COST-Milano
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Non-linear realizations of local supersymmetry

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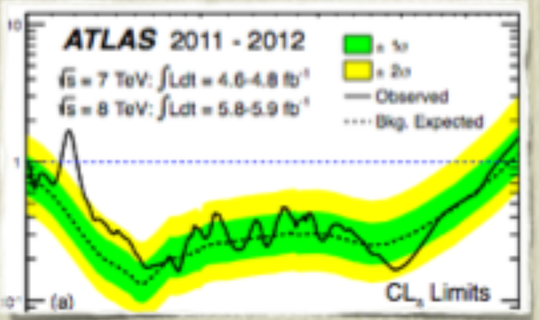
together with:

F. Zwirner, JHEP12 (2014) 172 [arXiv:1411.2605]
S. Ferrara and F. Zwirner, PLB572 [arXiv:1509.06345]
F. Farakos JHEP 1602 101 [arXiv:1512.02158]
E. Dudas and F. Farakos JHEP 1605 041 [arXiv:1603.03416]
N. Cribiori and F. Farakos PRD94 [arXiv:1607:01277]
N. Cribiori, F. Farakos and M. Porrati PLB764 [arXiv:1611:01490]
N. Cribiori, F. Farakos and F. Zwirner in progress

Standard Model success

- 2012: Higgs discovery

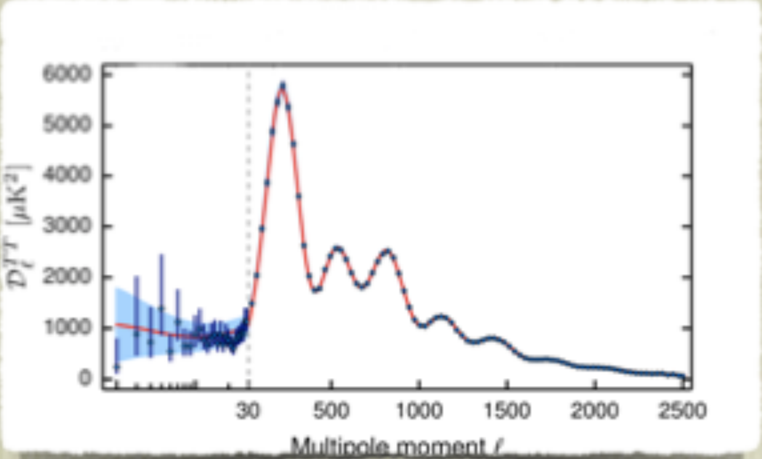


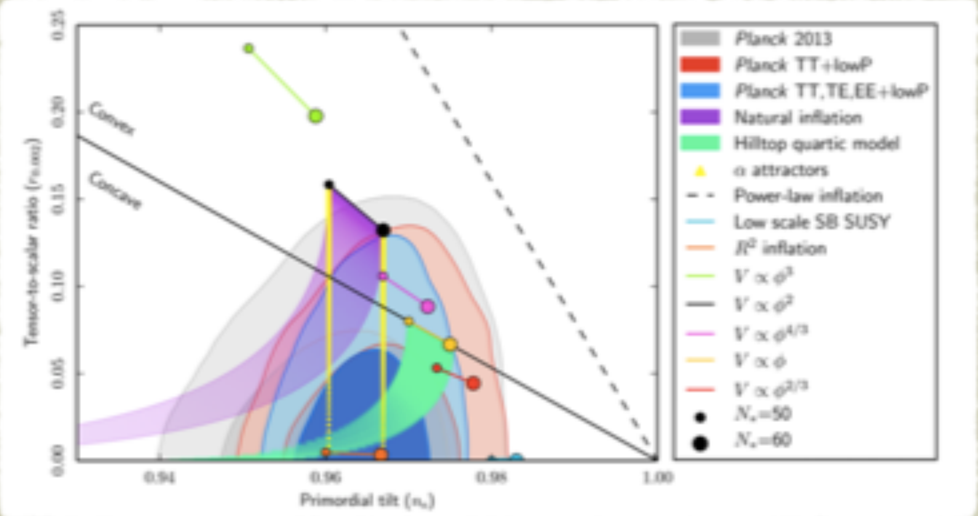
- 2013: Nobel prize to Englert & Higgs

- 2016: the 750GeV case

Planck-BICEP-KECK 2015

New impressive ***experimental progress*** gives new ***constraints*** on theoretical models describing the origin & evolution of our Universe





