New Structures in Supergravity Mediation

A solution to the fine-tuning problem ?

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Institut Pluridisciplinaire Hubert Curien (IPHC), Strasbourg, Theory Group[1],

IRN Terascale@Bruxelles:
BSM session
October 16-18, 2019

Outline

Outline

Supergravity Breaking

Supergravity

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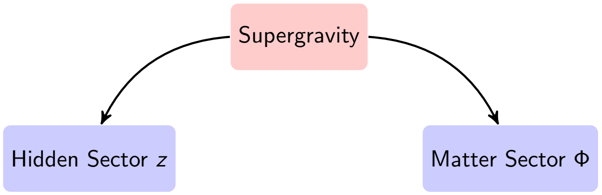

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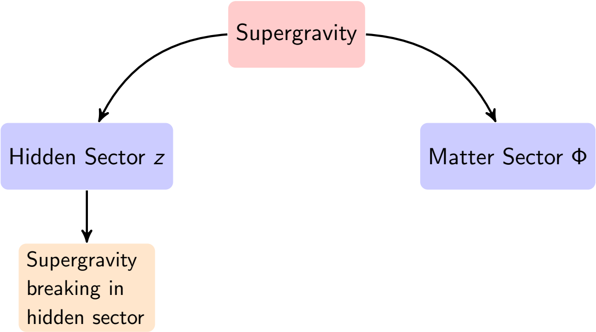

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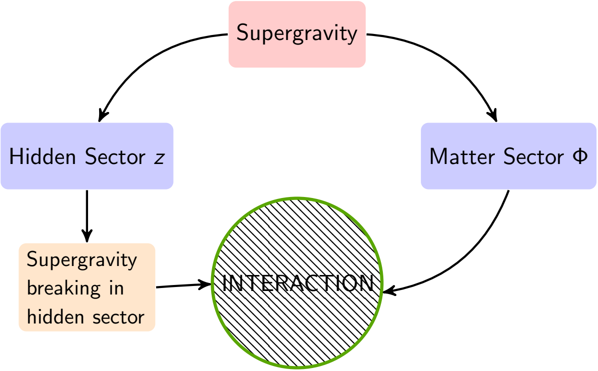

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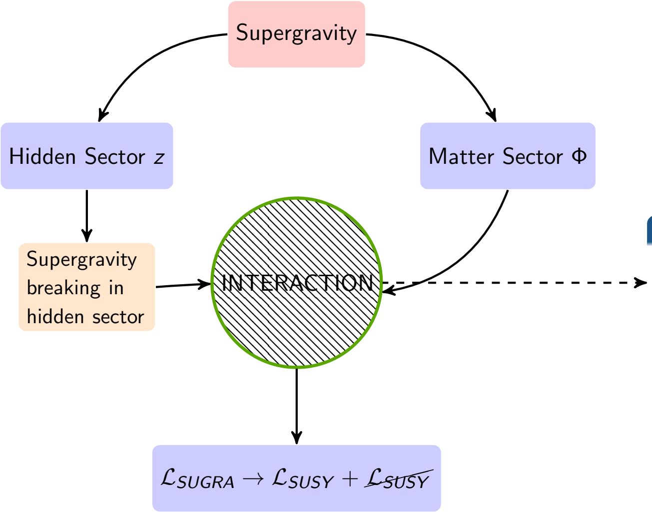
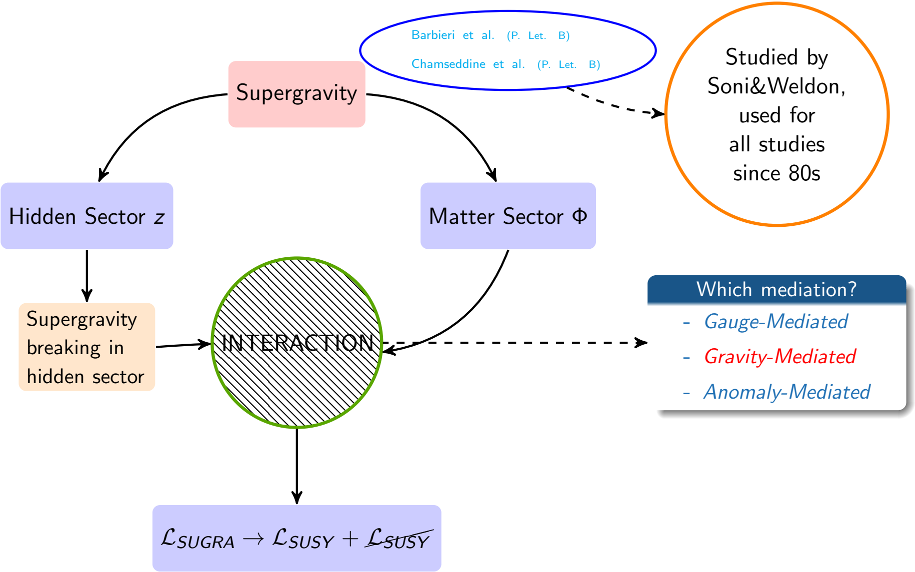


Which mediation?

- *Gauge-Mediated*
- *Gravity-Mediated*
- *Anomaly-Mediated*

Supergravity Breaking



Soni & Weldon solutions

Soni & Weldon Phys.Lett. 126B (1983) 215-219 (1983)

Expansion of the fundamental functions of Supergravity as power of $m_{p\ell}$:

- Kähler potential K (describing kinetic terms)
- Superpotential W (describing Yukawa interactions,...)

