Simple and direct communication of dynamical supersymmetry breaking

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with Francesco Caracciolo arXiv:1207.5376
also based on earlier work with Nardecchia, Ziegler, Monaco, Spinrath, Pierini
Leads to

- Gauge coupling unification
- Plausible dark matter candidate (with $R_P$, independently motivated)
- Calculable theory, can be extrapolated up to $M_{Pl}$

Needs to be broken, hopefully spontaneously

- Effective description in terms of $O(100)$ parameters

\[
W = \lambda_{ij}^U \tilde{u}_i^c \tilde{q}_j^c \tilde{h}_u + \lambda_{ij}^D \tilde{d}_i^c \tilde{q}_j^c \tilde{h}_d + \lambda_{ij}^E \tilde{e}_i^c \tilde{l}_j^c \tilde{h}_d + \mu \tilde{h}_u \tilde{h}_d
\]

\[
- \mathcal{L}_{\text{soft}} = A_{ij}^U \tilde{u}_i^c \tilde{q}_j^c \tilde{h}_u + A_{ij}^D \tilde{d}_i^c \tilde{q}_j^c \tilde{h}_d + A_{ij}^E \tilde{e}_i^c \tilde{l}_j^c \tilde{h}_d + m_{ud}^2 h_u h_d + \text{h.c.}
\]

\[
+ (\tilde{m}_q^2)_{ij} \tilde{q}_i^c \tilde{q}_j^c + (\tilde{m}_{uc}^2)_{ij} (\tilde{u}_i^c) \tilde{u}_j^c + (\tilde{m}_{dc}^2)_{ij} (\tilde{d}_i^c) \tilde{d}_j^c + (\tilde{m}_{lc}^2)_{ij} \tilde{l}_i^c \tilde{l}_j^c
\]

\[
+ \frac{M_3}{2} \tilde{g}_A \tilde{g}_A + \frac{M_2}{2} \tilde{W}_a \tilde{W}_a + \frac{M_1}{2} \tilde{B} \tilde{B} + \text{h.c.}
\]

- $m_{\text{sq}} > 1.4$ TeV (but $m_{1,2} \neq m_3$)
- $m_H \approx 125$ GeV? (but NMSSM, $\lambda$SUSY)
Origin of supersymmetry breaking
A wide class of models of supersymmetry breaking

SUSY breaking

Hidden sector

\[ \langle Z \rangle = F \theta^2 \]
\[ F \gg (M_Z)^2 \]
SM singlet

Z chiral superfield

MSSM

Observable sector

Q chiral superfield

\[ \int d^4 \theta \frac{Z^\dagger Z Q^\dagger Q}{M^2} \rightarrow m^2 \tilde{Q}^\dagger \tilde{Q}, \quad m = \frac{F}{M} \]
A wide class of models of supersymmetry breaking

SUSY breaking

Hidden sector

Observable sector

MSSM

?
A useful guideline: the supertrace constraint

- \( \text{Str } M^2 \equiv \Sigma_{\text{bosons}} m^2 - \Sigma_{\text{fermions}} m^2 \) (weighted by # of dofs)

- Ren. Kähler + tree level + Tr(T_a) = 0: \( \text{Str } M^2 = 0 \)

- Holds separately for each set of conserved quantum numbers

- MSSM: incompatible with \( (\text{Str } M^2)_{f, \text{MSSM}} = \Sigma_{\text{sfermions}} m^2 - \Sigma_{\text{fermions}} m^2 > 0 \)

- \( G = G_{\text{SM}} \): incompatible with \( \bar{m}_{\text{lightest } d\text{-sfermion}}^2 \leq m_d^2 - \frac{1}{3} g' D_Y \)

  (if \( D_Y < 0 \), consider up sfermions)
Addressing the supertrace constraint

Ren. Kähler + tree level + $\text{Tr}(T_a) = 0 \rightarrow \text{Str} M^2 = 0$

- **Supergravity:** non-renormalizable Kähler: $\text{Str} \neq 0$  
  FCNC ?

- **"Loop" gauge-mediation:** loop-induced: $\text{Str} \neq 0$  
  FCNC OK

- **Anomalous U(1)’s:** $\text{Tr}(T_a) \neq 0$: $\text{Str} \neq 0$  
  FCNC OK

- **Tree-level gauge mediation:** $\text{Str} = 0$  
  FCNC OK
Tree-level gauge mediation

\[ \int d^4 \theta \frac{Z^\dagger Z Q^\dagger Q}{M^2} \]

massive vector of a spontaneously broken \( U(1) \)
\[ G \supset G_{SM} \times U(1) \]
\[ M \approx M_V \text{ scale of } U(1) \text{ breaking} \]

\[ \Rightarrow Z, Q \text{ charged under } U(1) \]

\[ \tilde{m}_Q^2 = qQqZ \frac{F^2}{M_V^2 / g^2} \]
Need of extra heavy (through U(1) breaking) fields