Quantum Gravity

necessary to UV complete inflationary models (but we may never see tensor modes)

Old & New Hierarchy problems

HUGE
(vacuum energy)
$\langle V \rangle^{1/4} \sim 10^{-30} M_P$

Large
(gauge hierarchy)
$G_F^{-1/2} \sim 10^{-16} M_P$

little
$m^2_{W,Z,h} \lesssim 10^{-2} m^2_{spart}$

*LHC constrains SM-like scalar **h** at 125 GeV,*
*new bounds on **H, A, H**$^\pm$ and sparticles*

What about Susy?

*Supergravity relevant **iff** some superpartners (gravitino, MSSM sparticles...) are **light** with respect to KK/string/ Planck cutoff scale*

- *a.* ***Not necessarily all*** *superpartners*
- *b. Not necessarily at the* ***TeV/LHC scale***

Well motivated, but not granted.

If realized, challenges and opportunities for realistic supergravity models are related to BSM physics and inflation

What about Susy?

Supergravity relevant ***iff*** *some superpartners (gravitino, MSSM sparticles...) are* ***light*** *with respect to KK/string/Planck cutoff scale*

a. ***Not necessarily all*** *superpartners*

b. Not necessarily at the ***TeV/LHC scale***

If Supersymmetry is broken at ***high scales*** *we can still use it to* ***constrain*** *and* ***parameterize*** *effective theories and provide low-energy theorems*

NON-LINEAR SUPERSYMMETRY

From non-linear SUSY to constrained superfields

CASALBUONI-DE CURTIS-DOMINICI-FERUGLIO-GATTO

Simple example (global susy): $X = x + \sqrt{2}\,\theta\chi + \theta^2\, F^x$

$$K = |X|^2 - \frac{1}{\Lambda^2}|X|^4 \qquad\qquad W = f\, X$$

Linear susy in the region $\sqrt{f} \ll E \ll \Lambda$

Susy spontaneously broken at x =0, with susy breaking scale $\sqrt{f}$

Spectrum: massless goldstino + massive scalar $m = 4\dfrac{f}{\Lambda}$

*At scales **below m** we can build an **effective Lagrangian** for the goldstino*

From non-linear SUSY to constrained superfields

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Simple example (global susy): $X = x + \sqrt{2}\,\theta\chi + \theta^2\, F^x$

$$K = |X|^2 - \frac{1}{\Lambda^2}|X|^4 \qquad\qquad W = f\, X$$

At zero momentum:

$$\mathcal{L} = -f^2 + |F^X + f|^2 - \frac{1}{\Lambda^2}|2x\, F^x - \bar{\chi}\chi|^2$$

Minimized for

$$x = \frac{\bar{\chi}\chi}{2F^x}$$

Low-energy: ***constrained chiral superfield*** $X^2 = 0$

Chiral goldstino superfield

1972 VOLKOV-AKULOV
1978 ROCEK; IVANOV-KAPUSTNIKOV;
1979 LINDSTROM-ROCEK;
1983 SAMUEL-WESS
1989 CASALBUONI-DECURTIS-DOMINICI-FERUGLIO-GATTO;
2009 KOMARGODSKI-SEIBERG;
2011 KUZENKO-TYLER;

*Various actions, all equivalent to **Volkov-Akulov** via non-linear field redefinitions*

- *Non-linear realizations of **supersymmetry**:*
  - *Effective theories*
    some field particularly heavy and hence integrated out
  - *Brane susy breaking models*
    (high-scale induced by mutually non-susy branes)

Matter couplings using constrained superfields

Scalarless models
(orthogonal superfields)
$X^2 = 0 = XY$

BRIGNOLE-
FERUGLIO-ZWIRNER

Seiberg-Komargodski models

$XW_\alpha = 0$ *gaugino-less*

biggsino-less $\overline{D}_{\dot\alpha}(X\bar{H}) = 0$

$X(B - \overline{B}) = 0$ *real scalar models*

Lacks organizing principle *and derivation.*
Supergravity realizations may change results