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

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Requirment

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

Visible sector fields interactions **only present as $m_{p\ell}^{-n}$ with $n \geq 0$**

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$$\mathcal{L}_{SUGRA} \Rightarrow \mathcal{L}_{SUSY} - V_{soft}$$

Soni & Weldon solutions

Standard example : MSSM, NMSSM, ...
If we take the NMSSM:

$$W_0 = \lambda(z)\hat{S}\hat{H}_u.\hat{H}_d + \frac{1}{3}\kappa(z)\hat{S}^3 + y_u(z)\hat{Q}.\hat{H}_u\hat{U} - y_d(z)\hat{Q}.\hat{H}_d\hat{D} - y_e(z)\hat{L}.\hat{H}_d\hat{E}$$
$$+\frac{1}{2}\mu(z)\hat{S}^2 + \xi_F(z)\hat{S}$$

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Squared Scalar Masses

$$V_{Soft} = \sum_I m^2_\Phi \Phi^I \Phi^\dagger_{I^*} + \Big\{ a_u Q.H_u.U - a_d Q.H_d.D + a_e L.H_d.E + A_\lambda S H_u.H_d$$
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Gauginos Masses

Trilinear terms

Outline

Non-Soni-Weldon-Solutions (NSWS)

Moultaka G. Rausch de Traubenberg M. Tant D., International Journal of Modern Physics AVol. 34, No. 01, 1950004 (2019)

Soni-Weldon : Just the tip of the iceberg ?

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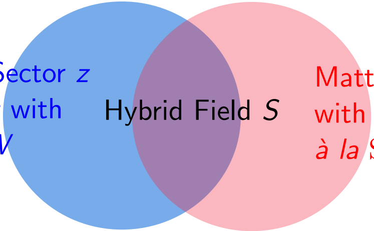

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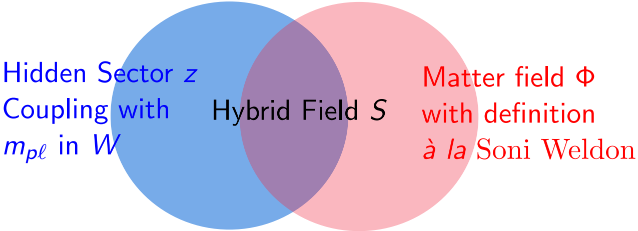

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We will focus on this new solution...

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- Will lead to **Hard breaking terms** with the following properties:
  - M-suppressed with energy scale $M \ll m_{p\ell}$
  - Controlled by Gravitino mass $m_{\frac{3}{2}} = \frac{M^2}{m_{p\ell}} e^{\frac{1}{2}\langle z \rangle^2}$ $(m_{\frac{3}{2}}^{NSW} < m_{\frac{3}{2}}^{SW})$
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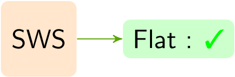
  - Controlled by VEV from hybrid fields : $\langle \mathcal{U} \rangle$ and $\langle S \rangle$
- NMSSM+K(≥ 1) singlets-like **with significant differences**

S2MSSM

SWS

SWS : Soni-Weldon solutions
NSW : Non-Soni-Weldon solutions

S2MSSM



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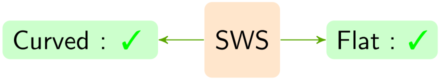

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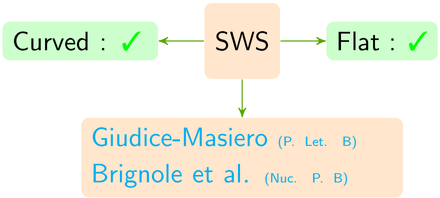

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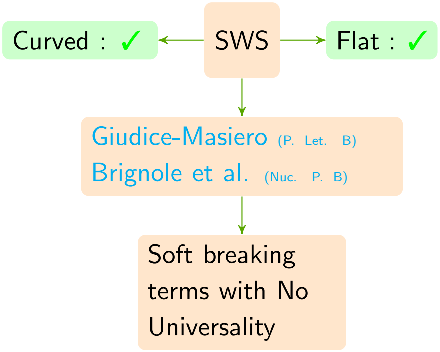

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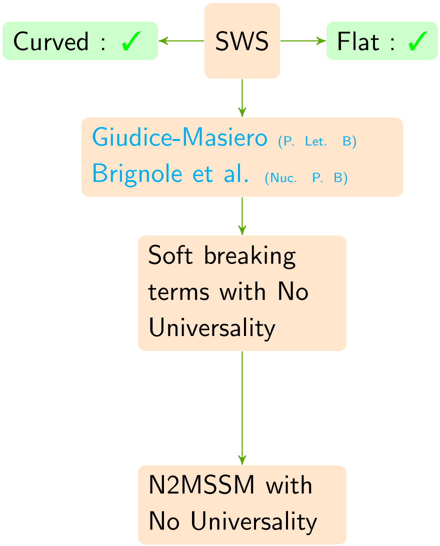

