Standard Model singlets and hard susy breaking in N=1 Supergravity

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L2C-Montpellier

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Based partly on: *G.M., M. Rausch de Traubenberg, D. Tant, Int. J. Mod. Phys. A34 (2019) 1950004-1-65*
+ ongoing collab: *S.low.SUGRA*, soutien projet IN2P3 (IPHC, L2C, LUPM, APC)

Outline

- Introductory motivations
- Supergravity in a nutshell
- The 35 years old logic of Supergravity mediated soft SUSY breaking ...revisited
- The other class of solutions (e.g. MSSM + 2, 3, ...n, singlets)
- prospective model-building and pheno, astro, cosmo...
- conclusions

Where is –Is there– (TeV) New Physics ??

- why is the Higgs so much SM-like??...(unitarity) why is it so light? ...(vanilla SUSY) why is it so heavy?

- is it elementary? ...is it composite?...

- No (direct) TNP experimental discovery so far, where contemporary paradigm expects it!

- seems to (seriously?) undermine the trust in the canons of TeV naturalness and fine-tuning.

Where is –Is there– (TeV) New Physics ??

1 → TNP realized in a more complex way? more data? different signatures? more data?

OR

2 → is the paradigm *half* wrong? ...TNP there but too heavy to be discovered at present energy frontiers? indirect glimpses from "low energy" observables?

OR

...

3 → is the paradigm *totally* wrong?

could be a double-edged razor:

message from (the) BSM at the LHC (?)

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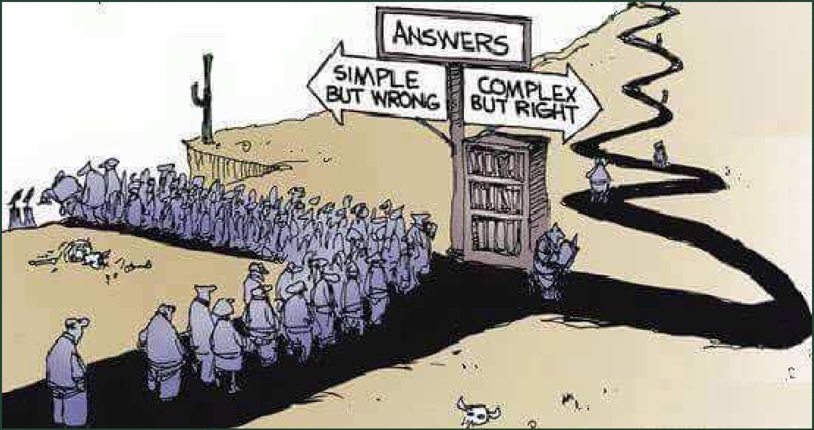

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light Higgs, natural SUSY, ...

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BUT!

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BUT!

In this talk we reconsider/question the yello arrow

N=1 Supergravity potential

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$$V_F = e^{\frac{K}{m_{p\ell}^2}} \left(\mathcal{D}_I W K^{IJ^*} \mathcal{D}_{J^*} \overline{W} - \frac{3}{m_{p\ell}^2} |W|^2 \right)$$

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with

$$\mathcal{D}_I W = W_I + \frac{1}{m_{p\ell}^2} K_I W$$

$$W_I \equiv \frac{\partial W}{\partial Z^I}, \quad K_I \equiv \frac{\partial K}{\partial Z^I}, \ldots$$

$K^{IJ^*} \equiv K^{-1}_{IJ^*}, \; K_{I^*J} = \frac{\partial^2 K}{\partial Z^{I^*} \partial Z^J}$ is the Kähler metric.

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$$\left(V_D = \frac{1}{2} (\mathrm{Re} f)^{\alpha\beta} (Z) D_\alpha D_\beta \right)$$

F-term (local)SUSY breaking

$$\langle F^I \rangle \neq 0$$

$$F^I = e^{\frac{G}{2m_{p\ell}^2}} K^{IJ^*} G_{J^*}$$

$$G = K + m_{p\ell}^2 \log \frac{|W|^2}{m_{p\ell}^6}$$

$$m_{3/2} = \frac{1}{m_{p\ell}^2} \left\langle |W| e^{\frac{1}{2}\frac{K}{m_{p\ell}^2}} \right\rangle = m_{p\ell} \left\langle e^{\frac{1}{2}\frac{G}{m_{p\ell}^2}} \right\rangle \, ,$$

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If SUSY breaking VEVs of hidden sector fields $\sim \mathcal{O}(m_{p\ell})$ then a strong consistency requirement:

all visible sector fields should not appear in the operators of the Lagrangian that diverge formally in the limit $m_{p\ell} \to \infty$.