Supergravity realizations through Lagrange multipliers

FERRARA-KALLOSH-VAN PROEYEN

General actions with auxiliary fields

FERRARA-KALLOSH-VAN PROEYEN-WRASE
FREEDMAN-ROEST-VAN PROEYEN

Unique organizing principle *and derivation from linear SUSY:*

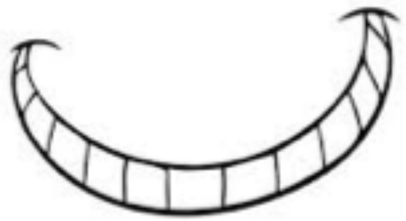
G.D., DUDAS, FARAKOS

$$\boxed{X\overline{X}\Phi = 0}$$

Consistently removes only the lowest component of Φ

Includes all known cases

Consistency constraints on allowed Φ



… Sgoldstino as Cheshire cat

The constraint implies that K and W can be expanded about X = 0:

$$K(X,\bar{X},z,\bar{z}) = h(z,\bar{z}) + X\bar{k}(z,\bar{z}) + \bar{X}k(z,\bar{z}) + |X|^2 g(z,\bar{z})$$

$$W(X,z) = W_0(z) + XW_1(z)$$

For the bosonic action, compute everything and set <x>=0 afterwards!

$$V = e^K(|DW|^2 - 3|W|^2)|_{x=0}$$

$$D_x W|_{x=0} = W_1(z) \neq 0$$

Nilpotent supergravity

Supergravity coupled to nilpotent field

ANTONIADIS-DUDAS-FERRARA-SAGNOTTI; BERGSHOEFF-FREEDMAN-KALLOSH-VAN PROEYEN; HASEGAWA-YAMADA

Contains only the *graviton* and one *massive gravitino*

$$K = X\bar{X} \qquad W = m_{3/2} + fX$$

The cosmological constant is ***arbitrary***

$$\boxed{\Lambda = |f|^2 - 3m_{3/2}^2}$$

Matter couplings

- Susy matter spectrum $m_{sp} \leq E \ll \sqrt{f}$
  - *linear realizations = ordinary superfields*
- Non-susy matter spectrum $E \ll m_{sp}, \sqrt{f}$
  - *non-linear realizations = Constrained superfields*

General lagrangians using previous rules

- Constrained auxiliary fields give ***potentials*** that ***differ*** from ordinary supergravity

Constrained supergravity

CRIBIORI-G.D.-FARAKOS-PORRATI

- (Old) Minimal supergravity multiplet in:
  - Chiral density $2\mathcal{E} = e\left\{1 + i\,\Theta\sigma^a\overline{\psi}_a - \Theta^2(m^* + \overline{\psi}_a\overline{\sigma}^{ab}\overline{\psi}_b)\right\}$
  - Curvature superfield

$$\mathcal{R} = \left\{m, 2\sigma^{ab}\psi_{ab} - i\sigma^a\overline{\psi}_a\, m + i\psi_a b^a, -\frac{1}{2}R + i\overline{\psi}^a\overline{\sigma}^b\psi_{ab} + \frac{2}{3}|m|^2 + \ldots\right\}$$

  - Auxiliary vector $\mathcal{D}^\alpha B_{\alpha\dot{\alpha}} = \overline{\mathcal{D}}_{\dot{\alpha}}\overline{\mathcal{R}}.$

Constrained supergravity

CRIBIORI-G.D.-FARAKOS-PORRATI

- (Old) Minimal supergravity action:

$$\mathcal{L} = \frac{3}{8}\int d^2\Theta\, 2\mathcal{E}\,(\overline{\mathcal{D}}^2 - 8\mathcal{R})e^{-\frac{1}{3}K(X,\overline{X})} + \int d^2\Theta\, 2\mathcal{E}\, W + h.c.,$$

- Constraints on the auxiliary fields:

$$X\left(\mathcal{R} + \frac{c}{6}\right) = 0$$

Constrains auxiliary scalar

$$X\overline{X}B_{\alpha\dot{\alpha}} = 0$$

Constrains auxiliary vector

No more Kæhler invariance!