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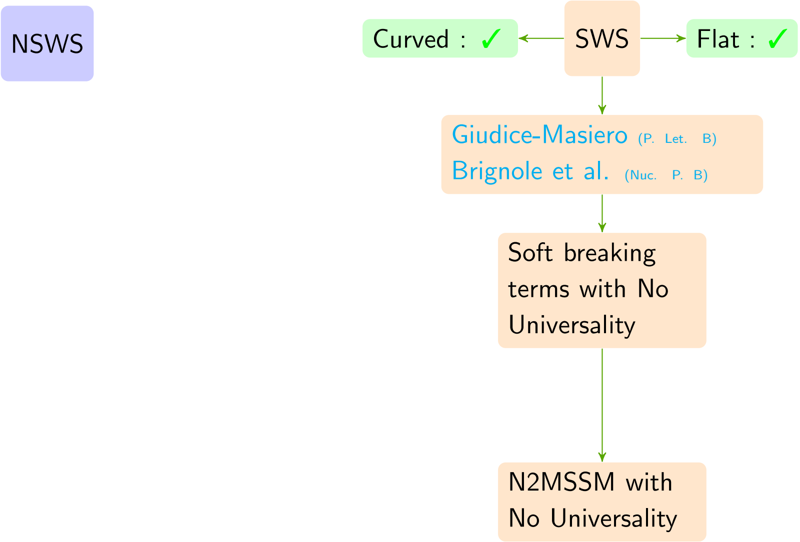

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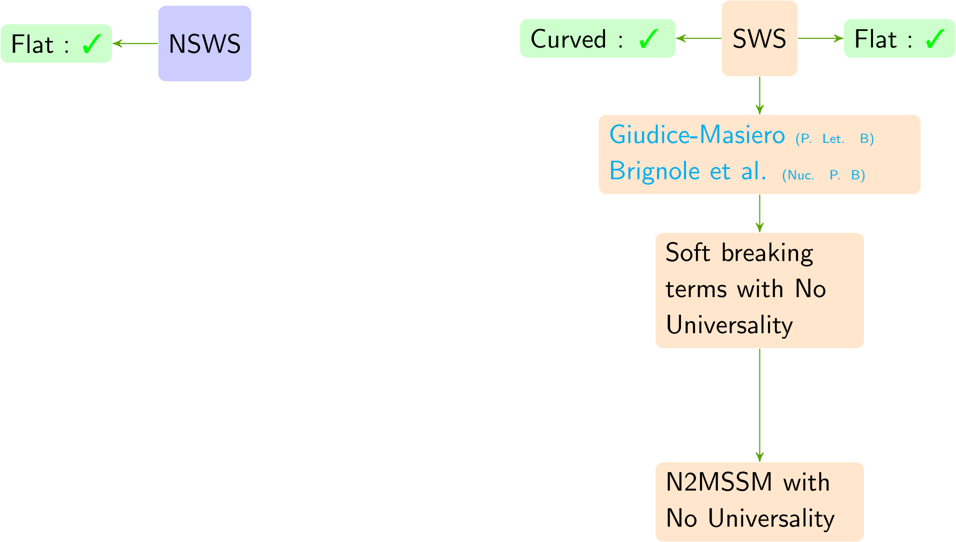

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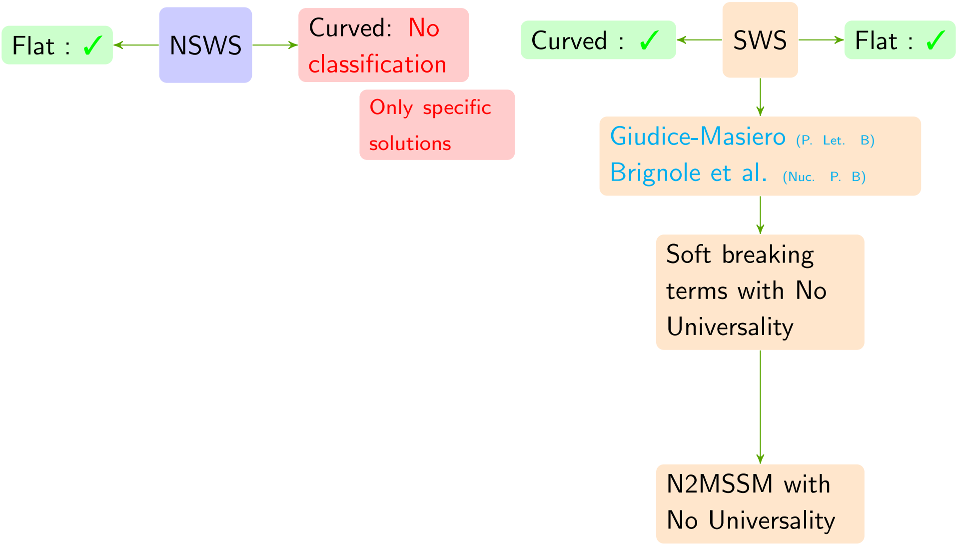

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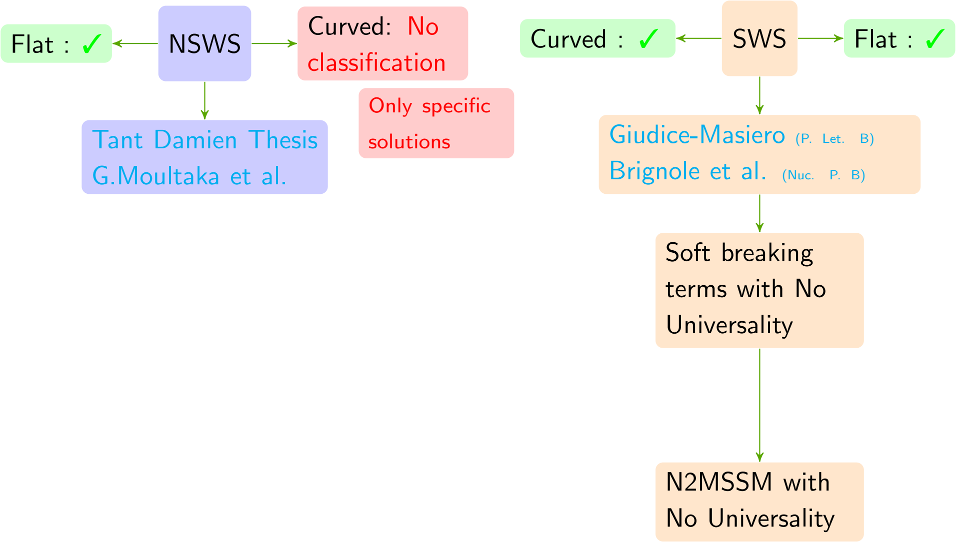

