GRAVITY AND GAUGE MEDIATION OF SUPERSYMMETRY BREAKING

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Outline:

- supersymmetry
- supersymmetry breaking
- mediation of supersymmetry breaking
- $\mu$ and $B\mu$ problem of gauge mediation
- cosmological vacuum selection
Beyond the Standard Model

supersymmetry

- no superpartners observed thus far – supersymmetry must be broken
- electroweak scale related to the scale of supersymmetry breaking
- the lightest supersymmetric particle is stable – a natural dark matter candidate
The structure of the MSSM

\[
\begin{align*}
V^a & \quad \text{vector multiplets} \quad \begin{pmatrix} A^a_{\mu} \\ \lambda^a \end{pmatrix} & h = \pm 1 \\
\phi^i & \quad \text{chiral multiplets} \quad \begin{pmatrix} \psi^i \\ \varphi^i \end{pmatrix} & h = \pm 1/2 \\
\text{gauge group} & \quad SU(3) \times SU(2) \times U(1) \\
& \quad \text{gauginos} (\tilde{g}, \tilde{W}, \tilde{B}) \\
& \quad 3 \text{ families, 2 Higgs doublets} \\
& \quad \text{squarks} (\tilde{q}), \text{sleptons} (\tilde{\ell}), \text{higgsinos} (\tilde{H}_{1,2}) \nonumber
\end{align*}
\]

\[
w = Q_h U^c H_2 + Q_h D^c H_1 + L_h E^c H_1 + \mu H_1 H_2
\]

\[
V_{F} = \sum_i \left| \frac{\partial w}{\partial \phi^i} \right|^2
\]
The structure of the MSSM

\[ -\mathcal{L}_{soft} = \varphi^\dagger m^2 \varphi + \left( \frac{1}{2} M_A \lambda_A \lambda_A + m_3^2 H_1 H_2 \right) + \tilde{q} A^U \tilde{u}^c H_2 + \tilde{q} A^D \tilde{d}^c H_1 + \tilde{l} A^E \tilde{e}^c H_1 + h.c. \]

explicit mass terms for scalars

\[ \mathcal{B}_\mu \]

explicit tri-scalar interactions

\[ w = Qu^U U^c H_2 + Qu^D D^c H_1 + Lu^E E^c H_1 + \mu H_1 H_2 \]

\[ V_F = \sum_i \left| \frac{\partial w}{\partial \phi^i} \right|^2 \]
Supersymmetry breaking

visible sector

mediation

gauge interactions, gravity, ...

hidden sector
• gauge mediation: natural suppression of flavour changing processes, works in the flat limit

• but: light gravitino, problematic c.c. cancellation, problems with correct electroweak breaking

• gauge and gravity mediation - can one mix them arbitrarily?

• or: to what extent the hidden sector needs to be separated from the observable one?

• degree of cosmological tuning?
Mediation of supersymmetry breaking

\[ w = -\lambda X \phi \phi \]

singlet, breaks susy
\[ \langle F_X \rangle \neq 0 \]

nonsinglet, e.g. 5, 5 of SU(5)

mass splitting between bosonic and fermionic components

\[ M_i = \frac{\alpha_i}{4\pi} N \frac{\langle F_X \rangle}{\langle X \rangle} \]

\[ m_s^2 = 2 \sum_i \left( \frac{\alpha_i}{4\pi} \right)^2 C_s^{(i)} N \left( \frac{\langle F_X \rangle}{\langle X \rangle} \right)^2 \]

10^5 \text{ GeV}
condensation + retrofitting

in string models:

* string instantons
* gauge instantons

\[ W_{LE} = W(T) + \mu^2 (\Lambda_{dyn}) X + m (\Lambda_{dyn}) \Phi^2 + \lambda X Q q + \lambda' X \Phi^2 \ldots \]

supersymmetry breakdown
\[ K = \bar{X}X + \sum_{i=1}^{n} \left( \bar{\phi}_i\phi_i + \bar{\phi}_i\phi_i \right) - \frac{1}{16\pi^2} f_4 \frac{(\bar{X}X)^2}{\Lambda^2} - \frac{1}{16\pi^2} f_6 \frac{(\bar{X}X)^3}{\Lambda^4} + \ldots \]

\[ W = \mu^2 X + \sum_{i=1}^{N} \sum_{j=1}^{N} \bar{\phi}_i(m_{ij} + \lambda_{ij}X)\phi_j + c \]

\[ R(\bar{\phi}_i) + R(\phi_j) = 2 \quad R(\bar{\phi}_i) + R(\phi_j) = 0 \]

\[ \delta K = -\frac{1}{16\pi^2} \text{Tr} \left[ \mathcal{M}^\dagger \mathcal{M} \ln \left( \frac{\mathcal{M}^\dagger \mathcal{M}}{Q^2} \right) \right] \]

\[ m_g \sim f \partial_X \det \mathcal{M} \]
$f_4 < 0$  

supersymmetry breaking related to spontaneous $R$ symmetry breaking

$M_P \rightarrow \infty$

$M_P < \infty$

$f_4 > 0$  

supersymmetry breaking related to soft $R$ symmetry breaking transmitted through gravity
Solutions

\[ X = \frac{1}{2\sqrt{3}} \frac{\tilde{\Lambda}^2}{f_4 M_P} \quad \text{if } f_4 > 0 \text{ and dominant} \]

\[ X^2 = \frac{8|f_4|}{9f_6} \tilde{\Lambda}^2 \quad \text{if } f_4 < 0 \text{ and } f_6 > 0 \]

\[ X^3 = \frac{16\pi^2}{9\sqrt{3}f_6} \frac{\tilde{\Lambda}^4}{M_P} \quad \text{if } f_4 \approx 0 \]

in all cases solutions exist if \( \langle X \rangle \lesssim 10^{-3} M_P \)

above this value of \( X \) the gravitational term gives to large negative slope
Supersymmetry and EW symmetry breaking

