Gravity mediated supersymmetry breaking:
Impact of new "hybrid" superfield sector on the Higgs sector

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IRN Terascale@Grenoble: April, 25, 2023

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Overview

Outline

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Gravitationnal interactions between a Hidden Sector $\{z^i\}$ and the Matter Sector $\{\Phi^a\}$

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Kähler potential & Superpotential:

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger$$

$$W(z, \Phi) = m_p^2 W_2(z) + m_p W_1(z) + W_0(z, \Phi)$$

Gravitino mass: $m_{3/2} = e^{K/(2m_p^2)} \langle W \rangle / m_p^2 = M$

SUSY Breaking terms: V_{SOFT}

- good renormalisation properties ($\propto \log \Lambda$)
- holomorphic or anti-holomorphic terms (ex: ϕ^2,$(\phi^\dagger)^3$...) + soft mass terms $\phi^\dagger \phi$

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New Solutions

Kähler potential & Superpotential:

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger + \mathbf{S^p S_p^\dagger}$$

$$W(z, \Phi) = m_p W_1(z, \mathbf{S}) + W_0(z, \mathbf{S}, \Phi)$$

$$\left\{ \begin{array}{l} W_1(z, \Phi) = W_{1,0}(z) + W_{1,p}(z)\mu_p^* \mathbf{S^p} \\ W_0(z, \Phi) = W_{0,p}(z)\mathbf{S^p} + W_0(z, \mathcal{U}, \Phi) \\ \langle \mathbf{S^p} \rangle \ll m_p \end{array} \right\}$$

$\mathbf{S}$: "hybrid sector", $\mathcal{U}^{\mathbf{pq}} = \mu^{\mathbf{q}} \mathbf{S^p} - \mu^{\mathbf{p}} \mathbf{S^q}$

Need at least 2 S for direct EW coupling

Gravitino mass: $m_{3/2} = e^{K/(2m_p^2)} \langle W \rangle / m_p^2 = \frac{M^2}{m_p}$

SUSY Breaking terms: $V_{SOFT} + \mathbf{V_{HARD}}$

- **HARD:** quadric divergences... but parametrically suppressed!
- **HARD:** non-holomorphic terms (ex: $\phi^2 \mathbf{SS^\dagger}$,...) $\rightarrow$ Can close loops!

Outline

S2MSSM: NMSSM-like with two hybrid fields $\{S^1, S^2\}$

Presentation of the model (R. Ducrocq, Proceedings 34th IGCTMP, 2023 & R. Ducrocq, PhD. Thesis, 2021)

How to incorporate the MSSM in these new solutions with non-flat Kähler potential?

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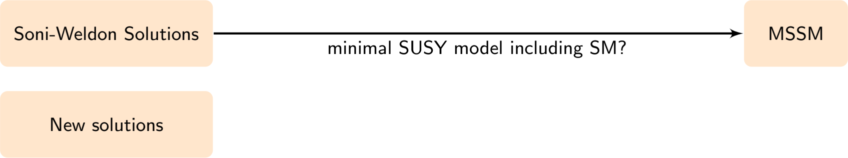

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Soni-Weldon Solutions	→ minimal SUSY model including SM?	MSSM
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New solutions → (minimal SUSY model including SM?) → **S2MSSM**

Superfields content ($G = SU(3)_c \times SU(2)_L \times U(1)_Y$)

Observable sector	**Hidden Sector**	**Hybrid Sector**
$\Phi_{MSSM} = \{H_U, H_D, Q, L, U, D, E\}$	$\{z^i\}$	$S = \{S^1, S^2\} \rightarrow \mathcal{U} = \mu_2 S^1 - \mu_1 S^2$

Non-universal Kähler potential and NMSSM-like Superpotential

$$K(\mathbf{z}, \mathbf{z}^\dagger, \mathbf{\Phi}, \mathbf{\Phi}^\dagger) = m_p^2 \mathbf{z}^{\mathbf{i}} \mathbf{z}_{\mathbf{i}}^\dagger + \Lambda_a(\mathbf{z}) \mathbf{\Phi}_{\mathbf{a}}^\dagger \mathbf{\Phi}^{\mathbf{a}} + \mathbf{S}_{\mathbf{p}}^\dagger \mathbf{S}^{\mathbf{p}}$$
$$W(\mathbf{z}, \mathbf{\Phi}, \mathbf{S}) = m_p W_1(\mathbf{z}, \mathbf{S}) + W_0(\mathbf{z}, \mathbf{S}, \mathbf{\Phi})$$

with

$$\left\{ \begin{array}{l} W_1(\mathbf{z}, \mathbf{S}) = W_{1,0}(\mathbf{z}) + W_{1,p}(\mathbf{z}) \mu_p^* \mathbf{S}^{\mathbf{p}} \\ W_0(\mathbf{z}, \mathbf{\Phi}, \mathbf{S}) = W_{0,p}(\mathbf{z}) \mathbf{S}^{\mathbf{p}} + \Xi(\mathbf{z}, \mathcal{U}, \mathbf{\Phi}) \end{array} \right\}$$

$$\Xi(\mathbf{z}, \mathcal{U}, \mathbf{\Phi}) = \lambda(z) \mathcal{U} H_U \cdot H_D + \frac{1}{6} \kappa(z) \mathcal{U}^3 + y_U(z) Q \cdot H_U U - y_D(z) Q \cdot H_D D - y_E(z) L \cdot H_D E$$