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\begin{aligned}
K(h, h^\dagger, \Phi, \Phi^\dagger) &= m_{p\ell}^2 K_2(z, z^\dagger) + m_{p\ell} K_1(z, z^\dagger) + K_0(z, z^\dagger, \Phi, \Phi^\dagger) \ , \\
W(h, \Phi) &= m_{p\ell}^2 W_2(z) + m_{p\ell} W_1(z) + W_0(z, \Phi),
\end{aligned}
$$

where $h^i \equiv m_{p\ell}\, z^i$.

- ...It so happens that these forms always lead to SOFT susy breaking when mediated by gravity!

- $\rightarrow$ subsequent literature adopted these forms even though SUSY breaking VEVs are not necessarily $\mathcal{O}(m_{p\ell})$:

$$W(h,\Phi) \rightarrow m_{p\ell}^2 W_2(z) + W_0(\Phi),$$

$\Rightarrow$ Planck suppressed couplings between hidden and visible sectors & soft susy breaking.

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$\Rightarrow$ Planck suppressed couplings between hidden and visible sectors & soft susy breaking.

$\Rightarrow$ All model-building and phenomenology of mSUGRA, cMSSM, SUGRAmed,...were based on the above result.

Requiring *tree-level* separation of high (here Planck) and low (here GUT, EW,...) scales is a prerequisite to mitigate potential hierarchy problems, irrespective of the ensuing strength of susy breaking.

Repeating Soni & Weldon's exercise

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Approach seemingly straightforward:

$$\begin{aligned} K &= \sum_{n=0}^{N} m_{p\ell}^{n} K_n(z, z^\dagger, \Phi, \Phi^\dagger) \ , \\ W &= \sum_{n=0}^{M} m_{p\ell}^{n} W_n(z, \Phi) \end{aligned}$$

inject in V_F and require positive powers of $m_{p\ell}$ to be $\Phi, \Phi^\dagger$ *independent*.

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BUT we stumbled on something...

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In this talk we focus on the simplest Kähler form

$$K = m_{p\ell}^2 z^{i*} z^i + \Phi^{a*} \Phi^a$$

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$$K = m_{p\ell}^2 z^{i*} z^i + \Phi^{a*}\Phi^a$$

$$V_F = e^{\frac{z^I z^{I^*}}{m_{p\ell}^2}} \sum_{c=0}^{2M} V_{M,c}[z, z^\dagger, \Phi, \Phi^\dagger]\, m_{p\ell}^c + \mathcal{O}(m_{p\ell}^{-1}),$$

Back up

$$V_{M,c}[z, z^\dagger, \Phi, \Phi^\dagger] = \sum_{n_-^{(0)} \le n \le n_+^{(0)}} \frac{\partial W_n}{\partial \Phi^a} \frac{\partial \overline{W}_{c-n}}{\partial \Phi^{a*}} +$$

$$\sum_{n_-^{(2)} \le n \le n_+^{(2)}} \Bigg(\Big(\frac{\partial W_n}{\partial z^i} + z^{i*} W_n \Big) \Big(\frac{\partial \overline{W}_{c-n+2}}{\partial z^{i*}} + z^i \overline{W}_{c-n+2} \Big)$$

$$+ \ \Phi^a \frac{\partial W_n}{\partial \Phi^a} \overline{W}_{c-n+2} + \Phi^{a*} \frac{\partial \overline{W}_n}{\partial \Phi^{a*}} W_{c-n+2} - 3 W_n \overline{W}_{c-n+2} \Bigg)$$

$$+ \sum_{n_-^{(4)} \le n \le n_+^{(4)}} W_n \overline{W}_{c-n+4} \Phi^{a*} \Phi^a$$

$$n_+^{(s)} = \min[M, c+s],$$
$$n_-^{(s)} = \max[0, c-M+s]$$

Back up

E.g. for $c = 2M - 1$:

$$\frac{\partial \overline{W}_M}{\partial \Phi^{a*}} \frac{\partial W_{M-1}}{\partial \Phi^a} + \text{h.c.} \sim_\Phi 0$$

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$$\{\Phi\} = \{\widetilde{\Phi}^a, S^1\}$$

$$W(z,S,\widetilde{\Phi}) = m_{p\ell}\Big[W_{1,0}(z) + S^1 W_{1,1}(z)\Big] + \; W_0(z,\widetilde{\Phi}) + S^1 W_{0,1}(z)$$

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BUT Planck suppressed coupling of S^1 to the rest of the visible sector.