- SU(5) x U(1) ⊆ G, flavour universal charges, q_Z > 0 for definiteness

- (l, d_c) = \( \bar{5} \): \( q_5 > 0 \) (\( m_{5}^2 > 0 \), tree level)
  (q, u_c, e_c) = 10: \( q_{10} > 0 \) (\( m_{10}^2 > 0 \), tree level)

- SU(5)^2 x U(1) anomaly cancellation: \( 0 = 3(q_5 + 3q_{10}) + \text{extra} \)
  (guaranteed if SU(5) x U(1) is embedded in \( SO(10) \))
  \( \Downarrow \)
  M from U(1) breaking

- Masses^2 (before EWSB)

|        | \( \bar{5} + 10 \) | extra = \( \Phi + \bar{\Phi} \) |
|--------|---------------------|----------------------------------|
| fermions | 0                   | \( M^2 \)                         |
| scalars | 0 + m^2             | \( M^2 - m^2 \)                   |
The extra heavy fields as chiral messengers

- U(1) breaking: $\langle Y \rangle = M$
- SUSY breaking: $\langle Z \rangle = F\theta^2$

- In concrete models: $q_Z = q_Y$

- $h \ Y \bar{\Phi} \Phi \rightarrow M_\Phi = hM$

- $k \ Z \bar{\Phi} \Phi \rightarrow M_g \sim \frac{\alpha \ k \ F}{4\pi \ h \ M}$
A wide class of models of supersymmetry breaking

SUSY breaking

Hidden sector

Observable sector

MSSM
Phenomenologically viable supersymmetric models not always are theoretically complete.

Theoretically complete models of susy breaking not always are phenomenologically viable.

Phenomenologically viable and theoretically complete models not always are extremely simple.
Reminder

Non-renormalization: \( W_{cl} = W_{all\ orders\ in\ PT} \)

\[ W = W_{cl} + W_{NP} \]

"Classical" breaking

"Dynamical" breaking

\[ M_{SUSY} \approx M_0 e^{-(2\pi/\alpha\ b)} \]
The (problematic) role of the R-symmetry

- An exact R-symmetry prevents (Majorana) gaugino masses

- Nelson-Seiberg: R-symmetry needed in a susy-breaking model where
  - i) the susy-breaking minimum is stable and
  - ii) the superpotential is generic

- Non vanishing gaugino masses then require
  - non generic superpotential (R-breaking) or
  - metastable susy-breaking minima or
  - spontaneous R-breaking or
  - Dirac gaugino masses
Spontaneous R-breaking in generalized O’R models needs R ≠ 0,2
(e.g. ISS flows to R = 0,2)

Even if R ≠ 0,2: the stability (everywhere) of the pseudoflat direction along which the R-symmetry is spontaneously broken forces $M_g = 0$ at 1-loop

More gaugino screening takes place (semi-direct)
A simple, viable, dynamical model: 3-2 + messenger/observable fields

[N=1 global, canonical K, no FI]
Reminder: 3–2 model

SU(3) strong at $\Lambda_3$ where SU(2) weak

$\begin{array}{ccc}
Q & 3 & 2 \\
U^c & 3 & 1 \\
D^c & 3 & 1 \\
L & 1 & 2 \\
\end{array}$

$G \supset G_{SM}$

$W_{cl} = h Q D^c L$

$h \ll 1$: calculability

SU(3) x SU(2) broken at $M = \Lambda_3/h^{1/7} \gg \Lambda_3$

SUSY broken at $F = h M^2 \ll M^2$

$\langle L_2 \rangle = 0.3 M + 1.3 F \Theta^2$

$\langle L_1 \rangle = 0$

[Affleck Dine Seiberg]
Details

\[ Q = \tilde{Q} = \begin{pmatrix} a & 0 \\ 0 & b \\ 0 & 0 \end{pmatrix} M \]

\[ L = \begin{pmatrix} 0 & \sqrt{a^2 - b^2} \end{pmatrix} M \]

\[ F_Q = F_{\tilde{Q}} = \begin{pmatrix} a\sqrt{a^2 - b^2} - 1/(a^3 b^2) & 0 \\ 0 & -1/(a^2 b^3) \end{pmatrix} F \]

\[ F_L = \begin{pmatrix} 0 & a^2 \end{pmatrix} F \]

\( a \approx 1.164 \)