$\Lambda_a(\mathbf{z}) \mathbf{\Phi}_{\mathbf{a}}^\dagger \mathbf{\Phi}^{\mathbf{a}}$: need a rescale of the fields $\Phi^a \rightarrow 1/\sqrt{\langle \Lambda_a \rangle} \Phi^a$ which modify the couplings $(\langle \Lambda_a \rangle > 0)$

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Goal: Phenomenological analysis of this new model (mass spectrum, one-loop contributions, ...)
Very complicated model (New contributions, form of the gravitino mass, ...)

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Example of new hard contributions:

$$\frac{M_2^2}{m_p^2} e^{|\langle z \rangle|^2} \left(\Phi^a \Phi_a^\dagger + S^p S_p^\dagger\right) \left(4|\xi_{3/2}|^2 - 2\right) \mathrm{i}_r \bar{\mathrm{i}}^t \mathbf{S}^\mathbf{r} \mathbf{S}_\mathbf{t}^\dagger \quad \text{with:} \quad \mathrm{i}_p = \mathcal{I}_p / (m_p M_2)$$

Can close very heavy S-loop and contribute to Φ-mass, etc.,... ⇒ **shift all mass spectrum upwords**

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Before full phenomenological analysis: need simple preliminary studies to understand the real nature of such solutions

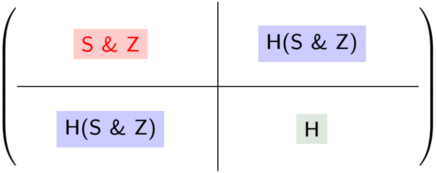
only consider $\Phi^a = \{H_U, H_D\}$ (no Squark/Slepton sector)
$\langle S^p \rangle$ & $\langle \Phi^a \rangle \simeq 0$
No direct couplings between the matter & the hybrid sector: $\Xi(z, \Phi, \mathcal{U}) = \Xi(z, \Phi)$

Preliminary analysis: impact of V_{HARD} on the Higgs boson mass

Mass matrix and order of magnitude of the S-loop

Assume only one field in the hiden sector z

To first order of $1/m_p$, the two sectors $\{z, S^p\}$ and $\{H_U, H_D\}$ can be diagonalised separately



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S & Z	H(S & Z)
H(S & Z)	H

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Assuming $\{\mathbf{S^p}\}$ ($\mathbf{p = 1, \ldots, n}$):

Only one state mix with z, & $(n-1)$ degenerated states with $m^2_{S^p} = m^2_{3/2}$!

$$\mathbb{M}^2_{\mathbf{S,z}} = \begin{pmatrix} |m_{3/2}|^2 \mathbb{I}_{n-1} & 0 & 0 \\ 0 & |m_{3/2}|^2 + b|\mathcal{I}|^2 & c|\mathcal{I}| \\ 0 & \bar{c}|\mathcal{I}| & d \end{pmatrix}$$

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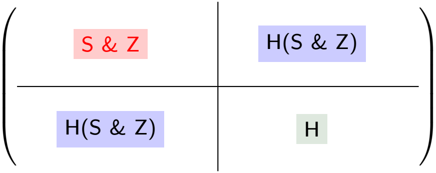

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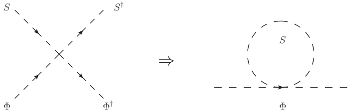
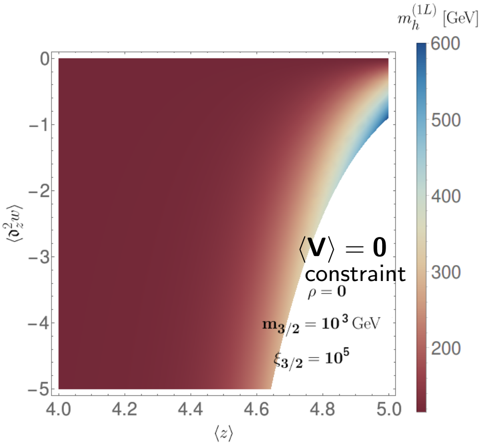
Consider only one S-field to calculate the order of magnitude: $S = \zeta' \sin\theta + S' \cos\theta$



$$\delta\mathcal{O} \approx \frac{1}{16\pi^2}(m^2_{\zeta'} \sin^2\theta + m^2_{S'} \cos^2\theta)$$