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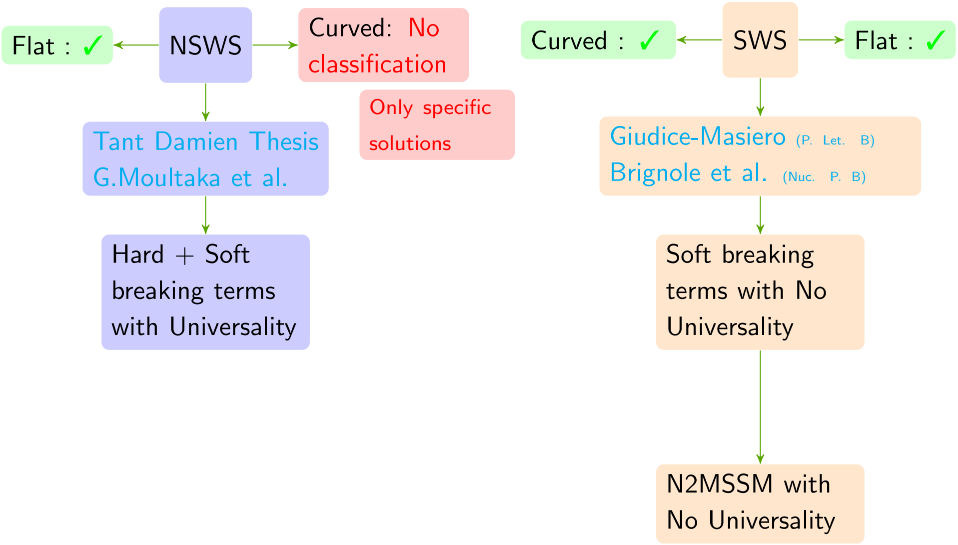

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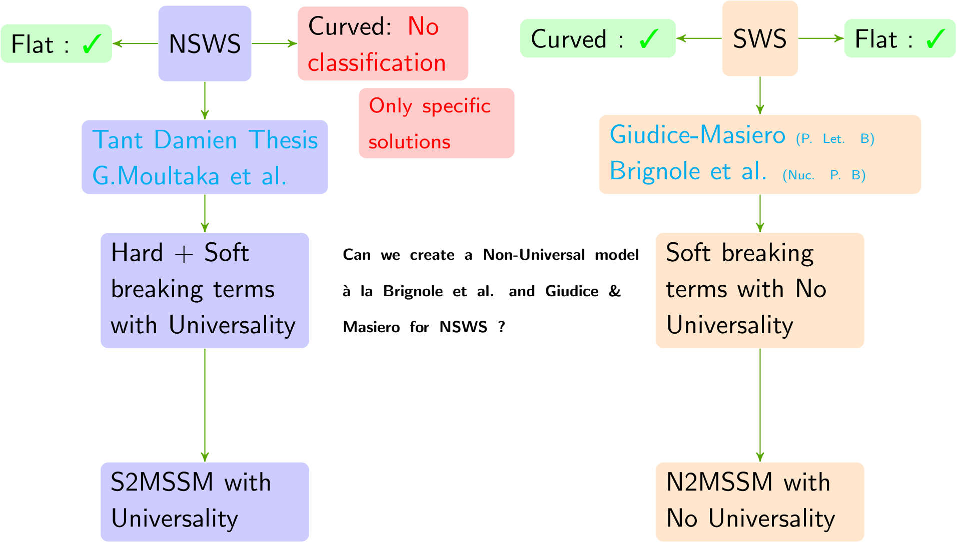

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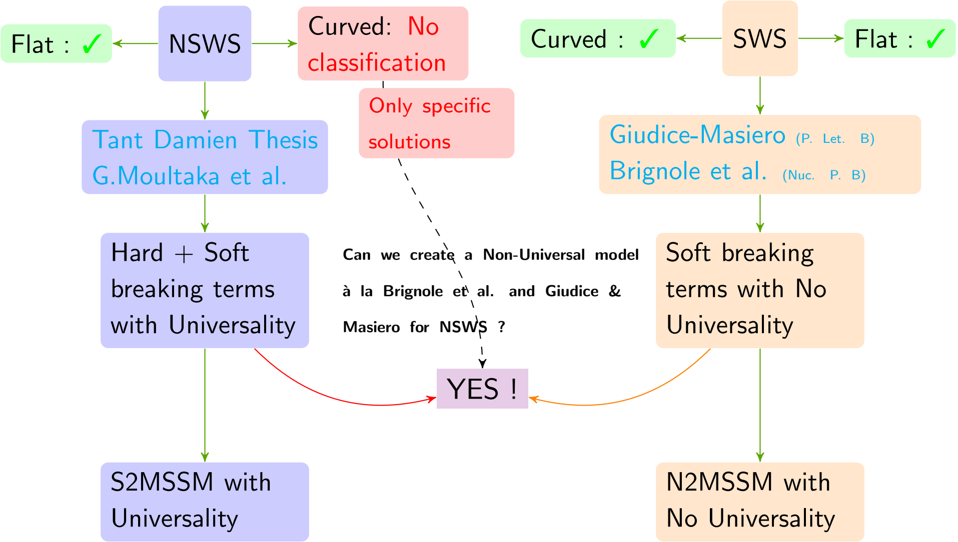