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$$W(h,\Phi) = m_{p\ell} W_1(z,S) + W_0(z,S,\widetilde{\Phi})$$

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where

$$W_1(z,S) = W_{1,0}(z) + \textstyle\sum_{p\geq 1}^{P} W_{1,p}(z) \sum_{s\geq 1}^{n_p} \mu_{p_s}^* S^{p_s},$$

$$W_0(z,S,\widetilde{\Phi}) = \textstyle\sum_{q\geq 1}^{k} W_{0,q}(z)\, S^q + \Xi(\ldots, \mathcal{U}_S^{pp_s} \ldots; \ldots, \widetilde{\Phi}^a, \ldots; \ldots, z^i, \ldots),$$

with

$$\mathcal{U}_S^{pp_s} \equiv \xi_{p_s}(z) S^{p_s} - \xi^{p_s}(z) S^{p_1} \text{ and } \mu_{p_s}\xi_{p_s}(z) = \mu_{p_1}\xi^{p_s}(z)$$

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- the gravitino mass: $m_{3/2} = \frac{1}{m_{p\ell}^2}\left\langle |W| e^{\frac{1}{2}\frac{K}{m_{p\ell}^2}} \right\rangle = \frac{M^2}{m_{p\ell}} e^{\frac{1}{2}|\langle z_i \rangle|^2}$

  $\rightarrow$ compare: $M e^{\frac{1}{2}|\langle z_i \rangle|^2}$; M some lower energy physics scale.

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- e.g. $\lambda S H_u \cdot H_d,\ \xi_F S,\ \frac{1}{2}\mu' S^2,\ \frac{1}{3}\kappa S^3$

$\downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow\ \downarrow$

$\lambda \mathcal{U}_S^{ab} H_u \cdot H_d,\ \xi_F^a S^a + \xi_F^b S^b,\ \frac{1}{2}\mu' [\mathcal{U}_S^{ab}]^2,\ \frac{1}{3}\kappa [\mathcal{U}_S^{ab}]^3$

$$\mathcal{U}_S^{ab} = \xi_F^{a*} S^b - \xi_F^{b*} S^a$$

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$$\mathcal{U}_S^{ab} = \xi_F^{a*} S^b - \xi_F^{b*} S^a$$

- the S-fields could be charged under (gauge) symmetries of secluded sectors $\rightarrow$ interesting Yukawa structures $(\mathcal{U}_S^{ab})_L \cdot H\ (\mathcal{U}_S^{ab})_R$
- ...

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$z^i \to z^i + \langle z^i \rangle$ in the Lagrangian

$$\Downarrow$$

SUSY breaking mediation to the visible sector

SUSY breaking terms

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$$V_{\mathsf{LE}}^{\mathsf{NSWS}} = \left|\frac{\partial \widehat{\Xi}}{\partial \widetilde{\Phi}^a}\right|^2 + m_{3/2}^2 \; |\widetilde{\Phi}^a|^2$$
$$+ \; m_{3/2}\Big((A-3)\widehat{\Xi}$$
$$+ \; \widetilde{\Phi}^a \frac{\partial \widehat{\Xi}}{\partial \widetilde{\Phi}^a} + \text{h.c.}\Big)$$
$$+ \; \mathcal{O}(m_{p\ell}^{-2}) \; ,$$

SUSY breaking terms

$$
\begin{aligned}
V_{\mathsf{LE}}^{\mathsf{NSWS}} &= \left|\frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a}\right|^2 + \left|\frac{\partial\widehat{\Xi}}{\partial S^q}\right|^2 + m_{3/2}^2\ |\widetilde{\Phi}^a|^2 \\
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&+ m_{3/2}\Big(\,(A-3)\widehat{\Xi} \\
&+ \widetilde{\Phi}^a\frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a} + \mathsf{h.c.}\Big) \\
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$$+ \; m_{3/2}\Big(\big(A - 3 + \langle A^{(S)}\rangle + (|b_i|^2 - 2)\mathbf{A}^{(\mathbf{S})} + b_i^* A_i'^{(S)}\big)\,\widehat{\Xi}$$

$$+ \; \widetilde{\Phi}^a\frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a} + \mathsf{h.c.}\Big)$$

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$$+ \ \widetilde{\Phi}^a \frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a}\,(1 + \mathbf{A}^{(\mathbf{S})}) + (1 + \mathbf{A}^{(\mathbf{S})})\,(S^q + \langle S^q\rangle)\frac{\partial\widehat{\Xi}}{\partial S^q} + \text{h.c.}\Big)$$