Approximation of One-loop Higgs boson mass



Several free parameters:

$$m_h^{(1L)} = f(m_h^{(T.L.+1loop\ Soft)}, m_{3/2}, \langle z \rangle, \langle \mathfrak{d}_z^2 w \rangle, \xi_{3/2}, M_{GUT}, \ldots)$$

Tree-level + 1-loop SOFT: $m_h^{(T.L.+1loop\ Soft)} = 115$ GeV

Notations: $W = M_{GUT}^3 w, \rho = \langle \partial_z \partial_\phi W_0 / W \rangle$

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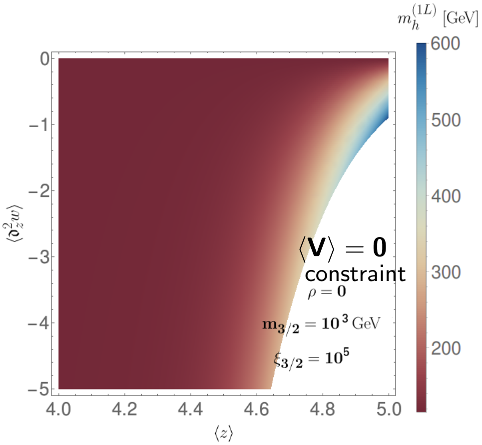

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$\langle z \rangle \approx 4$: **Several fields in the hidden sector?**

The same results can be naturally obtained by extending the hidden sector with n fields:

$$\frac{1}{m_p^4} e^{\sum_i |\langle z^i \rangle|^2} (\Phi\Phi^\dagger + S^p S_p^\dagger)(4\sum_i |\xi_{3/2i}|^2 - 2)\mathcal{I}_r \bar{\mathcal{I}}^t S^r S_t^\dagger$$
$$- \frac{2}{m_p^2} e^{\sum_i |\langle z^i \rangle|^2} \bar{\mathcal{I}}^q S_q^\dagger \mathcal{U} H_U \cdot H_D$$

Four fields z^i with $\langle z^i \rangle \approx m_p$ from the hidden sector may lead to $m_h \approx 125$ GeV. It remains a fine-tuning in the hidden sector

Notations: $W = M_{GUT}^3 w, \rho = \langle \partial_z \partial_\phi W_0 / W \rangle$

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Preliminary analysis: helps for the general analysis of the S2MSSM

Asuming the general form of the S2MSSM:

Effects from the vevs $\langle S^p \rangle$ & from the direct couplings $W_0(z, \Phi, \mathcal{U})$

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Example: Does the structure of the mass matrix in the $\{S, z\}$ sector remain?

A lot of new contributions in the mass matrix

$$\mathbb{M}^2_{\mathbf{S},\mathbf{z}} = \begin{pmatrix} \delta_p{}^q a' + e' + b' \mathcal{J}_p \bar{\mathcal{J}}^q & c' \mathcal{J}_p + f'_p \\ \bar{c}' \bar{\mathcal{J}}^q + \bar{f}'^q & d' \end{pmatrix} \quad \text{with} \quad \mathcal{J}_p = \mathcal{I}_p + \langle \partial_p W_0 \rangle \quad , \quad \partial_p W_0 = \frac{\partial W_0}{\partial S^p}$$

The structure is more complex... needs a complete numerical analysis of the mass spectrum

Loop contributions will not be the same... **Do such models still need several fields $\{\mathbf{z}^i\}$ for $\mathbf{m}_h^{(1L)} = 125$ GeV?**

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Deserves further investigations...

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$$M_Z^2\left(\cos^2\beta + \frac{\lambda}{\mathbf{g}}\sin^2\beta\right) \quad \text{with} \quad \tan\beta = v_U/v_D \;\&\; \lambda\text{: S/H-coupling in } W_{NMSSM}$$

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Starting from the mass matrix of the NMSSM ($\{\mathfrak{Re}(H_D^0), \mathfrak{Re}(H_U^0), \mathfrak{Re}(S)\}$) to identify usefull rules for the S2MSSM:

$$\begin{pmatrix} \varepsilon^2 c_6 & \varepsilon^2 c_7 & \varepsilon c_5 \\ \varepsilon^2 c_7 & c_3 & \varepsilon c_2 \\ \varepsilon c_5 & \varepsilon c_2 & c_1 \end{pmatrix} \quad \text{with} \quad \varepsilon = M_Z/v_S \qquad \Rightarrow \textbf{Only one eigenvalue} \propto \epsilon^2$$

Can be generalised to $n \times n$ matrix (in the lowest orfer of ε):

$$\begin{cases} \mathfrak{v}_p^i &= c_i \ (i = 1, 3, \dots, n) \\ \mathfrak{v}_p^2 &= \varepsilon^2 (c_1 - c_{1,n}^2/c_n) \end{cases}$$

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Can this be applied in the case of the S2MSSM? (need more calculations & verifications)

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Is such constraint in accordance with $\langle V \rangle = 0$ and $\langle \frac{\partial V}{\partial \phi^i} \rangle = \langle \frac{\partial V}{\partial S^p} \rangle = \langle \frac{\partial V}{\partial z^i} \rangle = 0$?