\( b \approx 1.131 \)
Coupling to observable fields: semi-direct GM

[Seiberg, Volansky, Wecht]
Our model

\[
\begin{array}{c|cc|c}
& SU(3) & SU(2) & G \\hline
Q & 3 & 2 & 1 \\
U^c & 3 & 1 & 1 \\
D^c & 3 & 1 & 1 \\
L & 1 & 2 & 1 \\
\Phi_i & 1 & 2 & \frac{R_{SM}}{R_{SM}} \\
\bar{\Phi}_i & 1 & 1 & \frac{R_{SM}}{R_{SM}} \\
\end{array}
\]

\[
\Phi_i = \begin{pmatrix} \phi_i \\ f_i \end{pmatrix}, \quad \phi_i
\]

\[
W = L \Phi_i \bar{\Phi}_i - M_{\Phi} \bar{\Phi}_i \Phi_i + \frac{F^{2}}{2} \bar{\Phi}_i \Phi_i
\]

\[f = \text{MSSM fields} \quad M_f = 0 \quad M_{\tilde{f}}^2 = +\tilde{m}^2
\]

\[\phi_i, \bar{\phi}_i = \text{messengers of MGM} \quad M_{\phi, \bar{\phi}} = M \quad M_{\phi}^2 = M^2 \pm F^2 - \frac{\tilde{m}^2}{2}
\]

\[\tilde{m}_\phi^2 = -g^2 T_3 \frac{F^2}{M_V^2} = \mp\tilde{m}_\phi^2 \quad \tilde{m}_\phi^2 = 0
\]

\([\text{no explicit mass term}]\)
More details

\[ \tilde{m}^2 = c \frac{F^2}{M^2} \]

\[ c = \frac{2a^8b^8 + 2a^2 + 4a^4b^4\sqrt{a^2 - b^2} - 2b^2}{3a^8b^6 - a^6b^8} \approx 1.48 \]

\[ M_i = 12 \frac{a^2}{\sqrt{a^2 - b^2}} \frac{\alpha_i}{4\pi} \frac{F}{M} \]

\[ M_3(\text{TeV}) \approx 0.35 \tilde{m} \]

\[ M > 10^{11} \text{ GeV} \]
Yukawa interactions and Higgs

Yukawa interactions

- SM fermions have $T_3 = -1/2 \rightarrow$ Higgs doublets have $T_3 = 1$ (triplets)
- $W_Y = \lambda^u_{ij} \Phi_i \Phi_j H_u + \lambda^d_{ij} \Phi_i \Phi_j H_d$

The Higgs sector

- Is model dependent
- Two additional Higgs pairs not coupled to the SM fermions
- The Higgs pair interacting with fermions has negative soft masses
**A-terms**

- Do arise from $\delta K = \langle L_2 \rangle$

- Because of the embedding of the messenger $U(1)$ in a larger group ($SU(2), SO(10)$)

- Numerically: $A_t \approx -\frac{\alpha y}{6 \alpha_3} M_3$ (no $A-m^2$ problem)
In order to get a 125 GeV Higgs
2-loop corrections to sfermion masses

- "Minimal" gauge mediation: \(O(1\%)\)  flavour-blind

- Matter-messenger couplings: \(O(3\%)\)  flavour-safe
More details

$$\delta \tilde{m}_f^2 = \frac{2y_f^* y_f^T}{(4\pi)^2} \left( \frac{T}{2(4\pi)^2} - 2c_f g_r^2 \frac{g_r^2}{(4\pi)^2} + \frac{y_f^* y_f^T}{(4\pi)^2} \right) \left( \frac{F_L}{M_L} \right)^2$$

$$T = \text{Tr} \left( 6y_q y_q^\dagger + 3y_{uc} y_{uc}^\dagger + 3y_{dc} y_{dc}^\dagger + 2y_l y_l^\dagger + y_{nc} y_{nc}^\dagger + y_{ec} y_{ec}^\dagger \right)$$

$$\left[ y^* y^T (8 \text{Tr}(y^* y^T) + y^* y^T) \right]_{12}^D < 1.5$$

$$\left[ y^* y^T (8 \text{Tr}(y^* y^T) + y^* y^T) \right]_{13}^D < 0.5 \cdot 10^2$$

$$\left[ y^* y^T (8 \text{Tr}(y^* y^T) + y^* y^T) \right]_{23}^D < 1.5 \cdot 10^2$$

$$\left[ y^* y^T (8 \text{Tr}(y^* y^T) + y^* y^T) \right]_{12}^U < 6.$$
Summary

Supersymmetry breaking remains the key of phenomenologically and theoretically successful supersymmetry models.

Phenomenological issues/guidelines: FCNC, fine-tuning

Theoretical issues/guidelines: Str, R-symmetry

A simple, theoretically complete, and phenomenologically viable option

Susy breaking is communicated by extra, SB gauge interactions

Messenger and observable fields are charged under the hidden sector gauge group

Positive sfermion masses arise at the tree level, in a dynamical realization of TGM, but are not hierarchically larger than gaugino’s

A-terms are generated, and are possibly sizeable