Constrained supergravity

Cribiori-G.D.-Farakos-Porrati

- Unitary gauge action:

$$\begin{aligned} e^{-1}\mathcal{L} &= -\frac{1}{2}R + \frac{1}{2}\epsilon^{klmn}(\overline{\psi}_k\overline{\sigma}_l\mathcal{D}_m\psi_n - \psi_k\sigma_l\mathcal{D}_m\overline{\psi}_n) \\ &- (m_{3/2}\,\overline{\psi}_a\overline{\sigma}^{ab}\overline{\psi}_b + \overline{m}_{3/2}\,\psi_a\sigma^{ab}\psi_b) - \Lambda, \end{aligned}$$

$$\Lambda = \frac{1}{3}|c|^2 + |f|^2 + m_{3/2}\bar{c} + \overline{m}_{3/2}c = \Lambda_S - 3|m_{3/2}|^2$$

- *Susy breaking scale:* $\Lambda_S = |f|^2 + \left|\frac{c}{\sqrt{3}} + \sqrt{3}\,m_{3/2}\right|^2$

Matter couplings different from “de Sitter” sugra

“Anything you want” supergravity

DELACRETAZ-GORBENKO-SENATORE

CCWZ procedure to construct dressed fields

$$A = D_G\left[e^{\mathcal{G}Q}\right] \circ a$$

transforming linearly under h

$$A' = D_G\left[e^{\mathcal{G}'Q}\right] \circ a' = D_G\left[h(\mathcal{G},\phi)\right] \circ A$$

Invariant lagrangian using ***dressed vielbein and gravitino***

No constraints on the parameters in the action:

- possible *violation of unitarity bounds*;
- consistency of the effective action

- **Brane origin of constrained superfields**
  - *Susy is non-linearly realized on antibranes* Dudas-Mourad
  - *For one anti-D3 on top of O3 the only dof is the goldstino*
  - The anti-D3 brane action can be written using the goldstino superfield

    Kallosh-Wrase
    Bandos-Martucci-Sorokin-Tonin
    Bandos-Kuzenko-Martucci-Sorokin
  - *anti-D3/O3 used in* ***KKLT***: uplift written with manifest susy using nilpotent fields

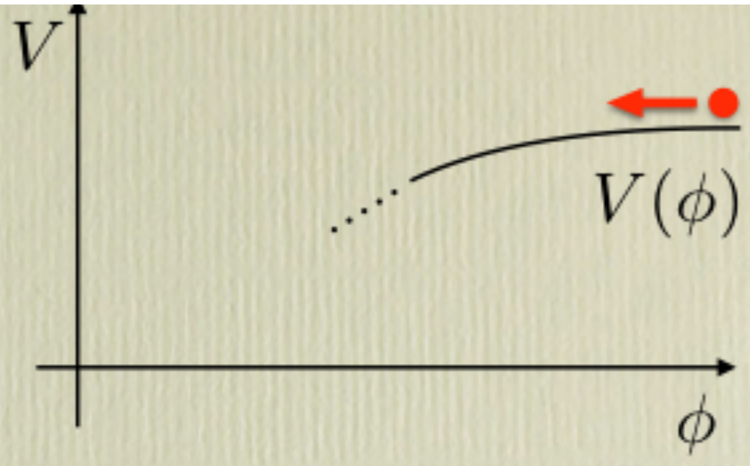
    Kallosh-Linde
    Bergshoeff-Dasgupta-Kallosh-VanProeyen-Wrase

    Kallosh-Quevedo-Uranga,
    Aparicio-Quevedo-Valandro,
    Dasgupta-Emelin-McDonough
  - *More constrained multiplets* arise from *world volume fields* of the anti-D3 brane

    Kallosh-Vercnocke-Wrase
    Bandos-Kuzenko-Martucci-Sorokin

Inflation And Non-linear SUSY

Simple single-field inflation

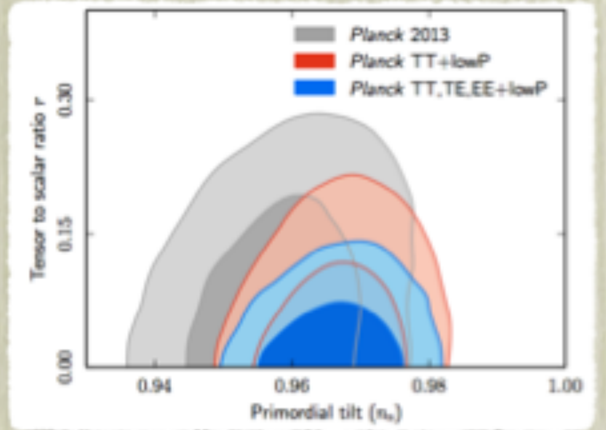


Slow-roll for canonical Einstein and inflaton kinetic term:

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta = M_P^2 \left|\frac{V''}{V}\right| \ll 1$$

actually:

$$n_s = 1 - 6\epsilon + 2\eta \sim .96$$
$$r = 16\epsilon < .12$$



Supergravity eta-problem:

$$V = e^K \left(|DW|^2 - 3|W|^2\right)$$

for canonical kinetic terms, $K = |\Phi|^2$

$$V \sim e^{|\phi|^2} \ldots$$ *too steep, no inflation!*

Solution: *shift symmetry* $K = K(\Phi + \bar{\Phi})$

inflaton: $\phi = -\frac{i}{\sqrt{2}}(\Phi - \bar{\Phi})$

However, generically need ***other fields*** to generate suitable potentials!

Example: $K = |S|^2 + \frac{1}{2}(\Phi + \bar{\Phi})^2, \qquad W = m\, S\, \Phi$

Goals:

Functional freedom:

Test supergravity flexibility to accommodate different inflationary models

Fit data, but interesting physics:

Understand physical phenomena leading to desired Kähler potential and superpotential

Effective single-field inflation

- *In the spectrum of a realistic supergravity, the **inflaton** is **not** the **only scalar** in hidden+observable sector*
- *Potentially* ***dangerous candidates***:
  - *Scalar partner of the inflaton (a)*
  - *Sgoldstino (complex scalar partner of the goldstino)*
  - *Squarks, sleptons, Higgs bosons*
- *It is simpler to deal with a single field to avoid large isocurvature fluctuations*

Constrained superfields provide a natural scenario to avoid

Constrained superfields provide a natural scenario to avoid most of these problems, but one has to satisfy some

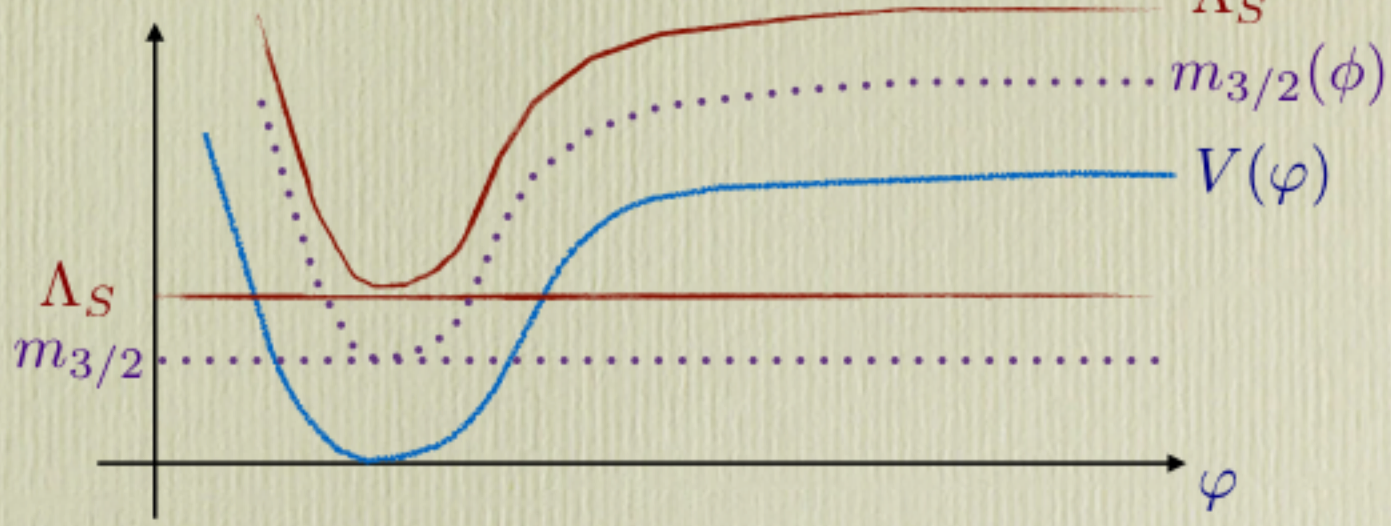
Consistency constraints G.D.-ZWIRNER

- $F^X \neq 0$ *during inflation and at the exit from inflation*
- *Unitarity bounds*
  - *In flat background, unitarity valid for* $E^2 < m_{3/2} M_P$
  - *During inflation may have milder bounds*

$$E_q^2 < m_{3/2}(\varphi) M_P$$

where $E_q \sim V_{inf}^{1/2} / M_P$ *is the typical energy scale of quantum fluctuations during inflation*