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Do all terms contribute to the SUSY Breaking with $v_{S^i} \ll m_p$ ($v_{S^i} \approx 0$)?

Need to analysis which terms do not contribute to $\langle F^i \rangle$ with $v_{S^i} = 0$
How it impacts the SUSY Breaking terms and the phenomenology?

If couplings not contribute to SUSY breaking:

Compensation between scalar & fermionic contributions → no quadratic divergences!

Outline

These new solutions bring new models and solutions to investigate

Done:

- Define a simple non-flat model based on the new solutions: the S2MSSM ✓
- Preliminary analysis on the impact of V_{HARD} on the Higgs boson mass ✓
  - Found configurations leading to $m_h = 125$ GeV corresponding to several fields in the hidden sector ✓
- Mass matrix in the general S2MSSM ✓

To be done:

- F-terms contributions **(Study in progress)**
- Numerical computation of the tree-level mass spectrum ✗
- One-loop radiative correction on m_h in the general case ✗
- Spectrum generator?... ✗

The analysis is tedious due to:
presence of new (hard and soft) contributions
several constraints applied
specific strucutre of these new solutions

BACK-UP

The "gravitino-rule"

In Soni-Weldon solutions:

$$m_{3/2} = \frac{1}{m_p^2} e^{K/(2m_p^2)} \langle m_p^2 W_2(z) + m_p W_1(z) + W_0(z,\Phi) \rangle \approx M^2$$

In the new solutions:

$$m_{3/2} = \frac{1}{m_p^2} e^{K/(2m_p^2)} \Big(\langle m_p W_1(z) + W_0(z,\Phi,S) \rangle + \langle \mathbf{S^p} \rangle \langle \mathbf{m_p W_{1,p}(z) + W_{0,p}(z)} \rangle \Big) \approx \frac{M^2}{m_p}$$

Since some Soft SUSY Breaking are $\propto m_{3/2}$:

New contributions generate a relation between some Soft SUSY Breaking and Hard SUSY Breaking (perturbations $S^p \to S^p + \langle S^p \rangle$)

"gravitino-rule"

Firstly: Relevant parameters for $m_h^{(1L)}$:

$\mathbf{m^2_{\zeta'}}$, $\mathbf{m^2_{S'}}$, $\sin^2\theta$, $|\mathcal{I}|^2$

- $\mathbf{m^2_{\zeta'}}$: Mass of the heaviest state
- $\mathbf{m^2_{S'}}$: Mass of the lowest state
- $\sin^2\theta$: Mixing angle in the basis $\{S, z\}$
- $|\mathcal{I}|^2$: Function present in the superpotential

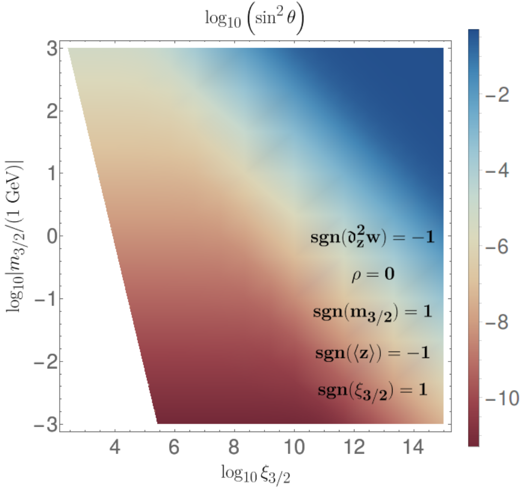
Several free parameters:

$$\{m_{3/2}, \langle z\rangle, \langle \mathfrak{d}_z^2 w\rangle, \xi_{3/2}, M_4, \langle \partial_z\partial_\phi\omega_0\rangle, ...\rangle\}$$

Notations: $W_0 = M_4^3\omega_0, W = M_4^3 w,\ M_4 = M_{GUT}$,

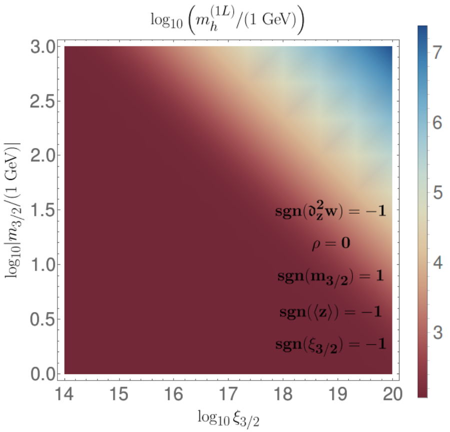
$$\rho = \partial_z\partial_\phi\omega_0/w$$

Example of possible configurations:



Approximation of One-loop Higgs boson mass

$$m_h^{(1L)} = \sqrt{m_h^2(TL) + \frac{1}{16\pi^2 m_p^2} e^{|\langle z\rangle|^2} \left(\mathbf{m}^2_{\zeta'} \sin^2\theta + \mathbf{m}^2_{S'} \cos^2\theta\right)\left(\sqrt{|\mathcal{I}|^2} + \frac{1}{m_p^2}(4|\xi_{3/2}|^2 - 2)|\mathcal{I}|^2\right)} \quad \text{with } m_h^{(T.L.)} = 115 \text{ GeV}$$



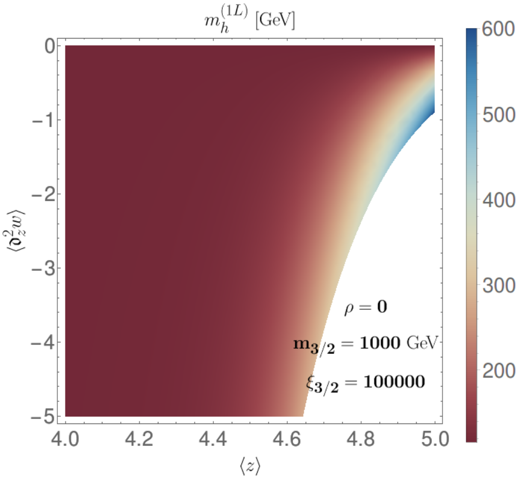
Several free parameters:

$$\{m_{3/2}, \langle z\rangle, \langle \eth_z^2 w\rangle, \xi_{3/2}, M_4, \langle \partial_z\partial_\phi\omega_0\rangle, \ldots\}$$

Notations: $W_0 = M_4^3\omega_0, W = M_4^3 w, \; M_4 = M_{GUT}, \rho = \partial_z\partial_\phi\omega_0/w$

Possible push-up effects for high $\xi_{3/2}$

Solutions for $m_h \approx 125$ GeV exists but are fine-tuned (with one S)



$4\langle z\rangle$: **Non-sense?**

Hard-breaking terms for several fields from the hidden sector:

$$\frac{1}{m_p^4} e^{\sum_i |\langle z^i\rangle|^2} \left(M_4^2 \phi\phi^\dagger + S^p S_p^\dagger\right)$$

$$\times \left(4 \sum_i |\xi_{3/2i}|^2 - 2\right) \mathcal{I}_r \bar{\mathcal{I}}^t S^r S_t^\dagger$$

$$-\frac{2}{m_p^2} e^{\sum_i |\langle z^i\rangle|^2} \bar{\mathcal{I}}^q S_q^\dagger \mathcal{U} H_U \cdot H_D$$

Several fields z^i from the hidden sector may lead to $m_h \approx 125$ GeV

Supersymmetry must be broken (ex : $m_{\tilde{e}_L} \gg m_e$)

Breaking mechanisms in SUSY not phenomenologically acceptable! $\Rightarrow$ **Supergravity & Hidden Sector**

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Supergravity

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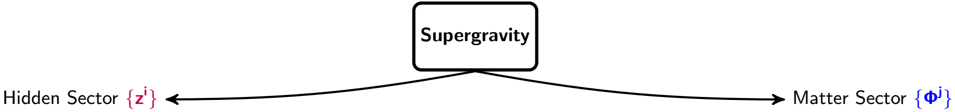


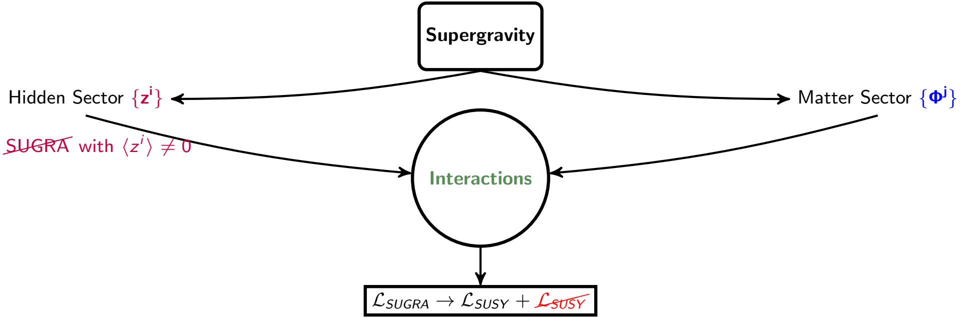
~~SUGRA~~ with $\langle z^i \rangle \neq 0$

New solutions in Gravity-Mediated Supersymmetry Breaking

Generalities on SUSY Breaking

Supersymmetry must be broken (ex : $m_{\tilde{e}_L} \gg m_e$)

Breaking mechanisms in SUSY not phenomenologically acceptable! $\Rightarrow$ **Supergravity & Hidden Sector**