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+ \; & \widetilde{\Phi}^a \frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a}\,(1 + \mathbf{A}^{(\mathbf{S})}) + (1 + \mathbf{A}^{(\mathbf{S})})\,(S^q + \langle S^q\rangle)\frac{\partial\widehat{\Xi}}{\partial S^q} + \mathsf{h.c.}\Big) \\
+ \; & e^{|b_i|^2} M^2 \mathcal{A}_{qr} S^q S^{r*} \\
+ \; & e^{|b_i|^2} M^3\Big(\big((A + \langle A^{(S)}\rangle - 2)a_q^* + A'\mu_q^*\big)S^q + \mathsf{h.c.}\Big) \\
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SUSY breaking terms

$$\begin{aligned} V_{\mathsf{LE}}^{\mathsf{NSWS}} &= \left|\frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a}\right|^2 + \left|\frac{\partial\widehat{\Xi}}{\partial S^q}\right|^2 + m_{3/2}^2\Big(|\widetilde{\Phi}^a|^2 + |S^q + \langle S^q\rangle|^2\Big)|1 + \mathbf{A}^{(\mathbf{S})}|^2 \\ &+ m_{3/2}\Big(\big(A - 3 + \langle A^{(S)}\rangle + (|b_i|^2 - 2)\mathbf{A}^{(\mathbf{S})} + b_i^* A_i'^{(S)}\big)\,\widehat{\Xi} \\ &+ \widetilde{\Phi}^a \frac{\partial\widehat{\Xi}}{\partial\widetilde{\Phi}^a}(1 + \mathbf{A}^{(\mathbf{S})}) + (1 + \mathbf{A}^{(\mathbf{S})})\,(S^q + \langle S^q\rangle)\frac{\partial\widehat{\Xi}}{\partial S^q} + \text{h.c.}\Big) \\ &+ e^{|b_i|^2} M^2 \mathcal{A}_{qr} S^q S^{r*} \\ &+ e^{|b_i|^2} M^3\Big(\big((A + \langle A^{(S)}\rangle - 2)a_q^* + A'\mu_q^*\big)S^q + \text{h.c.}\Big) \\ &+ \mathcal{O}(m_{p\ell}^{-2})\ , \end{aligned}$$

→ hard SUSY breaking induced by $\mathbf{A}^{(\mathbf{S})}$, (and $A_i'^{(S)}$ if $\langle S^q\rangle \neq 0$)

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→ parametrically small (?)

Pheno @ Colliders

Pheno @ Colliders

- direct coupling of the S-sector to the usual vis. sector needs *at least two* S-fields because:

$$\Xi(\ldots, \mathcal{U}_S^{1p} \ldots, \widetilde{\Phi}^a, \ldots, z^i, \ldots),$$

with

$$\mathcal{U}_S^{1p} \equiv \mu_1 S^p - \mu_p S^1$$

- the S-fields should be SM singlets because
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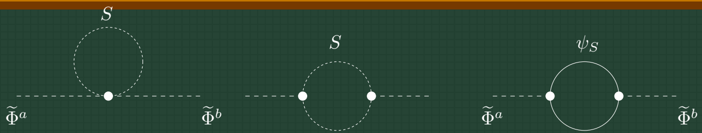
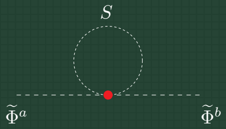
e.g. we need to construct an NNMSSM-like model but with some specificities:

- the NMSSM superpotential parameters, λ, κ, μ' and ξ_F are not just "doubled"; they are interrelated.
- the electroweak symmetry breaking conditions are different from normal NNMSSM
- SUSY mass spectrum, Higgs masses, etc.
- Renormalization Group Evolution unconventional:
  - effects of the VEVs of the S-fields on the running
  - effects of hard breaking terms
- other...