Consistency constraints G.D.-Zwirner



Also: mass in de Sitter gets contribution from Hubble parameter

Kallosh-Kofman-Linde-Van Proeyen
Kallosh-Linde-

Our models

Basic ingredient: nilpotent version of no-scale models:

S = no-scale field expanded at the self-dual point

$$K = |S|^2 \quad W = W_0(1+\sqrt{3}\,S)$$

For s=0, supersymmetry is broken: $|F_S|^2 \neq 0$

As in no-scale: ***broken*** *SUSY, vanishing vacuum energy*

In contrast to no-scale models:

- *Fixed gravitino mass* $m^2_{3/2} = |W_0|^2$
- *No flat directions, i.e. no massless scalars*

Adding unconstrained inflaton multiplet:

Adding unconstrained inflaton multiplet:

Take $K = \frac{1}{2}\left(\Phi + \bar{\Phi}\right)^2 + |S|^2$

Promote *W_o to an analytic "imaginary" function* $\overline{f(z)} = f(-\bar{z})$

$$W = f(\Phi)(1 + \sqrt{3}\,S)$$

Susy broken along S: $F^S F_S = 3|W|^2$

Relic of no-scale structure makes the potential depend only on

$$V = F^\Phi F_\Phi = e^{a^2}|f'(\phi) + \sqrt{2}\,f(\phi)a|^2$$

f properties make V(a) = V(-a) and fixes the other scalar

OUR MODELS

Adding unconstrained inflaton multiplet:

Take $K = \frac{1}{2}\left(\Phi + \bar{\Phi}\right)^2 + |S|^2$

Promote *W_o to an analytic "imaginary" function* $\overline{f(z)} = f(-\bar{z})$

$$W = f(\Phi)(1 + \sqrt{3}\, S)$$

Susy broken along S: $F^S F_S = 3|W|^2$

Inflationary potential is then:

$$\boxed{V_{inf} = \left| f'\left(\frac{i\varphi}{\sqrt{2}}\right)\right|^2}$$

and at the end of inflation $\langle F^S F_S \rangle = 3|f(0)|^2$

Salient features:

- *Inflaton potential controlled by derivative of f*
  therefore we can decouple inflation and SUSY breaking!
- *Wide functional freedom*

$$V_{inf} = \mathcal{F}^2(\varphi)$$

reproduced by choosing

$$f(\Phi) = -i \int d\Phi \, \mathcal{F}\left(-i\sqrt{2}\,\Phi\right)$$

Integration constant = susy-breaking scale

MATTER COUPLINGS

Coupling to matter is crucial for inflationary dynamics

- *We need to* ***balance*** *single-field inflation, with susy-breaking after inflation*
  - *no light matter fields during inflation*
  - *Supersymmetry and gauge symmetry breaking at the exit*
- *Inclusion of squarks/sleptons straightforward easily frozen at z = 0 during inflation*
  - *generic big masses for all fields in K (similar to eta-problem)*
- *More delicate to include fields that are flat directions SM-like Higgs*

Many different constructions with various appealing features:

features:

- *Different constraints allow for general inflationary potentials*
- *Simple and elegant embedding of Starobinsky* Antoniadis-Dudas-Ferrara-Sagnotti
- Less "problematic" matter fields *(removed sinflaton and inflatino)* Ferrara-Kallosh-Thaler
- *Consistent inflatino-less cosmology* Carrasco-Kallosh-Linde
- First attempts at matter couplings Kallosh-Linde-Wrase
- *First attempts at incorporating Kaehler corrections* Scalisi
G.D-Zwirner
- Inflation using global susy models Cribiori-G.D-Farakos-Zwirner

Summarizing:

Supersymmetry may still be relevant for pheno and cosmo if broken at "high" scale, but split spectrum

Much below heavy sparticles mass scale we should consider nonlinear realizations

Recent developments provide ***techniques***, organizing principles, ***consistency conditions*** *and* UV completions *of nonlinear realizations in global and local supersymmetry*

Many very appealing applications to inflation in supergravity