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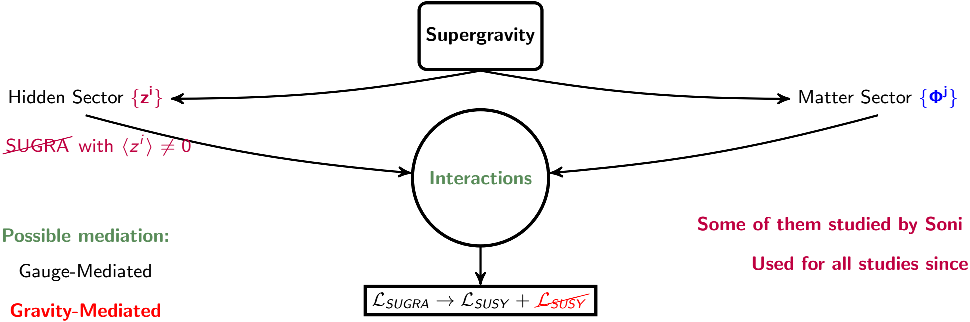

Possible mediation:

Gauge-Mediated

Gravity-Mediated

Anomaly-Mediated

Some of them studied by Soni & Weldon

Used for all studies since 80s

New solutions in Gravity-Mediated Supersymmetry Breaking

Soni & Weldon solutions (Sanjeev K. Soni, H.Arthur Weldon, Physics Letters B, 1983)

Not all forms of $K(\Phi, \Phi^\dagger)$ and $W(\Phi)$ lead to coherent SUSY Breaking
Expansion of the fundamental functions of Supergravity as power of m_p:

$$K = \sum_{n=0}^{r} K_n m_p^n, \quad W = \sum_{n=0}^{s} W_n m_p^n$$

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Requirement

At least one field from Hidden sector with $\langle z \rangle \sim \mathcal{O}(m_p)$ and $\langle \Phi \rangle \ll m_p$

Visible sector fields interactions **only present in V as m_p^{-n} with $n \geq 0$**

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Flat case: After solving a tower of differential equations... **Found two solutions:**

$$m_{3/2} = e^{K/(2m_p^2)} \frac{\langle W \rangle}{m_p^2} = M^2$$

Soni-Weldon solution (known since the 80's)

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger$$

$$W(z, \Phi) = m_p^2 W_2(z) + m_p W_1(z) + W_0(z, \Phi)$$

Before SUSY Breaking

$$V_F = e^{\frac{K}{2m_p^2}} \left(\mathcal{D}_i W \delta^i{}_{j^*} \overline{\mathcal{D}}^{j^*} \overline{W} - \frac{3}{m_p^2} |W|^2 \right)$$

Curved case:
$\delta^i{}_{j^*} \to (\mathbf{K}^{-1})^i{}_{j^*}$

After SUSY Breaking

$$V_F = \partial_i W' \delta^i{}_{j^*} \partial^{j^*} \overline{W'} + \mathbf{V_{SOFT}} + m_p^2 \Lambda$$

$\mathbf{V_{SOFT}}$: good renormalisation properties

$$m_{3/2} = \frac{M^2}{m_p}$$

New solutions (new field sector S)

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger + S^p S_p^\dagger$$

$$W(z, \Phi) = m_p \mathbf{W_1(z, S)} + W_0(z, S, \Phi) \text{ with } \left\{ \begin{array}{l} W_1(z, \Phi) = W_{1,0}(z) + W_{1,p}(z)\mu_p^* S^p \\ W_0(z, \Phi) = W_{0,p}(z) S^p + W_0(z, \mathcal{U}, \Phi) \\ \langle S^p \rangle \ll m_p \end{array} \right\} \text{ and } \mathcal{U} = \mu^p S^q - \mu^q S^p$$

S: new "hybrid" field sector with properties from both hidden and matter sector

Couplings proportionnal to the hidden sector

Couplings present in V in the limit $m_p \to \infty$

New solutions in Gravity-Mediated Supersymmetry Breaking

New solutions (G. Moultaka, M. Rausch de Traubenberg, D. Tant, Int. J. Mod. Phys. A, 2019)

$$m_{3/2} = \frac{M^2}{m_p}$$

New solutions (new field sector S)

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger + S^p S_p^\dagger$$

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S: new "hybrid" field sector with properties from both hidden and matter sector

Couplings proportionnal to the hidden sector

Couplings present in V in the limit $m_p \to \infty$

Such solutions generates new **parametrically supressed** **Hard** breaking terms

Curved case: $\delta^i{}_{j^*} \to (K^{-1})^i{}_{j^*}$

Before SUSY Breaking

$$V_F = e^{\frac{K}{2m_p^2}} \left(\mathcal{D}_i W \delta^i{}_{j^*} \overline{\mathcal{D}}^{j^*} \overline{W} - \frac{3}{m_p^2} |W|^2 \right)$$

After SUSY Breaking

$$V_F = \partial_i W' \delta^i{}_{j^*} \partial^{j^*} \overline{W'} + \mathbf{V_{SOFT}} + \mathbf{V_{HARD}} + m_p^2 \Lambda$$

