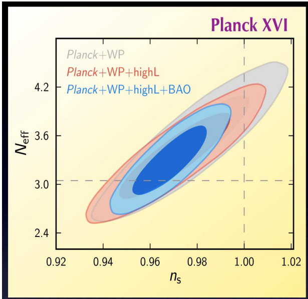
$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

Note that the two metrics are not the same

supersymmetric extension:

add D-term $\mathcal{R}\bar{\mathcal{R}}$ because F-term $\mathcal{R}^2$ does not contain R^2

$\Rightarrow$ brings two chiral multiplets [23]



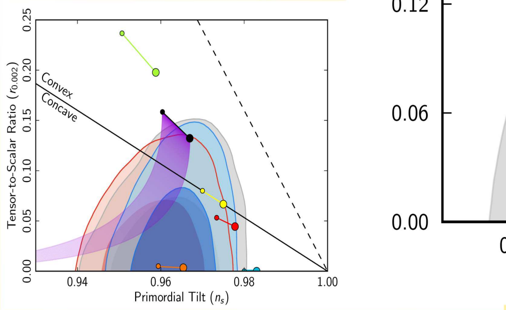
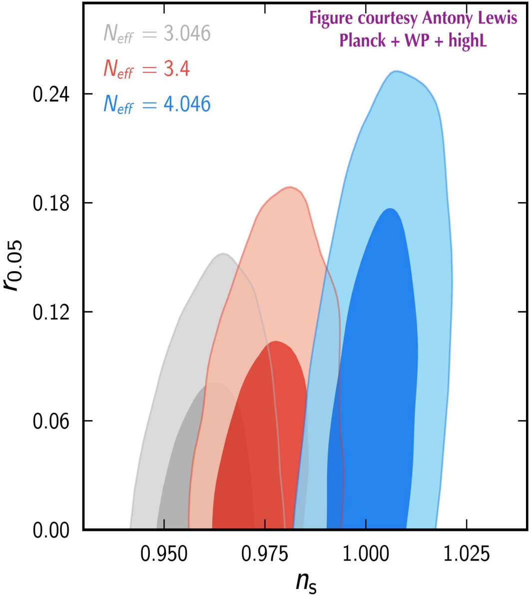


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.



Chiral curvature superfield:

$$\mathcal{R} = \left(u\,,\ \gamma^{mn}\mathcal{D}_m\psi_n\,,\ -\frac{1}{2}R - \frac{1}{3}A_m^2 + i\mathcal{D}^m A_m - \frac{1}{3}u\overline{u} \right)$$

u, A_m: auxiliary fields of the 'old minimal' $N = 1$ SUGRA

$$\mathcal{L} = \mathcal{R}\overline{\mathcal{R}}|_D + W(\mathcal{R})|_F = C\overline{C}|_D + [\Lambda(C - \mathcal{R}) + W(C)]_F$$

C, Λ: auxiliary chiral multiplets

$W(C)$ can be set to constant W_0 by Λ redefinition + few manipulations

$\Rightarrow N = 1$ SUGRA with 2 chiral multiplets

SUSY extension of Starobinsky model

$$K = -3\ln(T + \bar{T} - C\bar{C}) \quad ; \quad W = MC(T - \frac{1}{2})$$

- T contains the inflaton: $\mathrm{Re}\, T = e^{\sqrt{\frac{2}{3}}\phi}$
- $C \sim \mathcal{R}$ is unstable during inflation

  $\Rightarrow$ add higher order terms to stabilize it

  e.g. $C\bar{C} \to h(C,\bar{C}) = C\bar{C} - \zeta(C\bar{C})^2$ Kallosh-Linde '13
- SUSY is broken during inflation with C the goldstino superfield

Minimal SUSY extension that evades stability problem:

replace C by the non-linear multiplet X

Non-linear Starobinsky supergravity

$$K = -3\ln(T + \bar{T} - X\bar{X}) \quad ; \quad W = M\,XT + f\,X + W_0 \qquad \Rightarrow$$

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 - \frac{1}{2}e^{-2\sqrt{\frac{2}{3}}\phi}(\partial a)^2 - \frac{M^2}{18}e^{-2\sqrt{\frac{2}{3}}\phi}a^2$$

- axion a much heavier than ϕ during inflation, decouples:

  $m_\phi = \frac{M}{3}e^{-\sqrt{\frac{2}{3}}\phi_0} << m_a = \frac{M}{3}$

- inflation scale M independent from NL-SUSY breaking scale f

  $\Rightarrow$ compatible with low energy SUSY

- string realization? [28]

NL extended supersymmetry $N = 1_L + 1_{NL}$

Ambrosetti-I.A.-Derendinger-Tziveloglou '09 + '10

Goldstino in multiplet of $N = 1$ SUSY: vector or chiral?

brane dynamics $\Rightarrow$ Maxwell goldstino multiplet

gauge chiral multiplet$\big|_{N=2}$ $\mathcal{W} =$ (vector W + chiral X)$_{N=1}$

$$\mathcal{W}(y,\theta,\tilde{\theta}) = X(y,\theta) + i\sqrt{2}\tilde{\theta}W(y,\theta) - \tilde{\theta}^2\left[\tfrac{1}{4}\overline{DDX}(y,\theta) + \tfrac{1}{2\kappa}\right]$$

allow partial SUSY breaking $N = 2 \rightarrow N = 1$ ↗

I.A.-Partouche-Taylor '96

$\delta^* X = i\sqrt{2}\eta^\alpha W_\alpha$ $\quad$ $\delta^* W_\alpha = \frac{i}{\sqrt{2}\kappa}\eta_\alpha + \ldots$ $\leftarrow$ linear SUSY

$$\mathcal{L}^{N=2}_{Maxwell} = -\frac{1}{8}\int d^2\theta\, d^2\tilde{\theta}\,\mathcal{W}^2 + h.c. = \int d^2\theta\left[\frac{1}{2}W^2 - \frac{1}{4}X\overline{DDX} - \frac{1}{2\kappa}X\right] + h.c.$$

DBI action

Non-linear $N = 2$ constraint: $\mathcal{W}_{NL}^2 = 0$

$$\Rightarrow \quad X^2 = 0 \quad , \quad XW_\alpha = 0 \quad , \quad WW - \tfrac{1}{2}X\overline{DDX} = \tfrac{1}{\kappa}X$$ [9]

$$X = \kappa W^2 - \kappa^3 \bar{D}^2 \frac{W^2\overline{W}^2}{1+A_+ + \sqrt{1+2A_+ + A_-^2}} \qquad A_\pm = \frac{\kappa^2}{2}\left(D^2W^2 \pm \bar{D}^2\overline{W}^2\right) = \pm A_\pm^*$$

$$\Rightarrow \mathcal{L}_{NL}^{N=2} = \frac{1}{4\kappa}\int d^2\theta X + h.c.$$

$$= \frac{1}{8\kappa^2}\left(1 - \sqrt{-\det(\eta_{\mu\nu} + 2\sqrt{2}\kappa F_{\mu\nu})}\right) + \ldots = \mathcal{L}_{\rm DBI} \leftarrow \text{D-brane}$$

The FI-term is also invariant under NL SUSY

$$\mathcal{L}_{FI} = \xi \int d^4\theta V; \quad W = -\tfrac{1}{4}\bar{D}^2 DV; \quad \delta^* V = \frac{i}{2\kappa}\left(\eta D + \bar{\eta}\bar{D}\right)\theta^2\bar{\theta}^2 + \ldots$$

$$\Rightarrow \mathcal{L}_{Max}^{NL} = \mathcal{L}_{NL}^{N=2} + \mathcal{L}_{FI}$$

Conclusions

Non-linear supersymmetry: powerful tool for studying:

- low energy SUSY breaking $E << m_{susy} \sim 1/\sqrt{\kappa}$

  Volkov-Akulov action and goldstino χ couplings to matter

- $m_{soft} \lesssim E << m_{susy}$: goldstino $\equiv$ spurion coupled to supermultiplets

  $\rightarrow$ Non-linear MSSM : narrow but interesting region

  - new quartic higgs coupling $\Rrightarrow$ can increase the higgs mass

    reduce the MSSM fine tuning of the EW scale

- coupling to supergravity: straightforward but several open questions

  minimal SUGRA extension of Starobinsky model for inflation

- brane effective actions $\Rrightarrow$ brane dynamics

  $N = 2$ NL SUSY $\Rrightarrow$ DBI action and couplings to bulk fields