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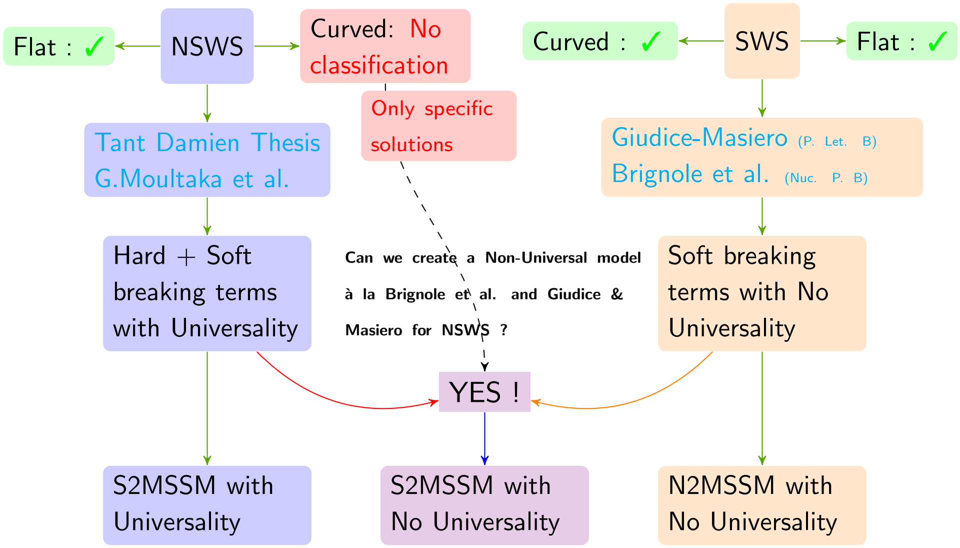

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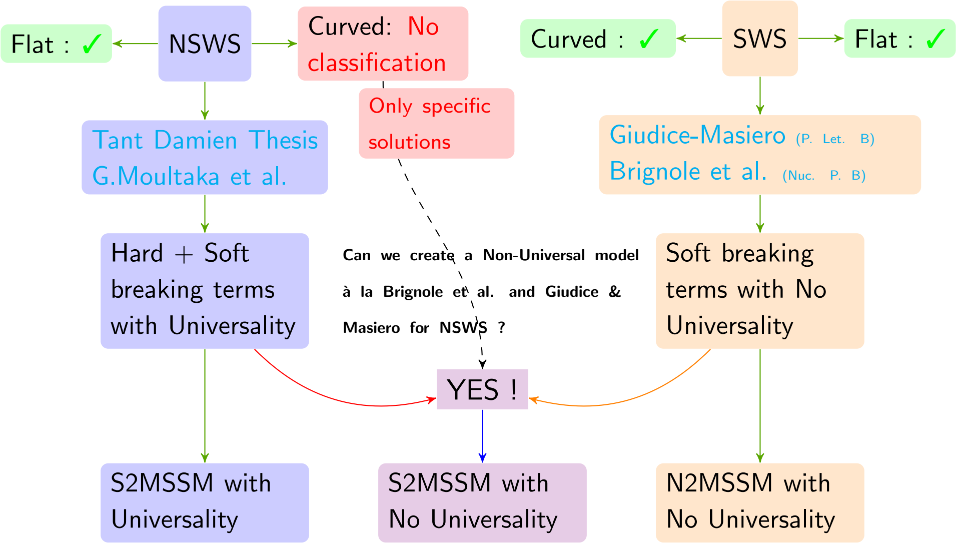

"S2MSSM"

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S2MSSM

A simplest NSW model: **S2MSSM**

Fields content:

- Matter Sector Φ, S^1 and S^2
  - $\mathcal{U} = \mu^1 S^2 - \mu^2 S^1$
- Hidden Sector z

N2MSSM-like (NMSSM + 1 gauge singlet) **with significant differences !**

$$W = m_{p\ell}\left[\hat{W}_0(z) + S^p \mu_p^* \hat{W}_1(z)\right] + \Xi(\mathcal{U}, \Phi, z)$$

$$K = m_{p\ell}^2 \hat{K}(z, z^\dagger) + S^p S_p^\dagger + \sum_I \Lambda_I(z, z^\dagger)\Phi_I^\dagger \Phi^I$$

with:

$$\Xi(\mathcal{U}, \Phi, z) = \lambda(z)\mathcal{U}\hat{H}_u.\hat{H}_d + \kappa(z)\mathcal{U}^3 + y_u(z)\hat{Q}.\hat{H}_u\hat{U} - y_d(z)\hat{Q}.\hat{H}_d\hat{D} - y_e(z)\hat{L}.\hat{H}_d\hat{E}$$