Example: $\frac{1}{6} F_{ijk}{}^l \phi^i \phi^j \phi^k S_l^\dagger + \frac{1}{4} E_{ik}{}^{jl} \phi^i \phi_j^\dagger S^k S_l^\dagger$ (gravitino-rule)

Scalar potential

$$
\begin{aligned}
V \;=\;& m_p^2 \left|m_{3/2}\right|^2 \Big(\frac{1}{\left|\xi_{3/2}\right|^2} - 3\Big) + e^{\left|\langle z\rangle\right|^2} \Big(\sum_p \left|\mathcal{I}_p + M_4^3 \partial_p \omega_0\right|^2 + M_4^4 \partial_a \omega_0 \partial^{a^*} \bar{\omega}_0 \langle (\Lambda^{-1})^a{}_{a^*}\rangle \Big) \\
&+ M_4^2 \Big((\langle\phi^a\rangle + \phi^a)(\langle\phi^\dagger_{a^*}\rangle + \phi^\dagger_{a^*}) \Big) \Big(\left|m_{3/2}\right|^2 \mathcal{S}^{a^*}{}_a + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} [\bar{m}_{3/2} S^p \, (\mathcal{S}_p)^{a^*}{}_a + \text{h.c.}] + \frac{1}{m_p^4} e^{\left|\langle z\rangle\right|^2} S^p S^\dagger_q \, (\mathcal{S}^q{}_p)^{a^*}{}_a \Big) \\
&+ \Big((\langle S^p\rangle + S^p)(\langle S^\dagger_p\rangle + S^\dagger_p) \Big) \Big(\left|m_{3/2}\right|^2 T + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} [\bar{m}_{3/2} S^r T_r + \text{h.c.}] + \frac{1}{m_p^4} e^{\left|\langle z\rangle\right|^2} S^r S^\dagger_t T^t{}_s \Big) \\
&+ \frac{1}{m_p^2} e^{\left|\langle z\rangle\right|^2} S^p S^\dagger_q \Big(\mathfrak{d}_z \mathcal{I}_p \mathfrak{d}^z \bar{\mathcal{I}}^q - 3 \mathcal{I}_p \bar{\mathcal{I}}^q \Big) \\
&+ \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} \Big\{ \Big(M_4^2 (\langle\phi^\dagger_{a^*}\rangle + \phi^\dagger_{a^*})(\langle\phi^a\rangle + \phi^a)\langle\Lambda^{a^*}{}_a\rangle + (\langle S^\dagger_p\rangle + S^\dagger_p)(\langle S^p\rangle + S^p) \Big) (\langle S^q\rangle + S^q)\mathcal{I}_q \times \\
&\qquad\qquad \Big(\bar{m}_{3/2} + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} S^\dagger_r \bar{\mathcal{I}}^r \Big) + \text{h.c.} \Big\} \\
&+ \frac{1}{m_p^2} e^{\left|\langle z\rangle\right|^2} \Big(M_4^2 (\langle\phi^a\rangle + \phi^a)(\langle\phi^\dagger_{a^*}\rangle + \phi^\dagger_{a^*})\langle\Lambda^{a^*}{}_a\rangle + (\langle S^p\rangle + S^p)(\langle S^\dagger_p\rangle + S^\dagger_p) \Big) \Big(\sum_r \left|\mathcal{I}_r\right|^2 + M_4^3 \bar{\mathcal{I}}^r \partial_r \omega_0 + M_4^3 \mathcal{I}_r \partial^r \bar{\omega}^0 \Big) \\
&+ e^{\frac{1}{2}\left|\langle z\rangle\right|^2} \Big\{ \bar{m}_{3/2} M_4^3 R^b{}_a (\langle\phi^a\rangle + \phi^a) \partial_b \omega_0 + \frac{M_4^3}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} (R^p)^b{}_a (\langle\phi^a\rangle + \phi^a) S^\dagger_p \partial_b \omega_0 \qquad (1) \\
&\qquad + [\bar{m}_{3/2} + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} S^\dagger_q \bar{\mathcal{I}}^q] (\langle S^p\rangle + S^p) [\mathcal{I}_p + M_4^3 \partial_p \omega_0] + \frac{M_4^3}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} (\langle S^\dagger_p\rangle + S^\dagger_p) \bar{\mathcal{I}}^p \Delta\omega_0 + \text{h.c.} \Big\} \\
&+ e^{\frac{1}{2}\left|\langle z\rangle\right|^2} \bar{m}_{3/2} S^p \Big(\frac{1}{\bar{\xi}_{3/2}} \mathfrak{d}_z \mathcal{I}_p - 3\, \mathcal{I}_p + \text{h.c.} \Big) \\
&+ e^{\frac{1}{2}\left|\langle z\rangle\right|^2} M_4^3 \Big(\Delta \mathfrak{d}_z \omega_0 [\frac{\bar{m}_{3/2}}{\bar{\xi}_{3/2}} + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} S^\dagger_q \mathfrak{d}^z \bar{\mathcal{I}}^q] - 3\Delta\omega_0 [\bar{m}_{3/2} + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} S^\dagger_q \bar{\mathcal{I}}^q] + \text{h.c.} \Big) \\
&+ \Big(\langle S^p S^\dagger_p\rangle + \langle \phi^\dagger_{a^*} \Lambda^{a^*}{}_b \phi^b\rangle \Big) \Big(3\left|m_{3/2}\right|^2 - \left|m'_{3/2}\right|^2 - \frac{1}{2m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} (\bar{m}'_{3/2} S^q \mathfrak{d}^z \mathcal{I}_q + \bar{m}_{3/2} \mathcal{I}_q (\langle S^q\rangle - 2S^q) + \text{h.c.}) \Big) \\
&+ \frac{1}{2m_p^4} \left|\mathcal{I}_p\right|^2 e^{\left|\langle z\rangle\right|^2} \Big(M_4^2 (\langle\phi^a\rangle + \phi^a)(\langle\phi^\dagger_{a^*}\rangle + \phi^\dagger_{a^*})\langle\Lambda^{a^*}{}_a\rangle + (\langle S^p\rangle + S^p)(\langle S^\dagger_p\rangle + S^\dagger_p) \Big)^2 \\
&- \Big(\Big(m'_{3/2} + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} S^p \mathfrak{d}_z \mathcal{I}_p \Big) \langle \phi^\dagger \partial^z \Lambda \phi\rangle \Big(\bar{m}_{3/2} + \frac{1}{m_p^2} e^{\frac{1}{2}\left|\langle z\rangle\right|^2} S^\dagger_q \bar{\mathcal{I}}^q \Big) + \text{h.c.} \Big)
\end{aligned}
$$