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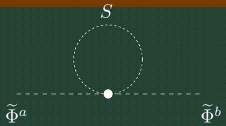

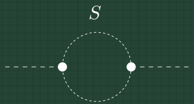

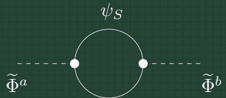

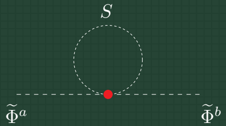

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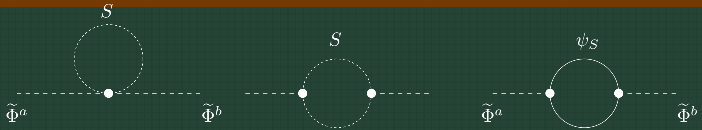

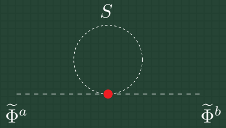

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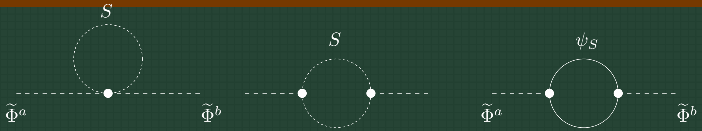

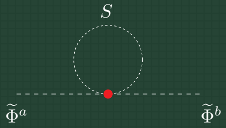

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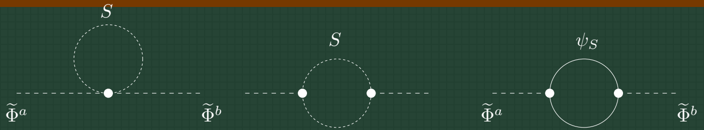

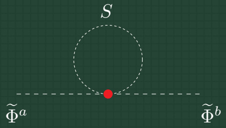

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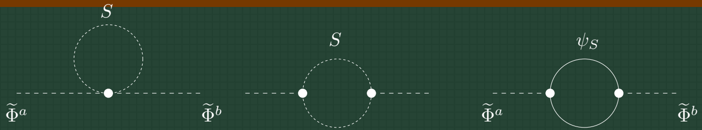

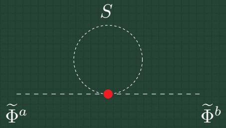

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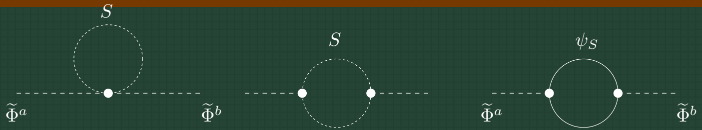

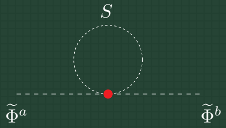

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e.g up to $\mathcal{O}(20\%)$ for $M_1 \lesssim \mathcal{O}(10^{15})$ GeV and $M_4 \sim \mathcal{O}(10^{16})$ GeV

Dark Matter

- the simplest case: one S-field

$$W(z,S,\widetilde{\Phi}) = m_{p\ell}\Big[W_{1,0}(z) + W_{1,1}(z)\,S\Big] + \; W_0(z,\widetilde{\Phi}) + W_{0,1}(z)\,S.$$

- various model-dependent mass scales:

$$W_{1,0} = M_1^2 w_1,\; W_{1,1} = M_2 w_{11} \equiv M_{11} w_{11}$$
$$W_{0,1} = M_3^2 w_{01}, W_0 = M_4^3 w_0$$

- coupling of S is Planck suppressed to both hidden z and visible $\widetilde{\Phi}$ fields. But leading couplings to z.
- S mass $\mathcal{O}(m_{3/2})$; z mass $\mathcal{O}(M)$
- e.g. depending on mass hierarchies, couplings $\mathcal{O}(M_2^2/m_{p\ell}^2)$ or $\mathcal{O}(M_1^4/m_{p\ell}^4)$

Inflation

- more than one S-field $\Rightarrow$ dependence on $\mathcal{U}_S^{1p} \equiv \mu_1 S^p - \mu_p S^1$ in the superpotential
- $\Rightarrow$ approximately flat directions $\mathcal{U}_S^{1p} = 0$ in the potential; partially lifted by Susy breaking terms.
- can this be interesting for inflationary scenarios?
  - revisit SUGRA inflation (η-problem, etc.)
  - multi-scalar scenarios, (geometric destabilisation, etc.)
  - other...

Further formal developments

- more general superpotential
- generalization of the classification to non-minimal Kähler
- the fermionic sector ?
- hidden sector VEVs $\ll m_{p\ell}$
- ...

Provisional conclusions and outlook

- separation of Planck and EW scales compatible with other structures than usually assumed.
- these structures suggest NNMSSM-like models, but with unusual SUSY breaking (including parametrically small hard breaking).
- can these be implemented into viable models (RGEs, mass spectrum, ...)?
- can they live better with the so far no SUSY experimental discovery? less fine-tuned H-125?
- pheno? DM ? cosmo? $\rightarrow$ S.low.SUGRA project (IPHC, L2C, LUPM, APC)