SUPERGRAVITY BREAKING IN HIDDEN SECTOR

S2MSSM

SUPERGRAVITY BREAKING IN HIDDEN SECTOR

$$V_{soft} = m^2_{\phi_I}\phi^\dagger_I\phi^I + (m^2_S)^q{}_p S^\dagger_q S^p + \Big\{\frac{1}{6}\hat{\kappa}\mathcal{U}^2\langle\mathcal{U}\rangle + \frac{1}{6}A_\kappa\mathcal{U}^3 + A'\mathcal{U}H_u.H_d$$
$$+ C_p S^p + a_u Q.H_u U - a_e L.H_d E - a_d Q.H_d D + \lambda'\langle\mathcal{U}\rangle H_U.H_D + \text{h.c.}\Big\}$$

S2MSSM

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$$V_{hard} = \frac{\left|m_{\frac{3}{2}}\right|^2}{M^2}\Big(Q_{I\,p}{}^q\phi^\dagger_I\phi^I S^\dagger_q S^p + Q'_r{}^t S^\dagger_p S^p S^\dagger_t S^r\Big)$$
$$+\Bigg\{\frac{\left|m_{\frac{3}{2}}\right|^2}{M}\Big(T_{I\,p}\phi^\dagger_I\phi^I S^p + T' S^\dagger_p S^p S^r\Big)$$
$$+\frac{m^\dagger_{\frac{3}{2}}}{M^\dagger}\Big(E^q\langle\mathcal{U}\rangle H_u.H_d + D^q_uQ.H_uU - D^q_eL.H_dE - D^q_dQ.H_dD + \frac{1}{6}\hat{K}^q\mathcal{U}^3 +$$
$$+\frac{1}{2}\hat{\kappa}a^q\mathcal{U}^2(\mathcal{U}+\langle\mathcal{U}\rangle) + D^q\mathcal{U}H_u.H_d + \hat{\lambda}\langle\mathcal{U}\rangle a^qH_u.H_d\Big)S^\dagger_q + \text{h.c.}\Bigg\}$$

S2MSSM

Differences with N2MSSM (NMSSM+1 singlet):

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- EW symmetry breaking conditions
- Mass spectrum
- RGEs (effects from hard-breaking terms)

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Fine-tuning and V_{Hard}

Constraints : $\langle V \rangle \approx 0, \langle \partial V \rangle = 0, \; \langle S \rangle \ll m_{p\ell}$

$$\left(\begin{array}{c|c} \text{S} & \text{SH} \\ \hline \text{SH} & \text{H} \end{array} \right)$$

S: Singlet submatrix
H: Higgs submatrix
SH: Higgs / Singlet mixing (off-diagonal)

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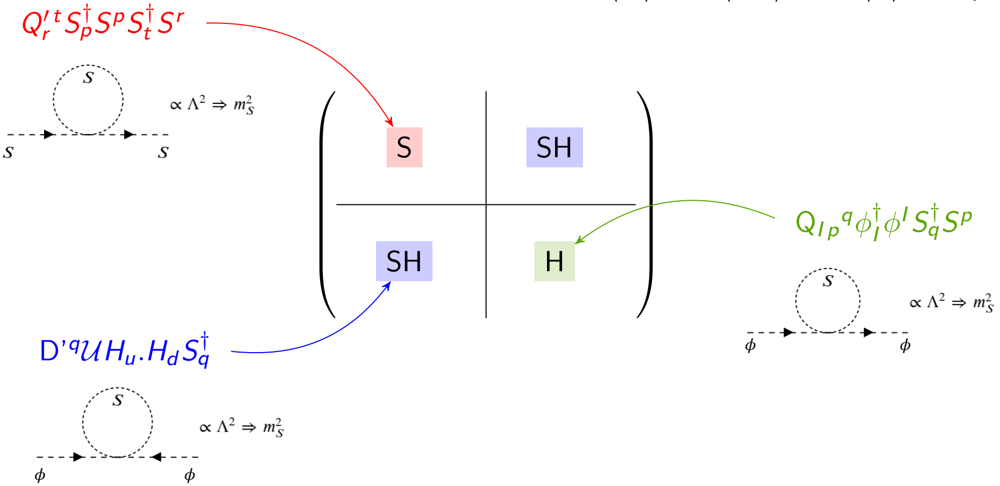

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Fine-tuning and V_{Hard}

Constraints : $\langle V \rangle \approx 0, \langle \partial V \rangle = 0, \; \langle S \rangle \ll m_{p\ell}$

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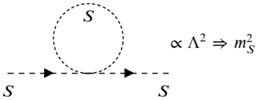

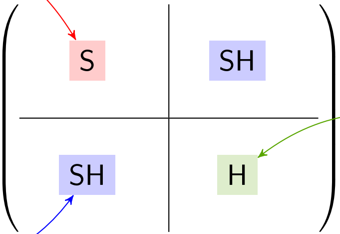

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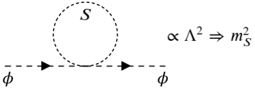

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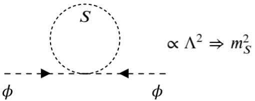

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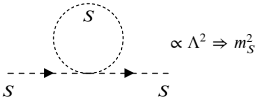

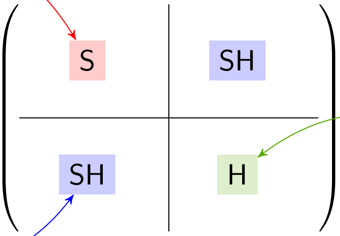

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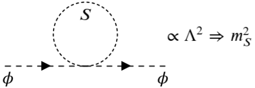