The $\mu$-$B\mu$ problem of gauge mediation

\[ w = \mu H_1 H_2 \]
\[ V \leftarrow \mu^2 (|H_1|^2 + |H_2|^2) \]

- why $\mu$ close to the electroweak scale? (forbid at all)

\[ \delta W = X H_1 H_2 \]
\[ B\mu \sim \frac{1}{16\pi^2} \left( \frac{F_X}{\langle X \rangle} \right)^2 \]

1/(16\pi^2) missing

\[ \delta K = \frac{X^\dagger}{M_P} H_1 H_2 + h.c. \]
\[ B\mu \sim \left( \frac{F_X}{M_P} \right)^2 \]

Natural supergravity contributions (Giudice-Masiero mechanism)

\[ \mu \sim \frac{F_X}{M_P} \]
\[ \delta K = \frac{X^\dagger}{M_P} H_1 H_2 + \text{h.c.} \]

\[ m_{3/2} = \frac{F^X}{\sqrt{3}M_P} \]

\[ m_{\text{scalar}} = \frac{\alpha(m) \sqrt{3}M_P}{4\pi} \langle X \rangle m_{3/2} \]

G-M: \( B\mu = \mu^2 \approx m_{3/2}^2 \)

hence raising \( X \) towards \( 10^{-3} M_P \)
gives \( \mu \approx M_Z \) and not to heavy scalars/gauginos
Doublet-triplet splitting

\[5_{SU(5)} \rightarrow (1, 2) + (3, 1)|_{SU(3) \times SU(2)} = \sum (m_s^{(i)})^2\]

\[M_i = \frac{\alpha_i}{4\pi} \Lambda_G\]

“universal” gaugino masses

\[m_s^2 = 2 \sum_i \frac{1}{N_{\text{eff},i}} C_s^{(i)} M_i^2\]

scalar masses inherit doublet-triplet splitting from the messenger sector

\[\frac{1}{N_{\text{eff},1}} = \frac{3}{5N_{\text{eff},2}} + \frac{2}{5N_{\text{eff},3}}\]

parameters of the model

\[\Lambda_G, N_{\text{eff},2}, N_{\text{eff},3}, M_{\text{mess}}\]
Doublet-triplet splitting

\[ \mu/\text{GeV} \]

\[ M_{\text{mess}} = 2 \cdot 10^{16}\text{GeV} \]

\[ B/\text{GeV} \]

\[ M_{\text{mess}} = 2 \cdot 10^{5}\text{GeV} \]
Doublet-triplet splitting

- **Neutralinos**
- **Charginos**
- **$u$ squarks**
- **Staus**

**Spectrum A “usual”**

*Note: The specific values and plots are not detailed in the image.*

**Spectrum F “2-3 split”**

*Note: The specific values and plots are not detailed in the image.*
Cosmological vacuum selection
\( T \gg \tilde{\Lambda} \)

\[
X = \frac{4\mu^2 c}{3\lambda^2 \tilde{\Lambda}^2} \sim \frac{\mu^4}{\lambda^2 \tilde{\Lambda}^2}
\]

\[
q_c^{\text{min}} = q_c^{\text{min}} = 0, \quad T > \tilde{\Lambda}
\]

\[
T_{cr} \approx 2\sqrt{\frac{\mu^2}{\lambda}}
\]

\[
T_S^2 = \mathcal{O}(10) \frac{1}{\tilde{\Lambda}^2} \frac{\mu^4}{\lambda^2}
\]
Cosmologically favoured region corresponds to mixed gauge-gravity case

\[ S = X \]

One needs displaced initial conditions (e.g. by inflation)

\[ \Lambda^2 \leq S_{initial} \leq \Lambda \]

\[ \lambda \leq 10^{-7} \text{ and } 10^{-3} \leq \Lambda \leq 10^{-1} \]
Susy breaking by rank condition

\[ W = \mu^2 X - \phi X \tilde{\phi} \]

\[ W = \mu^2 \text{Tr}(X_{ij}) - \phi_c^i X_{ij} \tilde{\phi}^j_c \]

\[ i, j = 1, \ldots, N_f \quad c = 1, \ldots, N_c \quad N_c < N_f \]

\[ F_{X_{ij}} = \phi_c^i \tilde{\phi}^j_c - \mu^2 \delta^{ij} = 0 \]

\[ \text{rank} \ N_c \quad \text{rank} \ N_f \]

no supersymmetric solutions!
Summary

- Transmission of supersymmetry breakdown may easily be a mixture of many schemes - the gauge-gravity system a good example.

- Advantages of various schemes can complement each other.

- Cosmological history of susy breakdown is sensitive to the nature of the hidden/transmission sectors.

- Measurement of sparticle spectra would really help...