where we recall that $m'_{3/2} = m_{3/2}/\xi_{3/2}$ and we have defined

$$
\begin{aligned}
\mathcal{S}^{a^*}{}_a &= \frac{1}{\left|\xi_{3/2}\right|^2} \Big(\langle \partial^z \Lambda^{a^*}{}_b (\Lambda^{-1})^b{}_{b^*} \partial_z \Lambda^{b^*}{}_a - \partial^z \partial_z \Lambda^{a^*}{}_a \rangle \Big) + \langle \Lambda^{a^*}{}_a \rangle \Big(\frac{1}{\left|\xi_{3/2}\right|^2} - 2 \Big) \\
&= -2\Lambda^{a^*}{}_a + \frac{1}{\left|\xi_{3/2}\right|^2} \tilde{\mathcal{S}}^{a^*}{}_a \\
(\mathcal{S}_p)^{a^*}{}_a &= \frac{1}{\bar{\xi}_{3/2}} \Big(\langle \partial^z \Lambda^{a^*}{}_b (\Lambda^{-1})^b{}_{b^*} \partial_z \Lambda^{b^*}{}_a - \partial^z \partial_z \Lambda^{a^*}{}_a \rangle \Big) \mathfrak{d}_z \mathcal{I}_p + \langle \Lambda^{a^*}{}_a \rangle \Big(\frac{1}{\bar{\xi}_{3/2}} \mathfrak{d}_z \mathcal{I}_p - 2\mathcal{I}_p \Big) \qquad (2) \\
(\mathcal{S}^q{}_p)^{a^*}{}_a &= \Big(\langle \partial^z \Lambda^{a^*}{}_b (\Lambda^{-1})^b{}_{b^*} \partial_z \Lambda^{b^*}{}_a - \partial^z \partial_z \Lambda^{a^*}{}_a \rangle \Big) \mathfrak{d}_z \mathcal{I}_p \mathfrak{d}^z \bar{\mathcal{I}}^q + \langle \Lambda^{a^*}{}_a \rangle (\mathfrak{d}_z \mathcal{I}_p \mathfrak{d}^z \bar{\mathcal{I}}^q - 2\mathcal{I}_p \bar{\mathcal{I}}^q) \\
T &= \frac{1}{\left|\xi_{3/2}\right|^2} - 2 \\
T_p &= \frac{1}{\bar{\xi}_{3/2}} \mathfrak{d}_z \mathcal{I}_p - 2\mathcal{I}_p \\
T^p{}_q &= \mathfrak{d}_z \mathcal{I}_q \mathfrak{d}^z \bar{\mathcal{I}}^q - 2\mathcal{I}_q \bar{\mathcal{I}}^q \\
R^a{}_b &= \delta^a_b - \frac{1}{\bar{\xi}_{3/2}} \langle (\Lambda^{-1})^a{}_{b^*} \partial_z \Lambda^{b^*}{}_b \rangle \\
(R^p)^a{}_b &= \bar{\mathcal{I}}^p \delta^a{}_b - \mathfrak{d}^z \bar{\mathcal{I}}^p \langle (\Lambda^{-1})^a{}_{b^*} \partial^z \Lambda^{b^*}{}_b \rangle
\end{aligned}
$$