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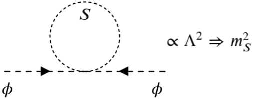

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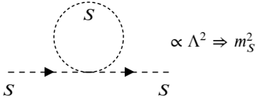

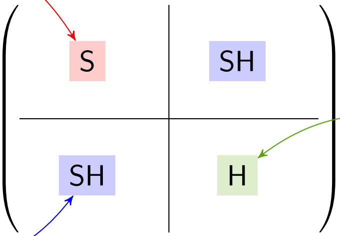

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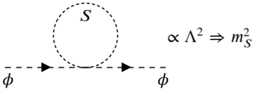

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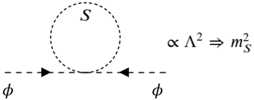

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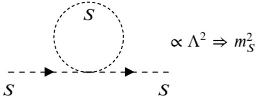

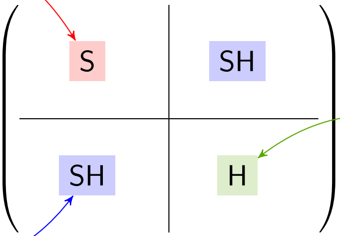

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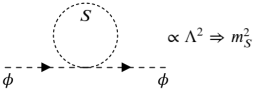

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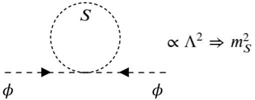

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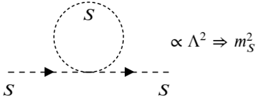

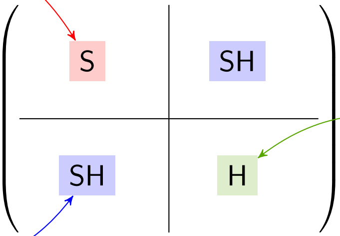

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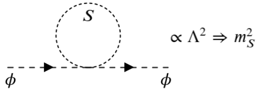

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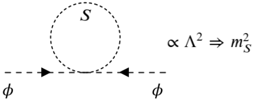

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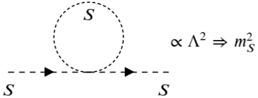

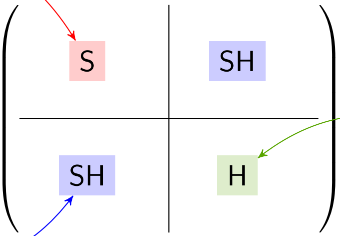

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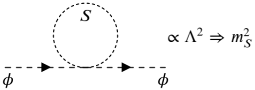

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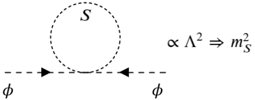

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Hard Breaking $\mathcal{O}(M_1^6/(m_{3/2} m_{p\ell}^5))$ and $\mathcal{O}(M_1^4/(m_{3/2} m_{p\ell}^3))$ **sizable!**

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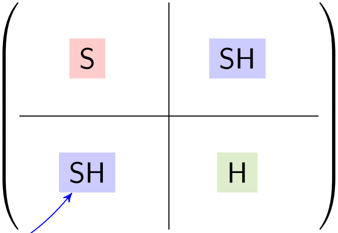
Seesaw mechanism and V_{Hard}

Let's take a look on Off-diagonal corrections...



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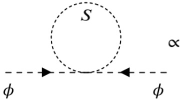

$\propto \Lambda^2 \Rightarrow m_S^2$

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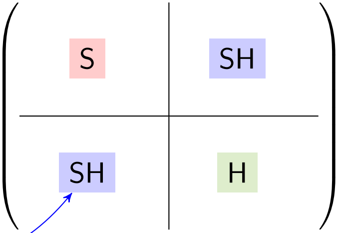

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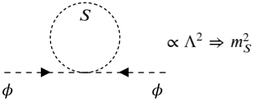

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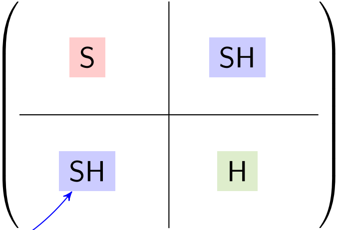

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$$m_H = m_H^{TL} - (\mathrm{Corr.})^2$$
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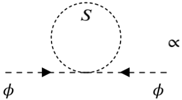

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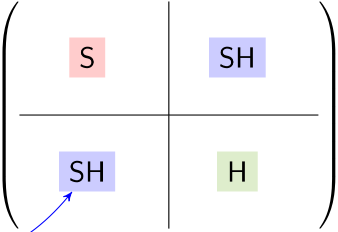

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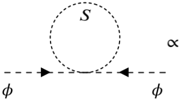

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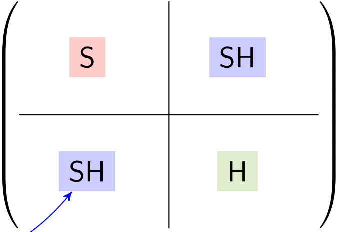

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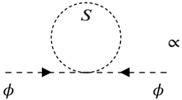

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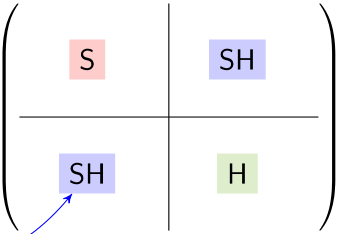
Seesaw mechanism and V_{Hard}

Let's take a look on Off-diagonal corrections...

Example:

- $m_{3/2} \sim \mathcal{O}(1)$ TeV
- $M_1 \lesssim \mathcal{O}(10^{15})$ GeV
- $M_4 \sim \mathcal{O}(10^{16})$ GeV

$\Rightarrow$ **5 − 20% loop correction to** λ



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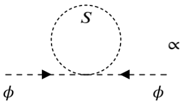

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Two approaches

1) Coleman-Weinberg (off-shell $p^2 = 0$)

$$\Delta V_{eff} = \frac{1}{64\pi^2}\mathrm{STr}\mathcal{M}^4\left[\ln\left(\mathcal{M}^2/M^2\right) - \frac{3}{2}\right] + \frac{M^2}{32\pi^2}\mathrm{STr}\mathcal{M}^2$$

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2) Diagrammatic (on shell $p^2 = m^2$)...

Outline

1. Supergravity
   - Supergravity Breaking
   - Soni & Weldon and Soft-Breaking terms
2. Non-Soni-Weldon Solutions
   - Hybrid fields and Hard-breaking terms
   - A simple extension of NMSSM: S2MSSM
3. Radiative corrections induced by Hard-breaking terms
   - Hard-breaking terms as a solution to the Higgs mass fine-tuning
   - Coleman-Weinberg eff. potential & Diagrammatic approach
4. Conclusion

Conclusion

- Soni & Weldon : finds solutions to consistent Supergravity breaking
  - Leading to Soft-breaking terms
  - Used since 80's for all phenomenological studies
- SWS is not the only possible solutions ⇒ Non-Soni-Weldon-Solutions
  - Leading to Hard-breaking terms M suppressed
  - The simplest possible model involve a new type of field : "Hybrid field"
- A simple model : S2MSSM (N2MSSM-like with significant differences)
- Radiative corrections on Higgs mass from Hard-breaking terms
- See-saw mechanism as a solution to fine-tuning problem
- V_{Hard} can possibly push upwards sfermions mass scale

LHC / Dark Matter / Cosmology ⇒ S.low.SUGRA project (IPHC,L2C,LUPM,APC)

Soni & Weldon solutions

Assumptions :

$$K = \sum_{n=0}^{N} m_{p\ell}^n K_n(z, z^\dagger, \Phi, \Phi^\dagger)$$

$$W = \sum_{n=0}^{M} m_{p\ell}^n W_n(z, \Phi)$$

Constraints on Matter Fields / Hidden Fields decoupling in $m_{p\ell} \to \infty$ limit :

$$K = m_{p\ell}^2 K_2(z, z^\dagger) + m_{p\ell} K_1(z, z^\dagger) + K_0(z, z^\dagger, \Phi, \Phi^\dagger)$$

$$W = m_{p\ell}^2 W_2(z) + m_{p\ell} W_1(z) + W_0(z, \Phi)$$

NSW Canonical solutions

Canonical solutions :

$$K = m_{p\ell}^2 z z^\dagger + \Phi\Phi^\dagger + S_p^\dagger S^p$$
$$W = m_{p\ell} W_1(z, S) + W_0(z, S, \Phi)$$

with :

$$W_1(z, S) = W_{1,0}(z) + \sum_{p \geq 1}^{k_1} W_{1,p}(z) \sum_{s \geq 1}^{n_p} \mu_{p_s}^* S^{p^s}$$

$$W_0(z, S, \Phi) = \sum_{q \geq 1}^{k_1} W_{0,q}(z) S^q + \Xi(\mathcal{U}_S^{pp_s}; \Phi, z)$$

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

NSW Non-canonical solution

An other non-Canonical solutions :

$$K = m_{p\ell}^2 K_2(z, z^\dagger, \Phi, \Phi^\dagger) + K_0(z, z^\dagger, \Phi, \Phi^\dagger)$$
$$W = m_{p\ell}^2 W_2(z, \Phi) + W_0(z, \Phi)$$

Decoupling Matter / Hidden for $m_{p\ell} \to \infty$ limit if :

- W_0, K_0 are arbitrary functions
- W_2,K_2 are arbitrary functions that should depend explicitly on Φ,$\Phi^\dagger$, subject to a **no-scale-like** condition :

$$\partial_I \mathcal{G}_2 \left(\frac{\partial^2 \mathcal{G}_2}{\partial Z^I \partial Z^{J*}} \right)^{-1} \partial_{J*} \mathcal{G}_2 = 3 \ , \ \text{with } \mathcal{G}_2 = K_2 + \ln \left| \frac{W_2}{m_{p\ell}} \right|^2$$

N2MSSM

N2MSSM = MSSM + 2 gauge singlets (NMSSM + 1 gauge singlet)

Phenomenological study in progress :

- RGEs (*SARAH*)
- Spectrum Generator (*SPheno*) + Work with Cyril Hugonie (LUPM) on *NMSSMTools*→*N2MSSMTools*
- Constraints coming from Higgs sector measurements (*HiggsBounds & HiggsSignals*)
- Constraints coming from Dark Matter (*micrOmegas*)

⇒ Recasting of $H \to aa$ analysis + Full space parameters scan

No-scale Supergravity

Fine-tuning problem on $\langle V \rangle$ for Cosmology

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

A possible solution : **No-Scale Supergravity**

$$\mathcal{D}_I W K^I{}_{J*} \mathcal{D}^{J*} \bar{W} = \frac{3}{m_{p\ell}^2} |W|^2$$

$V = 0$ at Tree-Level !
The gravitino mass is unfixed (no-scale) and is a free-parameter of the theory